UNIT OPERATIONS AND PROCESSING EQUIPMENT IN THE FOOD INDUSTRY

Transporting Operations of Food Materials Within Food Factories

Edited by

Seid Mahdi Jafari

Narjes Malekjani

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Dedication

To my dear wife Elham. Without her love and support, the completion of this work would not have been possible.

Seid Mahdi Jafari

To my dear sister Mona. Without her love and support, the completion of this work would not have been possible.

Narjes Malekjani

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Preface

The overall aim of Volume 3 *Transporting Operations of Food Materials Within Food Factories* is to explain the processing operations and equipment necessary for the storage and transportation of food materials within food production factories. These processes and unit operations are very important in terms of hygienic conditions and also economic feasibility. All chapters emphasize the fundamentals of experimental, theoretical, and/or computational applications of food engineering principles and the relevant processing equipment.

After presenting an introduction to food material handling within food factories in Chapter 1, "Receiving and storage facilities" are covered in *Part One* including storage vats, vessels, and tanks (Chapter 2), pallets and bags (Chapter 3), and silos and bins (Chapter 4). *Part Two* is devoted to "Liquid food transportation" including fundamentals of pumping/piping (Chapter 5), centrifugal pumps (Chapter 6), and positive displacement pumps (Chapter 7). Another important field, i.e., "Solid and semi-solid transportation" is explained in *Part Three* including the fundamentals of conveyors (Chapter 8), different mechanical conveyors (Chapter 9), pneumatic conveyors (Chapter 10), and hydraulic conveyors, bucket elevators, and monorails (Chapter 11). Finally, *Part Four* covers "General material handling machines in food plants" such as hand trucks, lift trucks, rich trucks (Chapter 12), and robotics (Chapter 13).

This book will be a useful reference for food engineers and can serve as a textbook for advanced undergraduate and graduate students in food science and technology, and also for technologists, researchers, investors, government officials, and all people concerned with food processing operations. This book will also be a useful reference for mechanical, electrical, chemical, and industrial engineers working in the field of food processing and within food factories as it will help them become familiar with particular food processing operations and equipment. All those who are engaged in food processing operations worldwide can use this book as either a textbook or a reference, which will give the readers good knowledge and understanding of different transporting facilities and equipment for various forms of food materials (liquids, semi-solids, and solids), as well as their novel applications in developing food processing factories. Some specific benefits are:

- Novel applications of pumping and conveying operations in the food industries
- Improving the quality and safety of food products with good transporting operations
- Different alternatives for transportation operations

- New opportunities in food processing through innovative transporting operations
- Concerns about the transportation of different food products and raw materials
- A better understanding of the equipment in transportation operations

In fact, the storage and transportation of raw food materials and food products within food factories is a common and frequent operation that needs the attention of experts and engineers. Nowadays, modern equipment with high automation is being applied in these unit operations, which every expert in food processing operations should be familiar with, and this is the main topic of the present book.

We appreciate the excellent cooperation of all the authors of the chapters for taking time from their busy schedules to contribute to this project. Also, we express our sincere thanks to all the editorial staff at Elsevier for their help and support throughout the project. Finally, a special acknowledgment goes to our families for their understanding and encouragement during the editing of this important project.

Seid Mahdi Jafari
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Chapter | One

Introduction to food material handling within food factories

Narjes Malekjani[a] **and Seid Mahdi Jafari**[b,c]
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1.1 Introduction

In food processing plants, independent of the production size, material handling should be performed. It includes handling of raw materials, intermediates, and final products from when they are received in the factory and stored as raw materials, during production processes up to the storage of the finished goods. According to the definition of the American Material Handling Society (AMHS), "Materials handling is the art and science involving the moving, packaging, and storing of substances in any form" (Kulwiec, 1985). There are also other definitions for material handling, e.g., another definition introduces material handling as "material movement and storage using appropriate equipment and approaches at the lowest cost" or "all movements in the plant except the inspection and processing operations." From another viewpoint, material handling is "the science and art of elevating, transporting, positioning, conveying, packaging, and storing of the materials."

In food processing plants, material handling is very important because food materials have a biological and fragile nature. They can be deteriorated by insects and microorganisms, so the proper design of transportation and storage systems in the food industry is more critical than in other industries. The surfaces of the equipment in contact with the food material should be constructed by stainless steel or other approved material that is resistant to corrosion and can be cleaned thoroughly. Also, sanitary fittings must be used and the pipelines

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should be designed in such a way that stagnation zones are eliminated and easy drainage takes place. Control of humidity and temperature of storage facilities and minimizing food contact to oxygen helps minimize the chemical deteriorative reactions (Rao, 2006).

Material handling is not generally considered a production process because it does not add any value to the product. It just helps the production process. Due to its high costs, efforts should be made to reduce or eliminate material handling as much as possible. In many cases, manual handling is replaced by mechanical handling of materials to decrease costs. The characteristics of material including volume, weight, and process throughput affect the handling process design and selection. The mentioned points indicate that the design of proper material handling facilities is very important in order to achieve an economical production process. Some of the most important requirements of a proper material handling design are shown in Fig. 1.1.

In order to yield greater efficiency of material handling systems, the following issues should be considered:

- Materials are better handled in bulks.
- All movements should be minimized and just necessary moves should be done. In order to do this, the related processes should be located at a close distance.
- It is better to group or package materials to be handled more easily.
- Manual handling is better minimized and continuous handling should be used.
- Automation should be applied when possible.
- The operations should be merged to avoid further movement between them.
- Material flow should be optimized and direct paths should be designed.
- All of the building height layers should be used.
- Handling equipment should be compatible with different applications.
- Gravity should be used when possible (Fellows, 2017).

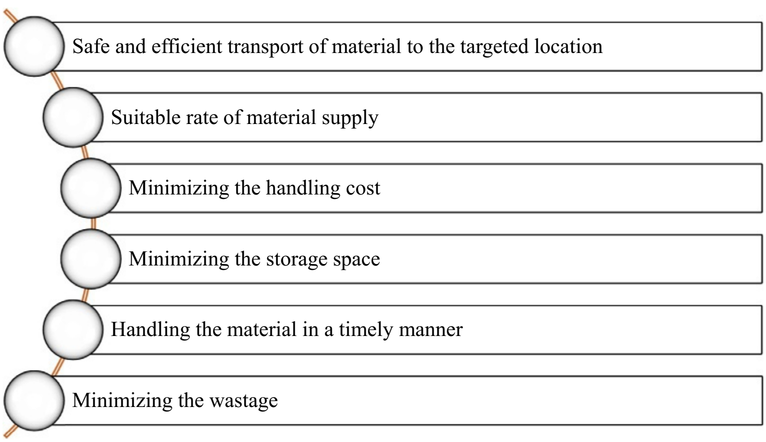

FIG. 1.1 Essential requirements of a proper material handling design.

1.2 Why material handling is important?

As was mentioned, material handling does not add any value to the product but it helps the production processes. A suitable design of material handling equipment increases the profitability of the plant. An improper material handling design might even cause the financial breakdown of a factory. A properly designed material handling system should be cost-effective, reduce the damage and accidents during handling, and improve the production efficiency by delivering the right amount of material at the desired place in the production line (Ray, 2007a,b).

1.3 Handling related food properties

The principal issue in the selection of material handling equipment is the type of material to be handled including gases, liquids, semi-liquids, and solids. Fig. 1.2 shows the handling related characteristics of different types of materials.

1.3.1 Density

Density is defined as the ratio between mass and volume (kg/m^3). It might change with temperature and pressure variation. Density is used in some quality control and equipment design purposes. One of the main applications of density is the size determination of the storage facilities. It is also important for sorting, grading, separation, mixing, size reduction, and many other processes (Ortega-Rivas, 2011).

For liquid or gas materials, the density definition is straightforward: the mass of the fluid that fills a unit volume. So when it is said that the density of water = 1000 kg/m^3, it means that 1000 kg of water occupies 1 m^3 of volume. In the case of particulate solids, they do not fill a vessel or container

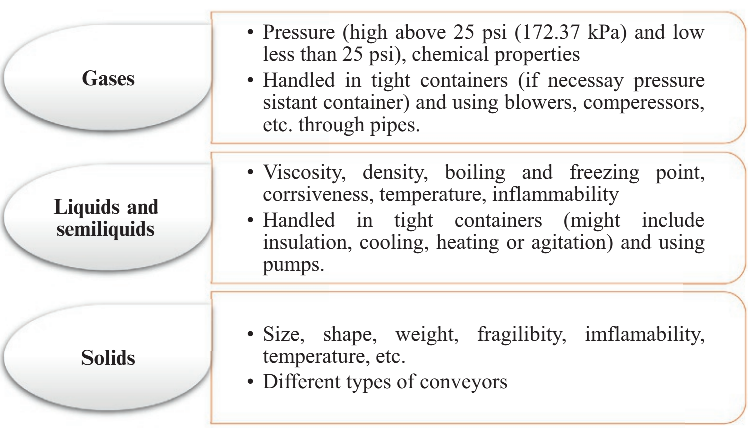

FIG. 1.2 The handling related characteristics and equipment used for handling different types of materials.

like liquids and gases because of special geometrical properties. So the concepts of solid density and bulk density are introduced for handling, storage, transportation, sorting, etc. in the food industry. Bulk density is a more common term for describing the density of powders and granular material and is defined as the mass of bulk divided by its volume. It is directly dependent on the density of particulate solids, their size, and geometry (Jafari, 2021).

1.3.2 Viscosity

Viscosity is defined as the internal resistance of the material to flow which is a very important property in piping systems. It changes with temperature variations during the thermal processing of food and affects the required power for pumping the food material. Based on the relationship between shear stress and shear rate, different fluids are categorized. If this relationship is linear, the fluid is called Newtonian; otherwise, it is called non-Newtonian. Water, fruit juices, cream, honey, and syrups are Newtonian food fluids while suspensions, emulsions, gums, proteins, and starches are non-Newtonian.

Information regarding the changes of fluid viscosity during operations involving temperature changes and shear stress is very helpful in their transportation and handling processes.

1.3.3 Geometrical properties

Agricultural raw products have different shapes and sizes depending on their variety and maturation. Geometrical properties include shapes, size, dimensions, and specific surface area of food units. If the food units are of regular geometry, it is much easier to transport them, especially using high-speed automated operations.

1.3.4 Flow properties

In liquids, density and viscosity are two important characteristics that determine the flow of liquids in the pipelines and also the resistance of storage facilities to the pressure related to the liquid head or hydrostatic head.

In a solid material, the aerodynamic and hydrodynamic properties are very important in their transportation by air and water streams. Conveying powders, granules, or small particulate food products is performed using hydraulic or pneumatic conveyors or by their weight (gravity). The properties of solids that are important for the design of storage facilities and solid conveying systems are density, size, shape, frictional properties such as angle of wall friction, angle of internal friction, failure properties such as failure function, ultimate tensile strength, cohesion, humidity, temperature, and also the environmental conditions (Varzakas and Tzia, 2015). More details about material handling related properties are presented in Chapter 8.

1.4 How to select a proper material handling system?

Conveying liquid and semi-liquid food materials is performed using pumping systems while mechanical conveyors are usually used to transport solid food materials, food containers, and packages. The process for handling gases and liquids/semi-liquids is usually called pneumatic conveying and hydraulic conveying, respectively. In the case of large food pieces, hydraulic conveying is also used. Pumps, conveyors, elevators, cranes, chutes, and trucks are the most important material handling equipment in food plants (Ray, 2007a,b).

In the case of solid materials, two classifications exist including bulk load and unit load. Unit loads refer to the formed solids of different shapes, sizes, and weights (Kill, 2013); for example, targeted products such as bags, containers, packaged material, etc. Equipment such as trucks are generally used to handle unit loads (Chapter 12). Also, some types of conveyors might be used for packaged and cartooned products (Chapter 9). Unit loads can be classified based on different characteristics, as shown in Fig. 1.3.

Handling material with the principle of the unit load has many advantages including cheaper and faster transportation, optimized space utilization, reduced damaged products, and also enhanced safety.

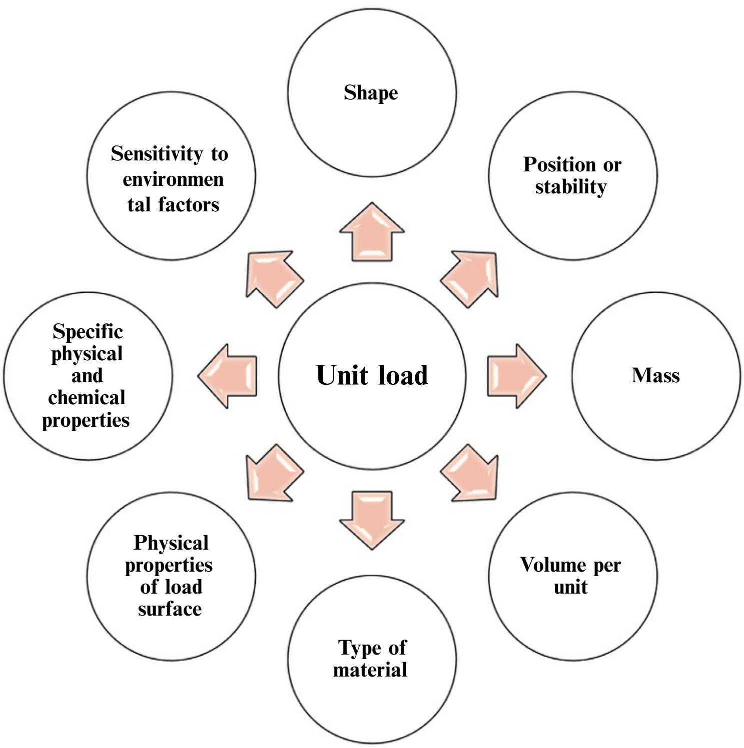

FIG. 1.3 Classification of unit loads.

The other categorization of solid materials is bulk load that includes lumpy, powdery, and granular materials such as sugar, flour, different grains, beans, etc. Some of the most important handling related properties of bulk materials are bulk weight, lump size, specific weight, water content, sensitivity to infection, flowability, angle of repose, temperature, abrasiveness, inflammability, stickiness, dust production, etc. Also, factors such as distance, frequency, and speed of the equipment should be considered in the selection of bulk material handling systems. Bulk materials are usually handled using different types of conveyors (Chapters 9 and 10), bucket elevators (Chapter 11), or when collected in containers and bags using cranes and trucks (Chapter 12). Bulk materials are stored in different types of silos and bins (Chapter 4).

In the food industry, the bulk handling equipment has many advantages in flour mills and the bakery industry. In the latter, the ingredients such as sugar, milk, flour, fats, glucose, and syrup are received in the form of bulks.

1.5 Material handling principles

Different principles have been developed for material handling equipment systems. Each of these principles is applicable in a specific material handling operation, so the suggestions in them might be contradictory to each other. Here just the basic principles are introduced and readers are referred to Ray (2007a,b) for detailed categorizations.

The first and most basic principle is the "planning principle." It mentions that all handling operations should be planned. In order to achieve such planning, the following suggestions are proposed:

- The plant layout must be considered carefully before designing the equipment and production lines.
- The correct location for the supply and disposal of material should be planned.
- Enough space should be considered for storage space.
- Materials should not be placed on the ground directly; instead, pallets, skids, etc., should be used.
- The same container is better used for transporting a material (if practicable).
- Economic motions should be taken into account.
- It is better to perform inspection or some operations during material transportation, if possible.
- Manual handling should be used wisely and at the minimum.

1.6 Classification of material handling equipment

It is possible to categorize the material handling equipment based on their working path/area, as follows:

- Fixed path: they can convey material from one point to another point. Examples of such systems include the chain mesh belts that convey bakery products in continuous baking ovens, sorting belts, and conveyor belts that supply empty cans.

- Fixed area: they can convey material within a specific volume such as cranes that handle heavy loads in a manufacturing plant.
- Variable path and area: they can move all around the manufacturing area such as forklifts, trolleys, dollies, and also manual handling facilities.

Material movements in food plants should be simple and also avoid cross-contamination of the final products by the ingredients and raw material. Table 1.1 presents some applications of material handling equipment (Fellows, 2017).

Another classification might be based on the equipment types including receiving and storage facilities, pumps, conveyors, trucks, and robotic handling systems, which is discussed briefly in the following sections.

1.7 Receiving and storage facilities

Storage of raw food material is a critical step that has a direct impact on processing effectiveness and final product quality. The two most important requirements in designing food storage equipment are: (1) the storage systems should be designed and constructed depending on the volume and type of the materials equipped with instruments to adjust environmental conditions; (2) monitoring equipment should be selected based on meeting high hygienic standards.

Prior information regarding deterioration mechanisms in certain food materials during storage is helpful to avoid spoilage and quality loss until entering the production line. Three main spoilage mechanisms of food materials include contamination by different microorganisms and insects, biochemical processes such as respiration in fruits and vegetables, enzymatic browning, oil oxidation, and physical deterioration such as damage, crystallization, and dehydration (Grandison, 2005).

The storage of raw food ingredients or final products can be performed under atmospheric or controlled conditions (temperature, humidity, etc.). The composition of the storage atmosphere, its temperature, and humidity are three factors that have a direct impact on product quality. So the environmental conditions should be controlled carefully based on the material to be stored.

1.7.1 Liquid storage

Liquid storage facilities are one of the most important equipment in dairy, juice, beverage, and many other food plants. The design of storage tanks is directly proportional to the nature of the product to be stored. For example, for dairy product storage tanks, more considerations and higher restrictions should be taken into account due to the high microbial risks. For syrups and liquid sugar, storage tanks can be made of mild steel or fiberglass made of food-grade resins. In the edible oil production industry, the storage tanks are made of mild steel (Rao, 2006).

To determine the volume of tanks, it is essential to know the density of the liquids to be stored. Liquid viscosity is also an important property that affects

TABLE 1.1 Some applications of material handling equipment.

	Conveyors	Elevators	Cranes and hoists	Trucks	Pneumatic equipment	Water flumes
Direction					*	
Vertical up		*	*		*	
Vertical down		*	*		*	
Incline up	*	*			*	
Incline down	*	*			*	*
Horizontal	*			*	*	
Frequency						
Continuous	*	*			*	*
Intermittent			*	*		
Location served						
Point	*	*			*	*
Path	*				*	*
Limited area			*			
Unlimited area				*		
Height						
Overhead	*	*	*		*	
Working height	*			*	*	*
Floor level	*		*	*		*
Underfloor	*				*	*
Materials						
Packed	*	*	*	*		
Bulk	*	*	*	*	*	
Solid	*	*	*	*	*	*
Liquid				*	*	*
Service						
Permanent	*	*	*		*	*
Temporary			*	*		

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the transportation and drainage of liquid foods (Ortega-Rivas, 2012). The data regarding the density of food material can be obtained from empirical equations that calculate the density based on another property; for example, calculation of fruit juice density based on the refraction index (Riedel, 1949), skim milk as a function of temperature (Short, 1955), cream as a function of fat content and temperature (Phipps, 1969), and tomato juice as a function of water and solid content (Choi and Okos, 1983). Details of liquid storage equipment are presented in Chapter 2.

1.7.2 Solid storage

Pallets are horizontal platforms used as a base for handling unit loads. Various types of pallets are available (Chapter 3). They can be made of wood, steel, plastic, aluminum, etc. Plastic pallets are widely used in the food industry due to good hygienic practices. They can also be easily cleaned.

Storage of bulk materials such as rice, soybean, corn, flour, peas, sugar, etc. is usually performed in silos and bins. There are various types of silos and bins available in the food and agriculture section. The selection of a suitable silo/bin depends on the properties of the materials to be stored. Generally, they should be resistant to moisture, insects, and rodents. Another important characteristic of silos/bins for the food material is the suitable in- and outflow of material. Details of silos and bins are presented in Chapter 4.

1.8 Liquid food transportation

Pumps are mechanical devices that use energy to raise the static pressure and flow rate of a liquid or semi-liquid material. The selection of a suitable pump is dependent on the type of material to be transported such as temperature, viscosity, flow rate, pressure, etc., and the specific conditions of food processing. The fundamentals of fluid flow and piping systems are presented in Chapter 5. There are two important classifications for pumps including centrifugal pumps (Chapter 6) and positive displacement pumps (Chapter 7).

1.9 Solid material transportation

Transportation of solids is generally performed using conveyors. The basic principles of material handling using conveyors are presented in Chapter 8. Different mechanical and pneumatic conveyors are introduced in detail in Chapters 9 and 10, respectively. In Chapter 11, hydraulic conveyors, bucket elevators, and monorails are introduced in detail.

1.10 Industrial transportation vehicles

Trucks are known as industrial vehicles providing a flexible approach for distributing various materials throughout plants. So information about these facilities is important in their selection and proper utilization. Different types of industrial trucks are used in food plants. They can move all around the plant and if special attachments are connected to them, they can handle different shapes of material. Nowadays, it is preferred to use electric trucks instead of combustion engines in food processing plants to avoid contamination of the food by exhaust fumes. These vehicles are classified into two categories including hand trucks (or non-powered trucks) that work manually and powered trucks that are operated using a motor (Ray, 2007a,b). The other category of trucks includes platform trucks, low-lift trucks, and high-lift trucks. In the platform trucks, the material is loaded or unloaded on a wheeled platform, using mechanical power or by hand. In low-lift trucks, they are able to lift the material off the ground and let them move freely. The material can be elevated in high-lift trucks and moved to the racking systems. In Chapter 12, different types of industrial transportation vehicles are explained.

1.11 Robotics for material handling

Technological developments in food processing are thriving on the utilization of robotics for automation in material handling and conveying, which are labor-intensive processes. Recent research showed that applying robots improved throughput, quality, flexibility, and consistency of work while decreasing ergonomic hazards for workers. The food industry has been evolving continuously in implementing robots due to the varied characteristics of different food materials such as shapes, sizes, and more importantly their vulnerability to mechanical damage. To develop successful robotic effectors, mechanical properties, handling difficulties, environmental and hygiene parameter effects must be considered for food handling operations with minimum damage. Chapter 13 focuses on the mechanism of end effector robots in the food handling processes, their classification, design parameters, and potential applications in various food industries.

1.12 Conclusions

Transportation of food materials within food factories is a mandatory operation in all food plants; it starts from receiving the raw material in the plant until storing the final product. Due to the biological nature of food products, it is very important that the material handling operations be performed in hygienic conditions with minimum loss and deterioration in the quality of the products. Many principles are developed for designing proper handling facilities. In this chapter, the definition, importance, and basic principles of material handling were discussed.

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PART | ONE

Receiving and storage facilities

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Chapter | Two

Storage vats, vessels, and tanks

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2.1 Introduction

To preserve the food quality and ensure the prevention of physical and microbial contaminations of food products, sanitary design, fabrication, and operation of food processing equipment involve the selection of appropriate materials of construction and proper design. Continuous or non-continuous cleaning and sanitation of the equipment should be conducted easily using appropriate techniques and by utilization of controlled, automated, and integrated processing systems. In food processing, plant and equipment maintenance is of utmost importance. Among the food industries, those which have more or less fluid products, with a higher level of mechanization and automation and stricter regulations, such as dairy processing plants are more advanced than other food processing plants (Tamime and Law, 2001).

In the design, construction, operation, and maintenance of the general food industry processing equipment, the properties and the cost of construction materials are the most important factors. These materials and their application are selected based on the principles of metallurgy and materials science. Metals, plastics, and glass-ceramics are the main materials being used in food processing equipment. Furthermore, in some special applications, wood and some natural fibers are being used. The mandatory properties of the construction materials used for the food equipment are as follows:

- mechanical strength
- easy fabrication
- easy repair
- corrosion resistance

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- hygienic properties
- desirable thermal properties.

The suitability for the anticipated application, the constructional and operational characteristics of the equipment, and the purchase and maintenance costs are the important selection criteria of food processing equipment materials (Saravacos and Kostaropoulos, 2015).

In order to permit efficient, safe, and hygienic operation, maintenance, and cleaning, every food industry equipment must be designed accordingly. Under the conditions of use, all materials processing equipment and packaging materials in contact with food must be inert to the food and must not migrate to, or be absorbed by, the food. The internal surfaces must be non-porous and smooth so that small food particles, bacteria, or insect eggs cannot remain in the microscopic surface pores. This prevents difficulties in dislodging and inhibits them from becoming a potential contamination source. All the food contact surfaces must be visible for inspection, or the equipment must be designed in a way that disassembling for inspection is possible. Additionally, routine cleaning procedures to eliminate the possibility of bacterial or insect contaminations should be in place. If such a design is not available or possible, the equipment must be readily accessible for manual cleaning. When clean-in-place (CIP) systems are used, it must be verified that the results attained without disassembly of the equipment are equal to those achieved by disassembly and manual cleaning (Baker, 2013).

Storage time in food processing and manufacturing may be short or long. A preliminary stage of processing might be short-term storage, as in the case of milk and tomato manufacturing, or it may be involved in a later stage, for example, in the case of supplementary substance addition. To secure a continuous flow of raw material in manufacturing, long-term storage is used, e.g., in the case of grain silos or the aseptic storage of concentrated juice in tanks. Measures must be undertaken in long-term storage, in order to protect the product from spoilage or degradation. The size of the storage equipment can be classified into large scale (silos, tanks) and small scale (pallets, boxes, vats) (Saravacos and Kostaropoulos, 2015).

By definition, a tank is a large receptacle for storing, holding, or transporting liquids and a vessel is a container for holding substances, especially liquids, for example, a cask, bottle, kettle, cup, or bowl. Although their design can vary significantly, storage vessels can be viewed as large, closed containers. Vats, which are large open basins or pans, are becoming increasingly uncommon in the modern food industry. The reason for this is that if the product is susceptible to microbial and other contaminations, controlling the open processes is very challenging. In the traditional processes, open vats are commonly used for fermentation processes, while in the modern food industry, closed processes have become more prevalent to avoid contamination and to ensure reproducibility. On the other hand, open tanks and containers are used in the food industry for handling less sensitive ingredients or for some processing steps, e.g., in the processes such as mixing or in transporting food from one process area to another (Hofmann, 2011; Holah and Lelieveld, 2011).

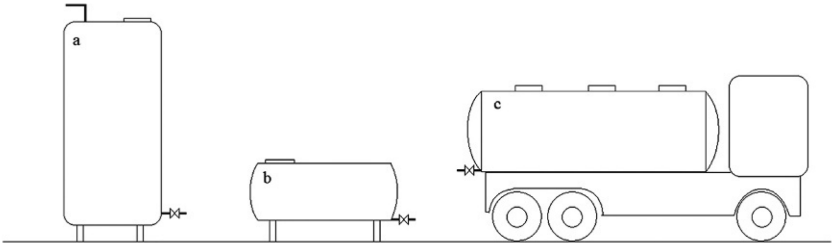

FIG. 2.1 Fixed [vertical (A), horizontal (B)], and transportable (C) tanks.

Fixed and transportable are two main categories of tanks which are used in food processing. The fixed tanks are subdivided into horizontal and vertical (Fig. 2.1). For the storage of liquid foods and fruit/vegetable concentrates and pulps in the food industry, tanks are widely used. Most tanks are cylindrical, but for reducing the height of horizontal tanks, they may have an elliptical cross section. Usually, the horizontal tanks are smaller than the vertical tanks. As in the cases of aseptic storage or controlled atmosphere storage (e.g., wine), product in tanks has little or no contact with the environment. Except for elevated small tanks, most tanks stand on the floor. Most tanks are immobile, but some tanks are transported by trucks, railroads, ships, or cranes (Saravacos and Kostaropoulos, 2015).

In the food industry, for the temporary storage of highly viscous foods such as concentrated juice, fruit pulp, processed cheese, dough, etc., or relatively small quantities of liquids, vats, and vessels are used. Additionally, using as auxiliary equipment in food processing is another application of vats and vessels. Cheese processing (cutting of crude cheese), filling of marmalade, sausage processing, and various kinds of mixing processes are some examples in which vats or vessels are used as auxiliary equipment. The upper ends of such vats and vessels are usually open; however, covers are used frequently. In terms of mobility, vats or vessels may be mobile or fixed. Metallic legs are often used as stands for fixed elevated vats or vessels. Bracket supports are used under vessels that have free space underneath. Mobile vats may be placed on mobile frames directly below the vat or they may have wheels at the end of their legs (Fig. 2.2A). Moreover, the bottom of the vessels can be regular conical (Fig. 2.2b1), irregular conical (Fig. 2.2b2), inclined (Fig. 2.2b3), or spherical (Fig. 2.2b4). When the contents should be cooled, heated, or maintained at a constant temperature, jacketed vats and vessels can be used (Saravacos and Kostaropoulos, 2015).

Stainless steel is the most used material used for of construction tanks, vats, and vessels used in the food industry. Usually, AISI 304 stainless steel is sufficient for the products which are not stored long in such equipment. In some cases, aluminum, glass fiber strengthened polyester, or plastic materials are also used (Green and Southard, 2019).

Self-draining design, flush joints for avoiding crevices, rounded corners, smooth welds, proper surface finish, and avoiding dead legs are general essential design requirements for maintaining easy cleanability and safe production

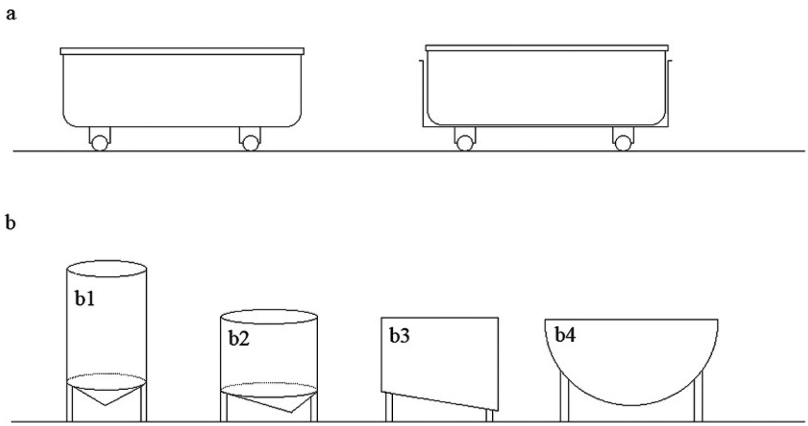

FIG. 2.2 Mobile (A) and fixed (B) vats and vessels [bottom types: Regular conical (b1), irregular conical (b2), inclined (b3), spherical (b4)].

conditions for tanks, vats, and storage vessels in the food industry (Holah and Lelieveld, 2011). Such designs provide the possibility of the application of automatic clean-in-place (CIP) systems (see Section 2.3.1) in combination with some special equipment including but not limited to spray balls, rotary nozzles. These nozzles also need to be self-draining and self-cleaning for a sanitary process (Meyers, 1959). The International Association of Milk and Food Sanitarians in 1953 published the 3-A Sanitary Standards stating that steel (18–8 stainless steel) piping and fitting should have a smooth (120 grit) surface finish (Rankin et al., 2017).

2.2 Industrial vats, vessels, and tanks: Types and applications

Food industry tanks and vessels have different components including a manhole, light and viewports, sampling cock, air vent, thermometer, liquid level gauge, agitator, ladder and top platform, and space for cleaning equipment. Manholes can be circular or oval-shaped and they should be gasketed and have tightening or locking mechanisms. A sampling cock (valve) is used for taking samples from the liquid stored in the tank and should have a sanitary design and be made of stainless steel. The air vent should also be made of stainless steel and is used to prevent vacuum in the tank during emptying of the tank or rapid cooling during CIP. Air vents should have a lid and a stainless steel removable wire mesh to prevent dust, insects, etc. Agitators can be vertical or horizontal and should have oil-less rotary seals and bearings (Choubey, 2017).

2.2.1 Dairy industry

Easy establishment of cleaning, sanitization, and drying is a mandatory design requirement in the modern dairy utensils and milk contact surfaces including dairy vats, vessels, and tanks. Moreover, to ensure proper cooling of the raw milk,

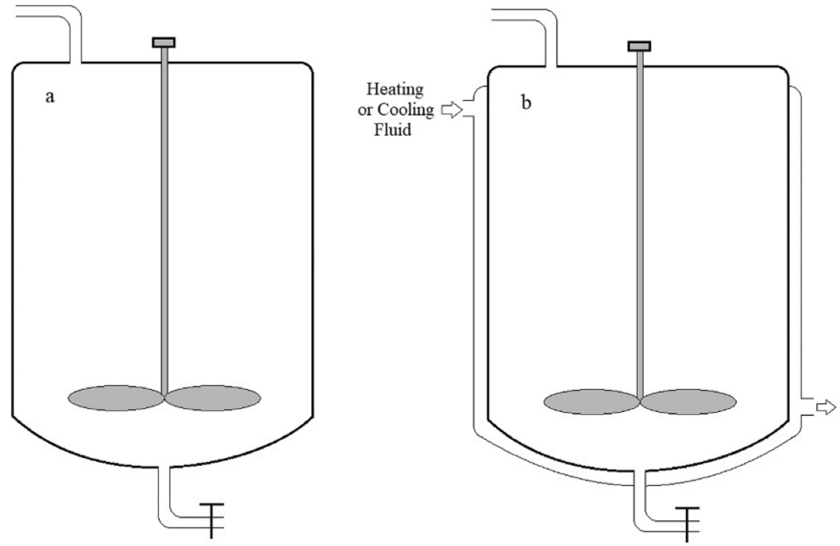

FIG. 2.3 Schematics of single-walled (A) and jacketed (B) stirred tanks.

farm milk cooling tanks also should be equipped with robust refrigeration and agitation systems. Proper cleaning and sanitizing of dairy utensils and plant equipment can ensure the microbial safety of dairy products (Singhal et al., 2020).

In the dairy industry, single-walled and jacketed (double-walled) stirred tanks are used for blending and adding flavors and colors to the dairy products such as ice cream formulations (Fig. 2.3), and aging vats are used in the cooling stage (Almena et al., 2020). Sometimes a third outer wall is added for thermal insulation.

In some traditional cheese production processes, the wooden utensil is preferred to the one made of stainless steel while most industrial-scale cheese productions are conducted use stainless steel equipment to produce cheese clots from pasteurized milk. Since such stainless steel vats cannot host lactic acid bacteria (LAB), inoculating the batch with commercial starter cultures is necessary for the acidification of curd. Commercial starters greatly affect the quality of the final cheese products. On the other hand, the biodiversity of LAB associated with raw milk and wooden equipment is considered a key factor for the organoleptic properties of traditional cheeses such as artisanal cheese. This way of processing, along with the use of indigenous breeds' raw milk, the addition of animal rennet, and the wooden vats, used for collecting and transformation of milk by farmers and cheesemakers, ensures the presence of natural starter microorganisms from various sources (Fig. 2.4), which can act as a desirable reservoir of dairy LAB. Since LAB can adhere to each other and to the wooden vat surfaces because of their self-produced extracellular polymeric substances (EPS) matrix, they can form "biofilms" containing an aggregate of microorganisms. Investigations on these vats have shown the dominance and the persistence of certain LAB species, mainly the common starter LAB (SLAB), such as curd

FIG. 2.4 Traditional wooden cheese ripening vat (Mirecki and Konatar, 2014).

acidification cultures including *Lactococcus lactis*, *Streptococcus thermophilus*, *Leuconostoc mesenteroides*, and *Lactobacillus helveticus*, and some nonstarter LAB (NSLAB) such as *Lactobacillus casei* and *Lactobacillus plantarum* play essential roles during the ripening period. Studies have never shown the presence of pathogenic bacteria on these vats; this could be due to the production of antimicrobial compounds such as bacteriocins in combination with the inhibitory action of the organic acids produced during fermentation by the biofilmogenic LAB (Gaglio et al., 2019; Settanni et al., 2012).

2.2.2 Edible oil industry

For the vegetable oils, rigorous attention must be paid to the maintenance of quality throughout the period from production to delivery to the final processor, especially when the movement of the oil occurs in large quantities and over substantial distances. At present, multicompartment parcel tankers are used for edible oil transportation over long distances. A parcel tanker is an ocean carrier ship that has several compartments for storing different liquids and avoiding their mixing (Fig. 2.5). If the liquid requires the control of temperature at loading and discharge, the parcel tankers are designed and equipped with efficient

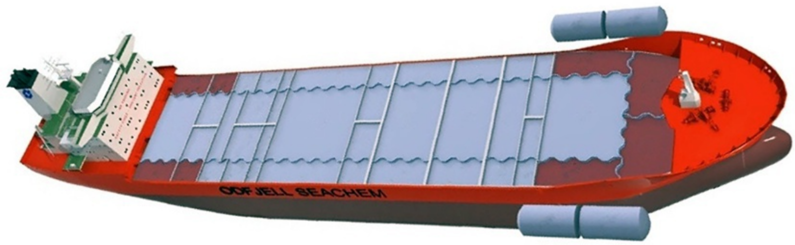

FIG. 2.5 Multicompartmented parcel tanker. *Adopted from Ladage, A., Baatar, D., Krishnamoorthy, M., Mahajan, A., 2021. A revised formulation, library and heuristic for a chemical tanker scheduling problem. Comput. Oper. Res. 133. https://doi.org/10.1016/j.cor.2021.105345.*

temperature control for various parcels of edible oils (Hamm et al., 2013; Neo et al., 2006). Therefore, in the intercontinental edible oil trade, the parcel tankers which are capable of carrying multiple shipments of different triglyceride oils have become the carrier of choice because they may also be used for some regional trade. These types of typical parcel tankers have suitable pumps for loading and discharging a variety of cargoes and they usually contain 35–45 tanks. In the past, a majority of tanks in such vessels were built using coated steel and may have had a few stainless steel tanks. However, stainless-steel tankage is more used in vessels built in recent decades. Although vessels with a smaller capacity are also used for edible oil transport, the total capacity of the usual vessels can be up to 38,000 m^3 of edible oil. (Hamm et al., 2013).

Three categories of parcel tankers are classified by the International Maritime Organization (IMO), of which for the carriage of vegetable oils and fats, types 2 and 3 are mostly utilized. In order to avoid environmental damage, type 2 tankers which are bulk chemical tankers use substantial preventative measures including a 6 m double bottom and a double hull of at least 0.75 m between the inner and outer hulls, whereas type 3 vessels have a single hull only and are used as a bulk chemical carrier. While IMO 2 ships are only allowed to load under 3000 m^3 of product into any single tank, IMO 3 ships are allowed to carry larger volumes. Additionally, according to the regulations, while the vegetable oils can be carried in certain type 3 ships, acid oils and fatty acid distillates must only be carried in IMO type 2 ships (Hamm et al., 2013).

The types of vessels and their operating requirements are defined by the IBC Code (Equipment of Ships carrying Dangerous Chemicals in Bulk) and important implications for the oils and fats trade are defined by MARPOL (The International Convention for the Prevention of Pollution from Ships). In these regulations, 32 fats and oils are listed under the ‘Vegetable Oils’ generic heading (Table 2.1); it should be noted that some of the fats and oils in this list have animal sources. These have a category Y rating and have been assigned a hazard profile by GESAMP (Group of Experts on the Scientific Aspects of Marine Environmental Protection), a technical committee sponsored by IMO, and seven

TABLE 2.1 Fats and oils are listed under the "Vegetable Oils" generic heading in MEPC.2/Circ document (IMO, 2020).

Number	Fat/oil	Number	Fat/oil
1	Castor oil	17	Palm kernel acid oil
2	Cocoa butter	18	Palm kernel oil
3	Coconut oil	19	Palm kernel olein
4	Corn oil	20	Palm kernel stearin
5	Cottonseed oil	21	Palm mid-fraction
6	Fish oil	22	Palm oil
7	Groundnut oil	23	Palm olein
8	Illipe oil	24	Palm stearin
9	Jatropha oil	25	Rapeseed oil
10	Lard	26	Rice bran oil
11	Linseed oil	27	Safflower oil
12	Mango kernel oil	28	Shea butter
13	Non-edible industrial-grade palm oil	29	Soyabean oil
14	Olive oil	30	Sunflower seed oil
15	Palm acid oil	31	Tallow
16	Palm fatty acid distillate	32	Tung oil

other agencies in the UN. Bulk shipment of vegetable oil products can only be carried in the sea if their name is included in the MEPC.2/Circ document (Hamm et al., 2013; IMO, 2020).

The vegetable oil industry is increasingly requiring stainless-steel tankage but for short storage of bulk moved edible oils, mild steel, stainless steel, and coated steel tanks of varying capacities can be used in the larger installations, ranging from 300 to 40,000 m^3 capacity. In some cases, tank heating is also available (Hamm et al., 2013).

The formation of flammable mixtures inside the edible oil storage tanks due to the residual solvent may lead to safety concerns. Since vegetable oils are usually stored in vessels without any inertization system at ambient temperature and pressure, a confined explosion of the storage vessel in the presence of accidental ignition can occur due to the formation of flammable mixtures by the accumulation of residual solvent vapor mixed with air. Such a formation of flammable mixtures is especially significant in the case of high residual solvent contents and high operative temperature that increase the probability of an explosion occurring in the presence of accidental ignition. Even though the residual solvent inventory in an edible oil refinery is limited, the potentiality of the formation of flammable mixtures during processing or storage cannot be neglected (Landucci et al., 2011).

2.2.3 Alcoholic beverages industry

Various vats, vessels, and tanks are used in the alcoholic beverages industry. However, the use of traditional vessels and containers is still of interest in some areas of the world. One such traditional container is called an amphora which is a jar with one or two vertical handles (Fig. 2.6). The first information regarding the use of amphorae, called kvevri, that were used for fermentation and storage of wines dates back as early as 6000 BCE to the ancient Georgians. The ancient Greeks and Romans performed grape fermentation in large clay containers called dolia. Instead, the aging and transport of wine occurred in smaller sealed terracotta amphorae. Consecutively, wooden barrels (Fig. 2.7) and stainless steel tanks in the wine industry replaced the clay containers. However, these three types of containers have a variety of effects on wine quality. Since stainless steel does not allow gas exchanges and does not release substances in the wines, it is generally considered an inert material. On the other hand, wooden barrels and amphorae interact with wines by releasing and adsorbing compounds and by allowing micro-oxygenation, due to their porous nature. However, very limited data are available on the oxygen transmission rate (OTR)

FIG. 2.6 Photographs of two ancient amphoras (Hansson and Foley, 2008).

FIG. 2.7 Wine aging wooden barrels (Nevares and del Alamo-Sanza, 2018).

through such containers in the literature. This is due to the fact that several factors such as stave thickness, wood moisture content (OTR increases as the moisture content decreases), types of wood, and measurement methods affect OTR (Baiano and Varva, 2019).

2.2.4 Non-alcoholic beverages industry

Some vats, vessels, and tanks that are used for non-alcoholic beverages are similar to those used in the alcoholic beverages industry. Non-alcoholic beverage mixing vessels are usually made of high-grade stainless steel, with sometimes a top cover that allows access for ingredient addition, which is an ideal unit for mixing beverage ingredients. The blending of the beverage ingredients can be carried out using different methods. In the bath blending method, the ingredients, usually powders or liquids, are mixed in a large batch tank (Lea, 2016). The mixing vessel is usually fitted with a stirrer; depending on whether sugar is to be added as a syrup or a crystalline solid (thus needing dissolution), the design and required power of the mixing tank can vary. To mix the components adequately, either a side entry unit or a top-mounted propeller stirrer is installed. In some cases, fixed baffles are mounted on the internal surface of the tank to improve mixing and prevent a liquid vortex (Fig. 2.8). Since a powerful liquid vortex can draw in unnecessary air in the product, the use of a stirrer that creates such a vortex should be avoided (Ashurst, 2016).

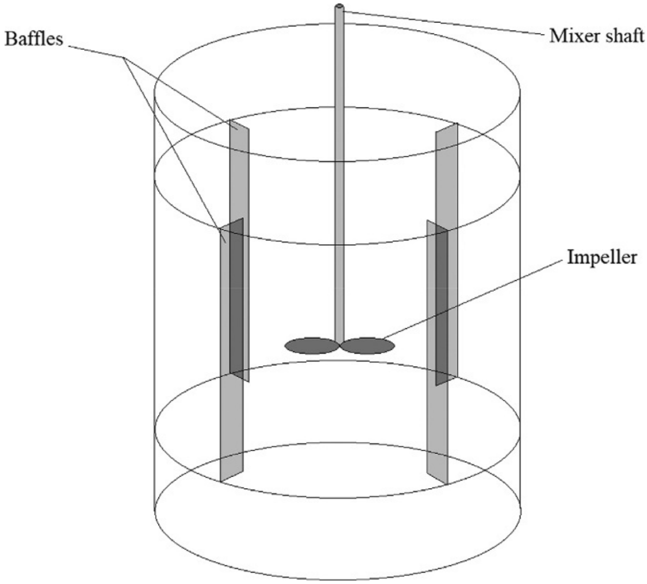

FIG. 2.8 Schematic of a mixing tank with wall baffles.

Additionally, bulk tankers are usually used to fill the storage tanks or silos and bulk ingredients can be weighed or metered directly from storage. Prior to addition to the main mixing tank, a smaller premix tank is usually used to combine the minor ingredients. To maintain temperature, heating or cooling may be needed for some of the ingredients that have an endothermic or exothermic solution reaction. For the mix and premix tanks, there is a variety of stirrers and mixers available. They range from specially designed high-shear mixing heads to simple propellers. Moreover, powders are dissolved either indirectly using a vortex-type mixer directly or a premix tank, or in the main mixing tank. In indirect mixing, in a vortex-type mixer, a horizontally mounted pump head to recirculate the fluid in the batch tank is used to create a vortex then the powder is added to the tank (Lea, 2016).

Another ingredient is carbon dioxide which is used for the production of carbonated beverages. Most of the time, carbon dioxide is delivered as a liquid, using special road tankers. It is then transferred to 5–50 tons pressurized vessels and held at 20.5 bar pressure at −17°C. A small refrigeration unit is usually used to maintain the temperature. Another type of pressurized vessel in this industry is carbonators which are also vessels pressurized with carbon dioxide gas to facilitate the absorption of carbon dioxide by the liquid (Steen, 2016).

2.3 Engineering aspects of tanks and vessels

Stainless steel is the most common building material for most food industry storage vats, vessels, and tanks that are made of stainless steel. Stainless steel is an alloy of steel containing iron, nickel, and chromium. It usually contains varying amounts of nickel and 9%–30% chromium as well as other elements such as copper, sulfur, titanium, niobium, molybdenum, etc. These elements are added to the alloy to modify the chemical resistance and mechanical properties of stainless steel. Despite its popularity in the food industry, stainless steel has some limitations including low thermal conductivity and is susceptible to corrosion by acidic products at high temperatures and acidic food such as some fruit juices and lactic acid-laden dairy products. Modification of the alloy components and fabrication conditions, as well as optimization of the processing conditions, and careful maintenance can deal with these limitations. Different types of corrosion can happen to the stainless steel equipment, namely general corrosion, aqueous corrosion, high-temperature corrosion, etc. Mechanical cleaning, passivation, electro-polishing, and pickling are some of the surface treatments that can be used to prevent corrosion in stainless steel equipment (Dewangan et al., 2015).

Independent of the product or the process, in order to maintain safe production conditions and easy cleanability, following general design requirement rules is necessary. The retention of the product within the equipment itself or some other part of the production process can lead to product spoilage or alteration; therefore, the production equipment must be designed to eradicate such problems. To a large extent, such preventive measures can help to ensure product safety. Then again, the design must allow for effective and rapid cleaning, if cleaning is necessary, and an adequate drying process if necessary (Hofmann, 2011).

2.3.1 Clean-in-place (CIP) considerations

The production of any high-quality product for human consumption requires the maintenance of the highest plant hygiene standards as a prerequisite. To fully assure the final product's quality, the highest care and attention must be paid to the cleaning and subsequent disinfection or sterilization of any item of processing plant or equipment. Cleaning-in-place (CIP) is now a routine activity in almost all dairy, beverage, and processed-food production plants (Tamime, 2009). CIP can be defined as an acceptably high and consistently reproducible process of circulating detergent chemicals and/or water through plant equipment, while the equipment remains assembled as it is in the production line. CIP must be carried out in a way that all food contact surfaces are properly cleaned, rinsed, and where necessary disinfected or sterilized. Thus, any discussion of engineering design in relation to hygiene and cleaning tends to focus on the design and installation of the equipment in this way (Tamime, 2009). Therefore, the food industry tanks and vessels must be designed in a way that appropriate CIP operations can be conducted in them without any problem or with a minimum requirement for disassembly.

Various types of CIP nozzles (also known as pressure spray heads) are used in tanks and vessels to ensure adequate and thorough cleaning, washing, and rinsing of the internal surfaces. A schematic presentation of some of these CIP nozzles is shown in Fig. 2.9.

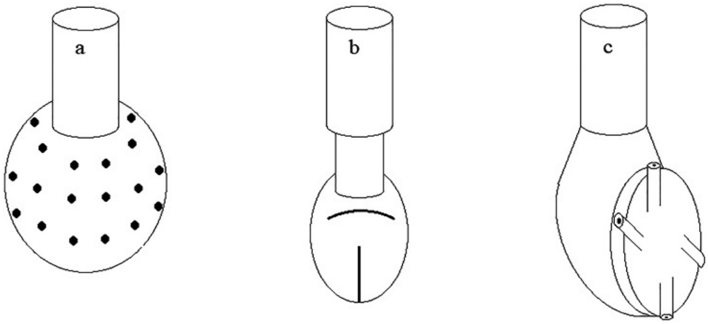

FIG. 2.9 Pictures of different types of CIP nozzles [static spray ball (A), rotary spray ball (B), and rotary jet head (C)].

The required fluid pressure for the CIP system depends on its design and the type of nozzles used in the system. Usually, static spray balls (Fig. 2.9A) are used in low-pressure systems, rotary spray balls (Fig. 2.9B) are used in medium-pressure systems, and rotary jet heads (Fig. 2.9C) are used in high-pressure systems. Increasing the design pressure of the CIP system reduces the required flow rate leading to lower effluent loads, a larger spray diameter, and better mechanical cleaning; however, the capital and operational costs of the high-pressure CIP systems are also higher (Tamime, 2009). Injector sprays and rotating shafts are other less conventional CIP nozzle designs that might be used in some food industries including the dairy industry. An injector spray consists of a mixing valve and a Venturi element that is connected to a detergent tank and a water supply. The detergent is drawn from its tank and mixed with water as high-pressure water flows through the Venturi and the surface to be cleaned is sprayed with this mixture. The rotating shaft is in fact a hollow rotating tube that is installed in the vertical axis of the storage tank, and a slotted jet with a fan shape is attached to it. Pressurized cleaning solutions are thrown out with a fan-shaped pattern while the shaft is rotating with a 5 RPM speed to completely cover the interior of the tank (Meyers, 1959).

2.4 Novel technologies in storage tanks and vessels

To meet the increasing requirements of modern processes in chemistry, the food industry, or biotechnology, as novel measurement techniques are developed, the determination of fill levels in liquid tanks is also under development. Since conventional mechanical measurement devices, e.g., floats, are not possible to install in some applications, contactless and non-invasive level measurement techniques have been developed. The ultrasonic pulse-echo measurement is one of the common new methods, but it is limited to simple applications. This is due to the fact that obstacles inside the tank can prevent the direct view of the acoustic sensor to the liquid surface, which leads to measurement failures. Another obstacle is the liquid's inhomogeneity that can affect the ultrasonic waves' time-of-flight and cause measurement errors (Rautenberg and Henning, 2003).

Automatic process control in any food processing industry including dairy processing can have a positive impact on product quality and by reducing energy usage, waste and costs, it can also improve the process economy. However, the vital principle of such process control is having a precise and exhaustive determination of the state or states of the process, while conventional sensing devices deliver single point information which is often not adequate. In a dairy processing plant, milk storage and mixing tanks at various locations are common process vessels. As an example, agitators with a specific speed and design are used in milk tanks in order to maintain a homogeneous state and inhibit gravitational cream separation. Furthermore, such an agitation process must not cause aeration, while mixing the milk well enough to prevent cream separation (Sharifi et al., 2014).

In order to detect any cases of aeration and cream separation due to faulty agitation, which is difficult to detect in an opaque solution or vessel such as milk storage tanks, the application of Electrical Resistance Tomography (ERT) can provide useful visual insights (Fig. 2.10). The application of information regarding the overall homogeneity or inhomogeneity of the stored milk can be provided using ERT. Additionally, any variation from the desired situation, such as the displacement of an agitator shaft or the presence of undesired objects (e.g., a powder lump), can be detected using this method. In this method, inhomogeneity is detected by the existence of a higher conductivity region (a case of higher concentration milk addition), different composition region (case of cream separation), air (case of aeration and vortex formation), lower conductivity region (case of water addition), and insertion of external objects (Sharifi et al., 2014).

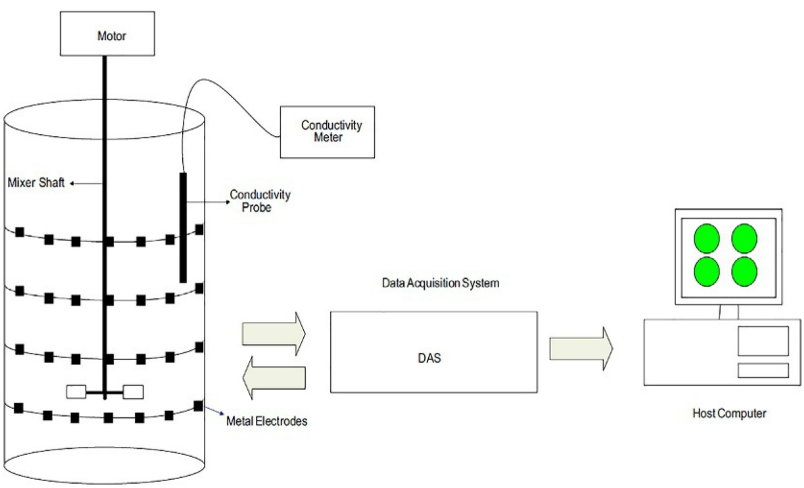

FIG. 2.10 Schematic diagram of a tank equipped with an Electrical Resistance Tomography system (Sharifi et al., 2014).

2.5 Conclusions

Storage vats, vessels, and tanks in the food industry are basic yet very important pieces of equipment. Although stainless steel seems to be the material of choice for the fabrication of food industry vats, vessels, and tanks, some traditional materials such as wooden containers or pottery have been reported to possess some unique properties that can contribute to the quality of some products such as cheese or wine. Novel sensing methods such as Electrical Resistance Tomography are also demonstrating appealing abilities in the inline determination of the condition and composition of storage tanks and are worthy of further research.

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Chapter | Three

Pallets and bags

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3.1 Introduction

Packaging can be an important resource for improving efficiency in the supply chain and advertising products and companies. The main processes of the supply chain, such as storage and transportation, are usually facilitated by reusable transport items (RTIs) (Zhou et al., 2018). A unit load is an assemblage into which a number of individual items are combined, typically on a pallet, to facilitate material handling and storage operations. With logistic and technology development demanding express transportation service and commerce on a global scale, the unit mode is widely implemented in logistics. Integrated packaging, such as pallets, container cages, and bags, is employed for a cheap, efficient, and convenient unitized logistics mode (Zhou et al., 2018).

Packaging can be thought of as composed of three parts: the primary package, in contact with the product; the secondary package, usually a shipping container, case or bags to group packages; and the tertiary package, such as a pallet, which has the function of a load unifier for transportation, storage, and distribution (Twede et al., 2007). Considering handling and transport, the pallet is the most used type of packaging worldwide. Rarely, it could be found that a logistic service is provided by the company without considering pallets. Despite the fundamental role of pallets, they are one of the most neglected constituents within handling transactions (Clarke, 2004). Generally, packaging is widely studied and designed, but only a brief description of pallets is given, although they can be considered the joint component between packed goods and transport in order to be efficient for handling management and cost reduction (Clarke, 2004).

A suitable definition of a pallet is: "Pallet is a portable, rigid platform used as a base for assembling, storing, stacking, handling, and transporting goods" (Bouffier et al., 1996). As a standardized platform for unit loads, pallets are widely utilized in manufacturing facilities, warehouses and distribution centers,

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and stores. Many pallets are designed to be repairable and reusable, so they can be reused for several shipping cycles.

Pallets in circulation can be considered as trade indicators of global economic trends. If the economy is strong, the demand for goods increases, which translates to a larger demand for pallets (Accorsi et al., 2019). There are roughly 5 billion pallets in use worldwide, and this value is anticipated to increase over the next 5 years (Murray, 2021). Although 95% of the produced pallets are made of wood, the use of nonwooden pallets, such as metal and plastic pallets, is increasing. For the food industry, nonwooden pallets are often used in applications where hygiene is a concern (Ibrahim, 2019).

Several associations, such as the US Grocery Manufacturers Association (GMA), the Canadian Pallet Council (CPC), and the European Pallet Association (EPAL), provide directives and good practices to use, collect, repair, and return pallets. This chapter summarizes the use of pallets and bags for unit load operations and provides a detailed description of the manufacturing methods, materials, tests, cleaning operations, requirements, and supply chain management considerations for pallets.

3.2 Packaging

Packaging fulfills five roles: socio-economic, protection, containment, information, and promotion. Packaging is affected by technological, political, ecological, economic, and demographic factors. A package protects the product stored within it, enabling ease and reducing the risk of damage during handling and transport operations, and assuring product safety and security as required by the customers (Sarker, 2020). Labels on packages provide information and promotion of the product identifying critical information pertaining to the product and entailing marketing or promotional information designed to appeal to prospective customers (Sarker, 2020).

Regulation adherence of the materials is focused on commercial goals considering product manufacture, environmental impact, and logistic cost. Packages are designed to be lightweight, easily packed, and physically robust. Deterioration and contamination are the most important packaging requirements for not only producers but also consumers (Sarker, 2020).

Primary, secondary, and tertiary packages possess different degrees of reusability, containment, and protection. Considering the unit load, the primary package is repackaged as a unit to facilitate transport and handling. Unitizing load is well described by Hammons as "a single item, a number of items, or a bulk material, that is organized and contained for storage and handling between two locations as a unit" (Hammons & Anderson, 1978). The primary packaging has direct contact with foodstuff, generally requiring a high degree of purity of materials and protection criteria for safety. Secondary and tertiary packaging, sometimes also reported as quaternary, were defined as repletely use distribution or transport packaging, generally requiring low levels of material contamination (Sarker, 2020).

Secondary and tertiary packaging is generally used in the distribution chain, and they are not perceived by the consumer, so they are not exploited for information and promotion (Sun, 2005). These packaging are typified by cartons, trays, boxes, bags, or pallets. In food and beverage applications, the packaging may need to incorporate specific conditions, such as low-temperature storage conditions for frozen foods (Sun, 2005).

Global trade is involved in large geographical areas for food distribution accounting for specific criteria as the logistic price and the upkeep of product quality over the transport (Sarker, 2020). Gas, temperature, and water vapor influence packaging as a function of different permeability coefficients, with the additional risk of microbial contamination. Accordingly, all packaging levels are important for protecting products. An environmental relative humidity (RH) range from 20% to 40% (corresponding to product a_w of 0.2–0.4) allows the reduction of the most degradation processes for fresh products such as fruit and vegetables, while for other types of products, such as cereals or dried products, it is a critical humidity range. Considering 75%–100% of RH, the acceleration of degradation processes is verified. Accordingly, packaging has a relevant role to avoid inadequate storage conditions during handling, but on the other hand it can cause deterioration reactions due to inapt control of relative humidity (Sarker, 2020). Goods and particularly foods go rapidly in modification reactions affecting quality and consumer acceptability, for this reason requiring a fast decision on the market (Sarker, 2020).

Furthermore, a series of drops or shocks, compression, and oscillation can be encountered during the transportation process. Some tools can be used to overcome these problems, as the packaging with the function of absorbing or filling, such as corrugated cardboard, inserts or wrapping, such as bubble plastic wrap (LDPE), EPS, or biodegradable starch beads, 'peanuts,' and 'pellets' used for impact deflection or absorption purposes can be used to protect products.

The food industry spends time and money to communicate the benefits of packaging from the negative perception of consumers and also in reducing waste along the whole supply chain, reporting that huge energy and costs, more than the cost of manufacture, are invested in packaging to protect food and goods. Packaging can reduce damages, increasing the shelf life of products and consumer attraction (Barlow and Morgan, 2013). "Green packaging" claims to pertain to so-called 5Rs: reduce, reuse, recycle, reclaiming, and reintegration (without degradation) of materials, which are also promoted by manufacturers.

3.3 Pallet

The term "pallet" is etymologically derived from French palette or blades, a small shovel; it is the name of several tools in various materials (wood, brass, iron, plastic, etc.) used to collect or dig. Considering loading, the pallet is recognized worldwide as a portable platform, used as a base onto which various goods are loaded. Pallets are commonly made of wood, consisting of rectangular strips interspersed and superimposed on strips also spaced between them to enable the forklift to uplift and move the unit load.

The practice of palletization began during World War II, as products had to be sent to the military by air or water in the most efficient way (Twede et al., 2007). Accordingly, in 1956, Alex Campbell developed the first automated pallet line production (Twede et al., 2007). Furthermore, lift trucks developed pallets utilization. By the end of the war, it was common practice for goods to be shipped on wooden pallets (Twede et al., 2007).

Nowadays, hundreds of millions of pallets manufactured in many forms and dimensions are sold each year to transport all types of products. Wood, plastic, metal, and board are the most used materials (Ibrahim, 2019). Pallets are so common that they can be found in every logistical transaction, such as transportation, packaging, storing, loading, unloading, and so on (Ren et al., 2019). Pallets are fundamental for goods shipment worldwide.

Pallets are defined in the ISO 445 standard as "rigid horizontal platforms of minimum height, compatible with handling by pallet trucks and/or forklift trucks and other appropriate handling equipment, used as a base for assembling, loading, storing, handling, stacking, transporting, or displaying goods and loads". In addition, ISO 445 defines a captive pallet platform that can be used internally by a single company, while a noncaptive pallet is a platform used cyclically through more than one company (private, corporate, or Government); an expendable or single trip pallet as one intended to be discarded after a single cycle; and a reusable or multiple trip pallet as one intended for multiple cycles (Hammons & Anderson, 1978). Pallets allow unitizing load for storing, stacking, handling, and transporting goods. Without pallets, many products would have to be manually lifted and kept together, resulting in higher handling and transportation costs (Buehlmann et al., 2009).

Pallets are designed to specific lengths and widths, depending on their anticipated functional and geographical use. The size of block pallets is reported as the top stringer board length, then the deck board length. For example, the standard Epal Pallet is 800 × 1200 mm. Nevertheless, the dimension of nonwood pallets is generally itemized as the longer length, followed by the shorter size (Clarke, 2004).

The six most commonly used pallet sizes at the international level, recognized by ISO (ISO 6780, T.C.I. 51, 2003), are reported in Table 3.1.

Pallets of different sizes are more commonly used in specific parts of the world or for specific industry sectors. For example, in Europe, the most common size for the past 50 years is 800 × 1200 mm. However, this size is rarely used in the rest of the world (Clarke, 2004). Beginning in the 1960s, the food industry in the United States started conversion from the 48. x 0 in. standard footprint, while the EIPS Computer Industry Pallet Task Group selected the 1200 × 1000 mm and 800 × 1200 mm sizes, due to their metric dimensions (Clarke, 2004).

Pallets can be classified into stringer and block classes, as shown in Figs. 3.1 and 3.2. A stringer class has three continuous longitudinally solid or notched

TABLE 3.1 Pallet footprints by ISO 6780.

Size (mm)	US size (inches)	Region
1200 × 1000	47.24 × 39.37	Europe, Asia
1200 × 800	47.24 × 31.5	Europe
1219 × 1016	48.00 × 40.00	North America
1140 × 1140	44.88 × 44.88	Australia
1100 × 1100	43.30 × 43.30	Asia
1067 × 1067	42.00 × 42.00	North America, Europe, Asia

With permission, Clarke, J., 2004. Pallets 101: Industry Overview and Wood, Plastic, Paper & Metal Options 1–10.

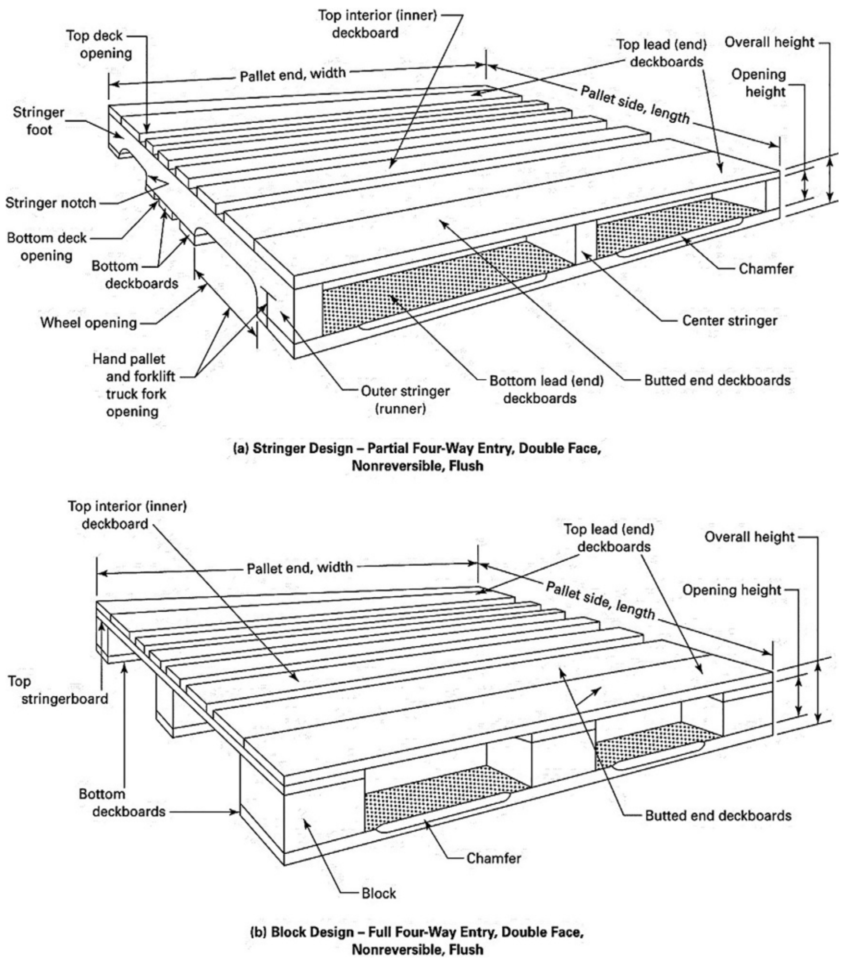

FIG. 3.1 Stringer and block pallets components. *With permission MH1, 2019. MH1-2005 Pallets, Slip Sheets, and Other Bases for Unit Loads 2019.*

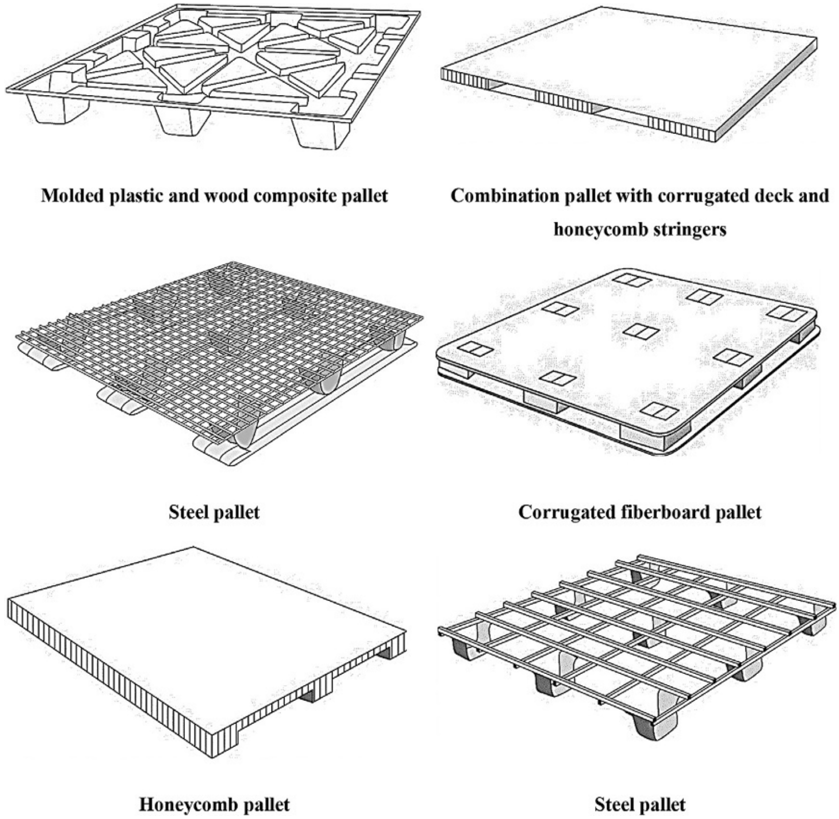

FIG. 3.2 Special pallets constructed with varying materials. *With permission MH1, 2019. MH1-2005 Pallets, Slip Sheets, and Other Bases for Unit Loads 2019.*

beam components that support the deck running the length of the pallet. Stringers are fastened together by deck boards (MH1, 2019). Pallets with notched stringers are called a "partial" four-way entry because they provide the ability to be picked up from all four sides, although some pallet jacks will not fit the notched opening (MH1, 2019). In the grocery industry, the notched stringer type is the most ordinary typology of a "white wood" platform, new and recycled.

A block class pallet is manufactured with nine blocks connected by stringer boards. The deck boards on the top are fastened to the stringer boards while the end deck boards are fastened through to the blocks (Bugledits, 2019). The block typology is usually designed for rental platform systems in the grocery industry because block pallets are stronger, more durable, even if more expensive than the stringer type. They have a true four-way entry that is accessible by any kind of forklift or pallet jack (Twede et al., 2007).

The US industry mainly uses stringer pallets rather than block pallets. This can be due to solid wood costing more to manufacture a block pallet than the equivalent stringer one. However, the block can provide an advantage, the full access on all four sides for both forklifts and pallet jacks (full four-way). On the other hand, the stringer one permits only forklift access on the sides if the stringers are incised (partial four-way entry), or on two ends if they are not notched (two-way) (Clarke, 2004).

Platforms classification can be done considering the deck board position: single-deck, double-deck reversible, double-deck nonreversible, flush, single- or double-winged, and single or double cantilever (MH1, 2019). A single-winged pallet has the top deck boards extended over the spacers, while a double-winged pallet has the upper and bottom deck boards extended over the spacers (MH1, 2019).

Another division concerns single-deck and double-deck pallets. The first category is without deck boards on the bottom, while the second one is reversible with identical top and bottom deck boards (MH1, 2019). Double-deck nonreversible pallets have different top and bottom deck boards that enable to be moved by using a pallet jack. A flush pallet has upper and lower deck boards that do not stretch over the blocks or stringers.

Furthermore, pallets are grouped based on their accessibility in two-way, partial four-way, or full four-way pallets (ISO 6780, T.C.I. 51, 2003). Two-way access pallets enable forklift arms and pallet hand jack handling from two ends only, while partial four-way access pallets have full entry flexibility at the two ends but are handled only from the two sides using a forklift. Full four-way pallets are the most useful platforms considering handling operations as they are open on all four sides enabling both forklifts and pallet jacks to enter (ISO 6780, T.C.I. 51, 2003; MH1, 2019).

Based on the end deck board position, pallets can be divided into unidirectional, overlapping, perimeter, or cruciform. The overlapping pallets have components superimposed. Instead, perimeter platforms are described as follows "the outer bottom parts arranged as a compete for frame with one or two center bottom components" (ISO 445, 2013).Unidirectional pallets have deck boards disposed parallel to the length or parallel to the width of the platform, while cruciform pallets have two middle bottom deck boards that are perpendicular to each other (ISO 445, 2013).

Strength, stiffness, durability, functionality, and purchase price are the parameters that affect pallet applicability; they are all connected, which means that optimizing just one will impact the others. Strength is the load delivery capacity by the handling and storage environments. The pallets should carry the whole load. Stiffness is a property linked to the resistance of the pallet to deformation. The pallet has to guarantee an unbreakable underload, but it should be not stiff enough to protect the product. Durability is considered the ability to resist the severity of the shipping and handling environments. Considering the returnable pallets, the design accounts for several trips, enough to economically justify the choice. Functionality is related to packaging and material handling equipment compatibility, including compliance to pest regulations, fire safety, and weight. Price is a fundamental aspect affecting industry decisions; pallet designs should account for price versus the value of the product shipped without damage to the customer, also considering environmental aspects, such as potential light packaging and material transport savings (Clarke, 2004).

3.3.1 Materials

Pallets were historically made of wood, but new, more functional, or economical materials are being used to make pallets as technological innovations progress and use requirements dictate. For example, wooden boxes were converted into grocery bags, glass bottles were progressively substituted by plastic, and so on. Standardization, reusable opportunity, and pest regulations are global market requests increasing the use of other materials (Clarke, 2004). Pallets of different materials can satisfy different customers' needs. For example, solid wood platforms are more cost-effective and stacking than plastic ones, but plastic pallets have been considered the new trend of the pallet industry for several reasons regarding pest regulations or reusable performances (Hassanzadeh Amin et al., 2018).

Several materials, such as solid wood, soft wood, plastic, corrugate paperboard, metal, and wood composite, can be used for pallet manufacture as shown in Fig. 3.2.

3.3.1.1 Wood pallets

Wood is the most used pallet manufacturing material and it is considered the most "cost-effective, and environmentally sustainable" material for pallet manufacture (Bugledits, 2019). Estimates indicate that wood pallets are used in more than 90% of applications worldwide (Mead, 2010).

Wood is a hard material exploited for construction and fuel for a very long time. It belongs from stems and roots of trees and other woody plants and it is characterized by fibrous tissue. Wood is an organic material composed of cellulose fibers embedded in a matrix of lignin which gives great resistance to compression. Historically, wooden shipping containers haves been used in the food industry for solid and liquid foods including fruits, vegetables, tea, wines, spirits, and beer (Fink et al., 2013).

In the past, all wood shipping platforms were nailed together manually. Eventually, assembly machines were invented to increase efficiency (Bugledits, 2019). The automation degree was continuously raised, so supplying and positioning the pallet parts could be completely performed automatically (Bugledits, 2019). The pallet components are specified in standards detailing the number and dimensions of fasteners as nails, staples, bolts, screws, or lag screws (ISO 445, 2013; ISO 6780, T.C.I. 51, 2003).

The primary advantage of wooden pallets is they are easy to manufacture and prototype. However, wooden pallets offer some disadvantages, including fasteners that can contribute to product damage; wood creates splinters that can contribute to punctures or lacerations; it can absorb and emit moisture; it can harbour vermin, and it can be highly variable.

Particular attention is paid to sanitization or sterilization of wooden pallets, with two international standards, the International Standard for Phytosanitary

Measures (ISPM), and the International Plant Protection Convention (IPPC). Wood pallets sanitization generally includes thermal treatment and fumigation (by using methyl bromide), as reported in ISPM 15 (Hassanzadeh Amin et al., 2018).

Apart from repair and reuse, wood pallets present three end-of-life options: mulching, disposal, or incineration. Mulching recycles the pallet but is quite expensive in terms of transportation and energy. Landfilling can contribute to energy recovery as the anaerobic decomposition of wood produces methane gas incineration but results in the emission of greenhouse gases. Furthermore, pallets treated with methyl bromide incineration practice could emit dangerous toxic chemicals (Hassanzadeh Amin et al., 2018).

3.3.1.2 Plastic pallets

The second most common material used for pallet manufacturing is plastic. As reported by Bugledits (2019) around 30% of pallet users deal with some type of plastic pallets. Plastic pallets are common in closed-loop storehouses, in the automotive, pharmaceutical, and food industry sectors (Clarke, 2004). Plastic platforms can be manufactured with thermal-sensitive resins or composite polymeric materials. Thermoset resins have arisen from petrochemicals and they are not so used for plastic platform manufacture because they are liquids at environmental temperature (Johnson, 2020). Thermoplastic resins are cheaper than thermosets. The two most used resins were: high-density Polyethylene (HDPE) and Polypropylene (PP) (Johnson, 2020). Another common plastic material for pallets is Polyvinyl chloride (PVC). PVC pallets are approximately 3–6 times the price of wood pallets. Filler materials and fibers are included in resin formulation to improve their performance. Generally, plastic employed for pallets includes additives such as UV inhibitors, fire or flame retardants, pigments, blowing agents, nitrogen gas, and cold temperature additives (Johnson, 2020). UV inhibitors are added to reduce ultraviolet radiation effects, while fire retardants increase the resistance to high temperature of the plastic to allow a sprinkler system time to extinguish a fire. Ammonium polyphosphate, magnesium hydroxide, and zinc borate are mainly used (Ibrahim, 2019).

Plastic pallets can be produced by different procedures, starting from high- and low-pressure injection moulding thermoforming, rotational moulding, compression moulding, blow moulding, and profile extrusion (Clarke, 2004; MH1, 2019). Considering high-pressure injection moulding, the resin is pumped up to a closed mold with pressure application. The thermoforming technique involves one or two soft plastic sheets and putting them into a form applying vacuum or pressure. A slower process is rotational moulding in which the resin is formed by thermal application, slowly rotating in the mold where it can reach the final form, successively cooled. Compression moulding is made by melting and compression of resin put into the machine until reaching the final product. Considering blow moulding, liquid plastics were forced into the form by using air with positive pressure. Another technique is the profile extrusion making resin by extruding the moldable plastic through a die into continuous profiles and after cooling down. Pallets were assembled after cutting the produced profiles (MH1, 2019). Plastic pallets are fastened in different ways. Snap fits with connections made by two interlocking clips compressed can be used. Welding is a different fasten system in which pallet components are connected by melting the parts together. Finally, adhesives or mechanical fasteners such as bolts, screws, and nails can be used to keep parts together (Bugledits, 2019).

Each process has positive and negative aspects. High-volume products concern a standard design made with foam or injection moulding. If several pallets of the selected design are needed, extrusion or rotational moulding should be chosen. In general, advantages consist in durability, low weight, cleanliness (including sanitization), resistance to odor (particularly important for the pharmaceutical and food industries), resistance to insects and vermin [exemption from the ISPM 15 phytosanitary regulations (ISPM 15, 2009)], weather resistance, and design potential. Plastic pallets can be customized by companies, for example, by selecting colours, which can increase consumer acceptability without an increased purchase price. On the other hand, high price, complicated design, friction and stiffness problem, and fire safety or repair troubles are the possible negative aspects (Clarke, 2004; Hassanzadeh Amin et al., 2018).

3.3.1.3 Composite pallets

A composite pallet includes materials like oriented strand board (OSB), particle board, plywood, and laminated veneer lumber (Clarke, 2004). Composite pallets have attracted great interest considering the implementation in the import/export sector, as a consequence of pest regulations. Composites are free from pest standards and cheaper than metal or plastic pallets (Clarke, 2004). Composites have a smooth and coverage deck surface, and also they are bug-free, dry, durable, recyclable, and easy to design. Despite this, they are expensive compared to wood and also under repair operations due to the presence of fasteners, instead of absent in the more resistant versions in plastic and metal (Clarke, 2004).

3.3.1.4 Paper-based pallets

Paper-based pallets include corrugated boards, honeycomb sheets, solid fiberboard, and molded pulp. Paper pallets are less used than wood or plastic but considered in small markets where quality and sustainability of products are fundamental aspects (Clarke, 2004). Paper pallets are recyclable and very light (being even more ergonomic), can lower freight costs, have a smooth deck dry surface that also guarantees bug absence. Paper-based pallets provide less protection against contaminants, less durable than the other considered materials, expensive, and subjected to moisture absorption (Bugledits, 2019; Clarke, 2004).

3.3.1.5 Metal pallets

Metal pallets are made with carbon steel, stainless steel, or aluminum. Carbon steel offers excellent durability at the lowest cost, while stainless steel does not need a paint coating and is preferred for such applications as a clean room environment (Clarke, 2004). Aluminum offers the durability of metal at a lighter weight. Carbon steel is the cheapest choice of metal, but metal pallets are expensive compared to wood pallets, even if the long-term usability can equilibrate cost. The advantages of metal pallets include strength, stiffness, durability, bug-free, no splinters, sanitary, and recyclability. The disadvantages that make metal pallets hard to apply in the food industry include their higher initial price, weight, low friction, and susceptibility to rust.

The main advantage of metal pallets is regarding durability and product protection, so they are usually used in closed loops (Clarke, 2004), such as military or in industries. These sectors exploit the metal properties of strength and stiffness, as well as their resistance to extreme environmental conditions or heavy weights (Bugledits, 2019).

3.3.2 General standards and requirements

Global trading imposed the necessity to address formerly regional or local concerns in a wider international context. For this reason, the ISO technical committee ISO/TC 51 "Pallets for unit load method of materials handling," has developed a wide portfolio of standards to meet these needs. ISO standards specify sizes, performance, and give guidelines for repair and reuse, together with a full set of definitions. Particular attention is given to wooden pallets since wooden pallets are most used. The committee has standardized the assessments for many parameters, such as timber size, strength, damage resistance, and fasteners. Regarding reusable pallets, there is a repair and inspection ISO standard developed jointly with the European Committee for Standardization (CEN) (Mead, 2010). According to the aim of creating an international standard for world trading, the American Society for Testing and Materials (ASTM International) published technical standards at the international level also concerning tertiary packaging. A comprehensive panorama of international standards for pallets is reported in Table 3.2.

Pallet standards pertain to both pallet design and pallet testing (Trevisani et al., 2014). Pallet regulations define requirements for product compliance, with technical specifications for packaging classification. Furthermore, some standards are dedicated to testing methods describing the possibility of re-utilization and performance definition (Trevisani et al., 2014). The main international standards are briefly presented herein, while national transpositions are not reported.

ISO 445 is one of the most known standards. It reports the nomenclature related to a pallet for transport and handling. Annexes defining terms relating to unit load handling and slip sheets are also included (ISO 445).

ISO 6780 specifies the principal dimensions and tolerances for new single-deck and double-deck nonreversible flat pallets of all entry types related to their transportation and handling by pallet trucks, forklift trucks, with particular attention to chamfers, clearances, openings, and wings (Trevisani et al., 2014). Acceptable quality levels for wooden components generally used for assembly of timber pallets, and parts affecting pallet performance, such as stringers, stringer boards, blocks, and deck boards, are reported in ISO standard

TABLE 3.2 International standards for wooden packaging.

International organization	Standard number	Standard topic
International Organization for Standardization (ISO)	ISO 445	Pallets for materials handling—Vocabulary
	ISO 6780	Pallets for intercontinental materials handling—Principal Dimensions and Tolerances
	ISO 8611-1	Pallets for materials handling—Flat Pallets—Part 1: Test methods
	ISO/TS 8611–2	Pallets for materials handling—Flat Pallets—Part 2: Performance requirements and selection of tests
	ISO/TS 8611–3	Pallets for material handling—Flat Pallets—Part 3: Maximum working loads
	ISO/TR 11444	Quality of sawn wood used for the construction of pallets
	ISO 12776	Pallets—Slip sheets
	ISO 12777-1	Methods of test for pallet joints—Part 1: Determination of bending resistance of pallet nails, other dowel-type fasteners, and staples
	ISO 12777-2	Methods of test for pallet joints—Part 2: Determination of withdrawal and head pull-through resistance of pallet nails and staples
	ISO 12777-3	Methods of test for pallet joints—Part 3: Determination of strength of pallet joints
	ISO 13194	Box pallets—Principal requirements and test methods
	ISO 15629	Pallets for materials handling—Quality of fasteners for assembly of new and repair of used flat, wooden pallets
	ISO 18333	Pallets for materials handling—Quality of new wooden components for pallets
	ISO 18334	Pallets for materials handling—Quality of assembly of new, wooden, flat pallets
	ISO 18613	Repair of flat wooden pallets
International Plant Protection Convention (IPPC)	ISPM	International Standard for Phytosanitary Measures (ISPM) Publication No. 15 Regulation for wood packaging material in international trade
ASTM International (American Society for Testing and Materials)	ASTM D1185	Standard Test Methods for Pallets and Related Structures Employed in Material Handling and Shipping
	ASTM D4169	Standard Practice for Performance Testing of Shipping Containers and Systems
	ASTM D6055	Standard Test Methods for Mechanical Handling of Unitized Loads and Large Shipping Cases and Crates

TABLE 3.2 International standards for wooden packaging—cont'd

International organization	Standard number	Standard topic
	ASTM D6179	Standard Test Methods for Rough Handling of Unitized Loads and Large Shipping Cases and Crates
	ASTM D6198	Standard Guide for Transport Packaging Design
	ASTM D6199	Standard Practice for Quality of Wood Members of Containers and Pallets
	ASTM D6253	Standard Practice for Treatment and/or Marking of Wood Packaging Materials
	ASTM F680	Standard Test Methods for Nails
	ASTM F1575	Standard Test Method for Determining Bending Yield Moment of Nails
	ASTM F1667	Standard Specification for Driven Fasteners: Nails, Spikes, and Staples
	ASTM D1761	Standard test methods for mechanical fasteners in wood
	ASTM D3043	Standard test methods for structural panels in flexure
	ASTM D4442	Standard test methods for direct moisture content measurement of wood and wood-base materials
	ASTM D4761	Standard test methods for mechanical properties of lumber and wood-base structural material
	ASTM D5456	Standard specification for structural composite lumber
	ASTM D5457	Standard specification for computing reference resistance of wood-based materials and structural connections for load and resistance design
	ASTM D7438	Standard practice for field calibration and application of hand-held moisture meters

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18,333. Several deviations from target thicknesses and widths for sawn timber are admissible because of the processing and sawing inconstancy. Sizes of timber and pallets are defined in ISO standard 18,333.

Pallets that have been repaired or are intended for reuse are required to comply with these standards.

Pallet retrieval is defined in ISO 18613. The standard indicates the maximum number of defects and damages consented to before a wooden pallet should be repaired or substituted, and also it reports the specific criteria that must be applied during reparations. Within three different times, pallets considered unacceptable must be repaired according to ISO 18613. Pallets that cannot be repaired must be discarded. Rejected wooden pallets can be reused for other purposes creating the opportunity for new products development and added value for waste reuse.

ISO 12776 specifies requirements for slip sheets. Slip sheets are thin sheets used as alternative pallets with the same aims as assembling in unit load, handling, transporting goods. Attention should be paid to lift truck attachment. A conventional forklift needs to be equipped with a special permanent or removable attachment for slip-sheet handling.

3.3.3 Standards for mechanical tests

Empty or loaded pallets are handled by forklift trucks or pallet trucks, placed in automated racking systems, stacked pallet-load on pallet-load, moved on conveyors, loaded in shipping containers, and moved from arctic to tropical conditions (Mead, 2010). Pallets are able to satisfy the needs of every user in any handling environment, for simple movements or for storage by guaranteeing safety in point-of-sale applications (Mead, 2010). Pallets are assembled from components, so their size and quality should be controlled with a series of standards. Standardized tests can be used to demonstrate their capability (Mead, 2010).

Strength, stiffness, and durability are directly related to the pattern and quality of fastener, grade, kinds, and water content of lumber components and the material handling environment. All these parameters enable to definition performances and reusability of pallet platforms (Mead, 2010). Durability, single-use, or reusable categories are the classifications given for test procedures (MH1, 2019). Pallets are also produced for a single use, with relative damage resistance able to survive at least one trip. On the other hand, reusable pallets carry more than one unit load as they are thought for repeated uses, involving sufficient damage resistance to account for multiple shipping without needing repair (MH1, 2019). Test methods and related criteria are reported herein (Table 3.3).

3.3.4 Cleaning and sanitizing treatments for food safety

The food industry pays particular attention to the safe production, storage, and transportation of food products. Pallets and bags come into contact either with packaging that contains food or with packaging that contains packaged food. Considering both cases, pallets and bags are exposed to environments that are less sanitary than the areas where food is packaged and prepared. It would be impossible to maintain sterility in every segment of the food chain, such as in transit through trucks and trailers (Boersig and Cliver, 2010). Food producers follow regulations, routines, and audit systems to assure the safest food supply chain possible. For example, wood pallets are heat-treated to prevent infestation, which is a common hygienic procedure, despite the negative aspects of increasing the cost of wood pallets (Twede et al., 2007). Generic requirements for pallets and packaging moving and storage should be tracked to guarantee

TABLE 3.3 Standards for test methods.

Test method	Standard number	Specifications
Flat pallets International Standards Organization—pallets for materials handling	ISO 8611	Part 1 described test methods. The reference standard is the 8611–1, in which it is defined test methods for new flat pallets evaluation for materials handling. Test are grouped according to different aspects, such as nominal load, maximum working load and durability comparison. It is not intended to be applied to Pallets with a fixed superstructure or a rigid self-supporting container that can be mechanically attached and contribute to pallet resistance are not considered in these standards.
		Part 2 defines performance needs and tests choice orientation. The standard describes specific requirements for new flat pallet and it terms also nominal load. In addition, in the part 2 are reported test methods for flat pallets considering several handling environments.
		Part 3 terms the maximum working load considering new flat pallets with defined payloads in different handling conditions.
		Part 4 qualifies methods for creep responses in stiffness tests prediction, accounting for plastic pallets using regression analyses. An example of estimation of creep procedure for stiffness tests for plastic pallets is presented. Regression analysis was used as conventional procedure for deflections during load and relaxation periods prediction.
standard for pallet assembly test methods	UNI EN ISO 12777-1	Standard 12,777 describes test methods for resistance to the extraction and tip assessment, and head of the nails, junctions, and clips for pallet. Flexural strength of the joining components and the extraction resistance of nails and staples are defined in the regulations. Results can also be affected by wood quality, so also this aspect is considered. Test methods regarding the determination of the bending resistance of nails, staples and other dowel-type fasteners are defined. In addition, test for strength in static bending and impact bend resistance are also included. All kinds of nails are considered in the test's method description. Particularly, part 3 describes joints resistance methods underwent to static load by determining stiffness and strength of nailed or stapled joints, wood to wood, wood to wood-based materials, wood to plastics or plastics to plastics. This part is fundamental to relates all types of nails including helical, annular ring, plain shank, twisted, and barbed up to 7 mm diameter and with staples.

Continued

TABLE 3.3 Standards for test methods—cont'd

Test method	Standard number	Specifications
Test methods for box pallets and main	ISO 445	Test methods presented in this standard concerns box pallets classified for load capacity carrying a uniformly distributed load used for test. The higher load could be smaller or larger than the nominal load of a box pallet. No minimum values are fixed, excluding tank and silo pallets. Therefore, the maximum load consented for a given design of box pallet differs according to the characteristics of the kind of load carried. This standard is aimed to the box pallet performances without load consideration.
Standard Test Methods for Pallets and Related Structures	ASTM D1185	In accordance with the standards, the distribution environment was achieved with static and dynamic tests. Statistic test is performed to determine the strength and stiffness of the pallets, so to estimate safe working loads. It is a compression test of the block or stringer deck spacers. Considering dynamic tests are performed to evaluate the physical durability and functionality of the pallet under handling and shipping conditions. These are sequential tests represents a type of hazard that occurs during distribution, which can damage the pallet or the unit load. Other test can be done to determine the resistance of the deck board, blocks or stringers to the impact forces caused by forklifts and pallet jacks during handling.
Vibration Test	ASTM D999	Transportation system results in vibration forces causing possible damages. Vibration test were carried out following the procedures of ASTM D999. A frequency scan was performed from 3 to 100 Hz in order to find the resonant frequency of the load, a sweep rate of 1 octave per minute, with a constant acceleration of 0.50 g, was used (sine vibration). Under the highest resonance frequency, each pallet load is tested (ASTM D999). Vibration test can be performed also with random vibration test, run under ASTM D4169. Truck level II with frequency range for 330 Hz. One pallet of each type from the previous handling tests was tested. After the test, the pallets were inspected to record the damage (ASTM D4169-04, 2001).

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safety and security materials. Accordingly, unprotected outdoors storage, particularly considering wooden pallets, must not be performed to limit biological and physicochemical contamination (Beyer and Gudbjörnsdottir, 2002).

Plastic pallets and bags are also used by the food industry for their hygienic characteristics. It is possible that a plastic pallet handled under unsanitary conditions would be safer than wood under the same conditions (Beyer and Gudbjörnsdottir, 2002).

Other studies note that bacterial colonies grow on the surface of plastic if there is a sufficient supply of nutrients and decrease within minutes of inoculation from a wood surface (Boersig and Cliver, 2010). When bacteria penetrate into a wood matrix, bacteria do not grow, but rather die due to the hygroscopic nature of wood, as well as the presence of secondary metabolites (tannins, lignin, flavonoids, and, in the case of the pine family, terpenoids) (Boersig and Cliver, 2010). In particular, pine wood has a more significant inhibitory effect than other species tested, with a tip message over the published literature that wood is safer than plastic (Boersig and Cliver, 2010).

A conventional food industry procedure intends to define dangerous and critical points to control in production, storage, and transport. Hazard Analysis and Critical Control Points (HACCP) is a systematic approach to food safety that identifies hazards in the food chain and proposes methods to control, monitor, validate, and verify the identified hazards. The nature of these hazards could be biological or Physicochemical. Companies are responsible to guarantee and attest with documents the procedures enabling food safety (Beyer and Gudbjörnsdottir, 2002). The standard can be applied within all sectors of the food industry, such as distributors and transport companies, suppliers of packaging, equipment, raw materials, and other accessories. The product manufacture definition must define raw materials, physicochemical and biological characteristics, provenance, shipping method, packaging, and storage conditions, creating a written trace for each considered material or product that was in contact with food (Beyer and Gudbjörnsdottir, 2002). Good Manufacturing Practices (GMP) were included in HACCP protocols guidance for safe manufacturing definition. GMP provides support to routine checkpoints for important phases such as incoming raw materials and outgoing goods/items, manufacturing, quality control, testing and documentation methods, pests control, hygienic design and maintenance, cleaning, disinfection, policies, and education (Beyer and Gudbjörnsdottir, 2002).

The increase in international trade volumes in recent decades has been responsible for the introduction of wood-infesting insects and plant pathogens, commonly associated with wood packaging material (WPM). Several insects and plants have become highly invasive and caused serious environmental and economic impacts. In response, Standards for Phytosanitary Measures No. 15 (ISPM15) provided details on approved phytosanitary treatments for WPM used in international trade (Haack et al., 2014).

Regarding the food industry, at the international level, control of pests is a compulsory requirement by law. Pest control of materials used for packaging aims to avoid the contamination of food and the diffusion of disease either removing the origin of risks or placing a barrier between the source and the food, and preferably by adopting an IPM (Integrated Pest Management) concept which includes preventing, managing, or eliminating pests (Beyer and Gudbjörnsdottir, 2002).

TABLE 3.4 HACCP and IPM principles (Beyer and Gudbjörnsdottir, 2002).

HACCP	IPM
Hazard analysis, microbiological hazard, chemical-physical hazards	Initial analysis, pests' control
Define CCPs Critical Control Points (process or production focus)	Identification of pest's area
Specify criteria for auditing	Specify tolerance levels for different pests
Monitoring CCPs	Monitor pest activity
Establish corrective actions	Apply IPM strategies
Written documentation	Documentation
Verify the correct functioning	Verify if the system works as programmed

IPM is a decision process that defines pest or identifies damages caused by the pest and precise location of the infestation through monitoring and inspections. According to Holmberg and Walling, IPM and HACCP procedures may be linked as reported in Table 3.4.

As previously mentioned, pallets, cases, cardboard boxes, trays, sacks, etc. should be stored in a proper way to prevent contamination and to facilitate cleaning operations.

Possible examples of sources for contamination or transmission of microorganisms are birds, rats, mice, and insects (Beyer and Gudbjörnsdottir, 2002). In addition, the hygiene of pallets and packaging can also be affected by other factors, such as humidity, temperature, pH, and aerobic (or also anaerobic) conditions, extending to as far as the quality of wooden pallets (Beyer and Gudbjörnsdottir, 2002).

Similar to what happens for food products, the water content of wood affects growing and survival bacteria (Beyer and Gudbjörnsdottir, 2002). Wood characterized by high water content promotes mold and bacteria growth. Considering transport to different worldwide regions, pest regulations are of utmost importance also for spreading disease and contaminations. About 27% is the critical moisture value (the fiber saturation point) below which water is not available for bacteria and mold, which can be traduced into the difficult condition of microorganism survival (Beyer and Gudbjörnsdottir, 2002). Accordingly, 20% is the moisture limit for wooden pallets to avoid bacteria, mold, and fungi growth. Therefore, pallets should be stored under controlled conditions (Beyer and Gudbjörnsdottir, 2002).

There are many types of products to clean and disinfect according to the different materials needed, types of contaminants, or microbes. The limit for "acceptable" contamination is ≤ 5 CFU/cm^2 (Twede et al., 2007). The criteria for materials and surfaces are often inspired by a condition of nontoxicity or resistance to detergents. Treatments with chemicals, preservatives, and irradiation have not been accepted by the US Food and Drug Administration (FDA) for use with food products (Twede et al., 2007). Water rinsing, high-pressure water treatment, foam cleaning, steam, or automatic machines are the most common cleaning methods.

High-pressure cold-water rinsing is a cheap but efficient method to clean and sanitize materials. Lethal temperatures of bacteria are different but generally already defined, so it can be possible to set the temperature of thermal treatment for easy elimination of microbes. Different food sectors, and different bacteria, such as gram-positive cocci, Gram-negative rods, and Gram-positive spore, present different temperature sensitivity. Thermal treatment was tested among 19 materials, such as plywood, waxed wood, wood, plastics, and stainless steel, and revealed that a range from 75°C to 100°C enables to obtain an acceptable safety level. Thermal treatment can be used for several types of wood utensils as well as for platforms such as pallets (Beyer and Gudbjörnsdottir, 2002).

A particular thermal treatment is kiln drying. It can be applied on the pallet for moisture reduction until 16%–18%. A sample procedure could involve a pallet producer who performs dehydration of the timber in an ordinary oven, transports the timber directly to a lorry, then places the timber in a storage room with controlled temperature and humidity (Beyer and Gudbjörnsdottir, 2002).

Thermal treatment with high temperatures (HT) up to 110–115°C for a defined time can be another possibility to sanitize or more precisely pasteurize wood (Beyer and Gudbjörnsdottir, 2002).

A combination of brushing and hot steam or hot water sprinkling with dispersion of microdroplets of water is another method used on pallets and packaging for cleaning and sanitizing purposes. The Electro Thermic Bacteriolysis (ETB) method has demonstrated a reduction of all pathogenic bacteria up to 99.9% in a very short time. This technique performs surface disinfection, opening another possibility for wooden pallet sanitation in combination also with other materials. Gamma-ray radiation has a very powerful antibacterial efficacy with good potential applicability for the future (Beyer and Gudbjörnsdottir, 2002). Ionizing radiations are not yet widespread, as some countries have restrictions in force and they are characterized by the high cost of treatment.

Microwave technology is also applied for pasteurizing wooden pallets and packaging, and it can be a very interesting alternative, very promising in the egg industry application (Beyer and Gudbjörnsdottir, 2002). Microwave technology is already applied knowing the potential power to move water molecules of the materials able to give responses exploitable for several purposes, as example estimates foodstuff parameters (Iaccheri et al., 2015; Ragni et al., 2013, 2017). The potentiality of the technique is also related to the treatment time; for example, green timbers were dried down to a moisture content of 8% in a very short time. The technique seems very promising for economic and environmental reasons (Beyer and Gudbjörnsdottir, 2002). An applied example is an already commercially available microwave hot air oven that was used in the egg industry to reach a temperature on the shell eggs of 90°C, at a frequency of 2.45 GHz. The killing effect was obtained both on egg dishes and pallets considering a water content ranging from 5% to 15% and 25% for egg dishes and pallets, respectively (Beyer and Gudbjörnsdottir, 2002). The microwave treatment combined with other techniques, such as high-pressure water sprinkling, can be a suitable opportunity for the food industry to clean and sanitize pallets for a closed loop (Beyer and Gudbjörnsdottir, 2002). The oven can be designed to develop a continuous process by using two opposite doors for pallets loading and unloading the oven. This setup can also be useful to divide the two opposite sides creating separation between the clean zone and the unclean one (Beyer and Gudbjörnsdottir, 2002).

3.3.5 Supply chain

The supply chain is a combination of processes to fulfill customers' requests and includes all possible entities such as suppliers, manufacturers, transporters, warehouses, retailers, and customers themselves (Govindan et al., 2015). The supply chain is a complex network that includes different business activities in which logistic management is an important part that plans, implements, and controls forward and reverse flow and stored goods and services. Logistics management can reduce costs and improve customer services (Ren et al., 2019; Twede et al., 2007).

The supply chain can be divided into the traditional forward chain and the reverse logistic chain (RL). RL is defined as "the process planning, implementing, and controlling the efficient, cost-effective flow of raw materials, finished goods and related information from the point of consumption to the point of origin for the purpose of recapturing value of proper disposal" (Govindan et al., 2015). Considering the pallet industry, RL considers the platform restitution from customers. Accordingly, RL is the suitable alternative for the re-usable market which gives very important value to a circular economy for environmental sustainability and economic benefit.

In this way, reverse logistics starts from end-users where used products are collected from customers and then attempts to manage products through different decisions that are undertaken including recycling, remanufacturing, repairing, and finally disposing of some used parts (Govindan et al., 2015; Hassanzadeh Amin et al., 2018). Retrieval procedures, such as used products recycling, RL, product disposal, repair or reproduction, and remarketing, are performed on returned products for repurchase (Hassanzadeh Amin et al., 2018). On the opposite side, the advantage of the forward chain is to supply services for customers' needs. Several authors think that a combination of RL and forward supply chains is the most convenient solution for closed-loop logistics (CLSC) (Accorsi et al., 2019; Hassanzadeh Amin et al., 2018). In Fig. 3.3 is shown a generic supply chain representing forward and reverse supply chains.

One of the relevant decisions regarding the logistics system could be based on the selection of an open or a closed network. In open logistics networks, empty pallets are not physically recovered from customers by the company even

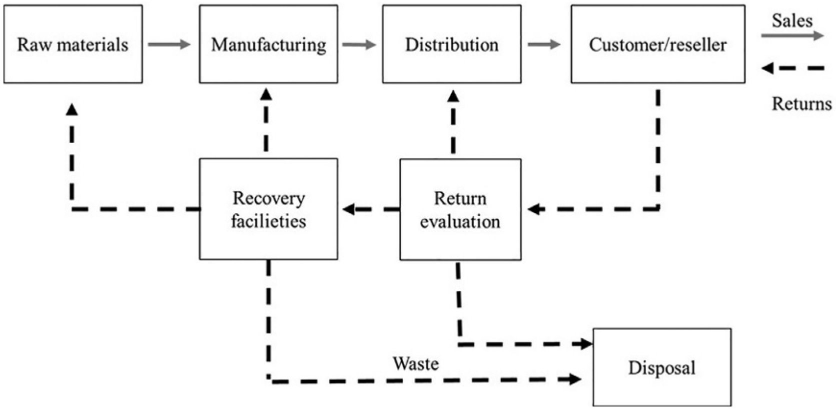

FIG. 3.3 The forward supply chain is a solid line, while the reverse is a dashed line (Govindan et al., 2015).

if the customer pays the company the actual empty pallet value (Elia and Gnoni, 2015). In closed-loop models, after or during the delivery process, empty pallets are picked back up by the company (Elia and Gnoni, 2015). The decision problems regard economic and environmental issues. Considering costs, the logistical costs of food production are within the range of 10%–15% of the product sales price, which presents an important factor for producers, wholesalers, and retailers (Ala-Harja and Helo, 2015).

The global logistics sector is based on millions of pallet platforms per year, usually taken for granted. The pallet life cycle is divided into five phases: raw material sourcing, manufacturing, transportation and use, refurbishment, and end-of-life disposal (Glock, 2017). In order to manage pallets efficiently, several pallet management strategies can be developed, including extensive use or rent (Ren et al., 2019). An integrated-logistics approach related to transport and packaging can yield dramatic savings and value depending on unit-loading techniques (Twede et al., 2007).

In recent years, supply chain management has received increasing attention involving returnable transport items, as a type of reusable packaging material. Pallets, boxes, crates, bags are examples of Returnable Transport Items (RTI) (Glock, 2017). When an RTI reaches its destination, it is emptied and sent back to the sender; it could be cleaned at each stage or at the end of the transport, and it could be necessary to test RTI before reusing them due to technical or legal reasons (Glock, 2017). It is evident that the advantages the use of RTIs offers can be realized fully only if the dispatch and return of RTIs as well as the interactions between the RTIs and the product that have to be shipped are appropriately managed (Glock, 2017). Good management can reduce costs and contribute to improving the sustainability of the supply chain by reducing waste (Glock, 2017). The specific characteristics of RTIs such as their weight or dimensions have a major impact on the logistics process and the costs that accrue in distributing and collecting RTIs (Glock, 2017).

3.3.5.1 Green supply chain and environmental sustainability

Environmental considerations have been a fundamental theme in packaging logistics, with special emphasis on the trade-offs and potentially increased costs associated with environmentally favorable decisions (Twede et al., 2007). The environmental impact of pallets depends on materials, manufacturing, and handling processes (Mazeika Bilbao et al., 2010). Considering manufacture, plastic pallets are lighter and may last longer than wooden pallets, but their manufacturing processes are energy-intensive and contribute to greenhouse gas emissions (Mazeika Bilbao et al., 2010). Plastic pallets can have a life of six years while the typical life of wood pallets is one-and-a-half years. On the other hand, wood pallets are cheaper and easily repaired (Mazeika Bilbao et al., 2010). Plastic versus wood materials for pallets is a difficult choice considering that they are platforms for repetably use, but with more energy and money spent. Another aspect that should also be underlined for better decisions is strictly related to the environmental impact. Plastics used for pallets manufacture are very different (e.g., HDPE and PET); sometimes they have no natural decomposition and, as a consequence, a huge pollution potential (Hassanzadeh Amin et al., 2018).

Is wood or plastic the most eco-sustainable material? It is an endless discussion between tree shoot down and depletion of resources incapable of being renewed (Bhattacharjya and Kleine-Moellhoff, 2013). Most experts believe that plastic pallets will not be adopted because they are expensive, and their value comes from their ability to be used for multiple trips. In addition, under the current supply chains, most pallets are not returned to the distributor; therefore, plastic pallets become a very expensive one-way pallet, and the cost would need to be passed on to the grocery store which the market would not bear (Bouffier et al., 1996).

Considering the production process of wood pallets, it involves less emission of carbon dioxide than that of plastic pallets. Contrarily, wood needs to follow requirements outlined in ISPM 15 which entail an additional cost due to thermal treatment or fumigation of shipped pallets. This switches the point of view toward plastic pallets which gives more opportunity due to less restriction for shipping products (Bhattacharjya and Kleine-Moellhoff, 2013).

Another aspect to take into consideration for plastic material is related to the toxicity of fire resistance additives. Due to their toxicity and persistence, several families of brominated flame retardants (BFRs) have been classified as persistent organic pollutants (POPs) in the Stockholm Convention, a multilateral treaty supervised by the United Nations Environment Programme. Nations that have signed the treaty must take administrative and legislative actions to avoid the environmental impacts of POPs (Sharkey et al., 2020). The US Environmental Protection Agency (EPA) in 2014 was the first agency concerned by the persistent and toxic nature of the chemical and the possibility of it leaching into food carried by iGPS pallets (Bhattacharjya and Kleine-Moellhoff, 2013; US EPA, 2014). The specific BFRs listed in the Stockholm Convention are Polybrominated Diphenyl Ethers (PBDEs), Hexabromocyclododecane (HBCDD), and Hexabromobiphenyl (HBB), chemicals which must therefore be heavily restricted. As an example, within the EU, hexabromobiphenyl (HBB), the PBDE commercial mixtures, and HBCDD are almost entirely prohibited in terms of both production and use in commercial goods. Waste articles containing excess concentrations of these BFRs are similarly restricted and must be disposed of in a manner that destroys or irreversible transforms the BFR. Specific exemptions and dedicated guidelines for these limits are defined by the Convention: for example, Penta- and Octa-BDE can be present in waste materials for recycling until 2030. Worldwide, China, Japan, India, and the United States of America have made significant advances in the regulation of POPs, in line with the provisions of the Stockholm Convention (Sharkey et al., 2020).

Pallet weight is a fundamental topic for transport efficiency (Bhattacharjya and Kleine-Moellhoff, 2013). Plastic pallets are lightweight than that of wood so less consumption of diesel is considered. Transport is a very important economic factor not only for shipping goods to customers but also for RL logistics and for repairing purposes (Bhattacharjya and Kleine-Moellhoff, 2013).

The environmental safeguard is focused on recycling. This is the aspect to broadcast without material distinction (Bhattacharjya and Kleine-Moellhoff, 2013). Mulch and animal bedding can be obtained by recycled wooden pallets. Regarding plastic, correct waste disposal involves a total re-utilization of material converted into new plastic with hundreds of possibilities. This last opportunity concerns costs, but also the manufacture of added values products became a sustainable process (Bhattacharjya and Kleine-Moellhoff, 2013).

Over the years, many changes have affected the food industry leading economic players to rationalize the resource use in order to accomplish the goal of the efficiency of the Agro-food system (Ibrahim, 2019).

The efficiency of agricultural production and the reduction of emissions are important frontiers of research in the technical and economic fields, with the main ambition of maximizing value instead of the traditional maximization of profit. The idea of value must be understood as benefits for the stakeholders in economic, social, and environmental domains (Ibrahim, 2019). Globalization puts more effort into waste reduction, or source reduction, which is an action that prevents the generation of waste. In this way, less material used in a package logically means that less will be disposed of at the end of the package life, and the pallet is part of the packaging. The safety of the product must be balanced against the function of the pallet which ensures waste reduction (Ibrahim, 2019). For a long time, the packaging industry has been concentrated on source reduction, accomplished for the most part with the goal of saving money by using less material for packages. For example, glass bottles, plastic bottles, metal cans, and many other package forms have become thinner and lighter over the years (Ibrahim, 2019).

3.3.5.2 Pallet pool

Standardized pallets are usually designed to last for several trips. Such pallets can be operated either using the so-called "buy/sell" strategy, where ownership of pallets is transferred together with the pallets, or alternatively the pallets can be managed using a "pooling" strategy where pallets are leased to customers without transfer of the owner paying the third part for each day of use (Bouffier et al., 1996). The wholesaler who received the goods returns the pallets to the pool and only incurs the cost of transportation. Or the wholesaler can lease the pallets and use them to transport goods to retailers. In that case, retailers have the responsibility of returning the pallets to the leasing company or pool (Bouffier et al., 1996). In the pooling strategy, pallets are usually marked in a company-specific way. In addition, radio frequency identification (RFID) trackers are increasingly used by pallet poolers, which allows for the data collection on the pallet's life cycle and location throughout the supply chain (Deviatkin et al., 2019).

Like other common property, grocery pallet ownership is expected to depend in part on the motivation to participate and the commitment to the environment as far as legal aspects are involved in the process (Twede et al., 2007). Pallets can also be repaired during their life cycle to prolong their service life and reduce cost with disposal of the pallets borne by the third party (Deviatkin et al., 2019). Using third-party pools would extend the life of each pallet because it is cost-effective for these companies to do so, and increased use of pallet pools should also cause an increase of recycled pallets (Bouffier et al., 1996).

As pallets are prime reusable packaging, many users take advantage of the available pallet pools. In general, pallet pools must be able to perform in any combination of handling and storage, considering also the worst-case scenarios. This is what the daily challenges in the life of a pallet look like (Mead, 2010).

Companies dealing with pallet pools have to pay attention to inspection and insurance of platforms quality depletion due to repletely use. The standard ISO 18613 defines the maximum imperfections permitted before which a pallet requires fixing up (Bhattacharjya and Kleine-Moellhoff, 2013). The returned pallets, shipped by customers, enable the opportunity for a platform compliance check. This system also helps inspection and repair procedures.

Cost-effectiveness is the main attractive characteristic for pallet pooling, coupled with environmental sustainability. It is recommended to consider the pallet's basic raw materials and affiliated costs as the basis for future development and researches (Bhattacharjya and Kleine-Moellhoff, 2013). Dealing with cost and raw materials can create other issues to resist by creating a model with ergonomic factors, for efficient and effective pallet pool systems, and managing them is the other interesting area of concentration. The sustainable achievement toward the substitute raw materials and the best possible option from recycling, reusing, waste reduction, and, on the whole, sustainability is a priority for future researches in this area (Ibrahim, 2019).

3.4 Big bags

Big bags are containers used to pack several products in various sectors of the production chain as bagging seeds for warehouses, packaging fertilizers, bagging inputs, among other applications. Its main features, apart from the volume, are strength and durability compared to other packaging (da Silva Barbosa Ferreira et al., 2019).

Bags carry out a lot of operations, such as protection against contaminants, containment in a unit load bulk solid particle, powder or liquid sample, and also communication of product information. Bags are generally the cheapest adaptable packaging available in a broad span of sizes and manufacture materials; they are able to satisfy all sorts of needs like no other packaging can do (Hanlon et al., 1998).

Accordingly, the production process can be performed in several diverse manners. Bags can be manufactured with different barrier permeability, being porous, or film line, but also coated. Traditionally, bags were obtained by recycling animal skin waste, then substituted with more practice and safer materials like paper, plastic, or textile films. Fabric is outmoded. Despite this, jute or cotton is still in use for bag manufactures (Hanlon et al., 1998). Plastic bags have become extensively available as these have been produced by high-speed machine, useful for export shipment as a vapor barrier for moisture-sensitive products. Particularly in the food industry, bags were used for vegetables that are stored and transported from processing plants to rural growers in big bags. Some types of packaging may accelerate the exchange of energy and mass between the stored goods and the storage medium. Storing products in permeable packaging allows the internal humidity to change with the environment, causing increases or decreases in water content until it reaches hygroscopic balance, causing deteriorations and reductions in the vigor and viability of the lot and in this way actively cooperating in the evolution of postharvest processes (Coradi et al., 2020). Otherwise storing goods in waterproof big bags, such as big bags with a laminated coating of polypropylene, are the most appropriate packaging for moisture-sensitive goods. Reason to the waterproof characteristics and the possibility of modifying the atmosphere, insulation from the environment and insects prevent several degradation processes (Coradi et al., 2020).

Strengthen materials for big bag manufacture are required which includes plastic fibers to obtain the desired texture (Hanlon et al., 1998). The big bag's shape can be rectilinear or tubular, either open or closed on top, and the bottom can be solid (Hanlon et al., 1998). Bags also keep the minimum shipping costs because of the lowest tare weight and the minimum space occupation. Big bags allow to be much more efficient regarding the space occupied during transport and storage; in fact, a bulk solid or a powder takes the biggest space standing alone instead of contained (Hanlon et al., 1998). Flexibility also involves a negative attribute; in fact, bags cannot stand alone on shelves like more rigid packaging with possible slippage problems also. Bags are also sometimes unattractive from the consumer's point of view (Hanlon et al., 1998). Durability is a questionable point compared to other packaging, even if it can be reinforced by incorporating scrims and laminated film. However, reinforcement increases the cost.

3.4.1 Paper bags

Paper bags are considered environmentally more sustainable than plastic bags. Paper bags are basically composed of plies, a series of superimposed layers useful for conferring mechanical characteristics to the material, and generally identified by the number of layers counting from the inner layer to the outer one. Several types of bags are classified according to plies, single, double, duplex, or multiple. The multiple plies are composed of laminates of paper and asphalt to increase texture resistance and contaminant protection (Sarker, 2020). Only paper plies were counted and the specific identification is made by the number of laminates and the weight of the product. Typical weights of kraft paper used for multiwall bags include 18.1, 22.7, 27.2, and 31.8 kg/m^2 (the weight of a sheet of paper, kg with a surface area of 1m^2) (Sarker, 2020).

Adhesives were used to seal different layers, starting from the starch or dextrin traditionally used but no more applied, passed to other techniques such as tying, stapling, taping, and sewing. Generally, a layer of tape is always inserted to check product sifting (Sarker, 2020). Particulate products were packaged automatically in a very rapid way in open bags. Big bags with valves are used for powdered goods to reduce dust during the tricky phase of filling. The valve is used to transfer the products into the machine for subsequent processes and is usually creased into the bag. There are threefold typology, such as flat, single, or double corner (Sarker, 2020). For example, when rodents or insects affect storage conditions of bags a pinch-bottom structure with the open-mouth closed with thermal sensitive adhesive is usually recommended for better product preservation.

An alternative vale for big bags with waterproof components is the pasted valve (PVE), produced with stepped-end plies. The production process implies several sites for an adhesive application that can be useful to fill the bag on top facilitating the opening procedures. The square bags belonging to this kind of asset have an efficient shape for storage and also enable the application of labels with marketing or product information (Sarker, 2020).

Regarding greaseproofness, a layer of glazed translucent paper can be put between plies for water protection. Polyethylene (PE) coatings are an example of a high vapor barrier, highly employed, but costly. Other barriers put inside as close as possible to the product, including films such as Polyester (PP), polyvinylidene chloride (PVDC), greaseproof paper, glassine, vegetable parchment, paper/cellophane laminates, metalized film, aluminum ply, wax paper, are all the materials used as a barrier to protect as much as possible the product from contaminant and moisture. Aluminum and metalized layers give a perfect barrier even if they are considerably more expensive than the alternatives (Sarker, 2020).

Fig. 3.4 shows the multilayers of shipping bags including self-opening and thermal sealed bag (PSOS), satchel bottom and pinch bottom (PBOM), or sewn open mouth (SOM), sewn open mouth (SOM), pinch bottom open mouth

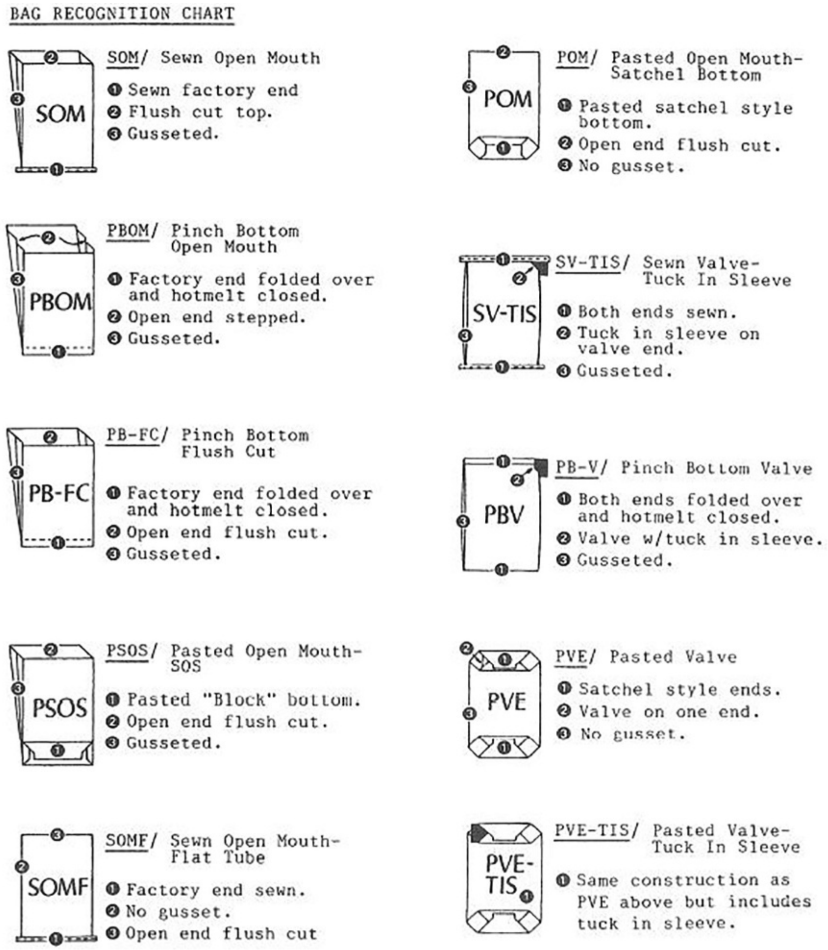

FIG. 3.4 Multiwall bag styles.

(PBOM), pinch bottom flush cut (PB-FC), pasted open mouth-SOS, sewn open mouth flat tube (SOMF), pasted open mouth-satchel bottom (POM), sewn valve-tuck in sleeve (SV-TIS), pinch bottom valve (PB-V), pasted valve stepped end (PVE), and pasted valve-tuck-in sleeve (PVE-TIS) (Sarker, 2020).

3.4.2 Plastic bags

Bags made with plastic materials are produced with very different machines and sealing techniques also considering film thickness; some examples are shown in Fig. 3.5. The price is variable firstly as a function of size. Two possible production techniques can be applied to produce tubular films. The first method regards a flat bag requiring only a cross sealed, open on top with gussets on both sides. The second one considers always a flat film folded from both sides and closed in the mid structure with a "back-seam" system, allowing both flat and gusset

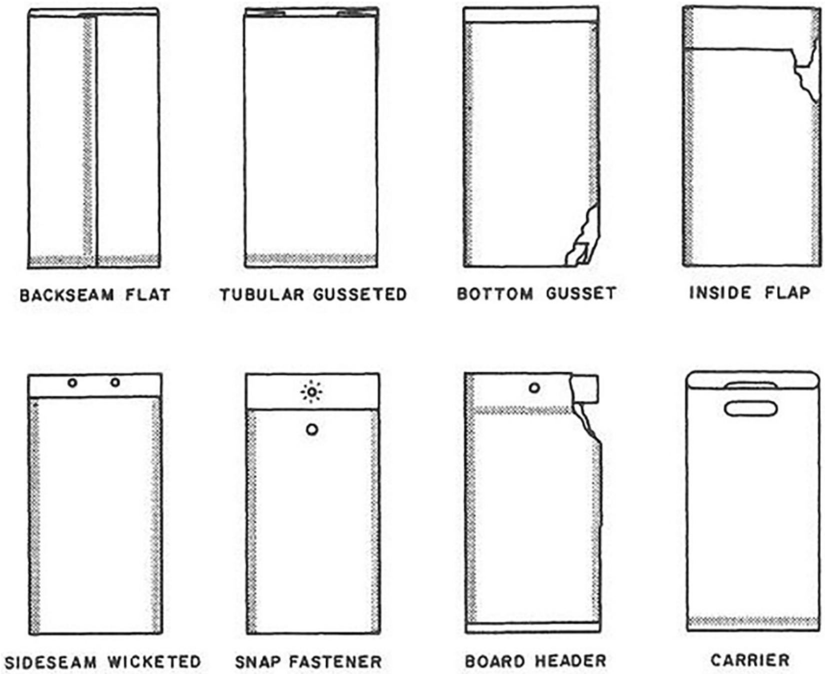

FIG. 3.5 Film tubing for bags.

sides. Plastic flat bags have an advantage; the flat surface enables a facilitate open on top and an easier folding of the sides. The sides can be holed and perforated for automatic fill and seal processes. Plastic bags provide a complete barrier against moisture and gas, and they can be resistant to mechanical stress. For example, two oriented layers were coupled and laminated into a very resistant film for big bags manufacture. A possible disadvantage of plastic bags concerns the right fix to the pallet platform, due to the possible slipping effect. To overcome this kind of problem, antislipper coatings were applied and allowed correct load stability on pallets (Sarker, 2020).

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Chapter | Four

Silos and bins

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4.1 Introduction

Production of food grains is the major source of sustainable income for the rural population (Mobolade et al., 2019) and is a major proportion of their diet giving them calories and proteins. In the tropical and sub-tropical regions, these grains are the food commodities that can be easily and hence, are widely stored. Some of these food grains are almost ready for consumption and have minimal processing while the others require a series of processing steps to make them suitable for human consumption. Being biological materials, these grains can easily interact with their ambient environmental conditions and thus require proper storage (Bucklin et al., 2019). The grains are stored in various forms at different stages of the food supply chain to provide the desired end product to the consumer (Mobolade et al., 2019).

The key reasons for which the food grains need to be stored properly are as follows:

- The grains are only produced seasonally while consumers need the product throughout the year.
- Food grains processing consumption sites can be different and far away from the production fields.
- Sometimes, the extra stock of grains needs to be stored for usage in case of emergencies like a flood, drought, famine, etc.
- Food grains are required as the seeding material for the next batch of the plantation.

Rice, wheat, corn, sorghum, lentil, soybeans, kidney beans, cowpeas, moong beans, etc., are some of the major food grains that are cultivated in tropical and sub-tropical countries (Asif et al., 2013). Due to the lack of processing units and adequate storage systems, a significant amount of the food grains get damaged, making them unfit for consumption. Also, a substantial amount of grains get impacted by climatic variations (temperature variation or change in the pattern of rainfall) or by natural calamities like drought and flood (Khatri-Chhetri et al., 2017).

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Post-harvest management of grains and the availability of suitable storage systems have always been major areas of concern leading to losses of grains in developing countries for a long time. The loss of these agricultural products results in the overall economy of these countries. After harvesting, the average amount of grains that the farmers keep for consumption by their own families is 60%–70%. Usually, the farmers store this proportion of grains in the indigenous and traditional storage structures (Kanwar and Sharma, 2003). They sell the remaining grains within 2–3 months of harvesting them. These grains are initially stored in bags or bulk for 1–2 months temporarily before storing them in a proper storage facility.

It is quite common that the storage structures vary with the regions and with the type of grains, for which the farmers use various principles and techniques which are the best to their knowledge for safe storage. Grain storage methods vary with the size of warehouses, or the type of storage (indoor or outdoor, community storage system, or individual ones), and also with the time period of storage, i.e., temporary storage or permanent storage. Also, these storage systems can be completely open ones, completely closed ones, or semi-open systems. Some of these traditional storage practices have been continued over the years with slight or no modification. These systems are serving the purpose successfully due to the knowledge and application of basic scientific principles in the initial stage itself. Although the storage techniques are usually designed by considering the climatic conditions of that particular region, it is noteworthy that the availability of natural resources and the traditional customs of the particular area also has a major role in governing the type of storage systems used (Mobolade et al., 2019).

Basically, the traditional grain storage methods are the knowledge and principles that the people of a region or community have evolved over time and have passed over the generations (Kanwar and Sharma, 2003). Some of these methods of storage are particular to the societal culture, so they can differ among nations, regions, villages, or communities. These indigenous storage methods have their origin connected to the regional culture along with the environment of that region. To minimize the post-harvest losses, farmers use various techniques such as drying the food grains to reduce their moisture content to prevent spoilage, using moisture-proof storage systems, and allowing sufficient aeration wherever required (Nduku et al., 2013). Some of the traditionally used storage techniques used in sub-tropical and tropical nations include solarisation, open-air storage, diatomite earth storage, storage in the gourds and Palmyra leaf bins, cribs, straw bins, earthen pots and bins, bamboo bins, storage bags, underground pits, mud-house storage, metal or plastic drums, and usage of camphor and other natural products (Mobolade et al., 2019).

A detailed and individual discussion of these traditional storage techniques is done in the further section of this chapter. Depending on the storage type, loading/unloading facilities, and control over the storage period, the modern grain storage facilities can be categorized into various types. Fig. 4.1 depicts the classification of modern storage systems. Conventional godown storage

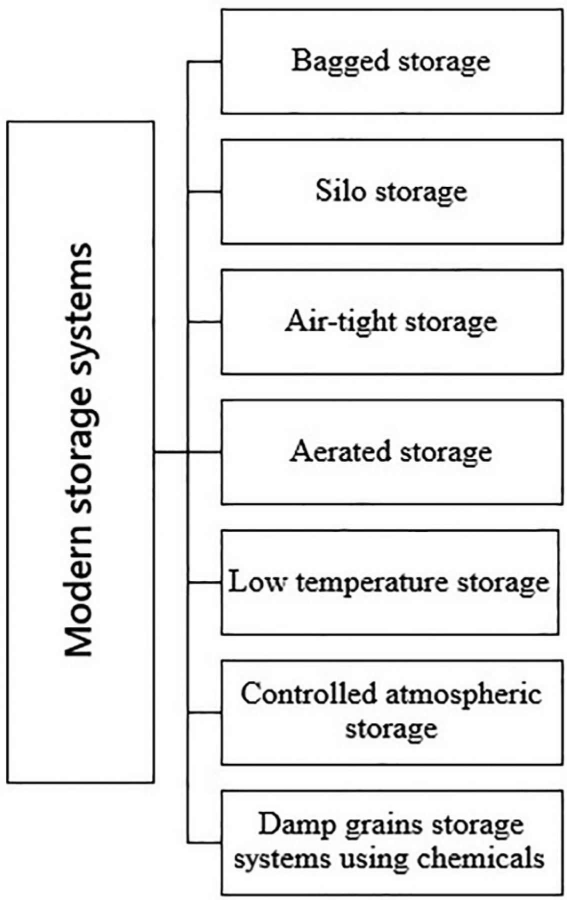

FIG. 4.1 Classification of modern grain storage systems.

involves the storage of grains in bags that are received from farmers, or storage depots and further distributed to local storage depots or ration shops.

Usually, the farmers ensure that the storage structure is ready before the start of the tentative harvesting season, but the exact time of harvest depends on the exact agro-climatic conditions. In developing nations, some examples of these storage structures are clay pots, baskets, bags made of jute, plant fibers, polyethylene, granaries, and cribs, while the storage structures for domestic usage include earthen pots, gourds, and containers made of plastic or metals. Apart from using these traditional storage systems, sometimes the farmers also use other traditional strategies like usage of certain herbs (like hot pepper, Mexican marigold, etc.), proper cleaning of storage structures, using pesticides before keeping grains, and trying to sell the food grains as soon as possible, in order to reduce the spoilage and losses (Mobolade et al., 2019).

The fundamental aim of any of the storage structures is to prevent the spoilage of food grains from rodent or insect infestation and microbial activity. Apart from these, it is necessary to maintain the dryness and low temperature for these grains throughout the storage period. With time, the application of synthetically produced insecticides has been increased, which has an adverse effect on the environment. This has led to scientific studies conducted for designing safe storage systems for food grains that have better sustainability and affordability.

The major drawback with the usage of a conventional bagged system is that these bags can easily absorb moisture from the atmosphere during humid climate and can transfer it to the food grains resulting in their accelerated spoilage. Another major drawback of bagged storage is that the walls and roof of the godowns easily get extremely heated in the hot and dry climatic conditions, and then they transfer this heat to the stacks of grains in closer proximity (around 1 m) to these areas, resulting in non-uniform moisture gradient in the stored grains (Bala, 2016).

Bins are the most common storage systems in rural regions of Asia and Africa and are made up of various plant-based materials with or without the usage of clay or mud (Chakraverty and Singh, 2014). Bins are metallic cylinders with a pointed roofing system including, in most cases, a ramp. They are silvery perforated metal frames with a larger radius than silos and varying heights. Silos are tubular manmade structures of cement, brick, steel, and timber (Mobolade et al., 2019). Its dome-shaped roofs are usually narrower and higher than bins. These silos can be made up of any of the materials like steel, aluminum, mud, plastic, concrete, or reinforced cement concrete (RCC), and can be of varying shapes and sizes (depending on the requirement). The RCC bins made in cylindrical shape provide maximum strength to the silos as compared to other materials of construction. Various studies have proven promising results of metal and RCC silos provided with temperature sensing and aeration facilities that can easily store food grains for years. Initially, these silos were made of concrete, but with modernization, the concrete silos have been replaced with RCC silos that have more durability, stability, and other desirable characteristics. The silos and bins are better storage systems for food grains as compared to other storage practices as they provide better control over the storage parameters and help in reducing the losses due to prolonged storage. These modern storage systems are discussed in a detailed manner in this chapter. The chapter will be covering basic principles of grain storage, different types of storage structures, various types of changes occurring in food grains during storage, the types of spoilage, and curative measures used for controlling the spoilage.

4.2 Storage principles

International agricultural output advances every year, necessitating a greater rate of technological innovation across the entire production process, from pre-sowing to reaping. Following harvest, grains are physiologically relatively stable; their stability, as well as viability, should be preserved by proper storage (Chakraverty and Singh, 2014). Only when the grains reach physiological maturity can they be harvested, and that technique is limited because mechanized harvesting is not possible. As a function, the grains remain in the crop till they attain a moisture level substantial enough just to allow mechanized harvesting. At this critical stage between maturation and harvesting, the grains are exposed to extreme weather conditions, which may impact their quality. This period is called the critical period. Further degradation is triggered by insects, fungi, rats, and rodent droppings. During the storage of grain in bulk, deterioration takes place due to interactions among multiple factors, such as physical, chemical, physiological, and biological factors (Chakraverty and Singh, 2014). A few variables to consider are temperature, moisture, oxygen, storage structure, physical, chemical, and biological properties of grain bulks, and microorganisms. They react well with grain in clusters (Ziegler et al., 2021). The degree of decomposition is incremental at first, however, when the desirable variables are defined or the keeping duration gets extended, a substantial decrease in grain quality and quantity occurs.

The loss of weight, temperature changes, changes in oxygen concentration, changes in moisture content, and the search for hygroscopic balances are all examples of quantitative losses. Flavor, smell, nutrient benefits, metabolite, physiological parameters including sprouting, elevated threat of aflatoxins, and trade deflation are all examples of qualitative losses. Temperature and moisture content are the most significant factors which can contribute to food crop damage among some of the set criteria (Ziegler et al., 2021). Rainfalls and climatic changes, as well as temperature fluctuation, do have a considerable effect on the yield attained. The following section covers the key factors of grain storage and gives insight into its impact on grain quality.

4.2.1 Moisture content

Moisture content is one of the most important components which influences grain properties and generates an environment that is suitable for the infestation of pests. The acceptable amount of moisture in kernels during preservation differs based on the species and the duration of the time those grains would be retained (Chakraverty and Singh, 2014). This is the first component to address since it aims to minimize insects and microbes from deteriorating stored crops. Listed below are important points to remember when planning safe storage:

- Moisture contents of grains below 13% stop most microorganisms and mites from growing.
- Moisture contents of stored grain below 10% stop most insect pests from growing.
- Moisture contents within a grain bulk are rarely uniformly distributed and unchangeable.

Higher moisture percentage in storage is undesirable because it affects the ability of grain to preserve viability (Volenik et al., 2006). The necessity of periodical moisture detection within a grain mass can never be justified. The number of crops, price, and grain processability are all impacted by seed water content;

hence it signifies its direct effect on the economic return. The humidity limitation for appropriate cereal storage in terms of insect pests and microbe infestation is around 12%–15%, which is stabilized to atmospheric humidity levels of approximately 81%–87%. If the grains are intended to be kept for a long time, they should be reduced to a moisture level of 9%–12%.

Joshi (1993) discovered that the impact of moisture content on pumpkin seeds, the pressure necessary to begin seed coat disintegration rose as the moisture content increased from 4.95% to 11.2% (dry basis). Deflections at pericarp or shell breakage grew as grain moisture content increased from 4.95% to 11.2% (dry basis), and that was considerably higher for seeds packed in the vertical orientation than that for seeds put in the horizontal position. Similarly, when the moisture level of the grain and seed grew to 15%, the energy absorbed by the seed and kernel raised both in lateral and vertical loading orientations. The energy absorbed dropped as the moisture content was increased. Waananen and Okos (1988) postulated that as water content increased, corn failure stress decreased whereas failure strain continued to increase.

4.2.2 Temperature

The temperature is another important basic factor to be considered along with the grain moisture and equilibrium relative humidity (Chakraverty and Singh, 2014). The relative humidity, which is in equilibrium with the grain moisture, varies with the temperature. The metabolic heat produced exclusively by dry grain is about 1×10^{-7} Cal/scc and by wet grain is $\sim 1.3 \times 10^{5}$ Cal/scc (Bala, 2016). The amount of heat produced by fungi, insects, and other organisms infesting the grain is much higher compared to the aforementioned values. For the storage of brown rice, low temperature is generally used in Japan as the rates of chemical and biochemical reactions are always slow at low temperatures. When evaluating temperature for a safe grain storage system, it is essential to take into account the following crucial points:

- pests and larvae do not thrive below 7°C,
- storage fungus would not proliferate below 0°C,
- the influence of temperature on a microorganism can indeed be correlated with the degree of kernel humidity.

Up to a specific temperature, the rate of grain respiration, microbe development, and chemical and enzymatic reactions speed up. So, when the temperature of the crops increases to approximately 25°C, it becomes very easily plagued by pests and microorganisms, while the rate of respiration increases at the loss of the chemical components. The temperature of the crop should always be factored in connection with all of its moisture levels.

4.3 Different storage structures

The role of grain production in developed and developing countries is minimal since agricultural production is seasonal and agricultural commodities demand is more evenly spread throughout the year (Montross et al., 1999). During this period, it becomes necessary to store excess supply during the harvesting season so that it can be gradually released to the market during the off-season. For stable agricultural production or economic stability in any country, quality food grains must be abundantly available to consumers for making different products and for marketing, as well as to farmers for growing healthy grains (Mobolade et al., 2019). Because of inadequate storage and processing facilities, a huge amount of food grains is being lost after harvest. It has long been a major challenge in developing countries to provide adequate post-harvest facilities or storage technology (Mobolade et al., 2019). In turn, this has led to a considerable waste of agricultural yield and consequent losses to the economy.

Grain storage is needed all year round to meet the demand for a plentiful supply of cereals and legumes. The purpose of grain storage is to maintain the quality of the grain either for a short-term storage period or for a long-term storage period. In order to prevent the development of Molds and insects, grain needs to be stored at a relatively low moisture content and a cool temperature (Bakker-Arkema et al., 1999). Depending on the type of crops grown, different regions have different types of storage methods, and producers have differing levels of effectiveness in adapting the basic concepts of grain storage (Mobolade et al., 2019).

4.3.1 Food storage structures

Traditionally, farmers store their grain un-threshed. The reasons for this are twofold: first, they do not have the time to thresh the grain following harvest, and second, they rely on the lower susceptibility of grain stored in husks to pest infestations (Moustafa et al., 2018). The storage period on the farm level generally lasts 7–14 months (Nagnur et al., 2006). Following harvest, the grain is housed in a variety of traditional storage units that are generally perfectly adapted to the existing socio-economic and climatic conditions and rely on locally sourced materials only. Generally, there are three types of small farm storage: open, partly open, and enclosed (Mobolade et al., 2019).

4.3.1.1 Systems for open storage

During unfavorable hot and humid climates, the only storage systems used are usually open storage systems, since the stored produce is still moist when it is put into storage. The widespread use of platforms standing on stakes, on which grains or glumes are stacked, is very prevalent. Rain is kept off by a straw roof. Crops are also sometimes found hanging on frames or under roofs of houses. As for the latter situation, the fire beneath them is used to dry them and repel insects. The produce will also continue to dry in storage because of the relatively high air circulation. The design of open systems is generally very simple however the storage hygiene is difficult to maintain.

4.3.1.2 Systems for partly open storage

Partly open storage systems have been very prevalent in semi-arid climates. They comprise wooden structures with only a hay matting upon which products are placed, along with receptacles made from dried branches or leaves. Grains are usually stored un-threshed, mostly in the form of kernels or glumes.

Foundations laid with stone help avoid contact with the earth, avoiding ground dampness from infiltrating the structure. Moisture protection is provided by a grass ceiling. Partly open storage systems offer greater protection from the elements than open-storage systems, however, they are less aerated and are not protected from insects.

4.3.1.3 System of closed storage

The most common container for storing corn, millet, lentils, rice, and groundnuts in arid regions is a closed-storage container made of mud filled with chopped straw, which is called banco. Generally, the crops are threshed before being stored. The mud used in the storage process is excellent at insulating and has a very low moisture content, making moisture and condensation virtually unheard of. Various sizes and shapes of containers can be found. A straw roof protects them against rain and a lid covers them. As a foundation, large stones prevent any moisture from entering the ground.

Condensation could develop in enclosed-storage systems, notably in metal structures. Ensuring consistent temperature control needs to be tailored, which can be accomplished by blocking sunlight. Enclosed systems offer good protection against insect invasions. Dry and cool conditions can be obtained, especially in mud buildings. Closed containers also create an airtight environment wherein insects and cereals use oxygen for respiration, forcing larvae to disintegrate. Residual oxygen is adequate to effectively maintain seeds sprouting.

Because clay structures are not water-resistant, they must always be restored or reconstructed regularly. This is a disadvantage in using enclosed structures. Subsurface trenches are a type of closed-storage technique that has been mentioned several times in the research as a possible technique of grain holding (Mobolade et al., 2019). There is no doubt about the benefits of being able to keep items cool and dry and unaffected by temperature changes while storing them. Keeping the pit sufficiently airtight and free from water can prevent the growth of insects and mites, as well as the growth of molds. A good location with appropriate soil type must be chosen (Chakraverty and Singh, 2014).

In many developing countries, storage by cribs and bag storage of cereals are still practiced on local farms, but bulk storage is displacing both methods globally. The bag storage method involves the placement of farm products inside jute bags after they have been harvested. In addition to being convenient to move, bagged storage allows individual farmer lots to be separated into a lot. A bag can be stacked under any cover and handled without any special equipment. Bags could be piled under any shade and managed with no use of special equipment (Montross et al., 1999).

In regions where manpower expenses are excessive, bag storage might be outrageously costly. Weaved jute, hemp, native grass, and cotton bags do not keep moisture, insects, or rodents out. However, polymer sacks are structurally robust and insect-proof, although they are pricier and more prone to UV deterioration. In storage facilities, fiber bags could be piled to a height of 8 m, while polymer sacks can only be packed to a height of 4 m due to slippage. Cereal sacks must be retained at least 6 in. off the floor using dunnage. Each pile should be divided into different units comprising 254 sacks, with just a row of 7 sacks longitudinally next to a series of 12 sacks widthwise, and also the stack dimension must not transcend 6×9 m (Bakker-Arkema et al., 1999; Montross et al., 1999). Following are the merits of bag storage structure:

- Purchasing, selling, or shipping products is easy with bags. Bags can also be easily loaded and unloaded.
- The bags can also be readily removed and treated if they are infested.
- Since the bag's surface is exposed to the atmosphere, grains do not sweat.

4.3.1.4 Cribs

It is a rectangular-shaped enclosed structure elevated between 0.2 and 0.8 m above the ground, which is an improvement on the platform structure. The building is built on the ground, supported by columns, and has well-vented sides made of hay, straw, wood, or wire mesh (Mobolade et al., 2019). Roofing material is thatch straw or iron sheet up to a maximum width of 50–70 cm, designed in a way that winds blow perpendicular to the length. As for the legs, it is equipped with a rodent-proof mechanism to prevent infestations. Cribs are designed to allow the drying process to continue while it is in use as ventilation occurs naturally. The result is good aeration, even in humid regions. Similarly, because of the free flow of air over the stored produce, it has the best function as a storage facility. They have evolved to be extremely beneficial, particularly for drying corn and paddy. Regardless of the weather considerations, the cobs are kept inside the crib for up to 4 months before getting marketed (Montross et al., 1999).

4.3.2 Conventional storage structures

Conventional grain storage and quality parameters trace back to when households devised them and handed those down to the next generation. Grain is contained in traditional storage buildings, which restrict leakage, help guard against rats, pests, and vermin which may make contact with crops during storage, and keep it secure both from factors like sunlight and rain (Ziegler et al., 2021). Nevertheless, almost all of these structures allow airflow and water to seep through, rendering them ineffective against pests, parasites, and fungus which are already prevalent in the crop during cultivation and thus are retained with it. Most smallholder farmers who use traditional storage methods combine the grain with natural preservatives like edible oils to avert premature disintegration.

Traditionally, two ways of grain storage were being used: temporary storage and extended storage strategies (Ziegler et al., 2021). Temporary storage methods include aerial storage, storage on the ground, and expansive wooden sites, which have been generally performed at field scale, whilst prolonged storage methodologies entail storage baskets constructed completely of organic materials, gourd vegetables, earthen containers, buckets, thick walls bins, and underground storage (Bucklin et al., 2019). Producers in one-fifth of emerging countries keep their produce in the hamlet. The percentage of total food crop yield retained at the farm level and the storage time is mostly determined by landholdings, consumer behaviors, workforce payment systems, as well as other variables (Olorunfemi and Kayode, 2021). Crops are sometimes kept indoors, outdoors, or subsurface among a wide range of materials varying from mud huts to sophisticated containers. These holding containers are made of a multitude of locally sourced resources and appear in a range of forms, shapes, dimensions, and functionalities (Dhingra, 2016).

The technique of killing insects by heating grain in the sun is called polarization. Villagers used to do it before preserving crops in regions where the temperature outside reaches 19°C or more (Mobolade et al., 2019). This process varies in duration depending on the items, and the dried grains are eaten to see whether they have dried sufficiently. This also pertains to crops that have been cultivated primarily for food instead of seed since seed potential may indeed be impaired. Farmer's sun-dry stockpiled grains by scattering them just on the ground, spreading plastic or canvas, grass mat, to reduce the amount of moisture and eliminate its most pathogenic agents. Kiruba et al. (2008) observed that exposing *Callosobruchus chinensis* larvae to solar radiation for a day destroys the larva found in parasitized lentils with complete egg death rates in colored bags.

4.3.2.1 Storage in bunker

Bunker storage also known as crib storage is an enhancement on the foundation platform, which is a square contained construction elevated approximately 1–2 m above the ground, anchored with pillars, and has well-ventilated sides composed of hay, palm fronds, willow, or thread mesh. This is blanketed with thatch fiber or metal sheets and is oriented so that the pervasive air moves transversely to the length of the fiber. To combat mice invasion, the limbs come integrated with a rat-proof system.

The bunker is designed in such a manner that the drying proceeds throughout storage resulting from natural circulation and also the unfettered access of wind over the preserved food. The crib was conventionally used to hold un-threshed crops. Such kind of storage unit is easy and affordable to build, however, it delivers limited protection from predatory insects, with retention loss from pests as well as rodents typically surpassing 35%.

4.3.2.2 Underground storage

Villagers in agro-ecological regions with poor water levels utilize underground grain storage to store large amounts of winnowed crops for extended periods. The subterranean trench is excavated in a circular or rectangular configuration, 2–5 m deep and 2–4 m wide, and shielded or covered using hay mat or wheat straw (Mrema et al., 2011).

Before loading, the edges and base are filled with chaff and hull; winnowed grains are loaded into the trench with sacks, and then after loading, hardwood planks are used to enclose the hole, which will then be covered with plastic or metal plate. This trench would then be disguised with a covering of chaff and just

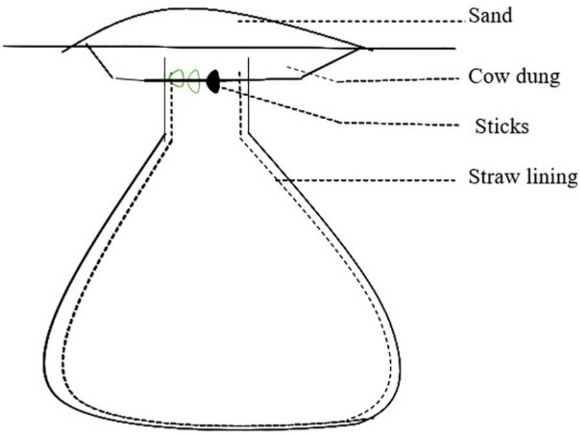

FIG. 4.2 Underground pit.

a mound of dirt, a boulder, or by spreading spikes around it as a means of protection from animals. Subsurface pits are said to retain grains stable for several seasons. These pits keep the grains cooled and sometimes store them hermetically. The underground pit for the storage of products is depicted in Fig. 4.2.

Nevertheless, temperature changes and field orientation were carefully examined in order to ensure the safety of crops. Because of the limited oxygen saturation, grains housed within that framework are guarded against pest damage. Without breaking, retention could last around 6 months to 6 years, but once accessed, entire stockpiled crops should be discharged. Underground trenches possess many advantages, such as strong protection from insects, fire, pests, and theft, as well as minimal construction and operating costs.

The major downsides of this technique are high grain humidity as storage duration increases, which contributes to fungal damage, reduced crop quality, and usability, as well as some nutrient value loss. Similarly, it was observed that grains on the upper side and all around the sides on the other hand can become frequently moldy and discolored. As the underground storage technique had many limitations it was no longer desired in the cereal grain sector and this paved way for the introduction of strategies like bag and bulk storage.

4.3.2.3 Storage in bags

In farms, villages, and commercial storage centers, short-term storage of food grains in bags is a typical storage facility. Depending on the region, woven sacks made from jute, sisal, native fiber, cotton, and other materials are used. Until the advent of polythene bags, these were commonly utilized. They are normally available in a variety of sizes, ranging from 30 to 120 kg.

Stacking grain in sacks is beneficial for small-scale farmers because they can keep it out of the elements and predators by storing it under a convenient shelter. Bags can be carried and handled without the necessity of special tools, and they also allow for the gas transfer and pest control in closed storage using fumigation techniques. Farmers put the bags on planks or frames that are lifted off the surface, stopping the crops from soaking moisture from the surface. The elevated base is preferable to the polyethylene platform since it permits air to circulate beneath the bagged kernels. It is simple to label the sacks and collect samples from each sack using this approach, but it is difficult to manage the items because they are in sacks. Furthermore, when compared to the bulk storage approach, fewer grains are stored per unit of space.

However, Mrema et al. (2011) has mentioned that bag storage has made huge strides owing to the reduced initial investment for storage facilities and also owing to the lack of adequate bulk storage areas. The key factors that influence whether bulk storage or bag storage is to be used include (1) grain type, (2) how long grain will have to be stored, and (3) whether a single grain type or a mixture of grains is to be stored.

4.3.2.4 Storage in bulk

Grains are frequently stored in bulk at the farm level in small outside granaries, woven baskets, or containers made of wood, metal, or concrete located under or inside the house. The capacity of these storages ranges from 300 to 1500 kg. Loss from insects, rodents, birds, and moisture uptake in traditional bulk storage systems is expected. Certain bulk storage techniques that were commonly used include storage in bunkers and warehouses.

4.3.2.5 Warehouse (shed) storage

Warehouses are a common choice for bulk handling companies. They are scientific storage facilities specifically designed to safeguard the quantity and quality of stored items. Sealing and aeration are critical components of bulk storage (Pekmez, 2016). Depending on the situation, aeration might be either ventilated or chilled. Thus, enhanced storage structures and scientific grain storage in warehouses are urgently needed to supplement traditional storage methods with contemporary inputs, offer farmers cheaper storage facilities, and minimize grain spoilage but requires meticulous site preparation, labor to handle large tarps, and machinery to move grain onto and off the grain stack (Mobolade et al., 2019).

Sheds and bunkers make insect infestation treatment difficult. The use of bags for short-term storage of grain on the farm may be a better option (Pekmez, 2016). As for the storage of cereals in a warehouse, the location, control of moisture content, and aeration of the cereals are all important factors. This technique can be used to store cereals and cereal products in bulk stacks, as well as sacks.

4.3.3 Bulk storage structures (silos and bins)

Storage structures for food grains that have been enhanced are called improved bulk storage structures. There has been some significant advancement to traditional storage facilities in this structure (Kiruba et al., 2008). Compared to conventional storage structures, this type of construction setup has a higher storage capacity and can store food grains for a longer period. Improved storage structures with capacities ranging from 5 to 300 tonnes are available.

A sophisticated storage system should be chosen to safely store stored grains and other products. Modern storage structures must be preferred first and above all else for their durability and expense (Mrema et al., 2011). Among the structures used to store goods are bunkers, bins, and tanks, which can be classified according to what they are used for. The most common modern bulk storage structures being highly sorted after grain storage are the silos and bins.

The silos are reinforced concrete structures designed to withstand loads placed on them. There is a significant difference in the size of the depth and the diameter of the silo (Krishna et al., 2020). As its name suggests, a silo is a storage bin used to store large portions of resources such as grains, kernels, and similar materials (Mobolade et al., 2019). The hopper is the area that is useful for unloading materials. Structural columns provide strength to hold the silos in place firmly.

Silos are anchored by framing, which could be composed of brick pavers, RCC towers, or reinforced RC pillars. Concrete Block pressure is exerted on the walls. Its foundation should transfer the resources which have been held, such as cereal grains (Krishna et al., 2020). According to structural principles, if the rupture plane of the material stored is not intersected by the free surface of the material contained in the bin, it is referred to as a silo. They are often round in cross section, while shallow-bins may well have square cross-sections (Patel and Patel, 2019).

Steel and reinforced high-strength concrete are the most widely used materials in the fabrication of silo storage structures. Using either material has its advantages and disadvantages. A circular-sectioned silo may be constructed using thin-walled plates without the aid of any stiffeners. The construction and design of silos are influenced by the quantity of goods stored, climatic conditions, and site conditions (Montross et al., 1999). Grains commonly are stored in vertical structures, in particular in reinforced concrete silos and steel bins. The most notable gain of vertical stockpiling is indeed the rapid grain release by means of gravity. There are many types of silos, including bunker-silos, tower-silos, and sack silos (Islam, 2020).

4.3.3.1 Tower silos

Tower silos are cylindrical constructions that are vertically stacked. Grain, wood chips typically unload from tower silos with air slides or shafts. Unloading is done with railroad cars, vehicles, and conveyors (Patel and Patel, 2019). Except for the topmost few feet, where there is very little weight to press downwards, the materials kept inside tower silos, also known as silage, typically pack well due to their weight. Nonetheless, this can be a disadvantage when storing materials like wood, for example Islam (2020). Tower silo for the storage of farm produce has been depicted in Fig. 4.3.

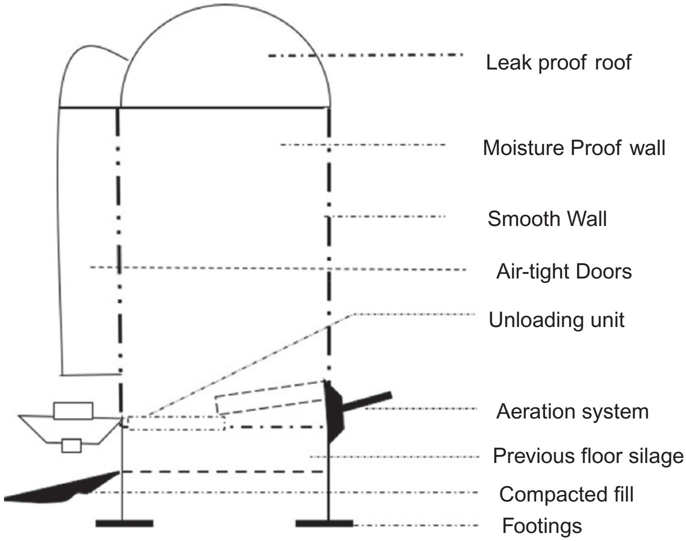

FIG. 4.3 Tower silo.

4.3.3.2 Tower silos with reduced oxygen levels

Low-oxygen silos ensure that forage is maintained across a reduced O_2 environment at all times. In other types of feedstuffs, they are used to contain cultured contents and to inhibit fungal deterioration (Islam, 2020). Reduced oxygen silos are just released into the atmosphere during the initial operation, and even the unloader chute is usually sealed to keep air out. This silo stands present in the atmosphere, but huge impervious sacks tied towards the silo's openings separate outside and inside air. The gas confined within the silo expands throughout the day as the sun warms it, and thus the bags break. Whenever the silo starts to cool at night, the air within shrinks, forcing the bags to inflate again (Islam, 2020).

4.3.3.3 Bunker storage

Bunkers are used primarily for storing the contents of underground homes (Bakker-Arkema et al., 1999). They are shallow structures. In bunkers, large ditches are surrounded by walls and used to store dry products or wet feed (Islam, 2020). To keep the trench airtight, the trench is covered with a plastic sheet after it has been filled. They are easy to build and are ideally suited for large operations because they are cost-effective (Patel and Patel, 2019). It is the depth and the angle of rupture that determine the ability of a bin to function as a bunker.

4.3.3.4 Bag silo storage

They are sizable tubular polymer bags filled with grain and thereafter covered from both ends. A forklift or perhaps a crane must be used to empty the silos. The sack is often torn in segments during unloading, but if it is not ripped, it can be retained and recycled (Patel and Patel, 2019). Bag-silos have the merit of being inexpensive and are widely utilized as a short-term solution when development or harvest conditions dictate more capacity, though some farms employ them throughout the year (Islam, 2020).

4.3.3.5 Plastic silo

Plastic silos intended for food storage are maintained in the cover or indoor spaces, away from sunlight, on some kind of elevated platform above ground level to facilitate convenient outflow of the stored grains. However, these designs lack strength and structural integrity and so are generally not preferred to use (Mobolade et al., 2019).

4.3.3.6 Metal silo

A metal silo is a shell structure composed of multiple segments fabricated in aluminum or stainless steel. As it is unlikely that a standard will be prepared for aluminum silos, the steel silos standard can be applied to the construction of metal walls in general (Rotter, 1998). Metal silos are generally either on-ground or elevated. On-ground silos can be very large light structures but are susceptible to wind loading when empty and to any loss of symmetry in solids placement within them while elevated structures are small but more efficient in performance (Montross et al., 1999).

It has become increasingly common to see metal silos as an effective and economical storage container for cereals and lentils in a hermetic environment resistant to water. Metal silos protect long-term food storage from rodents, insect larvae, and pests. Metal silos have become the best possible bulk storage facilities. Nevertheless, they ought to take precautions to avoid direct contact with sunlight by placing them in shady and ventilated areas of the establishment. Steel silos being metallic, despite their lighter weight and smaller components, can withstand large loads. Because of their higher density, they are impermeable to gas and water. Steel silos are less difficult to manufacture, erect, and operate or disassemble. However, the main downside is that it is susceptible to corrosion. Steel silos can indeed be accessed very easily via manholes outfitted with ventilation and thermostat devices.

4.3.3.7 Concrete silos

Precast concrete silos consist of small blocks that are held together by deep grooves around their edges, creating a shell of high strength (Islam, 2020). The disadvantage of these silos is that they are not mobile, so more equipment is required to move the cement. Concrete silos are known for their sturdiness, versatility, long durability, and fireproof properties. A typical steel silo wall has a thickness of 7 mm; typical walls of concrete silos have 130 mm. Therefore, concrete and steel silos have different volumes even when they have the same diameter. Concrete silos need protective coatings occasionally to avoid the damaging effects of environmental pollution (Patel and Patel, 2019). Concrete silos have the following significant advantages. These structures are moisture, vermin, and insect-proof; they are strong, durable, and easy to work with, virtually no food grain loss occurs during filling, storing, and emptying, and silos are wholly fireproof and have a long life. They should, nonetheless, be shielded from sunlight as well as other sources of heat to limit dampness, and therefore should be placed in dark, well-ventilated locations.

4.3.3.8 Storage in silos

A silo is a giant storage structure that is essentially a deep bin. In the construction of high-capacity silos, reinforced concrete structures (RCC) have been widely used. The storage time in a silo can range from 5 months to many years, and the total capacity extends based on the size of the silo, which is between 1 and a few million metric tons. A gliding cast, which is moved upwards constantly or progressively, is often used to construct larger silos made from concrete. Out from the top, reinforcements and cement are delivered. When apertures are appropriately enclosed, concrete silos can be rendered impermeable. Although concrete is a long-lasting and cost-effective material, as said it should be used prefabricated or precast. Steel on the other hand is arguably the most common building material for modern grain storage facilities in many countries. However, its use has been limited in many Asian countries. The diagrammatic representation of the steel silo has been presented in Fig. 4.4.

4.3.3.9 Storage in bins

Bins are storage structures with nothing more than a cover on the upper end that could contain the product. The bin storage technique can be used to store vast quantities of grains. To a greater extent, this storage solution is analogous to silos (Chakraverty and Singh, 2014). Grain bulk storage bins can all be composed of steel and concrete, standard or perforated galvanizing sheet. Mild steel

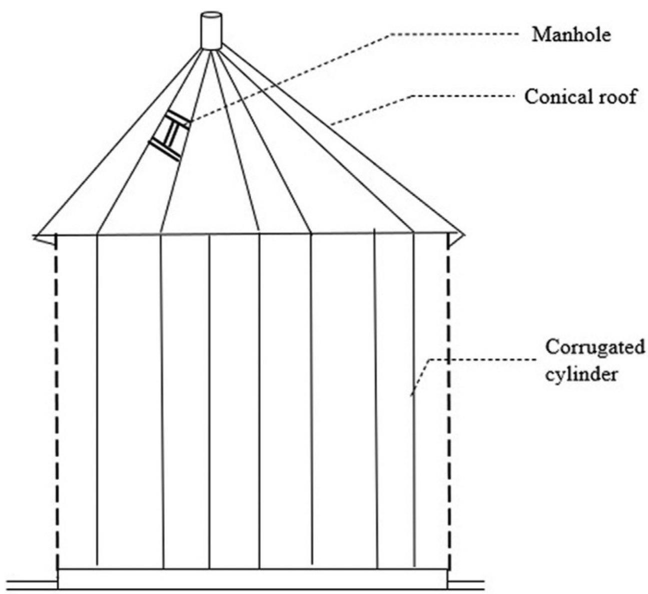

FIG. 4.4 Steel silo.

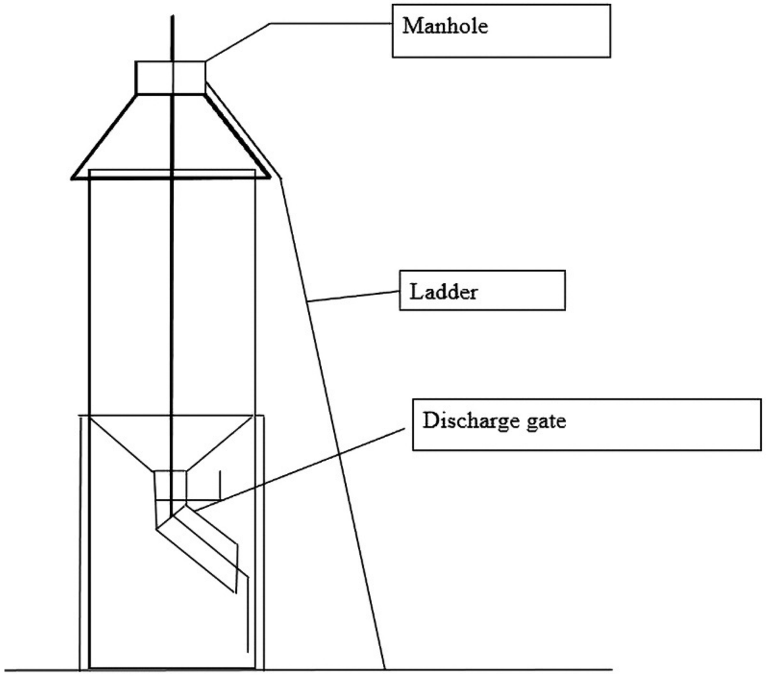

FIG. 4.5 Steel bin.

bins and R.C.C. bins are the most frequent types of bins in Asian nations. Modern storage bins have the following features:

- less pricey as well as convenient handling,
- very little area required,
- decreased costs on sacks,
- mechanization and automation for rapid handling and retaining quality of the product,
- security against birds and rodents.

Steel bin

It is mostly a pre-engineered enclosure with just a hopper base that sits outside. It is constructed of a folded Mild steel sheet with 15 gauge (Bakker-Arkema et al., 1999). This also includes a mechanical ladder and pulley setup for loading the grains. A steel bin for the storage of products is depicted in Fig. 4.5.

Aluminum bin

It is just a spherical construction that is positioned outside a processing establishment. A tubular body is composed of numerous curved metal panels and then a conical lid comprised of flattened aluminum plates constitutes the bin (Chakraverty and Singh, 2014). Both frame and roofing are linked using bolts and nuts. This aluminum bin is built on a 70-cm-high foundation or platform, that acts as a constant barrier against moisture. At about the same time, the grains may well be conveniently packaged owing to the outflow spout built in the platform. A vent on the rooftop is used to load the bin. Sealing systems are installed both on the bin and the spout (Chakraverty and Singh, 2014).

RCC-bin

RCC or reinforced cement concrete storage structure is impermeable and circumferential. This has a throughput of 2–7 tonnes. It is possible to establish it on the site. Bins with a volume of less than 5 tonnes can indeed be manufactured using RCC bands that are 40 cm high (Islam, 2020). Concrete is often used to seal the bands' seams. For loading and emptying grains, there is also a (70 cm) diameter aperture on the upper end and a spout close to the bottom. It is desirable to always have a slant at the bottom. Securing measures should be fitted in the manhole and outlet. RCC bin for the storage of products is depicted in Fig. 4.6.

Other storage structures

In addition to bins and silos, large cereal repositories often employ barns and warehouses for post-harvest storage (Montross et al., 1999). Though transferring material into and out of this storage method is more time-consuming and costly, the average fixed price per unit volume is significantly lower than

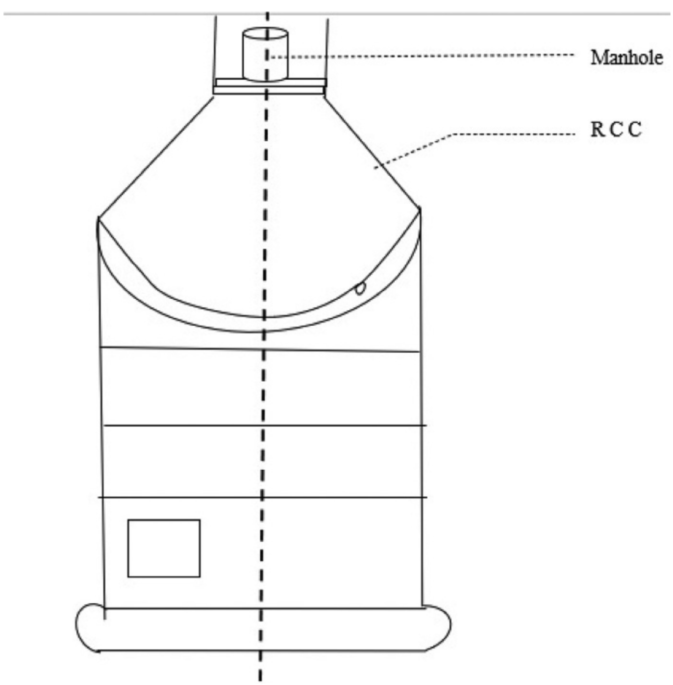

FIG. 4.6 RCC Bin.

that for vertical retention. Since the flow of air in a shed is just less constant than that in a bin during air circulation, the flow rate should be larger (Mobolade et al., 2019).

4.3.4 Changes in food products during storage

Stored grain is an artificial ecosystem actively interacting with abiotic elements like temp, humidity, and biological aspects like pests and rodents (Chakraverty and Singh, 2014). Time causes constant desirable and undesirable interactions, thereby inducing grain modification and sometimes degradation. Wide and varied handling practices yield different food characteristics, impacting bioavailability, body absorption, and total nutrient content. During storage, modifications in a food grain are influenced by oxidative reactions inside the grain and degradation induced by numerous biological organisms. These alterations and imbalances, nonetheless, occur synchronously during storage (Villareal et al., 1976). The key factors which affect the quality of the grain during storage are depicted in Fig. 4.7.

The following section focuses elaborately on the physical, chemical, and biological changes in grains during postharvest storage.

4.3.4.1 Physical changes

Atmospheric moisture and temperature are two significant physical factors that have garnered much attention in the research of grain degradation in storage. While grains are commonly kept at a level of moisture that is often considered safe, temperature and moisture fluctuate with time and place due to weather variations (Wallace et al., 1983). Thermodynamic changes drive moisture migration in stored grains, so predicting the consequences of naturally occurring weather variations is crucial when designing safe storage facilities.

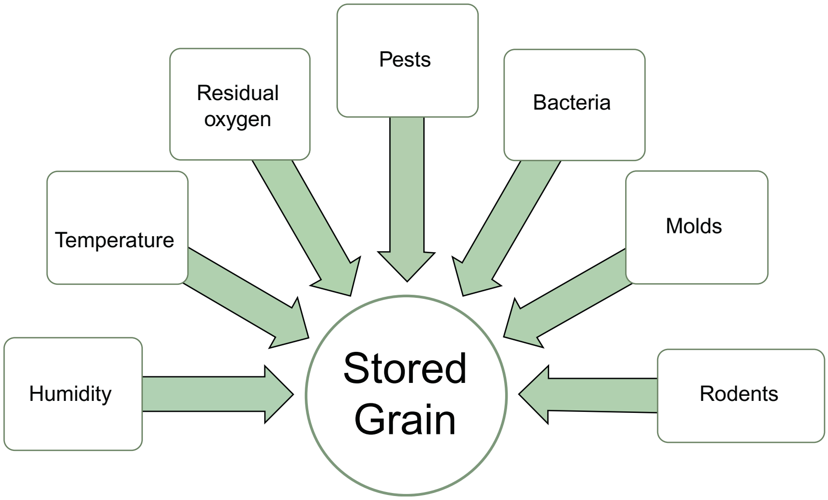

FIG. 4.7 Factors affecting grain quality during storage.

4.3.4.2 Chemical changes

Three main phenomena determine the chemical changes occurring in cereals during storage: activity of enzymes, oxidization, and respiration. In all cereal grains, enzymes break down the sugars, lipid, and peptides present. The increase in crop humidity amplifies these enzyme reactions (Pushpamma and Chittemma Rao, 1981).

As lipids are stored, a lipid enzyme in bran hydrolyses them into its secondary metabolites. Once grain heat and humidity are both excessive, FFAs increase rapidly. Additionally, the decomposition of lipids gets accelerated by the intervention of fungal growth. It is thought that fat auto-oxidation contributes to the development of stale flavor in old rice. Amylase hydrolyses starch, the major component of rice, into monosaccharides and disaccharides. Increasing concentrations of reducing sugar increase this process. Whenever the moisture of paddy is about 12%–14% and even the temperature is correspondingly less, this transformation is less pronounced in the crop (Chakraverty and Singh, 2014). Sugars also undergo fermentation whenever the water activity of kernels is high. As both ethanol and acetic acid are produced, together with an acid odor, throughout grain retention, simpler sugars and acidity rise, whereas non-reducing sugars decline. Grain storage is most sensitive to three factors: germination, non-reducing sugars, and level of acidity (Pushpamma and Chittemma Rao, 1981).

Besides enzyme reactions, oxidation due to the atmosphere leads to changes in sensory attributes. Like other cereal grain elements, vitamins deteriorate with time when stored in normal conditions (Wallace et al., 1983). Temperature gradients in bulk caused by changes in temperature surrounding the grain bin cause moisture to hydrate grains with uniform moisture contents. If the grain's moisture content remains constant, the equilibrium relative humidity of the air around it rises as the temperature rises. The result is that RH difference occurs in conjunction with temperature change in grains of uniform moisture, where the partial pressure rises and the level of dampness in the air intensifies as the humidity and temperature increase.

In addition, whenever a temperature difference occurs in stored products having uniform moisture levels, water vapor pressure and concentration gradients run in parallel to the thermal gradient, enabling vapor to permeate from high- to low-temperature zones. Because of temperature variations in the surrounding area of the compartment, convective-air currents form in the grains stored there (Chakraverty and Singh, 2014). While heated air transfers from a warm area to a cooler region in grains, it loses both moisture and heat. It produces moisture accumulation due to condensation at the top or bottom of the bin, depending on the direction of the natural convection of the air within the grain bin. The movement of moisture occurs primarily due to air movement through convection. Diffusion is responsible for moisture movement. There is a temperature disparity within the grain storage structure during the winter, as there is a low average temperature in the grain storage building. As the grain cools, the air in the grain flows downhill, across the bottom, and then back up near or in the middle of the bin, where both the air and grain are warm. The air passing through the core of the container collects moisture until it leaves the container or crosses the tops of the sidewalls. If no countermeasures are taken, the grain's moisture content may rise, thereby making the storage surface chilly leading to condensation, and causing it to rot (Chakraverty and Singh, 2014).

In the summer months, grain temperature is low in the storage, and the outside air temperature is high. As air flows past the cold base of the bin and down into the bottom, moisture condenses on the base. Heated air flows along the walls and upwards after being heated. When this happens, contamination occurs at the base of the bin. Moisture migration due to natural air circulation can be eliminated by minimizing or substantially reducing the difference in temperature along grain and bins. Due to the small temperature differences between bin walls and bin centers, moisture migration in tiny containers is slower than in large enclosures. Because heat has a shorter flow channel from the core towards the edges in a compact bin than that in a large bin, temperature fluctuations are lesser.

4.3.4.3 Biological changes

Infestations are always more prominent in places with significant humidity levels, although the temperature does have the largest effect on insect production. The speed of doubling at ambient conditions is such that a month-to-month exponential growth of 50 times the original number is hypothetically feasible. After 4 months, 50 pests at harvest could be doubled to 324 million. During storage, insect pests and fungus boost temp and dampness, and speed up the enzyme activity that would otherwise exist at a reduced level (Chrastil, 1990). In storage, fungal invasion is most severe whenever dehydration is poor, substantial numbers of pests are prevalent, generating a temperature gradient in the grains, or even just the preserved grain is subjected to severe dampness. All of these factors contribute to grain disintegration and loss of weight during storage. In addition to weight loss, increased crop deterioration results in nutritional loss and contamination with anti-nutritive substances.

4.3.4.4 Physicochemical changes

Paddy and other grains lose a variety of physicochemical characteristics during storage. Studies denote that retention altered the grain's expansion, toughness, and form. Coloration is another important criterion that has been observed to fluctuate after storage. After several months of paddy storage, few researchers suggested minimal color change, whereas others reported substantial color changes after more than 8 months of storage. Under poorly managed storage circumstances, the quality can rapidly deteriorate, but with low water activity, sterile conditions, and reduced O_2 exposure, the alterations remain minimal. Similar physicochemical modifications are also observed in other cereal grains, hampering their keeping quality.

4.3.5 Types of spoilage during storage

Different types of spoilage during storage such as weight loss, reduction in the germination of seed, spoilage due to a generation of respiration heat, and contamination by insects are discussed shortly as follows:

4.3.5.1 Weight loss

Several factors influence grain storage losses, including direct and indirect losses. Direct losses are caused by the physical degradation of crops, whilst indirect losses are driven by a deterioration in the quality and nourishment of the grains. Abiotic factors (temperature, relative humidity) and biotic stresses (insects, pests, rodents, fungi) generate storage losses. Storage life is also affected by moisture content and temperature (Mesterházy et al., 2020). In third-world nations, where grains are commonly stored in traditional storage structures without adequate concealment, direct and indirect storage losses are believed to be higher. The majority of these structures are not properly constructed and are made from locally—sourced resources, allowing biological, environmental, and other factors to damage stored grains. Food loss in the intermediate stages of the supply chain, on the other hand, is substantially lower in developed countries due to the availability of novel technology and advanced crop processing and storage systems. Insect and pest infestations are by far the most important of all biotic variables, causing catastrophic grain losses of 25%–50% (Mesterházy et al., 2020). According to research, once all quality losses and economic losses are taken into account, the proportion could rise even more.

Chakraverty and Singh (2014) reported that insects and pests were responsible for 80%–90% of grain storage losses. Owing to these infestations, it has been observed that maize of more than 30% of its weight was lost during storage at the farm level. According to Demianyk and Sinha (1988), larger grain borers were responsible for a significant portion (55%) of storage loss after 6 months of maize storage, preceded by losses attributable to grain weevil and lesser grain borer.

During its development from egg to adult, a grain weevil may consume about 15 mg of the rice kernel. A female weevil with triple generations of offspring per year has the biological capacity to reproduce 2,000,000 offspring, which could consume 1 million rice kernels. The warehouse moth, *Ephestia elutella*, is also reported to affect the germ of wheat grains, deeming them unsuited for sprouting. These reflect the degree of the losses caused by grain parasites, as well as the implications for mitigation (Chakraverty and Singh, 2014). To determine the weight loss due to insect infestation, grains are typically examined for the following factors:

- the number of insect-damaged grains (Nd)
- the weight of insect-damaged grains (Wd)
- the numeric value of intact grains (Nu)
- undamaged grain weight (U)

Insect-infested kernels are recognized by the existence of a narrow opening, which symbolizes the insects' exit from the grain after finishing their gestation period within it.

4.3.5.2 Reduction in seed germination

Germination is a complex phenomenon wherein a developed seed is ingested and must immediately switch from maturation to a germination-driven development in order to prepare for seedling growth. The pollen grain fertilizes the ovule multiple times, resulting in the seed. It comprises both a zygotic embryo that will emerge into the budding crop as well as a reserve tissue that will provide nutrition to assist seedling growth after sprouting (Chakraverty and Singh, 2014). This particular phenomenon is hampered due to the contamination done by the insects, pests, and specifically the grain borers. Seed quality gets drastically reduced because of the suppression of the germination potential.

Pest damage has increased in intensity and frequency in many crops due to climatic changes, farming techniques, the emergence of invasive pests, pest resistance to conventional insecticides, and the introduction of novel pest species. Besides contaminating plant components, insects also attack seedlings and pods, resulting in this decline in grain quality. When attacked by a germ eater, the likelihood of germinating grain is very low. In such cases, germination is severely compromised. A number of grain pests consume grain embryos, which decreases the percentage of seeds that germinate. Virus transmission might also cause indirect crop loss, which is prevalent in cereals. According to published findings, 6%–9% of crops in tropical and subtropical countries are destroyed during storage under conventional warehouse conditions due to varied factors of crop degradation, with pest infestation accounting for 85% of this loss.

4.3.5.3 Spoilage due to respiration heat generation

Heat and insect infestations are the two main types of deterioration that stored crops encounter. Decomposition follows the aforementioned, whilst overheating and breakdown may follow the latter (Wallace et al., 1983). Mainstream studies show that the phenomenon known as respiration is accountable for the heat energy released in the bulk of moist grains. Respiration refers to the exchange of gases between an organism and its environment, but it is technically a part of metabolism as it initiates and stops the oxidation process. During aerobic respiration, oxygen from the air diffuses or is transmitted to the cells, where it is oxidized, releasing carbon dioxide, water, and heat. This causes the grains' cellular contents to disintegrate, diminishing their physiochemical activities and making them more susceptible to further decay.

Similarly, it is well known that insects can also aggravate grain to overheat, and their proliferation enables other entities to perpetuate the deterioration. Our understanding of heat has remained rudimentary because inventory data have been constrained to the latter stages of the process, and scientific researchers have only succeeded in heating their experimental bins by admitting enormous numbers of larvae. According to Pimentel (2002), the frequency of insects essential to induce grain heating is so modest that most onlookers might classify such wheat as insect-free. Insect population size and surrounding parameters, such as temperature and grain moisture content, which can be measured in a warehouse, affect the amount of metabolic heat produced by an insect population.

At the apex of the outbreak, population sizes in warehouses reach 1000 weevils per kg. This means that at the end of heat generation, when temperature differences of 30–45°C persist, there is an enormous production of heat, and hence massive numbers of insects, indicating elevated insect concentrations or even sizable zones of blighted crops are observed (Chakraverty and Singh, 2014). Small hot patches are common, while exceedingly large hot accumulations are more prevalent. This is not surprising because, if allowed undisturbed, all hot spots will eventually reach their threshold. As seen before, the heat generation due to insect infestation has been used for potentially advantageous applications however, it also leads to detrimental effects of grain loss. Insect and pest infestations can cause grains to overheat, culminating in catastrophic grain degradation. It is reasonable to assume that the heating was induced by larvae proliferating slowly in the chilled granule till they released ample heat to create a massive temperature gradient.

4.3.5.4 Contamination by insects

Food grains, particularly milled goods infested by insect larvae, fecal matter, and discharges, quite often experience an increased grain quality loss. Many pests are only drawn towards plant vegetative components (e.g., green leaves), whilst others are predatory or parasitic on insects observed infesting stored commodities. The following approaches can be used to determine the presence of an infestation:

- optical assessment of exterior perforations.
- filtration techniques.
- gelatinization approach.
- carbon dioxide (CO_2) as a marker of infestation.

Apart from such approaches, the conventional AOAC approach for assessing milled grain for insects and fragments can also be used. Within the grain storage insect community, the following 12 species are considered to be important. This list encompasses Khapra beetle, borer beetle, grain weevil, paddy moth, grain moth, meal moth, pulse beetle, flour moth, red rust flour beetle, long-headed flour beetle, saw-toothed grain beetle, and the flat grain beetle. The first 8 species of insects are considered the major pests as they can destroy all types of stored grains. The latter four insects cannot harm intact kernels, but they can develop on fragmented or plagued ones. Because of this, the latter four species are classified as secondary pests. It is worth mentioning that the principal groups of stored grain pests are Coleoptera (beetles) and Lepidoptera (moths), which amount to approximately 70% and 7% of the total number of species, respectively.

In a broad sense, prolonged winter and rising seasonal temps would facilitate pests to accomplish their developmental cycles in shorter durations, resulting in a much-accelerated population increase. Varying stages of an insect's life span will demonstrate different levels of resistance to climate change, depending on the type of pest. Changing climate has different implications for different species and areas. Insect infestation, exacerbated by faulty grain storage procedures, causes massive storage losses in major grain-producing developing countries such as India. Rising temperatures will also cause some insects to relocate to colder places in order to secure their populations (Rajashekar et al., 2014). Insects that do not acclimatize could become extinct or develop into extremely resistant species. All these insects have significant detrimental effects like physical damage and chemical breakdown of the cereal grains.

Among the other biotic factors that would be affected by changing climate trends is the growth and development of microorganisms, particularly fungi. Deteriorative fungi can be found as spores in soil, rotting material, harvest equipment, and storage structures, and are collected by the harvester and dispersed among some of the cereals. For their development and growth, different species of spoilage fungus mandate differing levels of temperature and relative humidity. Molds that emerge on the green plant can sometimes be detected in grains under storage. On maturing grains in the farm, some of these molds may release hazardous pollutants which in turn lead to the spoilage of those grains.

4.3.6 Practices used for control of spoilage

Different practices used for control of spoilage during storage are discussed briefly below:

4.3.6.1 Curative measures

Pest control is divided into two main categories: curative and preventive. Curative control strategies aim to eliminate some or all of the pests that have invaded the host while preventive control strategies aim to limit the number of pest-host interactions, as well as the impact of such interactions (Pimentel, 2002).

Methods of prevention are broken down into the following categories: the first two are physical and mechanical; the third is chemical and hygienic measures (Chakraverty and Singh, 2014). The physical and mechanical methods comprise grain drying, heat treatment, cooling by aeration, and proper packing in air tight container. Chemical methods include spraying with chemical protectants and fumigation while the hygienic measures consist of precautionary steps taken to ensure optimum protection. Chemical techniques are the most successful among the curative procedures; they entail the use of pesticides, which are lethal to humans and require particular safety equipment to protect the personnel who administer these chemicals. Both strategies rely on the concepts of restriction, aversion, containment, and extermination, which can be implemented through governance, physical, social, microbiological, or biochemical ways.

4.3.6.2 Physical methods

Mechanical sieving and grading of grain, as well as flotation separation, are significant methods for removing pathogenic explants such as galls from seed for sowing. Infection control can also be assisted by tillage (Deshpande and Singh, 2001). Physical means of disease suppression include deep plowing of contaminated crop residue and incineration of grain stubble. Temperature (lower or higher), as well as diverse types of radiation, are by far the most prevalent physical agents adopted to control crop diseases. In concentrated, high-value agricultural and vegetable crop conditions, these strategies are more useful. For the stored grain products heating is an important approach that is deployed in which stored grain pests are exposed to a temperature of 55°C for more than 10 min or 45°C for 2 h, by which they will be killed. Soil disinfection (electric, hot water) also uses this technique.

4.3.6.3 Radiation

Insects exposed to beta rays or gamma rays develop physical abnormalities, of something like a loss of reproductive ability and sometimes even their lives (Agrios, 2010). This technique is generally considered as the direct method of irradiation where gamma rays provide high penetrating power and which also have the potential of being the most efficient grain storage pest control technology that is used (Chakraverty and Singh, 2014). Nevertheless, each of these strategies necessitates the procurement of a hugely expensive radiation facility. In the indirect method, irradiation can be used to sterilize adult males. In certain regions, releasing sterilized male adults regularly for roughly a year will completely eradicate the insect populations. Reinfestation coming from external sources of insects brought in proximity with the same stored grains may arise through indirect and other biochemical approaches (Chakraverty and Singh, 2014). As a result, all other approaches are only functional for a limited time.

4.3.6.4 Mechanical methods

For this strategy, the centrifugal force could be used effectively. The impact of flour on the encounter's rotating component and the casing is so strong in processing facilities that almost all stages of insect pests, including the egg, are exterminated (Chakraverty and Singh, 2014). The flour which has been processed with centrifugal force exits the machine. Sieving and winnowing are also two standard techniques used to combat grain pests in stored conditions. Red flour beetles, for example, are removed through sifting and certain insects like Rice weevils, for example, are collected and eliminated by winnowing.

4.3.6.5 Biological methods

Biological control can be thought of as systems based on addressing some part of the disease organisms' biology, such as genetic manipulation, selection for resistance in crop plants, intercropping, and grazing management, which are all examined independently (Chakraverty and Singh, 2014). In a more specialized sense, it refers to man's manipulation of disease organism/pest natural enemies, both foreign and indigenous, in order to control it. The use of natural enemies to eliminate insects and weeds has had greater success than the use of these intermediaries to control diseases in plants. Similarly, Biological control agents of an invasive organism can all be found in the country in question, screened for viability, manufactured, and administered in the same way as a biocide. The substance is referred to as a biopesticide since it integrates biological control and biocide administration (Pimentel, 2002). This sort of control has a lot of benefits, but it also has certain quarantine hazards. Insects, weeds, and pathogens have all been successfully controlled with biopesticides. The biopesticide is packed, handled, maintained, and administered in the same way as conventional pesticides in all these circumstances.

The production cost, the purity of the inoculum, and the organism's field efficiency play a part in the effectiveness of this sort of control. In contrast to conventional pest extermination, where the community bears the cost of research and development, biopesticides are typically developed by commercial entities to recover their expenses through sales revenue. This method can be used to combat both indigenous and foreign pests (Pimentel, 2002). Biopesticides can also be categorized by the type of insect that is being controlled. A bioherbicide, for instance, is a weed-killing biopesticide. There is indeed a lot of sub-division depending upon the type of agent employed. The word "mycoherbicide" refers to a bioherbicide composition that contains a fungal agent. In a separate approach, parasitic organisms are used for biological control. Wherever stored grains are infested with insects, parasitic hornets are nearly always present to feed on them. Similarly, certain bacteria and fungi existing in nature as parasites could potentially be used to control pests. This strategy is found to be beneficial to field pests, but it is yet to be validated on stored grain pest species.

4.3.6.6 Chemical methods

Pesticides and their proper application are critical in modern agriculture. Pesticides were once considered to be the practical alternative for all pest problems following their inception in the 1960s. The pre-emptive or scheduled use of insecticides is the most straightforward approach to pesticide application decision-making. This is based on the assumption that an infestation is always enough to inflict financial damage. When crop level is greater and damage levels are low, this risk-averse tactic may be justifiable in the near run. Pesticide resistance, secondary pest recurrence, extinction of natural enemy populations, and over-exposure of agricultural producers to dangerous chemicals outweigh the benefits in the long run. Pesticide hazards have been lessened by more sophisticated decision-making processes, lower dosing, and administration levels, improved aiming and delivery technologies, and more specificity.

4.3.6.7 Insecticides

There are two types of insecticides for grain storage pests: preventative and curative insecticides. After the first infestation, to prevent additional reinfestation from outside origins preventive insecticides can be used. Following the fumigation, a contact insecticide is added to the surface of the stored grains (Chakraverty and Singh, 2014). Insecticides are frequently treated to grain to regulate or minimize pest infestations during storage and, to a minor extent, to avoid damage to soil from pests such as wireworms and maggots.

Organochlorines, organophosphates, carbamates, and pyrethroids are the four major classes of insecticides. A modest number of other pesticides are also available. The most well-known organochlorine insecticide is DDT. Other organochlorines, such as deltamethrin, aldrin, and endosulfan, that have broad-spectrum activity, are stable and collect in the fat mass of mammals, similar to DDT. Any use of DDT as an insecticide is regarded as unacceptable due to the last two metrics, and it has been forbidden in most developed countries. Organophosphate compounds, which inhibit cholinesterase (a pulmonary enzyme), were created as a by-product of World War II nerve gas research. They are highly poisonous as a group, yet they only last a limited stint in the environment. As a result, the accuracy of their implementation is vital. This class of systemic insecticides is extremely effective against phloem-feeding pests.

Because of their low mammalian toxicity, pyrethrins, and pyrethroids are among the safest pesticides available (Hammond, 1996). Fish and non-target invertebrates, on the other hand, are highly poisonous. They have a limited tenacity and a robust interaction activity as well as considerable barrier properties. Transformation, mating, and larval and nymphal development are all regulated by pest growth regulators. As a reason, they are extremely insect-specific. Nevertheless, due to their delayed action, they are not appropriate as pesticides across all circumstances. Several novel insecticides are indeed being designed by upgrading existing pesticides or analyzing bioactive ingredients originating from pest pathogens.

4.3.6.8 Fungicides

Around the turn of the century, the first fungicides were found. Protectant fungicides and systemic fungicides are the two types of fungicides. The former creates an infection barrier on the plant's surface by either suppressing spore germination or killing pathogens on the surface, blocking their penetration (Mesterházy et al., 2020). Pathogens that have obtained access to the host are unaffected by these fungicides. The latter, on the other hand, is absorbed by the plant and prevents pathogen growth within it. Xylem is the major route by which they are transported. As a result, their primary travel direction rises slowly through the plant. Fungicides are sprayed to seed before actually planting to guard against a spectrum of seed and soil-borne plant infections. Several seed root rot and seedling leaf blight that originates during warehousing or just after seeding is guarded by chemical (fungal) diagnosis (Mesterházy et al., 2020). That is not a "remedy" and cannot seem to keep the crops disease-free across the whole growing season until they are self-sufficient.

4.3.6.9 Disinfestation and detoxification treatments

Disinfection is the process of eliminating a pathogen that has infected and entrenched itself in the live cells of a plant, such as loose smut of barley. Decontamination should be irrevocable, modified forms of toxins should be impacted with parent chemicals, products should not be toxic, and food should taste great as well as maintain its nutritional value (Karlovsky et al., 2016). Several techniques that were discussed earlier are effective in the disinfestation of the field and stored grains. Good agricultural practices, plant pathogens treatment, and appropriate storage environments together assist to decrease mycotoxin and harmful bacteria concentrations in the food supply chain, they do not however totally eradicate them. Complete removal and disinfection by the chemical or enzymatic transformation of mycotoxins and other pathogenic bacteria into less harmful compounds can help reduce these levels in food. Pathogen content can be reduced through processing procedures like grinding, soaking, heat treating, as well as screening. They can also be chemically detoxified by reacting with food and technical aid. It should be the top priority to develop technology to detoxify high-risk commodities (Karlovsky et al., 2016).

4.3.6.10 Fumigation

The fumigation process involves exposing grains to a deadly quantity of highly toxic gas for a lengthy period of time to kill insects (Arthur, 1996). Fumigants are pesticides that may be used to eradicate stored grain pests. In the gaseous form, fumigants can penetrate stored grains in sacks, piles, or bulk and destroy the insects hidden within. There is no lasting effect from these (Bell, 2000; Chakraverty and Singh, 2014). Among the three fumigants with prime importance, methyl bromide was the initial fumigant that was having abundant applications; however, it is set to be faded out in the 2nd decade of the 21st century (Bell, 2000).

Another substance, phosphine, is being administered in the 21st century. The third, sulfuryl chloride, is under review in numerous affluent countries with some ambiguity in the outcome. It is only accessible in a few nations and exclusively for the treatment of systems, not foods. After the fumigant is administered, it begins to evaporate in any fumigation procedure. The pace of evaporation is largely determined by the fumigant, method of application, temp, and rate of airflow. In practice, the boiling points of fumigants are equivalent to the molecular weights of their constituents. The use of fumigants, both liquid and gaseous, is widespread. Methyl bromide, a low-boiling fumigant that is gaseous at ambient temperature is referred to as a gaseous fumigant (Kumar and Kalita, 2017). Ethylene bromide is a liquid fumigant because it has a higher boiling point and stays fluid at ambient temperature. The strategies of applications for gaseous and liquid fumigants are unquestionably different. Solid fumigants, such as Al phosphide capsules, are also obtainable. They combine with the surrounding atmosphere to release hydrogen phosphide gas, which is toxic to living organisms (Chakraverty and Singh, 2014). Diffusion allows evaporated fumigant vapors to reach every crevice of any storage system. Because of air circulation, gas molecules diffuse. The diffusion rate is determined by the fumigant type. The sorption of gases by grains and structural components of the same storage system decreases the concentration of fumigant gases in any grain storage facility. The insecticidal effect is achieved by the fumigant gas reaching the insect's tissues through such aforementioned activities.

4.3.7 Storage costs in godowns and silos

Storage is an innate action that alters the market's connotations of external or preset parameters in the short to mid-term. The relative cost of storage per term, encompassing physical protection, insurance, and deterioration, is mainly positive yet minimal for the principal cereals, and also the assumption of constant pricing is a largely acceptable approximation. Storage capacity is seldom a limitation for something like the extent of international agricultural reserves (Chakraverty and Singh, 2014). Whenever costs are rising and budgetary stocks are minimal, market demand and utilization demand are indistinguishable. If one considers a particular grain to be a staple food, they often tend to be willing to forego various expenses in order to continue buying and eating it, resulting in greater consumption demand; substantial price modifications are necessary if consumption data seeks to accommodate the full implications of such a supply crisis.

When inventory levels are above minimum working stocks, storage demand, when added laterally to aggregate supply, makes market-rate far less vulnerable to demand or disinflation. For instance, in the early 1970s, a reasonable decline in global wheat yield at a time when unilateral stocks were more or less nonexistent ended up causing the yearly price to almost double. When crops are strongly associated, storing brings a positive relation in rates, which is far less significant. This could ease the spike in prices induced by either an unforeseen, protracted increase in consumption, such as with a govt surge in biodiesel products, but still, it cannot just ignore a long-term change in prices (Wright, 2011). Crop-producers can respond to changes in product relative rates by transitioning from one crop to another, accelerating output, or otherwise continuing to expand agricultural land.

In most instances, a transitory crop failure really would not result in a lag in distribution because the future value would indeed be irrelevant to the actual price. A bad harvest, on the other hand, raises anticipated costs just as grain is storable. The predicted supply response permits for further utilization of such stocks, reducing the current valuation spike driven by the yield gap. Rates of return to output are lowered whenever an abnormally large harvest rises cumulative stocks. Manufacturers react by decreasing the production and retaining significantly larger stockpiles, buffering the cost-effectiveness of the expanded harvest. Whenever reserves are transitory, competing adjustments for planned production may be exceedingly stable (Wright, 2011). Standard bag storage really does have the advantage of requiring no noticeable major financial investment. Financing requirements like interest on a loan taken for silo building and paddy procurement drove up the amount of rice storage in silos. The expenditure of dehydration with fuel oil was another important determinant. Nevertheless, if husks are being used as a biofuel instead of fuel oil, the drying expenditure would indeed be minimal.

The silo storage system had numerous benefits, including the potential to save physical labor, which would have been difficult to come around during prime plantation as well as harvesting periods (Chakraverty and Singh, 2014). Also, it minimized grain wastage and investment in gunnies, while still giving a comprehensive advantage in terms of prolonged sterile storage. Nevertheless, appropriate precautions have to be taken during the pre-cleaning, dehydration, and chilling of rice before being sent into silos.

4.4 Concluding remarks

A grain's ability to remain healthy and nutritious during storage is affected not only the conditions of production and harvest, but also by how it is stored and maintained according to appropriate conditions. Post-harvest losses pose a direct threat to the environment. Typical food loss occurs from the contamination with mycotoxins and during storage and so conscious effort has to be made for minimizing its impact. Nearly, 40%–70% of grains can be lost only due to the poor efficacy and lack of sound technical expertise. To counter this, several storage techniques are being introduced, which minimize those losses and ensure better handling of the processed grains, thereby aiding in extending the shelf life of the products. Novel designs of silos and bins are being implemented in the industries for storing food grains as well as other essential commodities. Similarly, several other treatments are being devised for the prevention of grain spoilage by insect and pest infestation to safeguard the stored grains. The economics of the storage of grains is also being thoroughly studied for estimating the storage cost and finding ways to minimize it. There is a great deal of scope for future studies on other efficient grain storage techniques to improve the global economy and provide safe food products for the global population.

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PART | TWO

Liquid food transportation

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Chapter | Five

Transportation and metering of fluids

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5.1 General elements and equipment of the system

In engineering practice, it is expected to utilize these relations to design or operate a system in which a fluid is transferred from one point to the other.

Transportation of fluids within a plant from the entrance to the exit can be accomplished through pipes of different materials and geometries as well as in cars or buckets. In the second means of transportation because there is no flow of the fluids the investigation shall be focused on the transportation in pipes or channels. Especially, when the food industry is considered, it is necessary that the transportation should be made in closed and sterile systems to secure the food from being contaminated by foreign materials and microorganisms.

In this sense, it is possible to make a list of elements and equipment that may be present in a fluid transfer system. These are

1. Pipes and/or channels,
2. Fittings and/or connection pieces,
3. Valves to change, adjust, or control the flow rate,
4. Flow rate measuring devices,
5. Pumps to supply the energy necessary to overcome losses due to friction in pipes, fittings, valves, changes in cross-sectional flow area, potential, and velocity heads.

For each one of the above five general groups, there exist many products depending on the different purposes of application. That is, else than the geometry of the pipe cross section being circular, square, rectangular, or an open channel the material of construction such as glass, stainless steel, steel, plastic, concrete, etc., together with the characteristic dimension, wall thickness, and other required specifications must exactly be defined. This implies the investigation of each group to be done separately.

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5.2 Pipes and channels

Piping covers a very large part of any process plant forming a network to transport various process materials from one equipment to another. In process plants through a series of activities performed in a particular order raw materials are converted into useful products and interconnected pipe and pipe components are used to transport raw material, intermediate product, and final product to the desired location.

The pipe is a straight, pressure-tight hollow length with circular, square, or rectangular cross section, used in the piping system to transport liquid, gas, and sometimes solids. Different types of pipes are used in different design conditions, considering technical and commercial parameters.

5.2.1 Pipe types and specifications

Fluids are mostly transported through closed passages of different sizes, wall thicknesses, material of construction, and cross-sectional geometry as pipes or conduits. Though they may be classified according to the wall thicknesses as pipe or tube, there is no definite discrimination. Nevertheless, as background knowledge, pipes are produced generally in lengths of 3–6–12 m, and they have relatively thick walls, rough inner surfaces, and larger diameters. They are produced by welding, casting, drawing, or spinning the molten material in a cooled casing. On the other hand, tubes can be of the above lengths or can be longer in the form of wound coils of copper and some plastics. They have thinner walls and nearly smooth inner surfaces and are produced by hot or cold extrusion or injection methods.

According to the intended use, pipes or tubes can be produced from metals, metal alloys, plastics, composite plastics, glass, ceramic, and wood. Polyvinylchloride (PVC) pipes and channels are very common for water transportation and irrigation works. In industrial plants or buildings low-carbon steels, which is also known as black iron, galvanized steel (zinc-coated black iron pipe), PPRC (polypropylene random copolymer), and PE (polyethylene), are highly used for water intended for human use. On the other hand, for drainage and sewer systems PVC and until recently cast iron pipes are used. Cast and forged iron pipes are used for special purposes. Especially for the transportation of liquid or semiliquid foods in pipes smooth, easily cleanable, inert, and noncontaminating materials are desired, special type stainless steel or glass are used as summarized in Table 5.1.

Cylindrical pipes present in the market are defined according to their diameters and wall thicknesses. Pipes with special diameters and wall thicknesses are manufactured upon order. As a nearly globally accepted reference, for galvanized or black, seamed, seamless, or drawn steel cylindrical pipes the standards established by American Society of Mechanical Engineers (ASME) are used. According to this procedure of identification cylindrical pipes are primarily designated by their ***Nominal Pipe Size*** (**NPS**) in the range 1/8 in. (3.2 mm) to 30 in. (76 mm). The nominal diameter for pipe diameters less than 12 in. is a rounded

TABLE 5.1 Materials used for pipes.

Metal		Nonmetal	Lined/clad
Ferrous	**Nonferrous**	**PPRC/PP**	**Rubber lined**
Cast iron	Copper alloy	PVC/CPVC	PTFE lined
Carbon steel	Nickel alloy	HDPE/PE	FRP lined
Alloy steel	Aluminum alloy	GRP/GRE	Glass lined
Stainless steel	Other alloys	Cement	Cement lined

PPRC, polypropylene random copolymer; PVC, polyvinylchloride; CPVC, chlorinated PVC; HDPE, high density polyethylene; GRP and GRE, glass fiber reinforced plastic and epoxy; PTFE, polytetrafluoroethylene; FRP, fiber reinforced plastic.

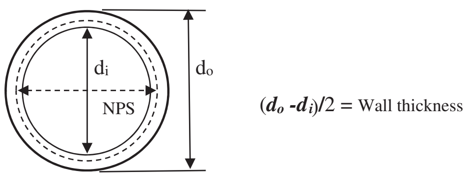


FIG. 5.1 Actual dimensions and NPS of a pipe according to ASME designation.

figure between the outer and the inner diameter of a pipe (Fig. 5.1). For pipes greater than 12 in, it corresponds to the outer diameter of the pipe. The outer diameters of pipes according to the nominal size do not change with the wall thickness. An important fact about this acceptance is that the connection of the pipes is done by external elements fitted to the pipe ends as shall be discussed in Section 5.2.3.

Wall thicknesses of the pipes according to ASME definitions are designated by ***Schedule Number*** (***Sc.No.***)**,** which approximately indicates the pressure a pipe can withstand. It is calculated using the expression 1000 (P/S), where P is the pressure in the pipe and S is the material's stress limit and has the values 10, 20, 30, 40, 60, 80, 100, 120, 140, and 160. Generally, for pipes having NPS < 8 in. only *Sc*.No. 40, 80, 120, and 160 are used, whereas for ordinary piping for heating or water supply *Sc*.No. 40 is applied. Under these codes, *Sc*.No. of 40 with NPS of 10 or lower are known as Standard (STD) and *Sc*.No. of 80 with NPS up to 8 are Extra Strong (XS).

The standard steel pipe dimensions for *Sc*.No. values of 40 and 80 according to ASME are given in Table 5.2. Other sizing terms used are ***Nominal Bore*** (**NB**) and ***Diameter Nominal*** (**DN**). These are the European equivalent of NPS. In these standards, pipe sizes are mentioned in millimeters where DN is the German equivalent of NPS.

In the food industry due to chemical inertness stainless steel or, in some plants, borosilicate glass pipes and equipment are used. Most foods naturally

TABLE 5.2 Standard steel pipe sizes of *Sc.* 40 and 80.[a]

NPS (in)	NB/ DN (mm)	Outside diameter (in.)	Outside diameter (mm)	Sc. No.	Wall thickness in mm (in.)	Wall thickness in mm (mm)	Inside diameter in mm (in.)	Inside diameter in mm (mm)	Inside flow area (ft^2)	Inside flow area ($m^2 \times 10^4$)
1/8	6	0.405	10.3	40	0.068	1.73	0.269	6.83	0.0004	0.3664
				80	0.095	2.41	0.215	5.46	0.00025	0.2341
1/4	8	0.540	13.72	40	0.088	2.24	0.364	9.25	0.00072	0.6720
				80	0.119	3.02	0.302	7.67	0.00050	0.4620
3/8	10	0.675	17.15	40	0.091	2.31	0.493	12.52	0.00133	1.231
				80	0.126	3.20	0.423	10.74	0.00098	0.9059
1/2	15	0.840	21.3	40	0.109	2.77	0.622	15.80	0.00211	1.961
				80	0.147	3.73	0.546	13.87	0.00163	1.511
3/4	20	1.050	26.7	40	0.113	2.87	0.824	20.93	0.00371	3.411
				80	0.1540	3.91	0.742	18.85	0.00300	2.791
1	25	1.315	33.4	40	0.133	3.38	1.049	26.64	0.00600	5.574
				80	0.179	4.45	0.957	24.31	0.00490	4.641
1½	40	1.900	48.3	40	0.145	3.68	1.610	40.89	0.01414	13.13
				80	0.200	5.08	1.500	38.10	0.1225	11.40
2	50	2.375	60.3	40	0.154	3.91	2.067	52.50	0.02330	21.65
				80	0.218	5.54	1.939	49.25	0.02050	19.05
3	80	3.500	88.9	40	0.216	5.49	3.068	77.92	0.05130	47.69
				80	0.300	7.62	2.900	73.66	0.04587	42.61
4	100	4.500	114	40	0.237	6.02	4.026	102.3	0.08840	82.19
				80	0.337	8.56	3.826	97.18	0.07986	74.17
5	125	5.563	141.3	40	0.258	6.55	5.047	128.2	0.1390	129.1
				80	0.375	9.53	4.813	122.3	0.1263	117.5
6	150	6.630	168.3	40	0.280	7.11	6.065	154.1	0.2006	186.5
				80	0.432	10.97	5.761	146.3	0.1810	168.1
8	200	8.625	219.1	40	0.322	8.18	7.981	202.7	0.3474	322.7
				80	0.500	12.70	7.625	193.7	0.3171	294.7
10	250	10.75	273	40	0.365	9.4	10.020	255	0.5475	508.71
				80	0.594	15.09	9.562	242.87	0.4987	463.04
12	300	12.75	324	40	0.406	10.31	11.938	303.22	0.7773	721.75
				80	0.688	17.48	11.374	288.9	0.7056	655.19

[a]*ASME B36.10 – Welded and Seamless Wrought Steel Pipe (Carbon & Alloy Steel).*

or during processing become acidic or alkaline and hence are corrosive. Any possible contamination or reaction with or from the surfaces in contact with the food must be avoided. Therefore, stainless steel pipes containing chromium and nickel (Cr/Ni) are suitable for this purpose, and of the special grades either SS-304 18/8 or 18/10 or SS-316 16/10/2 must be selected. The most basic difference between the two grades of steel is the presence of molybdenum in stainless 316 which has higher corrosion resistance to chlorides and chlorinated solutions. Stainless 304 usually consists of 18% Cr and 8% or 10% Ni. Stainless 316 is made up of 16% chromium, 10% nickel, and 2% molybdenum. The stainless steel pipes have four Schedule Numbers, i.e., 5, 10, 40, and 80, which have identical outer diameters with the corresponding NPS. To differentiate between the SS and the carbon or alloy steel pipes a suffix "S" is specified in the *Sc*.No., e.g., the 40S. The stainless steel pipe dimensions are given in Table 5.3.

The diameters given for thin-walled steel pipes are their outer diameter. The wall thicknesses are according to ***Birmingham Wire Gauge*** (**BWG**) and vary from 24 corresponding to the thinnest to 7 as the thickest. There is also **Standard Wire Gauge** (**SWG**) but the former is preferred. Condensed information is presented in Table 5.4.

In the case of nonferrous pipes considering the possibility of interchange or combined use with the steel pipes they are produced with outer diameters according to ASME standards and named using the material of construction. Therefore, in their labels, either **IPS** (iron pipe size) or **NPS** must be present. For example, a 2-in. IPS PVC or IPS PPRC pipe has the same outer diameter as the 2-in. standard steel pipe. However, owing to the difference in the tolerable pressure of these materials, the wall thicknesses are different.

TABLE 5.3 ASME B36.19M-2004: Stainless Steel Pipe (5S, 10S, 40S, and 80S).[a]

NPS (in.)	NB/DN (mm)	Outside diameter (in.)	(mm)	Wall thickness (in) 5S	10S	40S	80S
1/8	10	0.405	10.3		0.049	0.068	0.0950.
½	15	0.540	21.3	0.065	0.083	0.109	0.147
¾	20	0.675	26.7	0.065	0.083	0.113	0.154
1	25	0.840	33.4	0.065	0.109	0133	0.179
1½	40	1.050	48.3	0.065	0.109	0.145	0.2
2	50	2.375	60.3	0.065	0.109	0.154	0.218
3	80	3.500	88.9	0.083	0.12	0.216	0.3
4	100	4.500	114	0.083	0.12	0.237	0.337
6	150	6.630	168	0.109	0.134	0.28	0.432
8	200	8.625	219	0.109	0.148	0.322	0.5
10	250	10.75	273	0.134	0.165	0.365	0.5
12	300	12.75	324	0.156	0.18	0.375	0.5

[a]*For intermediate and greater sizes the original table should be used.*

TABLE 5.4 Condenser and heat-exchanger tube data for steel pipes (ASTM A450).

Outer diameter		Tube gauge (BWG) 10	12	14	16	18
		Wall thickness (in.)[a] 0.134	0.109	0.083	0.065	0.049
(in.)	(mm)	Inside diameter (in.)[a]				
5/8	15.88	0.357	0.407	0.459	0.495	0.527
3/4	19.05	0.482	0.532	0.584	0.620	0.652
7/8	22.23	0.607	0.657	0.709	0.745	0.777
1	25.40	0.732	0.782	0.834	0.870	0.902
1 1/4	31.75	0.982	1.032	1.084	1.120	1.152
1 1/2	38.10	1.232	1.282	1.334	1.370	1.402
1 3/4	44.45	1.482	1.532	1.584	1.620	1.652
2	50.80	1.732	1.782	1.834	1.870	1.902

[a]*For conversion to mm multiply the table value by 25.4.*

5.2.2 Selection of a suitable pipe size

To design a closed system for the transportation of a particular fluid with known properties and rate a sound cost analysis is required. In this respect, total investment costs concerning the possible pipe diameters and lengths from the most suitable material, the required fittings or joints, energy consumption, maintenance for the alternatives should realistically be determined for a final decision. In small works, predictions based on experience may be sufficient but for large-scale systems, it is correct to use the theoretical knowledge.

Primarily, operation at low velocities should be aimed where in the simplest sense this necessitates a compensation between the piping and the energy or more inclusively investment and operational costs. That is, an increase in one decreases the other, which can simply be shown by an economic balance (Peters et al., 2003). If the costs due to the investment and operation are C_I and C_O, respectively, the total cost (C_T) shall be

$$C_T = C_I + C_O \tag{5.1}$$

The derivative with respect to pipe diameter, D is

$$\frac{dC_T}{dD} = \frac{dC_I}{dD} + \frac{dC_O}{dD} \tag{5.2}$$

At the optimum cost condition $dC_T = 0$, and hence, $dC_I = -dC_O$.

TABLE 5.5 Approximate velocities of liquids in pipes under normal conditions.

Liquid	Flow condition	Velocity range (m/s)			
Low viscosity liquids	By gravity	0.15–0.30			
water and like,	Pump inlet	0.3–0.9			
μ_a (10^3 Pa s) <10	Pump discharge	1.2–3			
	Process line	1–3			
		μ_a(10^3 Pa s)			Nominal pipe diameter (in.)
		50	100	1000	
High	Process line	0.45–0.9	0.3–0.6	0.1–0.2	1
viscosity		0.75–1.1	0.45–0.75	0.15–0.25	2
liquids		1.1–1.5	0.75–1.1	0.25–0.35	4
	Pump inlet	0.06–0.15			
	Pump discharge	0.15–0.6			
Steam: <300 kPa	Process line	15–30			
>600 kPa	Process line	30–60			
Air and gases:100–400 kPa	Process line	9–30			

The velocity of a fluid in a pipe not only affects frictional energy losses but also causes erosion and wear of the pipe, can make noise, and may exert an effect called water hammer when a valve is closed suddenly. Further, though they are not strict, for the velocity of a process liquid under normal operating conditions the values displayed in Table 5.5 are worth keeping in mind. Especially, for cases in which rapid action or decision of the engineer is required, they are useful magnitudes.

On the other hand, for large-scale and complex piping systems cost of piping may represent a large proportion of the investment costs. In such conditions, it is best to determine the pipe diameters from the theoretical relations and with the aid of computers.

5.2.3 Methods used for joining pipes

As mentioned above, excluding copper and some plastic materials pipes are produced at fixed lengths in the range of 3–6 m depending on the manufacturer. Therefore, for the required pipe lengths different than these pipes must be joined to each other or cut to the desired size. Also, the terminals of the pipes must be connected to a vessel, a pump, or a valve. The joining method that can be used for a pipe depends on the pipe material as well as its wall thickness and the operational conditions.

Another aspect of piping for the transportation of a fluid between two points is the presence of sufficient support. According to dynamics, long and heavy materials exhibit depression under their weights in time. This depression may cause bending or buckling of the pipe with an extra load to the fittings and joints necessitating support of the pipe at sufficient intervals along the length. In the determination of the type and place of the supports to be used, expansion or contraction of the pipes due to heating or cooling must be taken into consideration as briefly discussed below.

5.2.3.1 Connection of pipes

Pipes with sufficient wall thicknesses may be joined by threaded fittings, flanges, or by welding as shown in Fig. 5.2. On the other hand, thin-walled pipes of suitable materials as copper and brass soldering, torch flame, pressing, and for the fragile materials like glass, hard plastics, concrete, ductile iron, etc., flanged, socket and spigot connections are possible.

In threaded joining the end of the pipe must be threaded appropriately by a machine which is expected to create a slight tapering along the thread. This is to have a tighter fit between the pipe and the connection piece whether a fitting or flange is used. Still, to avoid leakage a filling like flax or cotton fibers, grease, paint, liquid gasket, PTFE ribbon, and graphite paste is applied between the two threaded surfaces.

Despite the presence of a fitting or flange at the threaded end of a pipe, that part is weaker than the rest of the pipe. Therefore, for the systems under high-pressure *Sc*.No. of the pipe must be appropriate. Though it is possible to use threaded joints up to 12-in. pipe diameters, generally for sizes greater than 3–4 in. flanged or welded joints are preferred.

Connection of pipes by flanges is practiced for pipes having diameters greater than 2 in. These are usually two identical-sized 1–2 cm thick rigid cylindrical plates having an outer diameter about 2–3 times the outer diameter of the pipe with a hole at the center in the size of the pipe's outer diameter. They can be fixed to the pipe by threading or welding and to each other by four or more even numbered bolts and nuts. The meeting surfaces of the flanges can be flat or grooved and a gasket made from a suitable material having a hole of the size

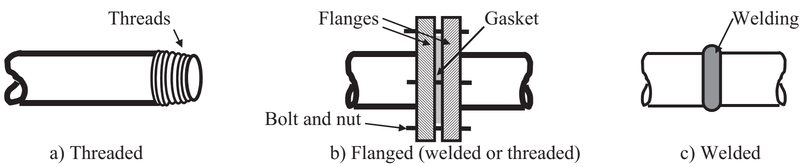


FIG. 5.2 Commonly used pipe connection methods.

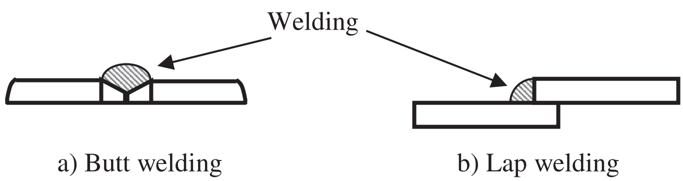


FIG. 5.3 Joining of metals by welding.

of the pipe is placed in between. If it is desired to isolate or terminate the piping a blind flange with no hole at the center is placed.

For long process pipes the most common method for joining two pipes, a pipe with a fitting or flange, is welding. According to Environmental Protection Legislations, the threaded and flanged joints are considered susceptible leakage points for pipes transporting volatile fluids. The advantages of welding compared to the two methods explained above are that it is leakproof, has greater strength at the joint with a disadvantage of necessitating cutting if the pipe is to be disassembled for replacement, etc. There are a number of welding methods and types of which the most suitable one must be used depending on the material to be welded. The two most common methods for metal–metal connections are shown in Fig. 5.3. For butt welding, the ends should preferably be beveled for better results.

Especially for thermoplastic and rigid plastic pipes heat fusion techniques are commonly used. The three types of conventional heat fusion joints currently used in the industry are *butt*, *saddle*, and *socket* fusion. Additionally, electrofusion (EF) joining is available with special EF couplings and saddle fittings. Less conventional methods are *mechanical bolt-type coupling, glue* and *socket, and spigot ends*. The latter type of end is generally used in ductile iron pipelines and nonmetallic piping pipelines such as PVC and GRE/GRP.

5.2.3.2 Expansion allowances and pipe supports

Most of the fluid transporting piping systems are in a way subjected to temperature fluctuations either internally or externally. Under these conditions it is inevitable to avoid expansion or contraction of the pipes in accordance with their coefficients and provisions must be provided. When a long rigid pipe is fixed at the support points it is very likely to experience bending, cracking, or buckling under changing temperature conditions. Therefore, at least an allowance to absorb these expansions or contractions is required.

In systems with long piping and under temperature influences pipes may be supported by rigid surfaces on which the pipe can be placed on clamps with springs, or sliding supports, or my rest on saddle-type rollers. Another possibility is to have them hanged by chains or bolts on a slump or roller or have them swing on a surface. Further applications are placing a sufficient number of U-extensions, circular extensions, or bellows at definite intervals (Fig. 5.4).

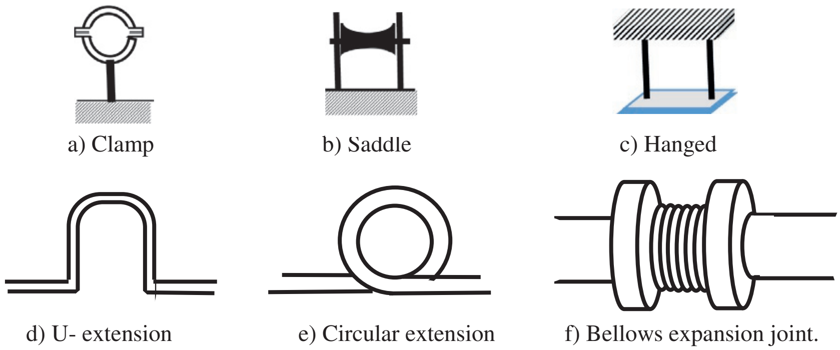


FIG. 5.4 Some examples of pipe supports and expansion provisions.

5.2.3.3 Fittings

Specific metal or plastic pieces called fittings can be attached to the metal or plastic pipe ends for some intended functional use. The attachment can be made by screwing the threaded parts, welding or heat, or electric fusion. These fittings are normally applicable to pipes of NPS 4-in. and below and carrying fluids at ordinary pressures. The NPS pipe size for which the fitting is to be used is indicated on the fittings. The strictly obeyed rule is the preservation of the consistency of the materials, i.e., metals with the fittings of same metal and plastics with the fittings of the same plastic. The most common types of threaded pipe ends are shown in Fig. 5.5.

To join two pipes of equal diameters two fittings, i.e., coupling and union are possible. A coupling is a short piece of pipe with threads on the inside or can be fixed by heat fusion to plastic pipes. It can be used to connect two pipes or to put a plug at the end of a pipe. Union is especially used to connect two identical-sized pipes where frequent repair or pipe replacement is required. The disadvantage is the possibility of leakage owing to three joining points.

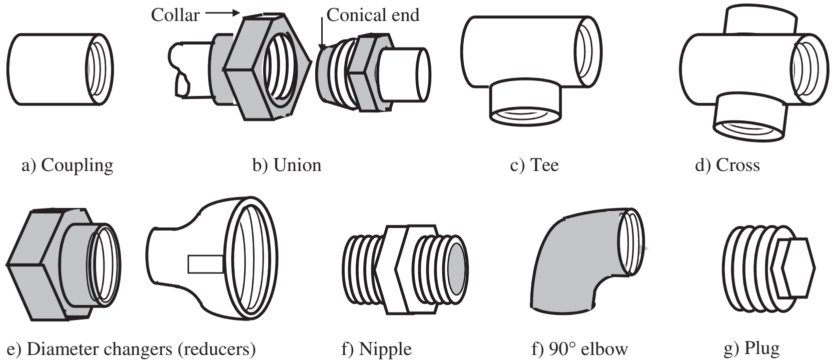


FIG. 5.5 Various types of fittings.

To add side branches to pipes Tee and cross, for 90° and 45° bends, elbows are utilized. To change the pipe dimension nipple and reducer combination is used.

5.3 Control of flow rate

In the transportation of fluids flow rate of the fluid must be adjusted and controlled to sustain the design value and production rates. Probably, one of the most troublesome decisions in the design and instrumentation of a process system is the selection of adequate and appropriate but yet economical valves, automatic control valves, and flow rate measuring devices. Occasionally, it may be required to stop the flow for some repairs or troubles on a line and upon completing the necessary work the flow must be readjusted but it must be secured that if there are branches fed from the same main line, these are affected at minimum or not at all. Therefore, a piping system must be equipped with a sufficient number of flow rate adjustment equipment and rate measuring devices.

5.3.1 Adjustment of flow

From the simplest to the most complicated industrial processes there exist numerous valves of different diameters, types, and purposes. Despite all the functional and structural differences all are present for the purpose of adjustment of the flow rate of the fluid by changing the magnitude of the flow area to affect the frictional loss, i.e., by pressure drop. Depending on the type of the valve this adjustment can be full-open, full-close, or may allow throttling. For example, a **check valve** allows flow in one direction only, and a **steam trap** allows only discharge of condensate. On the other hand, an **automatic control valve** may be used to regulate the flow rate, pressure, temperature, liquid level, or concentration in a system according to the response it receives from the respective sensor.

The frictional energy loss due to any valve present on a pipe carrying fluid is given in V1 Table 7.3 by Esin (2021). As can be seen from this table the energy loss increases with the reduction in the flow area. For example, a 25-fold increase in energy loss is encountered upon converting a full-open gate valve to the half-open position. Also, upon replacing a full-open gate valve with a full-open globe valve the loss increased by about 33 times. Therefore, together with the flow area and increase in the sensitivity of the valve for better control of flow increases the energy loss, hence the cost due to both the valve and the energy. Especially, an automatic control valve on a line is responsible for about 1/3 to ¼ of the total pressure drop in the system. Given below are the most common types of valves used in processes or at homes. It should be kept in mind that unless it is produced for a specific duty, all valves are closed when the hand wheel is turned clockwise and opened in a counter clockwise direction.

(1) ***Gate and globe valves*:** These are the most common and the simplest types. The gate valve offers less pressure drop, however, it has lower sensitivity, and further if dirt or material accumulates in the lower seat preventing the

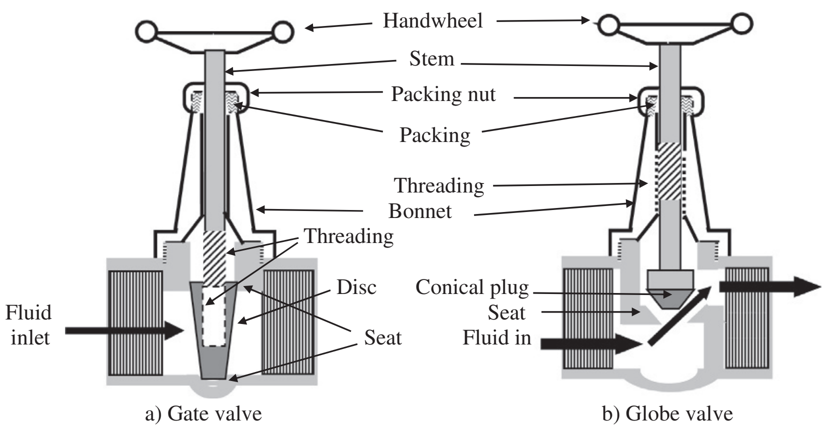


FIG. 5.6 A sectional view of gate and globe valves.

full-close condition, the fluid may escape. Though they are very much alike from the outside the basic difference in design is the up-down movement of the stem in the globe valve pushing or rising the plug to or from the seat whereas by rotation of the threaded stem end the disc is pulled up or pushed down in the gate valve. They are shown in Fig. 5.6.

Because stems of both valves have rotational movements they should easily be rotated. While providing this ease it is necessary to avoid leakage from the sides of the stem. For this purpose compressible packing materials like fiber threads, plastic rings, copper washers, rubber rings, etc., are placed around the stem and held in a leakproof condition by screwing the packing nut in just a sufficient amount. The most important points about the valves are their correct alignment as indicated by the arrow on their sides, and if the valve shall be brought to the full-open position, do not apply extra force when the limit is reached and even have a quarter clockwise turn to protect the packing and the threads from being harmed.

If greater sensitivity in flow adjustment or regulation is desired, **plug** or **needle** valves can be used despite their much greater pressure drop effect. In principle, they have identical design of the globe valves but the conical disc is in the form of a longer conical plug or needle as well as their hosting seats, and the up-down action is by fine pitch threaded stem for better control.

(2) ***Ball, butterfly, and slide valves*****:** These valves (Fig. 5.7) are one of the least dependable groups for the adjustment of the flow rate due to their operation principles. Ball valves have a ball or a cylinder with a hole about the size of the diameter of the pipe. The ball or the cylinder material is stainless steel or of a suitable material with a smooth surface and is rotated within a housing by an armor hand wheel connected to the extension of a stem from the ball or the cylinder. The housing material around the ball or the cylinder should be sufficiently tight to be leakproof and resistant to wear and should

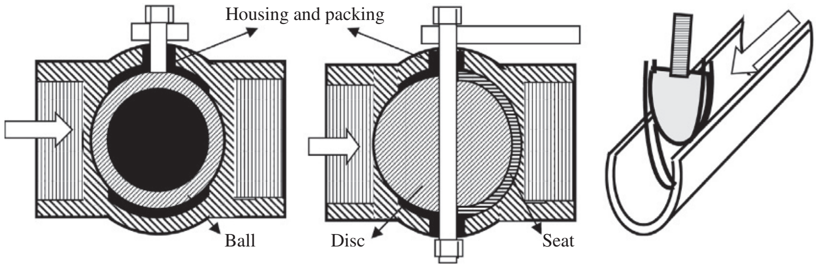


FIG. 5.7 Sections of ball, butterfly, and slide valves.

also have a hole of the size of pipe diameter which is aligned in the direction of flow. The area available for flow in between full-open to full-closed position is controlled by the relative alinement of hole of the casing and hole of the ball.,

A butterfly valve is a slightly elliptic disc within a cylindrical metal or plastic casing. The disc is of a suitable material with the short side a little less than the pipe diameter and opens or closes the flow area by rotating it about a quarter turn using an arm attached to the stem through the centerline of the disc surface. At the full-closed position to minimize the leakage, the disc rests on two semicircular seats located at a small offset to each other one piece on each side. In time due to the accumulation of dirt or matter on these seats, the disc cannot close the channel completely and is liable to leak. Therefore, they are used in simple systems where leakage or control is not very important.

Slide valves are usually used in irrigation, water drainage channels, or for the adjustment of the flow of solids to or from bins. A plate either rectangular or in the shape of the flow area geometry is pushed or pulled on a rail or slot to open or close the flow area. Because they cannot provide good sealing they are used in simple systems. Further, because the rails or the slot may become clogged with dirt or solids it may even become stiff.

(3) ***Valves for special purposes*****:** There is some indispensable equipment considered as valves though they do not adjust the flow rate but their presence in the system is a must. Among these **check valves** and **steam traps** are the most outstanding ones.

Check valves are used on lines to have flow only in one direction and no return due to increased downstream pressure or in supply tanks where again no backflow is desired. That is when a liquid is fed to a tank by a pump the system should be capable of holding the contents of the tank when the pump is stopped. This necessitates the presence of a check valve between the pump discharge and the tank inlet. There are several types of check valves named according to their flow stopping mechanisms where *lift, ball,* or swing types are the most common (Fig. 5.8). The most important

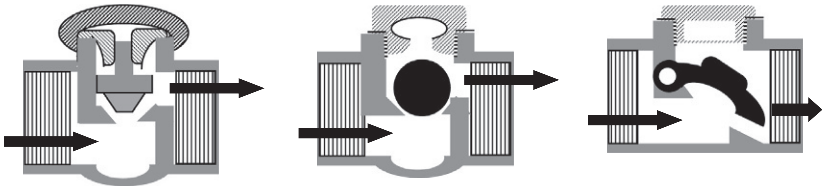


FIG. 5.8 Some types of check valves.

point in their installation is to have the correct fluid in-out direction and the valve seats in the horizontal position.

Steam traps are essential valves in systems where condensation of steam is desired, i.e., heating by saturated steam. If the system lacks this equipment then the steam fed shall leave the system as steam without condensation. A steam trap's essential element is a metal piece that has a high expansion-contraction coefficient like copper. This metal piece like bellows expands upon contact with steam and closes the exit. When the steam surrounding the piece condenses and partially cools, the metal contracts and opens the exit for condensate to be discharged. Inevitably, until the metal re-expands by contacting with steam some steam may escape together with the condensate.

(4) ***Automatic control valves*:** A process control valve operates according to the signal it receives from a sensor placed on an appropriate point in the system. Depending on the controlled variable of the system the sensor measures rate, liquid level, temperature, pressure, or concentration. Any one of these variables can be controlled by a flow regulating valve. The control may feedback or feedforward type where in both cases the value measured by the sensor is compared with the set value of the variable and the necessary action is taken according to the dynamics of the process and a signal is generated to adjust the flow rate.

Automatic control valves may be actuated by pneumatic, electrical, or most commonly by electronic means. For a more detailed study on process control a good background knowledge on fluid mechanics, heat and mass transfer, reaction kinetics, and differential equations is required.

5.3.2 Measurement of flow rate

The most important variables of a process are flow rate, pressure, temperature, and concentration values. The instruments measuring these can be either continuous or intermittent, process control aimed with printer and/or monitor output. As explained above for the automatic process control, because all of the variables depend on the flow rate, this variable must be continuously measured with sufficient accuracy.

A flowmeter suitable to the characteristics of the process can easily be selected from the available types. The important criteria for selecting one are an investment and operational costs, the operational range, and the sensitivity of the meter. That is, the sensitivity required for adjusting the flow rate of water to a water supply tank and the feed rate of a reactant to a reaction tank are definitely different.

According to their design, the flowmeters can measure mass rate, volumetric rate, or average velocity at a point located at a known sectional area. Those occupying the entire cross section of the flow area are named as **full-bore** and those located at a point on the radius are **insertion** flowmeters. Detailed descriptions of commercial flowmeters can be obtained from the manufacturers and found in the literature (Ginesi and Grebe, 1987), relations required for all are derived from the continuity and Bernoulli equations.

5.3.2.1 Full-section flowmeters

The principal aim is to create an artificial local pressure drop, the magnitude of which depends on the flow rate change. This can be achieved by changing the flow area or by causing it to do work such as rotating a small turbine. The pressure drop caused by the meter is recovered to a high degree at downstream. In the former types, the fluid is forced through an area smaller than the cross-sectional area of the pipe, which results in an energy loss and is measured as pressure drop as discussed by Esin (2021). The latter types utilize a special free solid figure of definite physical and geometrical properties kept at its terminal velocity by form drag. Outstanding ones are Venturi meters, nozzle, orifice meters, magnetic, vortex shedding, turbine, positive-displacement meters, ultrasonic meters, thermal flowmeters, and a number of additional special meters, some of which are explained below.

***Venturi meter*—**A Venturi meter is composed of three sections: an inlet truncated cone, a throat, and another truncated cone for discharge of the fluid as shown in Fig. 5.9A. It is attached in a horizontal position to the pipe by flanges where the upstream converging entrance is a 15–20° truncated cone, which causes an increase in the velocity of the fluid due to the contraction in the available flow area. The diverging truncated cone piece is a little longer with a cone angle of about 5–7° than the inlet piece to recover the pressure drop while attaining the pipe diameter again. As the joining piece of the two cones, i.e., at the throat, a

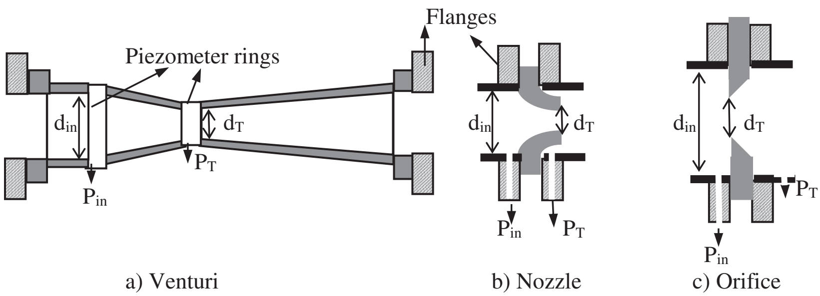


FIG. 5.9 Some full-bore flowmeters.

piezometer ring is present to equalize the pressure from all sides through holes connected to slots opening to an integral annular chamber. The annular chamber on the piezometer ring is connected to a pressure tap to reflect the static pressure at the throat. The other pressure tap is connected to the piezometer ring located just at the fluid entrance to the cone and the difference of these two pressures can even be read from a U-tube manometer (see Esin, 2021) or pneumatic, electrical, or electronic sensors. This value is then converted to a feedback signal and through transfer functions either visual or electronic is converted to volumetric or mass flow rate to compare with the set or desired value. Because the Venturi meters are manufactured with smooth surfaces and accurate dimensions they are somewhat more expensive than the other meters. They are not very suitable for gases and particulate matter containing liquids which may clog holes of the rings.

The basic relation for flow velocity can be obtained from the continuity and the mechanical energy equations written between the entrance and the throat points and simplified by using assumptions, assessments, and dimensions of the Venturi meter. The assumptions are negligible frictional energy loss in the meter and the fluid is incompressible. Further, because there is no pump between the inlet and exit of the meter the work-energy term, $\mathbf{W}_s$, and due to horizontal alignment the difference of the potential energy terms are zero. Thus, only the kinetic energy change and the pressure difference shall be left.

Accordingly, the mechanical energy balance can be rearranged as

$$\frac{\alpha_T < v_T >^2 - \alpha_{in} < v_{in} >^2}{2g_c} = \frac{(P_{in} - P_T)}{\rho} \tag{5.3}$$

From the equation of continuity velocity at the throat, v_T can be obtained assuming no change in the density of the incompressible fluid.

$$< v_{in} > = \frac{A_T}{A_{in}} < v_T > = \frac{d_T^2}{d_{in}^2} < v_T > = \kappa^2 < v_T > \tag{5.4}$$

$$< v_T > = \frac{1}{\sqrt{a_T - \kappa^4 \alpha_{in}}} \sqrt{\frac{2g_c(P_{in} - P_T)}{\rho}} \tag{5.5}$$

Because it is inevitable to avoid energy loss especially in the contraction section of the meter and assuming that the kinetic energy correction factors at the entrance and at the throat are about the same, by introducing a **Venturi coefficient C_V**, the final form becomes

$$< v_T > = \frac{C_V}{\sqrt{1 - \kappa^4}} \sqrt{\frac{2g_c(P_{in} - P_T)}{\rho}} \tag{5.6}$$

Though it is recommended to determine the Venturi coefficient experimentally, if the throat diameter is less than ¼ of the inlet diameter κ^4 shall be negligible (<1/256), which renders the contribution of velocity at the inlet as unimportant. Further, a well-designed and smooth surface Venturi meter should have a coefficient in the order of 0.98–0.99.

An expression identical to Eq. (5.6) can be derived also for the diverging section of the Venturi meter. In this section owing to the smaller cone angle, the energy loss is correspondingly less. In a Venturi meter, the expected energy loss is in the order of about 10% of $P_{in} - P_T$, which means about 90% is recovered in the diverging section.

Volumetric or mass flow rates can be easily calculated from Eq. (5.6) using the diameter of the throat and density of the fluid.

Example 5.1 The feed rate of cooling water fed from a 4-in. galvanized iron pipe is regulated by a Venturi meter having a throat diameter of 50 mm. According to the operational data when 3.0 kg/s water is fed through the system the pressure drop is recorded by the Venturi meter 116-mm water column. Calculate:

(A) Value of the Venturi coefficient.

(B) The energy loss when the maximum fluid velocity of 3 m/s is used.

Solution: The first part of the problem can be solved upon the rearrangement of Eq. (5.6) together with the mass rate to give the coefficient. For the second part, it is required to use the determined coefficient to calculate first the pressure drop and then conversion of this value to energy.

(A)

$$\dot{m} = \rho < v >_T A_T = \frac{C_v A_T}{\sqrt{1-\kappa^4}} \sqrt{2\rho (P_{in} - P_T) g_c}$$

$$C_v = \frac{\dot{m}}{A_T} = \sqrt{\frac{1-\kappa^4}{2\rho (P_{in} - P_T) g_c}}$$

Data are: For a 4-in. steel pipe, inner diameter is (Table 5.2) 102.26 mm; sectional area for flow is 0.00821 m^2; capacity at 1 m/s flow velocity is 29,560 kg/saat; density of water at 15°C is 999 kg/m^3, $\kappa = 50/102.26 = 0.489 \Rightarrow \kappa^4 = 0.0572$; and, $P_{in} - P_T = (0.116\text{ m})\,(999\text{ kg/m}^3)\,(9.806\text{ m/s}^2)\,(1\text{ N/m}^2/\text{kg/m.s}^2) = 1137.5$ Pa (N/m^2).

Therefore,

$$C_v = \frac{3}{\pi (0.05^2)/4} \sqrt{\frac{1-0.0572}{2(999)(1137.5)}} = 0.984$$

(B) Upon rearranging Eq. (5.6) for pressure drop,

$$P_{in} - P_T = \frac{(1-\kappa^4)\rho < v >_T^2}{4C_v^2}$$

$$< v >_T = < v >_{in} (d_{in}/d_T)^2 = < v >_{in} (1/\kappa)^2 = 3 \text{ m/s} (1/0.489)^2 = 12.546 \text{ m/s}$$

$$P_{in} - P_T = \frac{0.9428(999)(12.546)^2}{4(0.984)^2} = 38277.36 \text{ Pa}$$

If energy loss corresponds to 10% of the pressure drop then energy loss due to Venturi meter is

$$3\,827.4 \text{ Pa} \times (3 \times 0.00821) \text{ m}^3/\text{s} = 94.27 \text{ W} \approx 95 \text{ W}$$

Nozzle—As can be seen from Fig. 5.9 compared to Venturi meter there is no diverging section. Therefore, the energy loss is slightly greater than that of the Venturi meter; in other words of the total energy lost at the nozzle the recovered amount is less than 90%. In a well-designed nozzle the friction may be considered negligible as the velocity of the fluid is increased. This meter is especially used in the steam lines where for the flow velocity again Eq. (5.6) is valid with a change in the coefficient from C_V to C_N. The magnitude of the C_N is about 0.96–0.98.

Orifice—This flowmeter is more common than the first two owing to its simplicity to manufacture and placement though it offers less energy recovery. It is a 2–3-mm thick usually stainless steel circular metal plate greater than the outer diameter of the pipe to which it shall be placed. Depending on the size of the pipe an accurately bored circular hole or an opening of known size and geometry with a beveled conical backside to obtain a sharp edge around the hole is present either at the center or placed eccentrically (Fig. 5.10). However, it is not suitable for fluids containing particulate solids, and in the long run, the hole size may enlarge. Similar to the two meters discussed above, because the fluid is forced to pass through an opening smaller than the pipe diameter, the increase in the kinetic energy is compensated by a drop in the pressure. Hence, again Eq. (5.6) is valid with just a change in the coefficient to C_O where due to the sudden contraction and expansion only 60%–70% of the pressure drop can be recovered which renders the magnitude of the C_O to be 0.6–0.7. Further, because it is practically impossible to exactly determine the cross-sectional area of the most contracted flow area called ***vena contracta*** forming at a small

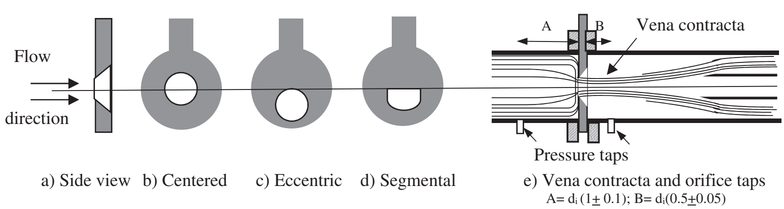


FIG. 5.10 Various types of orifice meters and vena contracta.

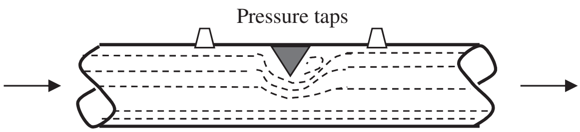


FIG. 5.11 V-element.

distance from the orifice (Fig. 5.10D) employment of the hole diameter in the equation also brings some error.

V-element—It can be visualized as if the hole and the area closed to the flow of the segmental orifice have exchanged their positions (Fig. 5.11). The V-shaped indentation or a wedge of a suitable material is fixed to the inner surface of the wall to reduce the cross-sectional area. Again this causes an increase in the kinetic energy at the expense of the pressure drop at that location. The accuracy of the measurement is quite high and the method is suitable for liquids containing solid particles or gas bubbles. The coefficient of the meter is around 0.8.

Rotameter—The principle difference of rotameters from the meters discussed above is the change in the area available for flow with the flow rate. Therefore, without causing an appreciable pressure drop the design is based on the flow through an inverse truncated conical conduit by keeping a solid float of known density and shape at its terminal velocity. The conical pipe is transparent to see the position of the float and is graduated to read-off the volumetric flow rate value for a specific float of known physical and geometrical properties ρ_F, $A_{Fp,}$ and V_F (Fig. 5.12). On the basis of terminal velocity conditions of a solid in a fluid, i.e., the buoyant and the drag forces are counteracted by the gravity force, at a lifted and fixed position of the float in the pipe, the area available for the flow of the fluid is less than the cross-sectional area of the pipe at that point A_z by an amount of vertically projected area of the float A_{Fp}. Thus, the volumetric flow rate Q is given by

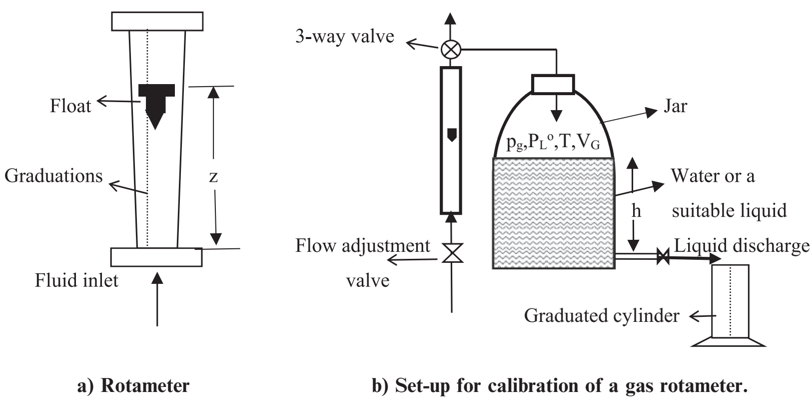


FIG. 5.12 Rotameter and set up for re-calibration of the scale.

$$\text{Flow area, } A = A_z - A_{Fp} = \pi\left(d_z{}^2 - d_F{}^2\right)/4$$
$$Q = v_{max}\pi\left(d_z{}^2 - d_F{}^2\right)/4 \tag{5.7}$$

Here, the velocity of the fluid is maximum because the minimum area available for flow at that 'z' point is considered.

Under constant operational conditions the float shall be remaining at a fixed 'z' elevation and the force balance can be solved for pressure drop in terms of volume of the float V_F.

$$\frac{F_D}{A_{F_p}} = -\Delta P = \frac{V_F(\rho_F - \rho)g}{A_{F_p}g_c} \tag{5.8}$$

When this is substituted in Eq. (5.6),

$$Q = v_{\max}A = C_R A\sqrt{\frac{V_F(\rho_F - \rho)g}{g_c\rho A_{F_p}\left[1 - (A/A_{Rz})^2\right]}} \tag{5.9}$$

where C_R is the coefficient of the rotameter, and because it includes the drag coefficient C_D, it depends on the Reynolds number calculated by using the hydraulic radius and v_{max} as well as the float's shape.

Graduations on the rotameters are made by the manufacturer based on the supplied float size, shape, and material according to the intended use for a gas or liquid at a certain temperature. This information is indicated on the rotameter as "Air, Nm^3/h" or "L/min Water at 20°C." Thus, if the rotameter shall be used with a different float or at a different temperature or with a different fluid its graduations must be calibrated for the system. An experimental setup is shown in Fig. 5.12 for the calibration of a rotameter to be used for gas at conditions different than the manufacturer's specifications.

A leakproof, gas or liquid, system is to be set up as shown in Fig. 5.12B and the jar is about more than half, filled with water or a liquid in which the gas is insoluble. The liquid discharge valve of the jar and the three-way valve are opened to the atmosphere keeping the jar side of the latter closed and waiting until the pressure equilibrium is attained. That is, the sum of the pressures (i) due to the liquid head 'h' in the jar above the discharge level, (ii) the vapor pressure of the liquid at T° $P_L°$, and (iii) the partial pressure of the gas of interest becomes equal to the atmospheric pressure P_{atm}. When the equilibrium is sustained there should be no flow of the liquid from the discharge and the height of the liquid in the jar is recorded as "h_1" and the volume of the gas phase above the liquid is V_{G1}.

$$p_g + P_L° + \rho_L gh = P_{atm} \tag{5.10}$$

When the system is at equilibrium adjustment valve is opened and the float is brought to a fixed height corresponding to a graduation mark. Then the three-way valve is turned to direct the gas to the jar and while the liquid is collected in a graduated cylinder time is kept with a stopwatch. Upon the collection of a sufficient amount of accurately measured liquid ΔV in the cylinder the three-way valve is again rotated to close the jar direction and opened to air and the time is recorded as Δt. To complete the run again the system is left to attain the new equilibrium with the new p_{g2} and h_2.

With the assumption of ideal behavior of air, the gas, and their mixture the following relations can be written from Eq. (5.10) and Dalton's law:

$$p_{g1} = P_{atm} - P_L{}^\circ - \rho_L g h_1 = n_{g1} RT/V_{G1} \tag{5.11a}$$

$$p_{g2} = P_{atm} - P_L{}^\circ - \rho_L g h_2 = n_{g2} RT/V_{G2} \tag{5.11b}$$

$$\mathrm{V_{G2} = V_{G1+}\,\Delta V} \tag{5.12}$$

These equations can be solved for $\Delta n_g = n_{g2} - n_{g1}$ to determine the amount of the gas, in moles, collected in the jar during the time Δt.

$$\Delta n_g = [(P_{atm} - P_L{}^\circ - \rho_L g h_2)\Delta V + \rho_L g (h_1 - h_2) V_1]/RT \tag{5.13}$$

If change in the height of the liquid $(h_1 - h_2)$ is in the order of few centimeters or if the experimental run is so adjusted that $h_1 = 2h_2$ and $\Delta V \approx V_1$ then it is possible to simplify the relation.

$$\mathrm{\Delta n_g = (P_{atm} - P_s{}^\circ)\Delta V/RT} \tag{5.14}$$

To calculate the mass rate or the volumetric rate molecular weight of the gas can be used with the ideal gas law. The units of the gas constant R and the volume ΔV must be consistent.

$$\dot{m}_g(\mathrm{kg/s}) = \frac{M_g \Delta n_g}{\Delta t} = \frac{M_g\left(P_{atm} - P_L^o\right)}{RT}\frac{\Delta V}{\Delta t} \tag{5.15}$$

$$Q_g\left(\mathrm{m^3/s}\right) = \frac{22.4(101.325)}{273R}\frac{1}{P_{atm}}\frac{\left(P_{atm} - P_L^o\right)\Delta V}{\Delta t} \tag{5.16}$$

5.3.2.2 Insertion (point)-type meters

Insertion-type flowmeters measure the pressure drop at a fixed point on the cross-sectional area of the pipe. They offer two possibilities of usage. In the first one by taking data along the diameter the velocity profile can be obtained and then this can be used to get the average velocity and hence the volumetric rate. On the other hand, as a second alternative, the value measured at a definite point

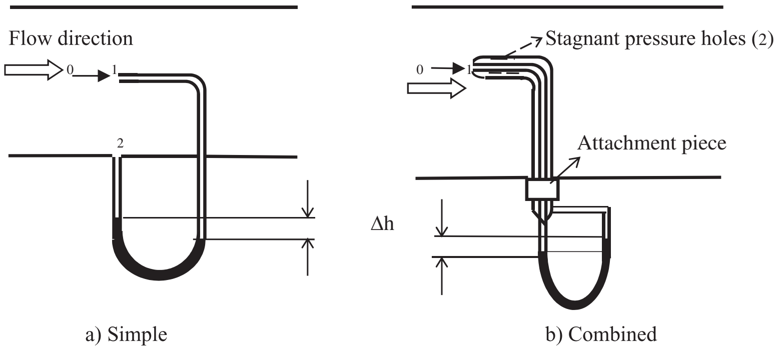


FIG. 5.13 Pitot tubes.

can be converted to the average velocity by multiplying with a predetermined coefficient and a meter constant. If this specific point can be adjusted on the centerline of the pipe then the measured velocity shall be v_{max}, which can easily be converted to the average velocity according to whether the flow is laminar or turbulent. Some of the most commonly used types are explained briefly below.

Pitot tube—This meter is used to measure the velocity at a selected radial position. The selected point may be the centerline for the maximum velocity or that corresponding to the average velocity. As can be seen from Fig. 5.13 open end of the inserted tube must be placed opposite to the flow direction to receive the full momentum. This is compared with the stagnant pressure measured at either the pipe's inner surface or the tube surface and reflected as a pressure drop by means of a U-tube or a suitable instrument.

If it is assumed that the diameter of the pitot tube is considerably smaller than the pipe diameter and shall not be causing any disturbance in the flow, hence no energy loss, then between points '0' and '1' Bernoulli equation can be applied. At the tip of the tube point "1" the flow stops and it is a stagnation point implying $v_1 = 0$. Further, because between these two points there is no pump work and potential energy change for an incompressible fluid the equation can be simplified to

$$\frac{P_0}{\rho} + \frac{v_0^2}{2g_c} = \frac{P_1}{\rho} \tag{5.17}$$

Here P_1 is the stagnation pressure and the equation can be solved for the impact velocity,

$$v_0 = \sqrt{\frac{2g_c(P_1 - P_0)}{\rho}} \tag{5.18}$$

Using the force balance for a U-tube manometer where the manometer fluid has a density ρ_M, the pressure difference between the points "1" and "2" is given by.

$$P_1 - P_2 = g\,(\rho_M - \rho)\Delta h/g_c \tag{5.19}$$

Now, if point "0" is taken very close to "1" and the potential energy difference between the points "0" and "2" is neglected then it is possible to assume $P_0 = P_2$ and Eq. (5.18) can be written independently of pressure difference.

$$v_0 = \sqrt{\frac{2g(\rho_M - \rho)\Delta h}{\rho}} \tag{5.20}$$

The final relation gives the velocity that shall be measured by an ideal pitot tube. To convert it to volumetric flow rate it is required to know the radial position of the tube and the velocity distribution as mentioned above. Further, for the assumption that pitot tube diameter is negligible compared to the pipe diameter to be valid the ratio should be less than 1/50. When this condition is not met then an experimentally determined coefficient must be introduced on the right-hand side of Eq. (5.20).

Though pitot tubes are cheap, simple, and do not cause energy loss they are not much used in industry but by researchers. Some of the disadvantages of pitot tubes are, tip of the meter is apt to be clogged and/or may wear out with time, location of the tip may not be exact and they not much suitable for gases due to low pressure.

***Other insertion meters*—**There are a number of insertion meters designed to measure the fluid velocity at a point in the diameter. According to the sensing element some of them are electrical, electronic, thermal, magnetic, and rotational. Generally, because most of them are for specific applications they are somewhat expensive. The most known and used ones are hot-wire and vane anemometers. Some of them are introduced below.

5.3.2.3 Different types of measurement devices

There are many flowmeters designed for specific condition working either according to the so far discussed principles or entirely different. Those worth mentioning are hot-film, laser-Doppler anemometers, ultrasonic and electromagnetic types, which are considered as expensive as well as simple designs using rotating blades or target meters using the stagnation principle of pitot tubes.

- **(I) Rotating blades:** Rotational effect caused by the impact of a flowing fluid can be transferred to a counter or a suitable monitor through gears, magnetic or electronic means (Fig. 5.14). Ordinary water meters, wet or dry gas meters, turbine meters, and velocity measuring vane anemometers utilize this method. Most of the recent models are suitable for computer control or can generate electronic signals or outputs directly transferrable to printers.
- **(II) Stagnation effect:** In principle, these meters generally use the drag or impact force by means of a surface placed normal to flow in the cross-sectional area. The force opposing the impact can sensitively be measured

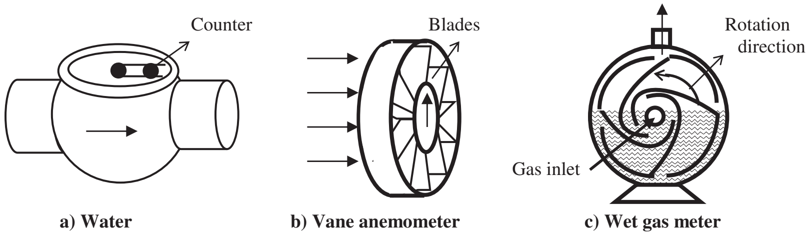


FIG. 5.14 Some common flowmeters.

and reflected as velocity or rate. In another similar meter, the pressure drop caused by eddies formed behind the surface is measured to determine the volumetric rate.

(III) Special effects: Among the flow meters in this group the laser-Doppler velocity meter combines reflection of the laser beam with the Doppler effect (Angus et al., 1969) and in a similar way meters using ultrasonic sound wave or magnetic properties instead of laser beam have been developed. The latter is especially used for blood flow rate measurements with electromagnetic sensors. Also, thermal meters for hot fluids flowing in a pipe having sensors placed at two different positions along the length of the pipe are quite common. All of the meters in this class can make measurements without necessitating the placement of an element into the pipe are quite special and precious.

(IV) Weir meters: The final group of flow meters worth discussing are weir meters used especially in open channels. These are either rectangular or V-shaped (Fig. 5.15) dam-like systems where the excess of the liquid flows over the weir. In the rectangular type, the crest "E" can be as long as the width "L." The theoretical relation is again obtained from the Bernoulli equation by considering only the conversion of the potential energy to kinetic energy.

A. Rectangular weir: If the linear velocities of the liquid at point "z" right above the crest and at location "1" are "v" and "v_1," respectively, then assuming that the velocity distribution is negligible with the horizontal streamlines just above the discharge and no frictional loss, the Bernoulli equation can be written

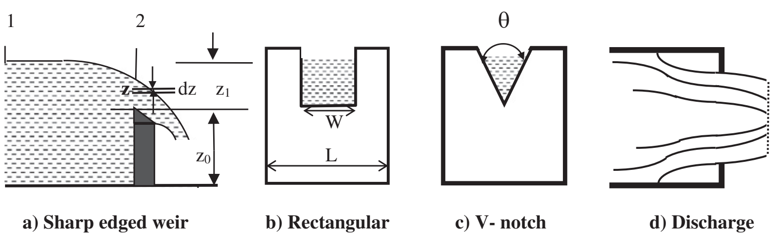


FIG. 5.15 Rectangular and V-notch flowmeters.

for the system confined between the points "1" and "2" and solved for the horizontal velocity just at the weir,

$$z_1 g + \frac{v_1^2}{2} = zg + \frac{v^2}{2} \tag{5.21}$$

$$v = \sqrt{2g\left(z_1 + \frac{v_1^2}{2g} - z\right)} \tag{5.22}$$

Now, if the volumetric rate is written for a differential area of size "Wdz" and integrated for the whole thickness from $z=0$ to $z=z_1$,

$$dQ = Wvdz = W\sqrt{2g\left(z_1 + \frac{v_1^2}{2g} - z\right)}dz \tag{5.23}$$

$$Q = \frac{2}{3}W\sqrt{2g}\left[\left(z_1 + \frac{v_0^2}{2g}\right)^{3/2} - \left(\frac{v_0^2}{2g}\right)^{3/2}\right] \tag{5.24}$$

If velocity of the fluid at point "1" is considered negligible the relation becomes

$$Q = \frac{2}{3}W\sqrt{2g}(z_1)^{3/2} \tag{5.25}$$

The result obtained through purely theoretical considerations and the assumptions is matched with the realistic data by using a preferably experimentally determined correction factor similar to the discussed devices. The magnitude of this discharge coefficient C_D is in the range of 0.6–0.65.

$$Q = \frac{2}{3}C_D W\sqrt{2g}(z_1)^{3/2} \tag{5.26}$$

A frequently preferred relation instead of Eq. (5.26) is the modified empirical Francis equation which can predict the flow rate in m^3/s within 3% deviation when all other terms are in SI units and C_D taken as 0.62.

$$Q = 1.84\left(W - \frac{nz_1}{10}\right){z_1}^{3/2} \tag{5.27a}$$

Here "n" is the number of end contractions or side edges narrowing the flow width. That is, for W = L it is 0.0, is equal to 1.0 when one of the edges is coincident with the channel wall, and is equal to 2.0 for the notch placed symmetrically in the channel width and W < L.

Example 5.2 An irrigation channel system is constructed as shown in Fig. 5.16 to water the planted area on both sides of the main channel. The water is

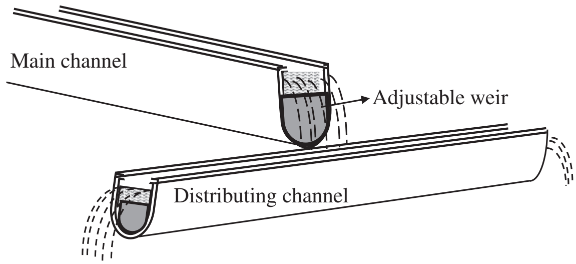


FIG. 5.16 Irrigation channels.

distributed to the sides by a second channel placed normal to the main one. The width of the main channel (L) is 0.5 m and the width of the weir is equal to that of the channel (W = L). If the flow areas above the weirs are rectangular, determine the following:

(a) The volumetric rate of water supplied by the main channel when the height of water above its discharge weir is adjusted to 10 cm.
(b) To what heights water above the two weirs on both sides of the distributing channel should be adjusted if it is desired to have the water shares of the sides as 1/3 and 2/3.

Solution: As W = L then $n = 0$ and because the correction coefficient is not given the Francis equation shall be used for the volumetric rate.

(a)

$$\begin{aligned} Q &= 1.84 L z_1^{1.5} \\ &= 1.84(0.5\ \text{m})(0.1\ \text{m})^{1.5} \\ Q &= 0.029\text{m}^3/\text{s} \approx 0.03\text{m}^3/\text{s} \end{aligned} \tag{5.27b}$$

(b) This means the water to be distributed to one of the sides shall be 0.01 m^3/s and 0.02 m^3/s to the other. Utilizing Eq. (5.27b) to solve for "z_1",

$$z_1 = (Q/1.84L)^{2/3} \tag{5.27c}$$

Therefore, the heights of the weirs at the two ends according to the specified rates are:

$$z_{11} = [0.01/1.84(0.5)]^{2/3} = 0.05\ \text{m}$$

$$z_{12} = [0.02/1.84(0.5)]^{2/3} = 0.08\ \text{m}$$

This means for the side receiving 2/3 of the water the weir should be 3 cm lower than the side receiving 1/3.

B. V-notch weir: As can be seen from Fig. 5.17 the width of the notch W increases with the height which can be easily expressed from the elementary geometry.

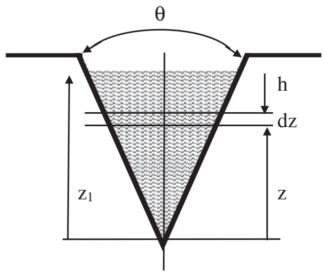


FIG. 5.17 V-notch weir.

$$W = 2z\ \tan\ (\theta/2) \tag{5.28}$$

From Eqs. (5.23) and (5.28) the differential volumetric rate through the area "Wdz" with the velocity at location "1" (**see** Fig. 5.15A) neglected is

$$dQ = Wvdz = W\sqrt{2g(z_1 - z)}dz \tag{5.29}$$

$$dQ = 2\ \tan\,(\theta/2)\sqrt{2g(z_1 - z)}zdz \tag{5.30}$$

To simplify the solution if "$h = z_1 - z$" is used as the variable and Eq. (5.30) is integrated within the limits of z_1 to 0,

$$\begin{aligned} Q &= 2\ \tan\left(\frac{\theta}{2}\right)\sqrt{2g}\int_{h-z_1}^{h-0} h^{1/2}(h - z_1)dh \\ Q &= \frac{8}{15}\tan\left(\frac{\theta}{2}\right)\left(\sqrt{2g}\right)z_1^{5/2} \end{aligned} \tag{5.31}$$

Again, because this theoretical relation is for frictionless flow and $v_1 = 0$ a correction factor C_D is introduced.

$$Q = \frac{8}{15}C_D\tan\left(\frac{\theta}{2}\right)\left(\sqrt{2g}\right)z_1^{5/2} = C_D'\tan\left(\frac{\theta}{2}\right)\left(\sqrt{2g}\right)z_1^{5/2} \tag{5.32}$$

The correction factor C_D has a value in the range 0.6–0.65, which also depends on θ and z_1. As an example, for 15-cm water height, its value is 0.62 for a 20° notch which is 0.60 for 90° one.

When the results of rectangular and V-notch weirs are compared it can be seen that the volumetric rate of flow depends on the 1.5th and 2.5th powers of liquid height z_1 at the notch for the rectangular and the V-notch weirs, respectively.

5.4 Flow-inducing machinery, pumps, blowers, and compressors

It was already shown in Fluid Mechanics Chapter (**Vol. 1, Ch. 7**) that in order to transfer a fluid from one vessel to another or to process equipment in a pipe, mostly external energy in the form of work is required. This energy added to the system to overcome all of the energy demands of the intended transport arising from, namely, potential, kinetic, pressure, and frictional losses. The energy required to meet the resultant of the present energy-demanding phenomena is imparted to the process fluid in the form of pump or shaft work W_S by a suitable pump, fan, blower, or compressor. Of these equipment, pumps are used for liquids and the other three for gases.

The classification of all these equipment is according to the operating mechanism as to how the work is transferred to the fluid from the element, i.e., by **positive displacement** using **reciprocating** action or **centrifugal** action. The former types are operated by a reciprocating cylinder within a bed creating suction to pull the fluid in the backward stroke and discharging it in the forward stroke whereas the latter types have rotating blades on a shaft in housing to push the fluid toward the discharge.

To meet the requirements of a very wide variety of fluids of different characteristics, behaviors, and process conditions a considerable number of special transfer equipment have been designed. That is, the fluid to be transported can be gas, gas–solid, gas–liquid, liquid, liquid–liquid, or liquid–solid in addition to the possibilities of exhibiting Newtonian or non-Newtonian behavior. As it is practically impossible to explain all of the suitable types for these possibilities, the primary aim here is to provide a background about the criteria in selecting the size, power, and general type of the equipment and its location within the system and then investigate the operational principles of the most general types.

Design and manufacture of a flow-inducing equipment is a special field governed by the manufacturers but the customer must establish the expected qualifications according to the relevant terminology. As a general rule, the gas moving machines operate at a higher velocity than that of the liquid. Further, the allowances and the tolerances between the moving parts are much smaller for the gas handling equipment to minimize the escape, and in the case of suction generating equipment, it is important to avoid leakage from the environment.

Therefore, the subject shall first be treated with respect to the basic principles and relations, which shall be followed by the analysis of the general equipment on the basis of fluid type.

5.4.1 General relations

For transportation of a fluid in a system the governing relations to calculate the magnitude of the work or thermal energy were discussed in a study by Esin (2021) in Vol. 1, Ch. 7 and were expressed as heads in Eqs. (7.72)–(7.76).

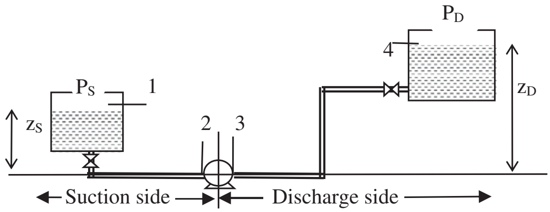


FIG. 5.18 A simple system for the transfer of fluid between the tanks.

Starting from these equations the work-energy as head required to transfer the fluid between the terminals 1 and 4 for the system given in Fig. 5.18 is

$$\frac{\dot{W}_s g_c}{mg} = \left[\frac{Pg_c}{\rho g} + \frac{\alpha < v_4 >^2}{2g} + z\right]_D + \frac{g_c \sum H_{sT}}{mg} - \left[\frac{Pg_c}{\rho g} + \frac{\alpha < v_1 >^2}{2g} + z\right]_S \tag{5.33}$$

When the frictional energy losses for the suction and discharge sides are separated and put in their respective sides

$$\begin{aligned}(-)\Delta h_{W_s} &= \left[h_P + h_v + z + \sum h_{sT}\right]_D - \left[h_P + h_v + z - \sum h_{sT}\right]_S \\ &= \sum h_D - \sum h_S\end{aligned} \tag{5.34}$$

In the final relation the terms corresponding to the energy losses due to friction and fittings on the discharge and suction sides Σh_{sTD} and Σh_{sTS}, respectively, are determined from Eq. (7.137) or Eq. (7.138) given in **V.1 Ch. 7**. If possible pipe length $L+$ equivalent length of fitting L_e simplification can as well be used employing data in Table 7.3 given in the same chapter.

$$\sum h_{sTD} = 2f \frac{\left(L_D + \sum L_{eD}\right)}{d_{iD}} < v_D >^2 \tag{5.35}$$

$$\sum h_{sTS} = 2f \frac{\left(L_S + \sum L_{eS}\right)}{d_{iS}} < v_S >^2 \tag{5.36}$$

As can be seen, the magnitudes of these energy loss terms increase with the respective velocities which cause a decrease in the energy contributed to the flow by the suction side and an increase in the discharge side, thus increasing the work-energy requirement of the system.

An important point to be noted is the presence of gas in the suction side especially when a liquid is drawn from a well. Generally, this gas is either the vapor of the liquid at that temperature or air trapped in the line and because of its compressibility or leakage, the suction cannot be performed. For this reason, if sufficient idle time is allowed especially for the reciprocating pumps present on the water wells, liquid in the pipe within the well shall be drained by gravity. Therefore, before re-start, the pipe must be filled externally with the liquid to remove the gas. On the other hand, the vapor pressure of the liquid in the suction side offers additional resistance to suction due to its specific pressure head. To account for that the actual contribution of the suction side known as the **net positive suction head (NPSH)** is calculated by deducting the head due to the vapor pressure of the liquid P_L^0 from the suction side. To have the fluid flowing NPSH must be positive in the order of at least a few meters for small centrifugal pumps and values up to about 15 m are recommended for very large pumps (Green and Perry, 2008).

For the relation again referring to Fig. 5.18 the absolute pressure head at the pump inlet h_2 is given by the mechanical energy balance between the points 1 and 2.

$$h_2 = \frac{P_2 g_c}{\rho g} = \frac{<v_{S1}>^2 - <v_{S2}>^2}{2g} + z_S - 0 + \frac{P_S g_c}{\rho g} - \sum h_{sTS} \quad (5.37)$$

When the vapor pressure of the liquid is deducted from the total head at point 2, NPSH is obtained.

$$\text{NPSH} = \left[h_2 + \frac{<v_{S2}>^2}{2g}\right] - \frac{g_c P_L^0}{\rho g} \quad (5.38)$$

When considered only from the energy balance point of view, the important pressure condition at point 2 is missed. Eqs. (5.33) and (5.34) are written for terminals 1 and 4 and when it holds a wrong impression about the operability of the system is obtained. In fact, if the magnitude of the pressure P_2 is slightly greater than the vapor pressure P_L^0 of the liquid in the system then it is possible that some liquid may vaporize within the transferring equipment. This is called **cavitation**, which severely reduces the efficiency as well as creates small cavities and channels on the surfaces of the blades causing wear and balance problems. This is the main reason why it is recommended to have NPSH a few to several meters depending on the pump.

5.4.2 Fluid moving machinery

As a resume of the knowledge above, any machinery used to transfer fluid is required to add a work head to the suction head to achieve the desired discharge head. This energy contributing equipment generally employ either a direct pushing action or a rotational motion by the torque applied through blades. Thus, based on the method of design used for the equipment they are classified as (i) **positive displacement** and (ii) **centrifugal** type.

In the first group, a piston reciprocating in a cylinder, a flexible diaphragm, or a positive-action rotary system applies a linear push to a definite amount of fluid drawn into a chamber and then forces it out at a higher pressure. The second type receives the fluid from the central point of rotating impeller blades, i.e., rotating eye, and spreads it out radially imparting a high-pressure head to the fluid. The machinery making use of this action are centrifugal pumps, fans, blowers, and compressors.

The selection of transfer equipment necessitates knowing the magnitude of the work required as well as the performance and operational characteristics of the capable equipment. This information is provided by the manufacturers among which the volumetric flow rate, flow capacity, power, and operational efficiency should be included as of prime importance. These should be followed by **reliability**, **robustness, ease of maintenance, cost,** and similar considerations. That is, simplicity and troubleless operation may be more important than operation at the maximum efficiency with few kW power gain.

Besides the classifications mentioned above the selection is also affected by some characteristics of the fluid as being compressible or incompressible, Newtonian or non-Newtonian, together with chemical and microbiological restrictions. The relations required to analyze incompressible fluids are already discussed in **V.1 Fluid Mechanics**. Though a sharp distinction is not made among this equipment in conventional terminology, generally the term pump is used for the equipment imparting energy to liquids, and aspirator, fan, blower, and compressor for gases. Further, though aspirators, fans, and blowers are mostly centrifugal machinery aspirators, fans are low-speed equipment supplying gas to open areas or ducts large volumes of gas at low pressures 5–10 cm water column. Hoods in laboratories or kitchens, air circulators, and hair dryers are some examples. On the other hand, blowers have a high speed and can develop discharge pressures of about 2 atm (20 m water column) to the gas. Compressors are generally used to discharge gases from 2 atm to a few thousand atmospheres as in natural gas pipelines where recompression or pumping stations are used at certain kilometer intervals along the line.

In the light of the preliminary information above the general characteristics and some common types of flow-inducing equipment are given below as pumps, blowers, and compressors.

5.4.2.1 Liquid moving machinery: Pumps

The following points are important and helpful in the specification of a pump for a defined load (Holland and Chapman, 1966):

The quantity of the liquid to be handled, the desired rate: This must exactly be established preferably as the maximum to determine the size and the capacity of the pump and also to consider whether several pumps can be used in series or parallel.

1. *The work head required*: The work head and power required from the pump is according to Eq. (5.33).

2. *The nature of the liquid to be pumped*: Besides the physical properties, density, and viscosity of the liquid, possible abrasive, corrosive chemical and microbiological interactions of the liquid must be considered for the material of construction of the pump, the glands, and the gaskets. For solid–liquid mixtures, the tolerance between the moving parts and the solid particles must be greater than the largest particle size.
3. *The nature of the power supply*: The power to actuate the pump can be obtained from an electrical motor, internal combustion, steam, or gas-driven engine.
4. *The continuity of operation*: The pump may be used only intermittently or continuously where in the former case corrosion, wear due to the start-up load, deterioration of the liquid hold-up, chemical actions, and microbial-bacterial problems are more common.

5.4.2.1.1 The positive displacement pumps

In this group of pumps, the reciprocating and the rotary types are encountered. In the former types, the pumping action is mostly intermittent whereas the latter types give continuous output.

(A) *Reciprocating pumps*

Pumps entering in this class operate by intake of the liquid from the supply tank into a definite volume and then with a forward stroke push it out at a higher pressure from the discharge which is approximately a sinusoidal motion. They are mostly used for the injection of small quantities of chemicals like inhibitors into the systems.

The piston and the plunger or ram pumps are the most common types of this class where in a piston reciprocates in a cylinder to fulfill the work (Fig. 5.19). The clearance between the piston and the cylinder has a very small tolerance to minimize the backflow of the liquid from the contact surfaces especially during the forward stroke. The end of the cylinder through which the rod of the piston passes must have an abrasion-resistant and leak-proof gland.

The suction inlet and the discharge exit are protected by check valves operating like a ball or lift type so that during suction the exit is closed to flow and the inlet to the cylinder is open, which is reversed in the discharge stroke. Therefore, in a single-acting pump system flow rate is intermittent whence there is no discharge during the backward or suction operation but only filling of the cylinder.

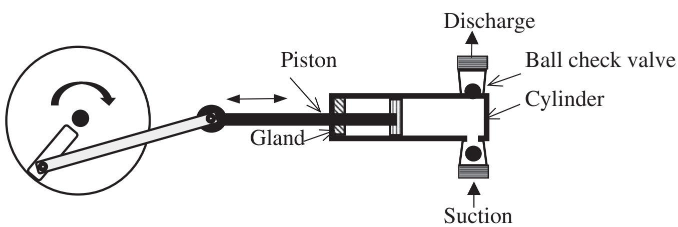


FIG. 5.19 Piston-cylinder scheme in a reciprocating pump during suction and no discharge.

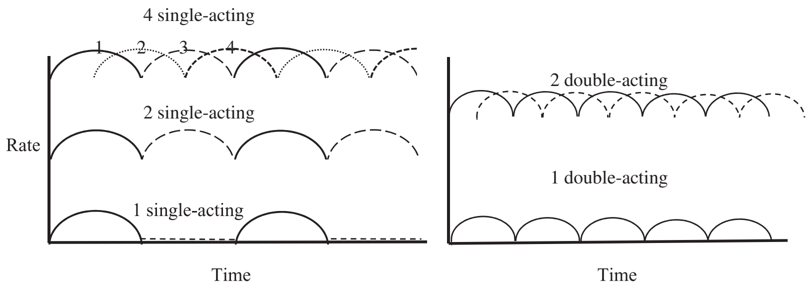


FIG. 5.20 Effect of using multipumps on the smoothing of flow rate.

To a degree, this problem is solved by using double-acting pumps in which there are two suction and two discharge ports on both sides of the cylinder and the liquid is pumped in both strokes during the reciprocating action which gives a smoother feeding. However, the side of the cylinder containing the rod has a smaller volume due to the rod volume. Because the volume of the liquid that can be pumped in one cycle is limited by the total volume swept by the piston both designs may be arranged as synchronized multisingle-acting or multidouble-acting to increase and smoothen the rate (Fig. 5.20). In most of such pumps, the reciprocation rate of the piston may be adjusted to increase or decrease the rate.

The periodical feeding action of the piston pumps may create a **knocking** effect, especially in long pipes due to the discontinuous flow of the liquid, which causes a decrease in the pressure imparted to the fluid as a result of momentum change of the liquid. To avoid this it is sufficient to either adjust the pumping cycle or place a pressurized tank after the discharge end. During the discharge period of the pump, a part of the liquid shall be passed to the tank compressing the gas (mostly air) confined in the tank head. Thus, as the pressure imparted to the liquid is gradually decreasing toward the end of the swept volume, the compressed gas will start feeding the make-up liquid to the pipe as the compressing pressure on the gas has ceased. This avoids discontinuity of the flow as well as will prevent the suction of air to the pump. This system is identical to that used in hydrophores for continuous water supply in the till buildings reducing pumping cost.

The plunger and ram pumps are of the same principle as the piston pumps with only slight differences in the ease of replacement of the parts, especially the glands.

Another pump using the same principle is the diaphragm pump. They have been developed especially for corrosive fluids or liquids containing abrasive solid particles. Its cylinder is composed of two compartments separated by a flexible diaphragm. In one compartment a plunger or piston operates to displace a noncorrosive liquid which in turn transmits it to the liquid in the other compartment by the flexible diaphragm.

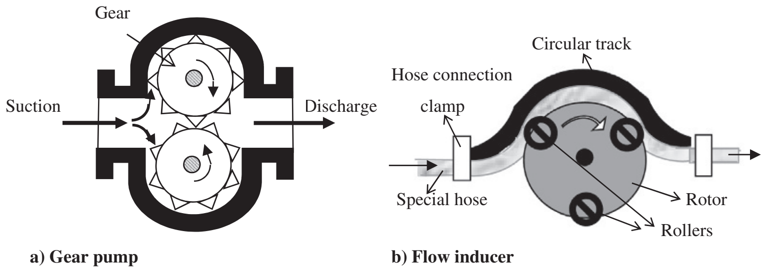


FIG. 5.21 Two positive displacement pumps.

(B) ***Positive displacement rotary pumps*:** The most common and conventionally used types are explained below.

1. **The gear pump:** One of the most common types in this class is the gear pipe shown in Fig. 5.21A. It consists of two gears rotating in reverse directions in a casing where only one is actuated by a motor. The liquid entrapped between the two gears and the wall of the casing is pumped after traveling a half cycle from the discharge. There are no valves on the pump and the entire principle depends on the very small clearance between the gear and the wall. However, this clearance may increase in time, which reduces the volumetric efficiency of the pump. Nevertheless, compared to the reciprocating pumps it offers the advantages of uniform and continuous feeding, and further, it is suitable for high-viscosity fluids like mineral oils, petroleum products, and wastes. But it is not recommended for solid suspensions due to the narrowness of the clearance between the casing and the gears.
2. **The flow inducer or peristaltic pumps:** These are special purpose pumps functioning by compressing the liquid in a special silicone or suitable flexible tubing by rollers. The tubing is fitted to a curved track concentric with the rotor carrying three rollers as shown in Fig. 5.21B. As the rollers rotate they flatten the tubing by pressing against the track surface which pushes the liquid to the discharge by positive displacement. They are used for pumping biological fluids, emulsions, creams, and the like liquids where contact with air or any material which may cause contamination is not at all desired. The tubing size can be 3–25 mm giving a rate of about 5–360 cm^3/s. The flow rate is adjusted by the rotational speed of the rotor and due to the relatively low capacity these are suitable for laboratories or small plants.
3. **Some special purpose pumps:** There are many pump designs that are especially for operations at high pressures, chemical or physically abrasive liquids, or liquid–solid mixtures. Among these, **mono, metering**, **lobe,** and **sliding vane** pumps are explained below.

   The mono pump has a helical metal worm rotating within a stator made of rubber or any other suitable material. Rotation of the rotor in the stator gives a uniform and quiet operation by forcing the liquid to the space

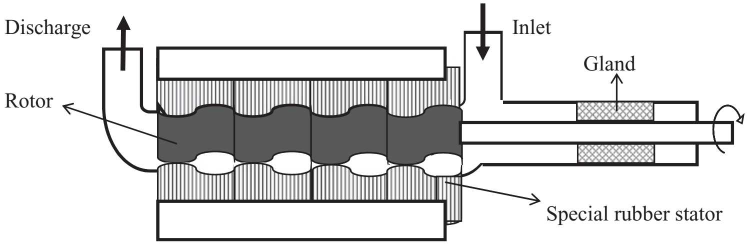


FIG. 5.22 Medium-sized mono pump.

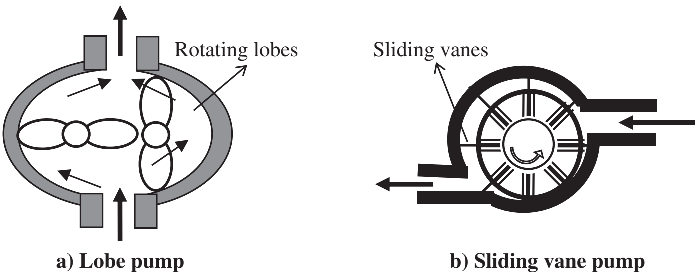


FIG. 5.23 Lobe and Sliding vane pumps.

between the rotor and the stator along the length as can be seen in Fig. 5.22. Depending on the opposing pressure the number of helices and hence the length changes. The mono pumps are mostly applied for pressure filters and transportation of muddy liquids. It must never be run dry as serious damage to the rotor and the stator may result.

The metering pumps are equipped with constant speed electric motors to provide a constant and accurately controlled volumetric rate of the fluid despite an increase in the opposing pressure. They are of plunger type and are thus suitable for low throughput and high-pressure applications by adjustment of the stroke of the piston. It is recommended to use stroke type for low rates and high pressures and may be arranged in stage for high rates and low pressures. The metering pumps are especially good for dosing works (Fig. 5.23).

In principle, the lobe pump is a version of the gear pump and the sliding vane pump is that of a peristaltic pump without a tubing. They are special pumps designed to meet the requirements of different systems.

5.4.2.1.2 The centrifugal pump

The centrifugal pumps are the most commonly used pumps in the industry. They contain a number of rotating impellers attached to a rotating rod inside a casing where the rod and the casing are located eccentrically. The fluid is fed from the center of the impellers and by centrifugal action is thrown toward the periphery of the casing. The direction and magnitude of the momentum that shall be

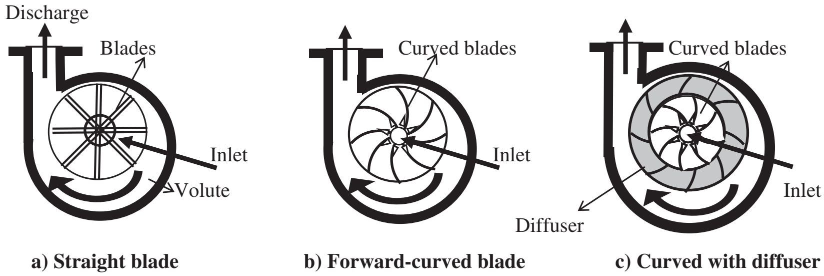


FIG. 5.24 Different centrifugal pump designs.

imparted to a fluid by rotation of the impeller blades depend on the position of the blades on the rod they are attached and their shape. To give acceleration to the fluid in the direction of a rotating rod the angle the impellers make with the rod may be about 90°. Therefore, the surface of the blades that accelerate the fluid is amost parallel to the rod. As an alternative design, the impeller blades are curved to give a greater tangential velocity to the fluid at the inner periphery of the casing. The fluid is discharged to a volute by the centrifugal force and leaves the pump through a tangential exit. The first type of blade is used in fans and blowers whereas the second type is used for pumping nearly all types of industrial fluids.

As shown in Fig. 5.24 the centrifugal pumps can be classified according to the shape of the blades as **straight-blade** and **curved-blade**. A further classification of the curved-blade types is due to the direction of the curve as **forward** or **backward** and with or without a **diffuser**.

In the analysis or design of the rotary equipment for transport or mixing of fluids torque and angular momentum relations are used. For the straight-blade and the curved-blade centrifugal pumps, these relations can be derived with the aid of Fig. 5.25.

From conservation of momentum relation Eq. (5.14), **V.1 Chapter 3** when gravity, pressure, and frictional forces are considered as negligible only F_r shall be left equal to the rate of change of momentum. At steady state because there shall be no change in the transferred mass rate, the simplified equation can be directly written.

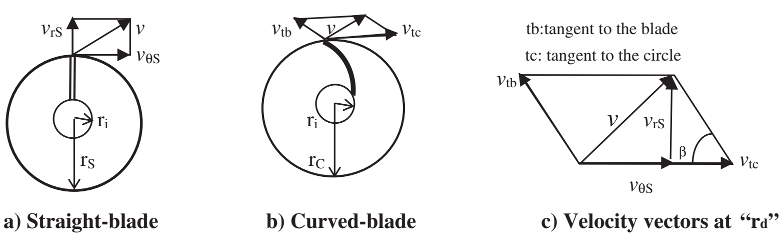


FIG. 5.25 Velocity vectors on the straight and the curved blades in a centrifugal pump.

$$F_r = \frac{d(mv)}{dt} = \dot{m}\Delta\vec{v} \tag{5.39}$$

This force F_r is the force applied to the fluid by the blade surface, which is F_θ according to Fig. 5.25A.

On the other hand, the torque T acting on the fluid at any point "r" along the blade is

$$T = F_\theta r = \dot{m}\Delta\left(r\vec{v}\right) \tag{5.40}$$

Now, the change in the magnitude of the momentum of the fluid in the direction from entrance through the center of the rod or eye of the blades to the tip along the blade can be written. If the boundary condition at the central point is considered as: velocity of the fluid in θ-direction is zero and "r_i" is negligible, then

$$\text{Straight} - \text{blade}: \quad Tg_c = \dot{m}(r_S v_{\theta S} - 0) \tag{5.41}$$

$$\text{Curved} - \text{blade}: \quad Tg_c = \dot{m}(r_C v_{rC} - 0) \tag{5.42}$$

Thus, assuming a frictionless ideal pump rotating at ω rad/s and no-slip condition on the surface of the blade, the following important virtual operational parameters can be determined. For the straight-blade:

$$\text{The power } P_W \text{ developed}: \quad P_W g_c = Tg_c\,\omega = \dot{m} r_S v_{\theta S}\omega \tag{5.43}$$

$$\text{Pump head}: \quad \Delta h_{W_S} = \frac{W_S}{m} = \frac{P_W}{\dot{m}} = \frac{r_S v_{\theta S}\omega}{g_c} \tag{5.44}$$

$$\text{Volumetric rate}: Q = v_{rS}\,A_p \tag{5.45}$$

where A_p is the area available for flow at the outlet of the impeller of width "b," hence $A_p \approx 2\pi r_S b$ and $\propto r_S$. For the curved-blade it is required to make the changes: $v_{\theta S} = v_{tC} - v_{rS}/\tan\beta$ and $v_{tC} = r_S\omega$.

These results indicate that the effect of the rotational speed of the pump ω on the basic parameters of the pump is

$$\text{Rate}, Q \propto \omega$$

$$\text{Work head}, \frac{W_p}{m} \propto \omega^2$$

$$\text{Power}, P_W \propto \omega^3$$

In the above relations the basic assumption is the ideal pump with no friction and energy losses. However, especially with the curved-blade pumps, the angle β between the velocity vectors v_{tB} and v_{tC} is small at the tip of the blades because

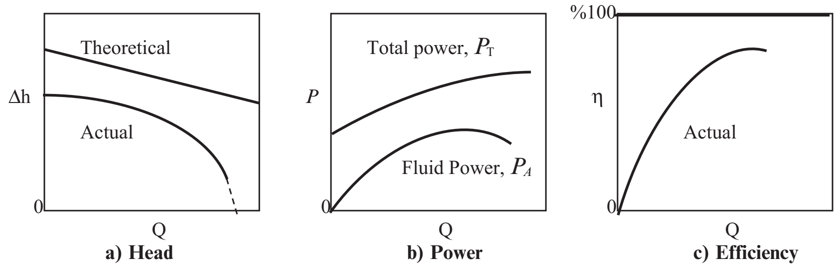


FIG. 5.26 Characteristic curves of a centrifugal pump.

of the circulation and the turbulence caused there. As can be followed from Fig. 5.26C this reduction in the angle affects the resultant velocity vector $\boldsymbol{v}$ and $v_{\theta S}$. Therefore, the basic parameters given by Eqs. (5.43)–(5.45) are smaller in proportion with this amount. The curves supplied by the manufacturers for the actual head, power consumption, and feed rate of the centrifugal pumps are known as the characteristic curves specific for that pump. Examples of these curves are shown in Fig. 5.26.

(1) ***Head-rate curve*****:** This is the first pump characteristic curve which is also known as head-flow rate or head-capacity curve. When the angular velocity $v_{\theta S}$ in the theoretical pump head relation given by Eq. (5.44) is expressed in terms of the radial velocity v_{rS} which is equal to Q/A_p by Eq. (5.45), it is clear that the theoretical or virtual head decreases linearly with the rate Q. On the other hand, the actual pump head is obviously less than the theoretical head and decreases with an increasing rate toward zero as the flow rate is increased. Zero head is the maximum possible flow rate a pump can supply, which necessitates that the suction head should be equal to the discharge head. Therefore, under ordinary or normal conditions volumetric capacity of a pump is below this value.

The first reason for the actual head to be less than the virtual is the circulation of the fluid at the tip of the impellers. Additionally, frictional loss due to the flow of the fluid on the surfaces changes in the flow direction of the fluid by hitting walls of the casing after leaving the blades, and the circular path it has to follow till the exit are sources for the extra energy losses. For a centrifugal pump as the frictional loss increases with the rate, the losses due to the others are at a minimum when the pump is operated at the optimum rate. Further, the physical properties of the fluid, i.e., viscosity and density also affect the pump head. When viscosity increases the frictional loss increases which in turn causes a faster decrease in the head with an increasing rate. On the other hand, though the density of the fluid has no effect on the head the power supplied by the pump is directly proportional to it.

$$\Delta P_{\text{A}} = \rho \Delta h_{Ws}/g_c \tag{5.46}$$

Accordingly, when the discharge pressures of two liquids one having a density of 900 kg/m^3 and the other 1100 kg/m^3 are compared for identical heads, pressures shall be 0.9 and 1.1 times that of water. The characteristic curves supplied by the pump manufacturers are for water unless it is a special order hence correction for viscosity is necessary (Holland and Chapman, 1966). Also, Eq. (5.46) indicates that for gases like air having densities in the order of about one-thousandth of that of water, the centrifugal pumps can develop pressures in this proportion compared to water. In fact, a centrifugal pump may need priming if it is initially full of air because the pressure developed by the pump is reduced in the ratio of the density of air to that of the liquid, which is mostly insufficient to transfer the liquid to the delivery line.

The head-rate curve for a centrifugal pump in any system has one ideal operational point. This point is located at the intersection of the characteristic head-rate and the operational head-rate curves. In other words, the operational point is at the intersection of the characteristic head-rate curve of the pump with the operational curve given by Eq. (5.48). It is also desired to have this point at the rate corresponding to the maximum efficiency of the pump, i.e., duty point. Fig. 5.26A illustrates how the characters and the operational curves are combined for assessment and decision.

The head-rate curve for the operational or system conditions is obtained by substituting Eqs. (5.35) and (5.36) into Eq. (5.34). and expressing the average velocities in terms of volumetric rate divided by the cross-sectional area $<v>=4Q/\pi d_i^2$.

$$\Delta h_{Ws} = \left[\frac{Pg_c}{\rho g} + \frac{\alpha < v>^2}{2g} + z\right]_D + \frac{g_c}{g}2f\left\{\frac{\left(L_D + \sum L_{eD}\right) < v_D>^2}{d_{iD}} + \frac{\left(L_S + \sum L_{eS}\right) < v_S>^2}{d_{iS}}\right\} - \left[\frac{Pg_c}{\rho g} + \frac{\alpha < v>^2}{2g} + z\right]_S \tag{5.47}$$

If the pipe diameters on both the suction and the discharge sides are the same then the total pipe length L_T shall be $L_S + L_{D,}$ and also the equivalent length of the valves and the fittings on the line can be taken as ΣL_{eT} (Eq. 5.47). Further, because for an incompressible fluid the velocity head terms at the inlet and the exit shall be canceling each other for the system described, the work head required can be simplified as

$$\Delta h_{Ws} = \left[\frac{g_c(P_{out} - P_{in})}{\rho g} + (z_{out} - z_{in})\right] + \frac{g_c}{g}2f\left\{\frac{\left(L_T + \sum L_{eT}\right)}{d_i}\right\}\left[\frac{4Q}{\pi d_i^2}\right]^2 \tag{5.48}$$

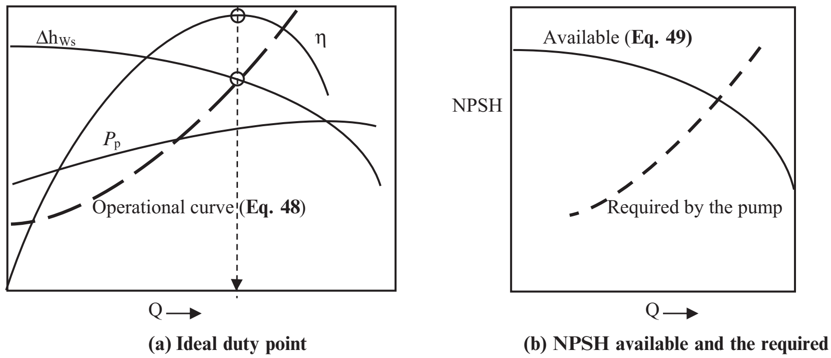


FIG. 5.27 Effect of the rate on: (a) characteristic properties of the pump and (b) NPSH.

This result indicates that the system head varies with the square of the volumetric flow rate provided the assumptions and the simplifications are valid and NPSH is positive. In case NPSH is negative the relation shall be invalid especially due to the cavitation effect.

The NPSH available to the pump also varies with the square of the rate like the operational curve. When Eq. (5.37) or (5.38) is written for the suction side from the pipe to the pump inlet accounting for the energy losses by friction and fittings but with the assumption of no change in velocity the result is Eq. (5.49). Again this shows a decrease in available NPSH with the square of the volumetric rate as shown in Fig. 5.27B.

$$\text{NPSH} = z_{in} + \frac{\left(P_{in} - P_L^0\right)}{\rho g} - \frac{g_e 2f}{g}\left(\frac{L_S + \sum L_{eS}}{d_{iS}}\right)\left(\frac{4Q}{\pi d_{iS}^2}\right)^2 \tag{5.49}$$

The important fact implied by these results is the possibility of operation of a centrifugal pump when the available NPSH is below the rate of the required NPSH. As a common practice in the systems with a centrifugal pump, a valve

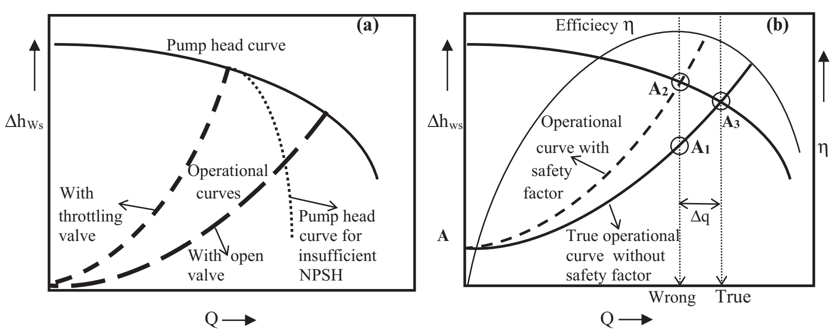


FIG. 5.28 A centrifugal pump: (a) insufficient NPSH and throttling and (b) wrong decision.

is placed after the discharge side of the pump. By throttling this valve the energy loss head due to friction shall be increased by the increase in ΣL_{eD} and hence the slope of the operational curve will be increased. It is clear from Fig. 5.28A that this also reduces the effect of cavitation. If higher rates are used the pump head shall drastically decrease vertically, which would force the pump to work under cavitation conditions.

As can be seen for the correct selection of a centrifugal pump for an assigned rate it is very important to correlate the operational head of the system with the pump-head characteristic of the pump obtained from the manufacturer. Therefore, the final remark on this subject shall be about a possible error that can be made in the pump selection.

One of the basic principles of design is making an allowance or adding an extra value as a **safety factor** to account for the assumptions made in the calculations, possible future expansions, loss of efficiency due to wear, etc. Such an attempt may result in an unsatisfactory solution when a pump is being selected for an operational head duty. In the calculation of the operational head the item of prime importance is to use valid and reliable data as much as possible and not to use any safety factor. The reason for this is shown in Fig. 5.28B and explained below.

As an example, variation of the operational head with the rate of a system is obtained using the available valid data in the most realistic way. This variation is the curve AA_1A_3 for which the duty point corresponds to A_3. However, just for the sake of being on the safe side when the determined values are increased by multiplying with a certain safety factor, the operational head curve becomes AA_2 for the desired rate corresponding to that at point A_1. Thus, the pump selected to operate with maximum efficiency for this rate shall be required to operate at a rate "**Δq**" higher than that corresponding to A_1 because the pump-head curve would intersect the true operational curve AA_1A_3 at A_3. As a result of this wrong selection, the pump would operate at lower efficiency and overloaded causing greater energy loss and wear.

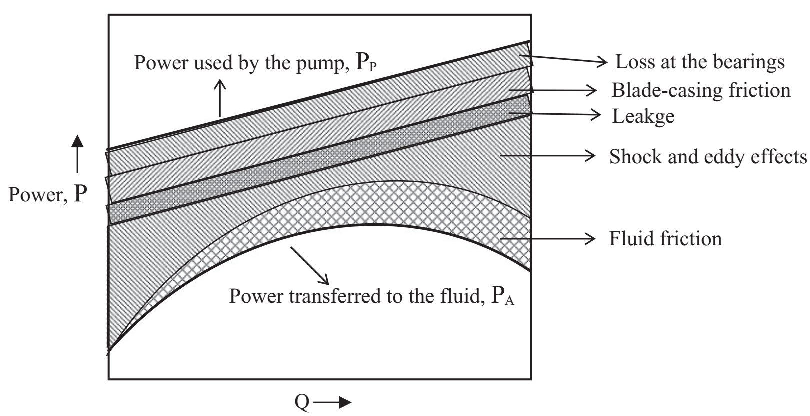


FIG. 5.29 Consumption of the power supplied to the pump.

(2) *The power-rate curve*: The difference between the powers transferred to the fluid and consumed by the pump is as given in Fig. 5.27B. The power loss is due to leakage, eddies formed behind the blades, fluid friction on the blades and the casing, shock, and bearings (Fig. 5.29). Loss by leakage is because an inevitable amount of fluid escapes to the back of the blades forming eddies as well and decreasing the volumetric rate. On the other hand, the stuffing box, the glands, or the gaskets of the bearings are placed tightly around the rotating shaft

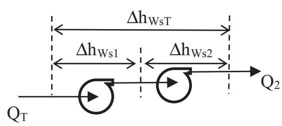
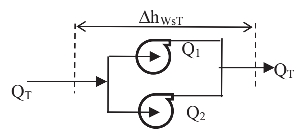
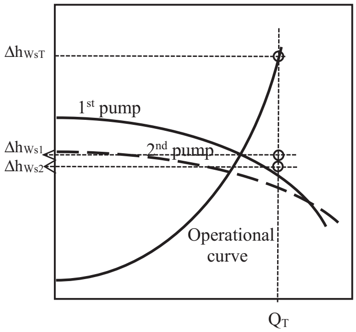
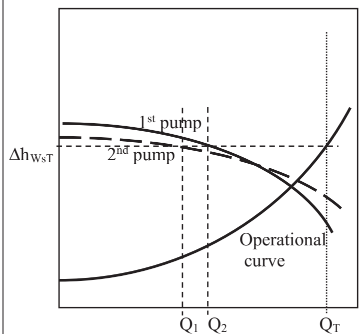
	Two pumps in series	**Two pumps in parallel**
		
Work head **Rate**	$\Delta h_{WsT} = \Delta h_{Ws1} + \Delta h_{Ws2}$ $Q_T = Q_1 = Q_2$	$\Delta h_{WsT} = \Delta h_{Ws1} = \Delta h_{Ws2}$ $Q_T = Q_1 + Q_2$
		
Method	I. Trial and error: Intersection point of the vertical through Q_T and the operational curve yields the total work head required on the ordinate. This value must be provided by the sum of the heads of the two pumps at Q_T. If not the procedure is repeated with new pumps. II.Graphical: A number of verticals are drawn at different rates to intersect the head curves of the two pumps and the sum of the Δh_{Ws1} and Δh_{Ws2} values for each is found as Δh_{WsT}. These are then plotted versus the rates and intersection at the desired rate is the solution.	I. Trial and error: A horizontal line is drawn from the work head required Δh_{WsT} to intersect the head curves of the two pumps and the operational curve. If the sum of the corresponding Q_1 and Q_2 for the pumps is equal to Q_T then the solution is complete. Otherwise, the procedure should be repeated with new pumps. II.Graphical: At different values of the total work head required horizontal lines are drawn to intersect with the head curves of the pumps. The sum of the rates Q_1 and Q_2 versus Δh_{WsT} is plotted to determine the intersection at the desired Q_T on the operational curve.

FIG. 5.30 Solution for two pumps in series and in parallel.

thus are sources of work-energy loss. This work-energy loss due to the friction is converted to heat energy causing heating up of the pump and its parts.

(3) *Efficiency-rate curve*: The curve shown in Fig. 5.27C is a general variation for the ratio of the power transferred to the fluid P_A to that used by the pump P_P, Eq. (5.50) with the volumetric rate Q.

$$\eta = \mathcal{P}_A/\mathcal{P}_P \tag{5.50}$$

On the labels of the pumps $\mathcal{P}_P$ value is generally specified as horsepower ***hp***. Therefore, in order to make a selection primarily the product of the work head and mass rate should be divided by the efficiency to convert it to the power of the pump by using Eq. (5.44) or (5.50).

$$\mathcal{P}_P = \mathcal{P}_A/\eta = \frac{\dot{m}\Delta h_{Ws}}{\eta} \tag{5.51}$$

Centrifugal pumps are mostly driven by electrical motors. These motors also consume some fraction of the electrical energy input to overcome their internal losses, which may be in the order of 2%–25% depending on the power rating of the motor. If cost analysis has to be made the efficiency of the motor must be included in the power consumption.

$$\text{Electrical power consumed}: \mathcal{P}_E = \mathcal{P}_A/\eta\eta_e = \frac{\dot{m}\Delta h_{Ws}}{\eta\eta_e} \tag{5.52}$$

Other useful information besides the characteristic properties which must be known about the centrifugal pumps are briefly discussed below.

(I) Priming: Priming is an important situation met when a liquid pump is kept idle for some time or right after the installment of a new pump as once mentioned above. According to Eq. (5.44), the theoretical head that can be developed by a centrifugal pump is proportional to the radius and the rotational speed of the blades. In other words, the head developed being independent of the fluid properties shall not change unless the radius, rotational speed, and the feed rate are changed. This misleading interpretation can be corrected by Eq. (5.46). Considering a pump that can provide a 10-m head can generate a pump inlet-discharge pressure difference of $10 \times 1000 \times 9.81 = 98.1$ kPa when it is pumping water. However, when the pump body and the inlet zone to the pump are filled with air at the ambient conditions, this difference shall only be around 0.1 kPa. A centrifugal pump can neither make suction nor discharge under such a pressure difference. Therefore, for the pump to operate either air within the pump should be replaced with water by a priming-water tank connected to the pump inlet, or a pump equipped with a self-evacuation system should be used.

(II) The affinity laws for centrifugal pumps: Starting from the theoretical equations relations between the centrifugal pumps with respect to pressure, rate, head, and NPSH can be derived from the known values of a pump through the affinity laws. For this process Eqs. (5.43)–(5.45) and continuity equation are sufficient.

With the aid of Fig. 5.25C if the angle "β" between the velocity vectors is around 90° then $\tan\beta \approx \infty$ and $\sin\beta \approx 1.0$ and from the trigonometric relations it is possible to take $v_{\theta S} = v_{rS} = v_{tC} = r_S\,\omega$. Now, if the area A_p and v_{rS} in Eq. (5.45) are expressed using the consideration above,

$$Q = v_{rS}A_p = C_1 r_S^3 \omega \tag{5.53}$$

In a similar way, the power transferred to the fluid given by Eq. (5.43) if the mass rate is substituted as the product of the volumetric rate and the density and further the volumetric rate is substituted from Eq. (5.52) the relation sought for the power shall be obtained. It is equally possible to achieve this result through dimensional analysis.

$$\mathcal{P}_{\mathrm{A}} = \rho Q r_S v_{\theta S}\omega = C_2 \rho r_S^5 \omega^3 \tag{5.54}$$

When the same procedure is applied for the work head and the NPSH by using Eqs. (5.44) and (5.53) with Eq. (5.39)

$$\Delta h_{Ws} = C_3\, {r_S}^2 \omega^2 \tag{5.55}$$

$$\mathrm{NPSH} = \mathrm{C}_4\, {r_S}^2 \omega^2 \tag{5.56}$$

It is quite useful to be able to write the characteristic properties of a pump in terms of the radius and the rotational speed of a centrifugal pump for the correlation of two **homologous** pumps with correct results. That is if an existing

TABLE 5.6 Affinity law relations for homologous centrifugal pumps.

Pump	Only diameter change	Only velocity change	Diameter and velocity change
Identical	$Q_2 = Q_1\,(D_2/D_1)$ $\mathcal{P}_{A2} = \mathcal{P}_{A1}(D_2/D_1)^3$ $\Delta h_{Ws2} = \Delta h_{Ws1}\,(D_2/D_1)^2$	$Q_2 = Q_1\,(\omega_2/\omega_1)$ $\mathcal{P}_{A2} = \mathcal{P}_{A1}\,(\omega_2/\omega_1)^3$ $\Delta h_{Ws2} = \Delta h_{Ws1}\,(\omega_2/\omega_1)^2$	$Q_2 = Q_1\,(D_2/D_1)\,(\omega_2/\omega_1)$ $\mathcal{P}_{A2} = \mathcal{P}_{A1}[(D_2/D_1)(\omega_2/\omega_1)]^3$ $\Delta h_{Ws2} = \Delta h_{Ws1}[(D_2/D_1)(\omega_2/\omega_1)]^2$
Homologous	–	–	$Q_2 = Q_1\,(D_2/D_1)^3\,(\omega_2/\omega_1)$ $\mathcal{P}_{A2} = \mathcal{P}_{A1}(D_2/D_1)^5\,(\omega_2/\omega_1)^3$ $\Delta h_{Ws2} = \Delta h_{Ws1}[(D_2/D_1)(\omega_2/\omega_1)]^2$

Q_1, $\mathcal{P}_{A1}$, Δh_{Ws1}, D_1, and ω_1: The known characteristic parameters for the pump at hand.
Q_2, $\mathcal{P}_{A2}$, Δh_{Ws2}, D_2, and ω_2: The characteristic properties of the new pump for its diameter and velocity.

pump of known characteristic properties is to be replaced with another pump having different characteristic properties or for small changes in the blade size and rotational speed the characteristic properties of the new pump can simply be obtained by proportionate. These relations are as given in Table 5.6.

Also, another relationship that can be used to classify the centrifugal pumps is the **specific speed** N_s which is a constant value calculated from the volumetric rate corresponding to the maximum efficiency of the pump. It is calculated by expressing the rate at the maximum efficiency in US gallons/min (=4.4 m^3/h), rotational speed as rpm, and head as feet and has the dimensions $(L/t^2)^{3/4}$. When Eq. (5.53) is solved for the radius r_S (or diameter D_S) and put in Eq. (5.55) and arranged for the ratio of the coefficients,

$$\frac{\omega^2 Q}{\Delta h^{3/2}} = \frac{C_1}{C_3^{3/2}} = \text{constant}$$

$$N_S\ \left(\text{ft}/\min^2\right) = \frac{\omega\sqrt{Q}}{\Delta h^{3/4}} \tag{5.57}$$

Example 5.3 It is planned to replace a curved-blade centrifugal pump having 20 cm blade diameter, 60 rpm rotational speed which when operating at a rate of 0.012 m^3/s at its maximum efficiency can supply a work head of 70 m, under an NPSH of 18 m by consuming 12,000 W power. Determine the characteristic properties of the two alternatives considered:

(a) A pump with a blade diameter 5 cm longer than the existing one,
(b) A homologous pump with about double the blade size but with the rotational speed halved.

Solution: If subscripts "1" and "2" are used for the existing and the new pumps
(a) When only the diameter of the pump is changed:
Blade diameter ratio: $(D_2/D_1) = 25/20 = 1.25$.

From Table 5.6: Only diameter change relations:

$$Q_2 = Q_1\ (D_2/D_1) = \left(0.012\,\text{m}^3/\text{s}\right)\ 1.25 = 0.015\,\text{m}^3/\text{s}$$

$$\mathcal{P}_{A2}/\mathcal{P}_{A1} = P_{P2}/P_{P1} = (1.25)^3 \Rightarrow \mathcal{P}_{P2} = 1.95\mathcal{P}_{P1}$$

$$\mathcal{P}_{P2} = (12\,000\text{ W})\ (1.95) = 23\,437.5\text{ W}$$

$$\Delta h_{Ws2} = \Delta h_{Ws1}\ (D_2/D_1)^2 = (70\text{ m})(1.25)^2 = 109.375\text{ m}$$

$$\text{NPSH}_2 = \text{NPSH}_1\ (D_2/D_1)^2 = (18\text{ m})(1.25)^2 = 28.125\text{ m}$$

(b) When changed with a homologous pump:
Rotational speed ratio of the blades: $(\omega 2/\omega 1) = ½$.

Blade diameter ratio: $(D_2/D_1) = 2$

From Table 5.6: Homologous pumps:

$$Q2 = Q1\ (D_2/D_1)^3\ (\omega_2/\omega_1) = \left(0.012\ m^3/s\right)\ (2)^3(1/2) = 0.048\ m^3/s$$

$$\mathcal{P}_{A2}/P_{A1} = (D_2/D_1)^5\ (\omega_2/\omega_1)^3 = (2)^5(1/2)^3 = 4$$

$$\mathcal{P}_{A2}/\mathcal{P}_{A1} = \mathcal{P}_{S2}/\mathcal{P}_{S1} \Rightarrow \mathcal{P}_{S2} = 4\mathcal{P}_{S1} = 4x12000\ W = 48\ 000\ W$$

$$\Delta h_{Ws2} = \Delta h_{Ws1}\ [(D_2/D_1)(\omega_2/\omega_1)]^2 = (70\ m)[(2)(1/2)]^2 = 70\ m$$

$$NPSH_2 = NPSH_1\ (1) = 18\ m$$

(III) Two pumps in series or parallel: In some systems, two identical or different centrifugal pumps are installed either in series or parallel depending on the requirement of the duty. In the first case, the discharge from the first pump is fed to the inlet of the second pump whereas in the second arrangement the feeding is made to both pumps and their discharges are combined. Using simple graphical methods the characteristic properties of the system can be obtained from the characteristic properties of the pumps as explained below.

To start with the first rate vs the work head characteristic curves of the two pumps and the operational curve of the system for the desired rate are plotted against the rate. The work head that must be provided by the pumps is placed on the plot as a horizontal line. The following work depends on whether the pumps are arranged in series or parallel. In Fig. 5.30 these two cases are presented.

When the pipes and the valves are arranged in the required order it is possible to have two centrifugal pumps operating in series or in parallel as illustrated above. The pumps may have different characteristic properties as shown in the figure or can be identical. In the latter case, of course there shall be only one work head curve in both cases. Also, when the pumps are arranged in series the total work head Δh_{WsT} for the rate Q_T shall be 2 Δh_{Ws} and when arranged as parallel the rate shall be 2Q for the total head Δh_{WsT}.

(IV) Multistage centrifugal pumps: It is the clear from the above discussion that when two pumps are arranged in series the resulting total work head is going to be greater. A single normal pump is capable of providing a head of 30 m, which can go up to about 200 m in special designs. For this reason, in systems where more than 30-m head is needed multistage centrifugal pumps are used. A multistage centrifugal pump consists of a number of stages in series wherein for each compartment a centrifugal pump driven by the same rod extending through the stages is present. The feed entering into the first compartment is transferred to the successive stages with increasing head after each stage and leaving the final stage at the desired head. As can be understood, the contribution of each stage to the work head is added to the head at the inlet to that stage, thus cumulatively increasing it to about the number of stages times that of a single pump.

5.4.2.2 Gas moving machinery: Fans, ventilators, blowers, and compressors

The equipment used for the transport and compression of gases is classified according to the magnitude of the pressure difference created. In the order of increasing pressure, they are named fans, blowers, and compressors.

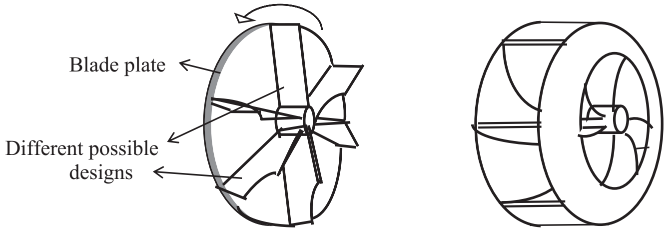


FIG. 5.31 Blade plate and different possible blade designs.

(I) ***Fans and ventilators***: Most of the fans and the ventilators operate on some principle of the centrifugal pumps. The blades may be straight or curved but being convex or concave does not create many vibration problems in the fans or the blowers. Two of the most common designs are shown in Fig. 5.31.

The blade plate and the blades are thin, lightweight metal or plastic materials and depending on the place and aim rotate in a plastic or metal casing. The gaps between the blades largely give a relatively small work head of about 0.15–1.5 m.

For the fans, especially those used for household purposes, a large percentage of the work head created is converted to the velocity head rather than the pressure head. The most important difference between the pumps and the gas moving equipment is the effect of temperature and pressure on the density of the gases. With regard to this fact, in the design of the fans and the ventilators, the gas is practically considered as an incompressible fluid because the change in temperature and pressure is negligible. A label present on the equipment contains its capacity either as standard cubic meters or as a volume unit approved by the related industry and its power mostly in horsepower (hp). In most of the applications, this standard volume corresponds to 23.6 m^3/kg mol at a pressure slightly above 1 atm, 1.003 atm (101.6 kPa), and at 15°C. Therefore, in the selection of a suitable fan or ventilator, the first step is the conversion of the environmental conditions to the standard volume.

Example 5.4 A modified atmosphere cold storage room with dimensions of $5 \times 5 \times 3$ m is to be kept at 0°C and 100 kPa pressure. The continuous air circulation system to be installed is required to have a capacity of circulating the storage room volume six times per hour with the modified air. Determine the capacity of the fan in m^3/min and the power that shall be consumed by the fan if it discharges the gas at 105 kPa with a velocity of 50 m/s when operating with 65% efficiency.

Solution: First it is required to calculate the volume of the room as it shall be the per hour modified air rate to be fed at standard conditions. With the assumption that the modified air behaves ideally at this temperature and pressure,

Volume of the room $= (5 \times 5 \times 3)\ m^3 = 75\, m^3$.

$$\text{Standard volume} = 75\ \text{m}^3 \left(\frac{100\ \text{kPa}}{101.6\ \text{kPa}}\right)\left(\frac{(273+15)K}{(273+0)K}\right) = 77.875\,\text{m}^3.$$

$$\text{Capacity required from the fan} = \frac{77.875\text{m}^3}{(1/6)\text{h}}\ \frac{1\text{h}}{3600\text{s}} = 0.1298\frac{\text{m}^3}{\text{s}} = 7.79\frac{\text{m}^3}{\text{min}}.$$

The power supplied to the air would be calculated from the work head using Eq. (5.47). As there is no frictional energy loss due to flow in pipes, negligible change in the potential energy between in-out points of the fan, and negligible inlet velocity with the kinetic energy correction factor at the discharge $\alpha \approx 1.0$, the equation can be simplified to

$$\Delta h_{Ws} = \left[\frac{(P_D - P_S)g_c}{\rho g} + \frac{\alpha\left(v_D^2 - v_S^2\right)}{2g}\right] = \left[\frac{(P_D - P_S)}{\rho g} + \frac{v_D^2}{2g}\right]$$

The only unknown factor in this equation is the density, which can be calculated either at the average conditions or taking the average of the values at the inlet and the exit. For illustration purposes, if the second alternative is used, then density of the modified air at the fan inlet would be

$$\rho_S = \frac{P_S M_A}{RT} = \frac{M_A}{V_{std}}\left(\frac{P_S}{P_{std}}\right)\left(\frac{T_{std}}{T_S}\right)$$
$$= \left(\frac{29}{23.6}\frac{\text{kg}}{\text{m}^3}\right)\left(\frac{100}{101.6}\right)\left(\frac{288.15}{273.15}\right) = 1.276\frac{\text{kg}}{\text{m}^3}.$$

The density of the modified air at the discharge of the fan (only pressure correction is required) would be

$$\rho_D = 1.276\left(\frac{105}{100}\right)\frac{\text{kg}}{\text{m}^3} = 1.340\frac{\text{kg}}{\text{m}^3}$$

Average density, $< \rho >= \dfrac{1.340 + 1.276}{2} = 1.308\dfrac{\text{kg}}{\text{m}^3}$

Mass rate of flow, $\dot{m} = \left(0.1296\dfrac{\text{m}^3}{\text{s}}\right)1.308\dfrac{\text{kg}}{\text{m}^3} = 0.1695\dfrac{\text{kg}}{\text{s}}$

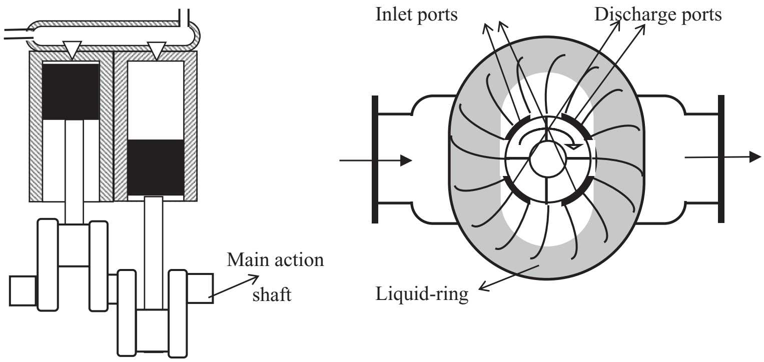
Power to the air, $\mathcal{P}_\text{A} = \dot{m}\left(\dfrac{W_s}{m}\right)\dfrac{g_c}{g} = \dot{m}\Delta h_{Ws}$

$$= 0.1695\left[\frac{(105 - 100)1000}{1.308(9.81)} + \frac{50^2}{2(9.81)}\right]W = 86.88\text{ W}$$

Power used by the pump, $\mathcal{P}_\text{T} = 86.88/0.65 = 133.66\text{ W} = 0.18\text{ hp}$ $(1\text{ hp} = 745\text{ W})$

As can be seen from the example the fan does not creating any appreciable difference in either the pressure or the density.

(II) *Blowers and compressors*: Again these gas moving equipment are not much different from those used for liquids except for some structural details. These differences are especially because the densities and viscosities of gases are much smaller than that of liquids. At ordinary pressures densities of gases are about a thousand times smaller than that of liquids, which necessitate the



a) Single–stage double action compressor. **b) Nash-Hytor compressor.**

FIG. 5.32 Piston and Nash-Hytor type compressors.

gas moving machinery to operate at higher rotational speeds. On the other hand, the clearances and the tolerances between the moving parts are much smaller to minimize leakage owing to the low viscosity of the gases. An additional feature is provisions for cooling as a consequence of the rise in temperature of the gas due to compression. Especially, because of this last condition when attainment of high pressures is required multistage compressors with interstage cooling facilities are used. Further, in the piston-cylinder type compressors at the end of the compression, a certain amount of gas is inevitably trapped at the end of the piston, and with the commencement of the suction period, this expands and remains in the cylinder reducing the efficiency.

Blowers and compressors are again designed as either positive displacement or centrifugal. The principal ones are given below.

(A) Positive displacement compressors: According to the mechanism used they are either reciprocating or rotary type.

(i) In the reciprocating compressors a piston moving in a cylinder enables suction and discharge actions. Identical to the internal combustion engines on a crankshaft more than one piston can be present (Fig. 5.32A). Because the speed is not very high, for high-pressure requirements centrifugal compressors should be preferred. One of the most important points in the design is the adjustment of the clearance between the surfaces at the tip of the piston and the gas discharge end of the cylinder. When this volume is even slightly greater than necessary the equipment would fail in attaining the desired pressure and operate at a lower efficiency. On the other hand, when the clearance is not enough the tip of the piston may hit the cylinder's discharge surface. Further, in multistage designs, it is possible to feed the discharge of a stage successively to the inlet of the next stage. With multistage reciprocating compressors very high pressures of around 350 MPa can be achieved. However, owing to the increase in the temperature of the gas interstage coolers using mostly circulating water must be present. As a consequence of cooling in each intercooling stage around 3%

decrease in the pressure is normal. The efficiency of these compressors is in the range 70%–90%.

(ii) The rotary compressors are considered in two groups according to their compression ratios as high and low. Examples of the two groups are the sliding vane for the first and the Lobo type (Rootes blower) for the second (see Fig. 5.23). Of course, for gases, the clearances and the glands are much tighter where a version of the sliding vane pumps is Nash-Hytor compressor (Fig. 5.32B) in which a liquid ring is present around the blades.

The work that must be done on gas by a blower or a compressor according to isothermal, adiabatic (constant entropy), or polytropic processes with the assumptions of ideal behavior, reversible process (no friction) are (Smith, 1950):

$$\text{Isothermal compression}: \frac{W_s}{\dot{m}} = \frac{RT}{M_S} \ln \frac{P_D}{P_S} \tag{5.58}$$

$$\text{Adiabatic compression}: \frac{W_s}{\dot{m}} = \left(\frac{\gamma}{\gamma - 1}\right) \frac{P_S}{M_S \rho_{MS}} \left[\left(\frac{P_D}{P_S}\right)^{(\gamma-1)/\gamma} - 1\right]; \gamma = C_p/C_v \tag{5.59}$$

$$\text{Polytropic compression}: \gamma \text{ in Eq.(5.59) is changed with } k = \frac{\ln(P_D/P_S)}{\ln(\rho_D/\rho_S)}; (1 < k < \gamma). \tag{5.59a}$$

Relations given above are "+" for the work done by the compressor. Utilizing them the power transferred to the gas can be calculated. If the volumetric rate of the gas at 273.15 K and 101.3 kPa is Q_o and its mass rate is replaced by its molar density ρ_{MS} (kgmol/m^3) and its molecular weight is M_S with the compressor efficiency "η" the equations become

$$\text{Adiabatic}: \mathcal{P}_A \text{ (kW)} = \frac{1.97 T_S Q_0}{M_S \eta} \ln \frac{P_D}{P_S} \tag{5.61}$$

$$\text{Isothermal}: \mathcal{P}_A \text{ (kW)} = \frac{0.371 T_S \gamma Q_0}{(\gamma - 1) M_S \eta} \left[\left(\frac{P_D}{P_S}\right)^{(\gamma-1)\gamma} - 1\right] \tag{5.62}$$

The efficiency of a compressor is defined for either isothermal or adiabatic operation. Therefore, it can be calculated from the ratio of the ideal work determined from Eq. (5.58) or (5.59a) to the actual work for a single-stage compressor. However, in large compressors, neither isothermal nor adiabatic compression can be achieved. The polytropic path is followed where $P_S/P = (\rho_S/\rho)^k$ and from the pressures and densities at the suction and at the discharge points specific value of the "k" is determined.

The expressions presented for both the work and the power are on the basis of ideal gas behavior and reversible process and thus for real gases, it can be recommended to use at least the compressibility factor **Z**. To estimate the power and the work required tables and charts prepared according to this approach are given below.

On the label of any blower or compressor, its capacity is given as "… Nm^3/h" according to national or international standards, which is for the suction side. Therefore, as the first task, the conditions prevailing at the location where it shall be used must be converted to that specified by the manufacturer. For this, it is sufficient to take the ratio of the real gas equation for the volumetric capacity with the compressibility factor Z at the two conditions, i.e., manufacturer and the prevailing,

$$\frac{Q_M}{Q_L} = \left(\frac{Z_M}{Z_L}\right)\left(\frac{T_M}{T_L}\right)\left(\frac{P_L}{P_M}\right) \tag{5.63}$$

where subscripts M and L are used for the manufacturer and the location. Additionally, if unit of the capacity given by the manufacturer Q_M is different than that used at the location Q_L then a time conversion factor S like 3600 s/h or 1440 min/day can be introduced.

$$Q_M = (S)Q_L\left(\frac{Z_M}{Z_L}\right)\left(\frac{T_M}{T_L}\right)\left(\frac{P_L}{P_M}\right) \tag{5.64}$$

Eq. (5.64) is frequently used especially in the United States for reciprocating compressors to estimate the power that shall be required to transfer a gas (**Engr. Data Book**, (Natural Gas Processors and Suppliers Association, 1972). In this relation, the power is calculated in *hp* by taking the manufacturer's capacity at 14.4 psia (99.28 kPa) pressure and at the inlet temperature as million cubic feet/day (*MMcfd*).

$$\mathcal{P}_{\mathrm{A}}\ (\mathrm{hp}) = (B)\ (\text{compression ratio in one stage})\ (\text{no of stages})\ (\mathrm{MMcfd})(F) \tag{5.65}$$

TABLE 5.7 Recommended values for B and F in Eq. (5.65).

B (hp)	(c/r)/stage	Specific gravity	F	No. of stages
22	>2.5	0.65	1.0	1
20	>2.5	0.8–1.0	1.08	2
16–18	1.5–2.0	0.8–1.0	1.10	3

where B is a coefficient with the unit of hp depending on the specific gravity of the compressed gas and the compression ratio (c/r) and F is another coefficient accounting for the pressure drop between the stages as given in Table 5.7.

Assignment of pressure as 14.4 psia for *MMcfd* is to have a cancellation in the equation. That is, when the American Engineering System of Units (**V.1** Ch.3**, Table 1.4**) is used for transferring a gas at a rate Q_L ft^3/min and at a pressure P_L and if the inlet temperatures at both locations are taken as equal with the compressibility factor $Z_M = 1.0$ then from Eq. (5.64)

$$MMcfd = Q_M\ \left(\text{million ft}^3/\text{day}\right)$$
$$= Q_L\left(\frac{ft^3}{\text{min}}\right)\left(\frac{1440\text{ min}}{\text{day}}\right)\frac{1}{Z_L}\left(\frac{P_L(\text{psia})}{14.4\,\text{psia}}\right)10^{-6}$$

$$MMcfd = Q_L\frac{P_L}{Z_L}10^{-4}\left(\frac{\text{ft}^3}{\text{day}}\right) \tag{5.66a}$$

In a similar manner, if the operational gas rate is in m^3/h and the local pressure in kPa then the conversion factors 35.318 ft^3/m^3, 24 h/day, and 99.28 kPa for 14.4 psia can be inserted in the equation to calculate *MMcfd*.

$$MMcfd = Q_M\left(\text{million ft}^3/\text{day}\right)$$
$$= Q_L\left(\frac{\text{m}^3}{\text{h}}\right)\left(\frac{35.32\,\text{ft}^3}{\text{m}^3}\right)\left(\frac{24\,\text{h}}{\text{day}}\right)\frac{1}{Z_L}\left(\frac{P_L(\text{kPa})}{99.28\,\text{kPa}}\right)10^{-6}$$
$$MMcfd = Q_M\left(\text{million ft}^3/\text{day}\right) = Q_L\left(\frac{m^3}{h}\right)\frac{P_L(\text{kPa})}{Z_L}\left(8.5378\times10^{-6}\right) \tag{5.66b}$$

The constant on the right-hand side of Eq. (5.66b) has the units (MMcfd.h)/(m^3 kPa) for consistency.

In the professional data books or handbooks, charts displaying the power requirements according to the compression ratio with the ratio of the heat capacities as a parameter could be found.

The capacity of a reciprocating compressor (piston-cylinder) is given by the product of the volume swept in unit time with the piston ***VSP*** and the volumetric efficiency η_{VE} and can be expressed in any unit. In relation form, for a compressor with a single-acting piston having a diameter "*D*" the *VSP* is

$$VSP = (\text{rotational speed of the main shaft})\,(\text{distance covered by the piston})\left(\pi D^2/4\right) \tag{5.67}$$

For a double-acting single piston or single-acting double piston compressor (Fig. 5.32A) the *VSP* above is doubled.

As mentioned at the beginning of this subject, there must be a clearance left at the gas discharge end of the cylinder between the piston and the cylinder surfaces. Due to this clearance capacity of the compressor is reduced and the following relation is proposed for the volumetric efficiency η_{VE}:

$$\%\eta_{VE} = (100 - Y) - (c/r) - CL\left[\frac{Z_S}{Z_D}(c/r)^{1/\gamma} - 1\right] \quad (5.68)$$

If the compressor is of lubricating type Y = 4 and if lubrication is not present then an extra 5% loss is considered. The clearance *CL* is simply expressed as the percentage of the cylinder volume and the compression ratio "c/r" of a stage in a multistage compressor containing "n" stages as the "nth" root of the overall compression ratio P_D/P_S.

$$CL(\%) = [(length\ of\ the\ cylinder) - (distanceswept\ by\ thepiston)/(length\ of\ the\ cylinder)]x100 \quad (5.69)$$

The compression ratio of the *i*th stage:

$$\frac{P_i}{P_{i-1}} = \sqrt[n]{\frac{P_D}{P_S}} \quad (5.70)$$

Example 5.5 In a cold storage establishment modified atmosphere having a composition of 2% O_2, 5% CO_2, and 93% N_2 is fed to the rooms at 2°C at a rate of 300 m^3/h. A two-stage reciprocating compressor with an interstage cooler can increase the pressure of the gas from 0.9 to 8.1 atm. Assuming that the interstage cooler can cool the gas from the stages to the inlet temperature estimate:

(a) The compression ratio and the intermediate pressure for minimum power consumption.
(b) The power consumption if the efficiency of the compressor is 80%.
(c) The cooling load of the cooler in Watts.

Solution: To have a correct follow-up of the system a block diagram representation of the process is drawn (Fig. 5.33.).

(a) For the power to be minimum the inlet temperatures of the fluid to the stages must be equal and performance of the compressor must be adiabatic and reversible. Accordingly when Eq.(5.59a) for each stage is written as $P_S \rightarrow P_{D1}$ and $P_{D1} \rightarrow P_D$ and added for total work of the two stages then it can be differentiated with respect to the intermediate pressure for the minimum.

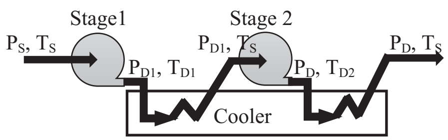


FIG. 5.33 Modified air compression system.

$$\frac{W_s}{\dot{m}} = \left(\frac{\gamma}{\gamma - 1}\right) \frac{P_S}{\rho_{mS} M_S} \left[\left(\frac{P_{D1}}{P_S}\right)^{(\gamma-1)/\gamma} + \left(\frac{P_D}{P_{D1}}\right)^{(\gamma-1)/\gamma} - 2 \right] \tag{5.62}$$

$$\frac{d(W_s/\dot{m})}{d(P_{D1})} = 0 \Rightarrow P_{D1}^{2(\gamma-1)/\gamma} = (P_S P_D)^{2(\gamma-1)/\gamma} \Rightarrow \frac{P_{D1}}{P_S} = \frac{P_D}{P_{D1}} \tag{5.59b}$$

Therefore, for the minimum power the compression ratio must be the same in each stage. Thus, $\frac{P_{D1}}{P_S} = \frac{P_D}{P_{D1}} = \sqrt{\frac{8.1}{0.9}} = 3 \Rightarrow P_{D1} = 2.7$ atm.

(b) First it is required to determine the γ and the Z values of the gas mixture. For an ideal gas $C_p - C_v = R$ and $\gamma = C_p/(C_p - R)$. For a gas mixture, heat capacity can be found from the partial molar contribution of the components. At the inlet temperature molar heat capacities obtained from the charts are (Esin, 2008):

$$C_{pO2} = 29.4; C_{pCO2} = 37.5 \text{ and } C_{pN2} = 29.14 \text{ kJ/kg mol K}$$

$$C_{pMix} = 29.4(0.02) + 37.5(0.05) + 29.14(0.93) = 29.56 \text{ kJ/kg mol K and}$$

$$\gamma = 29.56/(29.56 - 8.314) = 1.39$$

	O_2	CO_2	N_2	Mixture (partial molar contribution)
Mole fraction	0.02	0.05	0.93	
Mol. Weight (kg/kgmol)	32	44	28	28.88
C_p (kJ/kgmol.K)	29.4	37.5	29.14	29.56
T_c (K)	154.4	304.26	126.1	135.57
T_r (reduced)				275/135.6 = 2.028
P_c (MPa)	5.036	7.397	3.394	3.627
P_r (reduced)				91.19/3627 = 0.025
Z_S (at P_r and T_r)				0.98
Molar density (P/RT)				0.04 kgmol/m^3

Using these data the power can be calculated in alternative ways.

(i) Using Eqs. (5.65) and (5.66) and Table 5.7:

$$\text{MMcfd} = (300)\,(91.19)\,\left(8.5378\text{x}10^{-6}\right)/0.98 = 0.238 \text{ million ft}^3/\text{day}$$

$$\mathcal{P}_A\,(\text{hp}) = (20)\,(3)\,(2)\,(0.238)(1.08) = 30.845 \text{ hp}$$

(ii) Eq. (5.59b):

$$\frac{W_s}{\dot{m}} = \left(\frac{1.39}{0.39}\right)\frac{91.19}{(0.04)(28.88)}\left[2(3)^{(\gamma-1)/\gamma} - 2\right]\left(\frac{100}{80}\right) = 266.05\frac{kJ}{kg}$$

$$\mathcal{P}_{\mathrm{A}}\ (\mathrm{hp}) = (266.05)\ [(300)(1.1)/3600]/(0.745\ \mathrm{kW/hp}) = 32.73\ \mathrm{hp}$$

(iii) When solving by using the "ii" way a 3% loss in the pressure to the second stage is considered.

As can be seen, the results above are very close to each other where an efficiency of 85% instead of 80% or a value of 21 for coefficient B renders them about identical.

(c) The heat load of the cooler shall be calculated from the enthalpy balance for which primarily the temperature of the discharges from the stages must be determined. Assuming adiabatic system and hence the thermodynamic relation together with Eq. (5.70),

$$\frac{P_{D1}}{P_S} = \frac{P_D}{P_{D1}} = \left(\frac{T_{D1}}{T_S}\right)^{\gamma/\gamma-1} = \left(\frac{T_{D2}}{T_S}\right)^{\gamma/\gamma-1} \Rightarrow$$

Discharge temperatures from the stages: $T_{\mathrm{D1}} = T_{\mathrm{D2}}$

$$T_D = (275)(3)^{0.39/1.39} = 374.05\,K$$

Enthalpy change (Esin, 2008), $\Delta H = 2\,\dot{m}\int_{T_S}^{T_{D1}} C_p dT \geq \Delta H = 2\,\dot{m}\left(\sum \overline{C}_P\right) dT$

$$= 2(300/3600)\ (0.04)\ [29.66 + 38.73 + 29.19][374 - 275]\ \mathrm{kW}$$

Cooling load $= \Delta H =$ 64.4 kW.

This result is valid under the assumptions of adiabatic cooler and compressor hence no heat transfers to the system from the surroundings.

(A) Centrifugal blowers and compressors: These machines using the principle of conversion of kinetic energy to pressure energy with multistage and intercooling can reach up to 40 MPa pressure and 140 m^3/s rates. In their manufacture, delicate and utmost engineering are utilized to provide their most important operational and existence property of the leakproof structure. Therefore, sufficient lubrication of the glands and rotating parts are the most necessary condition for this requisite to be realized.

Depending on the number of the stages gas rates in the range of 850–350,000 m^3/h at the suction side are possible in the industry. In the low rate values of this range reciprocating and in the high rates positive displacement equipment challenges the centrifugal compressors necessitating a detailed comparative study on the operational and the fixed costs of the alternatives. For this, just like the centrifugal pumps, the characteristic property curves of the centrifugal compressors must be known. Just for a comparison, the characteristic head-volumetric rate of the three types of compressors is shown in Fig. 5.34A.

Basically, the performance of centrifugal compressors outside their design range is quite identical to those of the affinity laws of the centrifugal pumps given in Table 5.6. As shown in Fig. 5.34B when operated at speeds different than that

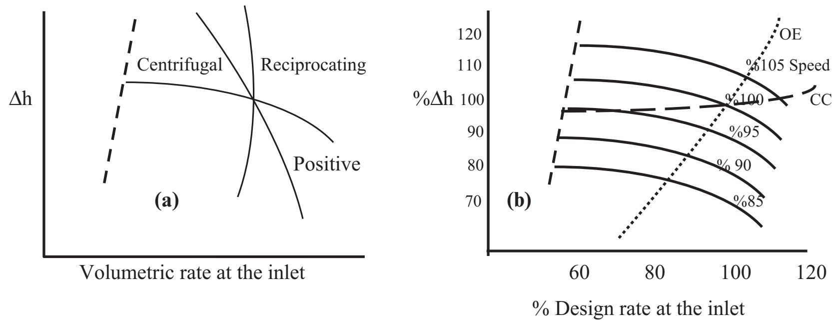


FIG. 5.34 The characteristic head curve of centrifugal compressors: (a) comparative and (b) rotational speed.

of the design value in percentage, the characteristic head curve may appear above or below the design (100%) value in proportion with the square of the ratio of the speeds. The curves OE and CC are the operational curves for the open-ended and closed-cycle conditions. Examples are the natural gas pipeline for the first and the refrigerant gas circulation in the refrigerator for the second.

The relations to be used for the centrifugal compressors are identical to those used for the positive displacement types. For reversible adiabatic operation the theoretical head that must be developed by the compressor is again given by Eq. (5.59a) in which P_S/ρ_{MS}, the term can better be approximated by $Z_{ave}RT$ where Z_{ave} is the average compressibility factor at the inlet and the exit conditions (Eq. 5.71). For polytropic compression, it should be kept in mind that "k" should be used for "γ" and divided by the efficiency "η" for the actual consumption.

$$\frac{W_s}{\dot{m}} = \left(\frac{\gamma}{\gamma-1}\right)\frac{Z_{ave}RT}{M_S\eta}\left[\left(\frac{P_D}{P_S}\right)^{(\gamma-1)/\gamma} - 1\right] \tag{5.71}$$

This relation accounts only for the work-energy that must be used to compress the gas and does not consider the frictional energy consumed by the compressor itself. The efficiencies of the centrifugal compressors are in the order of 60%–90% and the number of stages is governed by the head to be developed and the molecular weight of the gas. Under ordinary conditions, it is recommended to take this loss as 50 hp. (Natural Gas Processors and Suppliers Association, 1972).

The temperature of the gas discharged from the compressor for an adiabatic and reversible system by inclusion of the efficiency is given by

$$T_D = \frac{T_S}{\eta}\left[\eta + \left(\frac{P_D}{P_S}\right)^{\gamma-1/\gamma} - 1\right] \tag{5.72}$$

For polytropic compression (pc) if the efficiency is "η_{pc}," again the relation $k/(k-1) = [\gamma/(\gamma-1)]\eta_{pc}$ is used in the relation above.

The two extreme problems encountered with the centrifugal compressors are **surge** or **knocking** and **balking** or **choked flow**. Of these, surge is the consequence of inadequate pressure development to overcome the resistance on the discharge side or may be due to the unsteady behavior of the blades caused by insufficient feeding as a result of which intermittent backstrokes are created. Eventually, the compressor becomes overheated and if urgent precautions are not taken glands, bearings, and shaft may be seriously harmed. Balking or choked flow is caused by unsteady feeding and unless corrected the compressor cannot supply the desired head.

To avoid the failures shortly mentioned above or for precautions to be taken it is required to continuously control the temperatures and pressures of the gas at the inlet, interstage, and discharge as well as feed rate of the gas, rotational speed, and the power consumption of the compressor.

(III) ***Vacuum-creating equipment*****:** In systems where the pressure must be below 1 atm the equipment capable of sucking air or gas in the system and discharging it to the surroundings must be present. The vacuum-creating equipment sucks low-pressure gas in large volumes and discharge it at environmental pressure. As observed from this point of view, the rotary type vacuum pumps are preferred to the piston types. Also, **steam-jet ejectors** are widely used in the industry because they do not contain any moving parts and have high gas capacities.

The most commonly used rotary vacuum equipment are sliding vane or Nash-Hytor type with liquid sealing rings. It is possible to reach a pressure of about 1.3 Pa with the former types which is about 3.5 Pa with the latter most probably due to the vapor pressure of the liquid. However, if lower pressures are

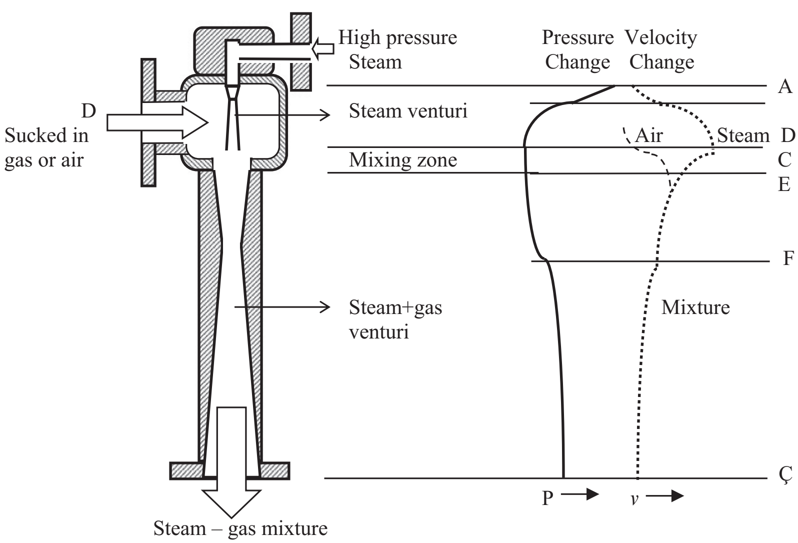


FIG. 5.35 A steam-jet ejector and the pressure and the velocity profiles built in it.

required this is overcome by using a liquid of lower vapor pressure as the sealing ring.

The principle of steam-jet ejectors depends on the pressure drop created by steam passing through a diverging–converging section at a constant entropy. This deficiency can be compensated by the withdrawal of the gas from the chamber to which it is connected. As can be followed from Fig. 5.35 this equipment contains two consecutive Venturies where pressure drop due to expansion of the steam entering at a pressure P_1 to the one in zone *A–C* mixes with the gas sucked from the line *D*. Along the zone *C–E* it is mixed with the gas and gradually compressed until the throat at point *F* where it expands and leaves the lower Venturi. Steam consumption depends on the compression ratio and the input steam pressure. In a single-stage system with a 6:1 compression ratio, it is possible to achieve as low as 17 kPa. For lower pressures, two or more evacuators should be connected in series. As a means of comparison, with a single-stage system 15–17 kPa can be realized, which is 3–15 kPa when two are in series, and by using three in series 0.5–3 kPa can be obtained. For lower pressures presence of rotary equipment at the initial point is required.

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Chapter | Six

Centrifugal pumps

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6.1 Introduction

The history of the first known devices using pumps dates back thousands of years ago. The first pumps were called "Noria," which looked like a water wheel. According to historians, Denis Papin, a French engineer, is the inventor of centrifugal pumps. In 1689, he introduced the first model of them. The pump he built had straight blades and consisted of only two blades housed in a fixed-width chamber. Then, instead of changing the blades' shape, he considered the collector shape to be a spiral with a fixed width to improve his design. Following Denis Papin's theory, Combs presented a paper on curved vans and their effect, which played a significant role in developing centrifugal pumps (Kruyt et al., 1999).

Pumps are one of the most widely used equipment in various industries. These machines are the beating heart of the industry, which are of great importance and application. This range of applications is seen in the industry, and pumps play a key role in water and sewage transmission networks, agriculture, infrastructure, and civil engineering activities. For instance, approximately 80%–90% of all pumps in a petrochemical unit are centrifugal (Girdhar and Moniz, 2011). Another application of centrifugal pumps is to use these machines instead of turbines in hydroelectric power plants (Carravetta et al., 2018).

Fig. 6.1 presents the two main categories of pumps, including dynamic pumps and positive displacement pumps (see Chapter 5). Of course, these two families can be divided into smaller groups that offer special services. It should be noted that all pumps have the same functional purpose, which is to add energy to the liquid to move it along the pipe and increase the pressure to overcome the force of gravity. It is clear that the mechanism of each type of pump to accomplish this goal is unique. Despite this high diversity, centrifugal pumps have far more applications than other types of pumps; in such a way

Transporting Operations of Food Materials Within Food Factories. https://doi.org/10.1016/B978-0-12-818585-8.00001-5

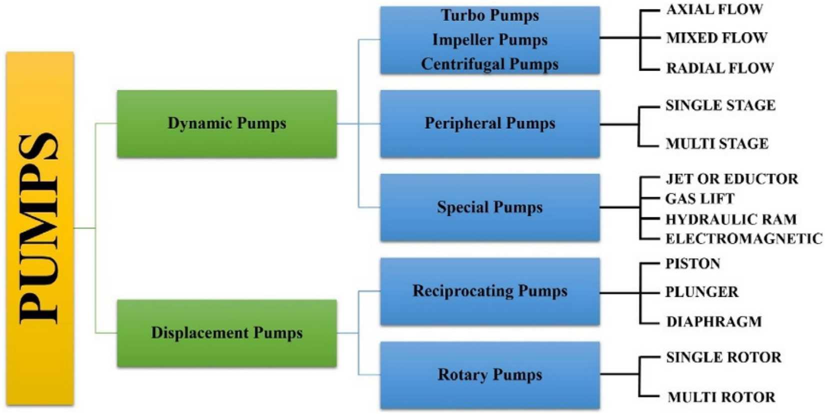


FIG. 6.1 Pump family.

that other types of pumps are used where centrifugal pumps are not efficient (such as pumping high viscosity fluids or biphasic fluids). In general, they are much better than other pumps in terms of operating range and performance (Karassik et al., 2008).

Selecting a centrifugal pump can be quite complicated. High reliability and the influence of applying centrifugal pumps in various industries are necessary, making the correct selection and design a serious challenge. There is no definitive and unified solution in any selection process. The pump selection process is a mixture of theoretical, experimental, and engineering judgments in each specific application. Centrifugal pumps are always part of a system. Without a "systemic approach" and a comprehensive review of the "pumping system," and how these pumps work with the whole system, selecting and designing a proper pump will not be possible. A systemic approach means a holistic approach focusing on each component's details or process to create a connection and coherence between them to achieve a single goal. The "systemic approach" makes it possible to examine all the pumping system components with each other. The cost of investment in a pump is generally small compared to the total cost of the plant. If the pumps are not selected properly, they will take severe revenge on the plant and impose a high cost. This chapter provides a comprehensive overview of centrifugal pump selection by identifying each component and ultimately combining them into a "whole unit" (Larralde and Ocampo, 2010).

In order to understand the nature of centrifugal pumps, one must first recognize the pump components and the variety of components. A centrifugal pump is a device whose rotor may rotate at a speed of 100 revolutions per second. This high rotational speed makes the design process and builds quality critical. The difference between large pumping facilities and smaller ones is their systematic view of pump performance as part of a whole system. This difference is due to the existence of more detail in the selection, design, fabrication, and assembly quality of the device, increasing the entire plant's efficiency and effectiveness. As a result, it is possible to achieve a longer lifespan along with optimal performance efficiency. However, if the centrifugal pump is not selected correctly, it does not matter which company supplied it, and most likely, due to this wrong choice, the device will not function properly. The wrong choice of pump is one of the worst mistakes in the industry, which includes mistakes in estimating the size and type of the pump, the material of the components, the sealing system, the type of drive, and the like concerning the "whole pumping system" (Bachus and Custodio, 2003).

There are eight quality steps to have an efficient pump, regardless of the manufacturer of the pump (Fig. 6.2). It may have happened a lot that a pump with a reputable brand has broken down during the start-up phase, or it has stopped working after a short time. On the other hand, it has been seen that

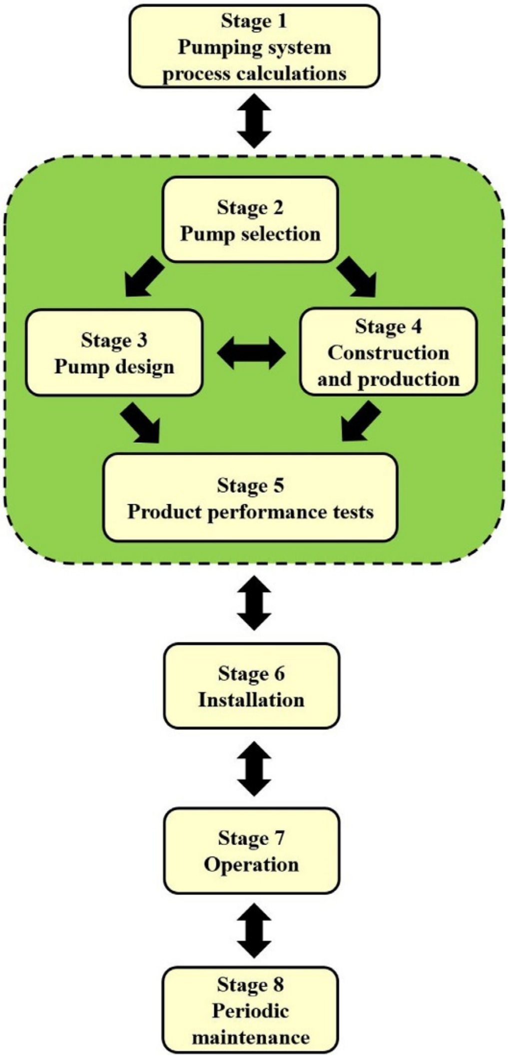


FIG. 6.2 Eight quality stages of centrifugal pumps.

an unknown pump manufacturer has built a pump that, in addition to a successful start-up, has also had the desired long-term function. But why did this happen? Did that reputable pump manufacturer make a big mistake? Or has this anonymous pump manufacturer achieved higher technical and manufacturing capabilities? The answer to these questions is in these eight quality control stages of centrifugal pumps, which briefly includes the following (Girdhar and Moniz, 2011; Gülich, 2008):

Stage 1: Correct process calculations. The purchaser or consumer must have an accurate estimate of what is needed. For example, if the required pressure of the pump/system is not calculated correctly, or if the nature of the fluid is not declared correctly, no pump in the world can be suitable for him. The first stage in quality control is to estimate and calculate process parameters accurately.

Stage 2: Correct pump selection. The next step in having a high-quality pump is choosing the right one. The best pump in the world can be damaged quickly if not used properly. This mistake is usually not detectable until the operation stage (final stage) and imposes many costs. Also, making a mistake at this stage is usually irreparable.

Stage 3: Correct pump design. There are several reasons for the inaccuracy in the design of the pump and its components. Whatever the reason, it will lead to rework and waste of resources in later stages. Design mistakes may involve the following:

1. incorrect design of hydraulic pump passes (impeller, screw, diffuser);
2. weak mechanical and dynamic design;
3. improper tolerance;
4. lack of attention to maintenance and operational issues;
5. lack of attention to comply with the standard and contractual requirements;
6. impossibility of production or unnecessarily complicated process;
7. lack of attention to the expected lifespan of the pump.

Stage 4: Correct construction and production. This stage means that pump parts and standard equipment production techniques must be using engineering and standard methods. In other words, the machinery and equipment used in the construction of the pump must be suitable for its design. In addition to the fact that the standard parts or equipment of the pump must have the correct production method, they must also be at the desired level in terms of appearance and dimensions and pass the specialized quality tests successfully.

Stage 5: Performance in accordance with product design. The pump device must pass the product tests successfully. This stage is a benchmark and control over the manufacturer's selection, design, construction, and production of pumps. If the inconsistent results of the pump performance tests are not detected at this stage, it will cost several tens of times more to fix it in the eighth stage and during the pump's operation.

Stage 6: Correct installation of the pump. The installation of the pump must be correct and under the engineering requirements. Many pumps have problems due to incorrect installation, lack of proper foundation, and chassis misalignment.

Stage 7: Correct operation. The pump must be properly operated and maintained. The best pump in the world is quickly damaged due to improper operation and maintenance. The most typical mistakes of this stage include the following:

1. the operator does not know the design conditions and how to operate the pump;
2. periodic monitoring and replacement of lubricants are not performed;
3. the effect of process changes on pump performance is unknown to the operator.

Stage 8: Correct periodic maintenance. Following cyclic instructions for maintenance increase the life of the pumps and helps maintain their designed condition. Although familiarity and knowledge of maintenance methods and techniques are a combination of different sciences, it is impossible to set maintenance instructions without sufficient awareness of the previous seven stages.

The first step in selecting and designing a centrifugal pump is to recognize the types of pumps available. Of course, it is difficult and practically impossible to present all aspects of these pumps in one chapter. In the first section, 38 types of centrifugal pumps and their applications and general specifications are introduced according to the standard of the Hydraulic Institute (HI). The second section deals with the relevant standards in designing, manufacturing, and evaluating centrifugal pumps. The next section describes the types of essential parts and components of centrifugal pumps. In other words, knowing each component's variety and application in different conditions is vital to select or design the correct centrifugal pumps. In the fourth section, the types of pump accessories are discussed. In the last section, the process of selecting centrifugal pumps is completed.

6.2 Classification and application of centrifugal pumps

6.2.1 Centrifugal pumps

Centrifugal pumps first produce pressure by accelerating the liquid using centrifugal force and then reducing the fluid's velocity inside. The fluid first enters the suction nozzle, moves toward the impeller eye, and passes through the impeller blades. The impeller, which rotates at the speed equivalent to the driver (electric motor, turbine, or diesel generator) of the pump, transmits energy to the fluid that moves from the impeller eye through the vane channel in the direction of the impeller's outer diameter.

The fluid must be available to the pump with sufficient energy to perform its function. The pump cannot suck fluid. A low-pressure zone is created in the pump inlet by placing the fluid in the pump inlet (according to the Bernoulli equation). The pressure difference between the suction tank level and the inlet causes a constant fluid flow to the pump inlet. Then, the imported fluid velocity increases under the influence of energy transfer and transfers from a lower radius to a greater radius in the impeller. Next, the fluid leaves the pump outlet at high speed. This current enters the volute, and part of the kinetic energy is converted into pressure (Gülich, 2008).

Table 6.1 compares the main characteristics of centrifugal pumps and positive displacement ones. Dependence of centrifugal pump performance on the pumping system and non-dependence of positive displacement pump performance on system specifications can be considered the most significant difference between the two categories.

6.2.2 Types of centrifugal pumps

The term "centrifugal pumps" includes not only radial, semi-axial, and axial pumps, but also side channel pumps, peripheral pumps, and liquid-ring pumps, the principles of operation of which are fundamentally different from the first group.

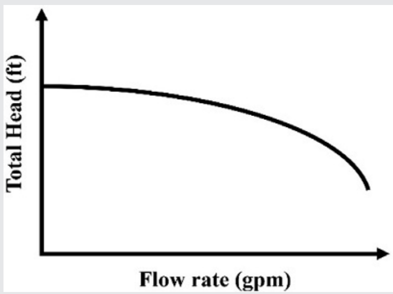
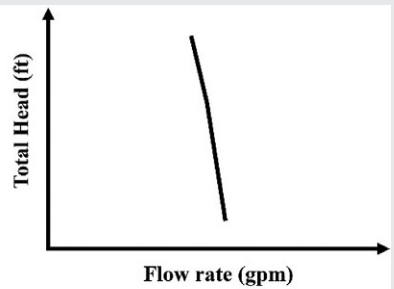
Pumps can be classified in many ways due to their many types and applications. The following is a small example of a relatively similar concept in the classification of pumps (Gülich, 2014):

a. *Principles of operation*: centrifugal pumps, side channel, positive displacement.
b. *Distinctive features*: such as self-priming.
c. *Types of pumps based on the flow direction at the impeller outlet*: radial, semi-axial, and axial.
d. *Types of pumps based on design*: single-stage, single-suction, dual-suction, horizontal, vertical, submersible motor pumps, submersible pumps, sealless pumps, magnetic coupling pumps, or canned motor pumps.
e. *Fluid*: Drinking water transfer pumps, boiler feed, condensate, sludge, pulp, acid, oil, gas, and liquid mixture.

In international standards such as HI, API, and ISO, pumps are classified based on their mechanical structure. In Standard HI, centrifugal pumps are classified into series overhung (OH), between bearing (BB), and vertically suspended (VS). Also, side-channel and peripheral pumps are classified as regenerative turbines (RT) series in this standard. Figs. 6.3–6.6 show the general classification of centrifugal pumps according to these standards. Table 6.2 provides a brief description of each type of centrifugal pump. In spite of the fact that a complete classification of these pumps is practically impossible, in each case, the most typical variety of designs is listed.

In Standards API 610 and ISO 5199, some centrifugal pumps are accepted based on their specific application. For example, in Standard API 610, 18 of the 38 types of centrifugal pumps in Standard HI are accepted for process applications in the oil, gas, and petrochemical industries. These pumps include OH1 to OH6, BB1 to BB5, and VS1 to VS7. Only 14 types are in full compliance with this standard (pumps OH1, OH4, OH5, and BB4 do not meet all the standard API 610) (Girdhar and Moniz, 2011; Gülich, 2008, 2014).

TABLE 6.1 Comparison of the main specifications of dynamic and positive displacement pumps.

	Dynamic pumps	**Positive displacement pumps**
Definition	They increase the pressure by rotating blades and increasing the speed of the fluid	They increase the pressure by operating on a certain volume of fluid in a given space
Types	Centrifugal/mixed/axial	Gear/screw/reciprocating
Specifications	Variable flow rate Fixed head in any flow rate Sensitive to fluid properties Sensitive to changes in the pumping system Self-limiting	Fixed flow rate Ability to change the head at a fixed flow rate Not sensitive to fluid properties Not sensitive to system specifications Not self-limiting
Head-flow rate characteristic curve		

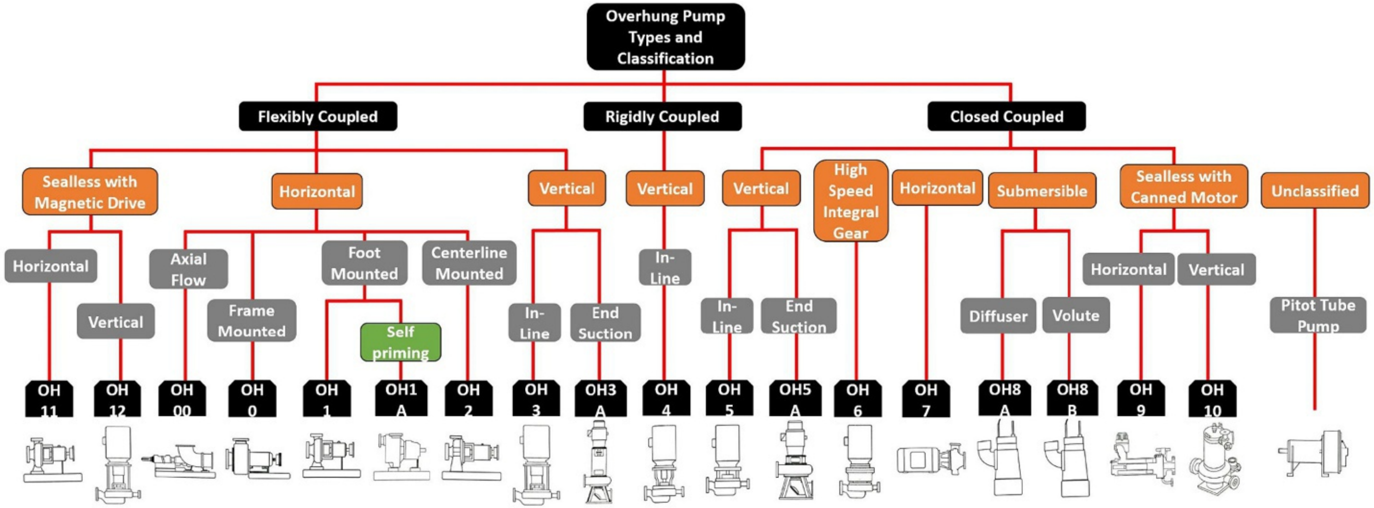


FIG. 6.3 OH series pumps according to HI standard.

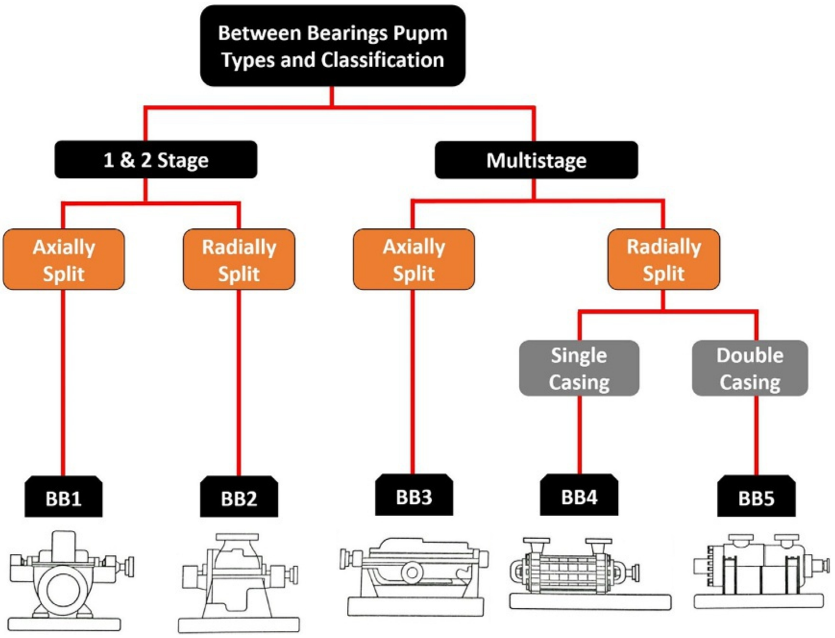


FIG. 6.4 BB series pumps according to HI standard.

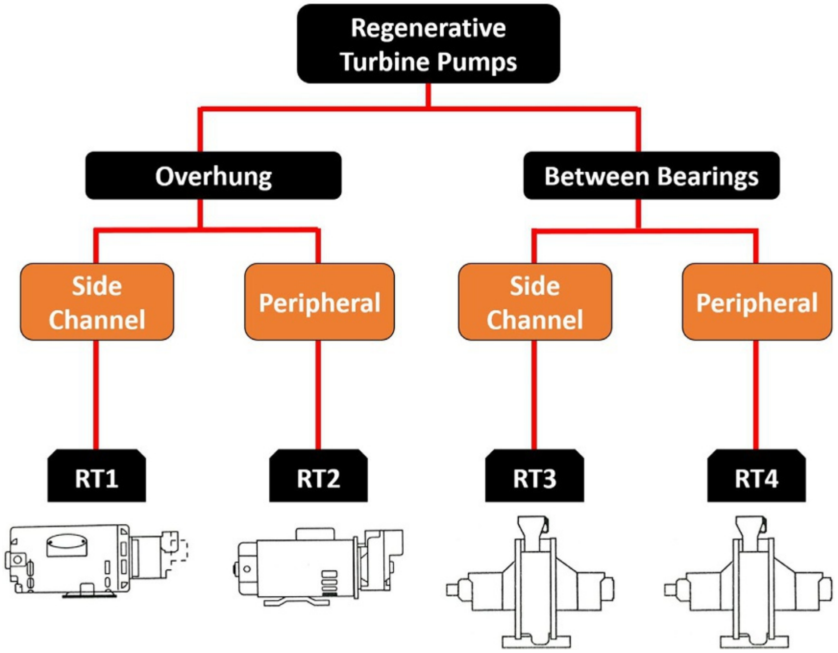


FIG. 6.5 RT series pumps according to HI standard.

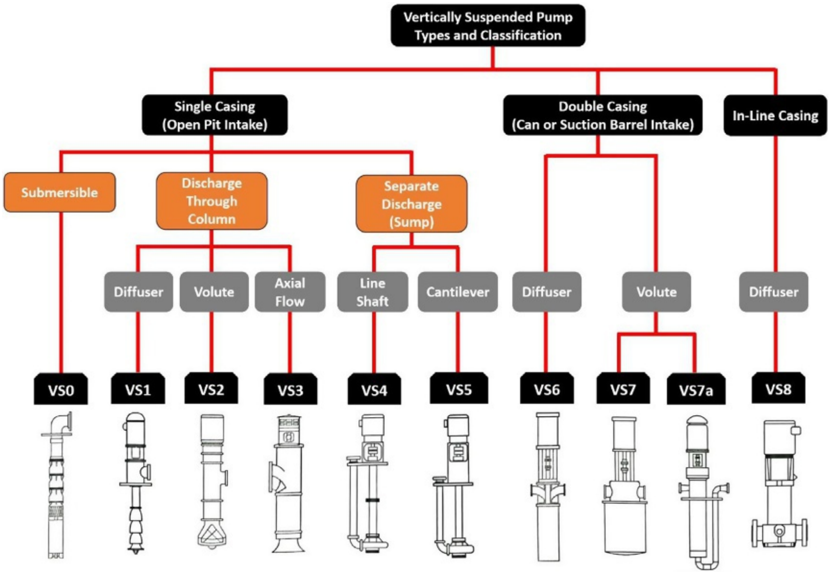


FIG. 6.6 VS series pumps according to HI standard.

TABLE 6.2 Application of centrifugal pumps (Gülich, 2014).

Application	Pump type	Power class (kW)	Specifications/applications/ special requirements
Standard pumps for general use	Single-stage, radial	2–200	Low investment cost
Process pumps	Single-stage, radial	10–300	High reliability, usually designed according to special standards Zero leakage, explosion protection, safety
	Multistage, radial, semi-axial	50–1000	
Cooling water pumps for power plants	Single-stage, radial, semi-axial	500–3000	Vertical pumps with high specific speed
Boiler feedwater pumps	Multistage, radial	100–2000	Industrial electricity generation
Boiler feedwater pumps for large power plants		5000–45,000	High-speed pumps with booster pumps, specially designed to prevent vibration and cavitation problems
Water injection pumps		1000–2000	Water injection into oil wells
Pipeline pumps			Transfer of water or oil to distant areas
Mining pumps		500–3000	Mine water pumps Abrasion due to sand in water

TABLE 6.2 Application of centrifugal pumps (Gülich, 2014)—cont'd

Application	Pump type	Power class (kW)	Specifications/applications/ special requirements
Irrigation and drainage pumps	Axial, semi-axial	200–2000	High flow rates depending on the amount of rainfall Abrasion due to sand in water
Sludge pumps	Radial, semi-axial, axial	10–1000	Open passages for flow Insensitive to blockage by foreign particles
Marine pumps		1–1000	Requires little space, insensitive to water penetration
Submersible pumps		5–500	Process industries, oil production, special hydraulic forms
Gas and liquid mixture	–	10–5000	For hazardous and toxic fluids (leak-free pumps) With enclosed motor or magnetic coupling
Sealless pumps	Single-stage, radial	5–250	Open flow passages for the passage of solids, Abrasion protection
Drilling pumps	Single-stage, radial	200–5000	Abrasion protection
Slurry pumps	Single-stage, radial	50–1000	Abrasion protection
Rocket pumps	Radial/semi-axial	1000	Very high vane tip speed, short pump life
Food industry	All cases	1–50	Clean pumps, lubricants should not penetrate, pumping fluid protection
Medical services (e.g., blood pumps)	All cases	Less than 0.1	Clean pumps, high reliability, lubricants should not penetrate, pumping fluid protection

6.2.3 Applications of centrifugal pumps

Centrifugal pumps have been employed in various applications, and it is impractical to count them all. In many systems, pumps are just one component of a complex process, but their failure can cause serious problems. For example, stopping the boiler feedwater pump in a large power plant stops the entire power plant's operation. Therefore, the need for maximum reliable performance is a prominent feature of many pumps. This reliability is not just for unique pumps; many mass-produced pumps, such as car cooling water pumps or building central heating circulation pumps, also require maximum reliable performance (Pumps, 2010).

A suitable division for different industries to survey the types of pumps required is as follows: (1) Food and beverage; (2) Chemical industry; (3) Petroleum industries (oil production, oil and gas transmission, pipelines, hydrocarbon processes); (4) Pulp; (5) Slurry; (6) Municipal water and wastewater; (7) Agricultural applications; (8) Applications of building installations; (9) Power generation industries; (10) Cooling tower; (11) Fire pumps (Girdhar and Moniz, 2011).

Many of the pumps' applications are not related to a specific sector in the industry within the above division. These uses are known as general services. General services pumps are usually not part of the plant's main process, and in case of failure or shutdown, the plant's production is not directly affected. On the other hand, process pumps are usually part of the plant's main process, and their performance will directly affect the amount of production. Special attention to the use and performance of pumps and their impact on the plant, selection, design, production, and inspection of pumps has a definite effect. All centrifugal pumps presented in Figs. 6.3–6.6 can operate as part of the main process. Still, the nature of the process and the reliability may be affected by the correct type of pump. In many cases, the correct selection of different centrifugal pumps is a compromise between technical and economic considerations. Besides, adequate access to local suppliers and the level of training and expertise of pump operators may affect pump selection (Pumps, 2010).

Table 6.2 gives some examples of some critical applications of centrifugal pumps. The power range and application characteristics presented in this table are not definitive. In each application, the most typical types of pumps and special requirements are mentioned.

6.2.4 Centrifugal pumps sizing

According to international standards HI, ISO 5199, and ANSI/ASME B 73.1M, the size of the pumps is based on the nominal size of the outlet flange and the nominal diameter of the impeller (in millimeters). A pump with a nominal diameter of 80 mm suction flange, 50 mm outlet, and a nominal diameter of 160 mm impeller is introduced in the SI system as a 50–160 pump. Suction size may also be added to the inch system, and the pump will be introduced as 3.2.6 with a 3-in. suction nozzle, 2-in. outlet nozzle, and 6-in impeller diameter. The size of ISO standard pumps may also be presented as 80-50-160 (https://www.lenntech.com/Data-sheets/Goulds-IC-L.pdf).

The pump outlet nozzle size is representative of the flow rate, and the nominal diameter of the impeller is also representative of the pump head. Consider two pumps with two sizes, 50–160 and 100–160. Since the second pump outlet's nozzle size is larger than the first pump, the second pump can pump more flow at the same rotational speed. Also, for two pumps, one sized 50–160 and the other 50–200, the second pump produces more pressure (at the same rotational speeds) due to its larger impeller diameter (Girdhar and Moniz, 2011; Graham, 2007).

6.3 Centrifugal pump standards

Various standards have been developed for centrifugal pumps. The most important ones for constructing these pumps are as follows.

6.3.1 ANSI/HI standards

The Hydraulic Institute (HI) was founded in 1917 and is currently the largest pump manufacturer organization in North America. This standard is dedicated to the design, selection, testing, and operation of various pumps. This standard is the main reference of all pump manufacturers. This standard is referred to in other standards related to pumps. This standard approach is based on training and standardization (Addie et al., 2007). In this standard, the following types of pumps are introduced and classified (https://www.pumps.org/downloads/HI_CD_3.0_Instruction_Guide_for_web.pdf):

- centrifugal pumps (horizontal, vertical, slurry, submersible)
- rotary pumps (gear, screw, blade, peristaltic, lobe, axial piston, and peripheral)
- sealless pumps (magnetic pumps and enclosed electro pumps)
- reciprocating pumps
- dosing and metering pumps
- direct-acting (steam) pumps
- air-operated pumps.

6.3.2 API 610 standard

Construction and testing standard of heavy process centrifugal pumps used in oil, gas, refining, and petrochemical industries. This standard is trendy among buyers and consumers due to the strict requirements in selecting and manufacturing centrifugal pumps. This standard's main application is for centrifugal pumps in process services in the upstream and downstream oil industries (Jones et al., 2016). In this standard, 18 pump models in three categories, OH, BB, and VS, are introduced for centrifugal pumps used in process services in the oil and petrochemical industries (Larralde and Ocampo, 2010).

6.3.3 API 685 standard

API 685 standard introduces the minimum requirements for sealless centrifugal pumps (magnetic pumps and enclosed electro pumps—Series OH9 to OH12 pumps) for oil, heavy petrochemical, and gas services. Many of these standard requirements are similar to API 610 standard (pumps with mechanical seals). Industrial experience has shown that when using sealless pumps, the use of API 685 standard for any of the following conditions can be a good choice (Bennett and Bryant, 2003):

a. Pump outlet pressure is 19 bar or more.
b. Suction pressure is 5 bar or more.
c. Fluid temperature is 150°C or higher.
d. Rotation speed more than 3600 rpm.
e. The nominal head is 120 m or more.
f. The impeller diameter is 330 mm or more.

6.3.4 ANSI/ASME B 73.1/73.1 M standard

Construction and dimensional specifications standard of horizontal end-suction centrifugal pumps for chemical process. This standard was developed in 1974 by the Centrifugal Pumps Committee for the Chemical Industry. The 1974 edition consisted of 15 pump sizes, which quickly increased to 20 sizes. Some information was added in the 1984 edition, such as pump dimensions, datasheets, cooling plans, mechanical seal drawings, and gland packing.

In 2001, with seven other sizes, the number of standard sizes accepted reached 27. These added sizes were based on consumer demand. Recent publications of the HI on base plate tolerances, flange force, preferred operating area, and Net Positive Suction Head (NPSH) spacing have been added to this edition (Girdhar and Moniz, 2011; Gülich, 2008; Pumps, 2010).

2012 edition of this standard includes several changes to further align with the HI and the American Petroleum Institute (API). B73.5 standard for polymer pumps was integrated with this standard. In this edition, API experiences on the mechanical seals' configuration and cooling plans are considered. Also, in this version, the new datasheet of these pumps has been added to the standard (Gülich, 2008).

6.3.5 ANSI/ASME B 73.2/73.2 M standard

Construction and dimensional specifications standard of in-line vertical centrifugal pumps for chemical processes. The first edition of this standard was published in 1975. This standard has been improved in line with the B73.1 standard. In the 2016 edition, more compliance with API and HI standards regarding mechanical seal configuration and performance acceptance tests has been established. In this standard, VB, VC, and VM pumps are equivalent to OH3, OH4, and OH5 pumps in HI and API 610 standards, respectively (Girdhar and Moniz, 2011; Gülich, 2008; Pumps, 2010).

6.3.6 ANSI/ASME B 73.3/73.3 M standard

Construction and dimensional specifications standard of sealless end-suction metallic centrifugal pumps for chemical applications. In 1991, the B73 committee of ASME standard was formed to develop a standard for sealless pumps, and the first edition of this standard was published in 1997. In 2003, this standard was improved, and more pump sizes were added. Sealless pumps (MDP) are equivalent to OH11 pumps, and enclosed electro pumps (CMP) are equivalent to OH9 pumps (Girdhar and Moniz, 2011; Gülich, 2008; Pumps, 2010).

6.3.7 NFPA 20 standard

The first American National Fire Protection Association standard for automatic sprinklers was published in 1896. The Fire Pump Committee was formed in 1899 with five members. Currently, the committee's new members include companies, factories, representatives of insurance offices, industrial risks insurers, government representatives, engineering organizations, and laboratories in the United States and Canada.

Early fire pumps had a manual startup. Also, these pumps were of the negative suction type in the late nineteenth and early twentieth centuries, as rotary and steam fire pumps were suitable for this mode. The fire pumps' tank was installed on the ground, as these pumps are more suitable for positive suction. Later, vertical turbine pumps (VS1 series pumps) were also employed for underground tanks. Besides, gasoline engine pumps were first introduced in the 1913 edition. Today, the number and application of these pumps have increased dramatically, and they are often automatic.

In the 1999 edition, the positive displacement pumps' requirements were presented for water mist and foam systems. In the 2010 edition, a new section was added for high buildings and the requirements for installing pumps in series. In the 2016 edition, multistage pumps are introduced. Various parts related to controllers have also been improved (Girdhar and Moniz, 2011; Gülich, 2008; Pumps, 2010).

6.3.8 ISO 5199 standard

Construction and technical specifications standard of Class II centrifugal pumps for general uses in industries. This standard applies to most general and industrial applications (such as the chemical industry) in centrifugal pumps and also, single-stage, multistage, horizontal or vertical pumps with any drive. This standard covers design features related to the installation, maintenance, and safety of pumps with chassis, couplings, and piping accessories. The dimensions and working point of the end-suction pumps' design of this standard are under ISO 2858 standard, and the dimensions of the chassis and their installation are in ISO 3661 standard (Girdhar and Moniz, 2011; Gülich, 2008; Pumps, 2010).

6.3.9 Other standards

Other standards related to pump construction, such as those mentioned above, may not be universally popular. Some of these standards have local and regional applications.

- *ISO 9905 standard* (https://www.iso.org/standard/17788.html): Technical requirements for Class I centrifugal pumps
- *ISO 9908 standard* (https://www.iso.org/standard/17790.html): Technical requirements for Class II centrifugal pumps
- *DIN EN 733 standard* (https://www.starpumpalliance.com/pump-lexicon/details/standard-din-en-733-pumps): Technical requirements for single-stage, single-suction centrifugal pumps with pressure class PN10
- *DIN 24255 standard* (https://www.tumapumpen.at/wp-content/uploads/2019/08/2.1-Normpumpe-DIN-24255.pdf): Technical requirements for single-stage and single-suction centrifugal pumps (old standard)

6.4 Main parts of centrifugal pumps

6.4.1 Impeller

As the key part and the rotating component within the centrifugal pump, the impeller converts the mechanical rotation to the velocity of the liquid. The pump impeller is indeed responsible for energy transfer to fluid. This component is made up of an inlet eye or a single opening at the center, through which the liquid is guided from the inlet to the outlet of the impeller by vanes. The angle and shape of the vanes depend on the flow rate. In terms of mechanical construction, there are three types of impeller classifications (Fig. 6.7): closed, semi-open, and open.

6.4.1.1 Closed impellers

The closed impellers have radial vanes located between the two discs. This type of impeller is used in pumps that need a low NPSH. They are most widely used to handle non-viscous and clear liquids.

6.4.1.2 Semi-open impellers

The vanes are enclosed with the shroud on one side only and are free from the other side. The semi-open impellers have higher efficiency because of the minimization of disc friction from the front shroud. They can be used in pumps handling viscous liquid such as paper pulp and liquids containing small amounts of suspended solids.

6.4.1.3 Open impellers

The vanes are free on both sides and are not enclosed with any shroud. Hence, there is no obstruction problem in these impellers. They are, in most cases, used in pumps handling suspended solids (Girdhar and Moniz, 2011; Stewart, 2018).

6.4.2 Pump casing

The pump casing is a containment vessel that collects fluid from the impeller environment. The pump impeller is placed within the casing. At the impeller outlet, liquid velocity increases as high as 30–40 m/s, although it has to be less

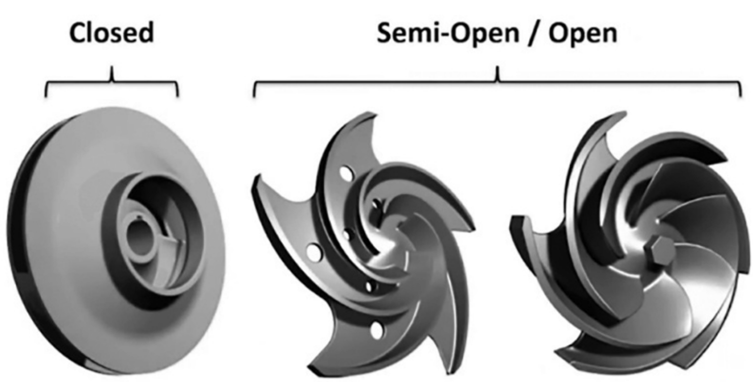


FIG. 6.7 Types of impellers (Stewart, 2018).

than 7 m/s. Recuperators lower the velocity in the pump casing by converting the kinetic energy in the liquid at the outlet to pressure energy.

The recuperators are:

- vaneless guide ring
- concentric casing
- volute casing
- vaned diffuser ring

6.4.2.1 Vaneless guide ring

This type of casing consists of two smooth discs. The distance between the two discs can be constant or increasing toward the outlet. The kinetic energy is converted into pressure energy depending on the ratio between the outer diameter (Do) and the inner diameter (Di). As the Do increases, the fluid velocity will drop, leading to an increase in the pressure level. Vaneless guide tings are usually used in low viscosity fluid and low head (Fig. 6.8A).

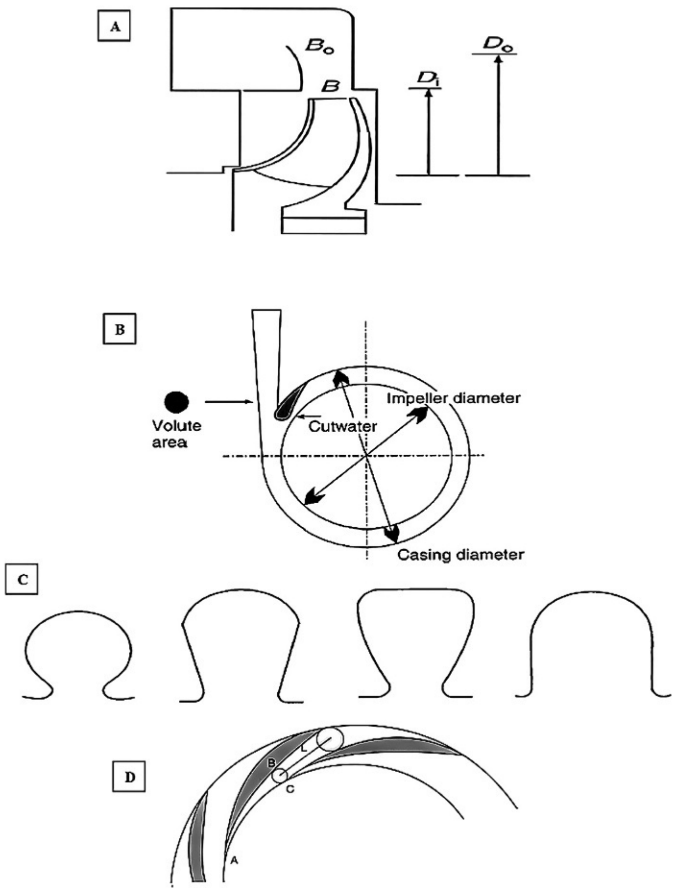


FIG. 6.8 (A) Vaneless guide ring, (B) concentric casing, (C) different forms of volute cross section, and (D) vaned diffuser ring (Girdhar and Moniz, 2011).

6.4.2.2 Concentric casing

In this case, the casing and impeller have the same centers (Fig. 6.8B). This method can be used in single-stage pumps and the last stage of multistage pumps. The proportion of the impeller diameter (d_1) to the casing diameter (d_2) is in the range of 1.5–1.2. The volute incorporates the maximum width of the impeller, and operation capacity is controlled by adjusting the volute diameter. In pumps with the concentric casing, the efficiency progressively drops when the Ns are above 600 US units. This type of casing is used when one of the following conditions is met:

- The pump uses a fabricated casing.
- The pump casing incorporates several impeller sizes.
- The volute passage is machined from a casting.
- Foundry limitations result in a larger impeller width.

6.4.2.3 Volute casing

This casing is the most common type of casing in centrifugal pumps. Unlike the concentric casing-type centrifugal pumps, the casing and impeller centers are not the same. In these pumps, as the distance between the impeller tip and the casing wall increases, the pressure energy increases more. Impeller vanes and shrouds can be trimmed down with the most negligible effect on the pump's overall efficiency. The volutes have various cross sections, such as circular, trapezoidal, and rectangular cross sections (Fig. 6.8C). Among *three geometries,* the rectangular section is generally used in small single-stage and multistage pumps since it is more economical, although its operating conditions are limited to Ns < 1100. Volute casings are in two *different* types: Single volute casing and Double volute casing. Single volute design is based on a constant velocity. The main advantage of a single volute casing is convenient casting and low manufacturing cost. The double volute consists of two volutes with an arc of 180°. The starting point of the second volute is 180° after the starting point of the main volute. This type of volute can be used for pumps with a flow rate higher than 125 m^3/h. However, the pump produced based on this method requires more cost compared to a single volute.

6.4.2.4 Vaned diffuser ring

As shown in Fig. 6.8D, the vaned diffuser ring is made of a series of vanes that are symmetrically placed and gradually widening passages. The distance BC shown in Fig. 6.8D is the space between the two vanes that act as a volute. The straight line L is the centerline of the vanes. This line can be straight or curved, with its direct form having higher efficiency. The number of vanes in the diffuser ring should be more than the impeller, but the difference in the number of vanes is not allowed to be excessively high. Usually, the diffuser ring has one more vane than the impeller. Since diffusers at high heads and low flows show maximum efficiency, they are used when the radial loads are more intense. They also outperform other types in converting fluid velocity to pressure, but the cost of purchasing them is higher.

This type of casing can only be used in large multistage pumps and vertical turbines (centrifugal deep-well pumps) (Girdhar and Moniz, 2011; Stewart, 2018).

6.4.3 Shaft

The transfer of energy from the drive to the pump impeller is the most critical function of the shaft (Fig. 6.9). The probability of shaft failure is high because it is under stress. The pump shaft is affected by destructive factors such as torsion stress, bending stress, axial stress, and vibration. The shaft design depends on factors such as shaft deflection, key stresses, mounted components, and critical speeds. Shaft size is one of the essential factors in energy transfer. This size is required to be large enough for a better energy transfer. Increasing the shaft diameter can lead to an increase in the entrance velocity and larger bearings. The shaft at the stuffing box is protected against wear by the shaft sleeve (Girdhar and Moniz, 2011; Stewart, 2018).

6.4.4 Sealing systems

The chamber blocks the shaft and chamber distance to prevent fluid leakage inside the pump. Lack of good shaft sealing can lead to downtime, environmental pollution, and endanger personnel safety. Two common systems generally are employed for sealing shafts: stuffing boxes (packing) and mechanical seals.

6.4.4.1 Stuffing box

The stuffing box or packing box is a housing that is used to prevent fluid leakage out of the pump or air leakage into the pump. If the pressure in the stuffing box is above atmospheric pressure, liquid leakage is prevented. On the other hand, if it is below atmospheric pressure, it prevents air leakage. The stuffing box comprises 4–6 packing rings and a gland for pressing packing rings down the shaft

FIG. 6.9 Shaft and sleeve shaft (Stewart, 2018).

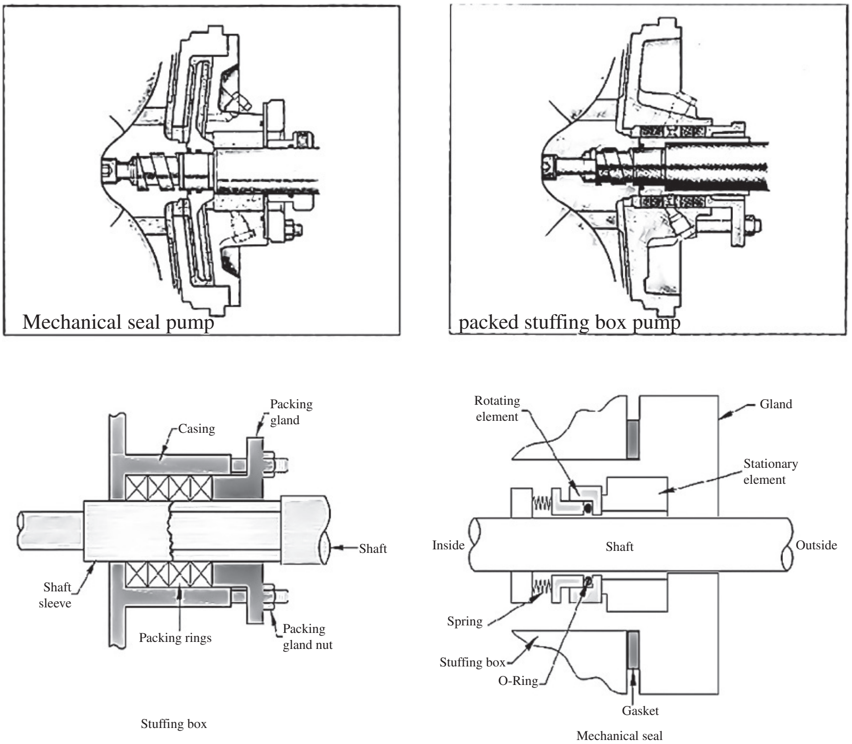


FIG. 6.10 Types of the sealing system (Stewart, 2018; Rayner, 1995).

(Fig. 6.10). In a properly operating stuffing box, the friction losses are commonly around 1% of the total pump power, independent of the size and kind of pump. The stuffing boxes have disadvantages such as the need for constant supervision, shaft wear when the gland is too tight, product leak if the shaft surface is not smooth, and some leakage between the shaft and the packaging for cooling and lubrication of the packaging material. Therefore, using a packing system for systems that have hazardous and expensive fluids is not reasonable.

6.4.4.2 Mechanical seals

Mechanical seals are one of the best and safest sealing systems available to prevent fluid leakage. This type of sealing contains two smooth faces: The first face is stationary on the pump bowl, and the second face is located on the pump shaft and is rotating (Fig. 6.10). The two main advantages of using mechanical seals over stuffing boxes are minimizing pump leakage and the possibility to use them under challenging conditions. The leakage resistance in mechanical seals is orthogonal, while it is along the axis of the shaft in the stuffing boxes. This sealing system is superior to packaging except for firewater pump applications. The mechanical seal should not be run dry, and it needs constant lubrication between the seal faces. The lubrication of these two faces is such that a thin film of fluid is placed on the seal faces, thereby improving their performance. Mechanical surfaces are polished to minimize leakage, friction surface, and heat generation (Rayner, 1995; Stewart, 2018).

6.4.5 Type of bearing

The components that support the rotational motion are called bearings. The main function of the bearings is to keep the correct alignment of the shaft against radial (the result of loads perpendicular to the centerline of the shaft) and axial loads (the result of thrust loads parallel to the shaft centerline). Pump bearings are classified based on several factors, including force direction and friction type. Depending on the direction of force, they are divided into two groups of radial and axial bearings. The bearings that maintain the radial and axial position of the shaft are called radial and thrust bearings, respectively. In most pumps, bearings are classified according to the type of friction, which includes two groups of sliding (hydrodynamically lubricated bearings) and rolling contact bearings. There is friction in sliding contact bearings or friction contact bearings such that they need boundary lubrication to reduce friction. This bearing is often used for low-speed applications. There are three main types of sliding bearings: journal bearing, flat plate thrust bearing, and Kingsbury. Journal bearings are only suitable for radial forces, while the other two types are only suitable for axial forces (Fig. 6.11). Since there is no friction in rolling bearings, they are called anti-friction bearings. In these bearings, spherical or non-spherical rolling elements are located between the rings or steel plates. This type of bearing has been designed to endure axial, radial loads, or a combination of both. Nevertheless, they have disadvantages such as limited load/speed capability and a specific life for the load. There are different types of rolling bearing, each used for specific characteristics. The three most popular types of bearings are the ball (single/double row), spherical (single/double row), and cylindrical bearings (Childs, 2013; Rayner, 1995; Stewart, 2018).

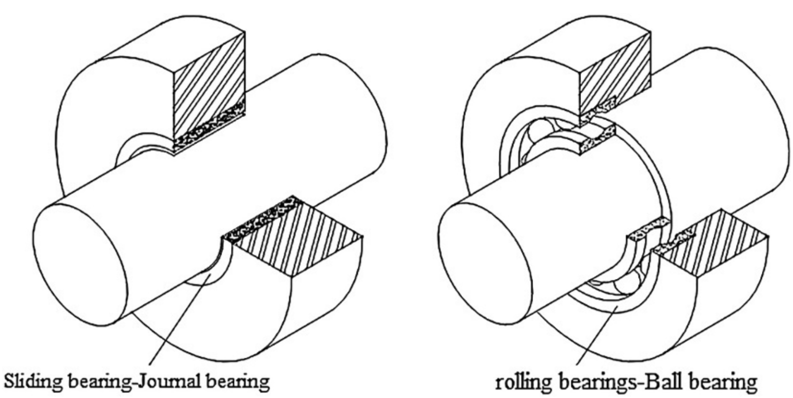


FIG. 6.11 A journal bearing and a ball bearing (Childs, 2013).

6.4.6 Sealing of bearing chambers

The life of the bearings is affected by the mechanical sealing of the pumps. Improper mechanical sealing performance may cause the bearings to fail. Bearing lubricant is contaminated by some factors such as rain, product leakage, and wash-down water entering the bearing housing, leading to catastrophic adverse effects on bearing life. Different types of external seals can be used to improve the internal condition of the bearing housing by protecting it from external materials and lubricant leakage. External seals can be divided into two non-contact seals and contact seal types. The contact seal causes additional friction because it has a contact point with the shaft. Rubbing speed is the main limitation of contact seals because they are in contact with the shaft. Contact seals usually operate at lower velocities. Radial shaft, felt, and V-ring seals are the most common types of contact seals. Non-contact seals fail to administer the bearing in the face of excess or inadequate pressure. Besides, they are not impervious to dust ingress. These seals are used in high rotation speed and high temperatures. This type of sealing is also called distance sealing since there exists a gap between the body of the sealing tool and the shaft, and this gap is filled with grease. The most common non-contact seals are the labyrinth seals, seal with a flinger, and gap seals (Dahmer, 2013; Girdhar and Moniz, 2011; Neale, 2013).

6.4.7 Lubrication of bearings

Bearings need lubrication to be evenly coated. Bearing lubrication is administered by lubrication systems including grease, oil ring, constant level oiler, and force-feed. Grease renders the ideal property of longevity in effect. Grease is an anti-friction oil used in smaller catalog pumps to protect metal surfaces from oxidation at a lower cost compared to oil. In lubrication of bearings with grease, filling more than one-third of the bearing cavities is not warranted, exceeding which will increase the temperature. In this case, the situation may render a devastating effect if the conditions are not modified. Rotation speed and operating temperature are two major factors in determining the lubricant type.

Oil is used as a standard lubricator in immensely large pumps. Also, it can be used in small pumps at certain industries such as chemical and oil refining complexes. Applying oil at high speeds has displayed adequate results. Oil is controllable intra-system and is further responsible for cooling the bearings. Oil is used if bearing cooling is desired at high speed. In the oil ring system, the oil rings are mounted on the shaft to remove the lubricant from the repository, transfer it to the top of the movable shaft, and ultimately transfer it to the bearings. These systems are not suitable for shafts with high loads. A constant level oiler system is used in pumps with ball bearings. In these pumps, a proper oil level must be maintained in the chamber. The force-feed system is typically designed to supply oil at a suitable pressure. This system consists of a reservoir, pump, cooler, filter, control valves, relief valves, pressure and temperature switches, gauges, and arid piping. Sleeve bearings may require a force-feed system (Rayner, 1995; Stewart, 2018).

6.4.8 Pump wear rings

An impeller is a rotating component of a pump, located within the pump casing. There must be a distance between these parts to prevent friction. The frictional contact will erode the contact surfaces of the impeller and casing. In this case, to solve the problem, the impeller and casing are needed to change, which involves high costs. Therefore, the wear rings are installed as metal nets on the impeller eye and pump casing. Using wear rings is an economical solution for solving the impeller and casing erosion problem. The only point at which the casing and impeller would contact is the location of wear rings. In case the contact surfaces are eroded, the problem can be solved by changing the rings. As a result, the replacement cost is minimized. The presence of wear rings between the impeller and the casing provides an economical renewable leakage joint. Wear rings in pumps are usually used in pairs; one is stationary and the other is rotating. The stationary ring is in the casing and has a concentric position with the impeller wear ring. The rotating ring is connected to the impeller. The wear ring used in the impeller is called the impeller wear ring. This ring has two types axial and radial. The wear ring used in the casing is called the casing wear ring. The impeller and casing wear rings are mostly used to prevent direct erosion of the contact surfaces of these two parts. Besides, the pressure difference between the impeller discharge opening and suction opening leads to recirculating of the pumped liquid. In this case, the fluid tends to pass through the distance or gap between the impeller and shell, and enter the suction opening, thereby declining the pump's efficiency. The smaller gap or distance between the two parts reduces the recirculation of the pumped liquid. Accordingly, another advantage of using wear rings is to minimize the gap between the impeller back and casing. The wear ring clearance affects the internal leakage and the pump efficiency. By reducing the wear ring clearance, the internal leakage decreases, and the efficiency of the pump increases.

There is a great variety of wear ring designs. The choice of the best type depends on several factors, including the liquid being handled, the pressure differential across the leakage joint, running speed, and pump design.

Flat and L are the two most widely used types of ring constructions (Fig. 6.12). In the flat-type ring, the leakage joint is a straight annular clearance. In a type L ring, the velocity of the liquid flowing into the suction eye of the impeller is low because there is a large axial clearance between the impeller and casing ring. Nozzle rings are a type of L-type rings that can guide liquid into the eye of the impeller (Rayner, 1995; Stewart, 2018).

6.4.9 Axial force balancers

The high-pressure liquid is produced by converting kinetic energy into pressure energy, trapped inside the clearances between impeller and casing walls. This high-pressure liquid exerts pressure on the outlet passages and shrouds of the impeller, resulting in radial and axial forces. The radial force is the result of producing dissimilar pressure in the volute, and the axial force that enters the pump

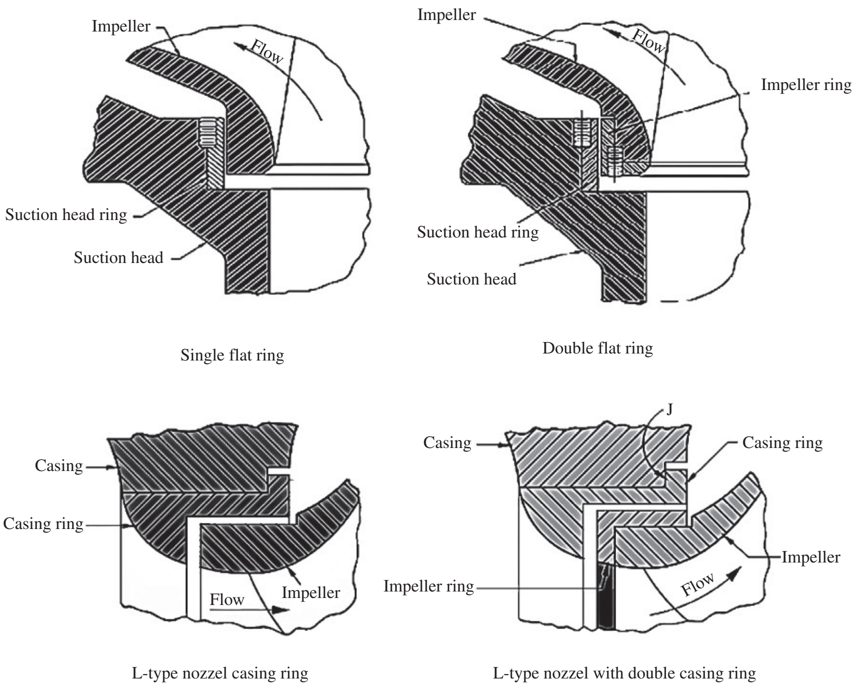


FIG. 6.12 Types of wear rings (Stewart, 2018).

in the axial direction is caused by different areas of the impeller exposed to trapped pressurized liquid (Pehlivan and Parlak, 2019). These forces are often balanced hydraulically or by other appropriate methods. If these forces are not balanced, they apply unwanted forces to the pump shaft, so, the structure of the pump is damaged, and the operation of the pump is disrupted. Despite all the design considerations, there is no equal pressure distribution on the two sides of the impeller. Moreover, the difference in the amount and direction of the flow velocity at the inlet and outlet of the impeller leads to different flow movements on the two sides of the impeller. As a result, there is always a thrust in the axial direction on a pump. This axial thrust must be reduced as much as possible (Nourbakhsh et al., 2007).

Controlling the axial thrust depends on the characteristics of the pump, including the type of pump, size, the impeller geometry, the hub diameter, the diameter of the front and back labyrinths of the impeller, the diameter of dorsal vanes, the pressure discharged by the pump, specific operating speed, and pump suction pressure (Budea, 2015; Szlaga, 2019). In small-sized pumps operating at low speeds, the radial force is low such that the thrust bearings can absorb the entire axial thrust. In comparison, medium and large pumps operating at high speeds need balancing systems to balance axial thrust. In single-stage pumps, the most common method of axial thrust balancing is to provide a balancing chamber. Due to pressure balance on two sides of the impeller, small holes are made on the back wall of the impeller. Besides, to eliminate the axial thrust, a circular wear ring is installed on the back wall of the impellers. The presence of this ring allows the liquid to be kept inside the balancing chamber. The number and size of holes must be suitable for the flow to pass with minimum pressure loss. The method of applying balancing holes in large single-stage single-suction pumps is undesirable. The reason is that the impeller flow pattern is disturbed under these conditions. A pipe connection is used in these pumps to build a balancing chamber instead of drilling holes in the impeller. Axial thrust on multistage pumps is significantly high, suggesting the importance of the efficient balance of this force in these pumps. The most common axial thrust balancing methods in these pumps are:

1. dividing the impellers into two separate groups and collecting each group asymmetrically;
2. forming groups containing two impellers such that two impellers face each other;
3. creating axial thrust balance by installing a balancing piston on one side of the shaft if the entrances of all the impellers are on one side;
4. in modern multistage pumps, the balance discs are often used to balance these forces (Nourbakhsh et al., 2007; Stewart, 2018).

6.5 Centrifugal pump accessories

Pump components and accessories make up the overall machine and make it work properly. This chapter will examine their necessity in centrifugal pumps by designing some parts and using different sources.

6.5.1 Coupling

Couplings for pumps usually fall in the category of general-purpose couplings. Purpose couplings are standardized and are less sophisticated in design. Couplings do not show a large investment compared to other connected equipment. Their service life is essential to reduce replacement parts and maintenance costs, especially potential equipment damage when connections fail. Choosing the proper connection improves performance and maintenance and reduces costs. The couplings fitted on pumps usually fall in any of the five types including gear coupling, grid coupling, disc coupling, and elastomeric compression-type coupling (Girdhar and Moniz, 2011).

6.5.1.1 Gear coupling

A gear coupling is a flexible mechanical element that is commonly used, consisting of a hub with external teeth and a sleeve with internal teeth (Fig. 6.13A). It is not easy to achieve a complete part of the device while working, so the coupling makes it simple to access this part with misalignment. In Fig. 6.13B, gear coupling tolerates misalignment through tooth reaction, the crowning of the tooth surface, and proper main diameter (Alfares et al., 2006; Girdhar and Moniz, 2011). Misalignment greatly affects the load distribution on the gear coupling teeth. When the coupling is leveled, the torque is evenly distributed among all the teeth, and the load is concentrated in the center of the side of the tooth. When the coupling is inadequate, the number of teeth in contact

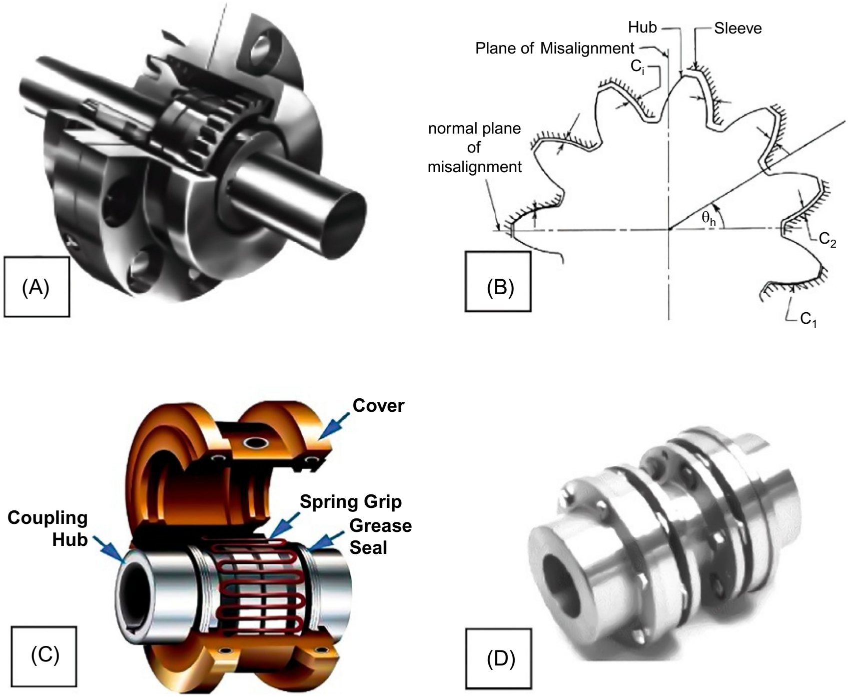


FIG. 6.13 (A) Gear coupling, (B) coupling tooth geometry (Alfares et al., 2006; Girdhar and Moniz, 2011), (C) grid coupling (Patel et al., 2020), and (D) disc coupling (Girdhar and Moniz, 2011).

decreases, and the maximum load on one tooth increases. In this area, the contact deviates from the lateral center of the tooth and moves to the edges of the tooth, which is likely to break. In general, coupling loads are a combination of misalignment, torque, and friction. (Guo et al., 2016). The crowning and round of the hub teeth and creation of distance (reaction between the gears) prevent clogging and cause small angular displacement between the sleeve and hub axes and allow us to have a relative axial slip (Brommundt and Krämer, 2005). Designing a suitable crown can not only increase service life but also reduce component replacement and reduce safety risks for operators. Many factors, such as dental materials and working conditions, can affect the performance of the coupling crown (Guan et al., 2019). The most common gear coupling failures are abrasion and tear due to lubrication problems because they leak with centrifugal force and over time in ring-type seals. If the lubrication is maintained, these couplings will work successfully for years (Mancuso, 1994).

6.5.1.2 Grid coupling

The network connection consists of two hubs, a shaft, a spring with a metal mesh, and a cover with a detachable property (Fig. 6.13C). Torque is transmitted through a metal mesh spring between two shaft hubs. In grid coupling, both hubs have high torque and damping fluctuations. These couplings have a unique ability to reduce vibration by up to 30% to protect equipment and power transmission because they hit the cover. They are easy to install and easy to maintain. The traction spring member absorbs the impact energy over time and reduces the peak load. The network breaks down for several reasons: misalignment, overload, and high torque. Grease is used to lubricate any tension that may occur between the net and hub. These couplings are not used in pumps with a power consumption of 750 kW (Girdhar and Moniz, 2011; Patel et al., 2020).

6.5.1.3 Disc coupling

A disc coupling is presented in Fig. 6.13D. The structure of disc coupling usually has two aspects; one is that they are made as an integrated structure, and the second is that they are connected as hubs. The flexible or metal part is located between the disc and the drum. These types of couplings are applied in pumps with a power of more than 75 kW. Bending and diaphragm shape can lead to changes in the stiffness of disc joints (Girdhar and Moniz, 2011; Li et al., 2019; Zhao et al., 2016).

6.5.1.4 Elastomeric compression type coupling

These couplings are more compact for compression designs and torque grading and have less torsional flexibility. Spider jaw is the simplest form of elastomeric compression type coupling and is used for centrifugal pumps. The coupling consists of a cross section of elastomers attached to a jaw and transmits force to them (Johnson, 1996). Fig. 6.14A and B are external and internal views of the coupling type of elastomeric compression by Solid Works software version 2020.

6.5.1.5 Elastomeric shear-type coupling

In shear-type couplings, the driving and driven hubs operate in separate plans, while the driving hub pulls the driven hub through an elastomeric element suspended between them (Fig. 6.15). Among all couplings, this type can probably take the maximum amount of parallel misalignment. These couplings are used in pumps below a rating of 75 kW. Compression coupling has more advantages over shear couplings, including more load capacity, tensile strength, more security, and easy installation (Girdhar and Moniz, 2011).

Centrifugal pumps are connected to the drivers through couplings. Couplings are either hard or flexible, so the selection is determined by the kind of pump and driver tolerance. Hard couplings have neither radial nor axial motion, so their use as a shaft in combining pumps and drivers with two or three bearings is limited (Karassik and McGuire, 1998).

6.5.2 Base plates

According to Stewart Maurice in 2019, the base plate is where the feet of the pump is connected to the foundation (Fig. 6.16A and B (CENTRIFUGAL PUMP 02 (1).pdf - Google Drive)). The base plate for the centrifuge should

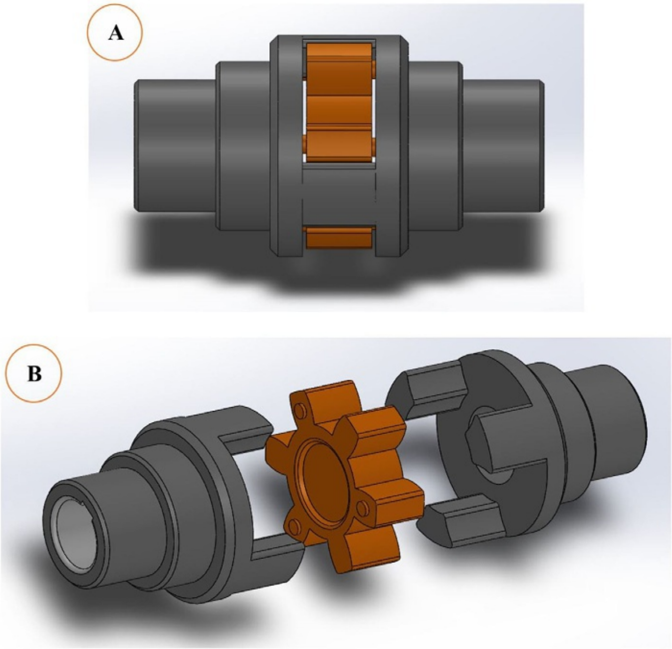


FIG. 6.14 (A) Exterior and (B) internal views of the coupling type of elastomeric compression.

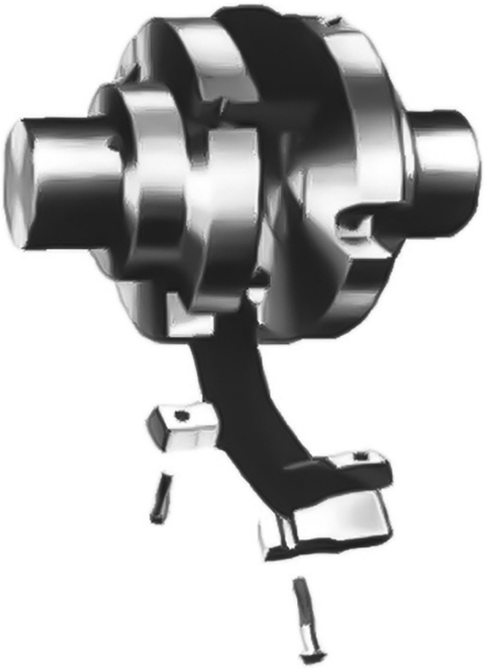


FIG. 6.15 Elastomeric shear-type coupling (Girdhar and Moniz, 2011).

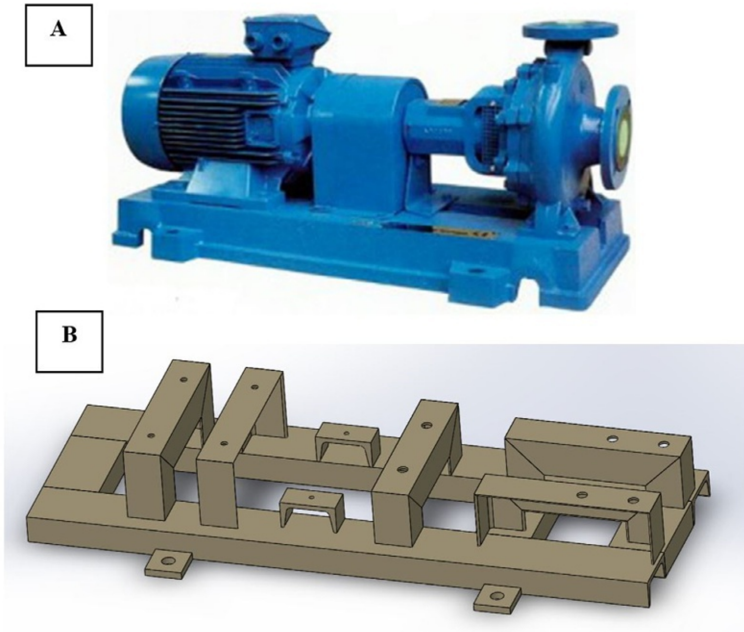


FIG. 6.16 (A) Centrifugal pump on a structural steel base plate (Stewart, 2019b) and (B) base plan designed by solid work (Brozoski, 2018).

be designed to not get out of control and is completely rigid. Therefore, it is necessary to check the alignment carefully before starting work. As the size increase, the weight on the base plane and its cost increase. A more rigid installation can be obtained by using individual bases or soleplates and building up the foundation to various heights under the separate portions of the equipment. The rigidity of the base plate used to mount the pump, and its drive chain will directly affect the life of the pump and its mean time between failures or repair. The base plate must support the installed equipment and the loads created by the pump and drivers. The cheapest base plate is a piece of steel channel and a rolled steel, the bases must have several features including:

(a) installed surface must be smooth and parallel,
(b) make sure that the base is level before pouring the grout,
(c) there is a way to grout the base,
(d) leak collection conditions are available (Stewart, 2019b).

The loads applied to the base plate are as follows (Gambhire, 2017):

1. The weight of the equipment itself (pump, motor, mechanical sealing system, coupling) and the main base weight.
2. Wet mass loads (wet weight with base structure).
3. Gravity acceleration ($9.8\ \frac{m}{s^2}$).
4. Maximum allowable loads.
5. Torque loads. The torque is applied to the center of gravity of equipment, pump, and motors.

6. Imbalance loads. When maximum force is applied to the center of gravity of the equipment.

Requirements set by Zeng and Schofield in 1996 (Brennan and Madabhushi, 2002; Zeng and Schofield, 1996) includes:

1. Complementary shear stresses must also be maintained in the end walls.
2. There should be no shear stress parallel to the vibration in the side walls.
3. Vertical placement at soil and boundary should be consistent to avoid initial centrifugal shear stress.
4. A stable movement to maintain tension should not occur at rest.

6.5.3 Drivers

Drivers must be able to produce the horsepower and torque required to drive mechanical equipment such as pumps, compressors, and fans used throughout the production facility. The most typical drivers are electric motors (usually induction and synchronous three-phase AC), internal combustion engines, and steam turbines. First of all, when working with centrifugal pumps, the motors should be checked (Stewart, 2019a). Alignment of drivers with pumps is permissible to the extent of tolerance. Therefore, when tightening the flange bolts, the pump level should not exceed 0.002 in. (Shiels, 2004). A turbine actuator rotates the pump shaft with the help of water vapor energy. Internal combustion is also an engine that runs on fossil fuels (diesel), and electric motors convert electrical current into the rotational current. Fig. 6.17 ((109) CAD CAM TUTORIAL - YouTube) shows the electric motor body for the horizontal axis centrifugal pump, designed by SolidWorks software.

The characteristics of electric motors are examined from two points of view (Eisenhauer et al., 2008):

General: The pumps are driven by an electric motor, the type of motor must be selected in such a way that the pump is not overloaded. All vertical motors must have a solid shaft structure, a motor with a hollow shaft will not be accepted. These motors are designed to operate at variable speeds, so the type of inverter must comply with the rules and requirements.

Balance: The power of these motors is 50 hp and more, and they design the pumps according to these motors.

6.5.4 Cooling water systems

The control of temperature generated in the stuffing box and bearings housings is a crucial factor in extending the life of packing, seals, and bearings, generally done by a cooling water closed circuit. This circuit, in turn, must be cooled by air through a radiator or water through a heat exchanger, each supplied by the engine manufacturer. Some rules of thumb when installing cooling water systems for stuffing boxes and bearing housings are as follows (Pumps, 2010; Stewart, 2019b):

- Pressurized oil system—maintain the temperature below 160°F (71°C).
- Non-pressurized oil system—maintain the temperature below 180°F (82°C).

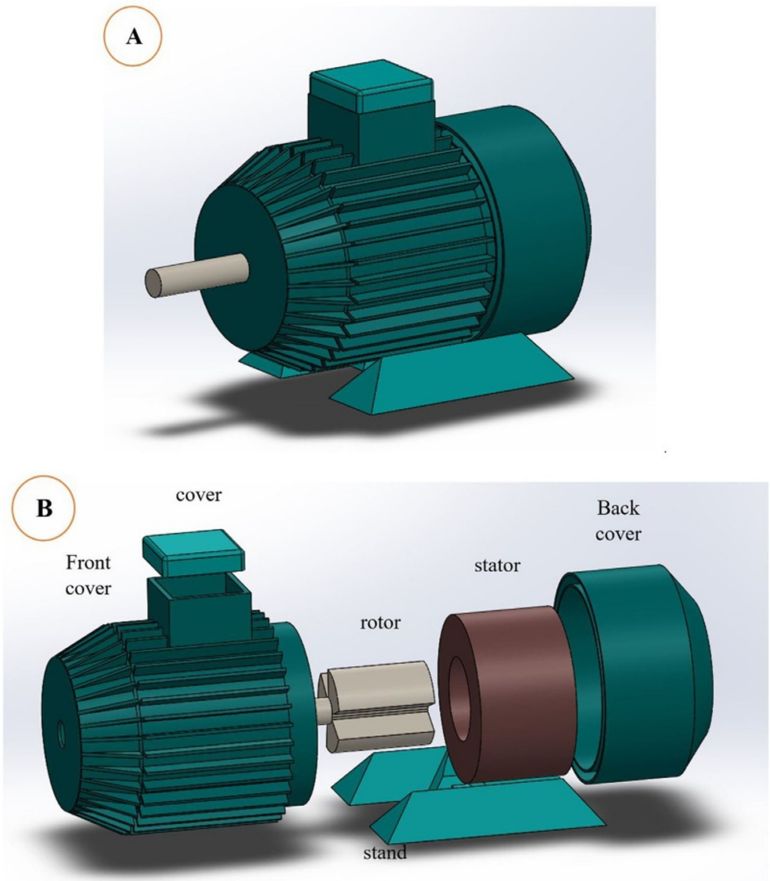


FIG. 6.17 (A) Electric motor body and (B) its parts for horizontal axis centrifugal pump, designed by Solid Works [CAD CAM tutorial (December 17, 2016)].

- Stuffing box with packing—maintain the temperature below 200°F (93°C).
- Stuffing box with mechanical seals—maintain the temperature below 180°F (82°C) unless sealing materials indicate the higher operating temperature is allowed.

6.5.5 Forced lubrication system of hydrodynamic bearings

Bearings should be inspected occasionally to ensure that enough oil is in the oil pockets. Oil rings should turn freely and supply enough oil to the shaft and bearings. Many interior parts of the pump, such as shaft sleeves in stuffing boxes, depend on water for lubrication (W.H. Lesser and Mines, 1950). Sometimes the lubrication system is also provided by the forced supply of oil to the driver bearing. A typical system is a combination of oil and a pump. The pump is driven by steam turbines or gear oil in the pump tanks. Such settings require the compatibility of the lubricating oil characteristic and the working temperature created by the manufacturers of the individual parts of the equipment. The use of oil rings for linear sleeve bearings, usually made with oil under pressure, is optional and not always justified. The function of the forced lubrication system is basically to supply oil to the bearing at the beginning of the pump operation before the forced feeding system has the time to do so. The bearings must have enough oil to meet their needs before delivery. A more precise lubrication system includes a drive axial oil pump that turns on before the main pump starts (Karassik and McGuire, 2012).

6.5.6 Cooling systems and lubrication of mechanical seals

Seals act as anti-leakage separators; if this method is impossible or for whatever reason it is uneconomical, the separation is done with minimal leakage in centrifugal pumps with different pressures. Mechanical seals must be cooled and lubricated with clean liquid to achieve longevity. In this case, low leakage rates can be expected from them. Two types of mechanical seals, single mechanical seals and double mechanical seals, are used in centrifugal pumps. If the pumped liquid is utilized, single mechanical seals are used because they are compatible with the environment when exposed to the atmosphere and do not crystallize. These seals are usually washed with the pumped liquid. Coolers can be installed in the flushing piping to cool the liquid with a heat pump and a cyclone separator. Jacket cooling located inboard of the mechanical seal is applied if the mechanical seal has to be protected from the hot liquid during a standstill. Double mechanical seals are normally used if the condition for the single mechanical seals is not acceptable. Double mechanical seals need to be flushed with clean and cool barrier liquid compatible with the pumped liquid and the environment. The barrier liquid is provided from an external seal system at a higher pressure than the pressure to be sealed so as not to contaminate the barrier liquid (Pumps, 2010).

6.5.7 Piping of centrifugal pumps and accessories

Poor plumbing design could undermine the overall competence of the pumping plant. The direction of rotation of the pump should be considered to designing the pump, since it may be the reverse direction of rotation of the pump so that the possibility of installing the pipe is more desirable. In the following, we will pay attention to some pipe terms (Figs. 6.18 and 6.19) (Lesser, 1950):

6.5.7.1 Discharge piping

Drain piping must be supported independently and close to the pump so that not too much pressure is applied to the shell when the bolts are tightened. It is generally recommended to increase the size of the pump nozzle, and if the needle nozzle is to be bent, its radius should be large to reduce friction head loss.

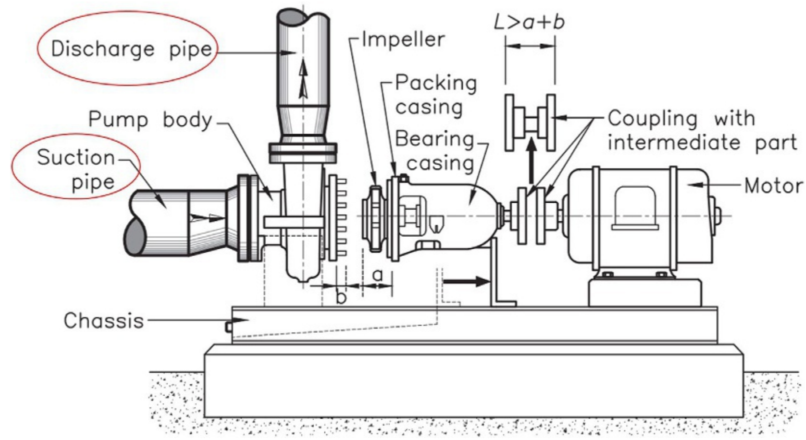


FIG. 6.18 Centrifugal pump installation and some pipe terms (Stewart, 2019b).

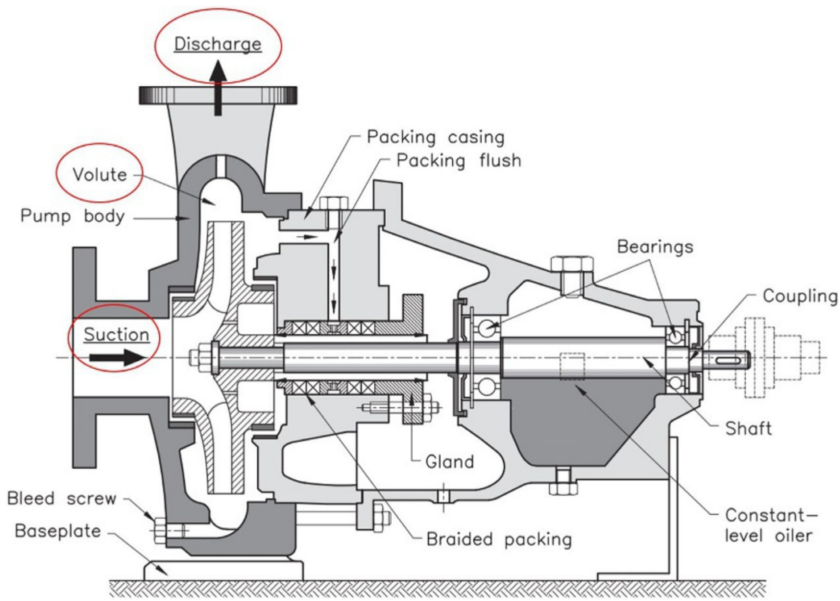


FIG. 6.19 Single-stage overhung pump from and some pipe terms (Stewart, 2019b).

6.5.7.2 Check valve

The main condition of a good valve is to allow free and unobstructed passage of water. In this case, friction loss is minimized, so it must be designed to pass the pump capacity through the flap with a medium lift.

6.5.7.3 Suction piping

It is vital to incline the suction line from the pump toward the sump. A high point in the suction line will fill with air, which will have an adverse effect on the operation of the pump. A straight taper reducer should not be used in a horizontal suction line because an air pocket will develop at the top of the reducer and the pipe.

6.5.7.4 Strainers

It should be so designed that a smooth and even flow of water will be obtained around the basket and through the basket slots, thus minimizing friction loss. Strainers having removable baskets or twin baskets can be cleaned more quickly than those from which the basket cannot be removed. However, they increase friction loss because of a change in the direction of water flow.

6.5.8 Foundation

Machinery foundations need special attention due to power transmission. Dynamic loads on the ground are static loads due to foundation weight, machinery, and accessories. The dynamic load of the device base is applied repeatedly over a long time, and its percentage is generally low compared to the static weight of the device and the support base. Therefore, soil behavior is essentially elastic (Prakash and Puri, 2006). The pump foundation must be normal in weight and volume to absorb the vibration of the pump. A concrete foundation is usually sufficient (Lesser, 1950). Foundation prevents torsional or linear movement of its base plate. The general rule for foundation design is that the mass of the concrete foundation is at least 5 times greater than the mass of the total equipment. This mass ratio is provided by the pump and drivers to absorb dynamic and static force. For pumps with less than 500 hp, the top of the base must be at least 3 in. wide (for large pumps 6 in.) and larger than the base plate. In addition, the foundation must be wide enough to support and completely dissipate the energy produced by the pumping equipment. Torsional flexing can cause a sharp increase in resonance, vibration, as well as misalignment of the driver and pump, resulting in separation of the base and slurry. With epoxy and cement slurry, ideally, the vibration created by the centrifugal pump can be absorbed (Mobley, 2001).

6.5.9 Coupling guard

Proper coupling guard design is required to protect couplings from damage, high-temperature protection of coupling chambers and oil-filled chambers (Bill Forsthoffer, 2005). Engineers designed guards for the highest level of safety and protection of rotating equipment.

6.6 Centrifugal pumps selections

Centrifugal pumps can be used for any kind of application due to their simple design, but many factors such as design, energy, flow, pressure, and suctions of pumps are significant to operate perfectly. Choosing the correct form of pump is the first step to ensure that, generally, it is preferable to select pumps with high speed. The suitable centrifugal pumps for specific services can be related to pump engineer, position, and overall cost (Lobanoff and Ross, 2013; Girdhar and Moniz, 2011).

6.6.1 Common errors in pump selection

Pump problems can reduce efficiency and cause a breakdown in the pump (Shmarlahu, 1996). There are lots of problems that affect centrifugal pumps when in use, which include both mechanical and hydraulic problems. The problems that will be addressed here will be hydraulic failures (cavitation, pressure pulsations, radial thrust, axial thrust, suction, and discharge recirculation), mechanical failures (bearing failure, seal failure, lubrication, excessive vibrations, fatigue), and other types of failure (erosion, corrosion, excessive power consumption). Some common errors, such as cavitation, poor system, design, and lack of maintenance, are not caused by the pump itself. Some other issues caused by cavitation, such as vibration, can lead to mechanical damage to the pump. Cavitation-related problems also have the potential to reduce pump life from 10 to 15 years, down to just 2 years in extreme cases (McKee et al., 2011).

6.6.1.1 Hydraulic failures

Cavitation

Cavitation is the formation of vapor bubbles in a moving fluid where the pressure of the fluid falls under its vapor pressure. It is the most common error in centrifugal pumps. Cavitation is frequently accompanied by noise, vibration, and a significant increase in discharge pressure, pulsation, and/or loss of flow. Cavitation damage, which occurs on the low-pressure or visible surface of the impeller inlet vane, is accompanied by four symptoms (Kamiel et al., 2015):

(a) Erosion—The collapse of the cavities in areas of higher pressure can exert lots of local stresses on the surfaces against which they are causing damage to the pump surfaces. Damage occurs because when the cavities erupt, the released liquid hits the pump's surface at high speed, which results in a high surface pressure that can be higher than the strength of the material. It is been obvious that cavitation damages increase rapidly with the increase in the volume of fluid.

(b) Noise—The sound of the cavities collapsing under higher pressure is a loud crackling sound like it was pumping stones. The sound of the noise resulting from cavitation is a measure of the severity of the cavitation. The noise can be heard in and around the pump suction.

(c) Vibration—Pump vibrations due to cavitation are characteristically high amplitude and low frequency, usually in the 0–10 Hz range.

(d) Reduction in pumping efficiency—The vapor bubbles created around the impeller cut off the flow of fluid being pumped, thus resulting in a reduction in output.

Pressure pulsations

Pressure pulsations only occur in high-pressure pumps, where the head of water is around 300 m. For high-head pumps, suction and discharge pressure pulsations may cause a vibration of suction, discharge piping, reduction in pump controls, and high pump noise levels. Pressure pulsations are also obvious in both the suction and discharge of centrifugal pumps.

Suction and discharge recirculation

Recirculation usually occurs during the reduction of flows, and it occurs due to some fluid around the impeller to the suction side. If this is found inside of the impeller, then it is known as suction recirculation. If this is found at the outlet of the impeller, then it is known as discharge recirculation.

Air in the suction pipe

Air in the suction pipework or entrained gas in the pumped media has the effect of reduced pump performance and creates the same symptoms as cavitation.

6.6.1.2 Mechanical failure

This kind of failure can arise in different parts of the pump, like bearing, sealing, and some errors in the impeller.

Impeller contact with casing/backplate

Contact is mainly attributed to:
- incorrect clearance between impeller and backplate
- worn bearings on the motor
- excessive high inlet pressure
- foreign object
- pressure shock
- incorrect rotation (Kim et al., 2009)

Bearing failure in motor

Bearing failure can occur for several reasons such as:
- excessive high inlet pressure
- temperature exceeding pump design limits
- cavitation
- coupling/Shaft misalignment
- inadequate lubrication
- excessive pressure surges (Kim et al., 2009).

Seal failure

Mechanical seals problem occurs due to the dry pumps. Most of the time to prevent this problem, pump-sealed packing is lubricated from external parts. Mechanical seals, in general, fail for two reasons: the lapped faces open up, or one of the seal components becomes damaged. When a seal face opens, it allows solids to penetrate the lapped surfaces (Marscher, 2002).

6.6.2 Pump specification

Some essential factors that specify centrifugal pumps include volume flow rate, efficiency, pressure, head, and power. It is important to know the features of pumps that significantly affect the operation of the pumps. The most important feature of the pump about flow rate and the head is related to the information on Net positive suction head available (NPSHA) (Güner and Özbayer, 2020).

(a) Flow rate: The pump can move the fluid through the whole system, usually expressed as gallons per minute (gpm). The capacity of the pump and flow rate should be in match to the system.

(b) Pressure: It shows the pump's resistance against the force per unit of area that is expressed by bar or psi (pound per square inch). It is the combination of flow rate and power to describe pump performance.

(c) Head: The head position is above the suction inlet, which helps the pump lift the fluid. Normally, centrifugal pumps are used instead of pressure to determine the pump's energy and resistance, but pressure refers to the specific gravity of the fluid. This part is related to the height of water in feet (ft) or meter (m) unit and is equivalent to the height it reaches.

Pump head (H) can be converted to pressure (P) using specific gravity (SG) of the fluid by.

$$P = 0.434 \times H \times (\mathrm{SG}) \tag{6.1}$$

Or by the density of the fluid (ρ) using gravity (g) by the following equation:

$$P = H \times \rho \times g \tag{6.2}$$

(d) NPSH: It causes due to some differences between the pump inlet pressure head and vapor pressure head. It is a very significant parameter in terms of preventing pump cavitation.

(e) Power: The power can transfer to the fluid by the effect of the net head, which is called output power (P_{out}) or it should be transferred to the pump (P_{in}) in terms of horsepower (hp); it represents the power of the pump that will do to the fluid, which can be calculated by

$$P_{\mathrm{out}} = \dot{m} \times g \times H = \rho \times g \times Q \times H \tag{6.3}$$

where ρ is fluid density, g is the acceleration due to gravity, Q is the volumetric flow rate, H is the pump head, and $\dot{m}$ is the mass flow rate.

(f) Pump deficiency (η_{pump}): It refers to the percentage of energy supplied to the pump converted to useful work. Eq. (6.4) shows the ratio between input and output power:

$$\eta_{\mathrm{pump}} = P_{\mathrm{out}}/P_{\mathrm{in}} \tag{6.4}$$

6.6.3 Type and size selection

6.6.3.1 Pump type

Centrifugal pump is the most common type due to its simplicity, capacity, high efficiency, flow rate, and ease of operation. The pump can help the fluid move, which flows from high-pressure to low-pressure regions by increasing the pressure in the fluid. Before purchasing the pump, we must know the type of pump for each application to ensure which is suitable for delivering that given flowrate to the given pressure. There are two main types of pump, roto-dynamic, and positive-placement. In a roto-dynamic pump, impeller rotation can impart energy to fluid and cause movement in it (Fig. 6.20). The amount of roto-dynamic pump outlet changes with pressure and is directly related to the fluid which passes through the pump (Jensen et al., 2004).

The other three classifications in the type of pumps are based on the flow of the impeller including radial, axial, and mixed flow.

(a) *Axial* flow pumps are based on high flow and low pressure. They lift liquid to the impeller shaft in the same direction. Pressure is developed by the action of the impeller vanes (Fig. 6.21A).

(b) *Radial* flow pumps are based on high pressure and low flow. They move liquid through the center of the impeller to the side of the impeller blades to the pump shaft. Pressure is developed by centrifugal force (Fig. 6.21B).

(c) *Mixed* flow pumps are a combination of both axial and radial flow pumps, with average flow and pressure. They move liquid out away from the shaft at an angle higher than 90°. Pressure is developed by both centrifugal force and the lifting action of the impeller (Fig. 6.21C).

Different type of pump is classified by their application (Gülich, 2008):

(a) Single-stage pump: Fig. 6.22A shows a pump that is very common in the industry, the area of their application is water supply, sewage, and chemical processing.

(b) Circulating pump: The pump that is shown in Fig. 6.22B is based on motor design. The motor and bearings are in touch with liquid to cold the pump,

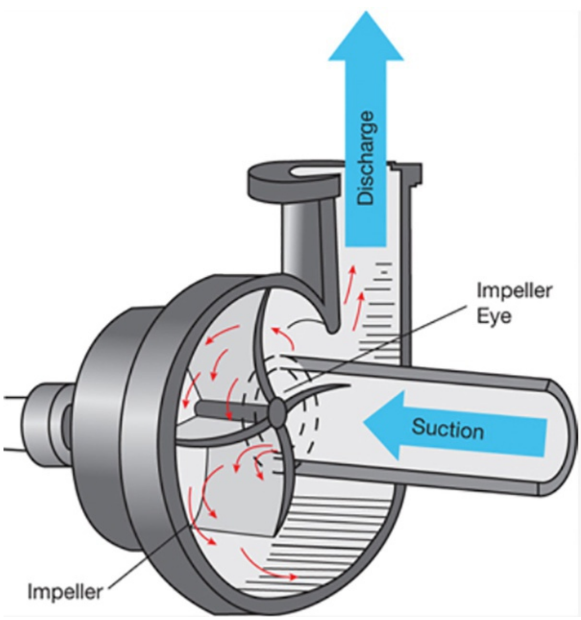


FIG. 6.20 Rotation of impeller (Jensen et al., 2004).

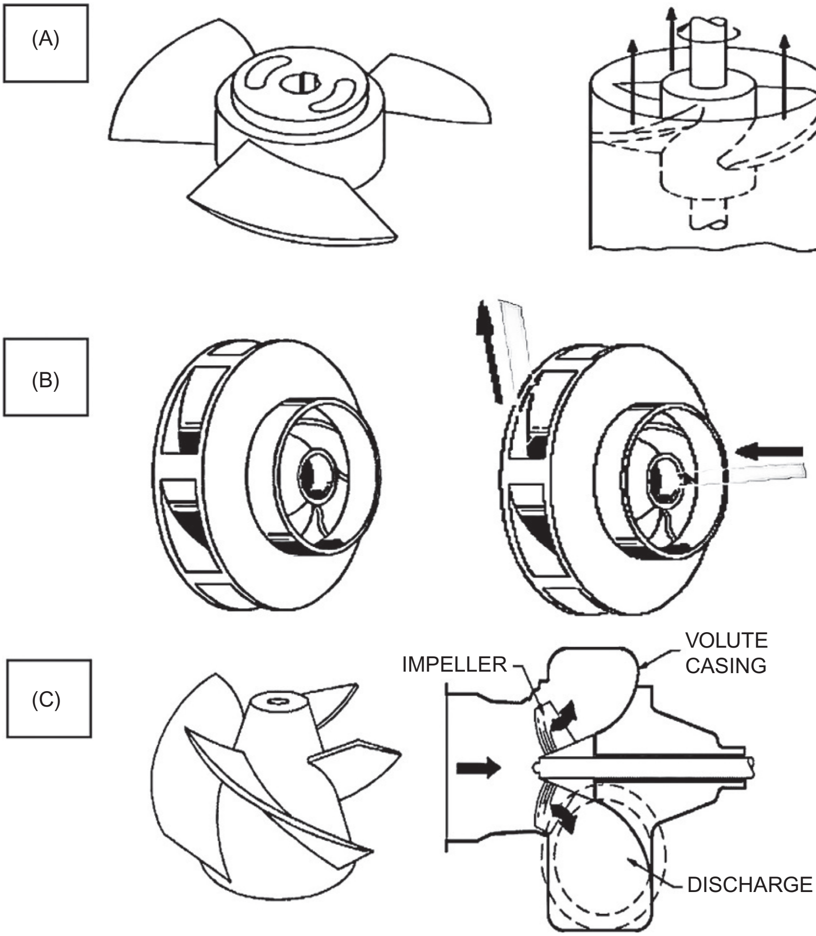


FIG. 6.21 (A) Axial flow impeller, (B) radial flow impeller, and (C) mixed flow impeller (Bachus and Custodio, 2003).

and this kind of pump is used when no shaft seal is required. When the liquid passes through the gas between different parts, it removes the heat made by the motor.

(c) Double-entry vertical booster pump: Fig. 6.22C shows that this pump feeds the pump in the pipeline to move drinkable water. Single-stage and double-entry both are designed for a specific speed of about 10–100.

(d) Multistage, single-entry pumps: If the specific speed falls to the lower efficiency level, the energy cost will unreasonably increase. Multistage pumps are used when the speed is not at the perfect level (Fig. 6.22D).

(e) 12-stage pump with double volutes: Fig. 6.22E shows a 12-stage pump with double volutes. This pump can remove the whole rotor after lifting off the upper half of the casing.

(f) High-pressure seawater pump: Fig. 6.22F shows a back-to-back arrangement of a 12-stage diffuser pump related to seawater.

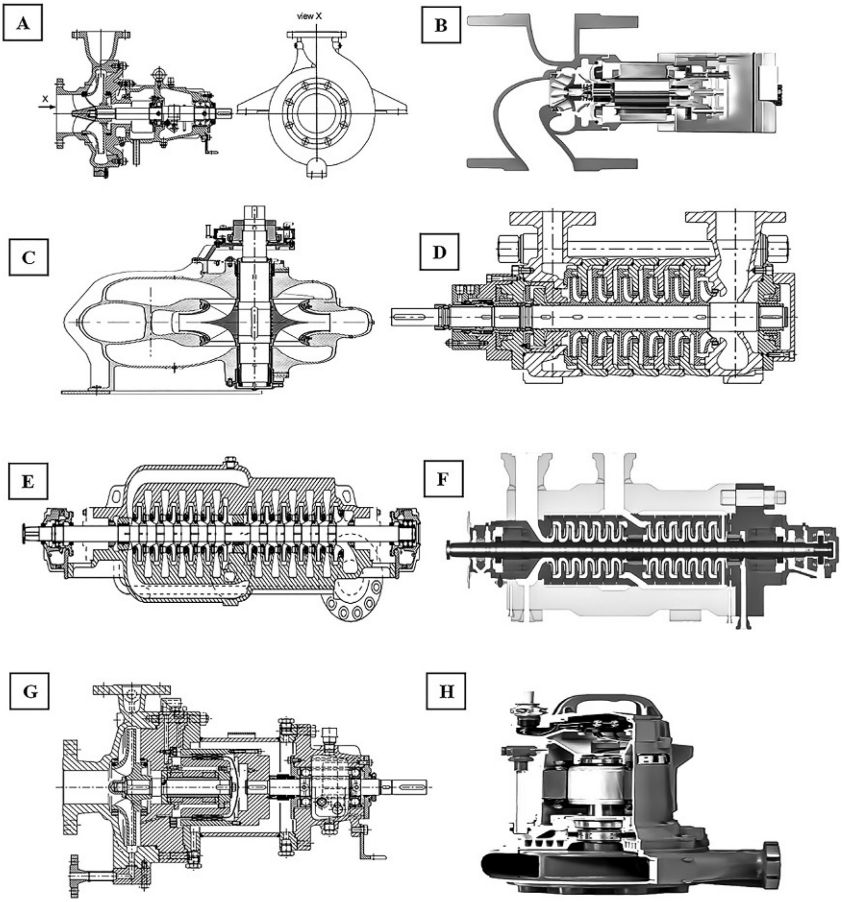


FIG. 6.22 (A) Single-stage volute pump, (B) circulating pump for central heating installation, (C) double-entry vertical pump, (D) multistage segmental pump with suction impeller and balance disc, (E) multistage, axial-split pipeline pump with double volutes, (F) high-pressure seawater injection pump, (G) sealless process pump, and (H) submersible sewage pump (Gülich, 2008).

(g) Sealless pumps: As shown in Fig. 6.22G, they are used when risky or toxic substances need to be prevented from leaking into the environment.

(h) Submersible pump: This pump can reduce the cost of pumping especially when there is a long pipe inside to move the fluid (Fig. 6.22H).

6.6.3.2 Pump size

The size of the pumps is related to the flow and pressure rating of the pump required for the process. The mass flow rate should be at a reasonable level to stabilize the process flow diagram and overcome the hydraulic resistance of pipe and valves to let the liquid move through the system. Hydraulic resistance is familiar as a system head that is directly related to the amount of pressure to reach the flow rate in the system. In the system head, whatever the faster liquid flow, the highest the system head reaches. The exact size of the pump is significant, and oversized pumps normally require more frequent maintenance than correct-sized pumps (Gülich, 2008).

6.6.4 Technical and qualitative criteria in the selection of centrifugal pumps

Normal selection criteria for centrifugal pumps are based on their design data [flow rate or capacity (Q), discharge head (H), impeller speed of rotation, and NPSH]. Knowing the criteria can help minimize energy, reasonable cost, and prevent production losses based on pump failure (Gülich, 2008).

The main qualitative criteria in the selection of centrifugal pumps are:

- the number of stages (single-stage, multistage),
- the place of the shaft (horizontal, vertical),
- the pump casing (radial, e.g., volute casing, axial, e.g., tubular casing),
- the number of impeller entries (single entry, double entry),
- the type of motor (dry motor, dry rotor motor, e.g., submerged motor, wet rotor motor, e.g., submersible motor).

These features usually refer to the qualitative criteria in designing and selecting this pump.

Technical pump selection criteria features include:

- the mode of installation,
- the nominal diameter (for the pump size, as a function of the flow rate),
- the rated pressure (for the wall thickness of casings and flanges),
- the temperature (e.g., for the selection of cooling equipment for shaft seals),
- the fluid pumped (abrasive, aggressive, toxic fluids),
- the type of impeller (radial flow/axial flow depending on the specific speed)

6.6.5 Production quality of centrifugal pumps

Centrifugal pumps are characterized by simplicity of design, provide high performance and pressure, and can be used in applications that require transportation of fluid containing impurities. They are well proven in operating conditions with permanent high loads and in complex operation modes. They are particularly effective for pumping large fluid volumes. The design of different parts of centrifugal pumps can lead to high quality of that. Whereas centrifugal pump uses energy, impeller and pumps circulation power to move fluid and vacuum situation in the pump makes fluid move toward the impeller by suction and even the impeller cause velocity in liquid and easily discharge it from the pump. So, the impeller part has a significant role in achieving a very high flow rate in a centrifugal pump. The most common pump shaft is made of carbon steel. There are lots of cracks to help seals and bearing and make low clearance and high surface quality. Both surface quality and clearance have an important impact on the impeller, especially the position and design of the shaft and the clearance in the impeller. If the steam valve is out of adjustment, it causes some stroke in the pump (Krutzsch, 1976; Okokpujie et al., 2017).

If it is much more than usual, the piston will break the cylinder head and then decrease the motion and capacity of the pump. So, having both piston and valves in the cylinder affect the quality of the centrifugal pump. As shown in Fig. 6.23A, by decreasing the steam, the motion will be fixed in the pump by some significant changes like putting a tappet between the valves. Size is another factor that affects the quality of the centrifugal pumps. As shown in Fig. 6.23B, large pump changes the lost motion by using nuts to the fitted form by moving the valves on each side till they hit the nuts. Sometimes it is better to change the steam valve while the pump is working, but it is impossible to perform this mechanism unless the steam removes as shown in Fig. 6.23C (Krutzsch, 1976).

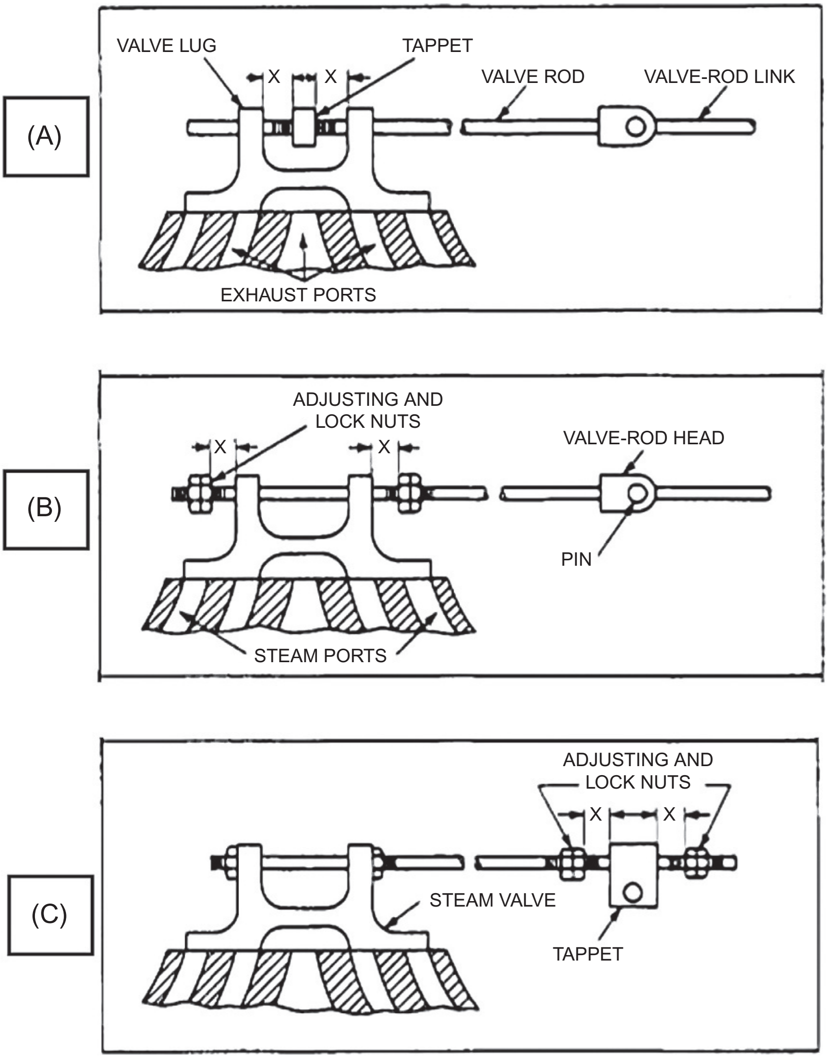
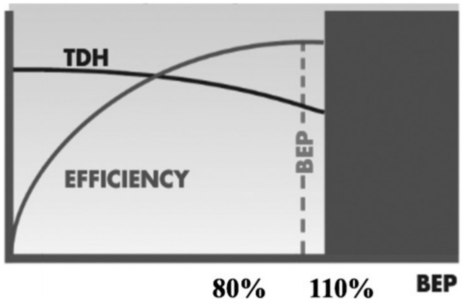


FIG. 6.23 Steam valve motion (Karassik et al., 2008).



FIGS. 6.24 BEP in centrifugal pump (Kernan, 2009).

Best efficiency point (BEP), the point that flow rate has the highest efficiency, is the perfect way to show the quality of the centrifugal pump. Just a few pumps operate in their BEP because the whole process is not steady. Unluckily, many pumps cannot reach this level. The proper size of the pump will have flow near the peak of efficiency. As shown in Fig. 6.24, the range between 80 and 110 has maximum efficiency and minimum risk. The total dynamic head (TDH) of the pump is a critical point with respect to the BEP (Kernan, 2009).

Based on the pump and risk associated with the cost of equipment, it requires some specific test on the quality of the centrifugal pump which normal test is hydro-test, pump performance, or NPSH-test. Overall, pumps configuration, including pump selection, performance, and design can affect the final quality of the centrifugal pump.

6.6.6 High-energy pumps

A high-energy pump is defined as an upper than a certain level. During the past decades, using the pump machinery was a lot and concentrated on power within the given volume, but it is affected by cost and improvement. The pump uses this energy to move fluid from one place to another at less pressure and flow rate. The perfect energy level shows that a smaller size and less stage in the multistage pump can cause more rotation speed and speed of high power in a centrifugal pump. Knowing the exact energy level in the centrifugal pump can prevent any damages such as cavitation, rotation, and erosion of the suction. Most pumps suffer from rotation, vibration, hydraulic stabilities, the problem with a component, and cavitation (Onari and Arzani, 2014).

If the energy level is obvious, operating and overcoming any kind of difficulties in pumps will be easy. The most concern regarding centrifugal pumps is they are high-energy pumping machinery, especially the interaction of flow related to mechanical and material response. Some factors in determining energy level are the total head and density and another parameter is pump-specific speed related to pump-and-impeller geometry. The specific head can connect two parameter head and specific gravity to define “High energy”. Based on general pump operation, the measure of high-energy versus low-energy is shown in Fig. 6.25 (Onari and Arzani, 2014). The line separating high and

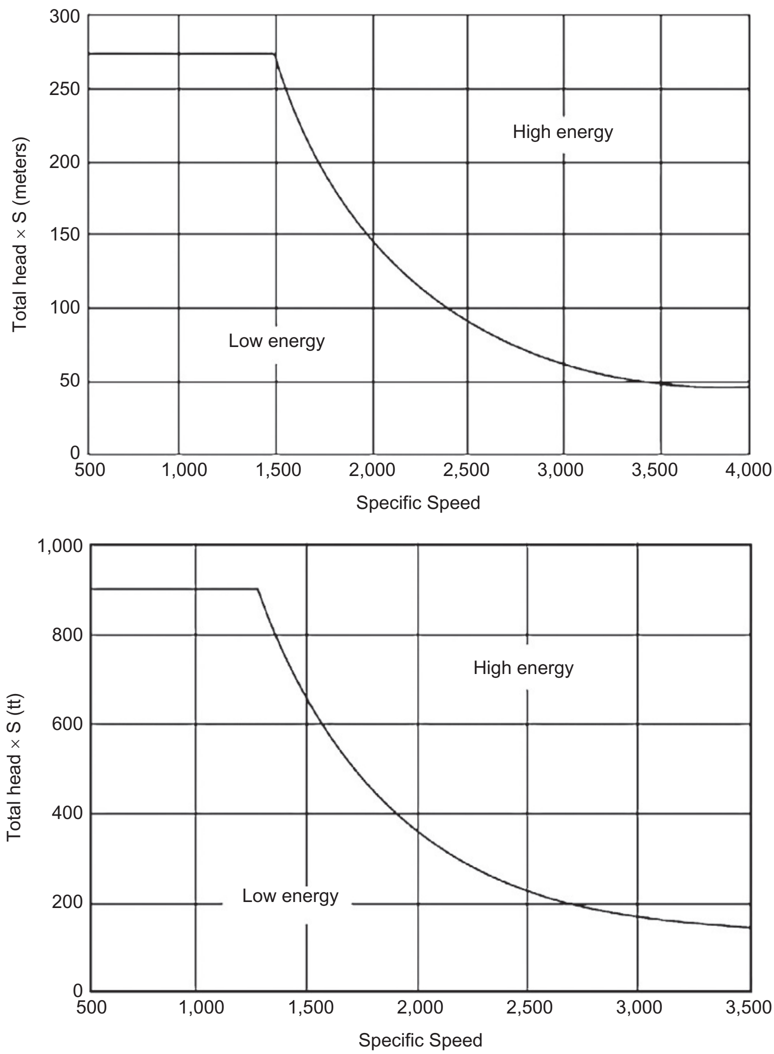


FIG. 6.25 High- and low-energy curves (Onari and Arzani, 2014).

low energy is almost constant level, but it is not exactly a separate line. It is considered as high or low energy in pumps really close to this line.

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Chapter | Seven

Positive displacement pumps

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7.1 Positive displacement pumps

Pumps are mechanical devices that use energy to raise the static pressure and flow rate of a liquid. Positive displacement pumps (PDP) work by forcing a liquid via mechanical equipment, such as a piston or plunger. Inside the pump chamber, the liquid volume is reduced until the liquid pressure equals the pressure of the discharge device. The liquid is mechanically pressed, resulting in a straight increase in potential energy to achieve the desired discharge (Stewart, 2018). PDPs can self-prime and operate at low suction pressures while producing high pressures. The capacity of a PDP is unaffected by the pressure against which it drives. By changing the pump's speed, the flow rate of PDP is generally controlled. They are typically employed in low-flow and high-head applications. Usually, they are used in smaller sizes and high-pressure areas, as well as for non-Newtonian liquids such as in food industries (Nesbitt, 2003). PDPs discharge a fixed quantity of fluid for each period of pump action. As long as the capacity of the power unit operating the pump is not exceeded, this quantity remains the same irrespective of the system's resistance to flow. However, a pump with many compartments may have lapping deliveries among individual compartments. Hence, unlike other pumps, a PDP creates a consistent flow independent of pump speed or discharge (Smith and Mobley, 2003). The selection and place of application of different PDPs are shown in Table 7.1.

7.2 Types of positive displacement pumps

PDPs are categorized as rotary and reciprocating pumps, based on the movement of the pressure-producing parts. Both types of pumps should have pressure

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TABLE 7.1 Selection and application of positive displacement pumps.

Type	Maximum pressure (psi)	Maximum flow (gpm)	Place of application
Reciprocating			
Piston	1500	800	Glycol pumps, steam generator feed pumps, condensate pumps, drilling mud pumps, and additive injection pumps are some of the most common applications but in the absence of solids only.
Plunger	6000	300	Same as piston pump, but solids are present.
Diaphragm	1000	10	Mostly used as a metering pump in regulated volume applications or where low flow rates and high solids concentrations are encountered.
Rotary			
Single screw or progressive cavity	200	450	Used for high-viscosity stocks (non-Newtonian), stocks with up to 30% (entrained) gas, and often for abrasive services. Not recommended for temperatures above 300°F or in carbon dioxide entrained gas services.
Two or twin screw	4500	8000	Used for low- and high-temperature liquids (up to 600°F) with and without abrasives, and as a multiphase pump (90% plus gas, the remainder liquid) with and without abrasives with unique design.
Three screw	4500	1000	Used in large machines for low-temperature, high-viscosity stocks (lower than progressive cavity) without abrasives and circulating lubrication fluid.
Rotary gear	700	150	To transmit recovered oil from a drain separator to a process oil/water separator, this device is used. Also utilized as a diesel transfer pump in high-viscosity applications, as well as for circulating lubrication oil for large machinery and other clean, high- and low-pressure services.

Source: *Source: Stewart, M., 2018. Surface Production Operations: Volume IV: Pumps and Compressors. Gulf Professional Publishing.*

releasing systems on the discharge side, either in the discharging pipework or designed for the machine. The pressure-releasing valves in pipework may release directly to the suction side of the pump or into the environment, depending on the nature of the liquid. To balance outflow, they may need pulsation dampening or surge vessels in discharge pipework (Moran, 2017). The detailed classification of the PDPs is shown in Fig. 7.1.

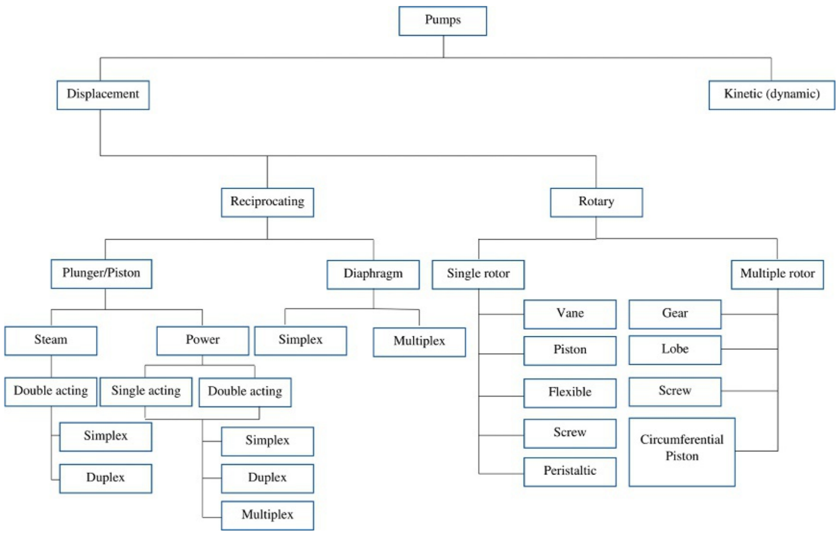

FIG. 7.1 Classification of the positive displacement pumps.

7.2.1 Reciprocating positive displacement pumps

A pump that holds a fixed amount of fluid near the suction nozzle and pushes it out through the discharge outlet after compressing it to the discharge pressure with the help of a diaphragm, plunger, or piston is known as a reciprocating pump (Henshaw, 1999). Such diaphragm, plunger, or piston pushes one or more boundaries linearly, adding energy to the fluid intermittently and continuous to-and-fro action of a diaphragm, plunger, or piston within a set cylinder or volume drives the liquid.

In general, on the cylinder head, there are two non return check valves. The outlet valve can be opened only outwards, and the inlet valve only inwards. The inlet valve opens as the piston retreats, drawing fluid into the expanding chamber. As the piston advances, the outlet valve opens, the inlet valve closes, and the liquid is forced against discharge pressure. Fig. 7.2 shows the schematic representation of a reciprocating piston pump.

Power pumps and steam pumps are the two types of reciprocating pumps. A power pump is made up of two parts: a power end and a liquid end. Power pumps are frequently powered by gasoline-powered or electric motors, or any device that gives a reciprocating or rotating movement to the pump. The liquid end is comprised of valves, outflow ports, inlet ports, and pistons or plungers. The frame, crossheads, connecting rods, bearings, crankshaft, and, in some cases, reduction gears make up the power end. Steam pumps are comprised of a steam cylinder and liquid end combined by a spacer cradle. Steam pumps can be powered by air or steam. Valve mechanisms and pistons make up the steam or air end. Steam pumps are not usually intended to allow any change in the output flow while they are running. As a result, they cannot be used as a metering pump in a system that requires regular flow rate adjustments.

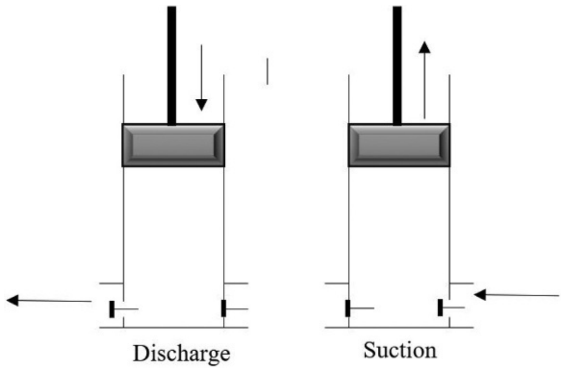

FIG. 7.2 Schematic representation of a reciprocating piston pump.

7.2.1.1 Types of reciprocating positive displacement pumps

Piston or plunger-type reciprocating pumps

The plunger or piston of a piston pump moves into the liquid after passing over a stationary packed seal (Fig. 7.2). The liquid is forced out of the cylinder by the seal, and the plunger movement causes the flow to increase and decreases alternately. The volume accessible in the cylinder rises as the plunger or piston goes backward (suction stroke), which opens the suction valve and allows the fluid to enter the cylinder. Similarly, the volume accessible in the cylinder decreases during the discharge stroke as the piston or plunger advances forward, the pressure of the fluid rises, and the fluid is forced out through a one-way discharge valve.

Piston pumps are classified as double-acting or single-acting and duplex or simplex pumps. If the fluid is pumped exclusively in one direction during linear movement, the pump is categorized as "single-acting." If the fluid is pushed in both directions during the motion, it is categorized as "double-acting."

More specifically, a single-acting pump's suction stroke takes a suction and fills the cylinder of the pump in a single direction only before the discharge stroke. A double-acting pump refills one end of the cylinder while emptying the other. On the return stroke, the previously emptied end of the cylinder is filled, and the previously filled end is emptied (Tackett et al., 2008).

Reciprocating PDPs can also be categorized according to the number of cylinders. A simplex pump contains one cylinder, a duplex contains two cylinders, a triplex has three cylinders, and so on. However, a duplex pump's pistons are driven such that when one piston is on its downstroke, the other one is at its upstroke, and vice versa. In comparison to a simplex pump of a similar design, the configuration of a duplex pump doubles the capacity (Volk, 2013).

Diaphragm-type reciprocating pumps

A reciprocating pump that uses a moving diaphragm within a stationary chamber is known as a diaphragm-type reciprocating pump (Fig. 7.3). Chemical injection, metering, proportioning, and controlled volume are all terms used

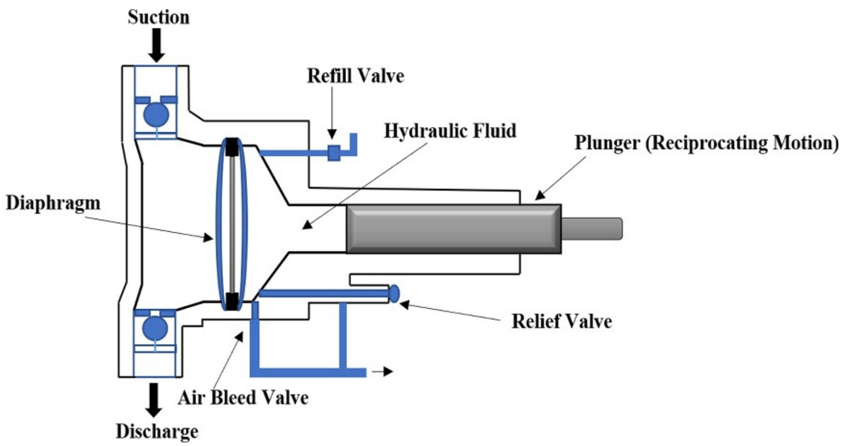

FIG. 7.3 Schematic representation of a reciprocating diaphragm pump.

to describe diaphragm pumps. The pump works in the same way as a piston/plunger, but in place of a cylinder, it uses an elastic pulsing diaphragm. The liquid is driven out when gas pressure is applied to one of the diaphragms. When the gas pressure in the suction line is relieved, the diaphragm flexes, allowing liquid to enter (Bajpai, 2018).

Diaphragms that are used are often made from Teflon or stainless steel, but elastomer-covered steel or elastomers are also used sometimes as diaphragms. The interspace of the diaphragm could be equipped with alarms to warn the industrial workers of process fluid contamination, such as conductivity, implying failure of the diaphragm. Such pumps can be mechanically driven or fluid-driven at variable or constant speeds. Diaphragm pumps can only operate at moderate temperatures and with low flow rates. However, a diaphragm eliminates wear due to the absence of any friction. Diaphragm pumps can also be utilized for fluids containing erosive particles for the same reason. They are affordable and easily changed (Bajpai, 2018).

7.2.1.2 Capacity of reciprocating pumps

A reciprocating pump's capacity (q) is the total amount of liquid transported per unit of time. At the specified working circumstances, the volume includes liquid as well as any entrained or dissolved gas. The capacity of the pump is calculated according to the following equations (Stewart, 2019b):

SI units

$$q = (1 - S)D \tag{7.1}$$

$$q = (1 - S)3600mnd \tag{7.2}$$

where

q = capacity of the pump (m^3/h).

m = number of diaphragms, pistons or plungers.

D = displacement of the pump (m^3/h).
n = pump speed (rpm).
d = displacement per pumping chamber (m^3).
S = slip, fraction.

FPS units

$$q = (1 - S)mnd \tag{7.3}$$

where

q = capacity of the pump (gpm).
m = number of diaphragms, pistons or plungers.
D = displacement of the pump (gpm).
n = pump speed (rps).
d = displacement per pumping chamber (gal).
S = slip, fraction.

The displacement is calculated per stroke per chamber of the diaphragm, piston, or plunger with no losses due to fluid compressibility or slip. When a pump runs at a certain speed, the overall displacement of all chambers is called the displacement of the entire pump. Also, when calculating displacement on double-acting piston pumps, the volume of the piston rod should be deducted. Slip is defined as capacity loss expressed as a proportion of displacement of the cylinder due to valve losses, volumetric efficiency, and stuffing box losses.

7.2.1.3 Efficiency and power of reciprocating pumps

The hydraulic power of the pump is determined using the following equations (Stewart, 2019b).

SI units

$$\text{HHP} = \frac{(\text{TDH})(\rho)(Q)}{367000} \tag{7.4}$$

where

HHP = hydraulic horsepower (kW).
TDH = pump head (m).
Q = flow rate (m^3/s).
ρ = fluid density (kg/m^3).

FPS units

$$\text{HHP} = \frac{(\text{TDH})(\rho)(Q)}{550} \tag{7.5}$$

where

HHP = hydraulic horsepower (hp).
TDH = pump head (ft).
Q = flow rate (ft^3/s).
ρ = fluid density (lb/ft^3).

The brake horsepower is the amount of power applied to the pump's shaft and is calculated as follows (Stewart, 2019b):

$$BHP = \frac{HHP}{E_m} \tag{7.6}$$

where

E_m = pump mechanical efficiency (%).

BHP = brake horsepower.

7.2.2 Rotary positive displacement pumps

A "moving chamber" is produced between a pair of spinning parts (rotors) or between the pump housing and a single rotor in rotary pumps, and the liquid moves with the "chamber" from one end (suction) to another end (discharge) (Garbus et al., 2008). Rotary pumps are typically used in situations where the viscosity of the liquid is exceptionally high or the flow rate is restricted, and alternative pumps are not economically viable. The most prevalent uses for rotary pumps are: supplying fuel oil to burners, transferring diesel fuel, fuel oil, and gasoline to day tanks, and supplying lubricating oils through process machinery bearings, turbines, reduction gears, and engines; and (William C. Lyons et al., 2016).

7.2.2.1 Types of rotary positive displacement pumps

Eccentric rotor

Sliding vane. In the gas and oil industry, the sliding vane eccentric pump (Fig. 7.4) is the most popular pump (Cella, 2020). It comprises a drum that spins eccentrically and has radial perforations for sliding vanes. As the rotor rotates, the vanes go in and out. In the housing, the rotor is positioned off the center. The vanes move out of the rotor as they turn past the suction port, maintaining a continuous connection with the casing. As the drum rotates, the fluid pressure rises and decreases, resulting in the discharge of the liquid. Sliding vanes can maintain a constant flow rate and a constant discharge pressure with minor pulsation at a given speed. They perform well with low-viscosity fluids and are wear-resistant. On the other hand, they are unreliable and inexpensive

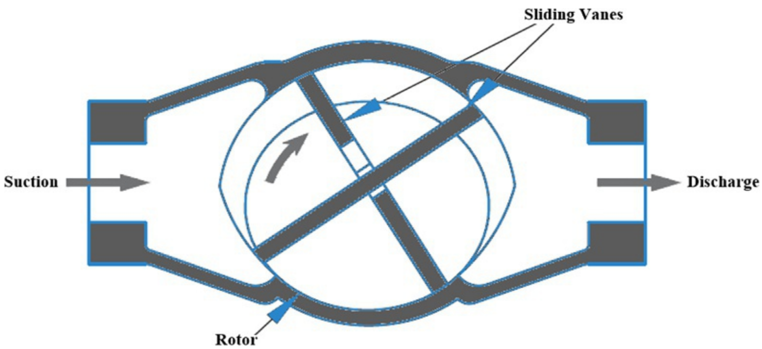

FIG. 7.4 Schematic representation of a sliding vane pump.

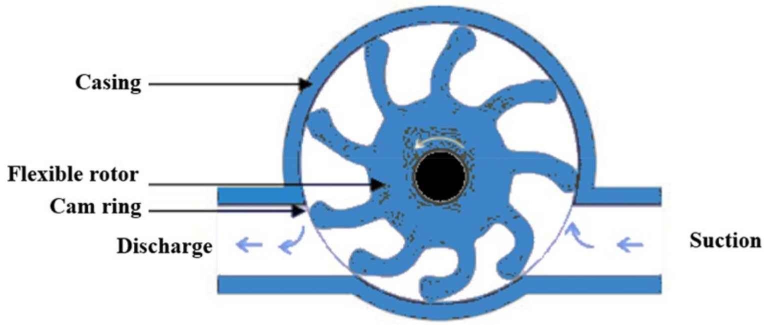

FIG. 7.5 Schematic representation of a flexible vane pump.

due to vane fractures. They are not suitable for highly viscous fluids because heavier liquids interfere with the sliding motion of the vanes.

Flexible vane. Flexible vane pumps have vanes made of a softer, pliable material attached to the rotor (Fig. 7.5). The vanes bend as the rotor rotates, conforming to the cylinder's eccentric geometry. They are easy to use, cheap, and able to produce a powerful vacuum. Only low-pressure, low-capacity, nondemanding applications are suitable for these pumps. They should not be used with high-temperature fluids and must not be allowed to run dry.

Gear pumps

Lobe, internal gear, and external gear are the three main types of gear pumps. Gear pumps transfer crude oil, heavy fuel, and lubricant oil for centrifugal compressors.

External gear. External gear pumps can produce high pressures, are compact, and are well-suited for viscous liquids. Pumps of this type are simple to build with various materials to assure compatibility with the pumped liquids, and they are ideal for shear-sensitive materials. The pump comprises two meshing gears of equal sized that revolve inside a housing, one driving and the other idle (as shown in Fig. 7.6). A vacuum is created when the gears on the pump's suction side are not meshed. The liquid is forced into the pump by atmospheric pressure, where it is carried to the discharge between the gear teeth and the casing. The

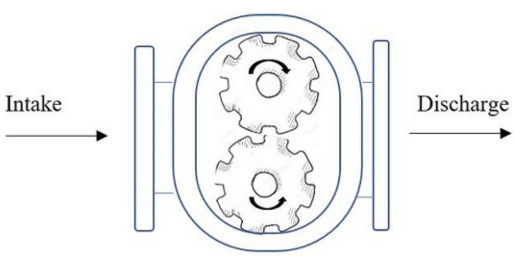

FIG. 7.6 Schematic diagram of an external gear rotary pump.

meshing of the gear teeth near the discharge produces a barrier that stops the liquid from returning. Gear pumps can be driven in either direction. When specialized characteristics, such as built-in relief valves or shaft seal bleed back, are used, extra caution must be exercised to ensure that the shaft rotation is precise.

Multiple gear sets on one shaft, such as helical, spur, and herringbone gears, are used to produce more capacity. Spur gears, which provide good contact between the teeth, are employed in low-capacity, high-pressure applications. This tight tolerance decreases slide while also increasing throughput. They tend to be loud and deflective. Helical gears are less expensive and eliminate shaft deflection, although they require thrust bearings. Herringbone gears are quiet, do not deflect, and do not produce thrusts; thus, they are less likely to slip. However, they are the most expensive ones. Fig. 7.7 presents the schematic representation of all three gears.

Internal gear. The drive shaft of an internal gear pump rotates a ring gear with inner teeth (Fig. 7.8), similar to an exterior gear pump. This pump's outside gear is attached to the driver and revolves concentrically in the casing. The inner gear is an idler that is eccentrically positioned. Between suction and discharge, the crescent remains fixed and seals the tooth cavities. They are only used in

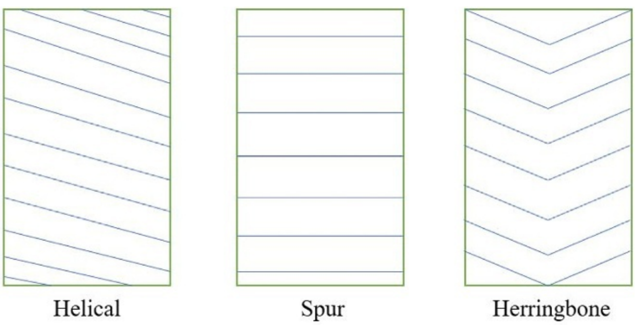

FIG. 7.7 Schematic representation of helical, spur, and herringbone gears.

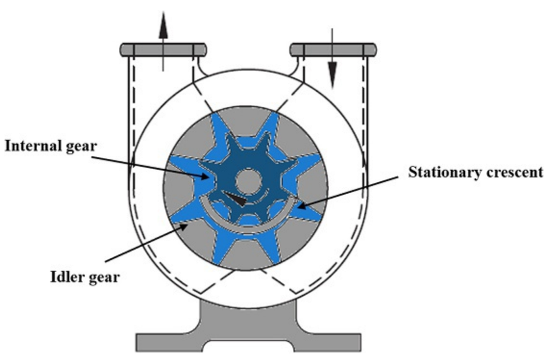

FIG. 7.8 Schematic diagram of an internal gear rotary pump.

clear services; nevertheless, they are better suited to services with suspended solids than screw pumps, external gear, or internal bearing due to material options. These pumps are dependable and affordable. Excessive back pressure or managing solids-containing fluids are the main drawbacks.

Lobe. Lobe pumps work similarly to gear pumps, but the revolving elements have two, three, or four lobes instead of gear teeth. Timing gears are used to drive the lobes, as they are unable to move each other. They have enormous void space between the lobes and the casing, which permits numerous products to be pumped without causing damage to the products. They are used in applications where the integrity of the product must be maintained (food processing) or where shear-sensitive compounds must be processed (chemical processing). Also, the chances of traces of pump building components such as steel, iron, etc., in the product due to wear is negligible as there is no metal-to-metal contact between the lobes. However, they are more expensive than vane or gear pumps, and they are more challenging to fix and maintain. They also require timing gears, which adds to the complexity and cost. The schematic representation of a lobe rotary pump is shown in Fig. 7.9.

Screw pumps

Single screw. A single-screw pump, sometimes known as a "progressive cavity" pump, is made out of a single screw that rotates in an elastomer or rubber stator (Fig. 7.10). It is a slow-speed pump with a huge physical size for the volume of liquid it pumps. The liquid is trapped between the threads of the interior stationary part and the threads of a revolving screw. Such pumps are used for liquids with high solids content and viscous liquids. They deliver consistent discharge pressure with minimal pulsation and deal with a wide range of liquids, from sludge to clean water, without requiring clearance or component changes. They are costly, huge, challenging to maintain, and bulky, with replacement parts being even more expensive.

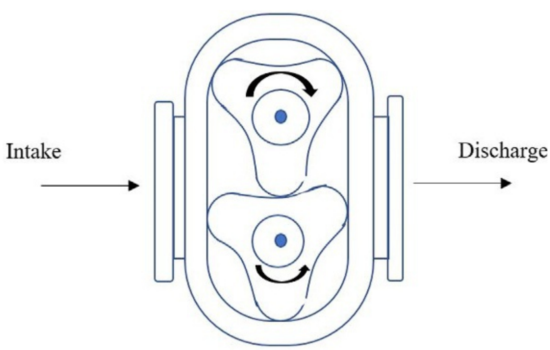

FIG. 7.9 Schematic representation of a lobe rotary pump.

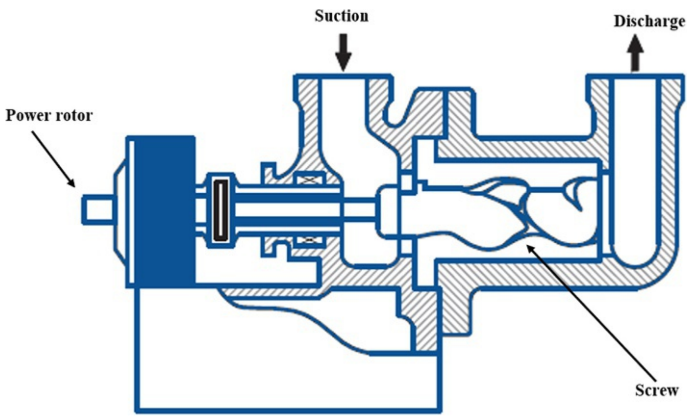

FIG. 7.10 Schematic representation of a single screw rotary pump.

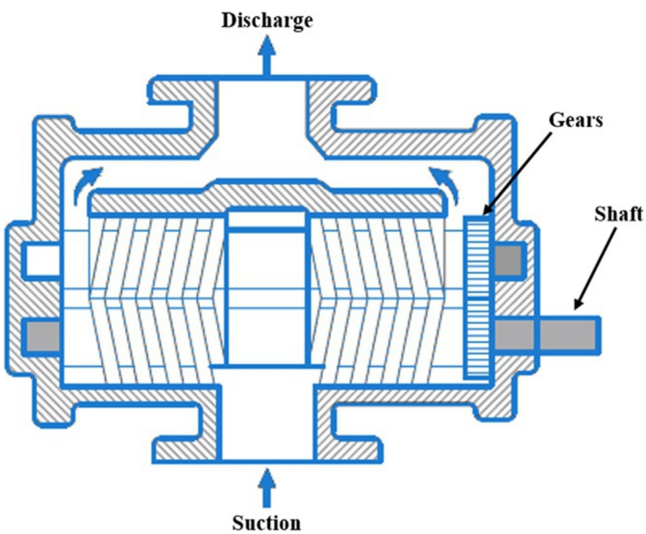

FIG. 7.11 Schematic representation of a two-screw rotary pump.

Two-screw. Two screws move within the stator or housing of the two-screw pump (Fig. 7.11). Both the screws are constructed with more clearance, so they only come into contact with the stator on rare occasions. Teeth contact between screws is avoided by using external timing gears. Antifriction bearings (ball bearings) support the screws, allowing the rotors to be precisely aligned. The bearings can be fitted externally or internally. The external-bearing two-screw pump has an advantage over the internal bearing two-screw or three-screw pumps regarding wear resistance in suspended solids applications; nevertheless, the cost is higher. The external bearing is suitable for services with low viscosities and lubrication capabilities. In services with suspended solids, neither the internal-bearing two-screw pump nor the three-screw pump should be used.

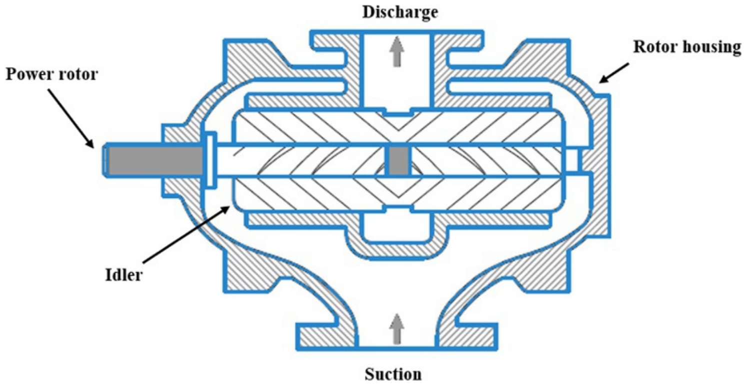

FIG. 7.12 Schematic representation of a three-screw rotary pump.

Three-screw. In a three-screw pump, three screws rotate within the casing or stator (Fig. 7.12). The casing acts as a journal bearing and sustains the rotors along their entire length. The mating teeth, stator, and rotors are all lubricated by the process fluid. As a result, the screw pump is referred to as the "internal-bearing" form of the screw pump. The power rotor, or center screw, is connected to the driver, and it drives the idlers, which are the other two screws. The three-screw pump has the advantage of just requiring one mechanical seal. They are used to provide lubricating oil to machines and engines. They are used to unload and load tankers and barges in huge capacities.

7.2.2.2 Capacity of rotary pumps

A rotary pump's delivered capacity is determined as follows (Stewart, 2018):

$$Q = Q_t - S \tag{7.7}$$

where

Q_t = theoretical capacity.
S = slip.
Q = delivered capacity.

7.2.2.3 Efficiency of reciprocating pumps

A rotary pump's volumetric efficiency is calculated as follows (Stewart, 2019a):

$$E_v = \frac{(Q - S)}{Q_t} = \frac{Q}{Q_t} \tag{7.8}$$

The E_v is one factor that influences the pump's overall efficiency, pump selection, and sizing.

A rotary pump's mechanical efficiency (E_m) is (Stewart, 2019a)

$$E_m = \frac{\text{HHP}}{\text{HP}} \times 100 \tag{7.9}$$

where

HHP = hydraulic horsepower (kW).

HP = input horsepower (kW).

7.2.3 Peristaltic positive displacement pumps

These PDPs are primarily utilized in applications that need limited capacity and low pressure. They are made up of an elastic tube compressed by linear fingers or external rotating rollers until only the tube material is in contact. No valves, shafts, or bearings are present. When necessary, the tube can be replaced or even thrown away. These pumps are frequently used in the food sector, scientific laboratories, medical applications, and numerous industrial processes that demand low but precise liquid distribution.

7.3 Positive displacement pump characteristic curve

For each cycle of pump operation, PDPs deliver a fixed liquid volume. As a result, the speed at which an ideal PDP runs is the only element that influences flow rate. Also, the pump's flow rate is unaffected by the system's flow resistance. The dashed line in Fig. 7.13 illustrates the actual performance of a PDP. This line demonstrates that as the pump's discharge pressure rises, some liquid will leak from the pump's discharge back to the pump suction, lowering the pump's effective flow rate. The rate at which liquid leaks from the pump discharge to its suction is called slippage (Driedger, 1996).

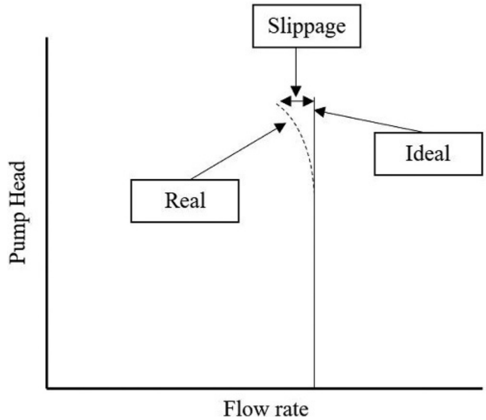

FIG. 7.13 Characteristic curve of a positive displacement pump.

7.4 Benefits and limitations of positive displacement pumps

7.4.1 Benefits

- The operating speeds of reciprocating pumps are substantially slower than centrifugal pumps. Hence, reciprocating pumps are better equipped to deal with viscous fluids.
- High efficiency regardless of required head changes; typical efficiencies range from 85% to 95% (Stewart, 2018).
- Self-priming and proficient in creating large capacities and high pressures.
- Pumping viscous, erosive, corrosive, or suspended solids-containing fluids is possible with PDPs.
- Because there is no stuffing box and only limited moving components, diaphragm pumps are inexpensive to repair and have a long life.

7.4.2 Limitations

- Reciprocating pumps have lower availability and higher maintenance costs because of large moving parts and the pulsating flow.
- They require more space and are heavier in weight.
- Require frequent maintenance.
- When a diaphragm leaks, power gas mixes with the process liquid, posing a hazard.
- To avoid cavitation, higher suction pressures at the suction flange are required due to the decreased pressure and pulsating flow through the valves.

7.5 Applications of positive displacement pumps in the food and beverage industry

The extensive range of applications in the food and beverage industries is a significant problem. The food and beverage industries encompass everything from pastry to drinking water. PDP is advantageous in this situation because viscosity does not necessarily affect performance, and speed is not necessary to achieve a specific pressure at the outlet (Nesbitt, 2003). Furthermore, even when going 'flat-out,' they tend to run far slower than centrifugal pumps, making them intrinsically low shear. Rotary pumps are widely utilized in the food processing industry. External gear pumps can handle viscous, clean liquids as well as liquids containing very small nonabrasive materials. As slip losses are decreased and absorbed power is increased, increasing viscosity tends to improve flow marginally. Because of few teeth and larger clearances, lobe pumps can handle much larger solids, for instance, pumping yogurt with whole cherries or strawberries. Adaptations for lobe pumps can be used to manage products with extremely high viscosity, almost dry materials. To push the product into the pump, a screw auger can be installed on the input. The screw auger serves as a booster pump, ensuring that the minimum inlet pressure is maintained. The screw auger can be equipped with an inlet hopper for manual filling or discharge from a conveyor or a rectangular duct for receiving the product from a vessel. Pumps that have been modified can handle products that would otherwise be considered "unpumpable." Sliding vane pumps are suitable for handling viscous products such as molasses, syrup, honey, chocolate, and watery products such as wine. The eccentric rotary piston pump is used extensively in the dairy and dairy products sectors and jam, chocolate, and cake mixture, among other things (Nesbitt, 2003). Hence, PDPs play a vast role in many industrial applications.

7.6 Considerations for maintenance and operations

Positive displacement pumps are dependable pumps. Proper operating and maintenance techniques are essential for a long pump life. Pump inspection should be done daily by all parties involved, including maintenance employees, operators, and engineers. This will ensure minimal downtime, prevent the removal of a working pump, and save money.

7.6.1 Liquid end inspection and maintenance

Liquid end inspection of the pump involves inspection of the plunger, packing, and valves of the pump. The pump must be separated, depressurized, and the driver must be locked out before these inspections can be completed. Even after the pump has been unplugged and depressurized, valve chambers should be opened with caution since pressure may still be trapped inside.

Inspection processes include the following:

1. All valves should be disassembled and removed.
   - Parts that have become broken or worn must be replaced.
   - Smooth seating surfaces are important.
   - Before reinstalling valves, the valve cavities must be cleaned.
2. The plunger should be inspected and removed for wear, particularly where it meets up with the packing
   - An outside micrometer should be used to examine the diameter of the plunger at different positions.
   - The plunger must be changed if it is broken or badly worn.
3. When a pump's liquid end is overhauled, new packing rings should be inserted.
4. Before installing new rings, the packing box bore should be inspected. Consider inserting a stainless-steel sleeve if the bore is worn.

7.6.2 Crankcase inspections and maintenance

Without taking the pump out of service, the following inspections can be conducted regularly. Nonetheless, before the crankcase is opened, the pump must be shut in and depressurized, as well as the pump driver must be locked out.

1. Brass or steel particles in crankcase oil indicate abnormal bearing wear and should be sampled and investigated.
2. Check for discoloration caused by heat or misalignment on the crankshaft and connecting rods.
3. Check the clearances of the crankpin bearings.
   - A standard clearance is four to six-thousandths of an inch. A greater reading could indicate wear on the bearings or the crankpins.
   - By adding or removing some of the shims that separate the two halves of the bearing, clearances can be changed.
4. Check the end play of the crankshaft (i.e., the extent the shaft can move along its own length). A dial indication and a pry bar are used for this.
   - Compare the reading to the manufacturer's recommendations.
   - Shims must be removed from the crankshaft end bearing housing if end-play is excessive.
   - Shims of the same thickness must be removed from both housings until the end play is acceptable.
5. Using a feeler gauge, check the clearance between the top of each crosshead and the crosshead guide.

7.6.3 Troubleshooting

If a pump fails to operate or produces less flow than expected, it is better to turn it off until the source of the problem is identified. The following is a list of general troubleshooting steps:

1. Examine the valves for any damage.
2. Look for evidence of burning or a lack of lubrication in the packing.
3. Check to see if the liquid is getting to the pump.
   - Examine the suction source for a sufficient flow of liquid.
   - Make sure the suction line's block valves are fully open.
   - Bleed off trapped vapor by opening bleed valves.
4. Verify that the downstream flowline is not blocked.
5. Rotate the pump shaft while the driver is disengaged and listen for any unusual noises (a stethoscope can be helpful).
   - Remove the crankcase cover and inspect the crankshaft for any damage or misalignment.
   - Look for any bent or broken parts on the crankshaft.
6. If everything appears to be in order at this stage, turn on the pump for a few seconds and check for proper shaft rotation.
   - Disconnect the pump from its driver and run the driver alone if the shaft is not moving or moving at the correct pace.
   - If the driver is working properly, the issue is with the pump.
   - If not, have the driver inspected by a technician or an electrician.

7.7 Summary

Pumps are mechanical devices that use energy to increase the flow rate and static pressure of a liquid. PDPs are used for non-Newtonian liquids, especially in the food sector. PDPs are categorized as rotary and reciprocating pumps, based on the movement of the pressure-producing parts. A reciprocating pump traps a fixed amount of liquid near suction, compressing it to discharge pressure, and then discharges it via the discharge nozzle. On the other side, in rotary pumps, a "moving chamber" is produced between two rotating elements (rotors) or between the pump housing and a single rotor, where the fluid moves with the "chamber" from the suction end to the discharge end. Reciprocating pumps were further classified as piston or plunger type and diaphragm type reciprocating pumps, while rotary pumps are divided into the eccentric rotor, gear, and screw pumps.

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PART | THREE

Solid and semi-solid transportation

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Chapter | Eight

Fundamentals of conveyors

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8.1 Introduction

Material handling is an important unit operation, which starts from receiving raw materials in food processing till dispatch of finished value-added food products. It can be described as the *use of proper systems and equipment for the transportation and storing of material at the lowest possible expense*. The transportation from fields/orchards to the plant, material handling within the plant according to the processing plant layout, and transportation again to the distributor, retailer, and finally to the end user or consumer can also be incorporated in material handling to handle the complete total movement plan or complete chain in agricultural processing. Non-perishable materials like grains, pulses, etc., are comparatively easier to handle due to lesser water activity in them. However, perishable food requires lower temperatures during long holding and transportation conditions. The cold chain has to be maintained from the plant grower/producer to the consumer till the consumption of the perishable products, which inevitably require refrigeration (need lower temperatures during storage), viz., tomatoes, apples, citrus, milk, cauliflower, etc.

8.2 Scope and importance of solid and semi-solid material handling systems

Material handling in food processing was performed manually; however, the discovery of wheels and levers attracted the application of mechanical handling of materials (Ray, 2008). Material handling remains one of the unit operations, which may vary from small to big according to the demand of the food processing operations. The unit operations start from handling of raw materials, systematic movement of intermediate products among various processes to delivery of finished products. Material handling does not add any additional

Transporting Operations of Food Materials Within Food Factories. https://doi.org/10.1016/B978-0-12-818585-8.00003-9

value to the food product; however, involvement of human interference adds value and quality to the food product. This remains the main reason to avoid material handling in small food processing units due to the lower turnover. However, it becomes inevitable due to the handling of a large volume/ weight of the materials in medium- to large-scale food processing industries. In cases where manual handling becomes costlier and unsafe (e.g., elevated temperatures, dusty ambiance, etc.), mechanical material handling cannot be avoided. Material handling should be effectively designed to suit the capacity of various machines to make it beneficial.

Material handling covers various unit operations, viz., conveying, holding/ storing, elevating, positioning, transporting, packaging, storing, and delivery of the material within food processing plants. The following points are to be considered for designing material handling systems:

(i) matching with the capacity of the equipment
(ii) efficient and safe delivery of materials
(iii) timely collection and delivery
(iv) effective utilization of intermediate storage space
(v) cost-effective

The material handling system should provide an adequate quantity of raw materials consistently to the continuous operations and batch operations according to the capacity. Oversize conveyors are turned off intermittently and demand irregular loads; however, undersize conveyors slow down the production capacity of the processing units. The material to be conveyed should not be damaged during the conveying process looking at the consideration of ambiance of the processing unit. The handling systems should have the capability of collecting the raw material from various vehicles used for collection from the field, i.e., milk vans, tomato trucks, sugarcane trucks, etc. Material handling should be adjusted within the limited place available in the unit to make other equipment be adjusted within the same space. The material handling option is the lowest in cost generally opted for the execution.

The main important advantage of using material handling is to enhance productivity, which will confer profitability. Some of the industries were even closed due to heavy and inefficient material handling practices. Effective and improved material handling allows the processing units to withstand their competitors. The advantages of using material handling systems are as follows:

(i) improvement of the production systems
(ii) reduction in damage of raw/intermediate and processed material
(iii) effective space utilization in processing operations
(iv) reduction of the overall cost
(v) maintaining the production timeline and round-the-clock continuous production
(vi) lowering the labor cost
(vii) avoidance of accidents
(viii) improved hygienic production consideration

Material handling has many advantages; however, it has certain limitations, which should be considered while designing the systems. The limitations are as follows:

(i) extra capital requirement for material handling systems
(ii) flexibility in shifting of processing equipment becomes limited
(iii) in case of failure of any one material handling unit, downtime is increased
(iv) an additional cost is also involved in maintaining the handling system

8.3 Classification of materials

As discussed in Chapter 1, the material handling equipment is designed according to the nature of the material in raw, intermediate, and processed form. The materials are basically classified on the basis of their form of existence according to the following:

(i) *Solids*: The molecules of food material are closely bound together and only vibration of molecules is possible. The material in this state has a definite shape, which can be changed in case of application of force during material handling; therefore, this state should be handled properly due to undesired change or distortion in shape. The majority of food materials are in solid form.

These can be further divided into mainly two types: unit load and bulk load (materials). Unit load refers to solid of various shapes, sizes, and mass. Bread loaves, packaged cookies, butter boxes, etc., refer to the unit load category and these can be counted easily in a number of units. Unit loads have specific characteristics, viz., dimensions, mass, shape, temperature, strength, etc., which are considered to design the material handling system. A specific type of handling cranes, jaws, and cavities are designed according to the shape and mass of the material. The bulk load is defined as the material available in loose form and cannot be counted in numbers, e.g., particles, lumps of particles, powder, etc.

(ii) *Liquids*: Generally, a liquid refers to an almost incompressible fluid that adapts to its container form but maintains a constant volume independent of the stress. It is one of the four basic states of matter (the others being plasma, gas, and solid), and is the only state with a definite volume but no defined structure. The important characteristics for designing material handling systems are viscosity, density, inflammability, corrosiveness, temperature, and freezing and boiling point. Some of the examples of liquid food materials are milk, vegetable oil, water, juices, etc. Water also remains in a fluid state at a normal temperature from 0 to 100°C and is also one of the main ingredients of food material. The maximum density of water is at 4°C, which reduces with the temperature rise.

(iii) *Semi-liquids*: These have intermediate properties of liquids and solids. They have the ability to flow but free flow does not occur. A large quantity of semi-solids is handled with a suitable pump and pipes. Heating and cooling are required to maintain the temperature for their flow behavior along with the agitation of food material. These semi-solids are filled in various types of containers for final packaging followed by storage and transport. Some of the semi-solid food materials are pulps, pastes, gravies, sauces, etc.

(iv) *Gases*: These have no fixed shape and volume and the density is lower in comparison to solids and liquids. The gases are conveyed through airtight and pressure-resisting containers. Compressors and blowers are also required to convey the gases from one place to another through an airtight pipeline. The insulation is also attached to a pipeline to maintain the temperature and reduction in loss of energy and the process of conveying is termed *pneumatic conveying*. Water is evaporated after getting energy from the ambiance and remains in the gaseous state. The steam is used in food processing industries and it needs to attain a 100°C temperature. A number of food processing operations use steam for thermal applications, viz., heating, pasteurization, sterilization, etc.

8.4 Engineering properties of food materials related to conveying systems

The food material may be divided into two basic groups based on their nature and structures, viz., crystalline and amorphous. However, looking into handling, it may be classified as "Hard to handle" and "Easy to handle" food products. The properties which are related to the conveyance of material are as follows (McGlinchey, 2008; Alspaugh, 2008; Fruchtbaum, 1988):

8.4.1 Angles of materials

The role of various angle is important to decide the flowing nature of the food materials. Some of the important angles for conveying are:

(i) *The angle of repose*: It is described as the highest angle that is created between the horizontal and conical surfaces when the material is allowed to flow freely on the flat platform. A lower angle represents the free-flowing nature of the material (Fig. 8.1).

(ii) *The angle of fall*: The formation of the conical pile is disturbed by the falling of a mass close to the pile, which makes the pile dislodge some material and lead to the formation of the lower angle of the pile (Fig. 8.1). The angle is termed as the angle of fall. The difference in both the angles indicates the free-flowing nature of grains/food materials; the greater the difference, the more the free-flowing nature is observed.

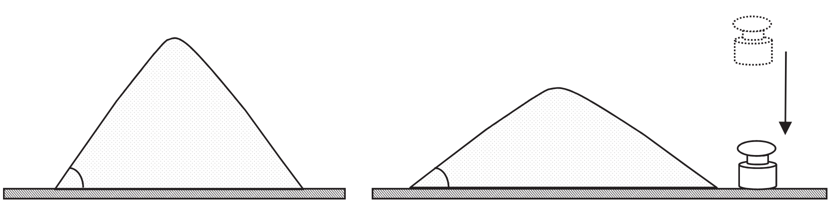

FIG. 8.1 Formation of the heap from free fall (i) angle of repose (ii) angle of fall.

(iii) *The angle of spatula*: The angle is known as the average of two angles of repose and the angle of fall formed during the formation of the heap.

(iv) *The angle of difference*: It implies the change between the "angle of fall" and the "angle of repose." The higher "angle of difference" represents the superior flowability of the powdery food material.

(v) *The angle of slide*: The angle at which the material starts sliding down on a flat surface due to its weight under the influence of gravity is known as the angle of the slide (Fig. 8.2). It remains most important while placing the food material on the conveyor through the hopper and dislodging the material from the conveyor.

8.4.2 Density

The density of the product is required to estimate feed rate computations, calculating hopper capacity. Since the bulk densities also include the volume of air while calculation, these are affected by the flow rate of grains, the height of fall, grain shapes, size, particle density, etc.

The bulk density is also classified into three types based on material handling: (i) Aerated bulk density (ii) Packed bulk density (iii) Dynamic/working bulk density.

(i) *Aerated bulk density*: It is expressed as the density of loosely packed grain without any consolidation force applied to it by measuring the mass of grain kept in a measuring cylinder of known capacity.

(ii) *Packed bulk density*: The packed bulk density of grain or food material in powdery form is defined as filling the container by tamping and refilling to compact the material followed by measuring the mass of grain kept in a container of known volume.

Compressibility: It is defined as a measure of compressibility of material in bulk that can be estimated by using aerated and packed bulk densities using the following expression:

$$\text{Compressibility} = \frac{\text{Packed density} - \text{Aerated density}}{\text{Packed density}} \times 100 \qquad (8.1)$$

The compressibility of material also provides information about the free-flowing nature. The value is about 20% by dividing the granular and powdery material. The higher value of compressibility indicates the non-free-flowing behavior of food material.

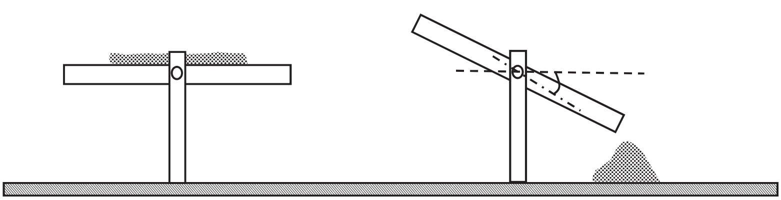

FIG. 8.2 Angle of slide.

(iii) *Dynamic or working bulk density*: It can be estimated by using aerated and bulk density according to the following expression:

$$\text{Dynamic/working density} = (\text{Packed density} - \text{Aerated density}) \times \text{Compressibility} + \text{Aerated density} \quad (8.2)$$

8.4.3 Flowing properties

(i) *Friability*: It is the property of materials for undesirable breakdown by degrading the food materials during the conveying. The consideration of friability for designing food processing conveying systems is mandatory.

(ii) *Dispersibility*: It is the property of food material to produce dust in the surroundings. The materials having a lower bulk density fine particle size are prone to produce dust because of flow like a gaseous material rather than solids. It can be estimated by determination of solid mass by removing the water from a sample through drying at a temperature of 105°C in a hot air oven for 18 h and using the following expression (Stephens and Meyers, 2013):

$$\text{Dispersibility } (\%) = \frac{\text{Solid content after processing}}{\text{Initial solid content}} \times 100 \quad (8.3)$$

8.4.4 Moisture content

The amount of water present in specific food products affects the material handling of food material, and sometimes it also remains a legal requirement according to the regulations.

The moisture content of grains is generally represented on a wet basis, which is denoted by the amount of moisture as a percentage of the initial mass of fresh samples. It is represented as $x\%$ (wb). The alternative method for representation considers the mass of moisture present in food per unit mass of dry grains and is represented as $x\%$ (db), which is denoted by the amount of moisture as a percentage of the dried mass of samples. The moisture content on a wet basis (wb) in food is the amount of moisture present in the food to the total amount of material. It can be represented by the following formula:

$$\text{Moisture content (wb)}, \% = \frac{\text{Amount of water present in food, g}}{\text{Total amount offood, g}} \times 100 \quad (8.4)$$

The moisture content on a dry basis (db) in food is the amount of water present in the food to the amount of dry material. It can be represented by the following formula:

$$\text{Moisture content(db)}, \% = \frac{\text{Amount of water present infood, g}}{\text{Amount ofdry material in food, g}} \times 100 \quad (8.5)$$

Conversion of dry basis to wet basis:

$$\text{Moisture content (db), \%} = \frac{\text{Moisture content (wb), \%}}{100 - \text{Moisture content (wb), \%}} \times 100 \quad (8.6)$$

8.5 Principles of material handling for selection of conveyors

The prime aim of a material handling system and conveyor is the reduction in the cost of processing and timeliness of production. A number of design considerations are being followed based on vast experience by industries. Sometimes these are also termed as basic principles for designing a material handling system. The design considerations are being kept in consideration based on specific industries or plants. In some of the cases, one consideration may have main criteria; however, any other consideration may not hold good for the same problem. The following criteria should be used sensibly for designing an efficient system (Fig. 8.3) (Ray, 2008; Stephens and Meyers, 2013; Pemberton, 1974).

8.5.1 Planning

The plan layout must be considered, and the correct location of supply and disposal must be fixed. Adequate storage space at the workspace must be provided

FIG. 8.3 Principles of material handling for selection of conveyors.

and storage on the floor should be avoided. The containers used in movement should be reused for better economy. Judicial use of manual manpower may be employed and space for inspection/monitoring during movement must be provided.

8.5.2 Systems

The entire scope of material handling activities from receiving to transportation must be considered. The processes may be planned to be integrated for exhaustively utilizing the handling process. Intermediate storage should be avoided and necessary flexibility for emergencies may be kept in mind. The system should also take care of the specific requirement of the suppliers/consumers.

8.5.3 Material flow

The material flow should be in proper sequence and equipment should be arranged optimally. It should avoid backtracking, zig-zag movements, etc., and related operations must be kept together or may be combined, if possible. Processing of heavy/bulk of raw material should be performed near the receiving section to minimize the movements. The obstacle in flows should be eliminated. Product layout should also be prepared.

8.5.4 Simplification

The material handling process should be very simple and unnecessary mechanization is not preferable. Unnecessary movement should be reduced, combined, or eliminated. Re-handling is generally not desirable and the material should remain in good condition after every material handling process. The use of a variety of equipment should be limited and should have adequate capacity.

8.5.5 Gravity

Gravitational movement is almost free of cost since it uses gravity wherever convenient to transport material. Roller conveyors, slides, slips between equipment/processes, and intermediate ramps can be used on separate floors. Sloping floors are popular in unloading a truck, whereas spiral chutes are being used for feed machines located at different levels.

8.5.6 Space utilization

The ideal use of building volume should be carried out. Equipment should be kept close together and a narrow aisle should be kept. Temporary storage should be minimized, and racks and containers should be used for higher stacking. Regular cleaning and inventory control should be maintained.

8.5.7 Unit size

The unit load (quantity, size, weight) should be maximized by examining the possibility of unitization of loads by using containers. The procured materials should be sufficiently large in size for optimizing conveying capacity.

8.5.8 Safety

Conveying and material handling equipment should have adequate safety provisions. Adequate safety guards, lighting, ventilation; maintenance of good equipment, housekeeping facilities, providing mirrors at aisle interactions should be taken care of. Defective equipment and material should not be used.

8.5.9 Mechanization/automation

Mechanization/automation is preferable in case of huge numbers or amounts of goods, repetitive transport, lengthy motions, dangerous transport/products, unnecessary care, the substitution of a significant number of handlers, hard materials, disposal of waste, and feeding and unloading of automatic high-speed processing machines. However, overmechanization should be prohibited.

8.5.10 Equipment

The equipment should be matched with material handling and process adopted. As far as possible, versatile and standardized equipment with judicious capacity in accordance with future capacity should be used.

8.5.11 Standardization

The material handling methods, equipment, containers, and pallets should be standardized to the extent possible for easy handling and suit new machines in case of replacement and various trucks.

8.5.12 Flexibility

The equipment used should have flexibility. The use of variable speed drives, attachments, accessories, flexible forklift machines, four-way pallet moveable conveyors has a comparatively greater advantage.

8.5.13 Deadweight

The deadweight used in handling should be minimized by using lightweight materials like aluminum, magnesium, etc. Traditional wooden pallets may be replaced with lightweight pallets, skids, containers. Selecting lightweight equipment is also a good choice.

8.5.14 Motion

Loading and unloading of material should be executed without ceasing the movement of handling equipment or the pause duration should be minimized.

Using self-loading and unloading equipment for the mechanized process is preferable. The movement of material handling equipment should be effectively exploited by handling in both directions. The use of devices like tipplers, bottom discharge containers, pallets, skids, etc., to accelerate the loading/unloading should be promoted.

8.5.15 Idle time

The material should remain in motion and unproductive/idle time should be minimized. The material should be delivered on time at all the places using handling equipment. The management of labor is also becomes easier by combining the tasks during conveying/handling of the material.

8.5.16 Maintenance

A proper maintenance schedule of all the material handling machinery should be followed to minimize outages. The operator should report any fault to the office. Keep an inventory of adequate spare parts and follow the maintenance procedure recommended by the manufacturer. Overloading of equipment should be avoided. Overmaintenance should also be avoided.

8.5.17 Obsolescence

Old equipment/procedures should be replaced with new and more efficient handling methods or equipment methods. Information about the new machines through various websites, conferences, journals, books, newspapers, factory visits, etc., should be kept updated and new equipment may be adopted based on their benefits.

8.5.18 Control

Material handling equipment should be properly synchronized with raw material intake, inventory and production used to improve production, and order handling. The materials may be marked and moved in containers, batches, lots, and sizes for visual checking/counting and quality control.

8.5.19 Capacity

The material handling equipment should be properly exploited to reach the full production capacity. Mechanical handling systems should be used for the uniform flow of materials. The return run of conveyors should be utilized and make the maximum use of space, equipment, and manpower.

8.5.20 Performance

High-performance material handling devices should be selected by comparing other methods of material transfer on the basis of initial cost, operating cost, and efficiency to observe the effect of the enhancement in production.

8.6 Classification of solid and semi-solid material handling systems and conveyors

The need and use of material handling equipment depend on the nature of industries, type of raw materials, manufacturing process, type of equipment/ machinery, and nature of the processed product. With the innovations taking place, the nature and need of material handling change every time. The material handling within food processing industries can be classified into the following categories (Fig. 8.4).

8.6.1 Conveyors

These are used for moving raw/bulk material continuously from one fixed point to another fixed point along a specific path. Generally, these are fixed and do not move within the plant. These include belt conveyors (flat, trough, closed, metallic, etc.), chain conveyors (apron, slat, crossbar, trolley, etc.), haulage conveyors (drag chain, flight, etc.), screw conveyors, roller conveyors, cable conveyors, hydraulic conveyors, and pneumatic conveyors (Dunlop, 2009; Tsakalakis and Michalakopoulos, 2015; Patrick and McGuire, 2010; Fayad and Skocir, 2009; Kulwiec, 1985).

8.6.2 Hoisting equipment

These are used to lift and put material at the desired place from time to time between one point and another within the periphery of equipment. These may be mounted on a moveable powered vehicle according to the requirement. These include hoists, a winch, an elevator (bucket, lift, etc.), a crane (jib, traveling, wharf, pillar, tower).

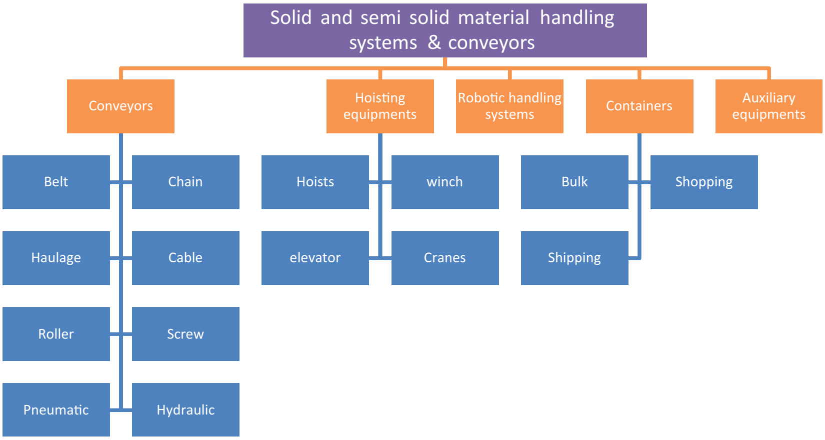

FIG. 8.4 Classification of material handling systems and conveyors.

8.6.3 Robotic handling equipment

These are used for handling raw materials at extreme conditions like elevated temperatures, pressures, etc., for feeding and taking out the processed material. These are accurate and generally controlled through automation. The neural network can also be used for controlling, monitoring, optimization of process parameters for robotic handling systems.

8.6.4 Containers

These are used to store raw, intermediate, and processed products for further processing or transportation to various warehouses, distributors, and end users. These include bulk containers (barrels, drums, tanks, silos, etc.), shopping containers (bags, box, cartons, trays, etc.), shipping containers, etc.

8.6.5 Auxiliary equipment

These are used to control the flow of material and packaging of processed products. These include gates, feeders, chutes, pallet loaders, forklifts, and packaging equipment.

8.7 Type of conveyors

8.7.1 Belt conveyors

A belt conveyor is preferred for transporting the grains, raw materials and generally moves the material horizontally from one location to another. It has several rollers, which supports an endless belt moving around the frame (Fig. 8.5). The idlers are placed flat to bear the load of material or in such a way to form a conveying trough, and they remain flat during the return side. The power is provided with a power source to the drive roller, which is usually fixed on the same frame, on which driven rollers are fixed, which provides aligned operation of all the rollers. Sometimes trippers are also provided to dislodge the material at any desired intermediate location.

Belt conveyors are popular due to their versatile use in various bulk produce. The use of conveyors may be sometimes limited to the width of the belt, stickiness of material, dust production during movement, etc. The belt conveyors

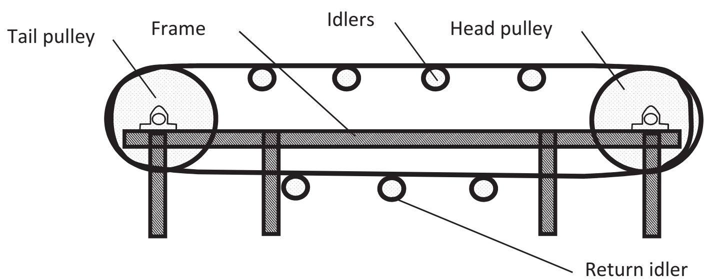

FIG. 8.5 Belt conveyor.

remain self-cleaning for use in the transport of friable materials like grains at lower moisture contents; however, cleaning in case of sticky/damp/ very fine material remains inevitable.

8.7.1.1 Belt conveyor elements

The belt conveyor has the following important elements:

1. Belt—For providing a supporting surface for moving conveying material (cotton/ rayon/ nylon/ polyester or combinations/ rubber/ reinforced belts).
2. Pulleys—For supporting the belt and controlling the belt tension.
3. Idlers—For supporting the belt for the troughing run and flat run-in return.
4. Drive—For imparting power to pulleys for movement of the belt carrying the grains.
5. Structure—For supporting and maintaining alignment of the drive, pulleys, and idlers.
6. Belt trippers—For dislodging the material in between, if necessary.
7. Belt cleaners—For cleaning the belt.
8. Belt-training device—For adjusting the belts.
9. Band brakes—For belts in an inclined movement to stop the belt from running backward.
10. Takeups—For keeping belt in tension (Gravity takeup preferred).

8.7.1.2 Design consideration

The belt conveyors are designed to obtain the highest performance at the least possible cost of material transported. The following information is required for designing a belt conveyor:

(i) Horizontal distance between feeding and discharge ends
(ii) Vertical height to be adjusted (lowered/lifted)
(iii) Kind of material
(iv) Bulk density of the material, kg/m^3
(v) Average capacity required, tonnes/h
(vi) Control over the flow of material
(vii) Nature of the material (friable/sticky/powdery)
(viii) Temperature of material (hot/cold)
(ix) Number and locations of loading/discharge points
(x) Choice of power source (electrical/engine)
(xi) Advanced option of weight measurement
(xii) Working hours and climatic operation

Generally, belt conveyors work well at an inclined angle of 15°; however, the use of belt conveyors at 25°–30° is also possible. Loading should take place at fairly low angles to allow the material to settle down and rest before a steeper slope because optimum speeds can be reached only when the material is settled before steep paths (Fig. 8.6).

FIG. 8.6 Inclined belt conveyor.

8.7.1.3 The capacity of belt conveyor

The capacity of the belt conveyor can be estimated using the cross-sectional area, belt speed, and bulk density of the material using the following formula:

$$\text{Capacity, tons/h} = 3.6 \times \text{Cross} - \text{sectional area}\ (\text{m}^2) \times \text{Belt speed}\ (\text{m/s}) \times \text{Density}\ (\text{kg/m}^3) \quad (8.7)$$

Q.1.: A flat belt conveyor (Belt width = 60 cm) is conveying wheat (780 kg/m^3) at a speed of 2 m/s. Estimate the capacity of the belt conveyor. Assume the angle of repose of wheat is 27°.

Solution:

Assuming the clearance per side for spillage prevention = 5 cm (Fig. 8.7) and conical shape formed,

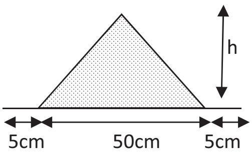

FIG. 8.7 Cross-sectional area for Q.1.

$$\begin{aligned}\text{The height of pile}, h &= (\text{base}/2) \times \tan\theta \\ &= (50/2) \times \tan 27 \\ &= 25 \times 0.51 \\ &= 12.75\,\text{cm}\end{aligned}$$

$$\text{The cross}-\text{sectional area of grain} = \frac{1}{2} \times \text{base} \times \text{height}$$

$$\text{The cross}-\text{sectional area of grain} = \frac{1}{2} \times 0.50 \times 0.1275 = 0.0319\,\text{m}^2$$

Now,

$$\begin{aligned}\text{Capacity, tons/h} &= 3.6 \times \text{Cross}-\text{sectional area}\left(\text{m}^2\right) \times \text{Belt speed}\,(\text{m/s}) \\ &\quad \times \text{Density}\left(\text{kg/m}^3\right) \\ &= 3.6 \times 0.0319 \times 2 \times 780 \\ &= 179.15\ \text{tonnes/h}\end{aligned}$$

8.7.2 Bucket elevators

The bucket elevators comprise several small buckets, which are placed on a chain or belt for picking up material from a lower elevation to discharge at a higher elevation (Fig. 8.8). These handle a variety of bulk materials in the food processing industry. As this lift, the solid food material in either the vertical or inclined condition requires less horizontal space. Small metallic buckets are fixed on an endless chain or belt which carries the material in open or closed form looking at the environmental condition. The design used in bulk material handling can be continuous and centrifugal discharge elevator.

It is a power-operated material conveying machinery that consists of a never-ending belt or chain which is attached to metal buckets and travels vertically or steeply inclined. The buckets move uni-directionally in a housing with a flexible belt/chain, collect bulk materials at the bottom of the equipment, and supply material to the top end. Fig. 8.8 demonstrates a standard bucket elevator with various building parts.

The main components of a lift are as follows:

(i) A flat endless belt or chain.
(ii) Drive pulley, which is mounted at the top end of conveyer and fixed on bearings.
(iii) Take up pulley, which is mounted at the bottom end of conveyer and fixed on bearings.
(iv) Metal casing for covering elevator legs, head at the top as well as boot section at the bottom fastened with flanges by fasteners.
(v) Buckets, typically of sheet metal and fastened at a certain pitch using screw and nuts, rivets.
(vi) Drive with gearbox and motors, which is attached to the drive pulley.

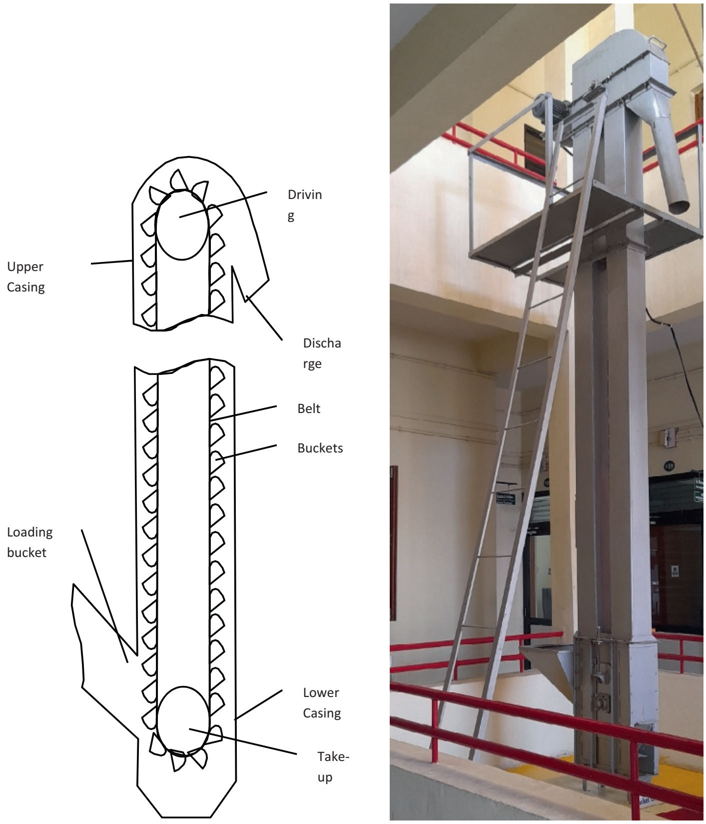

FIG. 8.8 Bucket conveyers.

(vii) Hold back brake on the top pulley to avoid the reversal motion elevator during powering off.

(viii) Delivery/unloading spout attached to the top part of the case where the material is unloaded.

(ix) Feed hopper is connected to the boot part to provide the elevator with the supplies.

(x) The elevator operations are monitored by manholes at the casing.

(xi) Belt and chain guide and guide sprockets for keeping them in a straight path are provided.

The easiness and effectiveness in conveying operations make these popular in various food processing industries. These are also popular due to the lower cost and less floor space requirement.

8.7.2.1 Types of bucket elevators

(i) *Centrifugal discharge elevator*—It is used in grain processing facilities/centers located across the country for long years. The unloading of the raw material is driven by centrifugal action. The food grains are collected into the bucket from the bottom opening and discharged at the spout mounted at the elevator head. Based on the method of delivery and use of material, two types of arrangement are available. The buckets are placed in a standard pitch in a centrifugal elevator to prevent obstructing loading and unloading operations. The buckets are filled by scooping and the discharge takes place via centrifugal operation. Operating usually in a vertical layout, these lifts are used for nearly all sorts of free-flowing products such as oil, wood, sand, mud, dry chemicals, sugar, etc. All chains and belts may be used, with a speed varying from 1.1 to 2 m per minute (Fig. 8.9).

(ii) *Positive discharge elevators*—These are identical to the centrifugal form; the only difference is that buckets are placed laterally on two chain wires (i.e., the buckets repose between two chains), which are fixed into two snub sprockets that invert the buckets for complete discharge. The speed of the lift may range from 0.6 to 0.67 m/min. Such lifts are designed with lightweight, soft, slow, and mildly tenacious materials. The feeding is achieved by digging or scooping buckets. An inclined lift is ideal for perfect gravity discharge.

(iii) *Continuous discharge elevator*—It is used for the removal of sticky and hygroscopic food products. Generally, it handles the food material at a lower speed to reduce the losses. Further, it can be a positive discharge elevator and Flight elevator. V-type buckets are utilized without any gap or vent among them in these types of elevators. The lifts are designed for treating bigger size food material objects, for which centrifugal emptying can be challenging to manage. The buckets are filled directly. As the buckets move through the head wheel, the flanged end of the previous bucket becomes a chute for transporting products gently to the unloading spot. The discharge is driven by gravity. This method of loading and unloading is particularly useful when handling fragile materials. As a pulling medium, both a chain and a belt are used. Speed is generally kept slow.

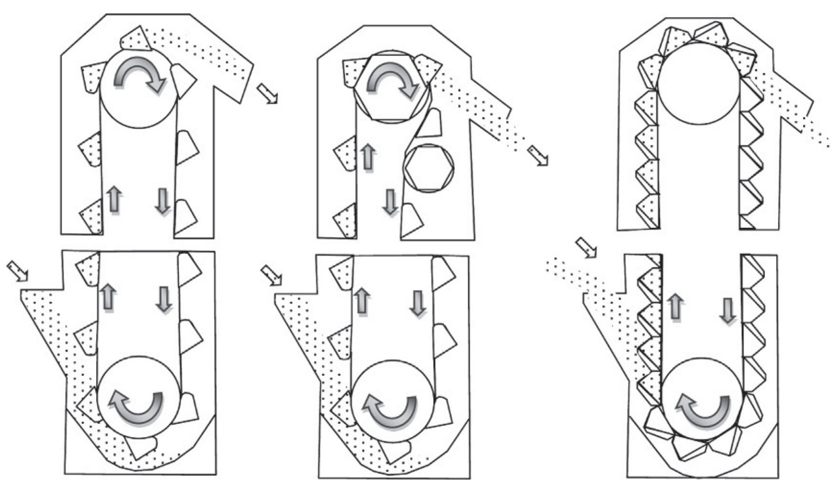

FIG. 8.9 Type of bucket elevators.

The lifts used are upright or sloping. A wider casing is provided to allow the sagging of the belt/ chain during the return in inclined elevators.

8.7.2.2 Buckets

(i) *A-type buckets*—These buckets are used for centrifugal and positive discharge of the material (Fig. 8.10A). A1 buckets for free-flowing and powdered material, A2 buckets for coal, sand, fertilizers, etc., A3 buckets for wet, stringy materials, coarse materials, A4 buckets for sugar, clay, salt are used.

(ii) *B-type buckets*—These buckets are used for continuous discharge (Fig. 8.10B). B1 buckets for sticky powdered and sluggish materials, B2 buckets for average materials, B3 buckets for large lumps and extra capacity, and B4 buckets for inclined elevators are used.

The capacity of the bulk elevator: The capacity (Q) in kg/h of a bucket elevator can be estimated using the following expression:

$$Q, \mathrm{kg/h} = C \times \frac{60 \times v}{s} \times \rho$$

where C = capacity of each bucket, m^3; v = elevator speed, m/min; s = bucket spacing, m; ρ = bulk density, kg/m^3.

Considering the bucket filling factors:

$$Q' = Q \times F$$

Q' = Corrected capacity of the bucket elevator, kg/h; F = bucket filling factor, a constant. ("F" varies from 0.4 for sluggish, moist materials to 0.85 for powdered materials).

8.7.2.3 Theoretical power requirement

$$\mathrm{hp} = \text{Capacity of elevator} \left(\frac{\mathrm{kg}}{\mathrm{min}}\right) \times \text{lift (m)} \times \text{factor}$$

Factor = 1.2 for elevators loaded on the bottom side and 1.5 for elevators loaded on the top side.

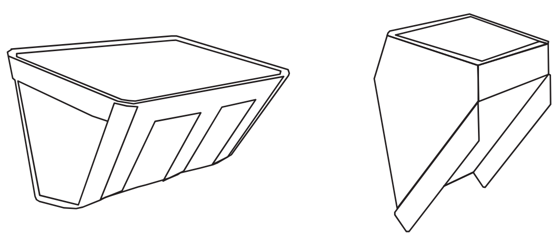

FIG. 8.10 Type of buckets (i) A-type buckets (ii) B-type buckets.

Q. What will be the capacity of a bucket elevator if the capacity of each bucket is $0.60\,m^3$ and there are four buckets in one belt and its speed is 1.2 m/min.

Solution:
Bucket elevator capacity = $0.60\,m^3$.
Number of buckets = 4

$$\begin{aligned}\text{Capacity}\left(\frac{m^3}{h}\right) &= \text{Bucket capacity}\left(m^3\right)\\ &\quad \times \text{number of a bucket per meter of belt}\\ &\quad \times \text{belt speed}\left(\frac{m}{\min}\right)\times 60\\ &= 0.60\times 4\times 1.2\times 60\\ &= 172.8\,m^3/h\end{aligned}$$

8.7.3 Screw conveyors

A screw conveyor is utilized to transport bulk food material through a U tube to circular tube by rotating a shaft having helical screw blades (Fig. 8.11). The material is fed in such a way as to maintain the flow at the bottom side of the circular tube. These are used for mixing the ingredients, loading and unloading grains and the intermediate processed product from silos for further processing. These conveyors provide high throughput and remain environmentally friendly as minimum/no dust is generated during the transport. These are popular in the food processing industry due to their simple structure, low cost, high efficiency, and minimum maintenance requirement. These are usually preferred for conveying the material for shorter distances due to the constraint of higher demand of power for longer distances. Screw conveyors are available in 75–600 mm size in diameter and from about 1 m to about 30 m in length.

A similar screw flight-based conveying arrangement in one equipment for pulping is shown in Fig. 8.12.

The physical properties of the material to be conveyed, viz., bulk density, moisture content, angle of repose, particles, remain important while designing the conveyor system. However, other important considerations for designing are the mass flow rate, distance to be covered, available space, ambiance, and economics.

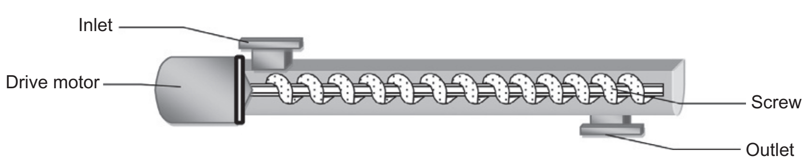

FIG. 8.11 Screw conveyor.

FIG. 8.12 Screw conveying of pulp.

The specific power requirement of the conveyor usually increases with an increase in the screw rotational speed, which also increases the volumetric capacity to the highest value, and an additional increase in speed results in a reduction in capacity. The capacity of the screw conveyor is 70–80 m^3/h and it can also be operated at an angle between 45° and 90°.

These can work in dusty, corrosive, or hazardous surroundings due to being absolutely enclosed. These are also preferred for conveying dry to semi-solid bulk materials due to the lower maintenance required as compared to the belt conveyor system. These also work well in multiple inlets and discharge points.

8.7.3.1 Types of screw conveyors

(i) *Horizontal screw conveyors*

Horizontal screw conveyors are the commonly used form of screw conveyor. These are available in a range of designs, sizes, distances, and construction materials to move bulk goods from one place to another.

(ii) *Inclined screw conveyors*
Inclined screw conveyors work from the horizontal level to a 45° inclination. The inclined screw conveyor is known as a vertical screw conveyor having an angle of inclination greater than 45°. When the degree of inclination rises, the transmitting capacity is decreased and the need for horsepower is enhanced by the effects of gravity and volume content. The performance of the conveying is influenced by the angle of incline, properties of bulk materials, the form of screw conveyor trough, and the pitch of the screw content. The construction of screw conveyors is suggested with the lowest possible tilt to maximize output.
(iii) *Shaftless screw conveyors*
A shaftless helix is used in this design which results in smooth movement of bulk materials without any clogging. The flawless solution for high moisture content material is a shaftless screw conveyor. These work well for handling bulk materials which are sticky and sluggish and have a higher conveying efficiency. These are very flexible and can be shifted according to the plant layout and bear less wear and tear because of the elimination of internal bearings.
(iv) *Vertical screw conveyors*
Vertical screw conveyors are a highly useful way to lift a variety of bulk materials at very steep or vertical angles. A screw conveyor is defined as having a vertical screw conveyor on a slope of more than 45°. The complex design makes it possible to fit almost every plant layout with the vertical screw conveyor. The vertical screw conveyor is an inexpensive and efficient feature of every bulk material handling operation with a limited number of moving parts. It remains ideal for handling dry to semi-fluid materials up to a capacity of 170 m^3/h. These have the ability to elevate bulk materials up to 10 m without the use of internal bearings and can remain totally enclosed in design for dust and vapor-tight requirements.

8.7.3.2 Types of screws
The screws of conveyors are designed to look into the characteristics of food materials.
(i) *Solid and continuous screw*
This is the most common type of screw configuration that has continuous flights. This may be available in full pitch and reduced pitch according to applications (Fig. 8.13). The difference between the center of a thread and the center of the next thread is equivalent to the pitch of a regular screw is equal to the diameter of the screw. Continuous screws are usually produced from a circular 4–8 mm sheet of steel with a hole that is equivalent to the diameter of the shaft. The portion is welded to the shaft and is joined to shape the whole length of the screw. The screw may also be positioned integrally with the shaft.
(ii) *Ribbon screw*
This type of screw is used for sticky materials and materials having poor flow characteristics (Fig. 8.14). Radial rods are used to fix the ribbon screw on the shaft.

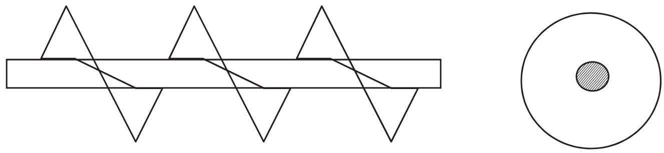

FIG. 8.13 Solid and continuous screw.

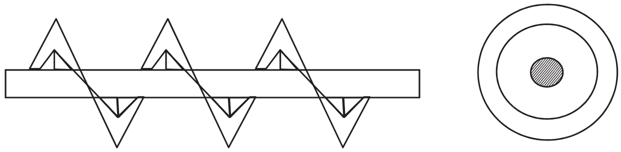

FIG. 8.14 Ribbon screw.

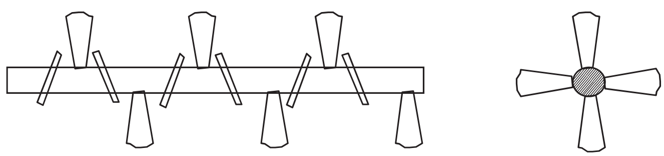

FIG. 8.15 Paddle flight screw.

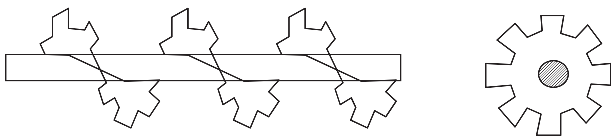

FIG. 8.16 Cut flight screw.

(iii) *Paddle flight screw*

This type of screw is used in processes where the mixing of materials is desired while conveying (Fig. 8.15). The shaft is fitted with paddle-type flights comprising straight and curved segments.

(iv) *Cut flight screw*

This type of screw is used in processes where light mixing of materials/ aeration of materials is desired along with the conveyance (Fig. 8.16).

8.7.3.3 Aspects of screw conveyor design

(i) *Recommended dimension of a screw conveyor*

The key components of the design of the screw conveyor are the diameter of the screw shaft, pitch of the screw, diameter of the helical screw, Width of the trough, Gap between the screw and trough, trough height, and thickness and screw flight thickness. An operation gap is kept between the trough wall and screw blade, which restricts emptying the trough completely in a horizontal screw conveyor. If more than one raw material is used, mixing can be performed. However, some damage in kernels is expected due to the pressing of kernels between the screw edge and through walls. Continuous friction is also exerted by trough walls during conveyance. These can be rotated in either a clockwise or counterclockwise direction, which does not affect the capacity of the conveyor.

(ii) *Effect of lump size*

The lump size remains a key factor while selecting the screw conveyor along with the capacity of the conveyor. The diameter of the screw is selected on the basis of lump size. Normally, the diameter of the screw should be greater than about 12 times the specified lump size or at least 4 times the unspecified lump size.

(iii) *Capacity of screw conveyor*

The capacity is affected by the screw diameter, inclination of the screw blade, shaft diameter, cross section of loading, and speed of the blade. The theoretical conveyance capacity of the screw conveyor can be estimated using the following expression (Fig. 8.17):

$$Q = \frac{\pi}{4}\left(D^2 - d^2\right) \times p \times n \times 60$$

$$Q = 47.2\left(D^2 - d^2\right) \times p \times n$$

where Q = Capacity of conveyor, m^3/h; D = screw diameter, m; d = shaft diameter, m; p = screw pitch, m; n = revolutions per minute (rpm).

The screw conveyors are also used to work in an inclined position to elevate the material upward; however, the capacity decreases with the increase in inclination. With an increase in angle from 15° to 25° from the horizontal, the capacity decreases from 25% to 50% from the capacity during horizontal conveying. The loading and unloading of the screw conveyor are usually done using a supply chute with an adjustable gate to supply the material uniformly at a regular pace to avoid overfilling and congestion. The product can be received in the last conveyor; however, the intermediate receiving point allows multiple point exits of material (Fig. 8.18).

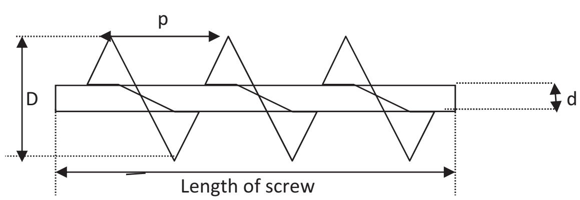

FIG. 8.17 Diagram of screw for calculation of capacity.

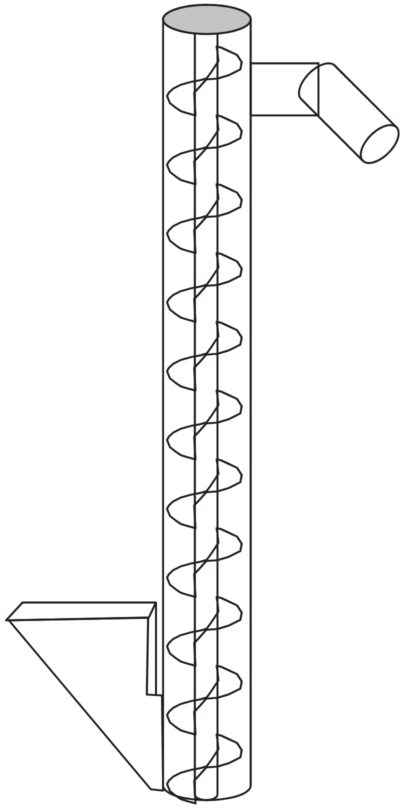

FIG. 8.18 Vertical screw conveyor.

8.7.4 Numerical problem

Q.1. A screw's diameter, pitch, and shaft diameter are 30, 30, and 5 cm, respectively. The conveyor is operated at a speed of 100 rpm. Calculate the capacity of the screw conveyor.

Solution:

Given: $D = 30\,\text{cm} = 0.30\,\text{m}$; $d = 5\,\text{cm} = 0.05\,\text{m}$; $p = 30\,\text{cm} = 0.30\,\text{m}$; $n = 100\,\text{rpm}$

$$Q = 47.2 \times \left(0.30^2 - 0.05^2\right) \times 0.30 \times 100$$

$$Q = 47.2 \times (0.09 - 0.0025) \times 0.30 \times 100$$

$$Q = 47.2 \times (0.0875) \times 0.30 \times 100$$

$$Q = 123.9\ \text{m}^3/\text{h}$$

Answer: The capacity of the screw conveyor at 100 rpm will be $123.9\,\text{m}^3/\text{h}$.

Q.2. A screw's diameter, pitch, and shaft diameter are 30, 30, and 5 cm, respectively. This is to be designed for conveying 145 m^3/h. Estimate the approximate rpm for the purpose.

Solution:
Given: $D = 30\,\text{cm} = 0.30\,\text{m}$; $d = 5\,\text{cm} = 0.05\,\text{m}$; $p = 30\,\text{cm} = 0.30\,\text{m}$; $Q = 145\,\text{m}^3/\text{h}$

$$145 = 47.2 \times \left(0.30^2 - 0.05^2\right) \times 0.30 \times n$$

$$145 = 47.2 \times (0.09 - 0.0025) \times 0.30 \times n$$

$$145 = 47.2 \times (0.0875) \times 0.30 \times n$$

$$145 = 1.239 \times n$$

$$n = 145/1.239$$

$$n = 145/1.239$$

$$n = 117 \text{ rpm}$$

$$n \approx 120 \text{ rpm}$$

Answer: For the rpm for conveying 145 m^3/h grain, the screw speed must be kept at 120 rpm.

8.7.5 Power requirement

The power requirement can be estimated using the following equation.

$$P = \frac{Q \times L \times W \times F}{4560}$$

where P = theoretical power requirement, hp.; Q = conveyor capacity, m^3/h; L = conveyor length, m; W = bulk density of material, kg/m^3; F = material factor

$$\text{Calculated power requirement} = 2 \times \text{theoretical power requirement} \; \{\text{If } P < 1.0\}$$

$$\text{Calculated power requirement} = 1.5 \times \text{theoretical power requirement} \; \{\text{If } 1.0 < P < 2.0\}$$

$$\text{Calculated power requirement} = 1.25 \times \text{theoretical power requirement} \; \{\text{If } 2.0 < P < 4.0\}$$

$$\text{Calculated power requirement} = 1.1 \times \text{theoretical power requirement} \; \{\text{If } 4.0 < P < 5.0\}$$

$$\text{Calculated power requirement} = \text{theoretical power requirement} \; \{\text{If } P > 5.0\}$$

8.7.6 Numerical problem

Q.3. A screw's length, diameter, pitch, and shaft diameter are 300, 30, 30, and 10 cm, respectively. The conveyor is operated at a speed of 50 rpm. Calculate the capacity for conveying paddy (material factor = 0.4, bulk density = 650 kg/m^3) and the power requirement of the screw conveyor.

Solution:
Given: $L = 300\,\text{cm} = 3\,\text{m}$; $D = 30\,\text{cm} = 0.30\,\text{m}$; $d = 10\,\text{cm} = 0.10\,\text{m}$; $p = 30\,\text{cm} = 0.30\,\text{m}$; $n = 100\,\text{rpm}$

$$Q = 47.2 \times \left(0.30^2 - 0.10^2\right) \times 0.30 \times 50$$

$$Q = 47.2 \times (0.09 - 0.01) \times 0.30 \times 50$$

$$Q = 47.2 \times (0.08) \times 0.30 \times 50$$

$$Q = 56.64\ \text{m}^3/\text{h}$$

Theoretical power requirement:

$$P = \frac{Q \times L \times W \times F}{4560}$$

$$P = \frac{56.64 \times 3 \times 650 \times 0.4}{4560}$$

$$P = 9.68\ \text{hp}$$

Since $P_{\text{theoretical}} > 5.0$, $P_{\text{actual}} = P_{\text{theoretical}} = 9.68$.

Answer: The capacity of the screw conveyor will be 56.64 m^3/h and the actual power requirement for the motor will be 9.68 hp.

8.7.7 Roller conveyors

Roller conveyors are popular in transporting unit-type loads in packaged form, which is conveyed on rollers placed in series and fitted on bearings at a fixed spacing on both sides (Fig. 8.19). The load conveyed on these conveyors should have one flat rigid surface to remain in contact with rollers for maintaining the stability while conveyance of the load.

The size of the unit load decided the size and spacing between the rollers to maintain continuous contact with at least two rollers at a time for stability. However, the path of movement may remain straight or curved. The advantage of gravity is one of the qualities of these conveyors; however, power is sometimes provided to all the rollers for controlling the speed of movement and nearly horizontal transport through chains or sprockets. These conveyors may be arranged in a straight section, curved section, or a combination of both. These can also be classified into two groups according to the power requirement as (i) an Unpowered or Idle Roller Conveyor (ii) Powered or Live Roller Conveyor.

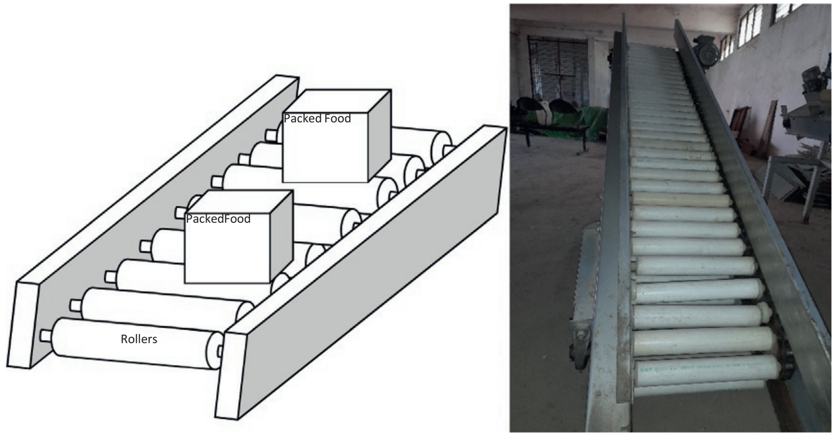

FIG. 8.19 Roller conveyors.

The rollers are not operated or driven by any external source in an unpowered roller conveyor. The loads may be conveyed over a series of rollers through pull or push using various mechanisms, e.g., endless chain, pusher, dogs placed on-chain or rope, rods, clamps, etc. Such conveyors usually run at a horizontal level, although at times such conveyors are granted a slight tilt to support the load movement, and about 1.5%–3% inclination means that the load moves through gravity. These are referred to as the "gravity roller conveyor." All or a specified number of rollers, depending on the chosen control configurations, are powered by one or more than one motor. The rollers transfer motion to the loads through the friction force acting on the surface of the load and conveyor rollers.

Roller conveyors are utilized for conveying nearly any unit load with a rigid riding surface that can move on two or more than two rollers. These are particularly used between buildings, in warehousing as storage racks, docks, foundries, rolling mill plants, manufacturing, assembly, and the packaging industry. The driven rollers may be mounted up to 10° or down to 17° in a slightly inclined position. The changing of the direction of rotation of the rollers is usually defined as reversing conveyors, and the load may be shifted in any direction. The rigid riding surface of any food material in the form of unit load can be transported using this material. Roller conveyors are used especially in production, assembly and shipping industries for manufacturing of equipment, structures, warehouses, storage racks, gates, foundries, rolling mills, etc.

They are often used as part of the composite handling framework for storage between workstations. But it is possible to utilize the limitations of roller conveyors only for items with solid flat surfaces and to travel at fairly short distances. Side guards are required to prevent the loads from falling off. The loads with acceleration also create risks while conveying. These power-operated roller conveyors can be classified on the basis of their driving mechanism. The following are the types of roller conveyors:

(i) *Belt-driven roller conveyors*
These rollers are driven by belts and provide high flexibility and speed. These provide hassle-free touchless transport within a limited space and remain useful for sorting and waxing operations of various fruits and vegetables.
(ii) *Toothed belt-driven roller conveyors*
Roller conveyors for box or package transport over large distances may be equipped with a toothed belt drive. The infinite belt is pushed against the rollers and can be moved over wide distances using a single motor. Their modular design makes these enormously adaptable for transportation.
(iii) *Chain-driven roller conveyors*
Chain-driven roller conveyors are suitable for heavy use and transport of crates. The durable construction is possible in steel or stainless steel, depending on the requirements and the environment.

Chain-powered roller conveyors are suitable for heavy systems and containers. The robust construction using stainless steel or steel depends on the requirements and the environment.

8.7.8 Chain conveyors

Chain conveyor systems are powerful and reliable conveyors used for the transfer of goods across a manufacturing line. A chain conveyor may be used for moving heavy products which cannot usually be transferred to a conveyor roller. Thus, pallets, shelves, commercial containers, and other goods with a durable lower surface are usually used. In various warehouses and delivery centers, chain transport networks are accessible where big, large products need to be managed.

8.8 Pneumatic conveyors

Pneumatic conveyors are well suited for transporting granular and powdered materials in food processing industries, viz., sugar, tea, coffee, etc. Dry air is used as a medium for conveying hygroscopic food materials. This compressed gas, usually air, is used to convey the material from the feeding unit to the discharge bin through a pipeline. The compressed air works as a carrier that may remain completely enclosed. The material moves in enclosed systems and pipelines, which enhances the adaptability of pneumatic conveyors. The pneumatic conveying works under negative, low, or high positive pressures. The conveying system provides better flexibility in conveying the material looking at the need of the plant layout and operations. These occupy very little floor space as pipe networks are usually installed on the walls, roofs, underground, which do not create any restriction in plant layouts. It also provides flexibility to the multiple point feeding layout and multiple discharge units using the same pipeline network.

The material conveyed in suspension mode by carrier gas is referred to as dilute phase pneumatic conveying. A higher velocity is selected moving the material in suspension mode. The speed is generally limited to 11 m/s for conveying very fine powder, which is extended up to 16 m/s for granular material, or it may remain more in case of higher density particles. The material conveyed in the non-suspension mode at a lower velocity as low as 3 m/s is termed as dense phase pneumatic conveying. The material may move along the bed on the inner bottom of the pipeline in bed flow or it may travel along with the full-bore plug of the pipe.

The solid loading ratio is one important factor, and it can be expressed as the mass flow rate of material conveyed to the air used for the material.

$$\text{Solid loading ratio} = \frac{\text{Mass flow rate of material conveyed, kg/h}}{\text{Mass flow rate of air used, kg/h}}$$

The value of the solid loading ratio for the dilute phase remains under 15, i.e., 15 kg/h with 1 kg/h air movement. The ratio can go up to 100 in the case of dense phase pneumatic conveying (McGlinchey, 2008).

The pneumatic conveying systems work on positive or negative pressure looking at the need of operation and product in food processing industries.

8.8.1 Positive pressure pneumatic conveying systems

The positive pressure conveying systems have a blower to create the flow of air. The material to be conveyed is kept in a feeding bin, which is being fed into the conveyor line. The material is conveyed through a closed pipeline and discharges the material in the discharge bin. A filter is provided to the discharge bin to restrict the material from moving away from the air (Fig. 8.20).

8.8.2 Negative pressure pneumatic conveying systems

These systems are preferred for conveying the material from multiple sources and delivering it in a single discharge bin. The material is taken up by the vacuum induced by the blower, which is installed after the filter of the discharge bin.

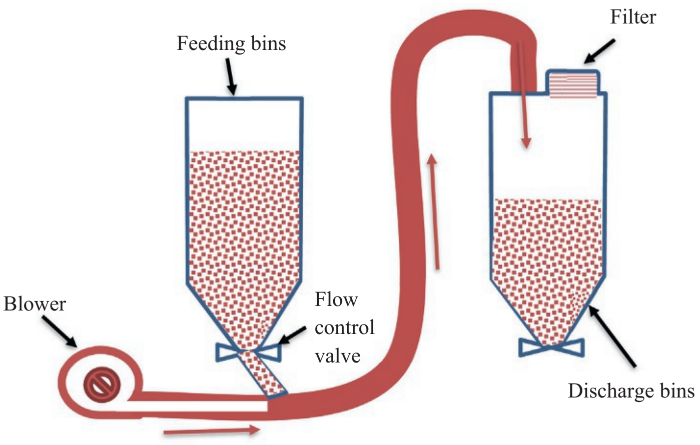

FIG. 8.20 Positive pressure pneumatic conveying systems.

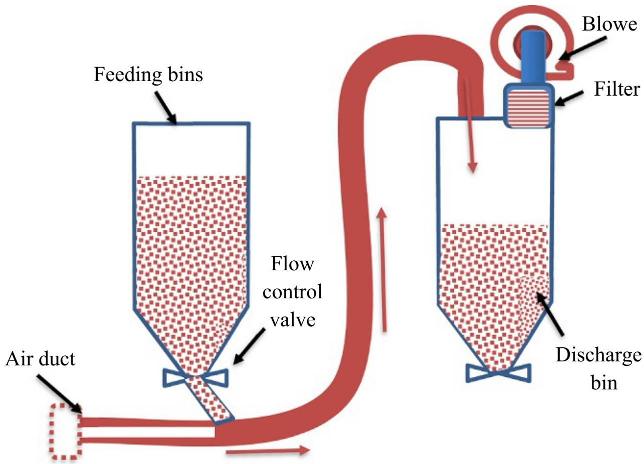

FIG. 8.21 Negative pressure pneumatic conveying systems.

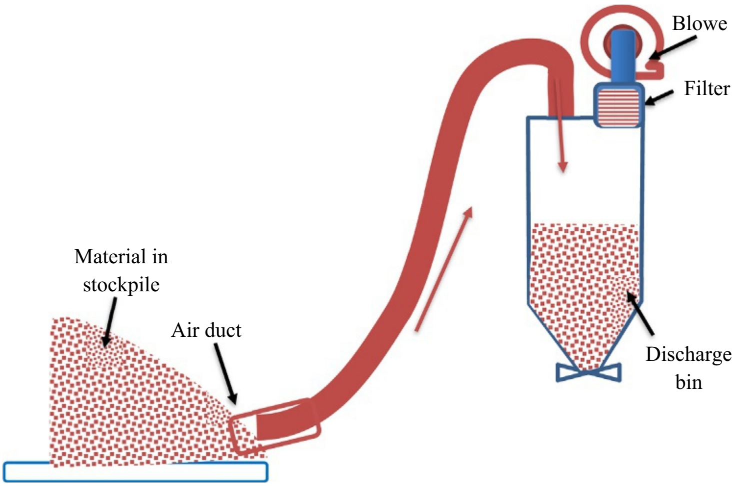

FIG. 8.22 Negative pressure pneumatic conveying systems from the pile.

The material can be taken up from the feeding bin by suction and conveyed into the discharge bin (Fig. 8.21). The negative pressure pneumatic conveying systems can also take up the material from the stored pile to convey it to the discharge bin (Fig. 8.22).

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Chapter | Nine

Different mechanical conveyors in food processing

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9.1 Introduction

Conveyors are the most frequently used material handling equipment (gravity or powered) commonly utilized for moving bulk or unit load continuously or intermittently from one point to the other where the primary function is to convey the material.

Belt conveyors are among the primary elements of many industrial processing systems (Daniyan et al., 2014). They may not have much impact on the product's processing or specified characteristics in most industries but in the food-processing industry, they are a source of major concern. A well-constructed and maintained belt conveyor can remove possible handling hazards while a poorly built belt conveyor can expose the product to hygienic hazards. Some other types of conveyors that are utilized are vibrational conveyors, screw conveyors, flexible screw conveyors, and aero-mechanical conveyors (Woodcock and Mason, 2012). A vibratory conveyor is a machine in which a trough is formed by turning the solid conveying system on the side. It covers the applications mainly in the food sector because of the ultimate importance of washing, sanitation, and lower maintenance reasons. A vibratory conveyor consists of a trough that is attached to a vibrating drive that aids in vibration causing the materials to move in a forward direction. Vibrating conveyors perform multifunctional tasks with their use to screen, orient, and separate different materials during the transportation process in food-based plants. A screw conveyor consists of a solid shaft or pipe fixed with helical flight pieces within a tubular or U-shaped trough. With the rotation of the screw, the cleanliness and the maintenance of the conveyor are

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attained. In the case of moist materials shaftless screw conveyors are available. A more advanced polyethylene-based food-grade tube having ultrahigh molecular weight entailing the rotation of a stainless steel/heat-treated and tempered carbon steel forms the construction of a flexible-screw conveyor. The simple installation, design, and flexibility of this conveyor allow its use for a huge mass of materials. Another development is the "rope and disc conveyor" or aero-mechanical conveyor (Lijun et al., 2004). This conveyor consists of uniformly spaced polyurethane discs that are attached to a wire rope. The continuous movement of the rope and discs in the loop form at a high speed inside the parallel placed tubes made of steel results in the production of an airstream that facilitates fluidization and entrains the material with respect to the airflow till it is obtained centrifugally at the outlet. This conveyor also helps in the movement of the material in batches and operates at any angle either in a circular motion or in a straight manner without causing any degradation to the material (basic conveyor). The recent past has witnessed rapid growth in legislation attempting to regulate the design as well as the condition of materials in contact with food. With rising demand in guidelines for providing comprehensive details and guidelines for enforcement (instead of legal remedy) including many certifications of systems such as Hazard Analysis & Critical Control Points (HACCP), International Food Standards (IFS), European Hygienic Engineering & Design Group (EHEDG), British Retail Consortium (BRC), etc.

In the light of rising costs in production, the interest in accurate conveyor and conveyor belt design has grown where the higher standards of hygiene are viewed as minimizing waste and potentially can save various costs like cleaning and disinfection costs in the face of rising water scarcity and labor-related problems. Sweeping generalizations for conveyor and belt design are difficult as the food industry requires to meet a variety of demands. Food materials may be hot or cold, oily, humid or dry and may undergo freezing, frying, baking, etc., on the conveyor. All of these factors will affect the necessary measures need to be taken to ensure that a system offers proper hygienic protection in a cost-effective way. The main focus of this chapter is on foods that have humidity whether fatty or aqueous for which washing can be used as a disinfection method. These comments can be used for dry products although cleaning methods and their cost-effectiveness will differ.

In this chapter, hygienic design aspects are reviewed for the following types of conveyor belts:

- friction and positively driven belts
- round- and V-profile belts
- plastic modular belts
- wire belts

This chapter describes issues involved in accurate design as well as those related to maintaining the appropriate hygienic procedures as they are currently perceived.

9.2 Basic design rules

The design mainly concentrates on hygienic objectives that shall help in ensuring (easy) cleanliness, protecting the processed product from contamination, and avoiding the attack of microorganisms and insects.

The designed system must allow the monitoring and control of the following aspects:

- The presence of sharp corners and edges should be avoided while designing the equipment.
- The design must be free from areas that may harbor microbes such as grooves, crevices, rough surfaces, and any similar areas where cleaning is difficult. Therefore, the designed equipment must facilitate easier cleaning.
- Equipment should be designed in such a way that there should not be contamination of the product with lubricating or hydraulic fluids.
- The equipment should be designed with few elements and open as possible.
- The designed equipment should not hinder product flow otherwise it may result in product accumulation.
- Parts such as hinges should be designed in such a way that they can be disassembled for cleaning and inspection.
- Horizontal surfaces should have a certain inclination to allow water to run off so that drying of the processing area after the cleaning will be easy.
- The building should be designed without blind spots where water, detergents, dirt, etc., may get accumulated and pose difficulty in cleaning.
- The design must include a space for storing dismantled parts.
- The design must comply with the rules and regulations of the specific standards of countries.

9.3 Materials of construction

Many countries follow different directives for materials that come into contact with foodstuffs according to their country's legislation. For example, in Europe materials contacting food must comply with regulation EC 1935/2004.

Some of the points that are considered while selecting the materials are as follows:

- The materials used for food equipment must not adulterate the food and also should not adversely affect organoleptic properties.
- The materials used for food equipment must not contain lead, cadmium, arsenic, or mercury, which may leach into the food and cause toxicity.
- Aluminum should be avoided where wet cleaning procedures are applied as it is not sufficiently corrosion-resistant. Compared to the electroplated materials the chemically plated materials are preferred because of their compactness and high durability. In nickel- and chromium-plated equipment, the integrity of plating should be regularly checked in order to ensure that it does not flake, which may result in contamination.
- Stainless steel is the most widely used material in the food industry as it offers excellent corrosion resistance. The selection of the most appropriate grade

among the wide ranges will depend on the intended application, i.e., amount of stress subjected, constraints of hardness, formability, weldability, and cost.
- The material surfaces should be smooth, nonporous, and free from cracks, crevices, and pitting, which can retain soil or harbor microorganisms after cleaning.
- Materials should have adequate resistance to corrosion, fatigue, stress, impact, abrasion, wear, and erosion. Materials that work during manufacturing may require additional treatments such as grinding or passivation to make them resistant to corrosion.
- If materials are coated that coating must be nontoxic and should offer sufficient resistance to cracking and flaking. Precautions should be taken so that no coating fragments leach into the product during processing and maintenance.
- Materials modified with antimicrobial additives should not be considered as a hygienic design because over a period of time microorganisms may build up resistance to such chemicals.
- The use of traditional materials should be avoided as they are considered hygienically hazardous.
- Plastic materials may be used as they offer advantages such as flexibility, corrosion resistance, etc., but some plastics that are porous and absorb product constituents should be avoided.
- Guidelines for hygienic seals must be consulted. Materials (like rubber) used for seals, gaskets, and scrapers, etc., may get damaged by excessive mechanical or thermal operations.

9.4 Design for manufacturing and assembly (DFMA) of conveyors

Work in the area of production and assembly design has been very useful in recent years for companies or industries that are developing their facilities and methods of production. A vast quantity of papers was published that investigated DFMA-related issues and applied various methodologies to achieve results that are efficient and cost-effective for the industries. However, little research has been done in the area of design of conveyors especially related to re-engineering of the conveyor design based on traditional methods. DFMA knowledge can be classified into broad categories like general guidelines, company-specific practice, and process-specific constraints.

For DFMA guidelines, the following points were compiled (Mize and Glenn, 1989):
- develop a modular design
- design for the minimum number of parts
- design parts for multipurpose
- design parts for easy fabrication
- minimize the variations in part

- minimize handling
- design for ease of assembly
- evaluate assembly methods
- use parts of known capability with no marginal overstress
- avoid separate fasteners
- avoid adjustments
- avoid flexible components that are difficult to handle
- use known and proven vendors and suppliers

9.4.1 Modular conveyor belts

A modular conveyor belt consists of individual plastic modules linked with or without joint rods. They have a toothed underside allowing them to be driven positively by sprockets under low tension (due to their own weight). Modular belts have high strength and high resistance to impact, abrasion, corrosion, cleaning agents, and other physical and thermal influences. Modular belts are used where complex curves such as the converging and diverging lines are present. For example, cooling lines, cooling spirals in bakeries, and individual quick-freezing freezers. The availability of a variety of modular belts and their suitability for applications in the food industry makes it difficult to pick a hygienically superior model. The presence of semi-solids, juices, and pastes accompanying the production of many moist foodstuffs can render the entire surroundings of a conveyor hazardous due to the inability of a modular belt to allow seepage and offer product containment. Over the last two decades, modular belts have been the popular choice due to their general acceptance and mechanical versatility even though modular belt design only relies on links and pins which are not considered hygienic. The present hygienic guidelines are beginning to raise questions related to the universal acceptance of modular belts for the foods that are in direct contact. In the food and beverage industry, conveyor systems used are highly automated and customized to carry products such as drink bottles, food cartons, and cans in production and assembly lines. Most of the food processing industries involve cans for continuous operations. Cartons and bottles are required to move at a specified speed for filling or conveying operations. This requires an efficient and reliable conveyor system ranging from overhead types, floor-mounted types of rollers to chain or belt-driven conveyor systems.

In recent years, demand for low-cost efficient conveyor systems has made manufacturers review their current design principles or methods which can result in alternative means to manufacture low cost but reliable conveyors. Usually, conveyor systems are made based on the specific locations and conveyor belts based on their synchronized speeds. Any change in installed or existing conveyor system is very difficult and expensive. In today's rapidly changing industrial markets, there is a need to implement a new manufacturing strategy, a new system operational concept, and a new system control software and hardware development concept that can be applied to the design of a new generation of open, flexible material handling systems (Ho and Ranky, 1994). It should be noted that most of the research works in the food and beverage industry are aimed at improving the operations of mechanical conveyor systems and integration of sophisticated hardware and software to design conveyor systems. Ho and Ranky (1997) proposed a new modular conveyor system (both 2D and 3D) which consists of an open reconfigurable software system based on the open system architecture model.

9.4.2 Round and V-profile belts

Round and V-profiles conveyor belts have narrow extrusions with either V or round shape depending on the specific industrial requirements. They are used to convey solid and lightweight materials like fish, meat, and sliced products in bakeries as well as for separating and spreading the food coating and toppings in packaging lines. The use of profiles as the conveying system enables a strong grip with minimal contact between the product and the profiles. Few types of V-profile and round belts are meant for conveying heavier materials by reinforcing with a tensioning member. However, for splicing these profiles the system must not allow fibers from the tensioning member to get trapped onto the surface of the profile (Kold and Silverman, 2016).

9.4.3 Open mesh wire belts

These consist of a metal wire of open mesh formed into strands that are interwoven together. The function of this woven hooked linkage is to allow the belt to articulate without the use of enclosed hinge joints or pin that provides open access for cleaning and disinfection. For positive driving, the belt usually toothed sprockets harmonized to the belt pitch are utilized as presented in Fig. 9.1.

Open mesh wire belts are wear- and cut-resistant having wider conveying applications in straight lines, round curves, and in horizontal as well as inclined elevations. They consist of an open structure that allows fluid, air, or media to pass through the belt and can be operated at a wider temperature range (150–800°C) (Kold and Silverman, 2016).

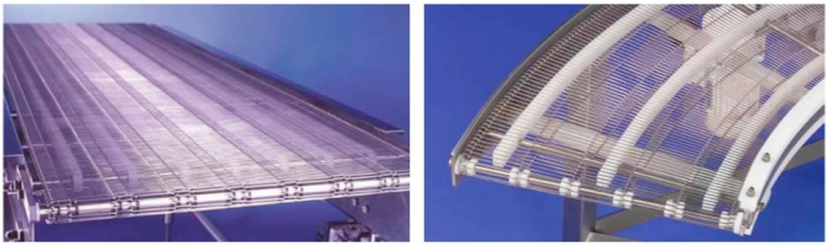

FIG. 9.1 Wire belts with toothed sprockets.

9.4.4 Food-grade conveyor belts

The material used for food-grade conveyors must be approved according to EU1935/2004, EU 10/2011, and local legislation. The color of food-grade conveyors is usually blue and white but blue is preferred because it helps in easier detection of contaminants in the food industry. The belt surfaces are textured in such a manner that it provides proper grip or release properties. However, while designing it should be ensured that the texture of the cleaning regimen is cleaned without trapping any contaminant. However, belts with special features like side walling, guides, and flights involve scrapers that hinder the disinfection and cleaning of belts.

9.4.5 Fabric-reinforced/ply belts

These types of belts are made from one or multiple embedded synthetic fabric carrier or carcass layers driven by a pulley with or without a friction surface or lagging. Fabric-reinforced conveyor belts are used for linear and curved conveying and are relatively inexpensive. The belts are susceptible to abrasion and corrosion due to the layers of ply (Kold and Silverman, 2016). The porous plastic susceptible to light scratching can result in small microscopic cavities that trap contamination. These types of belts should be carefully monitored and are used in nose bar transfers in bakeries where small products or dough in high volumes are fed from one conveyor to another. The fabric-reinforced belts can be smoothly textured on the top surface.

The fabric-reinforced conveyor belts are made endless by welding in a press or using mechanical joining methods. The mechanical joints allow the belt to be dismantled which is not recommended for hygienic belts as they allow easy passage for germs and bacteria.

9.4.6 Homogeneous flat belts

Homogeneous belts also known as monolithic belts are made from solid extrusion of thermoplastic elastomer resulting in the formation of dense structure and do not have a reinforcing fabric layer (Lewan and Partington, 2014). The belts are somewhat similar to fabric belts in their applications (horizontal, trough, elevators, and gooseneck conveyors) with the exception of narrow transfer applications with nose bars and curved conveyors (Fig. 9.2).

The specific application, mode of operation, and material of construction determine the thickness, hardness, and specific typology of homogeneous belts.

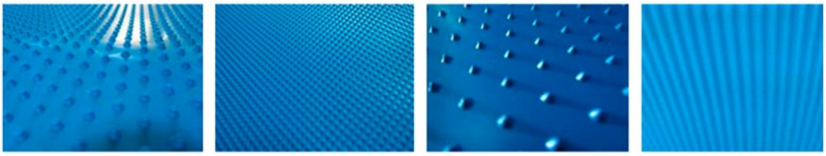

FIG. 9.2 Homogeneous textured belts.

9.4.7 Positive-drive homogeneous belts (tooth-driven, light conveyor belts without woven fabric mesh)

Positive-drive homogeneous belts like friction-driven homogeneous belts are made from either one extrusion of thermoplastic elastomers (TPEs) or by welding teeth to the flat homogeneous extrusion. Usually, these belts do not possess any additional reinforcement; but some types have embedded tensioning members within the homogeneous layer. The positive-drive mechanism eliminates friction rollers by means of an array of teeth on the underside which consists of a sprocket or a toothed drive placed over a drum motor or on a standard conveyor axle. Since they are homogeneous with no exposed fabric layers, they present a high level of hygiene, thus eliminating the contamination of food products in direct contact with the belt (Kold and Silverman, 2016). The positive-drive homogeneous belts offer numerous advantages in food-contact applications, viz., easy maintenance with minimal breakages, long operational life, and effective disinfection and cleaning due to the absence of or a low level of hygienic blind spots, thus saving water, disinfecting and cleaning chemicals, and cleaning time.

9.5 Food conveying systems and their hygiene

This subject is contentious but is at the heart of the issue of food hygiene in conveying lines, in that the belt is generally the main element not produced from stainless steel that is allowed to intentionally come into contact with a foodstuff. In this context, the hygiene operations and the issues that shed light on the realities of belt usage behind the procedural demands and influence the cleanability of a belt for ply/fabric belts, homogeneous friction-driven belts, and modular positively driven belts will be discussed.

9.5.1 Cleanability

Cleanability describes the propensity of food-processing equipment to be cleaned and disinfected and rendered free of soil. Microbes, dirt, and other contaminants are usually trapped in between the mechanical elements of the conveying systems like belts and elevators, leading to cross-contamination of the food products. It is therefore important to establish cleaning and disinfection procedures for these conveying systems to maintain quality assurance and safety of the food products being conveyed (Kold and Silverman, 2016). Easy cleaning operations can ensure the safety of foods as well as lower the cost of production. However, some specific attention is needed with each belt type which includes the following:

(i) With regards to friction-driven fabric belts, the best possible method for disinfecting and cleaning is the clean-in-place (CIP) operation. A new belt possesses a smooth and homogeneous surface and is therefore easy to clean. The sealed and dense surface of the belt limits the ingression of contamination into the edges and scratched surfaces of the belts. The sealed edges should be inspected frequently for signs of wear and tear. It is important to completely dry the belt surfaces before the next use to inhibit microbial invasions.

Chemical degradation due to the use of disinfectants or the physical damage due to wear and tear of the conveyor's results in poor hygiene of the operations involved. The configuration of the conveying systems therefore should allow easy and proper cleaning of the conveyors.

(ii) The cleaning operation for friction-driven homogeneous belts can be carried out either manually or through CIP. The belt must have sealed and dense surfaces and the bottom side of the belt need to be cleaned the same way as the top surface. In cases where the belt is supported by a flat plate, full accessibility for underside cleaning is necessary. Waved side walling (Fig. 9.3) has to be avoided in the case of the products that trap easily in between waves.

(iii) Positively driven homogeneous belts are light in weight and therefore easy to lift manually for cleaning. A spray bar cleaning system may be superfluous in this perspective; however, it only cleans the parts of the belt sprayed as well as some sprocket surfaces but not blind spots. These elements require extra attention for cleaning as they are directly in the path of the product flow and will often trap the product.

(iv) Metal-to-metal contact points in hooked joints are not static as the belt articulates during the operation. The open hooked joints and low belt tension allow access for disinfecting and cleaning. Care should be taken when cleaning the belt with chemical sanitizers and disinfectants so that belt surfaces do not undergo pitting or fragmentation.

Apart from this, the effectiveness and the applicability of the cleaning process mainly depend on the following factors:

(a) *Time between cleans*: The cleaning operations of the food products are more or less dependent on the sensitivity of the product to contamination and regulations related to its safety and hygiene. However, this can greatly

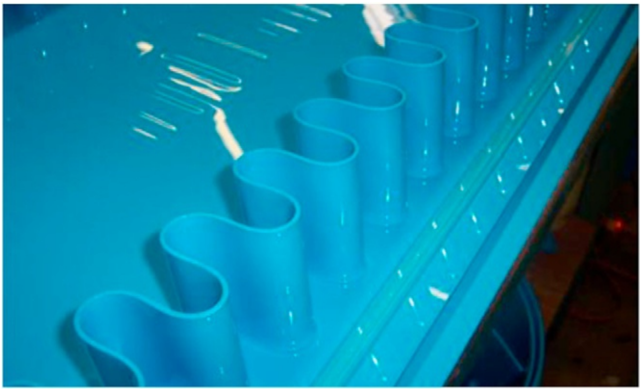

FIG. 9.3 Belt with guides and waved/concertinaed side walling.

affect the cost of production as frequent cleaning operations demand much use of water, chemicals, and manpower. Further, the regular exposure of the conveyors to chemicals during these operations greatly affects their life.

(b) *Length of cleaning procedure*: Conveyors requiring much lengthy cleaning procedures demand much cleaning time, which ultimately increases cost and potentially provides more room for errors due to complexity in cleaning procedures.

(c) *Type of cleaning operations required*: Usually, under certain circumstances, the ability of a given belt type to stand up to cleaning operations can go beyond the prescriptive nature, advisable for a belt of that type.

(d) *Quality of fabrications*: Elevators and some horizontal belts are usually affixed to the belt by heat-welding, high-frequency (HF) welding, or by mechanical attachment. The common features of the elevators and belts include guides, flights, and side walling. It, therefore, becomes critical to inspect these features and should be taken into consideration while designing these features.

(e) *Propensity to erode, fragment, or delaminate; porosity*: All the aforementioned processes result in wear and tear. High wear and tear necessitates frequent belt replacement. As such, the belts and conveyors have to be manufactured from highly rugged materials that can withstand extreme operating conditions and do not frequently undergo wear and tear.

(f) *Splicing, vulcanizing, closing belts*: Faster wear and tear and accumulation of dirt in the conveying belts occur at the point where two ends meet. Therefore, implementation of modular belts for conveying has been recommended in view of the ongoing hygienic risk.

(g) *Belt choices*: The lifetime, ease of the cleaning operations, and efficiency of the belts get often obscured by the purchase price.

9.6 Conclusions

The perception of maintenance of suitable hygienic conditions is an important issue related to the use of mechanical conveyors. Appropriate utilization of conveyor and conveyor belts during the manufacturing procedure is required not only for sustaining the hygienic levels but also for the reduction in the cost of cleaning and disinfection. The broad spectrum of food, their properties, perishability, and demand of the food industry stimulate the system certainty to maintain proper hygienic levels in a cost-effective manner.

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Chapter | Ten

Pneumatic conveyors

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10.1 Introduction

Among the various methods of material transportation, pneumatic conveying is one of the most common and the most versatile conveying technologies. Over the last decades, the development of pneumatic conveyors has led to many advantages such as lower cost, reliability, cleanliness, and low contamination (Tan, 2009).

The history of using an air stream to transport solids dates back to 1859 when the Roots brothers patented the Roots blower, which enabled the pneumatic transfer of materials (Klinzing, 2018a). Increasing applications of pneumatic transport can be seen by recent developments and an increase in the diversity of these systems (Litovchenko, 2015). Due to the high flexibility of the pneumatic conveying system in different conditions and its wide applications in different parts of the industry, in recent decades, it has a major share of the solid material transport market (McGlinchey, 2009). According to predictions, the economic growth of this industry will be about 30 billion dollars by 2025 (Klinzing, 2018b).

During the recent decade, this method has become one of the common methods of material transporting in different industries including energy, food, chemicals, minerals, plastics, pharmaceutical, ceramic, metallurgical, etc. Pneumatic conveyors are used for transferring dry bulk materials in granular and powdered form using the energy of a pressurized carrier gas which is mostly air or nitrogen. The materials move inside pipes and troughs due to gas flow and the pressure difference between the transportation starting and ending points. There are two basic forms of pneumatic conveyors: positive pressure, which blow material along a pipeline, and negative pressure (vacuum systems), which convey material by means of suction (Suhane and Agarwal, 2012). Combinations of negative and positive pressure systems (suck-blow systems) are also applied extensively in many industries (Klinzing et al., 2010). These conveyance structures are

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also available in the dilute-phase (lean-phase) mode, which works in low pressure and high velocity; and dense-phase mode, which works in high pressure and low velocity (Wilms and dos Santos, 2002). Besides these general working principles, there are various criteria that affect the designing of pneumatic conveyors such as the characteristics of the material to be transported, conveying distance, delivery rate, feeding and discharge elevation, and so on, which mean that there are many possible configurations of pneumatic conveying systems. The study on pneumatic conveying involves many subject branches and is of great practical significance to manufacturing production (Silin et al., 2012).

Pneumatic conveying is widely used in several food processing plants and in food transport and storage facilities (Saravacos and Kostaropoulos, 2002) to transfer granular food solids, grains, and powders (Alehosseini et al., 2021). One of the first uses of pneumatic transport in the food industry was reported to be at the end of the 19th century in London for unloading wheat from barges to flour mills (Reed and Bradley, 1991).

Although pneumatic transport is more energy-intensive than mechanical transport systems, making pneumatic conveyors more advisable to be used for transportation of fine particles over short distances, this is an economic limitation, not a technical one (Klinzing et al., 2011). Because of the many advantages of pneumatic conveying systems including containment and flexibility of pipeline transport for bulk solids (Barbosa-Cánovas et al., 2005; Zheng and Liu, 2011), less contamination of conveyed material (Kumar and Mallick, 2015), and preventing loss of desired volatiles from foods (Alehosseini et al., 2021), they can be recommended as the most suitable method for material handling particularly in large-scale, continuous food processing plants (Saravacos and Kostaropoulos, 2002). Different food materials including wheat, corn, flour, beans, tea, coffee, granular sugar, barley, spray-dried milk powder, and peanuts are transferred using this approach (Barbosa-Cánovas et al., 2005; Ghafori et al., 2011; Saravacos and Kostaropoulos, 2002). Pneumatic conveyance is used on a large scale in almost all modern cereal grinding installations (Tănase and Danciu, 2011).

Considering the importance of the pneumatic conveying systems, this short chapter is dedicated to giving information on these systems. First, the advantages and disadvantages of pneumatic systems are presented. Then the different applications of pneumatic conveyors in the food industry are mentioned. Afterward, components and different classifications of pneumatic systems are described. Finally, a brief but useful description of the pressure drop in a pneumatic conveying system is provided.

10.2 Advantages of pneumatic conveying

There are a large number of advantages reported for pneumatic conveyors. Some of the advantages of these systems are clean transportation, system flexibility, large capacity, low maintenance, low manpower costs, transportation of a large variety of products, high security, and easy automation and control. More descriptions about some of the pros of the pneumatic transportation systems are given below.

10.2.1 Dust-free transportation

Mechanical transportation of powdered and bulk materials can spread dust and microparticles such as mechanically abrasive and chemically aggressive elements into the surrounding air. This issue can induce several problems such as damage or even failure to mechanical devices and systems and health hazards to employees. Since pneumatic conveyors are enclosed structures, these systems are virtually dust-free and clean, if they are properly constructed and maintained. On the other side, cleanliness and preventing the transported materials from contamination, which are obtained by pneumatic conveying systems, make these systems the preferred choice for transporting sensitive products, such as foods and drugs. Materials that are transported open to the atmosphere can be affected by dust, insects, air moisture, and pollution, which can lead to contamination and spoilage of materials that, in turn, can pose significant threats to public health.

10.2.2 System flexibility

In pneumatic conveyors, the materials are transported by means of a gas flow through pipelines. This combination makes these systems more flexible, compared to mechanical methods, in structure design and handling of different materials having various specifications.

In terms of design, different geometric schemes can be employed in the pneumatic transportation systems to achieve different routing options. Pipeline direction can be easily changed using bends to change the conveying path, and the pipelines can be routed up walls, across roofs, or even underground using horizontal, vertical, and inclined line designations (Klinzing, 2003; Mills et al., 2004).

These systems can be used to transport materials in very small spaces. With appropriate equipment selection and arrangement, pneumatic conveyors can be also expanded to be used to transport materials over long distances. Another aspect of the design flexibility in pneumatic conveyance systems is that these systems can transfer materials from one or multiple feeding point(s) to one or multiple discharging point(s). These different inlet/outlet options can be obtained easily by appropriate system reconfiguration.

In terms of materials to be transported, a vast variety of materials can be conveyed via pneumatic conveying systems. These conveyors are used in different industries including the agricultural and food industries, chemical and pharmacological industries, and mining and mineral industries for the transportation of powdered and granular pellets and even irregularly shaped small particles (Zinchenko, 2015). About 300 types of materials are reported to be transported by pneumatic conveyors (Anonymous, 2001; Bhatia, 2019; Klinzing et al., 2010; Mills, 2016).

10.2.3 Lower operational cost

Unlike mechanical conveyors which have a large number of moving mechanical parts, pneumatic conveyors have a minimal number of moving components, reducing the average number of maintenance actions.

Pneumatic conveyors generally consist of simple pipes or tubes, negative or positive pressure pumps, feeding and discharge systems. Having few key mechanical elements makes the pneumatic transportation systems easier to maintain, less prone to failure, and have a longer expected working life. Furthermore, in the case of failure, the damaged part can be repaired or replaced individually without moving or removing the other parts. Additionally, working fluids in pneumatic conveyors are mainly air or nitrogen abundant in our world, and the result is lower operating costs.

10.2.4 Higher safety

Having a minimum number of moving parts and fewer maintenance requirements leads to lower exposure to potential dangers and higher safety to the facility operators and maintenance crew. Moreover, since the materials are transported through sealed pipelines in pneumatic conveying, these systems are more suitable for transportation of hazardous materials such as chemicals in a more healthy and less environmentally damaging manner and prevent facility workers' exposure to dust and airborne chemicals which can cause several health issues ranging from simple coughing to even heart failure.

10.2.5 Easier automation

Due to the nature of pneumatic conveyors that use compressors and gas, the automation process of these systems is easier than that of other conveyors. It is possible to automate and control the flow of materials by installing appropriate electric circuits, panels, and PLC programs. The operator can easily monitor and control the transportation process using a touch screen monitor. The final discharge point can also be controlled. By taking advantage of this feature, silos and food processing facilities can easily automate the material transfer between different production stages and lines.

10.3 Disadvantages of pneumatic conveying

Along with their advantages, there are also some drawbacks that need to be considered. These disadvantages are higher power consumption, wearing out of system components and pipelines by abrasive conveyed material, requirement of a larger dust collection system, limited conveying speed of fragile material, and inadequacy for transportation of some materials such as sticky or combustible bulk solids. More descriptions about some of these issues are discussed in the further subsections.

10.3.1 Limited conveying speed of fragile material

High conveying speeds can lead to breakage and degrading of delicate materials during transportation. Such fragile materials should be transported at low speed in the dense-phase conveying mode.

10.3.2 Higher energy consumption

In pneumatic conveyors, energy is used mainly for air compression and stream to transport materials. The energy consumption is high, especially in the cases where the materials are transported over long distances.

10.3.3 Inadequacy for transportation of some materials

Pneumatic conveying systems are not appropriate for moving pastes, slurries, and wet, high-fat, and sticky materials. These nondry products can stick together or to the pathway walls resulting in a buildup in the pipelines and, in turn, can cause part or even full blockage in the conveying system, if it is not monitored and treated.

The transportation of combustible materials is another challenging issue of pneumatic conveyors. Suspension of combustible materials in the air, which is abundant in pneumatic conveying, can lead to fire hazards in warm conditions or beside an unwanted ignition. Having high pressure with a fire triangle (air, heat, and combustible material), the explosion is ready to happen, if precautions are not taken properly. Besides precautions, accurate monitoring, precise detection, and on-time reaction are essential in these cases. Additionally, it is also proved that pneumatic conveying is not a suitable choice for transportation of large particle size and high bulk density products like stones.

10.4 Applications of pneumatic conveying in the food industry

One of the most important applications of pneumatic conveyors is in the food industry which has a history of several decades of successful use of these conveyors in different food processing plants. A wide variety of food materials in the powdered or particulate form can be transported by pneumatic conveyors. Pneumatic conveyors are used for unloading food materials from transportation vehicles such as trucks or ships, gentle moving of material between different processing units, and carrying the processed foods to packaging or storage structures.

Food processing plants accept the higher energy requirement of pneumatic conveyors compared to mechanical conveyors, because of the important advantages of pneumatic conveyors which can continuously transport food material throughout the facility on the processing lines from one or multiple collection openings to either a single or multiple discharge points. In the food processing industry, most of the materials are friable or fragile and need to be transported gently with minimum or even no damage. Material velocity in the conveying path is a determining factor in the material damage. In this regard, the dense-phase conveying mechanism is the preferred option for food material transportation, because in these conveyors the moving speed of the material can be decreased so that no break or degradation is incurred in the product. This advantage also allows the dense phase pneumatic conveyors to be utilized in the transport of blended materials with a segregation tendency between processing steps or to the packaging section.

In terms of grain handling, a wide range of grains including wheat, rough rice, corn, coffee grains, sunflower seeds, beans, soybean, canola seed, lentil, peas, nuts, etc. can be conveyed pneumatically. Pneumatic conveyors can be used for unloading trucks and filling silos, lifting grains from ground pits to fill silos and bins, silo emptying and truck loading, continuous conveying of grains to dryers, mixing different grains with specified doses in blenders, and grain bagging. The mentioned grain materials are used as raw materials in many food processing industries, indicating the use of pneumatic conveyors in a wide range of food processing plants.

The remarkable advantage of pneumatic grain transfer is that after the conveying process is completed, no grain remains at any point of the conveyor line and the whole grain is transferred without almost any loss.

Flours obtained from wheat, corn, rice, beans, and nuts are very fine materials that can be conveyed by either dilute or dense phase pneumatic conveyors. The dilute phase transporters are more common; however, the dense phase systems are used in some cases where a very high conveying capacity is desired. Grain flouring facilities undoubtedly understand the importance of pneumatic transportation systems for conveying the intermediate stocks in the grinding and flour preparation. In a wheat flouring plant, besides the applications mentioned above, the pneumatic systems are also used for material transport to/between machines such as de-stoning, mixing, and cracking of wheat grains. Pneumatic systems are also applied for transferring the finished product to the storage and packaging departments.

In the sugar industry, pneumatic conveyors are the most preferred option for material transport in different sections. Both dilute and dense phase systems are used in this industry. Powdered sugar is conveyed through the conveying pipes in the cloud form by diluting it in the air. Positive pressure is mostly used; however, vacuum type conveyors can also be used for short distance transportation. In the case of granular sugar, the high velocity of conveying which occurs in dilute phase systems can break the material. Therefore, the dilute phase pneumatic conveyors are used for granular sugar transportation only if the size reduction is not a concern, such as conveyance of the granules to the milling machines or bakeries (Thorn, 2011). This allows profiting from advantages of dilute phase systems such as higher rate transportation, lower cost, and simpler operation. In some cases where it is important for the granules not to be damaged, such as ornamental uses or drink mix products, the sugar granules are conveyed using well controlled dense phase systems.

In the fish processing industry, dense-phase pneumatic transportation systems are used for conveying a wide range of sizes of fish food pellets over horizontal and vertical paths very reliably with an appropriate transfer rate and without line blockages.

10.5 System components

A pneumatic conveying system consists of some basic elements like an air supply system (positive or negative pressure), feeding devices, conveying ducts, bends, and separation devices. The main components of a pneumatic conveying system are illustrated in Fig. 10.1.

10.5.1 Air supply

Air supply is the most important component of the system and is called the heart of a pneumatic conveyor. The airflow and pressure requirements of the conveyor are the main parameters for selecting the air supply system. This unit can be divided into three categories of fans with a maximum working pressure of 20 kPa, roots type blowers (rotary lobe blowers) with a maximum working pressure of 50 kPa, and compressors with a maximum working pressure of 250 kPa (Klinzing et al., 2011). The fans can be divided into four categories of axial flow, radial flow, mixed flow, and cross flow base on airflow direction. The fans and blowers usually have high volumetric flow rates at a relatively low working pressure, but the compressors have a high working pressure at low volumetric flow rates.

10.5.2 Feeding devices

The feeding device is a crucial component of a pneumatic conveying system. This unit regulates the feed rate of solids into the line. It can be divided into three categories of low pressure (LP) and high pressure (HP) due to the air working pressure.

10.5.2.1 Low pressure feeding devices

This feeding device type can be used from vacuum applications to pressure in the order of 100 kPa. The LP devices are divided into rotary feeders and venturi feeders. In the following sections, these types of feeders are discussed.

Rotary valves (rotary air lock)

This feeder is one of the most commonly used devices in the pneumatic conveying industry. The two main components of the feeder are the bladed rotor and fixed housing. The rotor consists of a shaft in which some blades are welded around it. The rotor is driven by a motor and operates in the housing. The spaces between the blades, which are referred to as pockets, are filled with materials at the inlet port. Then by rotating the feeder, the materials are transferred and discharged at the outlet port. This feeder is sometimes referred to as the rotary air lock feeder, because of its application in some pneumatic conveyors as an air

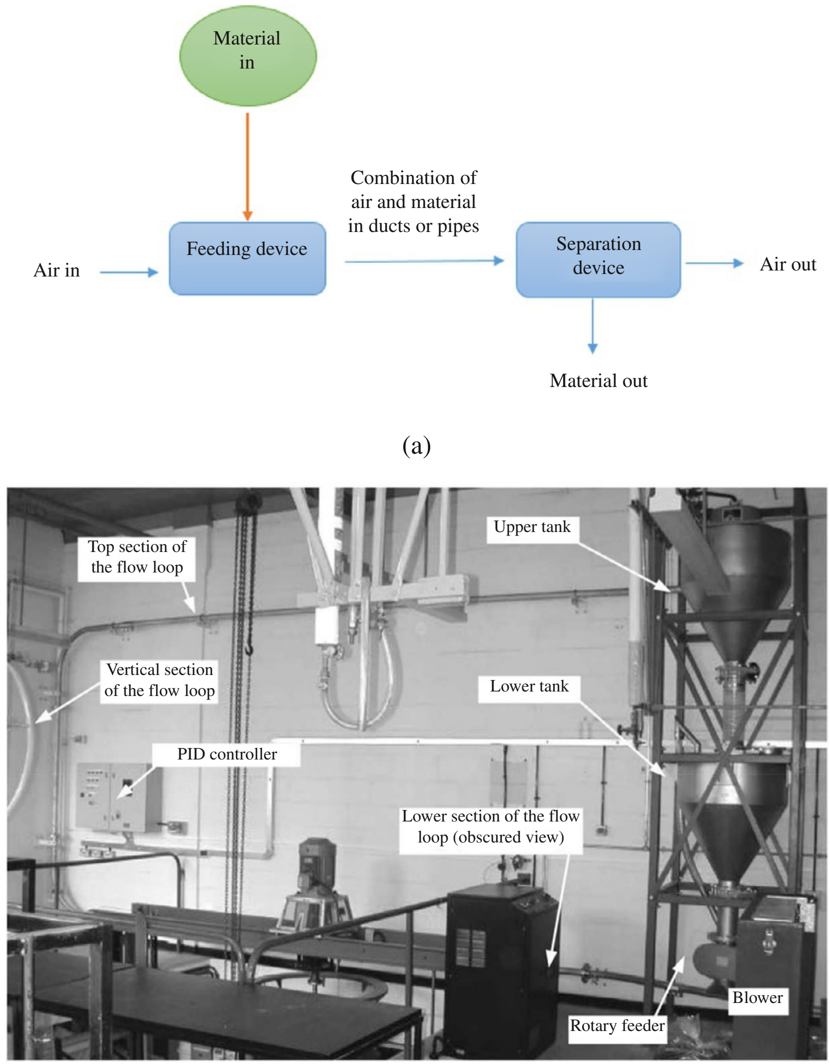

FIG. 10.1 (A) Components of a typical pneumatic conveying system, (B) a sample pneumatic conveying system (Jaworski and Dyakowski, 2002).

lock. A rotary valve feeder is absolutely recommended for conveying free-flowing and nonabrasive materials (McGlinchey, 2009). Two views of this feeder are shown in Fig. 10.2.

Venturi feeders

The principal operation of this feeder is based on Bernoulli's principle in fluid mechanics. Due to the lack of moving parts in the venturi feeder, it is potentially suitable for use in systems for conveying abrasive and friable products (wheat,

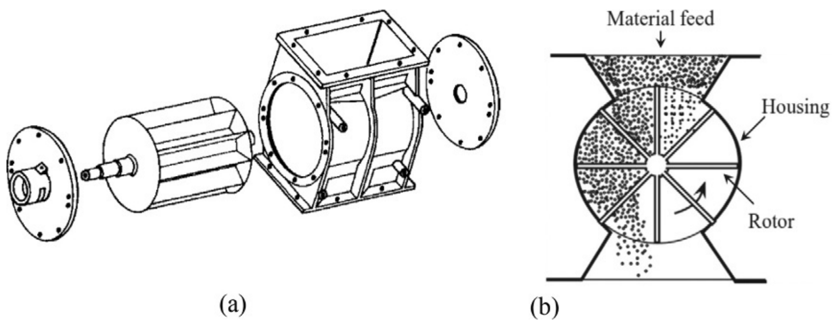

FIG. 10.2 A typical rotary valve feeder, (A) extended perspective parts view and (B) cross-sectional view. *Panel A: Adopted from Klinzing, G. E., Rizk, F., Marcus, R., Leung, L., 2011. Pneumatic Conveying of Solids: A Theoretical and Practical Approach (vol. 8). Springer Science & Business Media with permission; Panel B: Adopted from Mills, D., 2016. Pneumatic Conveying Design Guide, third ed. Elsevier with permission.*

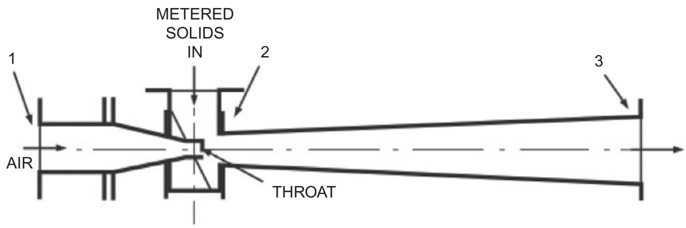

FIG. 10.3 A schematic view of a venturi feeder. *Adopted from Klinzing, G.E., Rizk, F., Marcus, R., Leung, L., 2011. Pneumatic Conveying of Solids: A Theoretical and Practical Approach, vol. 8. Springer Science & Business Media with permission.*

maize, potato crisps, etc.). On the other hand, the operation of this feeder is restricted to low solid flow rates for transporting short distances.

It comprises an air entraining nozzle section, a cylindrical entrance for solids, and a divergent outlet. The airflow in the nozzle section reduces the air pressure (negative pressure) and increases the air velocity. By feeding the solids from the supply hopper into the cylindrical section, the high velocity airflow makes contact with the solids, and the mixture of air and materials is discharged through a divergent outlet (Crowe, 2005). The schematic view of this feeder is shown in Fig. 10.3.

10.5.2.2 High pressure feeding devices

A blow tank (blow vessel) is one of the conventional high pressure feeding devices. The volume of blow tanks used in pneumatic conveying systems varies up to 50 m^3 or more. These feeding devices have no moving mechanical components. So they are a good candidate for conveying brittle materials like agricultural grains or livestock feeding. In addition, by using a blow tank, there is no need to use a supply hopper. The other benefits of using a blow tank as a feeder

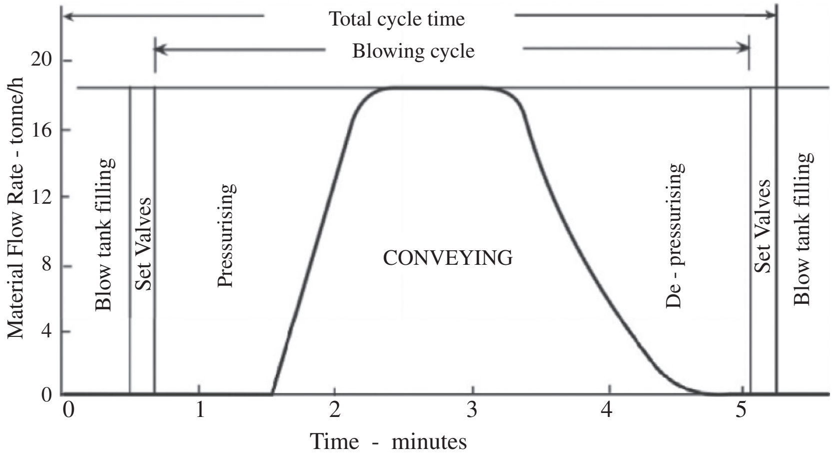

FIG. 10.4 Typical working cycle for a blow tank. *Adopted from Mills, D., 2016. Pneumatic Conveying Design Guide, third ed. Elsevier with permission.*

can be expressed as low maintenance, low wear of the feeder, low degradation of the materials, and noise reduction. The drawbacks of this system are batch operation, unsuitable for very sticky commodities, and difficulty in controlling the discharge rate. Fig. 10.4 shows the batch operation of a typical blow tank. As is obvious, conveying of solids is not continuous and the tank operates under maximum capacity for a short time.

A complete conveying cycle of a typical blow tank consists of filling solids, pressurization, conveying, and depressurization.

Generally, two configurations of blow tanks are used in the pneumatic conveying industry: top discharge and bottom discharge. The top discharge blow tank is suitable when the limitation of physical space occurs. This type of blow tank is used for conveying fine powders. This blow tank needs a membrane fluidization system for discharging the solids. Using a top discharge blow tank, it is not possible to discharge the solids completely. The bottom discharge type is a good candidate for conveying fine and coarse commodities. In this blow tank, the materials are fed into the pipe due to their gravity, and the discharge operation is completely done. Unlike the top discharge blow tank, there is no membrane and fluidization system for discharging in the bottom discharge type.

10.5.3 Conveying ducts and bends

10.5.3.1 Ducts

Considering the basic concept of pneumatic conveyors, which is the moving of material on gas stream through pneumatic pathways, ducts are very important structural elements in pneumatic transportation systems in which the materials are transported. Pipes are defined as conveying ducts that have a circular cross section. In a pneumatic transport system, along with the gas mover that is included for the generation of pressure or vacuum in the carrier gas, enclosed tubing should be used to transfer the material from the pressure tank to one or the respective receiving units. Depending on the applied positive or negative displacement blower, products are pushed or sucked through the pipes. Pipes are made of different materials depending on the type of material/materials to be transported through.

The most preferred material for pneumatic lines is stainless steel. Alternatively, other common materials are mild steel and aluminum. Plastic tubes are used in some light duty conveying works over short distances. Glass or rubber pneumatic pipes are also available. In recent years, materials such as polyethylene, polystyrene, and polycarbonate have also been used for manufacturing pneumatic transport pipes.

Other engineering characteristics of the conveying pipings, including length, diameter, and routing design, depend on factors such as product particle size, desired velocity, and blower pressure. In general, the inside diameter of the transfer tubes should be at least three times the largest diameter of the transported material to prevent the product from becoming blocked in the tube (Klinzing et al., 2011). Small diameters and high loading ratios can cause a pressure drop and clogging of the pipe.

The pneumatic ducts should be resistant against erosive wear. The interior side of the pipes should be completely smoothed with no roughness or obstacle to protect the conveyed product from mechanical damage and to minimize duct wear.

It is important for the pneumatic pipelines to be completely sealed to avoid leakage or exposure to the ambient air, moisture, and pollutions. The other important point to be considered is the necessity to protect pipelines from the accumulation of electrostatic charges that can occur due to the product rubbing on the tube. Electrical grounding should be installed on the pipes and equipment.

10.5.3.2 Bends

The geometry or the routing of the pneumatic conveyors is provided by bends to change the direction of the product pathway. The use of bends in pneumatic conveyors is unavoidable, as bends contribute to the flexibility of pneumatic conveyors. On the other side, problems such as flow rate reduction, pipe wear, and product damage are possible at bending sections. Design precautions should be considered to minimize these challenging issues. As a general instruction, sharp bends should be avoided, and for the bends having an angle of more than 45°, the bend radius should be at least six to eight times larger than the pipe diameter (Hellevang, 1985).

In pneumatic conveyors, bends are generally divided into three categories, including common radius bends, common fittings, and special bends (Dhodapkar et al., 2009; Tripathi et al., 2019).

Common-radius bends

These bends are created by bending standard tubes. The bending radius in this category is up to 24 times larger than the diameter of the conveying pipe. According to the ratio of turning radius to pipe diameter, the common-radius bends are divided into four different categories: elbow, short radius, long radius, and long sweep bend. If the bend radius is equal to or up to three times larger than the tube diameter, it is called the elbow. In short-radius bends, the bend radius is from more than three times to seven times the tube diameter. This ratio is 7–14 for long-radius bends, and 14–24 for long-sweep bends. Bend erosion and product damage may occur in the impact zones of these bends. Although longer radius bends increase the pipe length, pipe erosion and product attrition will be reduced. Schematic views and some characteristics of short-radius and long-radius common bends, such as impact zones, are illustrated in Fig. 10.5 (Dhodapkar et al., 2009).

Common fittings

Another type of bend that is popularly used to change the conveying direction in pneumatic transportations systems is common fittings that are divided into mitered bends and tee bends.

Mitered bends are obtained simply by the angular cutting of one or both of the pipes to be jointed and then jointing them together. Different direction change angles can be obtained, but the most common angles are 45° and 90° (Fig. 10.6A and B).

Tee bends, which are used to a 90° change conveying direction, have an additional dead-end sequence at the bending region. It is like a two-way joint with one of its outlets blocked. This stagnant part acts as a cushion and prevents the material from attrition and the pipe from wear (Fig. 10.6C). The problem with common fittings is the intensive drop in material pressure at the joint

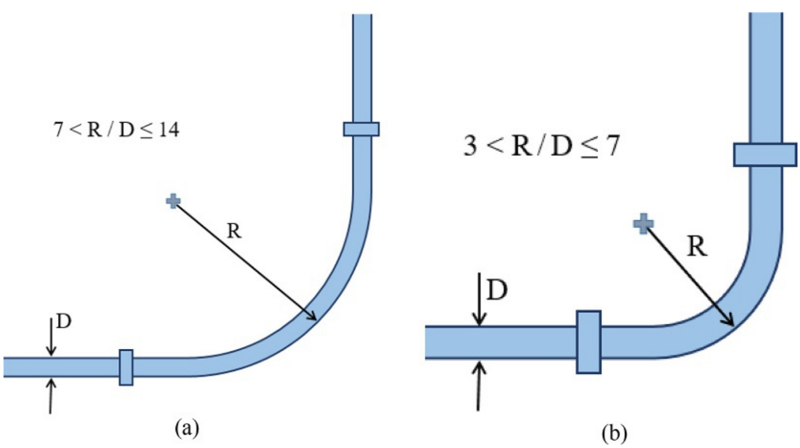

FIG. 10.5 Schematic cross section of long-radius (A) and short-radius (B) bends; D: tube diameter, and R: bend radius.

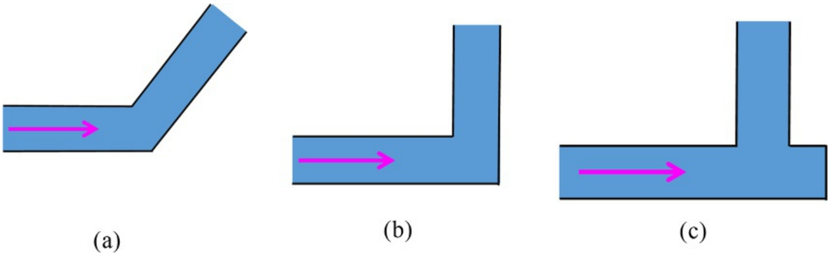

FIG. 10.6 Schematic cross section of common fittings; Mitered bends (A and B), and tee bends (C).

section, which can be as much as three times higher than the long-radius bends (Dhodapkar et al., 2009).

Special bends

Innovative designs of bends that are developed to reduce product damage and bend erosion are categorized as special bends. These designs try to minimize the particle-to-particle and particle-to-wall impacts by taking measures such as changing the bore formation and changing the inner/outer bend radius at different points. Two of the most common innovative bends are the gamma bend and Gericke bend (vortice el bend). Gamma bends have an angular formation at their neck which causes the product to be slightly accumulated at the impact zones of the bend. This formed shield reduces the material collisions with the bend wall, which in turn reduces the damage of the product and abrasion of the pipe. Gericke bends, which are exist with 45 and 90 degrees turnings, have a bulbous chamber on their neck in which the moving product is filled (or circulated in some conveying velocities) and acts as a cushion (Dhodapkar et al., 2009; Klinzing et al., 1997). Some of these novel bend designs are presented in Fig. 10.7.

For more information about bends in pneumatic transportation systems, a very comprehensive description of different types of bends is provided by Dhodapkar et al. (2009).

10.5.4 Gas–solid separation devices

The gas–solid separation unit is the last component of each pneumatic conveyor for separating the solids from the conveying airstream. Particle size is an important factor to select the type of separation device. A variety of gas–solid separation devices are used in the industry: gravity settling chambers for coarse materials, centrifugal cyclone separators for finer materials, and fabric filters for dust (Mills, 2016).

In the gravity settling chamber, the materials are separated from the air due to their gravity. It is the simplest equipment that can be used in pneumatic conveyors. A schematic view of this separation device is shown in Fig. 10.8. This device is not suitable for separating solids with a low density or fibrous nature.

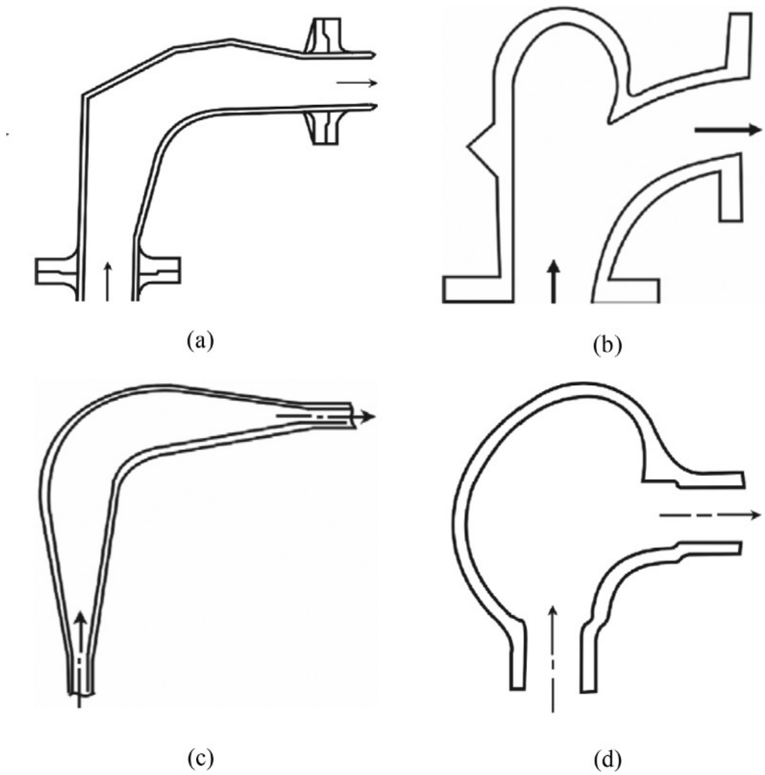

FIG. 10.7 Schematic cross section of some novel bend designs; (A) Gamma bend, (B) vortice el bend, (C) Expanded bend, and (D) flow bow (Mills, 2016).

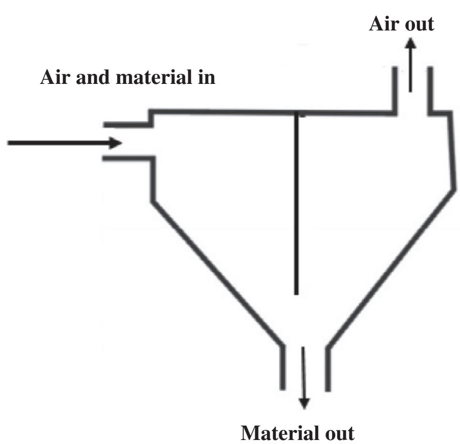

FIG. 10.8 Schematic view of the gravity separator device.

The cyclone is one of the most widely used air-solid separator. Cyclones are hopper-shaped and generally made of steel. The advantages of this device are simplicity, low cost, low maintenance and energy consumption, and a relatively low pressure drop. It can be used for collecting particles 5 μm in diameter or larger (Swamee et al., 2009). The separation efficiency of this system is between 60% and 90% (Boumans, 2012). The cyclone separator utilizes centrifugal force within a chamber to throw out the bulk of solids from airflow. Fig. 10.9 shows the principal operation of this system.

According to the literature, by increasing the cyclone length and reducing the radius, the efficiency of the cyclone will increase (Boumans, 2012). One of the most popular design guidelines for cyclones is the Stairmand design which was first developed by Stairmand in 1951 (Stairmand, 1951). A typical view of this cyclone type is represented in Fig. 10.10.

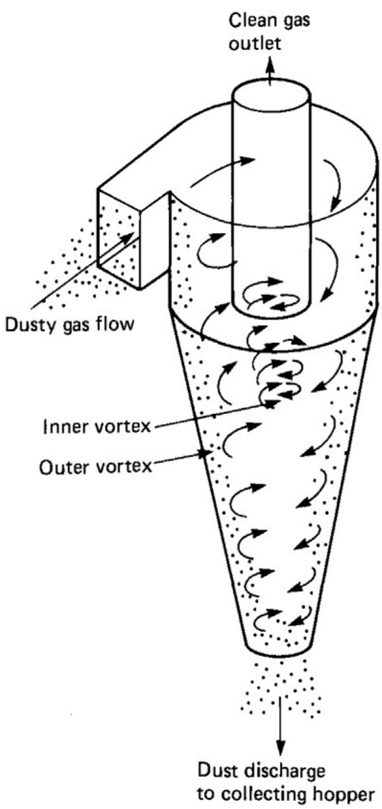

FIG. 10.9 Schematic view of centrifugal cyclone operation. *Adopted from Shamlou, P., 1988. Handling of Bulk Solids: Theory and Practice. Elsevier with admission.*

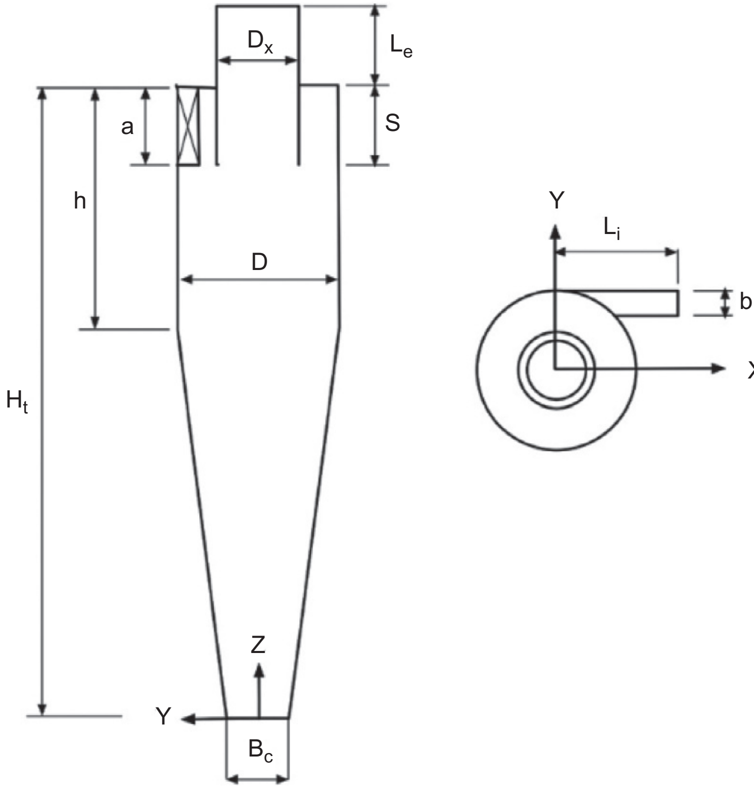

FIG. 10.10 A sketch of a Stairmand cyclone separator. *Adopted from Elsayed, K., Lacor, C., 2010. Optimization of the cyclone separator geometry for minimum pressure drop using mathematical models and CFD simulations. Chem. Eng. Sci. 65(22), 6048–6058 with permission.*

Fabric filters are used in the pneumatic conveyors for removing residual dust from the airstream. During the handling and processing of particles in pneumatic conveyors, the breakage and abrasion of larger particles to small solids are possible. These small particles are generally called dust. The resulting dust is dangerous and flammable. They must be removed quickly and completely from the pneumatic conveying system. In general, dust is created anywhere grain is moved, loaded or unloaded, agitated, and transferred from one point to another point (Boumans, 2012). The separating efficiency of this device is high (about 99%) and its performance is acceptable. This device is capable of removing large dust particles as well as very small materials with low density. According to the high efficiency, in some cases, the filters have replaced the cyclones. It may be constructed of a variety of materials, felted or woven. The schematic view of using the fabric filter in a pneumatic conveyor is represented in Fig. 10.11.

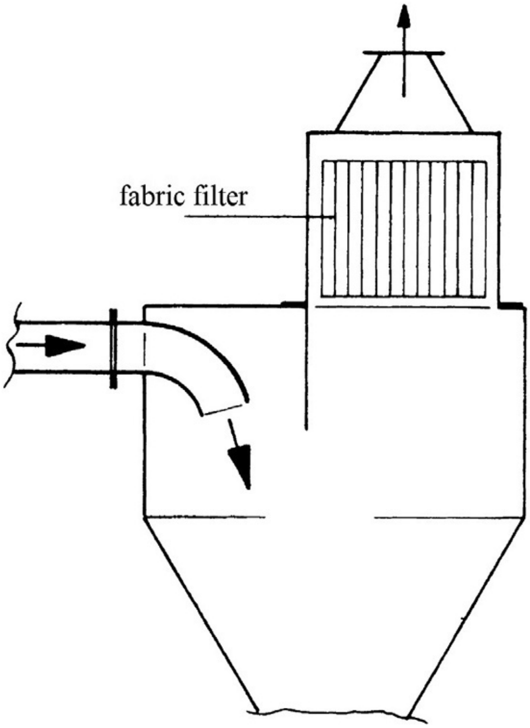

FIG. 10.11 Schematic view of a fabric filter used in a pneumatic conveyor. *Adopted from Boumans, G., 2012. Grain Handling and Storage. Elsevier with permission.*

10.6 System types

In this section, different classifications of pneumatic conveying systems are evaluated.

10.6.1 Classification by the flow pattern

In this classification system, the pneumatic conveying systems are categorized into two subsections: dilute (lean) phase and dense phase.

10.6.1.1 Dilute phase

Conventional pneumatic conveyors are frequently operated under dilute phases. This technology has a long history since the studies of Gasterstadt in 1924 (Klinzing, 2018b). Using high velocities and large amounts of air, the dilute phase of pneumatic conveying can be available. In other words, the solid materials are fully suspended in the airstream along with the entire system. This mode is most appropriate for transporting any solid material. The collision of solid materials is negligible and the mass flow rate of solids is low. The high velocity of material conveying in the pipes causes high power consumption, pipe erosions, and material degradation (Rinoshika and Suzuki, 2010). According to the literature survey, it can be concluded that these conveyors are frequently limited for operating at less than 1 bar pressure gauge.

10.6.1.2 Dense phase

In this phase, the particles move close together, transport at low velocity, and the mass flow rate of solids is very high. Unlike the dilute phase, the materials in the dense phase are conveyed in nonsuspension mode for the entire system. Because of the low velocity of the solids, material degradation and pipe erosion are reduced dramatically. This dense phase is the most optimal conveying mode of flow in pneumatic conveying of solids (Jones and Williams, 2008).

Types of dense phase regime

According to the literature survey, there is a broad classification of dense phase conveying in pneumatic conveyors (Dhodapkar et al., 2009). But two distinct categories of this mode are moving bed flow (fluidized dense phase) and plug (slug) flow. In the moving bed flow, the materials are conveyed in the shape of dunes on the bottom of pipes. Materials with good air retention characteristics and a mean particle size of 50 μmicrons and lower are good candidates for use in this conveyor type. In the other mode, the material is conveyed as full bore plugs separated by air gaps. This conveying mode is suitable for materials with good permeability such as grains, seeds, polyethylene, and nylon pellets. The transportation of these two modes is shown in Fig. 10.12A and B.

10.6.1.3 Criteria for recognizing the flow pattern

The recognition of the flow pattern of gas–solid in pneumatic conveyors is an important factor. A variety of different criteria can be identified for discriminating flow patterns in pneumatic conveying systems. These criteria are SLR, air velocity, saltation velocity, predictive charts, and phase diagrams.

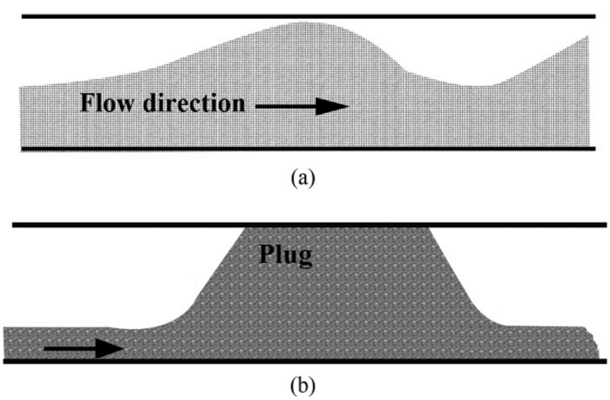

FIG. 10.12 Typical views of: (A) a moving bed flow and (B) a plug flow.

Velocity of air

According to these criteria, in dilute phase systems, the air velocity is varied between 12 and 16 m/s for powder and granular products, respectively. For transporting of solids in the dense phase, the value of air velocity is reduced to 3 m/s and lower.

Saltation velocity

In the dilute phase flow, when the air velocity falls lower than the minimum conveying value, the saltation phenomena of solid particles along the horizontal pipe are observed. If the conveying velocity of solids falls below the saltation velocity, the system is operated under a dense phase. Otherwise, the dilute phase flow is concluded.

Solids loading ratio (SLR)

The SLR is a useful criterion in helping to recognize the flow. In the literature, it is also known as the phase density or mass flow ratio. This dimensionless parameter is defined as the ratio of solid mass flow rate to air mass flow rate. The value of SLR remains constant along the length of the pipeline, which is a beneficial feature of this ratio. Other characteristics of the pneumatic conveyors such as air velocity and volumetric flow rate are not constant during the transporting operation. When the SLR is less than 15, the air-solid system is operated as a dilute phase. In the dense phase conveyors, this ratio is above 15. In some high dense phase (extruded flow or ultra-dense phase) conveying systems, this ratio is about 500 or higher (Mills, 2016).

Predictive charts

In the literature, some practical charts were used for predicting the flow patterns and behavior of solids which provide valuable information to the design of pneumatic conveyors. Some of these charts were developed by Geldart (1973), Dixon (1996), Mainwaring and Reed (1987), and Pan (1999). One of the most beneficial charts is Geldart's diagram which was first developed by Geldart in 1973. This classification is based on the fluidization behavior of granular materials. In this diagram, the variations of particle size versus relative density difference between the solid particles and the fluid phase are represented. According to this diagram, the materials are divided into four categories: A, B, C, and D. Group A is aeratable, which includes materials with a high level of air retention. This category is a suitable choice for moving the bed dense phase flow. Group C includes cohesive powders which are difficult to fluidize but represent good air retention capability. So this category is also a good candidate for moving bed flow. Group D materials tend to show high permeability behavior. This group has a potential candidate for plug flow dense phase conveying. The materials corresponding to group B usually have poor air retention and permeability. These particles are not appropriate for dense phase conveying. They show bubbles for all air velocities. Quadruple classification of the materials

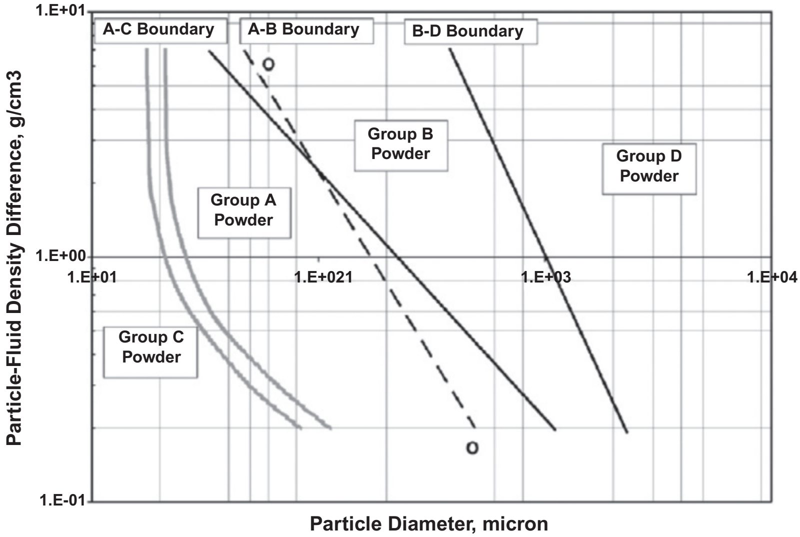

FIG. 10.13 Classical Geldart's diagram of powders. *Adopted from Yang, W.-C., 2007. Modification and re-interpretation of Geldart's classification of powders. Powder Technol. 171(2), 69–74 with permission.*

TABLE 10.1 Examples of materials in the Geldart classification method and their conveying characteristics.

Properties	Group A	Group B	Group C	Group D
Type of material	Powder	Coarse	Cohesive fine powder	Granular
Density ($kg\,m^{-3}$)	1000–4000	1000–5000	>2000	<3000
Mean diameter (μm)	20 to 50–100	50–100 to 500–1000	<20	>600–1000
Type of flow in a conventional system	Moving bed	Hard to convey in dense phase	Can convey in dense phase in difficulty	A possible candidate for plug flow

From Sanchez, L., Vasquez, N., Klinzing, G. E., & Dhodapkar, S., 2003. Characterization of bulk solids to assess dense phase pneumatic conveying. Powder Technol. 138(2–3), 93–117 with permission.

based on Geldart's diagram (Fig. 10.13) with their conveying behavior is listed in Table 10.1.

Phase diagram (Zenz plot)

The phase diagram is also known as the Zenz plot which was first developed by Zenz and Othmer (Botterill, 1961). In this diagram, the pressure gradient in a pneumatic conveying system is plotted versus superficial air velocity at different solid flow rates. Superficial air velocity is defined as the volume flow rate of

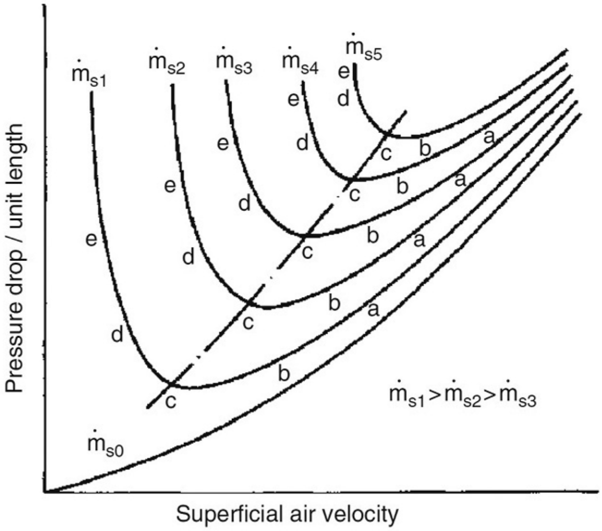

FIG. 10.14 General phase diagram at a varying solids flow rate. *Reproduced with permission of Klinzing, G.E., Rizk, F., Marcus, R., Leung, L., 2011. Pneumatic Conveying of Solids: A Theoretical and Practical Approach, vol. 8. Springer Science & Business Media.*

the air through a unit cross-sectional area of the pipe. This diagram can be represented for both horizontal and vertical pneumatic conveying. A typical phase diagram for horizontal conveying of fine materials is presented as Fig. 10.14. The dashed line through the minimum pressure gradient (pressure drop per unit length) is called the division line between the dense phase on the left and the dilute phase on the right. It should be noted that the solids flow rate which is defined as $\dot{m}_{S5}$ is more than the others ($\dot{m}_{S5} > \dot{m}_{S4} > \dot{m} > \dot{m}_{S2} > \dot{m}_{S1} > \dot{m}_{S0}$). When only air is transferred in the conveying pipeline ($\dot{m}_{S0}$ case), the pressure gradient increases with increasing superficial air velocity. But when a mixture of air and solids is conveyed in the pipeline, by decreasing superficial air velocity, the pressure gradient decreases to a point c and then increases. This point is equivalent to the saltation velocity and shows the minimum pressure gradient. When the system is working at a minimum pressure gradient, it has an economical operation. In addition, by increasing the solids flow rate, the diagram shifts upper.

10.6.2 Classification by working pressure of the system

In this classification method, the pneumatic conveying systems are categorized into three subsets of negative pressure (suction), positive pressure (blowing), and a combination of negative–positive pressure (suction-blow or pull-push) systems.

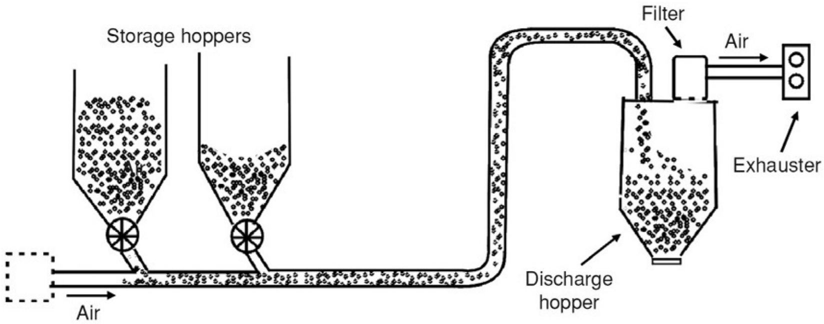

FIG. 10.15 Negative pressure system. *Adopted from McGlinchey, D., 2009. Bulk Solids Handling: Equipment Selection and Operation. John Wiley & Sons with permission.*

10.6.2.1 Negative pressure system

In this system, the products are transported by using air at less than atmospheric or negative pressure. This system usually used for transporting the solids from multiple sources to a single hopper. The rotary valve can be used in this type of system as a feeder (Mills et al., 2004). A sketch view of the negative pressure systems is represented in Fig. 10.15.

10.6.2.2 Positive pressure system

In this system, the conveying operation of the materials is done through the air that has a pressure above the atmospheric pressure. This system is widely used in pneumatic conveying systems that are usually available for conveying the materials from a single source to multiple hoppers. A wide range of feeders could be used in the positive pressure system from Venturi or rotary airlock to blow tank (Dhurandhar et al., 2018). A typical schematic view of a positive pressure pneumatic conveyor is shown in Fig. 10.16.

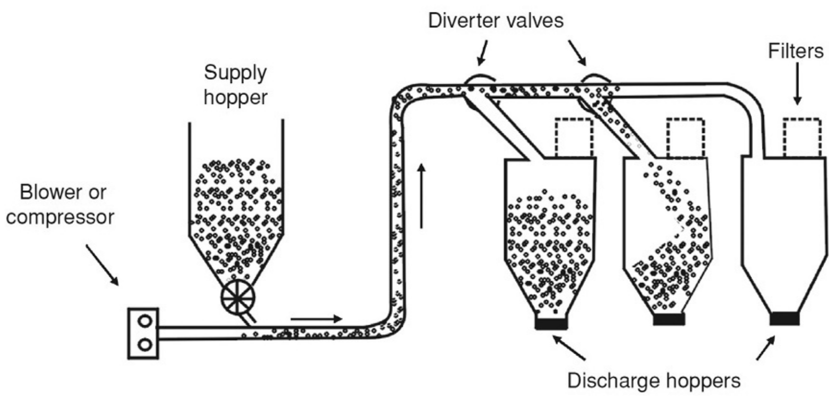

FIG. 10.16 Positive pressure system. *Adopted from McGlinchey, D., 2009. Bulk Solids Handling: Equipment Selection and Operation. John Wiley & Sons with permission.*

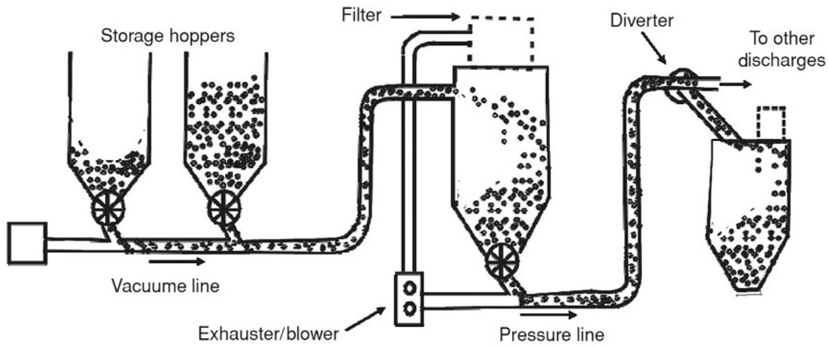

FIG. 10.17 Combined positive and negative pressure system. *Adopted from McGlinchey, D., 2009. Bulk Solids Handling: Equipment Selection and Operation. John Wiley & Sons with permission.*

10.6.2.3 Combination of negative and positive pressure systems

The combination system is often used in order to have the advantages of both positive and negative pressure systems. A schematic view of this system type is presented in Fig. 10.17.

10.6.3 Classification by loop configuration

In this segmentation method, pneumatic conveyors are classified into open-loop and closed-loop. Pneumatic conveying in most systems is operated under open-loop configuration.

In open-loop systems, the air is vented after a single pass through the pipelines. But in closed-loop systems, the air is recycled to the feed point. A typical view of a closed-loop system is represented in Fig. 10.18.

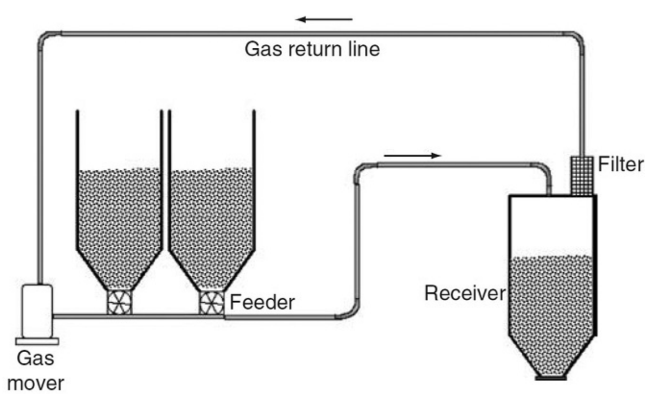

FIG. 10.18 A typical view of a pneumatic conveyor with a closed-loop configuration. *Adopted from Crowe, C.T., 2005. Multiphase Flow Handbook. CRC Press with permission.*

10.7 Pressure drop in a pneumatic conveying system

The pressure drop that occurred in pneumatic conveyors is due to some variables, the most important of which are frictional forces. These forces are air-to-pipeline wall friction, air-to-solids friction, solids-to-solids friction, and air-to-solids friction (Setia et al., 2016). In addition to these factors, the steam of gas and product needs to be accelerated at some points along the straight pathway or after bends, which can cause a pressure drop. In addition, the weights of the conveying gas and the conveyed product contribute to a pressure drop in the vertical conveying tubes (Rhodes, 1990).

Although there are correlations for determining the pressure drop in pneumatic pipelines, these equations are not entirely precise. Two distinct methods were applied by the designers for estimating the pressure drop in the pneumatic conveying systems. In the first method, the air-solid flow is considered as a mixture fluid. Using classical fluid dynamics equations such as Darcy-Weisbach equation, the pressure drop could be estimated. In this approach, the Darcy friction factor is renamed to a mixture friction factor. It could be expressed as

$$\Delta P = \frac{\lambda_m \rho_b L V_s^2}{2D} \tag{10.1}$$

where ΔP is the pressure drop, λ_m is the mixture friction factor, ρ_b is the bulk density of solids, L is the length of conveying, V_s is the solids velocity, and D is the diameter of the pipeline.

Some researchers have used this approach in their studies, of which Weber (1991), Karparvarfard and Vakili (2010) and Rahmanian-Koushkaki et al. (2020) are of interest.

In the second method, the pressure drop is a combination of losses due to air and solids. In other words, two friction factors are used in this approach. The equation used is represented as below:

$$\Delta P = \frac{(\lambda_a + \mathrm{SLR}\,\lambda_s)\rho_a L V_a^2}{2D} \tag{10.2}$$

where λ_a is the friction factor due to the air, λ_s is the friction factor due to the solids, SLR is the solids loading ratio, ρ_a is the air density, and V_a is the air velocity. This approach was first developed by Barth (1958). In recent years, some researchers have used this equation for predicting the pressure drop in pneumatic conveyors (Jones and Williams, 2003; Mallick, 2009).

10.8 Conclusions

In order to have an efficient and safe conveying, scientific knowledge about the engineering properties of the material to be conveyed, and the engineering characteristics of the conveying systems is required. In the food industry, there are so many products in powdered or granular forms, which can be conveyed through pneumatic systems. The great advantages of pneumatic conveyors, such as clean and safe transportation, flexibility, ease of automation, and capability to be readily integrated with other devices in the processing line, make pneumatic transport a desirable choice for material transport in food processing industries. There are, however, some points such as energy consumption and conveying speed of fragile material, which should be considered in the designation and application of these transferring systems. So the pneumatic transportation systems were basically focused on in this chapter. The concepts, pros and cons, main components, and divisions of these conveyors were explained.

Even with the useful information presented in this chapter, it is still a starting point for those who are interested in engineering design and practical implementation of the pneumatic conveying systems.

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Chapter | Eleven

Hydraulic conveyors, bucket conveyors, and monorails

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11.1 Hydraulic conveyors

Using fluid mediums like water and air, transporting solid materials of different sizes is carried out through pipelines. Thus, transportation systems or conveying systems are classified as hydro and pneumo transportation systems (Uzi and Levy, 2018; Kalman et al., 2019). Specifically, hydraulic conveyors (Fig. 11.1) are those in which water jets act as a conveying medium for bulk material transportation through pipes or troughs (Saravacos and Kostaropoulos, 2002). Food processing plants contain agricultural raw materials transported and stored in bulk (Grandison and Brennan, 2012). These raw materials are conveyed to processing using hydraulic conveyors by open water channels and flumes. Food materials, e.g., citrus fruits, tomatoes, and sugar beets, are conveyed to the juice extractors using mechanical elevators that can also play the role of washing equipment (Saravacos and Kostaropoulos, 2002). Pumping and piping systems are required for long-distance transportation against a pressure drop (Nourbakhsh et al., 2007). Large food pieces can be handled using volute-type centrifugal pumps with special impellers. Pumping food materials, like whole fruit, potatoes, carrots, beets, and fish can be done without quality damage. The pump construction materials can be expensive stainless steel or less expensive cast iron (Alehosseini et al., 2021).

Transporting Operations of Food Materials Within Food Factories. https://doi.org/10.1016/B978-0-12-818585-8.00013-1

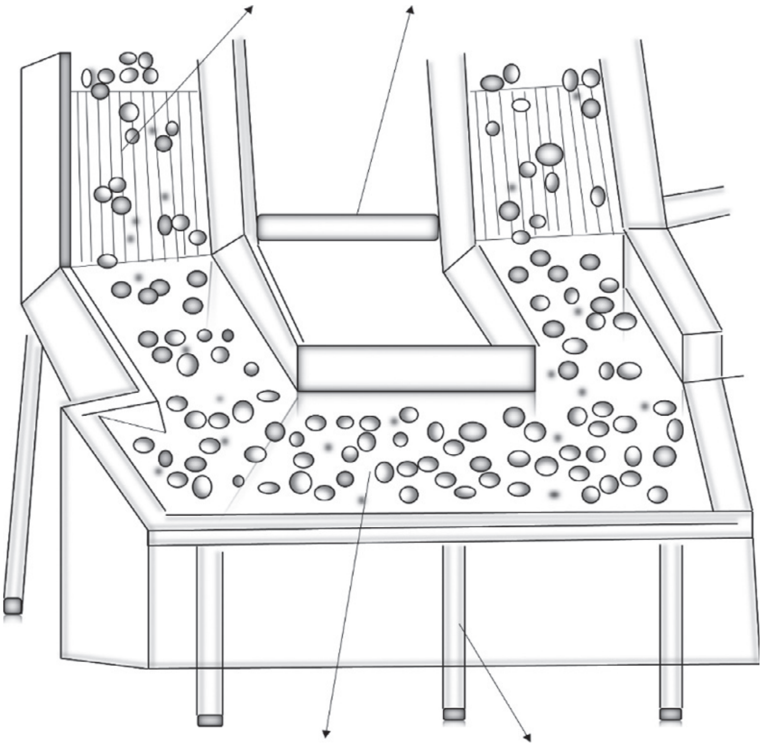

FIG. 11.1 Schematic diagram of hydraulic conveyor.

11.1.1 Principle

The controlled movement of food materials in any hydraulic conveying system is done through a prime mover called fluids (water, any other liquid). Along with the prime mover, other mechanical attachments like a lever, screw jack, etc., aid in the movement process. However, high magnitude-controlled forces can also be applied to these fluid systems, which will provide both linear and rotary motions. Thus, an enclosed fluid-based system that uses pressurized liquids (mainly incompressible) as a transmission source is known as a hydraulic system. The working of this hydraulic system is based on the principle of Pascal's law, which states that the pressure in an enclosed fluid is uniform in all directions (Lim, 2007).

Fig. 11.2 shows a hydraulic system in two different areas A1 and A2. In the figure, the force experienced by the fluid can be taken as a multiplication factor of pressure and cross-sectional area. According to Pascal's law, as the pressure exerted will be the same in all directions, a smaller force will be felt by the small piston and a larger force will be felt by the large piston. Therefore, by providing an input of smaller force F1, an output of larger force F2 can be generated with the use of hydraulic systems.

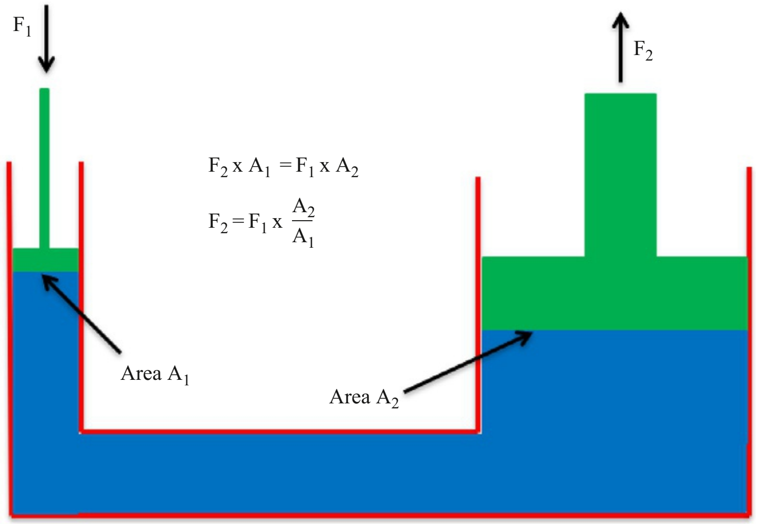

FIG. 11.2 Schematic diagram representing the principle of hydraulic system.

11.1.2 Components of a hydraulic conveying system

11.1.2.1 Pumps

Various types of pumps are available for handling food materials and slurries. The two main categories include reciprocating pumps, which are further classified into plunger and piston types, and the other is rotodynamic (centrifugal) pumps. Among these two classifications, the reciprocating type (Fig. 11.3) being a positive displacement machine is considered most significant because of its ability to attain high pressures (even capable of restarting flow in a blocked pipe) (Wang and Yamaguchi, 2002).

On the other hand, much higher sized particles (of size ≥100 mm diameter) can be passed through centrifugal pumps (Fig. 11.4) without severe damage. The three factors that can be considered when selecting pumps for food materials or slurry are (a) the pressure needed, (b) the actual flow rate, and (c) the slurries' nature because of solid particle dimension, and abrasiveness (Shook and Roco, 2015).

11.1.2.2 Dewatering equipment

Water or the carrier liquid removal at the emitting end of a pipeline is considered a significant issue as it can be a determining component in the study related to the feasibility of a pipeline. In general, finer particles offer more difficulty to dewater. The three essential processes involved in dewatering are:

(i) Particle sedimentation can be either natural or assisted by centrifugal action.

(ii) Filtration, where water is drained out of a cake solid, can be natural or assisted by centrifugal action, vacuum, or pressure.

(iii) *Thermal drying*: Among all these processes involved in the dewatering plant, selecting a particular method depends on the nature of the slurry to be dewatered, the required final dryness, and cost considerations.

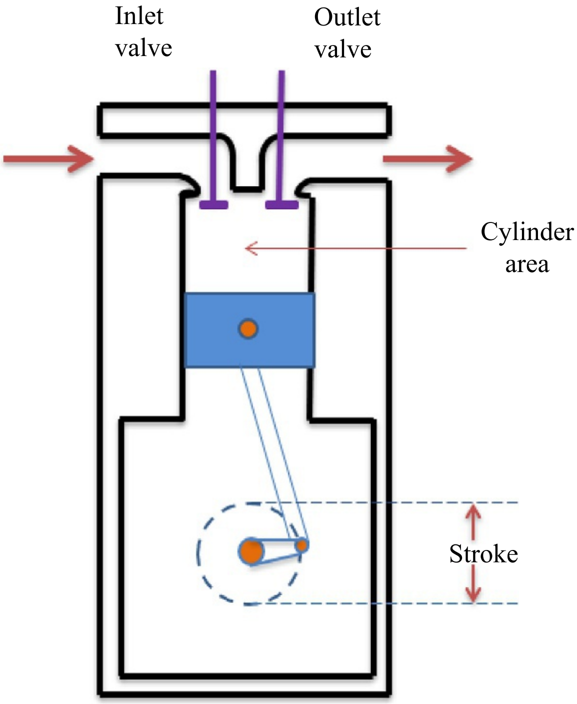

FIG. 11.3 Reciprocating or positive displacement pump.

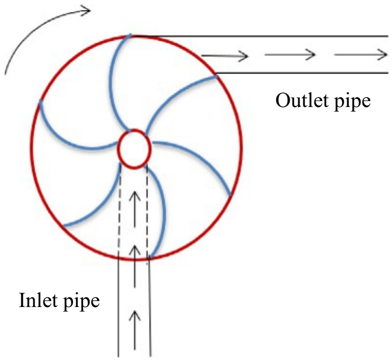

FIG. 11.4 Centrifugal pump.

11.1.2.3 The pipeline

The pipelines should combat enforced pressure and the need for consciousness towards the consequences of corrosion and erosion. Mild steel is majorly used for operational slurry pipelines. Installation costs could be reduced by using pipe sections of lowered wall diameter at the places where tension will be below. The wall thickness of a steel pipe will be in the range of 5–15 mm. Reinforced concrete, abrasion-proof steel, and high-density polyethylene (HDPE) are a few other materialistic substances suited for pipelines where corrosion is a problem. Linings made of rubber or plastic may be used to tackle wear and tear while managing abrasive slurries. The slurry pipelines may undergo erosive wear when the channeled material is abrasive, and the conveying velocities exceed 3 m/s.

11.1.2.4 Slurry preparation plant

Milling or grinding are the operations done during slurry preparation in which bulk solid is reduced to a satisfactory dimension for conveying and is later mixed with conveying liquid prior to passing the reduced solid into the pipeline of conveying. During the slurry preparation, a striking balance is needed between all the particle sizes, which gives optimal flow attributes of slurry. This reduced solid dimension is also required for succeeding processes like dewatering done at the emitting end of a pipeline. For extremely fine particles, despite the good flow properties of the slurry, dewatering will be difficult. While coarse (rough) particles need higher velocity rates to get conveyed (hence involve more extensive energy utilization and greater rates of erosion).

11.1.3 Other design considerations

For constructing any food processing equipment, the general recommendations include

(i) the material should be homogeneous,
(ii) inert (nonreactive with fat, oil, and salt),
(iii) should not adulterate the food by transfusing deleterious substances, nor affect the organoleptic properties of food,
(iv) chemical resistant (nondegrading, corrosion-proof),
(v) hygienic (nontoxic, easily cleanable, and nonmold supporting),
(vi) physically durable and mechanically stable (resistant to stress, abrasion, impact, wear, heat, moisture, steam).

Because of satisfying all the properties mentioned above, metals and alloys can be used to construct equipment in food industries, especially for hydraulic conveyors construction. Alloys for food contact can be aluminum, iron, silver, copper, tin, nickel, zinc, cobalt, chromium, and a few more. Plastic elastomers can also be used for the construction of hydraulic conveyors.

11.1.4 Applications in food industries

- Conveying fish, shrimp, and prawns.
- Conveying fruits from storage to the processing section.
- Conveying and cleaning vegetables.

11.1.5 Advances

In the field of hydraulic conveying, one of the most important recent development or advancement concerns the transport of coarse materials such as cereals, pseudo-cereals, legumes, nuts, and seeds.

11.2 Bucket elevators

A bucket elevator (Fig. 11.5) or Grain Leg is mechanical equipment used to transport the granular materials vertically during processing (Taher et al., 2014). The material is collected into the bucket through gravity while the belt powered by the motor pulls the buckets up vertically and discharges the material into collecting hoppers or bins, or silos.

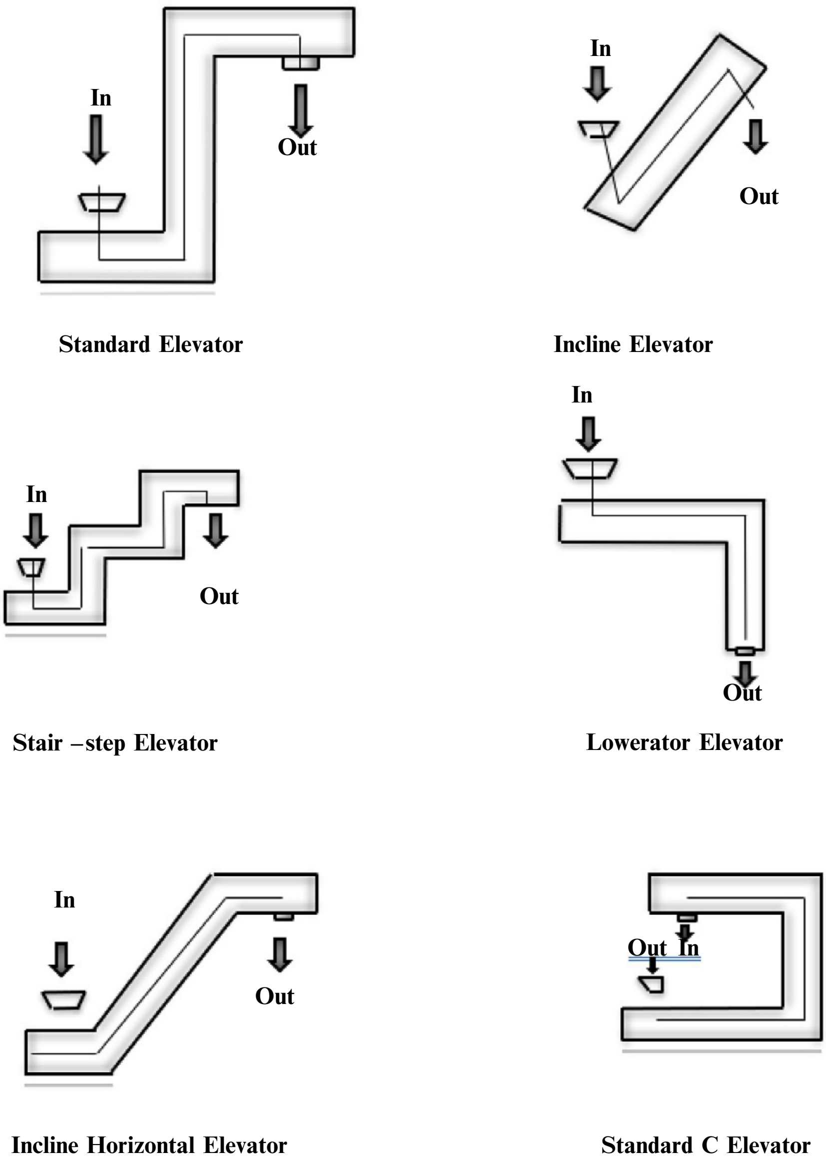

FIG. 11.5 Different designs of bucket elevators.

11.2.1 Types

Classification of bucket elevators is based on five types (Boac et al., 2014; Chen et al., 2020)

(a) Based on types of discharge—centrifugal, gravity, horizontal, positive.
(b) Based on leg type—single, twin.
(c) Based on the type of bucket use—single, double.
(d) Based on load—low, medium, heavy.
(e) Based on capacity—low, medium, heavy.

11.2.1.1 Centrifugal discharge elevator

The material discharge is carried out by using centrifugal discharge (Fig. 11.6) and at relatively high speeds. This type of discharge is used for grains. The grains are discharged at the top of the elevator.

11.2.1.2 Continuous discharge elevator

The material discharge is carried out using gravity and at relatively low speeds. This type of discharge (Fig. 11.7) is used for free-flowing and sluggish materials. The discharge is done on top of each other and is mainly used to carry complex materials.

11.2.1.3 Positive discharge elevator

The discharge elevators (Fig. 11.8) elevate delicate materials like popcorn, potato chips, and candy. Gentle handling is needed in this case of the discharge as it discharges the delicate materials. The bucket is mechanically flipped to discharge material.

11.2.2 Components

(i) *Head*: It is made of heavy-duty galvanized steel. Used for clean discharge and consists of the motor (Fig. 11.9).

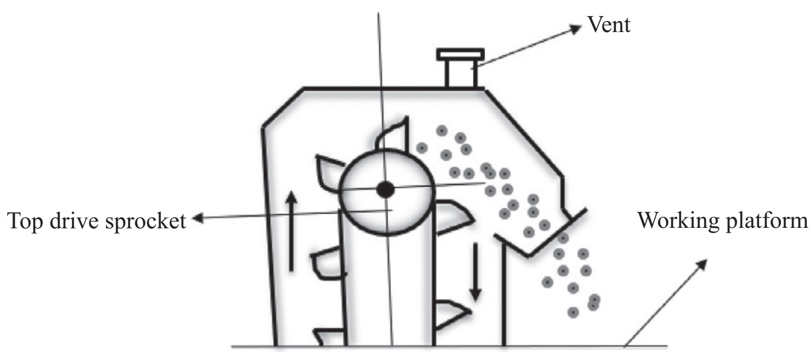

FIG. 11.6 Centrifugal discharge elevator.

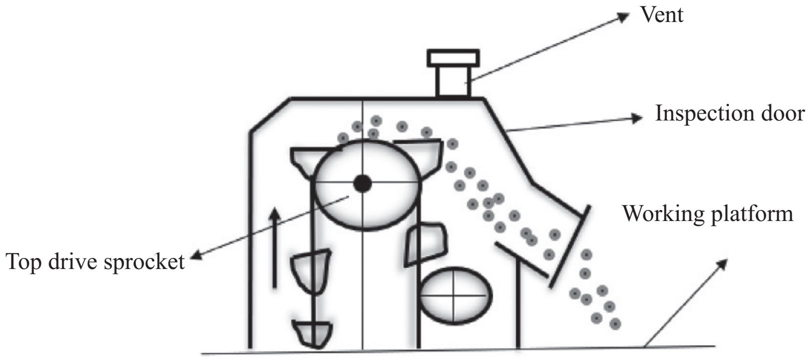

FIG. 11.7 Continuous discharge elevator.

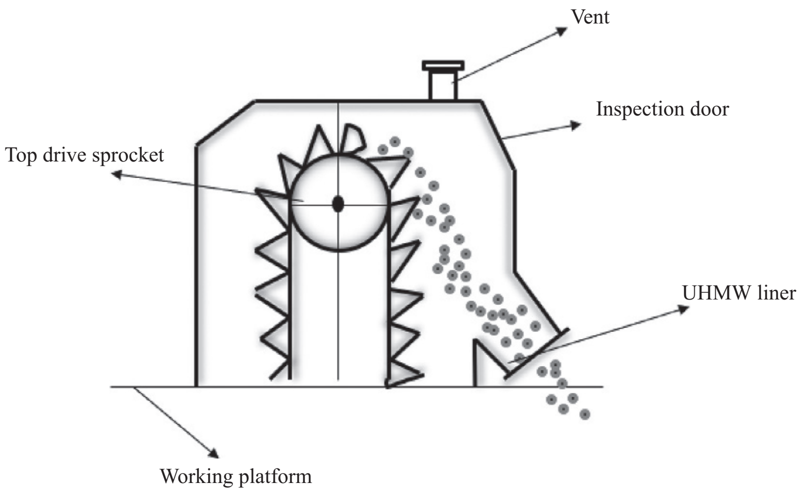

FIG. 11.8 Positive discharge elevator.

(ii) *Head cover*: It covers the head section, and accessible internal components can be done.

(iii) Head Pulley is crowned and fitted with taper-lock bushings and nonslip rough top lagging for maximum traction.

(iv) *Shaft mounted*: It is made of quality arms and drives sheaves. It is a gear reducer and also has an easily adjustable arm.

(v) *Bearings*: These are of high quality and are heavy-duty bearings. Easy maintenance is done, which eventually leads to longer shelf life.

(vi) *Belt*: This is made of high strength PVC belt for minimal strength and impregnated solid carcass prepunched for easy bucket mounting.

(vii) *Buckets*: These are made of high-quality polyethylene CC. Steel buckets are also available. These are mainly used for conveying the material.

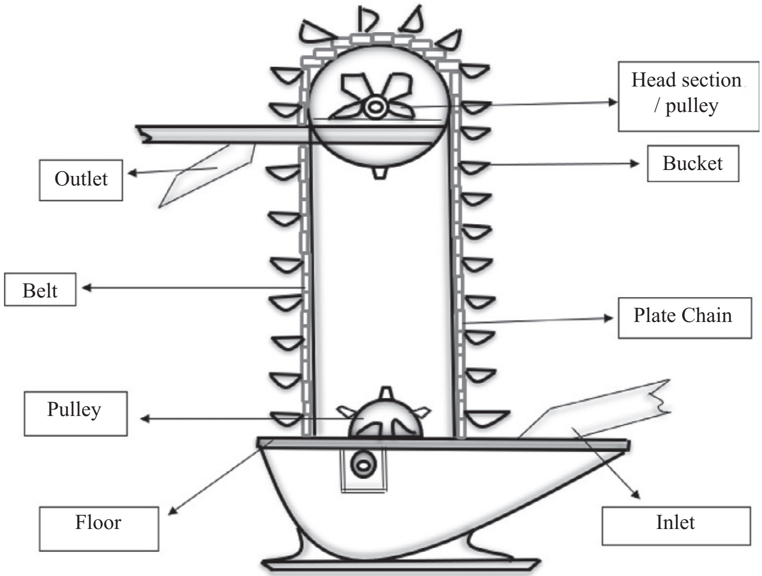

FIG. 11.9 Bucket elevator.

(viii) *Trunking*: It is made of heavy gauge ASTM A-526 G90 galvanized steel. This is double seamed and welded for perfect alignment. It consists of inspection sections for easy access to belts and buckets through doors.

(ix) *Boot*: It is made of heavy gauge galvanized steel. This is the down section of the bucket elevator. It is easy to adjust take-ups for the boot pulley.

11.2.3 Design considerations

Bucket elevator mainly consists of the following parts (Yanko, 2007; Janjai and Bala, 2012; Nishi et al., 2015):

- Buckets to transfer the material.
- A belt to carry the buckets.
- A source to move the belt.
- A source for collecting and discharging the material, for maintaining belt tension, and for protecting the elevator.

The design of bucket elevator mainly considers the following criteria:

- dimension, capacity, and speed
- roller diameter
- belt power and tension
- pulley diameter
- motor selection

11.2.4 Applications

There are many uses for bucket elevators in industries like food, pharma, chemicals, plastic, and many related industries (Khalil et al., 2013; Boac et al., 2014; Violidakis et al., 2017; Patel et al., 2021). In food industries, bucket elevators are used:

- To discharge grains into silos or collecting units.
- For granular type materials.
- To discharge sluggish and nonfree-flowing materials.
- For delicate products like popcorn, potato chips, and candy.

11.2.5 Advantages and disadvantages

Advantages:

- Have long lives.
- Free of maintenance.
- Less labor is required.
- Low space occupation.
- High lifting height.
- No environmental pollution.
- No dust and good sealing.

Disadvantages:

- Sensitive to overload.
- High purchase.
- Installation costs.

11.3 Monorail

Monorails are designed to move material or products to improve efficiency and throughput. In general, monorails move a product from one location to another. The monorail is a connection between warehousing and production areas. It can be constructed with several frame materials, including aluminum, and stainless steel. The monorails can be equipped with various motor and controller options, stand options, and accessories. Further, these systems are often integrated with robots for maximized automation. The monorail runs in two separate loops: the shipping warehouse to the production lines and one from the shipping warehouse to the empties warehouse (Miller et al., 2014).

11.3.1 Principle

The monorails effectively transport the materials without ground space/floor. Monorail conveyors are highly efficient to move the materials independently on the rail system. The power and control signals are supplied to the monorail attached to the carrier rail through the collector wires, which leads to the movement of materials. These rails are connected to either ceiling or suspended to the column supporting the steel structure. Monorails are categorized/classified in different food industries (Fig. 11.10).

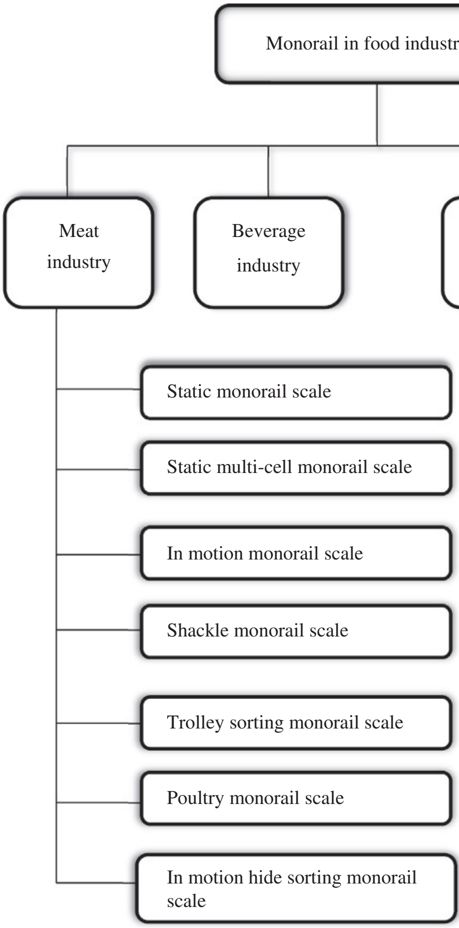

FIG. 11.10 Schematic diagram representing the application of monorail in food industries.

11.3.2 Heights of monorails

The heights of monorails are classified into three types:

- Bleeding monorail
- Dressing monorail (by hand or mechanically skinning)
- Cooler monorail (evisceration and splitting)

The different heights of monorail are designed based on different types of slaughtered animals. The height of the monorail is allocated based on animals like buffalo/cattle, sheep/goat, and pig.

S. no.	Height of monorail	Cattle/Buffalo	Sheep/Goat	Pig
1.	Bleeding monorail	15.5–16 ft./ 186 in/ 4.72 m	10.5–11 ft./ 126 in/ 3.20 m	9 ft./ 108 in/ 2.7 m
2.	Dressing/skinning monorail	11–12 ft./ 132 in/ 3.3 m	10–10.5 ft./ 120 in/ 3.04 m	7.5–8 ft./ 90 in/ 2.28 m
3.	Cooler monorail	11 ft./ 132 in/ 3.3 m	9–9.5 ft./ 108 in/ 2.74 m	6.5–7 ft./ 78 in/ 1.98 m

(a) Bleeding monorail

In line slaughter system (Fig. 11.11), the carcass should be hoisted up for the bleeding. The carcass moves along with the overhead monorail/line. It is suitable for bovines, sheep/goat, small ruminants, and pigs.

(b) Dressing/skinning monorail

In this place, different operations take place such as hide removal and skin (by using hydraulic type cattle skin removal, dehider, and skinner), removal of the head, evisceration (edible offal, casing, paunch manure, and inedible offals), splitting, trimming, and a final wash of carcass.

(c) Cooler monorail

The carcass is moved to the chill room after the final wash with the help of a cooler monorail. In the chill room, the temperature of slaughter animals is less than 7°C for the carcass, less than 4°C for poultry, less than 3°C for offals. The free movement of cool air around the hanging carcass and the rail spacing for beef carcass is 0.9–1 m, 0.7 m for pigs, and 0.5 m for lamb.

11.3.3 Monorails in the meat industry

Every meat industry, despite its size, has to transfer the carcasses of the animals they are processing. It is continuously carried out on a rail, that is flat, or round. After initial entry of the live animal into the industry, to the point it is slaughtered, the carcass will be placed on a trolley that rides down the rail. Each of these animals needs to be weighed initially to figure out the yields after the animal has been processed.

The monorail scale is a unique weighing device primarily used by animal slaughter or harvesting facilities. The mechanical monorail load cells of the hanging monorail structure are mounted approximately 10 ft. in height in the air, firmly attaching levers to the earth. The lever train transfers the measurable load down. The installation is completed by connecting the digital weight indicator to the scale structure and weight test calibration. Cattle processing hook is presented in Fig. 11.12.

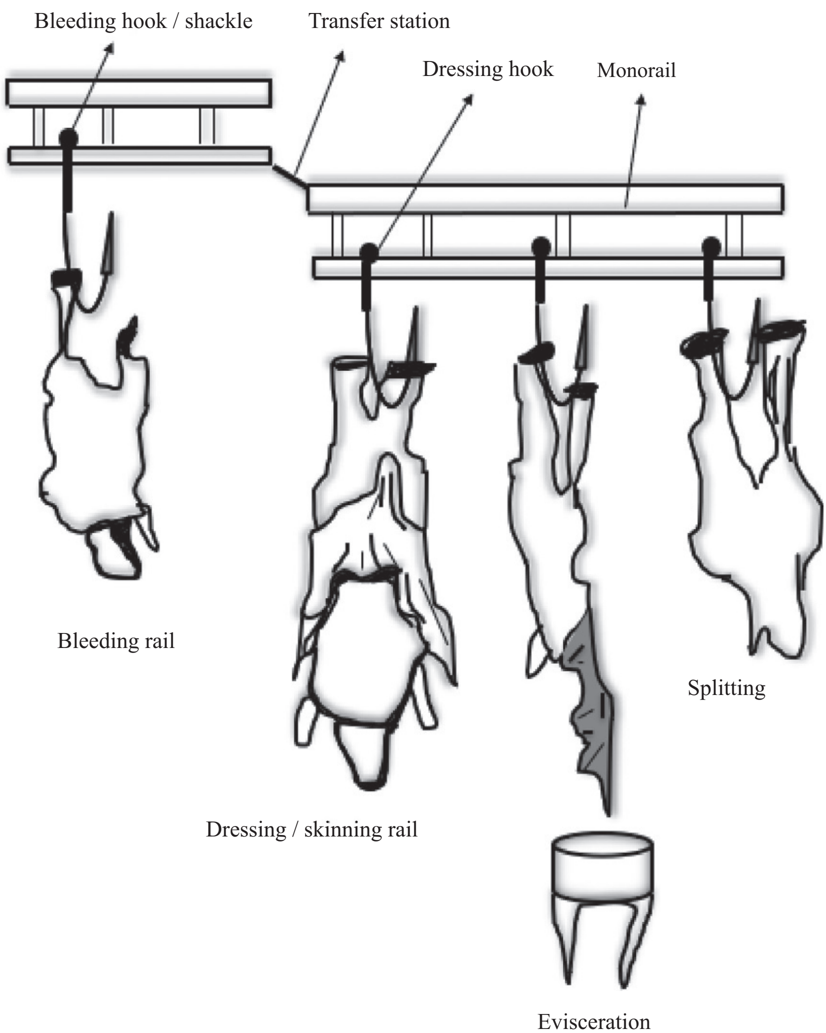

FIG. 11.11 Line slaughtering system for sheep (in vertical position).

11.3.3.1 Static monorail scale

The monorail could be a static, i.e., overhead monorail track scale that weighs hanging meat throughout the process (Fig. 11.13). It is constructed totally from stainless steel that contains a hermetically sealed load cell that stands up to high atmospheric pressure and temperature. In static monorail, the carcasses are stationery, when the weighing process is carried out.

Applications:

- beef, pork, and lamb carcasses weighing
- processed food on hanger racks
- smokehouse rail scale
- static weighing of individual carcasses

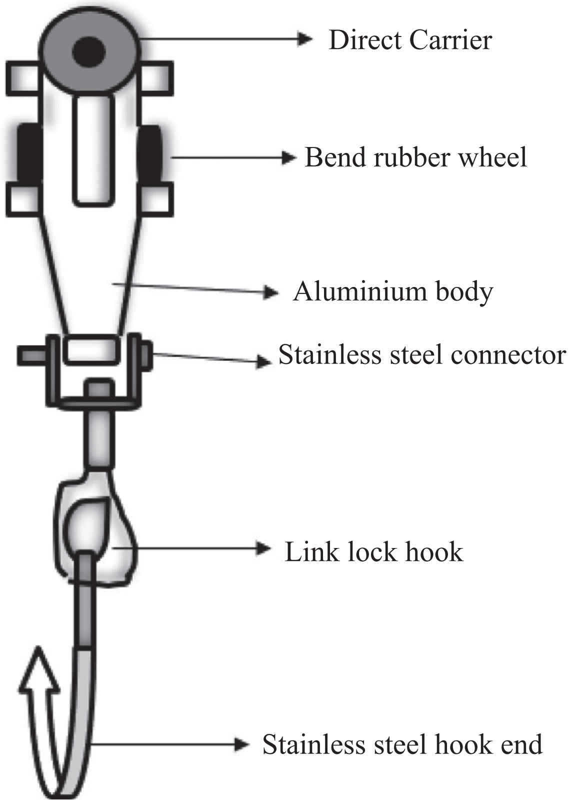

FIG. 11.12 Cattle processing hook.

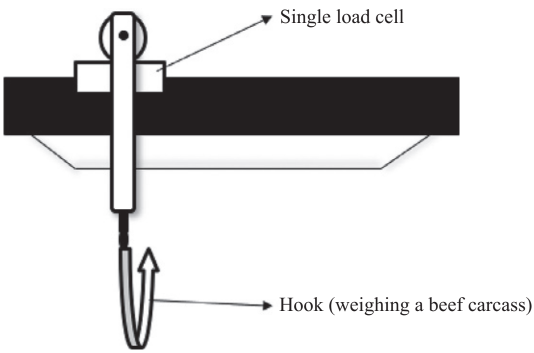

FIG. 11.13 Static monorail scale.

(i) Static multicell monorail scale

The multi-cell static monorail scale (Fig. 11.14) is designed for a challenging environment and highly accurate system of rail weighing for different sized meat-processing operations.

Applications:

- smokehouse rail weighing
- static weighing of whole carcasses

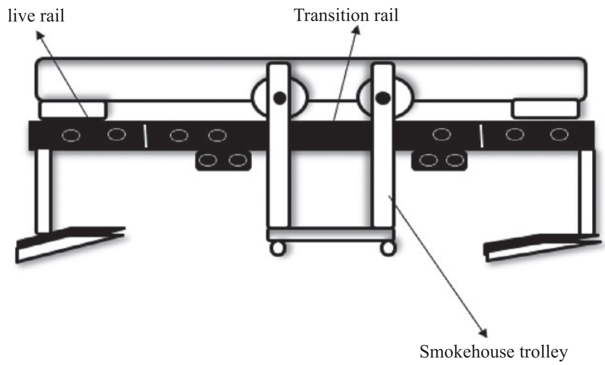

FIG. 11.14 Static multi-cell monorail scale.

(ii) In-motion monorail scales

In-motion (also referred to as dynamic) scales (Fig. 11.15) work with the plant's overhead chain. These scales weigh the dead body on the trolley as it moves down the rail. In motion monorails, the carcass does not stop during the weighing process, and it includes a motor and power drive chain on the scale. They can be done in two different ways:

1. One way is to replace a part of the rail and weigh the trolley because the overhead chain pushes it.

2. A second way is to replace a part of the rail with a scale that includes an independent drive to pull the trolley away from the overhead chain.

This way removes any inconsistencies that are in play from the overhead chain. These scales can be placed in several places throughout the plant: most notably right after the animal is killed (called the hot scale) and right after it comes out of a cooler (called the cold scale).

Applications:

- Weighing of pork carcass, and lamb carcasses.

(iii) Shackle scale monorail

These monorails (Fig. 11.16) are recognized highly for delivering highly accurate carcass weights and are designed especially for weighing the

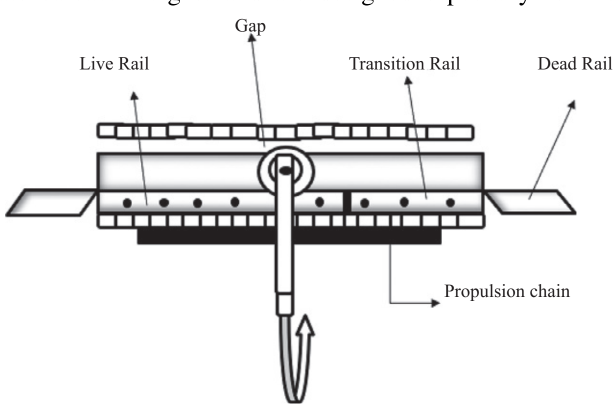

FIG. 11.15 In-motion monorail scale.

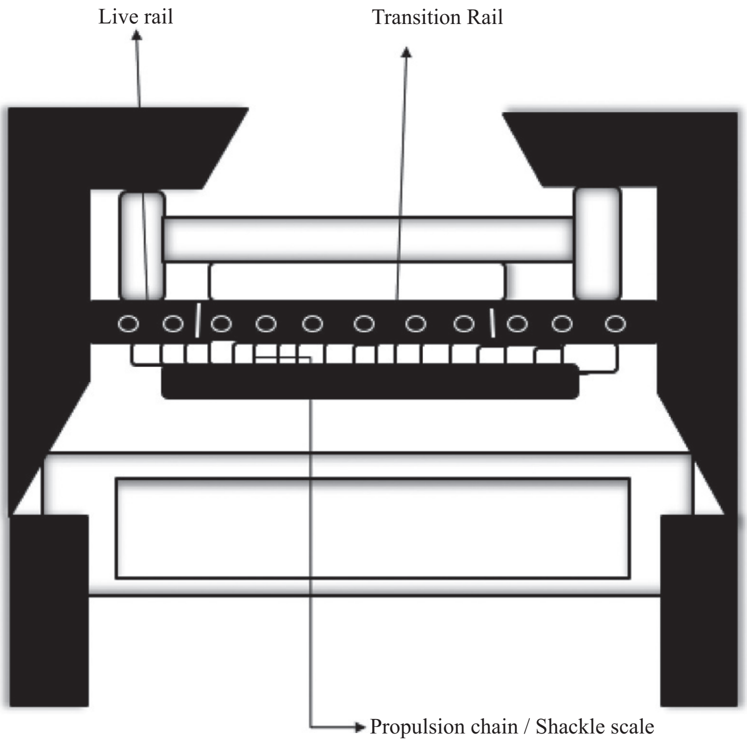

FIG. 11.16 Shackle scale monorail.

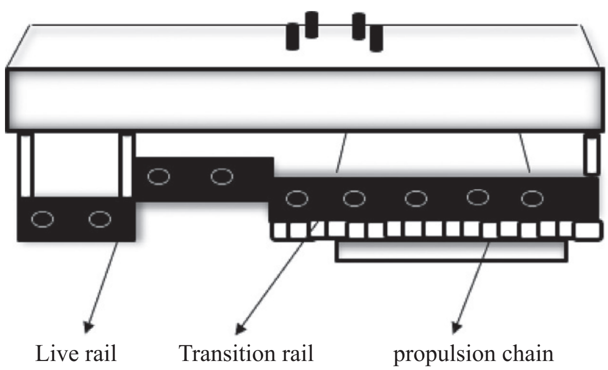

FIG. 11.17 Trolley sorting monorail scale.

whole carcass. The shackle scale was specifically designed to weigh whole beef carcasses. The in-motion shackle scale accurately weighs up to 4500 lbs. capacity, which gives accurate carcass weights.

(iv) Trolley sorting monorail scale

This monorail (Fig. 11.17) scale is designed to be placed as soon as the trolley departs from transport. The scale is to mount in the declining section of the rail and directly after the discharge of the trolley. The weight is compared against higher and lower weight limits to determine a pass or reject.

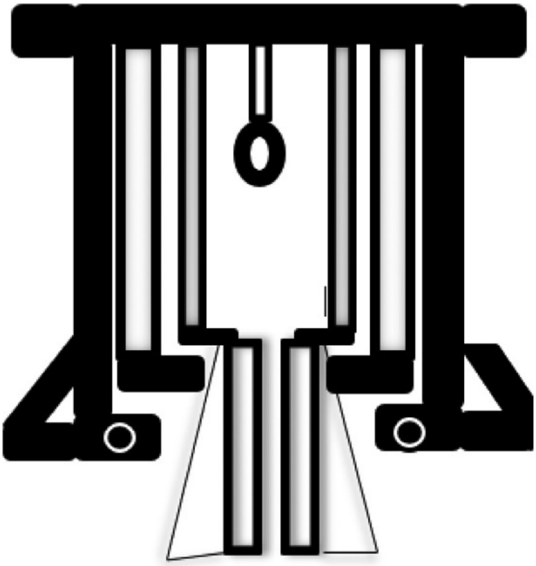

FIG. 11.18 Poultry chain monorail.

The scale is to mount in the decline section of rail after the trolley release. The features of this monorail are single load cell, high accuracy, ability to enter values for high weight, and low weight for ejection.

Advantages:

- calculate the trolley tare weight automatically without the use of labor
- for transferring a trolley, labor usage is reduced
- tare weights trolley will be accurate

(v) Poultry monorail scale

Poultry monorails (Fig. 11.18) are reliable and accurate monorails. This monorail scale is used in challenging places of slaughtering plants. The slaughter plant chain provides the propulsion and brings in the weighing section. As the trolley aligns with the scale live section, photo-eye activation takes place, and the cycle of weight starts. After the second photo-eye gets activated, the weighment cycle ends, and the trolley comes out of the scale live section. Stainless steel is used in the construction of monorail scale structures. The load sensors repel water as the load cell gets sealed. The indicator port detects individual birds' weight and provides information to the post computer.

The features of this monorail include high accuracy, dual or single load cell design that allows the minor possible scale divisions, and transition rail gradually loads weight onto the live rail, easy installation compared to similar units, construction of monorail by using stainless steel, to repel water sealing of load cell occur.

(vi) In-motion Hide sorting monorail scale

The hide sortation and tracking system (Fig. 11.19) allow processors to arrange hides based on the weight and type. The ability to sort cured hides to maximize efficiency.

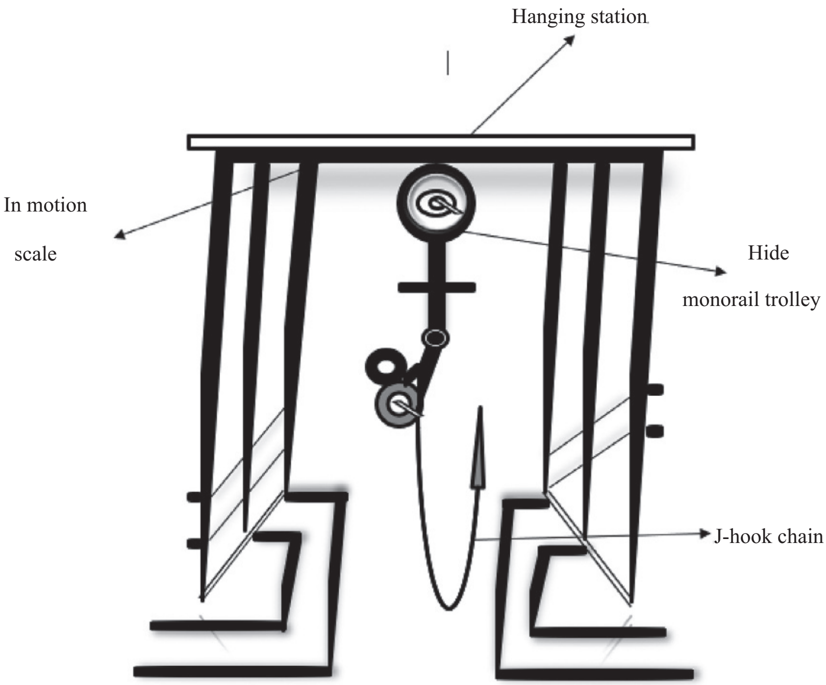

FIG. 11.19 In-motion hide sorting monorail

Advantages:
- Sort hides are based on weight, cured to maximize efficiency.
- Sorting parameters and performance can be sent to a computer to see the reports in real time.
- Significantly reduce sorting labor costs.

11.3.4 Monorail conveyor for beverage industry

Monorails are used for several applications in the beverage industry (Fig. 11.20), where the material has to be affected, distributed, and processed stepwise. With these monorail systems that include standard construction, the conveying system contains self-propelling shuttles that are precisely constructed to meet the stress of economic load carrying in numerous weight capacities. Here, the utilization of standardized components also ensures that maximum process value is delivered through the system.

Inverted monorails are preferred in the beverage industry for conveying the bottles and are easily coated or packaged during the time on an inverted monorail system.

11.3.5 Monorail in the tea factory

Monorails are those that are used for transporting heavy and bulk materials. Mechanized carrying of tea leaves at different stages of method and many modern methods of automation are adopted in a tea factory (Fig. 11.21). Monorail

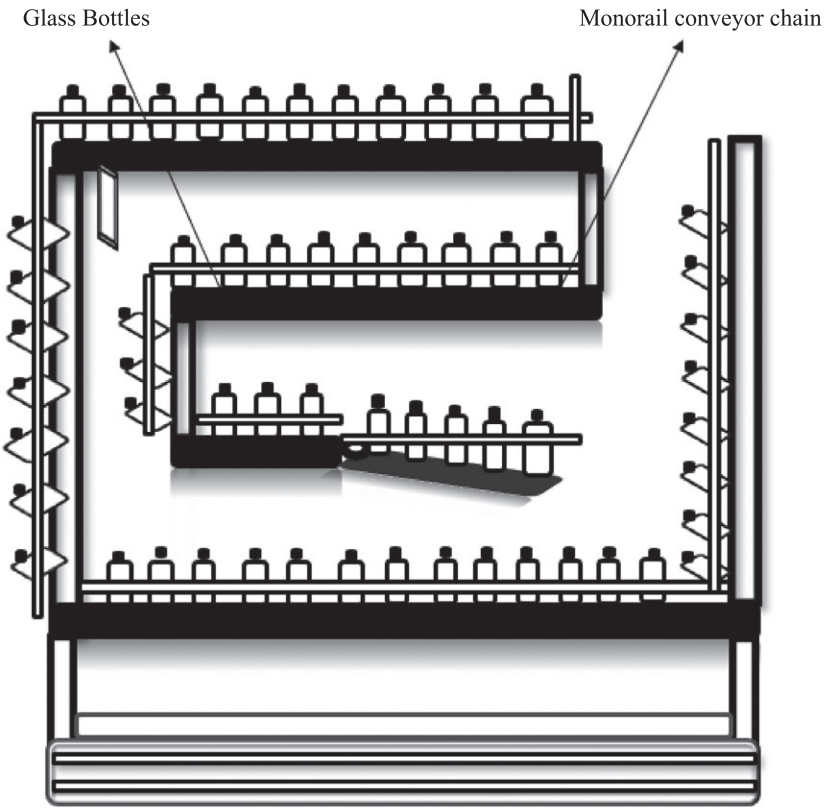

FIG. 11.20 Monorail conveyor for beverage.

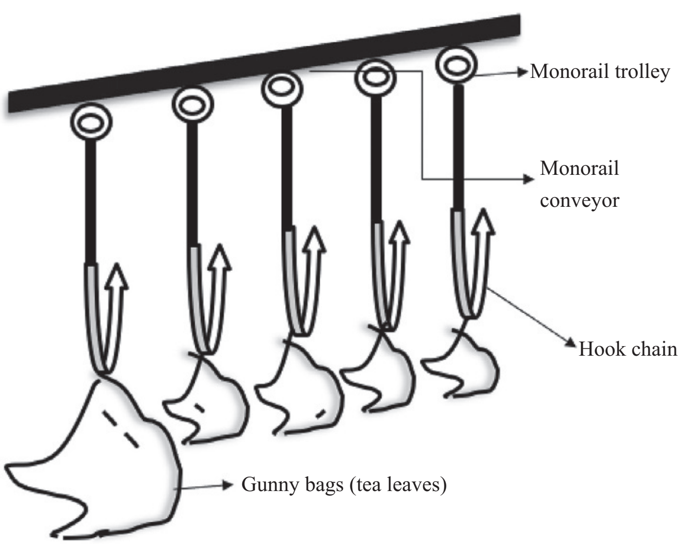

FIG. 11.21 Monorail in the Tea factory.

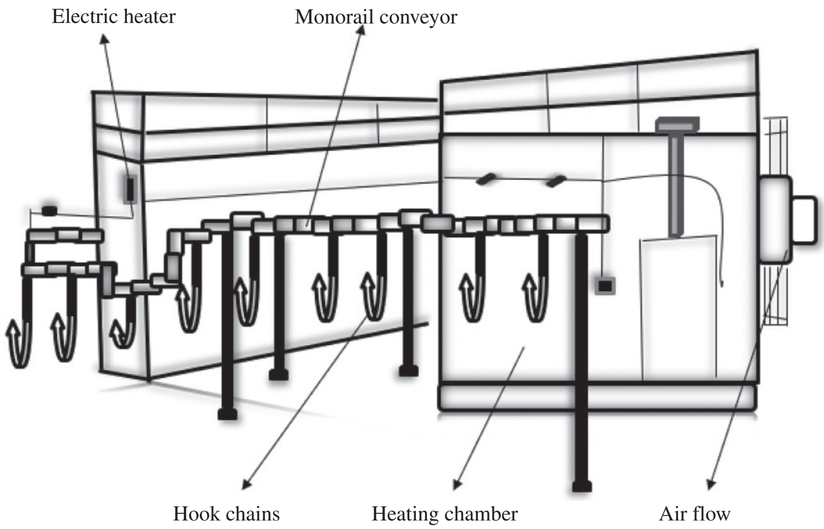

FIG. 11.22 Continuous monorail oven conveyor.

within the sharpening room ensures simple handling of rollers. This is often provided along with an electric hoist or manual and is custom-designed to suit the sharpening room.

Advantages:

- minimizes manual handing
- the time reduces between collection and processing of leaf
- reduces manpower
- the wastage is eliminated during the transportation of the leaf
- ensures continuous supply of leaf to the processing line

11.3.6 Monorail in the bakery industry

Continuous monorail ovens.

Industrial applications for monorail conveyor ovens include paint curing, varnish curing, and moisture removal. These are used for curing and drying applications in electric motor, paint and coatings, electronics, automotive, metalworking, plastics, and rubber industries.

Monorail conveyor oven (Fig. 11.22) features include aluminized steel construction for corrosion resistance, pneumatically operated product entry, and exit lift doors to minimize heat loss and maintain zone isolation, complete temperature, air handling and conveyor control system, custom track designs on one level or multiple levels or travel, electric, direct gas-fired heat or indirect gas heating systems, electric, direct gas-fired heat or indirect gas heating systems, automated loading and unloading, temperature ranges up to 500°F, with close tolerance uniformity. The efficiency and effectiveness are maximum in the case of the monorail conveyor oven.

Advantages:

All processed and packaged products are moved on a monorail at some stage in a life cycle. There are various reasons to install the monorail, including product movement and flow.

- Improved efficiency.
- Labor-saving.
- Speed and throughput.
- Safety and ergonomics.
- Reduce product handling.

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PART | FOUR

General material handling machines in food plants

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Chapter | Twelve

Transporting vehicles/ trucks used in food plants

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12.1 Introduction

In an ideal food processing plant, the machinery, humans, and materials work in line with each other in an efficient and well-coordinated process to yield a productive and safe environment. Management decisions that are made about the machinery, processes, logistic systems, and material handling facilities, safety, and especially hygiene in the food plant, determine what happens in the working environment. The principle of unit load states that the operating materials in a plant should be handled in an optimized way using transportation means to minimize the number of movements for a specified amount of material.

Material handling includes transportation of different sizes and shapes of materials with various loads and shapes such as boxes, pallets, bags, bottles, etc. Trucks are known as industrial vehicles providing a flexible approach for distributing various materials throughout plants. So, information about these facilities is important in their selection and proper utilization. These vehicles are classified into two categories including hand trucks (or non-powered trucks) that work manually and powered trucks that are operated using a motor (Fig. 12.1) (Ray, 2007). Other categorization of trucks includes platform trucks, low-lift trucks, and high-lift trucks. In the platform trucks, the material is loaded or unloaded on a wheeled platform, using mechanical power or by hand. In low-lift trucks, they are able to lift the material off the ground

Transporting Operations of Food Materials Within Food Factories. https://doi.org/10.1016/B978-0-12-818585-8.00006-4

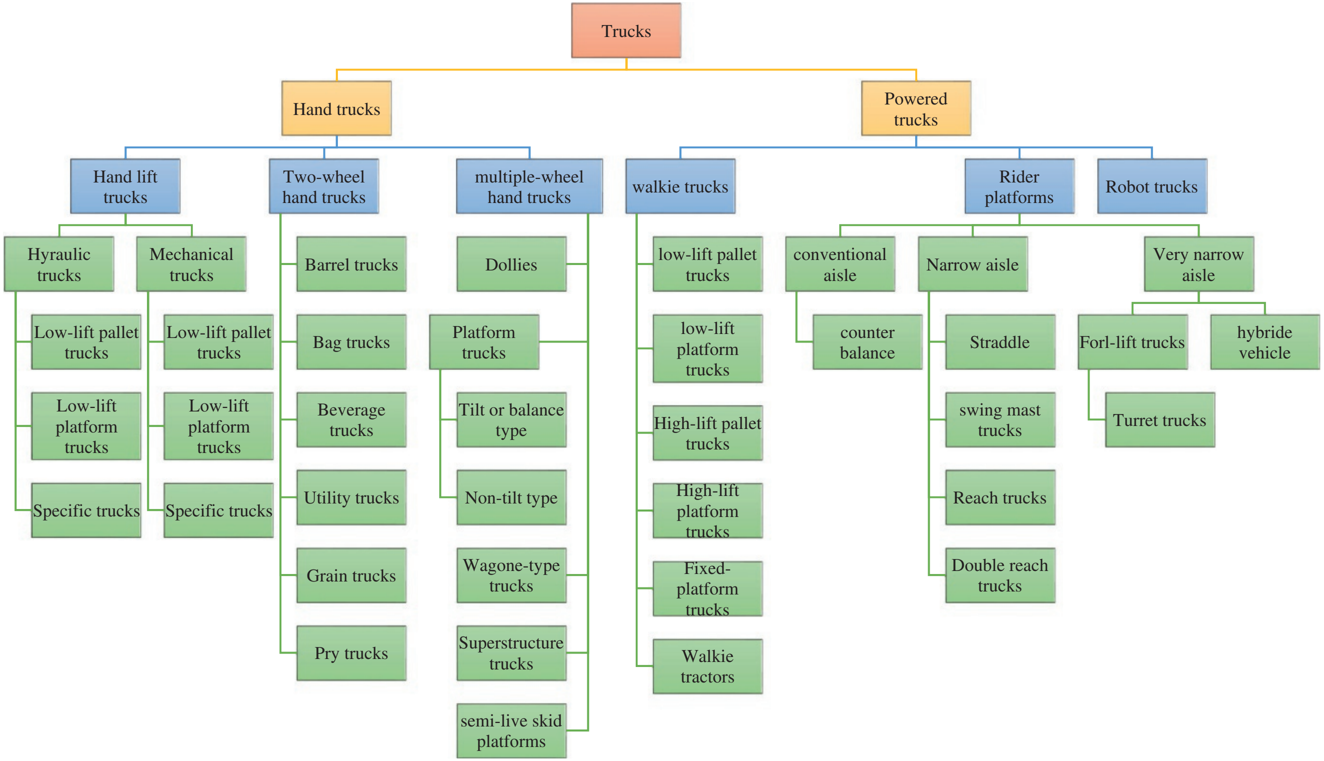


FIG. 12.1 The classification of different types of trucks.

and let them move freely. The material can be elevated in high-lift trucks and moved to the racking systems. In this chapter, different types of industrial vehicles are introduced.

12.2 Hand trucks

Although mechanization has been highly recommended in the recent years, employing manually operating trucks is widespread in most manufacturing plants, where the area is restricted or the time that sporadic demand is increased (Ray, 2007). Fig. 12.2 shows some of the possible cases where the application of hand trucks is superior. As mentioned in the previous section, numerous economical designs have been created for hand trucks in the food industry such as no-lift (sack trucks and drum dollies), low-lift (hand pallet and stillage trucks), and high-lift (manual stacking trucks) machines, which may be equipped with different tools such as forks, platforms, or jib cranes. As indicated by its name, hand trucks are not provided by any propelling power (Baker, 2013). However, in order to develop the range of their employments, manually directed trucks are attached with different hydraulic or electrohydraulic lifting equipment in modern designs. Generally, manually propelled trucks based on the number of wheels are categorized into three groups: (1) hand lift trucks, (2) two-wheel hand trucks, and (3) multiple-wheel hand trucks (Rajesh, 2016).

12.2.1 Hand lift trucks

These hand trucks are provided with a mechanism of lifting their platform, which can be rolled under a pallet or skid, and raised to lift the pallet or skid with load to clear the ground and then move this load from one place to another. Depending on the lifting mechanism, these are grouped into hydraulic or mechanical types. Hand lift trucks are widely used in small- to medium-sized manufacturing industries using pallets, skids, and/or containers (Baker, 2013; Kulweic, 1985).

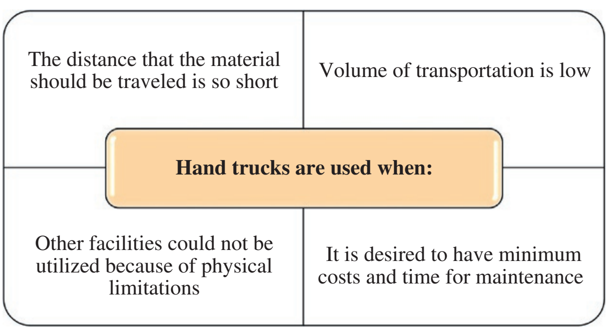


FIG. 12.2 Some of the possible utilization of hand trucks.

12.2.2 Hydraulic hand lift trucks

Hydraulic hand lift trucks enjoy great mechanical advantages because their operation is based on a simple lever and need less power to elevate the burden. Two classes of such lifts have been introduced namely foot- and hand-operated. The elevating mechanism in both lift types is activated by driving the handle arm up and down such as the handle of a pump for a well (Allegri, 1992).

12.2.2.1 Hand low-lift pallet trucks

In this type of truck, the loads are elevated and pulled only via hand power, and the frame of the truck is designed in such a way that it is able to move between the top and bottom boards of a pallet (Kulweic, 1985).

This class of trucks is composed of large frontward wheels attached to a steering handle equipped with the main frame via a linkage or hydraulic system and linked to the back wheels, which are generally held down in the main frame (Apple, 1972). Extra small wheels or slides ate installed at the main frame end in order to help the operator to push the forks forwards the packet. There are opening in the both front and back of the bottom deck causing the truck to be able to enter from each end. After setting the truck on the pallet, the operation of the lifting mechanism causes the small wheels located on the rear of the truck to move down by pallet opening to lift the pallet about 2–3 in. (50–76 mm) over the ground for transporting (Larsson et al., 2003).

The hand lift truck is employed cooperatively with opening bottom pallets. In designing this truck, the main object was to decrease the number of handlings. In this type of truck, the change of material position or moving freights between operations is swiftly achievable through loading them on the pallet (Childs, 2003). Hand pallet trucks are only designed for horizontal transportation and are not an appropriate option for stacking. In addition, such trucks can suitably be coupled with powered fork-lift trucks and applied in the condition in which power trucks cannot function such as load terminals, packing places, or transporting loaded pallets in the boxcar, trailers, etc. (Baker, 2013; Kulweic, 1985).

It has been broadly admitted that the standard trucks exploited in the industry should be possessed 27 in. (685 mm) wide and their length should be equal to the pallet length (Childs, 2003). These trucks are designed for loads with up to 60 in. (1524 mm) length, 453–2721 kg (1000–6000 lb) load capacities, and 4 in. (101 mm) lift to supply greater under clearance (Ray, 2007). Pallets employed with such trucks should own specifications including 8 in. (203 mm) openings on the bottom side as well as 6 in. (152 mm) center and chamfered boards for the entry of trucks (Rajesh, 2016).

12.2.2.2 Hand low-lift platform trucks

Such trucks consist of the forwarded wheels linked to a steering handle which in turn connected to the main frame. The rear wheels, coupled with the same frame, are moved up and down through the hydraulic system. Platforms can be solid and the trucks are commonly employed with skids (Larsson et al., 2003).

The specifications of this type of truck are 453–2721 kg (1000–6000 lb) capacities, 18–27 in. (457–686 mm) widths, 27–30 in. (686–762 mm) length in 6 in. (152 mm) increments, and 6, 7, 9, and 11 in. (152, 178, 228, and 279 mm) elevating heights. Based on their application, the trucks are constructed by wood or steel platforms (Fruchtbaum, 2013).

12.2.3 Mechanical hand lift trucks

A system of levers is applied in the construction of the mechanical hand lift trucks instead of hydraulic cylinders applied in the hydraulic ones. The function of such trucks is comparable to the hand jack of an automobile (Apple, 1972). The platform is elevated by activating a handle lifting a pawl that descends into a slot or groove. Release of the pawl leads to lowering. Various modifications have emerged for this unit. In a single-stroke, low-lift unit, a latch on the tow handle employs an elevating lever attached to the platform (Kulweic, 1985). The platform is fastened into a lifted position via another latch dropping for lowering. The tow handle may be connected to a spring, which assists the operators to bear the weight of the handle and holds of the floor when the unit is not in the operation (Ray, 2007).

It is of paramount importance the initial cost of light loads reduces that this purpose is accomplished by mechanical hand lift trucks. However, such trucks need more effort to function in comparison with multiple-stroke type trucks (Allegri, 1992).

12.2.3.1 Multiple-stroke truck

This type of truck needs five strokes for arising and it elevates 4 in. (101 mm). The operation is conducted by double-faced pallets owning a 3.5 in. (89 mm) opening for the entry of the truck, rear wheels have 3 in. × 5 in. (76 mm × 127 mm) diameter and are found in aluminum, plastic, rubber, and steel (Kulweic, 1985).

12.2.4 Two-wheel hand trucks

The basic structure of two-wheel hand trucks is composed of two long handles stabilized through several crossbars. An axle connecting two wheels is installed at the end of trucks. Holding the horizontal position of hand trucks during either loading or unloading time is provided by fixing two short legs on each handle (Kulweic, 1985). Two main groups of two-wheel hand trucks are Eastern type and Western type (Fig. 12.3).

The Eastern type possesses a conical structure that their wheels are set outside the frame and a height range of 48–60 in. (1219–1524 mm). In these frames, cross members can be either curved or flat, and also handles can be either straight or curved based on requirements. The Eastern type of truck is an appropriate option for moving massive objects such as bags, barrels, boxes, cartons, etc. (Allegri, 1992; Kulweic, 1985). The Western type owns a parallel structure and its wheels are installed inside the frame and also has a height of about 1.20–1.60 m (48–60 in.). Such as eastern ones, designs of cross members and

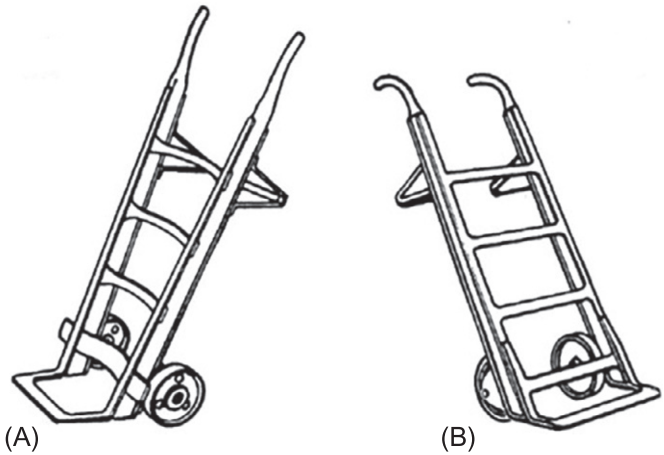


FIG. 12.3 (A) Eastern type and (B) western type hand trucks (Kulweic, 1985).

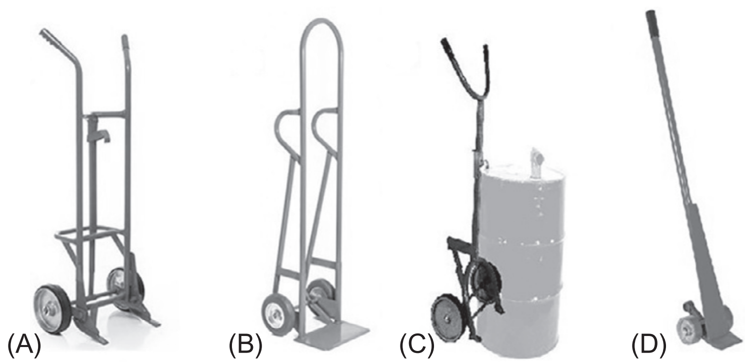


FIG. 12.4 Different types of hand trucks (A) barrel hand truck, (B) beverage hand truck, (C) drum hand truck, and (D) pry hand truck.

handles can be different based on their application. This form of handle truck is generally used for transporting heavy materials throughout motor trucks and railroad terminals. In this way, two reinforcing members are set on the truck length and act as additional supports for cross members. A range of designs for two-wheel trucks has been inspired by these two basic frames that will be remarked here (Fig. 12.4) (Kulweic, 1985).

12.2.4.1 Barrel trucks

Barrel trucks are specified in order to move massive barrels and drums (Fig. 12.4C). Short nose prongs, that act based on a hook mechanism, has been considered in designing such trucks that lead to barrel trucks vertically located on the floor at their right angles. It should be noted that floating axles have been provided for most parts of barrel trucks. All of these designing variations are accompanied by new structures of wheel equipment cause loading, handling, and unloading processes to facilitate (Apple, 1972).

12.2.4.2 Bag trucks

These trucks can be designed based on eastern or western types depending on their special usage to move various sizes of grain or powders bags. However, modifying the length and structure of the nose in designing bag trucks takes comfort in handling different bags (Baker, 2013).

12.2.4.3 Beverage trucks

This class of trucks (Fig. 12.4) has a specific design for handling beverage products. In this way, three different handle designs have been evolved for beverage trucks including tipped-top bar handle, single-grip handle, and double-gripe handle. In addition, parallel side rails and a plate or open nose are the other characteristics of this truck (Fruchtbaum, 2013; Kulweic, 1985). In the unloading status, beverage trucks have the capability of maintaining their upright position at right angles to the floor. Owning interchangeable axles is one of the distinctive features of beverage trucks providing the possibility of changing the size of the wheel without causing the trucks to lose their balances. In spite of being light, beverage trucks are inflexible preserving their stability throughout passing doorsteps and another curbing (Allegri, 1992).

12.2.4.4 Utility trucks

Regarding as general-purpose machinery, utility trucks are usually applied for transporting materials of different sizes, shapes, bulk, and weight. A flexible approach has been taken for designing these trucks based on the client's requirements (Apple, 1972; Kulweic, 1985). Accordingly, a set pattern cannot be defined for this truck. In view of quick handling is a serious matter inefficient use of utility trucks, being light along with robustness is their principal features that should be noted in their designing. The main area of applying this group of trucks is distributing beverages in the food factories (Baker, 2013).

12.2.4.5 Grain trucks

As implied by its name, grain trucks are widely applied for handling the grain loading in their bags, and their main structure is based on eastern-type trucks with some modifications such as installing guards on wheels and considering longer noses to protect grain bags. Furthermore, some models are decorated with hub caps to prevent bags from tearing (Fruchtbaum, 2013; Kulweic, 1985).

12.2.4.6 Pry trucks

This type of truck (Fig. 12.4) is adjusted for handling materials being extensively massive and heavy for typical two-wheel trucks and employed in motor trucks, cargo cars, warehouses, and generally where the area is restricted. Obviously, by their name, pry trucks lift the load through a lever nose and move it away in a rolling motion. It should be stated these trucks are mostly driven by two people (Baker, 2013; Kulweic, 1985).

12.2.5 Multiple-wheel hand trucks

A platform assembled on more than two wheels is the basic structure of these trucks. Although in this class of trucks, the required powers for pushing or pulling the platform are generally transmitted by handles, some models have been designed without handles or at least detachable handles (Baker, 2013; Ray, 2007).

12.2.5.1 Dollies

Dollies (Fig. 12.5) can be manufactured with a wood or metal framework according to the type of handling loads. However, having no handles is their principal characteristic. Basically, four different schemes can be assumed for dollies including four or six firm wheels for short and straight handling, three or four free swiveling casters for short, straight, angle, or rotating motions, two firms along with two swivel casters for straight, angle, or rotating motions, and six tilting wheels, in which either central wheels have larger diameters or central axles are set on different surfaces, are also applied for straight, angle, or rotating motions. Customers' preferences and load properties are the main influential parameters in choosing dollies (Allegri, 1992; Kulweic, 1985).

The platforms of dollies can be in different shapes of triangle, rectangular, or circular depending upon their specific applications. For example, the purpose of designing triangle dollies is to facilitate their pushing under tilted barrels and boxes. In some models, rollers are used instead of or along with wheels; stevedoring dollies possess a row including four rollers set up on both sides of the steel frames may result in straight movement. Timber dollies have a single large roller installed in the middle of the frame in such a way form right angles to the load axis and also movement lines. In manufacturing some dollies, the application of both rollers and swivel casters results in their 360° lateral revolutions (Apple, 1972; Kulweic, 1985).

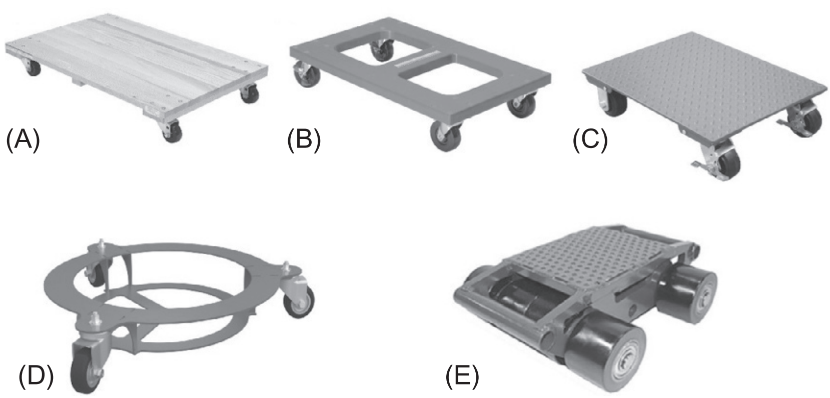


FIG. 12.5 (A) Wooden dolly, (B) plastic dolly, (C) steel dolly, (D) keg dolly, and (E) bull dolly rollers for extremely heavy materials and machinery movement.

12.2.5.2 Platform trucks

Platform trucks are structurally the larger type of dollies; based on their wheel positioning in chassis construction, they are categorized into two main groups: tilt (or balance) and non-tilt versions. It should be noted that the frameworks of these trucks are chiefly rectangular shaped and based on the requirement, may be manufactured in various sizes of light-, medium-, and heavy-duty classifications (Baker, 2013; Rajesh, 2016).

Tilt or balance type

In this version (Fig. 12.6A) of platform trucks, the chassis is loaded on the rigid wheels located at the center of the platform and also, a series of one or two swivel casters with smaller diameters placed at or near ends of the platform. This design provides the possibility of maneuverability by shifting loads between wheels and swivel casters at ends through a minor tilting movement (Baker, 2013; Kulweic, 1985).

Non-tilt type

In this class of trucks (Fig. 12.6B and C), rigid wheels are located at one end and swivel casters with smaller diameters are set at the other end. Therefore, this design leads to a condition that all wheels would be active at all times. The platform is constructed by corner posts or different kinds of steel salt rows in order

FIG. 12.6 (A) Tilt and (B) non-tilt platform trucks, (C) racked platform truck, and (D) semi-live skid platform.

to prevent loads from spilling or slippage (Apple, 1972; Baker, 2013). In heavy-duty work, these trucks own heavier chassis and the heavier running gear is designed in tilt on balance versions with similar movements and it should not be employed on steep ramps. In addition, these platforms can be provided with reinforced materials and proper couplers so that they would be a suitable candidate for use in light-duty trailers or towline conveyor tools (Kulweic, 1985; Rajesh, 2016).

12.2.5.3 Wagon-type trucks

The difference between this group of trucks and standard non-tilt ones is that swivel casters are substituted with either a knuckle-steer setting or a fifth-wheel fabrication in accompany with a tongue-type handle is provided for pulling the trucks. This truck is an appropriate option for long and overhanging loads that their pulling is highly difficult. The knuckle-steer setting provides the highest stability for these trucks since it supports a large four-point wheel, which does not allow the loads to spill or tip (Allegri, 1992; Kulweic, 1985).

12.2.5.4 Superstructures trucks

Superstructures, based on their function, have various designs from corner stakes to sealed containers. Both platform trucks and their superstructures can be made from only wood, only metal, or combination. Also, a mixture of fiber or canvas with wood or metal or both of them may be employed in the construction of some superstructures. It should be stated the size of wheels and casters would be varied according to the height of platform trucks and rating of unit loads (Kulweic, 1985; Rajesh, 2016).

12.2.5.5 Semi-live skid platforms

This class of platforms has two wheels on one side and two constant legs on another side (Fig. 12.6D). In the loading status, this structure only functions by assisting a lift jack which is a long handle driven on a pair of wheels and a hook. Assembling hood over the wheels caused the coupling to engage with the dead end of the platform and eventually through a jacking or praying movement, the truck would be lifted from the floor. It can be concluded that this frame is similar to a three-wheel suspended platform truck (Apple, 1972; Kulweic, 1985).

12.3 Powered trucks

Powered trucks have their own source of driving power. Manufacturing-powered industrial trucks have been developed globally after the World War II. The powered trucks can be categorized based on action mode, control mode, travel mode, lift height, power source, and wheel type (Kulweic, 1985; Ray, 2007). According to their height of lift, the powered trucks are classified as no-lift trucks (e.g., the tractor-trailer platform truck), low-lift trucks (e.g., a pallet or stillage trucks), and high-lift trucks (e.g., fork lift and stacking trucks)

(Kulweic, 1985). Recently, several types of powered trucks with regard to their specific application have been evolved.

Although different sources of power have been considered for these machines; the most suitable option for trucks employed in a food processing plant is the electrically charged battery power due to the high sensitivity of food production units to pollution caused by fire and fume and smoke (Baker, 2013). Battery powers enjoy advantages in terms of being efficient, tailored, and affordable. The practical alternative offered to battery powers is the internal combustion engine but the source of motive power should be considered carefully; for instance, using diesel and petrol is not acceptable in food processing establishments due to the production of detrimental exhaust fumes. Liquefied petroleum gas (LPG) is an appropriately clean source of power but the vehicles using this type of fuel should be equipped with exhaust purification systems and are restricted to function in perfectly ventilated regions (Kulweic, 1985; Ray, 2007).

There are various parameters that should be considered in order to single out the most adequate vehicle in each single food factory such as distance, the weight of loads, numbers of loading per work shift, height, and level of related operations. Obviously, the weight and volume of loads per trip are the most significant factors determining the required capacity of trucks (Childs, 2003).

The arbitrary transporting system is described as the one without additional maneuver and manual handling such as fork truck pallet and lift truck stillage. The fork truck pallet has a wide range of uses especially in small food unit operations and is an ideal system for load and tiers of vehicles (Senker, 1980). Low-lift truck stillage is more preferable for heavy loads that are not required to be lifted or tier to the high elevation or/and carried in an outboard state. When the traveling distance is long or the weight of loads is high, tractor-trailer systems are the proper options. In these conditions, the tractor-trailer vehicle must be equipped with an external loading and unloading device (Larsson et al., 2003). Otherwise, the cost of manually handling these operations may destroy all of the savings in the haulage expense. A combination of truck pallets with tractor-trailer systems through simple tools may lead to employing fork-type trucks for ordering pallet loads on the trailers. In this state, a fork truck should be considered for the unloading process at the destination (Kulweic, 1985).

It is recommended that in order to select a well-suited powered truck system, the following factors being considered: floor condition (being flat, smooth, and string), height and width of doors along with transportation path, and width of intersecting corridors (being vast enough to provide the condition of satisfactory passage of two trucks and their loads simultaneously) (Baker, 2013; Kulweic, 1985). Also, in the storage area, one-way traffic should be considered for the corridors that are individually applied for roadways. Since the mentioned regulations may not be noticed by truck manufacturers, constructors should precisely calculate the adequate area for facilitating the passage of truck systems (Kulweic, 1985; Ray, 2007).

12.3.1 Walkie trucks

12.3.1.1 Low-lift pallet trucks

Low-lift pallet trucks (Fig. 12.7A) as the most well-known walkie trucks are self-loading trucks coupled with wheeled forks whose dimensions cause the forks to be able to move between the top and bottom sheets of double-faced pallets. In order to transport objects, wheels move down to the spaces between the bottom sheets to elevate the pallet from the ground (Fruchtbaum, 2013; Kulweic, 1985).

Non-powered low-lift trucks have the capacity of 1000–2500 kg and their fork expansions let them employ pallets with 800, 1000, and 1200 mm area. In double-faced pallets, fork lengths should be correlated with the pallet length to certify that the wheels protrude the lower boards of the pallets. This class of trucks is generally employed for medium travel distance or material weight (Rajesh, 2016; Senker, 1980).

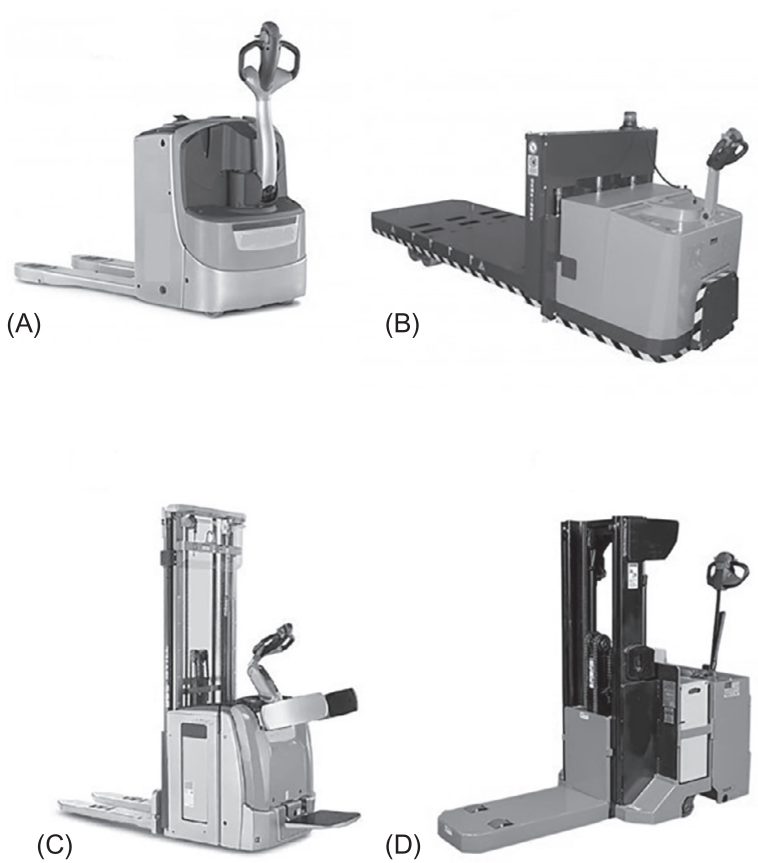


FIG. 12.7 (A) Low-lift pallet truck, (B) low-lift platform truck, (C) high-lift pallet truck, and (D) high-lift platform truck.

The powered low-lift pallet trucks have up to 6000 kg capacity and it is about 3000 kg for double-faced trucks. The dimension of these trucks has been adapted for pallets with combinations of 800, 1000, and 1200 mm. However, the trucks with 4000–6000 kg capacity are only able to carry single-faced pallets (Apple, 1972; Kulweic, 1985). These trucks are reasonable options instead of riding-type lift trucks for transporting materials in horizontal short distances. Also, walkie/rider trucks are widely used in longer hauls. In this way, operators not only can ride on the truck but also can remotely control the truck's movement. In riding states, travel and walkie speeds are 10 and 5 km/h, respectively, and the position of the operator can be in the center or at the front of the trucks (Kulweic, 1985). The former one is generally employed for order-picking loads to the position closer to the operator. Owning to the higher transport speed in the operator-applied states, the trucks are frequently connected with caster wheels to provide a stable condition on the trucks for both operator and load (Baker, 2013).

The emergence of pallet-less or slip-sheet loading caused low-lift pallet trucks to be compatible with this hanging strategy. In the fabrication of this type of truck, applied platens for slip-sheet loads are considered to be split due to preserving their capability to carry standard pallets (Senker, 1980). This diversity may result in the slip-sheet loads being picked up from the floor, deposited on the pallet, and then transported. Moreover, the reverse process can be conducted at unloading places (Larsson et al., 2003).

The other well-known derivation of the trucks in question is provided by attaching them with fork assemblies that led to concurrently convey two pallets 1000 mm wide and 1200 mm long in which wheels protrude via the holes in the lower part of the pallet on the back end of the truck (Allegri, 1992; Kulweic, 1985).

12.3.1.2 Low-lift platform trucks

Low-lift platform trucks (Fig. 12.7B) are known as self-loading trucks connected to a load platform considered for conveying bins and skids. There is a broad variety of platforms manufactured to be conformed to skids. The lowered height of platforms is varied but its minimum is 150 mm. Despite pallet trucks, the wheels of platform trucks are not certainly a fragment of a linkage, but they are joined to the truck framework. As platform trucks have not been designed to undertake double-faced trucks, their wheels have a larger size than the pallet types (Kulweic, 1985; Ray, 2007).

The capacity of this class of trucks is generally about 2000–6000 kg, but they can be manufactured in a capacity of 10,000 kg for a specific purpose. In some cases, the platform is manufactured through a "skid adapter" option in which double-faced pallets can be carried via the adapter lifted and locked in a vertical state. This happens for single-faced pallets when the skid adapter is laid on the forks (Kulweic, 1985).

12.3.1.3 High-lift pallet trucks

High-lift pallet trucks (Fig. 12.7C) as another type of self-loading truck coupled with a raising mechanism in order to perform tiering (Kulweic, 1985). Counterbalanced trucks are a kind of powered high-lift trucks provided with load-occupying tools, where the loads are suspended ahead of foreside wheels. This design cause trucks to enjoy all of the high-lift features of rider fork-lift trucks and have the capability of loading single- and double-faced trucks, skids as well as bins and attaching with all of the supplementary parts of rider-type trucks (Baker, 2013; Ray, 2007).

Walkie high-lift pallet trucks have been introduced as straddle trucks have horizontal constructive parts that support the projection of wheels forward from the basic structure of trucks. Compared to counterbalanced trucks, straddle trucks are able to perform in tight corridors and loads are handled between outrigger hands of the trucks. The main application of these trucks is carrying pallets or skids of uniform size (Kulweic, 1985). Fork over arm trucks, known as non-counterbalanced trucks, are the other type of high-lift pallet trucks. In the design of these trucks, forks are considered over the load wheels and these trucks only can handle bins, skids, and single-faced pallets (Senker, 1980).

As a self-loading truck, walkie reach trucks have a specific means for carrying loads. Accordingly, it is intentionally extended frontward to pick up and drop off the loads and retracted backward to transport the loads (Childs, 2003; Kulweic, 1985). These trucks are able to convey pallets in various sizes hold them close together since the base arms cannot move into the rack parts; therefore, trucks can be employed with any available installed rack and this is the advantage of this class of trucks over the straddle ones (Childs, 2003; Fruchtbaum, 2013).

12.3.1.4 High-lift platform trucks

Similar to fork over arm trucks, high-lift platform trucks (Fig. 12.7D) are self-loading vehicles coupled with a load platform and initially are considered for carrying and tiering skids but they are not able to transport single-faced pallets (Apple, 1972).

12.3.1.5 Fixed platform powered trucks

These trucks have a predetermined level without any possibility of elevating their platforms for loading various materials. Therefore, the object should be manually located on the platform. The maximum capacity of this type of truck is up to 40 tons and is specifically appropriate for carrying heavy loads. Trucks with smaller capacity are known as load carriers (Baker, 2013).

Drop platform truck and drop center baggage truck are well-known normal platform trucks in which the central platform is set between two rows of wheels and is very close to the floor (Kulweic, 1985).

12.3.1.6 Walkie tractors

As a powered truck, Walkie tractors primarily have been designed to pull one or more non-powered trailers, trucks, and other versatile loading vehicles and have the capacity of drawing loads of 4000 kg (Baker, 2013; Kulweic, 1985).

12.3.2 Rider trucks

Rider trucks are generally manufactured in "families" according to their chassis capacity. In addition, based on the load capacity rates, they are categorized into different groups 450–900 kg (1000–2000 lb), 900–2300 kg (2000–5000 lb), 2300–3600 kg (5000–8000 lb), and 3600–4500 kg (8000–10,000 lb), and machines for loads more than 4500 kg (10,000 lb) (Kulweic, 1985). Although capacity ranges are confirmed by manufacturers, the potential of a truck to carry a specific load is determined by the truck capacity and the relation between it and chassis capacity. Trucks with a capacity less than 4500 kg (10,000 lb) are again classified based on their corresponding aisle width necessities and methods of controlling vehicles, which may be done by the rider operator or remote control (Kulweic, 1985; Larsson et al., 2003). Remote-controlled vehicles, i.e., walkie trucks are used in the low-lift height or the low-speed practice, which have been discussed previously.

The rider-type trucks are generally utilized in material transporting and warehousing functions in which fast load movement is the matter. According to the aisle width requirements, trucks are split into three categories, namely, conventional, narrow, and very narrow aisle (Kulweic, 1985; Ray, 2007).

12.3.2.1 Conventional or standard aisle

The primarily manufactured fork trucks were the counterbalanced ones in which the vehicle weight behind the gravity center of the load balanced the overturning movement. The aisle width requirement for these trucks is in the region of 3.1–4.6 m (10–15 ft) for 48 in. × 40 in. (1200 mm × 1000 mm) pallets (Kulweic, 1985). The counterbalanced fork trucks are the early class of conventional aisle vehicles that can be powered by either electric sources or internal combustion engines. The latter one has gasoline, diesel, or LPG types (Childs, 2003; Kulweic, 1985).

Counterbalance trucks

These trucks can be found in two main versions; sit-down rider and stand-up rider. The sit-down rider types are effectively correlated with long-distance movement because it is not required that the operator mount and dismount the trucks. Also, this group of trucks has a higher load capacity owning to their long wheelbase (Baker, 2013; Kulweic, 1985). Reversely, the stand-up rider version of these tucks because of possessing a shorter wheelbase has a lower capacity than sit-down rider ones and can operate in a narrower aisle (Ray, 2007). The stand-up rider version is more suitable for short-distance movement because the stand-up position of the operator causes the vehicle frequently to mount and dismount based on requirements (Baker, 2013).

The loading capacity of the counterbalance truck is identified by the ratio of the load center to the gravity center of the truck. Sit-down rider trucks have a loading capacity of 900–4500 kg (2000–10,000 lb) and more while stand-up types have the loading capacity of 900–2300 kg (2000–5000 lb) (Kulweic, 1985).

12.3.2.2 Narrow aisle

Attempts to decline the aisle area required to load transporting lead to aisle width requirement decrease to about 2.1–3.1 m (7–10 ft). Trucks that are compatible with this specification are recognized as narrow aisle trucks and they are mostly powered by electrical sources (Ray, 2007). Straddle-type trucks, as a type of narrow aisle vehicles, apply outrigger arms to straddle the loads. As a result, the required counterbalancing weight to barricade overturning would reduce (Apple, 1972; Kulweic, 1985). True straddle-type trucks enjoy high stability and low weight due to these vehicles having a low gravity center; thus, loads can be handled completely through the footprint of the trucks (Baker, 2013).

Reach trucks are one of the different versions of straddle trucks in which they do not straddle the whole length of loads, but preferably employ a pantograph-type tool to develop forks over the outrigger arms (Kulweic, 1985). Accordingly, low values of counterbalancing should be considered for this group of trucks in order to support their stability during the extended state of loads (Ray, 2007). Double reach trucks, the other type of straddle trucks, have an additional long pantograph part that can hold two pallet loads leading to provide higher storage capacity without any increase in aisle requirements (Baker, 2013). Swing-mast trucks are the other member of this group that uses a rotating-type mast to put loads at the right angle of travel direction; therefore, storage is conducted within a narrower aisle compared to conventional counterbalance trucks (Kulweic, 1985).

Straddle trucks

Straddle trucks are known as true non-counterbalanced trucks since the loading capacity as well as the stability of these trucks are provided via outrigger arms straddling loads. These trucks are small and stable because they hold loads within their wheelbase (Baker, 2013). In addition, as loads must be held between straddles in this type of vehicle, they are not convenient for extra-wide loads because the straddle width across expands and augment the aisle width requirements of the vehicle. Straddle machines can be designed as a stand-up rider or walkie type and the length of straddles for order-picking application can be varied between 1.5 and 1.8 m (5–6 ft) (Kulweic, 1985).

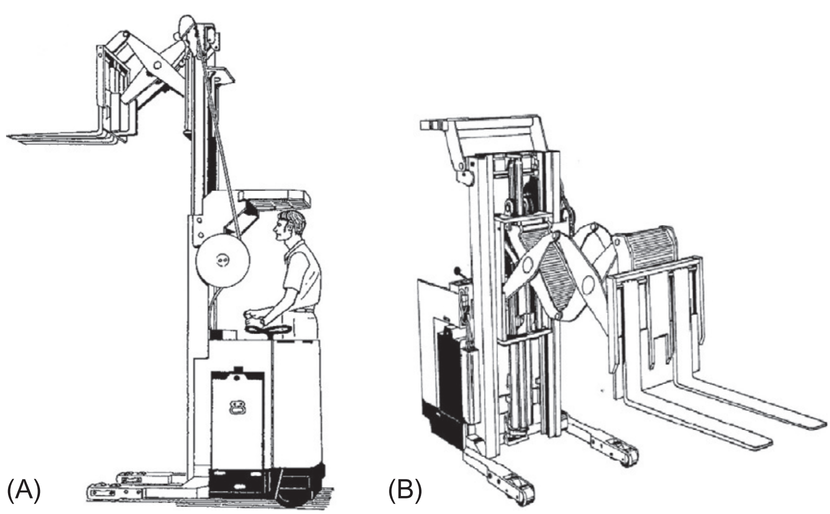
In the straddle vehicles, as straddles and loads have the same length, the stability of machine and aisle size are specified by the entire width over the straddles (Baker, 2013). Therefore, in case of elevating small and heavy loads to uplifted heights, the width over the straddle should provide sufficient stability may lead to the extremely wide aisle. In this situation, it is recommended that another type of truck be applied (Apple, 1972; Kulweic, 1985).

Swing-mast trucks

The swing-mast trucks are the other version of side-loading counterbalance trucks. These trucks are assembled with a rotating mast instead of a rotating fork employed in turret trucks (Ray, 2007; Senker, 1980). These variations restrict the ability of swing-mast devices to rotate the loads only in a right-hand direction. This limitation causes swing-mast trucks to leave the aisle and turn around to store and retrieve the loads from the opposite side of the aisle. Since swing-mast trucks have the capability of operating within narrow aisles 1.8–2.4 m (6–8 ft), they are highly similar to conventional counterbalance trucks (Kulweic, 1985). The additional weight of rotating mast trucks as a consequence of the presence of the rotating mast instrument needs a considerably greater truck capacity in order to obtain a similar loading capacity to conventional counterbalance ones (Kulweic, 1985; Ray, 2007).

Reach trucks

Reach trucks (Fig. 12.8A) are a type of straddle trucks in which the ratio of outrigger arm length to load length is about one-half, accordingly, trigger arms do not require a wide space to straddle loads (Allegri, 1992; Ray, 2007). When an ordinary load with a width of 40–48 in. (1016–1219 mm) is supposed to convey, the minimum straddle width needed to certify the sufficient load stability causes the pallet load to move back inside the outriggers (Kulweic, 1985). In reach trucks, loads are stored and retrieved through the pantograph-mounted fork in which the fork extended some inches more than the length of outrigger arms. Furthermore, the type of handling operation depends on the ratio of the load size to the outrigger spacing. When the outrigger opening is higher than the load size, loads are directly retracted and transported; while the load size is higher than the outrigger spacing, the forks are stretched out to the forepart of the truck, and



(A) (B)

FIG. 12.8 (A) Reach truck and (B) double reach truck.

loads are lifted up, elevated, and retracted to the place over the outriggers (Baker, 2013; Kulweic, 1985). This load retraction method is known as "up and over" needs extra movement space and/or a first-level pallet row with an opening height to conduct the fork maneuver (Ray, 2007).

Reach trucks are a kind of semi-counterbalanced machine since loads are not completely encompassed within the wheelbase. Subject to the load size, the load center is nearly located over the centerline of outrigger wheels (Ray, 2007). If loads are expanded, the stability of machines is provided by the truck counterbalance capacity and the outrigger width (Baker, 2013; Rajesh, 2016). Moreover, reach trucks partially depend on the counterbalance impact to maintain the stability of loads during transport. When the loads are completely extended, loads are all together in front of the outrigger wheels. Substantial counterbalancing effects are derived from the battery and truck weight to retain the stability of truck with loads about 1800–2700 kg (4000–6000 lb) due to the long wheelbase and the rear position of both operator and battery (Kulweic, 1985).

Two different kinds of outrigger wheels can be observed in the framework of reach trucks. One of them has dual 4 in. × 5 in. (101 mm × 127 mm) casters in each outrigger arm. The other one has an individual 5 in. × 12 in. (127 mm × 305 mm) wheel in each outrigger arm (Kulweic, 1985). The large wheels are able to more effectively deal with rough and cracked floors than smaller ones and are an appropriate option for the pallet loads that can be withdrawn within the outriggers (Baker, 2013). If the load size is higher than the outrigger spacing, the "up and over" retraction strategy must be applied. In this regard, small dual wheels are employed to minimize the elevating height needed to withdraw to loads over the outriggers to the transport position (Kulweic, 1985; Senker, 1980).

Double reach trucks

Double reach trucks (Fig. 12.8B) have a high degree of similarity to the conventional reach truck (Senker, 1980). Nevertheless, the pantograph tool is considered in their design to allow the further extension of about one-half depth of loading pallets beyond the forepart of the outriggers. Double reach trucks have mainly been designed to maintain double deep pallet racking (Kulweic, 1985; Senker, 1980). The front load is held in the typical way in which the trucks are moved toward the pallet rack and the load is located in the earliest storage place. When the load is supposed to be located in the second position, the double reach trucks have to be moved toward the rack through mast assembly, which is near to the supporting beam of load. If the forks are extended, the further extension capacity of double reach trucks causes the loading pallets to be positioned in the second storage place (Kulweic, 1985). In this way, requirements should be considered to provide the straddles or straddle the lower pallet on the floor or equip its bottom by placing the pallet on a rack supporting beam (Allegri, 1992; Senker, 1980).

Two vital functioning dimensions in double reach trucks are the maximum throat size for the pantograph instrument or load basket and the reach distance of the pantograph mechanism. The storage window of pallet racks must enjoy adequate clearance to make the pantograph tool extend to the back position (Kulweic, 1985). In the case of the loading pallet that is not as high as the greatest dimension of the load basket or pantograph throat, a huge amount of storage space is wasted because extra height is needed for equipment access; however, is not required for material storage (Kulweic, 1985; Senker, 1980).

If loads are extremely deep or the reach capability is inadequate, the second load will not be able to directly be located in the defined position. In this situation, a "double bite" approach should be employed. Accordingly, the backload is placed as far rear as possible, the forks are withdrawn lightly, and "the second bite" is applied to locate the load in the right position (Kulweic, 1985). In addition to being slow, the double bite strategy causes a kind of inconsistency in the movement of the second load and disordered storage design (Senker, 1980).

12.3.2.3 Very narrow aisle

In order to improve the storage efficiency of material carrying trucks, aisle width requirements have been more declined through placing loads at the right angle of the movement direction and side loading of loads from trucks into the storage location (Childs, 2003; Ray, 2007). It should be explained that side-loading trucks are more commonly known as turret trucks thanks to incorporation with a rotating fork or turret assembly. The presence of rotating forks causes forks to be placed at either the right or left side of the aisle and holds the loading pallets. Depending on the configuration of these trucks, the operator can stay at the floor level or move with loads through a mast-elevated cab. The latter causes the operator to control the storage process and order picking more effectively (Kulweic, 1985).

The other strategy to manufacture very narrow aisle vehicles is converting the technology of automated storage and retrieval (AS/R) vehicles to hybrid machine ones. Hybrid machines are manufactured as a result of incorporating the technology of mast in AS/R vehicles with the technology of battery-powered wheels of fork-lift trucks (Kulweic, 1985). Thus, when the vehicle moves between aisles, it is run by battery power, and during performing within the aisle, the vehicle is driven through an AC power source saved by top-mounted collectors. Furthermore, AC power can be employed for recharging batteries. Thus, a combination of the technology of both aisle transfer machines with fork-lift trucks led to produce high speed and lift AS/R vehicles (Baker, 2013; Kulweic, 1985).

Typical fork-lift trucks

The main components of a typical fork-lift truck (Fig. 12.9) are overhead guard, mast assembly, single-, two-, three- or four-stage mast, fork carriage, fork, wheelbase, load center, tires, and power source (Kulweic, 1985). Based on the mentioned parts, various types of fork-lift truck have been designed and manufactured introduced in the following sections.

FIG. 12.9 Main components of fork lifts (Cottingham, 2018).

Turret trucks

Turret trucks enjoy the specifications of both side-loading and counterbalance trucks. A long wheelbase considered in the design of these trucks ensures their stability. The position of the batteries and operator placed at the rear of the machine obtain an adequate counterbalancing weight to certify the stability of load at extremely elevated height (Kulweic, 1985). Turret trucks deviate from conventional counterbalance ones in the mast width, which is developed to approximately the total width of the trucks and acquire the enhanced stability for the higher elevation (Apple, 1972; Senker, 1980).

Turret trucks can function in the very narrow aisle because of the side-loading character of the rotating fork tool in which forks and loads rotate to a position perpendicular to the direction of the aisle movement and finally are side loaded to the storage site (Allegri, 1992; Kulweic, 1985).

The other unique feature of this group of trucks is that besides lift, they are able to carry out two basic load motions. In this regard, rotation revolves the load to either right or left of the movement direction in the aisle. Traverse is a type of side-to-side travel of loads and generally is utilized for the storage and retrieval practice to raise and settle loads in the pallet rack (Kulweic, 1985; Senker, 1980).

The mechanism of the turret head can be conducted in both J and L head configurations. The J head apparatus has been considered to simplify the rotation of loads in the working aisle. However, the eventual height of the fork lift in this configuration is limited due to the overhead support device. The throat size of the head restricts the load lift managed by this system. Furthermore, the greater support structure rises the value of suspended weight causing the load capacity of the truck to reduce compared to other turret fork types (Kulweic, 1985; Larsson et al., 2003).

The L head apparatus which is extremely more practical is not subjected to the throat limitation; accordingly, it is more acceptable for loads with different heights. Also, the lower height of the L head apparatus leads to trucks storing loads in a higher height than the J ones (Kulweic, 1985; Larsson et al., 2003).

In order to load rotation in a working aisle, the fork rotation and traverse tools should be synchronized which is obtainable through installing controls on trucks (Senker, 1980). However, load rotation during truck motion is not approved by the majority of manufacturers. In fact, a broader aisle should be considered when load rotation within the aisle is required. Therefore, in the design of aisles, fork rotation, and traverse tools, the load diagonal dimension, as well as width and length of the load, must be considered (Kulweic, 1985; Rajesh, 2016).

A man-up model, as a kind of conventional turret truck, owns an operator platform at the forepart of the vehicle. The position of operator leads to applying these vehicles for order picking, pallet storage, and retrieval. Moreover, being operators close to the load cause they directly manage storage and retrieval processes without requiring additional tools such as shelf height selectors or guide marks (Childs, 2003; Kulweic, 1985).

In man-up turret trucks, the presence of the operator platform in front of vehicles increase the load center; therefore, extra mast bracing configurations such as mast supports, varied mast construction, and geometry as well as balanced reaction chains have been considered in manufacturing of the vehicle (Apple, 1972; Kulweic, 1985).

Hybrid trucks

As mentioned previously, hybrid trucks own the technology of both fork truck and AS/R machines. These vehicles operate on AC power within the storage aisle and on self-contained batteries outside the aisle. The man-up version of hybrid machines causes the operator to control the storage and retrieval functions directly and also provides the order-picking procedures. AC power and guided-aisle equipment increase the speed of machines within the storage aisle by over 2.1 m/s (400 ft./min). Despite high-lift turret trucks owning almost the maximum storage height of 12.2 m (40 ft), this height for hybrid trucks is about 18.3 m (60 ft). The other benefit of hybrid type trucks is their capability of synchronous movement, raising and dropping of loads within aisles leading to decreased cycle time and enhanced productivity (Kulweic, 1985; Senker, 1980).

Hybrid trucks are adapted with shuttle table apparatus elevating loading pallets from below while fork tools lift loads from inside fork pockets. Furthermore, shuttle apparatus facilitates the storage and retrieval operations via direct travel of loading pallets over the aisle without performing any rotational maneuver or needing extra aisle width (Kulweic, 1985).

12.3.2.4 Special vehicle

Beyond the three main types of fork trucks mentioned previously, there are special vehicles in capacities less than 4500 kg (10,000 lb) these trucks are both advantages of side-loading trucks operating in narrow aisles and straddle trucks applied for order picking (Kulweic, 1985). Aisle characteristics of side-loading vehicles are similar to narrow aisle ones but they generally need larger maneuvering spaces at the end of storage aisles when transporting long loads (Allegri, 1992; Ray, 2007). Moreover, these devices are provided with traveling masts to prevent the loads from locating in a transport state beyond the truck bed. In addition, the order-picking vehicles are assembled with a platform that leads to the operator picking loads from racks in the storage spaces, locates them on the pallet carried on forks that are found in front of the operator platform (Baker, 2013; Kulweic, 1985).

12.3.3 Robot trucks

Robot trucks or automated guided vehicles (AGVs) are referred to the driverless machines that are automatically directed and possess the ability to convey loads (Chapter 13). In these systems, two distinct guidance are applied; one of them employs a guidewire inserted in the floor, while the motor of AGV through an electrical induction connected to it and receive the signals. The other one is equipped with photoelectric sensors that follow colored tracks on the floor. Both instructions provide benefits and restrictions (Kulweic, 1985; Ray, 2007). Although inserting wires are well priced and may compromise the floor's hygienic conditions, the possibility of causing serious trouble by this wire after installing is negligible. Despite being cost effective, colorful guidelines on the plant floor may deteriorate during time as a consequence of being exposed to external interference (Kulweic, 1985; Ray, 2007). Therefore, in order to maintain the operation efficacy of these vehicles at a high level, they should be restricted to move only in the predetermined smooth and well-preserved roots. However, the major part of these drawbacks has been eliminated recently as a result of free-path vehicle advent.

In some novel-designed devices, AGVs receive path-related signals in an X–Y coordinate pattern through a computer (Ray, 2007). Moreover, this type of computer chooses the most appropriate path for connected vehicles and controls their speed and stop points. Although these modern devices find the root by implementing electronic maps, access to more accurate data about their position in some situations such as loading or storing the burdens of pallets is required (Allegri, 1992). This has been achieved by equipping the aforementioned vehicles with an odometer and a low-intensity rotating laser. The latter one has been applied to scan the barcodes set throughout the length of paths (Apple, 1972; Ray, 2007). There are various types of AGVs equipped with different apparatus such as chain, fork, roller, and salt conveyors that carry transfer vehicles, infrared, radio, and ultrasonic transmitters. These AGVs have the capability of programming in a way that conducts particular functions. These trucks have the capacity of picking up or dropping down loads with 0.5–6 ton weight, but they are mostly designed for 1 ton or fewer objects (Kulweic, 1985).

12.4 Conclusions

In this chapter, industrial truck equipment employed for the material handling as well as daily consignments and wares distribution in various sites of a food plant including warehouses, transport depots, etc., were introduced. Furthermore, the operational and structural characteristics of various hand and powered trucks such as their capacities, dimensions, and specific applications were presented in this chapter. Based on the presented specifications, it is recommended the most appropriate vehicles for each industrial unit operation should be provided based on the requirements and plant features.

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Chapter | Thirteen

Robotics for general material handling machines in food plants

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13.1 Introduction

Food processing is one of the largest, if not at the top of the industrial hierarchy, sectors responsible for feeding the ever-growing population of the world. Fundamentally, the food industry is derived as the extended version of domestic procedures undertaken in the home kitchen with a focus on food preparation and design. Being a dynamic strategic component in all national economies, their positive contribution to the global societal concerns in diverse cuisines and food demand is still evolving with technologies. Besides, increasing consumer demands, as well as changes in the environment and legislations in maintaining desired quality, have redirected food producers to adopt large-scale "flexible" automation processes instead of the traditional manual intensive manufacturing approaches. However, it is to be noted that whether it be fruit or vegetable, cereal grain or nut, dairy or meat, and packaging-related industry, the most critical factor above demand is the customer satisfaction that drives the desired repeat sales to sustain industries throughput. This further acts as a powerful responsive tool to embed within an advanced automated environment that is heavily supported by industrial robots (IRs).

Industrial robots are mechanical manipulators controlled by computer programming specified in repeatability, preciseness, accuracy, and mostly desired for reliability aspects (Alam et al., 2018). From a more technical perspective, the International Standards Organization (ISO) defines an IR as, "A multi-purpose, re-programmable, automatically controlled machine with several degrees of

Transporting Operations of Food Materials Within Food Factories. https://doi.org/10.1016/B978-0-12-818585-8.00005-2

freedom that may be either mobile or fixed for use in large-scale handling and operations." Condon and Odishaw (1958) defined degrees of freedom as the number of independent coordinates required to represent the total directional movements of robot parts. This feature defines the spectrum of usability in handling numerous unit operations in food processing plants, which will be discussed in the following sections.

Generally, IRs have been seen to overtake every corner of operational industries. International Federation of Robotics (IFR) reported that there was almost a linear increase from 64,000 to 81,000 units from 2017 to 2019 in the operational stock of IR alone in the food sector (IFR, 2020). In today's competitive food and agriculture industrialization regime, IRs have been successfully integrated into many unit operations from farm to fork. Food industry manufacturers have reported a 25% increase in productivity in 2017 since IRs took over the manual approach (IFT, 2017) and have anticipated growth at a compound annual growth rate (CAGR) of 12.8% in IR use, to reach a value of USD 2.5 billion by 2022. Besides, its largest explorers have been identified as Asia Pacific countries (50%) followed by Europe (25%), and North America (25%). This substantial projection has been assigned to the strictness of the food safety regulations (circumscribing to hygienic and safety standardization) that act as the mainstream criteria although they are used to perform tasks such as cutting, mixing, palletizing, splitting, picking, placing, and packaging food products (Gray et al., 2013). To adhere to the Generally Recognized as Safe (GRAS) product, the robot has to identify potential defects and conduct inspections through learning. This is achieved through High Definition (HD) cameras attached to either the processing line or the robot parts. IRs usually have two basic components, i.e., a manipulator-like articulated links (Pires, 2007) and an end-effector [also known as end of arm tooling (EOAT)/Business end of the robot] that can be programmed to conduct a sequence of motions to perform the above-stated tasks. As the end-effectors remain in direct contact with the food product, this chapter will cover their types, principles, design consideration/prospects, and the range of applications in food manufacturing industries.

13.2 Robotics

Before moving into the range of articulated manipulator links and end-effector types, there is a need to understand the basic working principle of these systems. As discussed in the previous section, the number of independent coordinates (degrees of freedom) defines a robot's reachability to a designated point. To perform this repetitive task, the articulated links can be designed to move with linear (Cartesian system), angular (cylindrical or spherical system), or a combination of both coordinate systems, depending on the complexities of joints (links) used with the end-effectors. Fig. 13.1 illustrates the types of links that can be embedded with a particular end-effector (not limited to the one shown in Fig. 13.1).

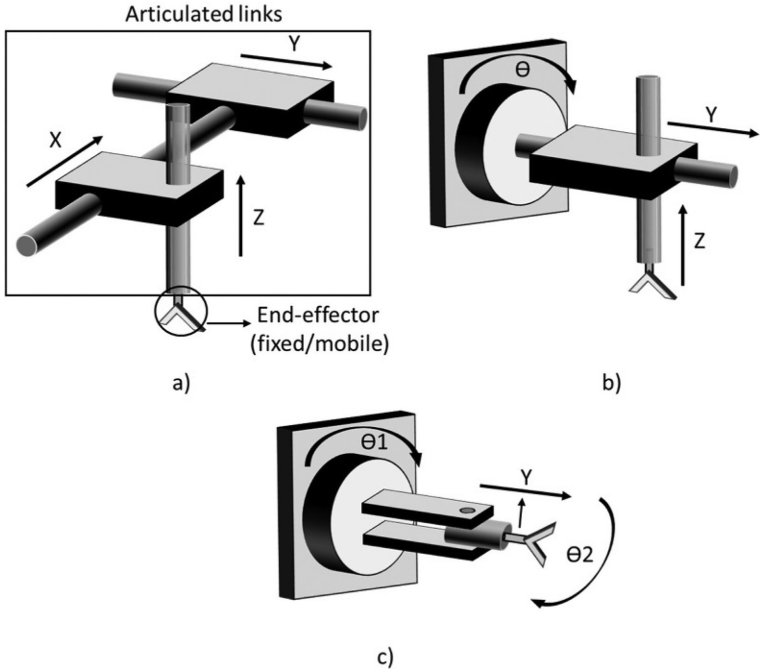

FIG. 13.1 Robot coordinate systems describing the degrees of freedom: (A) linear systems; (B) cylindrical systems; and (C) spherical systems.

Linear working robots (Fig. 13.1A) have three joints, ensuring the movement of the attached EOAT in a Cartesian system, i.e., X, Y, and Z orthogonal axes. The axes of the linear robot are manufactured from some form of linear actuator that is either custom made by the end-user from drive components or purchased as a pre-assembled system. Not every form of linear robot works on a typical Cartesian geometry. They are employed with two parallel axes configurations, i.e., 2X-Y, 2Y-Z (or 2X-Z), or 2X-Y-Z that move the robot out from the linear system into the typical gantry robots. The basic difference lies in the use of actuators on each axis segregating in having different stroke lengths or payloads. Robots of this type are highly user-friendly with extended horizontal or vertical motions and with a heavy lift capability. However, they intend to consume a large workspace than other robots due to their extended arms.

Cylindrical robot systems (Fig. 13.1B) have one rotational unit about the base and two linear joints along the arms controlled by the actuators. This working profile adapts proficiently when working against gravity particularly useful in connections with behaviors that have rotational symmetry about the longitudinal axis as can be depicted from Fig. 13.1B. On the other hand, spherical (also known as polar) coordinate robots (Fig. 13.1C) are known to have one linear unit with two rotational joints as shown in Fig. 13.1C. They are stationary robot arms with near-spherical or spherical work envelopes having control solutions less

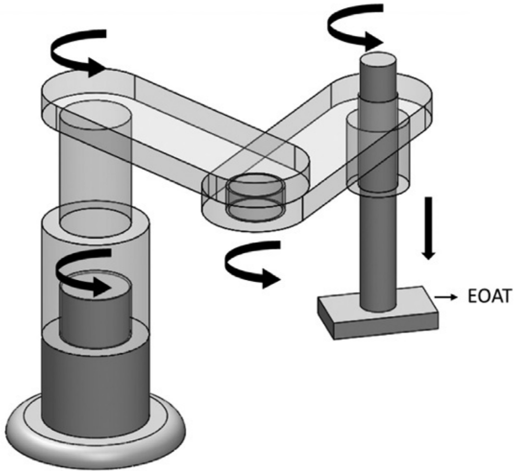

FIG. 13.2 SCARA robot model (>3 rotating joints) with an end effector.

complicated than the articulated horizontal or vertical link arms. Though the link shown in Fig. 13.1C is not spherical, the reachable places can still be calculated in a polar system. These three joints form the basis of any advanced or complex system that is being implemented in the 21st century. Further embedding links would give more flexibility however, would not change the reachability. The Widely known SCARA (Selective Compliance Assembly Robot Arm) robots fall into this category with hybrid systems. This technological innovation was first designed by Hiroshi Makino, a professor at the University of Yamanashi, which is pliable in the XY-axes and rigid in the *Z*-axis (Fig. 13.2), hence the term "Selective Compliance." SCARA's are faster than conventional linear robot systems.

This makes SCARA useful in vertical assembly operations, however, the arm is a lever that limits its outreach. Sometimes this feature is taken care of by the six-axis robot, however, their application is limited to automobile industries due to high costs. All these systems (links) direct the functioning of the end-effector, yet the actual unit operations carried out in the respective food plants are managed by different EOATs.

13.2.1 Classification of end-effectors

Food handling should be a highly delicate process to maintain the overall integrity of its intrinsic properties. With an advantage in working under harsh environmental conditions and with subtle process parameters (most important) compared to a human hand, end-effectors have been pliable in responding to the demands of complex mechanical engineering combined with food process innovations and safety requirements. Various end-effectors have been devised that can be embedded with a particular robot system to carry out versatile works. This section will cover the EOAT types and their working principles/physics to provide the reader with a basic idea of their system starting from detection to handling operations. There are two most crucial EOATs that manage the whole automatic handling process in food plants: sensors and grippers. Gripper's operating criteria directly depend on the sensor's output and one cycle can be completed as low as in milliseconds. The next sections describe the different sensors and grippers that have been implemented with their shortcomings in sophisticated food handling operations.

13.2.1.1 Sensors

Human hands operate under the constant supervision of sensory feedback under the control of the brain. This provides a constructive approach to pliable and adaptable grasping and other manipulative actions that currently robotic society is trying to implement. All robotic grippers should work consolidating with the intricate physical environment and functional variables to benefit in the aspects of stability, sense of touch, adaptability, visual acuity, and reliability (Wolf et al., 2006). Fig. 13.3 shows an overview of the types of sensors that are currently or could be used in the future to make the grippers more intelligent (Monkman et al., 2007).

Switching sensors are used to signal the desired position status of the EOAT in the form of a discrete binary on–off process. This includes the spatial position to open or close the EOAT to grasp or drop the workpiece. Switching sensors are further classified into proximity, reed, touch, and hall sensors. Proximity sensors are non-contact switches that respond when the workpiece comes into close range in the sensing field of the switch. Monkman et al. (2007) suggest that the responsive phenomenon could be realized by an inductive, transmissive,

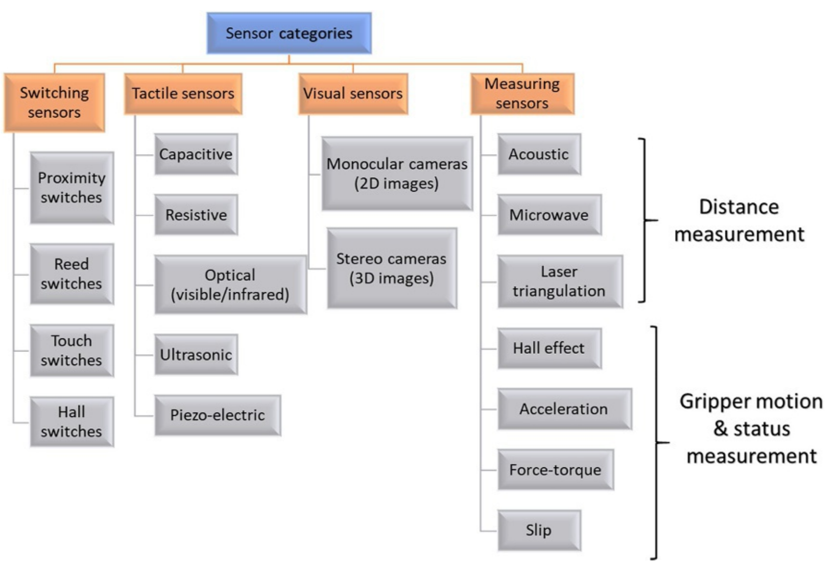

FIG. 13.3 Classifications of robotic sensors.

reflective, or a capacitive manner. Reed sensors operate by a magnetic field that executes the opening and closing status for the gripper (Zikria et al., 2011). Hall switch acts on a similar principle but varies its output voltage based on Hall effects (Ramsden, 2011). Touch switches specifically operate after touch as they can simply register the threshold after receiving the touch signal.

Tactile sensors work on a similar principle as touch switches. Through physical contact, they can measure tactile-related properties such as temperature, pressure, vibrations, and moisture within any food object (Monkman et al., 2007). These properties can be concisely sensed by sub-classified sensors as mentioned in Fig. 13.3. As a visual perspective cannot be considered as a standalone attribute to decide on food quality, these sensors could act as a further feedback tool to fulfill the above purpose.

Visual sensors are an intrinsic part of the automation process, however, as stated earlier they cannot be treated as only EOATs for food quality estimation. Wolf et al. (2006) suggested that visual sensors can be integrated onto the gripper's tip (probably finger types as shown in Fig. 13.4) to control the grasping process and make them more precise.

Measuring sensors work on a similar principle as switching sensors but they do not use the binary approach as of the latter systems. They constantly update the dimension of the grasped material and adjust the gripper holding in terms of slippage and movement.

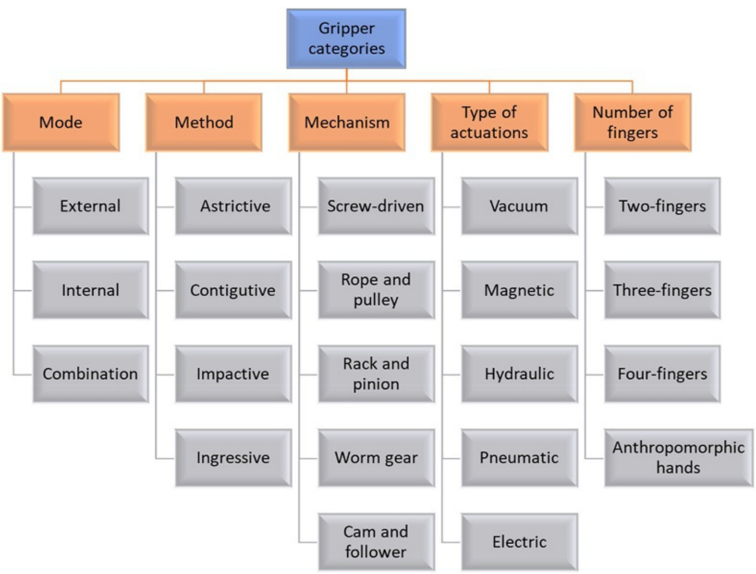

FIG. 13.4 Classification strategies of robotic grippers. *Based on Zhang, B., Xie, Y., Zhou, J., Wang, K., Zhang, Z., 2020. State-of-the-art robotic grippers, grasping and control strategies, as well as their applications in agricultural robots: a review. Comp. Electron. Agric. 177, 105694.*

13.2.1.2 Grippers

A gripper is a business tool mounted at the end link of the arm to grasp, perform basic unit operations or carry and place the designated workpiece. After the sensors have detected the potential workpiece to act upon, these tools come into effect to carry out the next phase of the unit operation.

Secure operations require firm contact with the object without any potential damage or slip. These sophisticated demands make it tough for the grippers to perform unless a general intuition is fed up with complex programming or mechanical advanced technology. Since the development of the first gripper in 1975 (Tai et al., 2016), these aspects have urged the robotic research community to propose reliable and adaptable grippers for diverse food objects. Monkman et al. (2007) suggest that grippers can be as simple as two-fingers to avoid the cost of implementation of the system but at the same time if we are concerned about the mode of grasping, there could be as many as five categories. A more detailed classification of grippers segregated according to design and operation is shown in Fig. 13.4. However, in the food industry, their application is limited due to the need for sophistication (including food safety standards) and cost.

All the stated grippers are required to perform the basic function of transferring the desired force from the arm link to the workpiece. Any unit operation involves the acceleration either through the local movement or due to gravity. The acceleration due to local movement is a function of any change in magnitude and velocity vector while gravity acts always in the perpendicular direction to its horizontal plane. This will provide the largest force during vertical handling operations.

Grippers categorized into actions (modes) are called internal and external systems or sometimes with a combination of dual modes. In external mode, the closing force of the gripper (basic grippers according to the type of actuators and number of fingers) holds the food object. It requires the shortest stroke length and is the most popular form of grasping. While internal grippers operate on the opening force as the object needs to be held from the center of gravity. Christoph Wittwer invented a dual-purpose gripper (Wittwer, 1980) with a sliding block actuated toggle linkage to exert an input force to a two-finger gripper. This tool is now commercialized by ABB Robotics Inc. but is yet to be explored in the food industry.

Classification based on the physical operation proposed by Monkman et al. (2007) has been broadly acknowledged by researchers. Astrictive grippers exert a binding force in one direction and the force may be produced by suction, electrostatic charge, or magnetic forces. Contigutive grippers operate by thermal or chemical (surface tension) adhesion with the workpiece in a single direction. In the case of thermal adhesion, the principle of surface phase transition is predominant where the contact area falls below the freezing point temperature of the water and when brought in contact with any wet subject forms a thin ice film developing enough vertical holding force. Subsequently, the surface is heated to release the food subject or in some cases sliced off using a knife (Gjerstad et al., 2006). Impactive grippers execute direct mechanical force against the workpiece from one or two directions to develop the grasping behavior. While Ingression grippers permeate through the workpiece to grasp for executing desired operations. There are two types of pins used for permeation: short pins for surface penetration in flat workpieces and long pins for deep penetration in irregular food objects. This penetrating gripper is suitable for soft food products without rendering any significant harmful effect on its quality, however, among all the other physical method-based grippers this has to adhere mostly to the hygiene and safety standards for GRAS purposes. Gripper object materials and types with examples can be found in Monkman et al. (2007) study. Till now it can be understood that all the gripper categories are interlinked and their working principle depends on one of the other methods.

Gripper's classification based on the mechanism was first proposed in 1982 starting with a basic screw-driven approach. Subsequently, Vollm et al. (2007), Lanni and Ceccarelli (2009), Silva-Caballero et al. (2011), and Modler et al. (2012) proposed the worm-gear, rack and pinion (as a two-finger gripper), cam and follower pairs, and rope and pulley grippers, respectively. According to actuation, grippers can be electric, hydraulic, vacuum (suction-based), pneumatic (working on Bernoulli principle), and magnetic grippers. For versatility, an electromagnetic grasping approach is widely preferred because of its adaptability to various shapes and sizes of the workpiece without any sensory response (Brown et al., 2010) however, it lacks agility (Tai et al., 2016). Hydraulic grippers include piston wedge or direct-acting piston designs. In direct-acting design, a hydraulic force is acted upon by the piston directly connected to an EOAT while in the wedge design the piston acts upon a wedge system that transfers the force to the EOAT. Unlike electromagnetic ones, these grippers have only one motor that can power the hydraulic fluid to supply the required energy to the piston. Suction-based grippers grasp the workpiece by creating an inward force with the suction cups (Reddy and Suresh, 2013). These cups do not generate total vacuum but rather certain underpressure (local pressure < atmospheric pressure) at the gripping area. They are non-intrusive and reliable in a confined space but are sometimes not appropriate for non-porous or irregular materials. There remains a high risk of air leakage into the suction cups. If the airflow from the leakage is higher than the ejector capacity then the amount of underpressure will decrease resulting in loss of the grip. Recently, this issue has been overcome by Coanda grippers (Natarajan et al., 2018). An alternative to this principle is to use the suction created by high-speed fluid (air) flow in the radial direction. These type of actuators falls under pneumatic grippers (Fig. 13.5). In this type, the airflow is deflected by the workpiece to flow in the radial direction creating a decrease in local pressure between the gap according to the Bernoulli principle (Chua et al., 2003). Thus, resulting in higher suction (with desired hygiene standards) than conventional suction caps in the perpendicular direction of the gripper's surface. However, the coefficient of friction is virtually zero and this is a major concern because additional contact areas need to be established for proper handling of heavy and irregular food products.

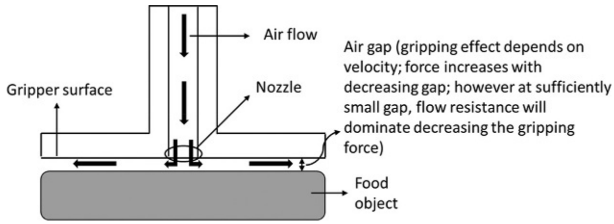

FIG. 13.5 Working principle of pneumatic (Bernoulli) gripper.

The last classification is based on the number of fingers. In this category, the number of contact surfaces is decided by the number of fingers interacting with the workpiece. As stated earlier, two-finger EOAT is the simplest form of the gripper in today's robotics catalog. They mimic around 60%–70% of the human handling approach with cylindrical, parallelepiped, and pyramidal shapes in real-world applications (Hugo, 2013; Ceccarelli et al., 1992). They rely on friction to generate force (opposing sliding along the surface) to grasp the object which further depends on the direction of the object's acceleration known as force-fit grip. To avoid sliding, the opposing sliding force at the gripper surface should always be greater than the combined force due to gravity and the robot's acceleration due to movement. These tools will come to a close when the finger force equals the reaction force from the workpiece. But this behavior could be different with soft food materials thus, demanding frequent adjustments to exert nominal safe pressure to avoid textural damage. Detailed information on the forces required during different movements is described by Lien (2013). In the case of the anthropomorphic hand, the total degree of freedom is always less than the human hand. Besides, the adroitness of a human hand cannot be 100% impersonated due to the forces that are controlled by the human nervous system. Though some laboratory-based hands are developed, their industrial use is still under process due to extremely high costs (Thayer and Priya, 2011).

13.3 Design consideration of robots and machine learning

The handling of food in a commercial food processing plant is the most labor-intensive part and hence needs automating the handling process by maintaining a high level of hygiene. To achieve a safe and low-cost automated handling process, industries are now looking increasingly toward robotic manipulation. However, the widely held industrial robots are unsuitable for explicit use in food processing due to the non-uniformity and delicate nature of the food materials. So, to design the robotic handling system for food industries, the unique functional requirements are to be kept in mind from the very onset of the design process. Three broad design considerations have to be considered by the designers before construction namely food properties, design of every part of robots considering hygiene, and industrial requirements such as cost and speed.

13.3.1 Design considerations based on food properties

Food materials requiring handling are mostly non-rigid materials and some of them are two-dimensional, flat, and can be slippery or adhesive. Moreover, handling of foods such as jelly blocks, polymer sheets, and sliced meat presents additional challenges due to their surface delicacy and high risk of product contamination. Most commercially available end-effectors (grippers) are not appropriate for handling food products where the products appearance, quality, and safety characteristics are the foremost requirements. For example, needle grippers can be used for pricking purposes, however, the degree of piercing the product's surface needs to be properly devised that might vary with product types. An adhesive gripper will also have hygiene problems as it could scratch the surface during a potential drop. Therefore, food surface properties are important design criteria for constructing end-effectors that should be suitable for correct manipulation at high speed for profitable pick-and-place operations for industrial applications. During handling, the product behavior is affected by the following parameters that need to be considered with utmost priority while designing the end-effectors:

i. F ood surface properties.
ii. Hygiene and safety during handling.
iii. Environmental conditions such as temperature, humidity, and pressure.

Based on the above parameters, designing food industrial robots involves various steps that analyze food features and production requirements to identify the most relevant physical configuration for the end-effector mechanisms as described below.

13.3.1.1 Defining food types, surface properties, and processing conditions

The first step of designing industrial robots involves identifying the food material and its surface properties. Most of the food products vary significantly in shape, size, color, and texture, and are non-rigid. Hence, utmost attention should be given to the gripper designing stage to account for its compatibility against deformation during handling when they are in contact with hard and/or rough surfaces eventually affecting the organoleptic properties. The following five types of food products that involve the utilization of robotic automation in their processing stages have been reported:

i. Fruits and vegetables.
ii. Cereal grains and nuts.
iii. Milk products that include mostly handling of semi-solid and solid products derived from milk such as cheese, butter, and milk-derived sweets.
iv. Meat, poultry, and eggs that include red meats from cattle, sheep, pigs, and white meats from chicken and other such poultry, kinds of seafood including fish, shellfish, and other sea creatures, either raw or in cooked form.
v. Bakery and confectionery products including bread, cakes, pastries, sweets, and chocolates.

The state of the foodstuffs is important for designing the robot end-effectors as a liquid or semi-liquid food product is not feasible for the robots to handle. Storages fitted with sensors such as tanks, pipes, and fillers are more appropriate for liquid and semi-liquid products like milk and beverages (Bader and Rahimifard, 2020). The structural state of the food materials such as integrity, wetness, hardness, etc., is an important consideration for material handling that should also be considered during this process. Raw, cooked, and frozen states are the broad categories of the food product conditions that greatly affect the design of the end effectors. The design depends on the minimum force required to lift an object by assessing its hardness or firmness during the formation of the grasp (Friedrich et al., 2000). Softer objects need increased contact area and less gripping force to pick up. The selection of the end-effector's mechanism and suitable gripper technology for the foodstuff being handled is also affected by rigidity and deformability as described in Table 13.1.

Alteration of the food structure being handled leads to product deformability. Deformable products are easily damaged by the application of pressure, whereas elastic foods retain their structure. Non-rigid foods in whole or in cooked conditions refer to deformable products whereas frozen foods are non-deformable. Handling these two types of food products requires a different mechanism in end-effectors. Robotic gripping technologies described by Taylor (1995), which can be used for deformable food products are mechanical holding using gripper fingers that can be used for fish and poultry products and surface attraction using vacuum grippers or suction cups for handling eggs, fruits, and vegetables. In both these arrangements, the gripper surface can be added with complaint foam to avoid any bruising or unacceptable damage. Thermal (Freezing) gripper for handling non-deformable frozen foods can be designed by using the concepts of Stephan and Seliger (1999), who developed a gripper by rapidly freezing water vapor ($-10°C$) that was distributed on the contact spot through an integrated nozzle, resulting in holding of the food material. Further,

TABLE 13.1 Food surface characteristics that pose challenges for the automatic handling.

Food surface characteristics	Examples of foods to be handled	Challenges involved for the end-effectors
Soft and fragile	Tomatoes, plums, berries, eggs, pastries	Likely cracked or damaged under pressure
Semi-rigid	Whole fruits like apple, pear, apricot, nuts, cheeses, meat, and poultry loaves	Likely bruised under pressure
Irregular shapes and sizes	Banana, dry fruits, whole chicken, turkey	EOAT's will require visual tools to assess each item
Slippery surfaces	Cut fruits, peeled vegetables, fish, meat	Loss of grip by slippage
Uneven surfaces	Avocado, pineapple, dragon fruits	Likely affects surface grip

air pressure was applied to liquify the frozen vapor, which ultimately releases the gripped material. Other examples of manipulation mechanisms that could be used for food material handling are pushing, scooping up, translating, rotating, placing, or turning over operations.

13.3.1.2 Hygiene and safety during handling

Food safety is an important aspect of the food industry from a consumer health and product shelf-life point of view. The contact surface of the food materials during processing and packaging should be clean enough to keep away any kind of contamination from microorganisms. To achieve such a stringent requirement, the hygienic aspect of robotic manipulators and end-effectors is essential. Three major types of contamination should be taken care of for the design of the food industry robots:

i. *Toxic substances:* Traces of toxic materials can adhere to the foodstuffs during handling through robots and thus be transmitted to the consumer. Therefore, all gripping devices should be constructed from non-toxic materials. Stainless steel is the most suitable material for construction for the hygienic design of the robot end-effectors as it is inert and corrosion-free. Some other engineering materials are currently under investigation for non-toxic, safe, lightweight, and low-cost robot design.
ii. *Microbiological contamination:* Food processing, handling, and packaging facilities are favorable for the growth of bacteria and fungi due to the availability of organic material, high humidity, and temperature conditions. Traces of food material left on the contact surface of the gripper leads to the development of microorganisms. Condensed water from frozen meat or fish left out on the gripper's surface usually results in bacterial contamination. Therefore, during design, provision for waterproof construction, trace inspection on all external parts, and spray jet cleaning should be considered. The gripper design should be such that there should be a minimum accumulation of the food traces on the contact surfaces after each processing cycle.
iii. *Discoloring:* Sometimes, material structure alters a bit due to local pressure from gripping actions, which may lead to discoloring of the food product. Though a minor discoloring does not affect the nutrient value of the product, it still can be considered a visual quality defect by the consumer. Precision in the force-displacement measure is therefore important during non-rigid food materials during handling.

13.3.1.3 Environmental conditions during handling

The design of the food industry robot should be such that it must be able to cope with the harsh environment of food processing and handling, which is mostly humid and hot. As robots are a means to replace human operators in the food industry, environmental extremes such as chemical, pressure, temperature, work cycles (duration and speed), and masses should be kept in mind during the structural construction of the robots. Holmes and Holcombe (2010) conducted industrial trials for washdown applications using a robot prototype and highlighted the difficulties of functioning in such an environment. Therefore, the robot must also be reliable in operation to keep production slowdown to an absolute minimum.

1. *Design consideration based on various parts of the robots*
   - **i.** *Configuration of end-effectors:* Basic configuration of the end-effectors should be to transfer the necessary force from the robot arm to move the object without drawing any food particles into the joints (Lien, 2013). Rotary configuration should be preferred over linear configuration or SCARA configuration of the end-effectors to avoid such accumulation of contaminants. However, rotary delta robots employ universal joints, which are difficult to clean. The most suitable rotary configuration is the articulated arm configuration, which has a small number of easy to seal joints and is well suited for the hygienic design of food industry robots.
   - **ii.** *Degrees of freedom*: Numbers of the degree of freedom of the end-effector depend on the type of material to be picked and placed, mostly four or six degrees of freedom are used (described in Section 13.2). But, looking into the food handling operations, except for some exceptions, most of the tasks are performed on a conveyor belt and can therefore be accomplished using four articulated degrees of freedom (Masey et al., 2010). An additional uncoordinated degree of freedom can be added, where the workpiece being handled needs to be tilted out of the plane. By choosing suitable degrees of freedom for the design of the robot end-effectors, the cost of construction, mass, and inertia of the robots can be significantly reduced.
   - **iii.** *Reach and workspace*: The end-effector should reach across the full width of the conveyor belt to pick objects both on the near and far ends. Picking at high velocities (80–100 picks/min) is required only in the region directly above the conveyor, where the majority of tasks are carried out and the much lower speed is acceptable in other regions of the conveyor belt (Masey et al., 2010). Therefore, the speed of the robot should be accordingly optimized to reduce the unnecessary movement of the end-effectors which ultimately saves cost and energy and also simplifies the design process.
   - **iv.** *Transmission:* Links and joints of the robots are designed based on the type of transmission system, which can be either electric, hydraulic, or pneumatic to perform several motions (as described in Section 13.2). The design of the transmission system depends on the type of end-effector motion. For example, the rotational motion of one shaft is transmitted to another with the help of gears and timing belts are used to transfer power from the motors to each of the joints. The wear and tear of the transmission system should also be taken care of during the design of the robot as it can affect the performance of the robot during handling. Standard ball bearings are used in the transmission system to

minimize friction and parts should consequently be designed to keep stresses below the premature fatigue failure level. The material of construction of the transmission system is also a design consideration as it might contaminate the food to be handled. Pulleys should be constructed with lead-free aluminum alloy. Additionally, the selection of motor and gearhead for robotic transmission should include a dynamic simulation of the robotic end-effector motion mechanism.

v. *Actuators:* An actuator is a component of the robot that is responsible for moving and controlling a mechanism or system that requires a control signal and a source of energy. The selection of actuators for robotic operation in a food industry depends on the cost, life cycle, hygiene, and speed. Pneumatic actuators are commonly used in the food industry due to their low cost and ease of operation. However, it is difficult to control an accurate position without the use of mechanical stops. Hydraulic actuators are not considered for the design of food handling robots as there is a risk that hydraulic fluid may contaminate the product. AC motor-operated robotic actuators, despite their high initial cost, have a high service life and are comparatively easy to control and reliable.

13.3.2 Machine learning for robotic motion and control

Machine learning (ML) is the method of training the machines to learn the data through the execution of algorithms that automatically create knowledge representation models based on a database (Variz et al., 2019). A robust database is provided to the algorithm for iterative adjustment learning of the mathematical model. The performance of the model can be improved by adding a greater number of sample data. Machine learning is used for human-machine interface, decision-making for the end-effectors, and trajectory for picking and placing of the food products. Machine learning techniques in combination with machine vision are used for intelligent, collaborative, and adaptive robotic inspection, and picking and handling systems. Robotic handling of food products can be accomplished by sequential steps consisting of image acquisition, image processing, decision-making, path planning, and task implementation.

13.3.2.1 Machine vision for sensing the object

Machine vision system employs image acquisition through RGB or near-infrared cameras, feature extraction through image processing, and manipulation through deep learning algorithms with trained data sets that are used for the detection of food material. In the case of quality inspection, the machine learning algorithm commands the end-effector such that if the feature of the product does not match the algorithm, the robot would reject the interaction and move to the next minimal point. For handling the product, the algorithm detects the product feature and commands the gripper according to the product type, shape, size, and form for picking and placing following a particular trajectory. For robotic manipulators performing such tasks, visual observation ability

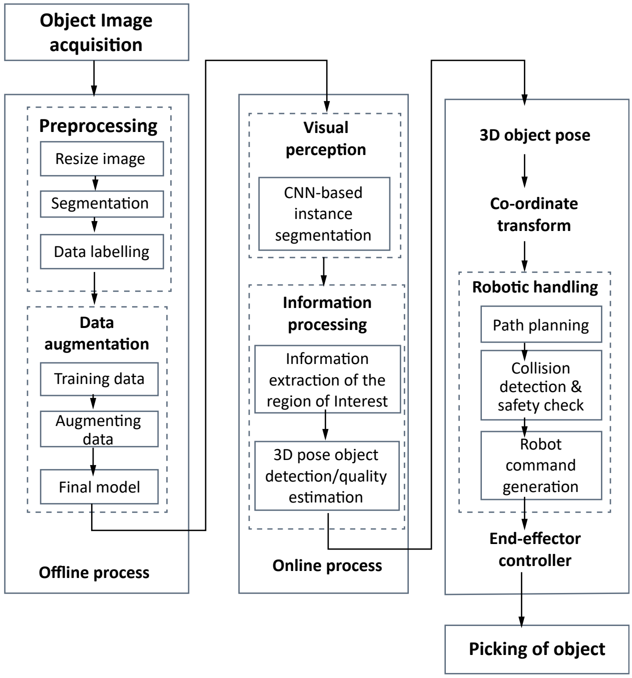

FIG. 13.6 General architecture of a robotic handling system in a food processing industry.

is required before bringing the information to the processor. The information processing and decision-making processes are similar to the analytical processing of the human brain, which orders limbs to accomplish any particular task. Likewise, a robotic manipulation system uses different actuators to perform tasks depending on their complexity. Fig 13.6 indicates the state of the art of a robotic food handling system using artificial intelligence for object detection, decision-making, and handling.

Image processing is an indispensable part of a machine vision system that improves the quality of images for correct identification of the desired food parameter and subsequently acts upon them. It usually follows steps such as (a) pre-processing, (b) image segmentation, (c) feature extraction based on image representation and description, and (e) classification of objects (Paul et al., 2020). Image pre-processing is used to improve the image quality by eliminating undesired distortions such as background subtraction, noise removal, polygon shape creation, smoothing, histogram operations to enhance the objects, etc. (Paul et al., 2020).

Segmentation of the objects is not trivial because of the noise in the background. Traditional methods have relied on thresholding or morphological operations so that they are more efficient at the less complicated objects and plain backgrounds. For this reason, recently machine learning techniques have been applied to discriminate the objects. Afterward, various features can be extracted to represent the characteristics of objects such as color values, shape properties, principal component analysis, fast Fourier transform (FFT), histogram of wavelength, gray-level co-occurrence matrix, etc. (Wan et al., 2002). Based on the extracted features, machine learning and deep learning techniques can be used for the classification of objects. Deep learning can automatically train deep multiple layers by analyzing RGB images or input features. It has also shown significant advances in the food industry with an outstanding performance by handling a significantly large amount of data (Kamilaris and Prenafeta-Boldú, 2018; Kawano and Yanai, 2014).

13.3.2.2 Mathematical models for robotic manipulation

Decision-making and manipulation by the robotic end-effector can also be accomplished by the application of mathematical and statistical methods to extract and analyze the pixel information consisting of acquired RGB images (Workman et al., 1996). Similarly, the NIR camera produces both spatial and spectral data and their processing involves the reduction of dimensionality with the retention of meaningful information and the establishment of the mathematical relationship between the spectra and reference data for classification and quantification of important quality parameters (Mishra et al., 2018). Advanced machine learning algorithms for object detection and manipulation have been a significant focus of research over the past 20 years. Developers often proceed through three stages of an algorithm when dealing with new data such as pre-processing, model construction, and validation. Machine learning can be grouped according to its application as detection or picking (Amigo et al., 2013). For the automatic extraction of information, machine learning is an important aspect of object sensing and manipulation. The machine learning techniques are grouped into three broad categories based on the final manipulation of the product as shown in Fig. 13.7.

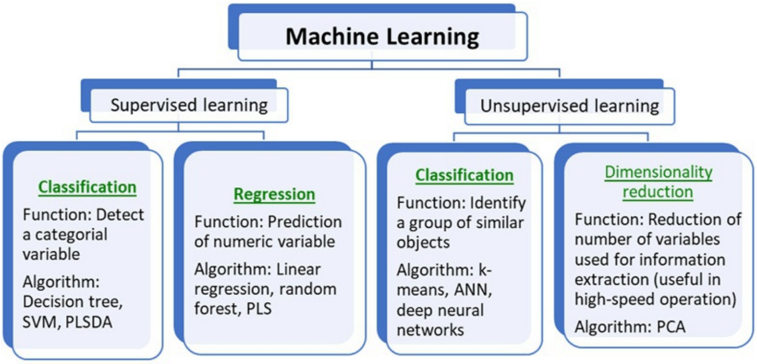

FIG. 13.7 Broad classification of machine learning techniques used for robotic manipulation in food industries.

Mathematical models correlate the image with the desired features to detect the object for handling or to detect the anomaly in the food materials for sorting. The principal component analysis is the most used algorithm in chemometrics for pattern recognition, where the data is orthogonally transformed into a new coordinate system such that the highest variance of the data lies in the first few coordinates, namely principal components (PCs) (Wold et al., 1987). The *k*-means clustering involves dividing samples into k clusters based on the minimum distance from the centroid, whereas hierarchical cluster analysis (HCA) classifies the samples into clusters by calculating the distance between each sample group (Srivastava et al., 2018). A supervised classification strategy involves labeled data sets for training the model and subsequently classifying the unknown dataset. Linear discrimination analysis (LDA), quadratic discrimination analysis (QDA), partial least-squares discrimination analysis (PLSDA), and support vector machine (SVM) are typical examples of supervised learning models (Alpaydin, 2020). Artificial neural networks (ANNs) are one of the most trending object detection model construction algorithms. ANNs employ artificial neurons that combine the neuron input with their internal activation function and an optional threshold to produce the desired output. The training of ANNs is done by the search of the weight and thresholds of the activation function that minimizes the observed error. Several other mathematical models alone and combined with other image features are also currently under investigation, viz., SVM and least-squares SVM (LS-SVM) and deep neural network algorithms (Caporaso et al., 2018).

13.4 Application of robotics in food industries

In general, food is a broader term that includes a range of products with unique physio-chemical, mechanical, and sensory characteristics which imposes challenges against automation in the food industry. In general, robotic application in the food industry is a bit tricky as it depends on multiple pre-considerations. The first and most important consideration is the type of food commodity to be handled, such as grains, fruits, vegetables, nuts, meat, milk, etc. The second most crucial consideration is the quality attribute of the selected commodity to be dealt with, such as shape, size, color, defects, etc. Based on the above two considerations specific type of sensor is employed, which identifies and quantifies the quality parameters and sends a signal to the end-effector robot to execute the robotic operations such as picking, placing, cutting, etc. Moreover, unlike other industries, the application of robotics intended for the food industry needs higher attention as the end product is targeted for human consumption. Ironically, most of the robotic applications in the agricultural sector proposed to date are dedicated to pre-harvesting and harvesting operations (Stoelen et al., 2015; Bac et al., 2013; Amatya et al., 2016; Wang et al., 2017; Colmenero-Martinez et al., 2018). However, in the postharvest management of food products robotics is yet to attain its maximum potential. This section will emphasize existing robotic applications in some of the important processing sectors under the broad category of the food industry.

13.4.1 Fruit and vegetable processing industry

Fruits and vegetables are high moisture commodities and prone to physical damage during handling and processing. Besides, there is a wide difference observed in the color, size, and shape of the fruits/vegetables within the same cultivar. That is why automation in agriculture promises superior and efficient handling of the product by excluding human interference (Wu et al., 2018) as shown in Fig. 13.8.

A continuously growing concern around a healthy living style has created the need for robotics and automation to ensure consistent and guaranteed quality of food. In connection with that emergence of various sensors has been noticed in the last two decades. Some of the applications of these sensors include estimation of compositional variations such as sugar content, acidity, and internal abnormalities like rind puffing, rotten core, etc. in fruits and vegetables. The most common quality parameters considered during the handling of fruit and vegetable industries are color, shape, and size and are measured through machine vision systems. However, the major barrier that comes to the detection efficiency of machine vision is glossy surfaces that exist in the case of specific fruits/vegetables. The cuticle layer made up of cutin and wax causes glossiness which reflects backlight to the optical sensor hence, obstructing high-quality image acquisition. It has also been noticed that irregularity in the shape of the fruit can cause unexpected glares or uneven illumination on the fruit surface irrespective of the optimized lighting condition. Different methods of imaging techniques have been used in grading systems to measure the size, color, shape,

FIG. 13.8 Examples of robotics application in the fruits and vegetable processing industry such as (1) picking and placing of apples, (2) cutting of onions, (3) color-based classification of tomatoes, and (4) grading of apples. *Source credit: (1) Robotics Plus, (2) The Spoon, (3) HortiDaily.com, and (4) INTECNO s.r.l.*

and defects of fruits and vegetables. The monochrome charge-coupled devices (CCD) are most commonly used for surface level detection. Whereas for the subsurface defects or quality estimation high-end measuring approaches using UV rays, X-rays, and computerized tomography are used.

13.4.1.1 Pick and place

In the fruit and vegetable industry, commercial pick-and-place systems are available that use object localization technologies to locate and pick objects. Dzitac and Mazid (2012) have proposed the application of cheap depth sensors like Xtion and Kinect (primarily used in gaming applications) for the sorting and packaging of various fruit and vegetables. The depth information obtained through these sensors provided flexibility to the robot and make object localization possible even without hardcoding the exact coordinates. This technology is expected to have a potential advantage in sorting and packing fruits and vegetables which do not need very precise depth location information as in the case of mangoes, tomatoes, oranges, pineapples, etc.

Most recently, Dewi et al. (2020) have attempted to develop a robot, imitating the human arm for the sorting of fruits. They considered red and green tomatoes and purple/reddish and green grapes for the experimental trials. In such a scenario grading and sorting are mostly done based on color and size which is achieved by employing a camera, the eye of the robot. The other component of the sorting robot was a proximity sensor attached to the end-effector to sense the distance between the end-effector and the fruit. The end-effector is nothing but the gripper which does the actual sorting according to the size and color of the fruits. The sorting, picking, and placing effectiveness was found to be higher for the tomatoes than the grapes, which varied in the range of 60%–90%. Surface illumination was observed to be the main culprit behind the lower effectiveness. For specific sorting requirements, image sensors are accompanied by weight sensors when the classification is done based on weight (Clement et al., 2012).

13.4.1.2 Primary processing

The primary fruit/vegetable processing like cutting, slicing, peeling, etc. are deliberately relied on human workers due to their flexibility in handling and manipulating the food products. These labor-intensive processes have huge possibilities for upgradation through automation and robotic intervention. However, the primary requirement for achieving this goal would be the understanding of the geometrical deformation of the fruit/vegetable as a function of the applied forces during handling and processing. Hence, the developed setup for the handling of fruit/vegetables should respond following the induced deformation. Davis et al. (2008) have attempted an innovative approach for handling freshly sliced tomato and cucumber to be implemented in a continuous sandwich-making line. They studied the effectiveness of the gripper through the development of a robot cell. The gripper was used in combination with an ABB Flexpicker robot and a vision system that aided vegetable slices to be automatically placed on the loaf of bread. The processing speed of the developed robot was over 40 slices per minute which surpass the contribution of two human workers. Peeling and grading of leeks is another example of an application of robotics in the primary processing of vegetables. Kondo (2013) had elaborated on the robotic intervention in the peeling of leeks. A synchronized cutting, cleaning, and binding operation took place in a continuous processing line to produce various grades of leeks based on their weight. Such pre-processing systems were initially deployed in several Japanese agricultural facilities.

13.4.1.3 Classification

The need for robotic grippers in the fruits and vegetable sector is not just limited to holding and processing but also expands its territory into the measurement of some of the physical properties as well. However, the ultimate application remains grading and classification. Talens (2014) had worked on a pneumatic robot gripper with a target to classify mangoes based on their firmness. Although pneumatic gripper is common but considering the importance of the texture and firmness of any fruits/vegetable, specific care needs to be taken while designing the gripper. Moreover, the peel and pulp firmness vary during the storage period which imposes further challenges in finalizing the threshold vacuum level. Generally, the fruit is grasped with a suction cup capable of generating a suction force of around 60 N which can be sufficiently large to suck the inside out of any soft fruit (Flemmer and Flemmer, 2011). In his experiments, Talens (2014) had used the gripper inertial sensors which could classify the mangoes into three destructive firmness categories, with an accuracy of 93.6%. Another popular application of vacuum grippers is handling frozen hamburgers with robots.

Rice (2008) reported about FlexPicker robots which can efficiently handle up to 150 burgers a minute and place them into cartons. Besides, in the larger picture, such application has a narrow scope as not just the variation exists among the variety of fruits but there is also variation within the same bulk of fruits. To address this situation a universal robotic gripper is required which can be used to handle delicate food products with varying shapes. Pettersson et al. (2010) had designed a novel magnetorheological robot gripper targeting similar applications in mind. The robot gripper developed by them was mounted on a six-axis robot utilizing the effects of a magnetorheological (MR) fluid for grasping purposes. The grippers were pouches filled with MR fluids that experience increased yield stress when a magnetic field is applied. The regulated yield stress within the pouches containing MR fluid helps in gripping as the gripper is molded around the object, irrespective of size and shape. Most importantly the gripped object encounters a minimal force in such an arrangement. In the specific study by Pettersson et al. (2010) a KUKA KR5 Sixx six-axis robot (Augsburg, Germany) was used for the pick and place tests, and an overhead mounted Cognex In-Sight 5400 camera (Natick, MA, USA) was used for vision data acquiring. The gripper sends gripping information to the robot when the product is secured in the grip to carry out the grading and sorting operations.

13.4.1.4 Grading

For grading and packaging operations, robots are being used extensively. The last two decades have experienced significant innovation around the performance of the robots which are now capable of achieving a standard cycle in 300 ms. Such performance, however, could not be realized with fruits/vegetable grading as both the pickup and release steps require extreme precision to maintain the integrity of fruits. Kondo (2009) explained an automated fruit grading system consisting of a "providing" robot for placing and orienting the fruit and a grading robot that investigates any form of surface injury by rotating the fruit while capturing images. One of the major problems encountered during fruit packaging is the unstable positioning of the fruits within the holding pockets as the fruit tends to roll over owing to its shape. That is why the fruit must be placed in the tray and allowed to settle before initiating the next phase of picking. But, on the flip side, the above consideration increased the processing time, and at this speed, the commercial implementation of robots gets impacted due to unacceptably long payback time. However, the cycle time can be improved if several fruits are picked up together. Flemmer and Flemmer (2011) have cited one such work in which a robotic packing arm with a 36-suction cup end-effector was designed to pick up and pack a full tray of kiwifruit. Besides, such arrangements are technically challenging to configure, and the packing is inherently inflexible.

The International Federation for Produce Standards (IFPS) assigns a Price look-up (PLU) code to items such as fruits, vegetables, dried fruits, herbs, and nuts to identify the type, variety, and size of conventionally grown produce. These four-digit codes are printed over a small sticker which is applied on the surface of every individual produce. Most recently Liu et al. (2019) have developed an innovative robotic system for laser marking on fruits as a substitute for applying stickers which have been in practice. Their developed setup consists of six components, i.e., compliant gripper, robotic arm, machine vision module, laser marking unit, conveyor, and a robot controller. The compliant gripper was 3D-printed fingers made up of flexible thermoplastic filament. A topology optimization technique was used to design these fingers. The fingers are mounted over a vertically moving platform to provide displacement input for the gripper. Followed by the displacement input the compliant gripping fingers deform elastically in a rhythmic fashion to grip the fruits and place them on a moving conveyor. The fruits carried through the conveyor get inspected by a machine vision setup which guides the robotic arm to move the fruits to the laser marking unit where the PLU code is printed over its skin. This approach is more sustainable than the existing sticker application method and expands the opportunities for robotic intervention postharvest handling of fruits and vegetables.

13.4.2 Cereal grain and nut processing industries

The application of robotics in cereal grains handling is quite limited mostly due to the high processing capacity. The sorting of grains is the only process practiced in the grain industries which can be linked to robotic intervention. Optical sorting is the technique used for sorting a vast quantity of grains on a commercial scale. The optical sorting machines consist of a camera or lasers and a noncontact ejector. The former is responsible for the detection of defective grains whereas the latter is meant to separate the defective grains from the good ones. The first of its kind optical sorter was invented by E.H. Bickley during the early 1930s for the sorting of beans (Eisinger, 1999). Currently, a UK-based company called Buhler Sortex Ltd. designs and manufactures several optical sorting machines to deal with a range of products such as cereal grains, pulses, coffee, nuts, etc. Because of their high handling capacity and hygienic operating environment, these machines are hugely popular (Hamid et al., 2013).

13.4.2.1 Cereal grains

Among the cereal grains, rice was the first to be sorted on a commercial scale and it remains the largest market for optical sorting machines. The optical sorters are expected to detect defects such as yellow grains, chalky kernels, under-milled grains, and mud balls. However, the major use of these machines revolves around separating the darker grains from high-quality polished rice intended for export. To deal with the high processing capacity in rice mills the grain is made to pass through the sorters in two passes. With technological advancement, highly sensitive and responsive sensors have been developed which led to improving the capacity of the sorter by five times in the last four decades (Hamid et al., 2013). Apart from rice, there are other cereal grains like wheat and rye which are now sorted using the optical sorter for some specific processing needs. For example, rye is sorted to remove ergot whereas wheat is sorted for the production of breakfast cereals. Recently, two University of Nebraska-Lincoln graduates have built a grain bin robot that can detect grain weevil and limits farmers' exposure to bin dangers (Fig. 13.9A). Further technology transfer research is underway to validate its implications for different grain types/bins. With a clear-cut advantage of optical sorter over the conventional mechanical sorter, a wider application of this technique is expected in the coming days. Similar to the previously discussed robotic application in fruits and vegetables, the color sorter used in the grain industries consists of an optical and ejection system. The grain is fed into the machine in a continuous flow where the optical system captures the images of every single grain moving in the stream. The captured images are then analyzed by an image processor which ultimately identifies the location of the defective grain in the free-falling stream of grains and a signal is sent to the ejection system to separate the unwanted grain. The ejection system is an assembly of ejectors that can be fired independently in the form of compressed air to deflect the defective grain from the normal trajectory of the falling grains. However, such a non-contact ejector is

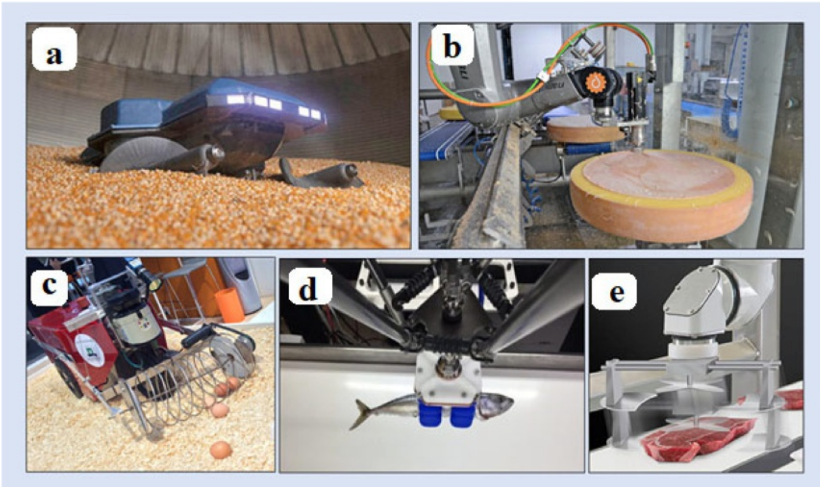

FIG. 13.9 Application of robotics for (A) grain management within storage bins, (B) de-rinding and coating irregularity in cheese, (C) eggs collection inside the poultry barn, (D) fish grading, and (E) meat processing. *Source credit: (A) AgUpdate, (B) BNP Media, (C) Institution of Mechanical Engineers, (D) Soft Robotics Inc., and (E) FANUC CORPORATION.*

useful for dealing up to a certain weight of the products beyond which alternative ejection systems such as flippers are used.

13.4.2.2 Nuts

In nut industries, mechanical injuries are a prime concern due to the hulling and shelling process. The traditional optical sorter was proven to be the better choice over the manual grading for removing the obvious defects which are visible to naked eyes. However, with the growing demand for safety, accuracy, and consistency, the nut producers are now expected to use alternate methods for separating defective elements like curly hull, in-shell, hard shell, etc. which are hard to detect with the traditional color sorter. This led to the introduction of IR sensors with a multi-channel optical sorting arrangement for improving the accuracy and capacity of sorting. Moreover, the response time of ejectors has drastically come down to 100 μs with the advancement of ejection systems. This evolution of optical sorters has revolutionized the almond sorting industry by substituting the involvement of hand pickers. The detection efficiency has further improved with the application of two sensor technologies, i.e., indium gallium arsenide (InGaAs) sensor technology and shape sorting technology.

In the case of walnut shelling, many of the nuts suffer mechanical injury leaving small broken and a sizable amount of product ranging between 2 and 15 mm. Even smaller pieces of shell that remain with the shelled nuts post shelling operation could be identified when the InGaAs technology was used in the optical sorting machine (Hamid et al., 2013). Nuts being a high-value product, is essential to prevent or minimize the nut fraction in the waste residue. That is why resorting to the rejected fraction is usually done which is also known as reverse sorting. Extensive research has been going on around the globe for the detection of various quality parameters in nuts using non-destructive technologies. This would be instrumental in the construction of next-generation robots deployed in nut processing industries.

13.4.3 Dairy processing industries

Dairy processing industries require intensive labor, raising the cost of production by 1.5 times. Human activity in dairy processing industries is more often quick, monotonous, and repetitive which subsequently leads to less motivation among the workforce, poor product quality, and prone to accidents. Automation and robotics play a major role in coming over all these drawbacks by performing the same tasks in a more precise and accurate way and that too in very less time as compared to humans.

The utilization of automation and robotics have been effectively accomplished in a wide scope of dairy processing industries managing well-defined processes and products (Hurd et al., 2005). Anyway, there are specific research challenges related to the utilization of robots in the dairy process industries (Peters, 2010). The first is that the items being dealt with are variable in size, shape, weight, and position so that some type of smart sensing will be employed. The second is that the product to be taken care of is often sensitive and covered with either elusive or thick substances, thus the end impact must be deliberately planned in the way that it deals with the product rapidly with secure lifting and without deforming. The third is cleanliness, quality, and consumer safety. However, all three difficulties have been acknowledged by current robots.

Automatic milking system (AMS) or milking robots are one of the best and significant use of robots in the dairy processing industries. Robotic milking allows the cattle to release milk according to their schedule making the process voluntary. Following an underlying preparing period, cattle are milked with restricted human interaction. In AMS, each cattle is fitted with an electronic label that permits the robot to recognize it.

At the point when a dairy animal enters the robot, her ID tag is perused and she gets a feed reward customized to her level of production. The robot at that point cleans the milking portion, joins the milk cups, and starts the milking cycles. When milking is finished, the cups disengage in each quarter, get done with milking, and leave the robot (Butler et al., 2012; Higgs and Vanderslice, 1987). The Swedish dairy equipment company DeLaval introduced the world's first commercial robotic milking machine at a pilot farm at Quamby Brook, Tasmania, Australia which has a capacity of milking 90 cows per hour with the help of five robots (Legg, 1993).

Extensive use of robotics has also been reported in cheese packaging, slicing and curd slicing, etc. Robots stir curd, transfer cheese molds, cut, turn, package, and palletize cheeses. Cheese portion multiplexing is one of the latest inventions in the use of robotics in the dairy industry making 12,000 portions/h, in more hygienic conditions than in manual operations, with high productivity (Fig. 13.9B).

Coordinated sensors and estimating frameworks empower the basic usage of complex cycles. Squares of cheddar show up on wooden boards at the robot picking region. The uncommon gripper permits the cheddar squares to be picked and put onto transport for additional handling. Cheddar divide multiplexing is probably the most recent development in the utilization of mechanical technology in the dairy industry. The robot can make up to 12,000 parts for every hour. They are discovered to be more sterile than manual activities and have high profitability that could result in a rate of profitability under a half-year (Iqbal et al., 2017).

13.4.4 Egg, meat, and seafood processing industries

13.4.4.1 Egg processing industries

Robots have now become indispensable for modern egg processing industries. Among different assignments, robots feed the winged animals; transport, handle, and pack eggs; and oversee shed ventilation. Integrated conveyor belts to collect and move eggs to the packing zone are a nice example of robotics application in the modern egg processing industry.

Conveyor belts wipe out the need to deal with eggs, which is particularly significant in present-day sheds with layered pens. Egg assortment utilizing transport lines likewise diminishes chances related to manual egg assortment at statures and under the low intensity of light. For instance, gathering, checking, reviewing, and pressing eggs has been generally mechanized in the cutting-edge egg processing industry (Fig. 13.9C). Robotics is likewise applied to control the shed chamber temperature and humidity. Completely robotized frameworks are constrained by a computer that screens different sensors for temperature, humidity, gas levels, etc. Ventilation is maintained by the computer to keep up the natural boundaries inside the ideal solace levels.

A robot used in the egg processing industry ranges from semi-automatic to fully automatic. The conveyor belt system is a good example of a semi-automatic system where it can automatically count the number of eggs passing a particular point but does not decide on how it should operate. The fully automated system contains sensors around the egg collection belt to screen the weight of eggs at an explicit place such as around nest boxes. The data is used by the robot's computer control framework, which is programmed to count eggs at a specific area dependent on the egg's weight. Extra eggs superseding the prescribed limit increases the risk of cracking or breaking the eggs in the nest boxes. The robot is programmed in such a way that it senses the overweight and moves the egg collection belt further to avoid the risk of breakage thus reducing poor product quality and quantity. The fully automated robots in the egg processing industry also include artificial intelligence, aided by computer vision capabilities.

13.4.4.2 Meat processing industry

Robots play a significant role in meat processing industries, reducing the cost of production and occupational injuries and increasing hygiene and process efficiency at the same time.

The strength of advanced robotics, especially in boning rooms where work costs are high, is in their capacity to play out the necessary monotonous errands more effectively and reliably than is as of now possible (Food Science Australia).

Advanced imaging technology and a robotic cutting arm are used by Georgia Tech researchers to automatically debone chicken and poultry products. The robot uses the intelligent slicing and deboning of poultry meat as it avoids any bone chip in the meat pieces thus ensuring maximum meat yield and food safety (Fig. 13.9E). The use of robots in beef production included splitting the whole carcass into different shapes of sides. The Meat Industry Research Institute of New Zealand (MIRINZ) has used robotics and automation in sheep and lamb slaughtering. A series of sophisticated robots have been used for the automation of the pig slaughter line process by SKF-Danfotech, a Danish company in cooperation with Danish Meat Research Institute (DMRI). The automation and robotics involved in Pig slaughter line, slice, pack, and ship the product to the customer after deboning and cutting the meat. Robots with vision sensors are cutting the time taken to ascertain the accurate cutting and deboning of pieces, their hygienic packing, and hustle-free transportation.

13.4.4.3 Seafood processing industries

The food industry has relatively less involvement in automation and robotics as compared to other industries and the same is true for seafood processing industries. There has been constant effort to equip automation and robotics in fish processing companies to achieve products quicker with low energy consumption, higher product throughput, and better quality. The seafood processing industry still uses many semi-automatic machines that operated only when there is regular assistance from the operator. The reason for the non-adoption of robotics in seafood processing industries may be due to several reasons, one being the low profit margin and unavailability of technically skilled manpower. The other reason for the poor involvement of robotics in the seafood industry is the variability of product shape, size, and structure which is the main hurdle in developing sensors and manipulators (Litzenberger, 2009).

Seafood processing industries require machines and equipment to be hygienic and can withstand the environmental condition where they are processed. This makes the development of robotics in this sector to be costly. The moist condition of the processing area poses a bigger challenge for robots than temperature and thus restricts their use of it. The robots equipped with conditions to work in more humid conditions and satisfy the cleanroom standards are 10%–20% costlier than the traditional industrial robots. In the fish handling industry, diverse creation zones have distinctive cleanliness reviewed levels. In high-hazard zones, severe cleanliness prerequisites are set for the gear, offices, and administrators. Robots and holding instruments, as other hardware, should be planned to utilize clean plan standards, being effectively launderable by utilizing both basic and acidic cleansers. One arrangement is that the robot might be canvassed in a plastic cover to improve the cleaning (Chinello et al., 2011).

Kinds of seafood including fish and many marine animals are processed in a continuous phase where the product is moved down in a manufacturing line to be handled in both ways, i.e., manually and mechanically (Fig. 13.9D). The innovative approach of integrated machine learning, artificial intelligence, and image processing can help in developing automation and robotics solving grading, inspection, and processing tasks. The robotics in seafood processing industry has manifold advantages such as:

- **i.** less floor space
- **ii.** improved efficiency
- **iii.** Improved handling and maintenance operation
- **iv.** increased yield and reduced wastage
- **v.** enhanced consistency and flexibility of operations.

13.4.5 Food packaging

Robotics and automation have been widely and effectively used by numerous food packaging manufacturers including meat, poultry, dairy, seafood, dessert, snacks, and beverage industries (Purnell, 1998). The use of robotics in packaging industries includes handling unwrapped products, placing and filling products at the desired place, loading and unloading products and arranging them in arrays, and last but not least palletizing and depalletizing beverages cans, bulk containers, cases, bundles, bags, etc.

Two-axis packaging, four-axis palletizing, and six-axis palletizing and handling robots are typically involved in picking up, packaging, and palletizing products in food industries. The robots used in these operations are robots with conventional applications and are a little different from robots in different industries in hygienic design and high-speed operations (Fig. 13.10). Most of

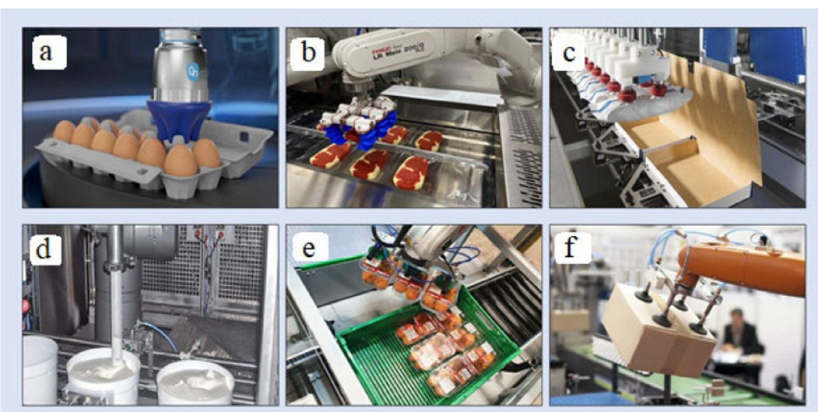

FIG. 13.10 Robotics in packaging applications such as (A) packaging of eggs, (B) meat packaging, (C) snack and bakery products packaging, (D) ice-cream packaging, (E) fruits packaging, and (F) bulk packaging and palletizing. *Source credit: (A) Endeavor Business Media, (B) PMMI Media Group, (C) Bosch, (D) Stäubli International AG, (E) RMGroup, and (F) READY Robotics.*

the food packaging robots now feature IP-67 which helps in providing dust-free operation. They can also work under high humid conditions. The smooth surfaces of these robots give no chance for contaminants to retain over its body. Companies like Raymond Clavel, Fanuk, and KUKA have launched a series of robots in packaging manufacturing in the last few decades. Raymond Clavel in the early 1980s developed "Spider" robots that could pick and place light objects (<1 kg) such as cookies. Fanuk had launched five-axis M-430iA/2 F in 2006 having the capability of high-speed picking and packing and operating up to 120 cycles/min with 1 kg payloads. KUKA robots are featured with IP protection, food-grade oil in the reducers, white coating to withstand industrial sanitizers, and a stainless-steel control cabinet. Similarly, LR Mate 200iB is equipped with a vision/sensor which can weigh and measure the product dimension to assess their density.

Robotics and automation provide numerous advantages like increased efficiency, hygiene, output rate, flexibility, and reduced cost of operation. Despite all the development in automation and robotics, there are numerous challenges to overcome in the food industry which mostly deal with heterogeneous raw materials.

13.5 Limitations in industries and future scope

The biggest concern in today's ever-growing globalization is to keep up the pace with increasing job prospects. Industries are and will always have to comply with the trade-off between automation and manual labor irrespective of the economic aspects of a country (how developed it is). Though the agriculture domain has seen some innovations over the last two decades in the uplifting of the initial step in the process of "farm to fork," the major concern still lies in maintaining the hygiene standards during the food processing step. With increasing demand that runs parallel with the increasing population, the industry throughput and safety principles have to be adhered to according to the strictest policies. These aspects can only be maintained if frequent safety checks are conducted on the robotic end-effectors that come in direct contact with the food material. Unlike in automobile industries, these end-effectors have to undergo feasibility studies that will explore the potential of developing relatively safe (GRAS) and low-cost devices that are compatible with variable food geometry and properties. However, sensors are always subjected to constant developments. Potential innovation aspects in the field of the feasibility of robots in the food industry could be as follows:

i. Currently, the commercialized platform only includes grippers that are mainly used for food packaging purposes. Articulated process tools such as cutters, peelers, or other essential tools for unit operations are still used on a basis of a semi-continuous system, and their inclusion as an end-effector/business tool could re-shape the industrial output to a new level. Such a concept could be useful in lower to medium production runs while addressing the minimization of water requirements, adhering to de-contamination procedures, and perfecting hygiene operations.

ii. To make the above process more tangible, hybrid systems could be proposed where sensor feedback could be incorporated into process tools. This will allow self-learning leading to efficient decision-making in real-time processes and sometimes act as an interface between the target and the end-effector.

If the above-stated concepts are successful, such EOATs will be a critical addition to the rising array of effective robotic systems now used in the food industry, to meet the miscellaneous demand of its engineering profile.

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