10

Food engineering

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Key points

- Food engineering involves a detailed study of numerous unit operations and a fundamental understanding of momentum, heat and mass transfer relevant to food processing.
- This chapter introduces concepts relevant to the hygienic design of equipment used for processing, handling and storage of foods, application of common process control systems, and approaches used in handling wastewater generated in a food processing plant.
- These topics are presented in sufficient detail to gain an appreciation of the important role of engineering in selected aspects of food processing.

10.1 Engineering aspects of hygienic design and operation

In a food processing plant, raw food is converted and processed into desired products using a variety of equipment. In designing food processing equipment for any given purpose, an engineer must consider numerous criteria that are inherent to a process. For example, in designing a heat exchanger, one must consider the heat transfer, fluid flow, and various physical, chemical, and biological changes occurring in a food. Furthermore, an underlying criterion in designing food processing equipment is the sanitary design. Each equipment and product in a food processing plant must adhere to some unique requirements to ensure sanitary operation. There are several general sanitary requirements that are common to most equipment design. In this section, we will consider many of these considerations that a food engineer must carefully address whenever designing food processing equipment. More details on topics presented in this section are available in Jowitt (1980) and Ogrydziak (2004).

10.1.1 Food process equipment design

Hygienic design of equipment is essential in a modern food processing plant. A major concern in processing foods is to prevent microbial contamination that may be facilitated in poorly designed equipment. Such equipment is difficult to clean or may require longer cleaning times and more use of chemicals. The key principles of hygienic design are as follows:

- Use materials of construction that are suitable for hygienic processing of food.
- Product contact surfaces must be easily accessible for inspection and cleaning.
- Incorporate design features that prevent harboring microbial accumulation and their growth.

To ensure clean food processing equipment, the product contact surface has an important role. If the surface is rough and/or porous it will most likely allow food particles to build up and it will be more difficult to clean when compared with a smooth, polished surface. The contact surface must not chemically interact with the food and its ingredients. It should be free of corrosion and it must be inert to the chemicals used during cleaning.

If the contact surface is hidden during visual inspection, it would be impossible to know whether it is properly cleaned. Therefore, all contact surfaces must be accessible during inspection and cleaning. In some cases, it may require complete disassembly; in other circumstances ports for inspection may be strategically located. Often, access doors are provided to inspect the contact surface. The door fasteners should be easy to open without the use of tools; quick release type fasteners are preferred. Many of the small equipment such as pumps should be installed 15 cm or more from the floor, whereas larger pieces of equipment should be elevated 30 cm from the floor so that the floor areas under them are easily cleaned. Sealing process equipment to the floor should be avoided as sealants (such as caulking) crack over time.

The noncontact surfaces should be designed to prevent accumulation of any solid materials. These surfaces should prevent any absorption of liquids or water.

Motors used to power equipment should be placed where any lubricant used in the motor does not contaminate the product. Direct drive systems are generally preferable. While drip pans may be used, they should be avoided as much as possible by using a direct drive system. Another source of contamination in drive systems is bearings. Use of food grade material such as nylon, sealed or self-lubricating bearings are preferable. Additionally, seals should be nontoxic and nonabsorbent. It should be easy to remove seals for inspection and sanitation purposes. Hoods used to exhaust steam or dust collection should be easy to clean. For processing liquid foods, kettles should be of the self-draining type. For kettles equipped with mixers, the mixer lubricant should not enter the product.

If steam is to be directly injected, then any additives used in the boiling water must be food grade. Compressed air coming into contact with food or food contact surfaces must be free of dust, pollens, and lubricant oils. Many lubricants used in compressors are toxic. Filters placed on the discharge may be necessary to prevent any dust or pollen. Desiccants and filters are useful in removing undesirable materials.

10.1.2 Construction materials

Numerous materials are available to fabricate food processing equipment. However, each material has its advantages and limitations, and these should be carefully assessed prior to their selection. For product contact surfaces, the interaction between the product and contact surface must be carefully evaluated.

10.1.2.1 Stainless steel

This is the most common material used for fabricating food processing equipment. Stainless steel is an alloy of iron and chromium. When chromium is added to iron in excess of 10%, it imparts resistance to corrosion. Additional elements are added for specific purposes. In reference to food processing equipment, an 18-8 grade (18% chromium and 8% nickel) is ideal in the fabrication of processing equipment. Within the 18-8 grade, there are different types that impart special properties:

- Type 302 is used for outside surfaces mainly for appearance.
- Type 303 has additives such as S and Se. It is mostly used for fabricating shafts, and castings. Its precipitates are harmful.
- Type 304 is less susceptible to corrosion. It is used in tubing and in situations where mild corrosion is anticipated.
- Type 316 is highly heat resistant and it has superior corrosion resistance. When severe corrosion is anticipated, type 316 is most suitable. When processing equipment is to be used for high temperature processing, then type 316 is more durable.

  There are different types of finishes available for stainless steel. A flat finish, referred to as 2 B finish, is available as standard from steel mills, whereas numbers 6 to 8 refer to highly polished finish.

10.1.2.2 Titanium

Titanium is a light weight (approximately 44% less than stainless steel) but very strong metal. It is resistant to corrosion.

10.1.2.3 Inconel

Inconel, an Ni-Cr alloy (containing 77% nickel and 18% chromium), is more ductile than steel and it is resistant to corrosion.

10.1.2.4 Mild steel/iron

This is used for non-contact surfaces or products such as dry ingredients and syrups. Steel and iron corrode in such applications.

10.1.2.5 Aluminum

Aluminum reacts with hydrochloric acid and caustic solution. It is a soft material and easily subject to gouging and scratching. Aluminum is used for certain butter and dry product applications. It should not be used when cleaning requires strong caustic solutions or corrosive action of dissimilar metals.

10.1.2.6 Brass/copper/bronze

These may corrode when cleaning chemicals are present. Also, they may impart undesirable taste and flavor to the food, which may be problematic. As a result, brass or bronze are not acceptable for product contact surfaces or surfaces that may come into contact with cleaning solutions. However, in nonfood contact areas they are acceptable.

10.1.2.7 Plating materials

The use of plated metals should be carefully evaluated. For example, galvanized iron (iron coated with zinc) is unsuitable for juice, as the fruit acids can dissolve zinc. However, for framework applications it may be quite suitable.

10.1.2.8 Tin

Tin is extremely resistant to corrosion, but it is soft and easily scratched.

10.1.2.9 Cadmium

Cadmium is toxic and any cadmium-plated surfaces including fasteners should not be used.

10.1.2.10 Glass

Glass should be avoided and replaced with polymeric materials. Glass is used only when there is a demonstrated functional need. In that case clear, heat-resistant and shatter-resistant type of glass is used.

10.1.2.11 Wood

Wood should be avoided as splinters and slivers can cause problems.

10.1.2.12 Wire

Wire should be of materials that have magnetic properties so that metal detectors can effectively remove it along the processing line.

10.1.3 Construction features

During equipment fabrication, several construction features require careful attention to avoid locations for insect infestation or product soiling that is difficult to remove during cleaning.

- Lap seam: insects may harbor in tiny cracks, crevices, and where one piece of metal is spot welded onto another. Weld material should be ground. Metal ends should butt together.
- Ledges: contact zone ledges must be avoided where product may accumulate.
- Void areas: spaces that are difficult to access for cleaning, where insects may harbor, must be eliminated and sealed.
- Dead ends: dead ends in pipes and screw conveyors may trap product and therefore they must be avoided.
- Rolled edges: rolled edges are necessary to strengthen the edge of sheet metal. If the rolled edges are not properly sealed then they may harbor bacteria.
- Rounded corners: corners should be rounded to be easily cleaned.
- Coves: corner welds should be ground smooth.
- Seams: it is preferable to have continuously welded joints to avoid seams.
- Cracks: continuous welding should be used. Any caulking may be used in nonproduct contact surface areas.
- Frames: use of tubular shapes is preferred to avoid excessive dust collection. Horizontal framing members should be at least 12 inches from the ground.

- Product zone welds: these should be continuous. For milk, and egg processing equipment, a ground flush finish is necessary.
- Caulking materials: silicone for sealing crevices or exterior nonproduct contact surface only may be used. Caulking is not acceptable for product contact surface.
- Paint: only nonproduct contact surfaces may be painted. Those parts that have both product contact and nonproduct contact are subject to washing and should not be painted.
- Lubricants: where a lubricant may come into contact with food, only those given in 21 CFR Part 178-375 (US FDA) are permitted. For example, a light coat of mineral oil on rolls may be used to prevent the sticking of cheese.
- Finish: smoother finish results in easier cleaning of the surface. The product contact surfaces are milled or polished to a high degree of smoothness that prevents microbial adherence. The most recommended surface finish is number 4. A number 4 finish has a maximum Ra of 32 micro-inches or 0.8 microns. Ra number is the average height of roughness expressed in microns or micro-inches. The welded junctions are also ground and polished to number 4 finish. A 150 grit silicon carbide, when properly applied to stainless steel, is equivalent to number 4 finish.
- Gaskets: for junctions containing gaskets, there should be no tight recesses or protruding unsupported gasket material that may harbor microorganisms.
- Fasteners: wing nuts, "T" nuts, or Palm nuts are preferable over hex or dome nuts. The fasteners must facilitate easy cleaning and dismantling. Exceptions are made where vacuum, pressure, or safety issues are involved.

10.2 Cleaning and sanitizing

Cleaning and sanitizing in a food processing plant involves a number of steps. The first step is to remove any gross soil. Then a chemical agent is used to remove any visible soil residues. Next, a rinse of a cleaning agent is used. The rinse is followed by the use of a sanitizer that assists in killing, removal, or inhibiting any microorganisms. If necessary, a final rinse cycle may be used to remove the sanitizer.

Cleaning is influenced by temperature, time of cleaning, concentration of chemicals, and the mechanical action used in cleaning. Use of higher temperatures during cleaning of fat and grease is beneficial; however, it should not be excessively high to cause protein adhesion to a surface.

The various types of soils from food are shown in Table 10.1 based on their solubility in water. Many properties of soil are important in determining the ease or difficulty in removing it, for example, particle size, viscosity, surface tension, wettability, solubility of a liquid soil in a solid soil, the chemical reactivity with the substrate, the attachment of soil to a surface or entrapped in voids, and any forces such as cohesion, wetting, or chemical bonds that influence the attachment.

The selection of a cleaning compound depends upon:

- the type of soil on the surface;
- the type of surface to be cleaned;
- the amount of soil on the surface;
- the method of cleaning (such as soaking, use of a foam, or clean-in-place);
- the type of cleaning agent – liquid or powder;
- the quality of the water;

Table 10.1 Various types of soil from foods and the detergents used to remove them (adapted from Katsuyama, 1993).

Type of soil (from food)		Detergents used
Water soluble	Sugars, salt, organic acids	Alkaline (mild)
	High protein foods (meat, fish and poultry)	Chlorinated alkaline
Partly water soluble	Starchy foods, tomatoes, fruits and vegetables	Alkaline (mild)
Water insoluble	Fatty foods (fatty meats, butter, margarine, oils)	Mild or strong alkaline
	Stone forming foods: mineral scale from milk, beer and spinach	Chlorinated or mildly alkaline, alternated with acid cleaner each 5th day
	Heat-precipitated water hardness	Acid

Table 10.2 Various types of detergents used in cleaning food processing equipment (Ogrydziak, 2004).

Detergents	Advantages	Disadvantages
Water	Water effectively dissolves sugars and salt Use of high pressure (600–1200 psi) water is effective in removal of many soluble and insoluble solids	Limited use in cleaning
Alkaline	In presence of fats, it produces soap In presence of denatured proteins, it produces soluble peptides	Corrodes aluminum, galvanized metal and tin Rinses poorly Causes precipitates to form in hard water
Strong alkalis (NaOH)	Strongest detergent Low cost Good germicidal value	Very corrosive to nearly all surfaces including metal, glass and skin Rinses poorly No buffering capacity Poor deflocculating and emulsifying power
Mild alkalis (carbonates, borates, silicates, phosphates)	Moderate dissolving power Less corrosive than strong alkalis	
Soaps (Na^+ or K^+ of fatty acids)	Effective in washing hands in soft water	Not very soluble in cold water Limited use as cleaner in food plants
Acids	Dissolve mineral deposits, hard water stone, beer stone, milk stone and calcium oxalate Some acids are sequestering agents Used at pH 2.5 or lower (0.5% acid)	Not effective against fats, oils and proteins
Inorganic acids (hydrochloric, sulfuric, nitric, phosphoric acids)	Used with corrosion inhibitors Phosphoric acid is used for hard water films on tile	Hydrogen ion is corrosive to metals especially stainless steel and galvanized iron
Organic acids (acetic, lactic, citric)	Not as corrosive as inorganic acids Causes less irritation of skin Citric, tartaric and gluconic acids have chelating properties Used with corrosive inhibitors	

- the amount of time available for the cleaning cycle;
- the cost of the compound.

Cleaning involves first the separation of the soil from the surface, followed by dispersion of the soil in the detergent medium. It is important that the soil must not redeposit on the surface.

The effectiveness of a detergent is evaluated based on its:

- penetration and wetting ability;
- control of water hardness;
- efficient removal of soil;
- ease of rinsing;
- noncorrosiveness to the surface.

The desired properties of detergents are obtained by proper mixing of selected chemicals. Various types of detergents and their key characteristics are noted in Table 10.2.

10.2.1 Sanitizer

A sanitizer used in the food industry must produce a 99.999% (or 5 log) reduction in populations of 75–125 million *Escherichia coli* and *Staphylococcus aureus* within 30 s at 20°C (70°F). The purpose of using a sanitizer is to destroy pathogens or other organisms on a clean surface. Furthermore, the sanitizer should not adversely affect the equipment or the health of the consumer.

Sanitizers may be classified as physical and chemical. Some of the commonly used physical

Table 10.3 Physical sanitizers used in food processing equipment (Ogrydziak, 2004).

Physical sanitizers	Typical treatment	Comments
Steam	15 min at >= 170°F or 5 min at >= 200°F	
Hot water	Immersion for 5 min at 170°F	In practice, use > 180°F for > 15 min for large pieces of equipment
Hot air	> 356°F for > 20 min in hot-air cabinet	Measure temperature at the coldest zone
UV light	Limited to translucent fluid streams	Used for treating bottled water

sanitizers used in food processing are shown in Table 10.3.

A large number of chemical sanitizers have been developed specifically for the food industry. Some of the more common chemical sanitizers are as follows:

- Hypochlorites: one of the most widely used sanitizer in the food industry is the liquid form of sodium hypochlorite. Microbes are destroyed by hypochlorous acid (HOCl).
- Chlorine gas: when chlorine gas is injected in water, hypochlorous acid is formed. Since the solubility of gases decreases with increasing temperature, its effectiveness in high temperature applications should be carefully examined.
- Chlorine dioxide: chlorine dioxide gas is widely used in treating process water for fruits and vegetables at concentrations up to 1 ppm. It is more effective than hypochlorous acid under alkaline conditions up to about pH 10. Often, chlorine dioxide is produced on site and it is an expensive method of sanitizing.
- Organic chlorides: organic chlorides form hypochlorous acid at a slow rate. Their rate of microbial kill is also slow.
- Iodophors: an iodophor contains iodine and a surfactant that acts as a solubilizing agent. When mixed with water, iodophor releases free iodine at a slow rate. Often, iodophors are blended with phosphoric or citric acid to ensure optimal pH (4.0–4.5). Iodophors are effective sanitizers for a large range of microorganisms but less effective against spores and bacteriophages. They may stain plastic and uncleaned stainless steel surfaces. In diluted form they are nontoxic.
- Acid–anionic surfactant compounds: these compounds include anionic surfactants and acids such as phosphoric or citric. They are stable at high temperature but are ineffective at pH above 3.5. In dairy processing equipment, they are effective in controlling milkstone (a carbonate formed during the processing of dairy-based products), and they are noncorrosive to stainless steel.
- Fatty acid–anionic surfactant compounds: fatty acids such as octanoic and decanoic are used along with surfactants. They are notable for causing reduced foam.
- Peroxyacetic acid sanitizers: these include an equilibrium mixture of hydrogen peroxide, acetic acid, and peroxyacetic acid. They break down into oxygen, water, and acetic acid. They are effective against a broad range of microorganisms including spores, viruses, and molds. They are effective at cold temperature.
- Quaternary ammonium sanitizers: also referred to as "quats," these sanitizers involve a cationic surfactant molecule combined with a chlorine anion. They are stable at high temperatures and effective over a broad range of pH and in the presence of organic matter. They are not compatible with chlorine sanitizers. If the concentration of quats is less than 200 ppm then no water rinse is required after treatment.
- Sequestering agents: these compounds form soluble complexes with metal ions. Their primary function is to prevent film formation on equipment and utensils. Common chemicals used for this purpose include tetrasodium pyrophosphate, sodium tripolyphosphate, and sodium hexametaphosphate. Phosphates are unstable in acid solutions.
- Wetting agents: wetting agents are used to wet surfaces. They can penetrate crevices and woven fabrics. Anionic wetting agents act as emulsifiers for oils, fats, waxes, and pigments. Examples are soaps, sulphonated amides, and alkyl-aryl sulphonates. Some of these agents foam excessively. Nonionic wetting agents such as ethylene oxide-fatty acid condensates are excellent detergents for oil. They may be sensitive to acids.

Table 10.4 Cleaning related items in and around a food processing plant (Ogrydziak, 2004).

Zone	Specific items	Items that require attention during cleaning
Outside the factory	Grounds	Weeds are harbors of pests such as rodents
	Parking areas	Dirt and weeds introduce contamination into plant
	Waste disposal	Odor, food source for pests, rodents
Receiving area	Containers	Any residual food product that will attract pests
	Silos, tanks, bins	Any residual organic matter and encrusted product that may serve as food for pests
	Floors, gutters, walls	Any residual raw material, cracks, or crevices
	Construction materials	Peeling paint, rust, corroded parts
	Loading docks	Dirt, filth, broken wood, plastic, splinters
	Freezers and coolers	Dirty drains, cracks in walls
Preparation	Flumes	Any product residue, biofilms
	Belts, conveyors, elevators	Any food residues or organics
	Washers	Grime and residual food, dirt, organics
	Peelers	Product residues, grime, organics
	Slicers	Product residues, fats, oil and grease
	Floor, gutters, walkways	Dirt, crevices, cracks
	Insect and rodent control	Cracks, access areas, gaps
Processing	Conveyors	Spaces between interlocking belts, underneath belts
	Tanks and pipes	Welds, CIP equipment maintenance
	Fryers	Oil filters, deposits in steam hoods
	Floors, drains, gutters, walkways	Bacterial infestation
	Hoods, filters, screens	Dirt
Packaging	Conveyors, packaging machinery	Dust, dirt
	Filters	Dust
	Tubing, piping, pumps	Surface dirt
Warehousing	Pallets	Rodent droppings, insects, splinters
	Floors and walls	Rodent droppings, spilled product
	Docks	Dirt, spilled products
	Trucks	Maggots under trailer floor, dirt

Cationic wetting agents such as quaternary ammonium compounds have an antibacterial effect. They are not compatible with anionic wetting agents.

In a food processing plant, cleaning extends both indoor and outdoors. Different areas inside the plant and surrounding areas require special considerations to keep them clean. Table 10.4 describes various items that should be considered in maintaining a clean environment in food processing plants.

Since food plants require frequent cleaning, dismantling equipment can be time consuming. To avoid long shutdown periods, it has become common to use the clean-in-place (CIP) technique. In a CIP system, pipework is cleaned by pumping water with appropriate detergent in a turbulent mode. Chambers, tanks, and other larger vessels are cleaned by installing spray balls or rotating jets. These devices ensure that every nook and corner inside the vessels is cleaned. After cleaning with detergent, sanitizers are used to disinfect the interior surfaces. With appropriate process controls, the CIP system can be operated in a completely automated mode after each shift.

10.3 Process controls

Process control may be defined as manipulation of process variables so that the desired product attributes are obtained. The variables employed in a process have a marked influence on the final attributes of the product. Therefore, an appropriate control of these variables is an important objective in food processing operations.

Advances made in computer technology since the 1970s have made it possible to automate process operations. By controlling process variables, the desired consistency of operation is achieved along with reduced costs of production and improvements in safety. When equipment begins to deviate from what it is designed for, automatic controls provide a higher level of consistency than if human intervention is allowed that often leads to higher levels of variability. The production productivity is enhanced as less out-of-specification product is produced. Automatic controls provide a higher level of screening of unsafe conditions to improve overall safety of the equipment.

10.3.1 A feedback process model

Consider a manual temperature control installed on juice being pumped through a steam heat exchanger. The temperature of the juice is the control parameter. The measurement device is a thermometer used to measure temperature. An operator decides whether the temperature is too hot or too cold. A steam valve is used to make adjustments. If the juice temperature is too high, then the operator adjusts the valve towards the closed position. This is an example of a negative feedback control, because a positive error requires a negative response from the operator. Initially the operator adjustment may be too large. When the desired set point is approached, the operator is able to make finer adjustments.

A simple feedback process model is shown in Fig. 10.1. The process variable is measured and compared with a set point, and this generates an error signal. For the given error signal, an algorithm is used to determine the type of control response. The control response manipulates the control element. Thus the control variable is modified and the loop is repeated. With decreasing error, the control response becomes smaller.

As shown in Fig. 10.1, the information flows through various elements of the control loop. The key elements of a control loop are described below.

10.3.1.1 Transducer

A transducer is a sensing element that detects the process variable. It converts the signal into some measurable quantity. Often the measurable quantity is an electrical signal. For example, a thermocouple receives information about temperature and converts it into a millivolt signal.

The output signal of a transducer may or may not be convenient to transmit for long distance. The modern control systems can accommodate a variety of signals, such as millivolt, frequency, and variation in current. The output signal may or may not be linear with respect to the measured quantity.

10.3.1.2 Transmitter

Transmitters help in converting the measured variable into a standardized signal. Often the variable is linearized to the measured signal. Typical output of

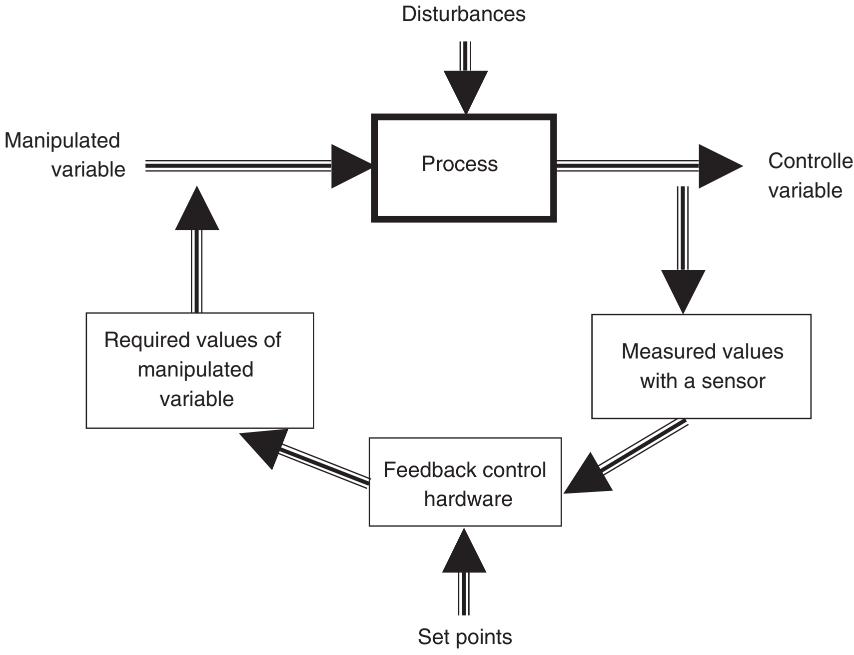

Figure 10.1 A feedback control system.

Table 10.5 Common sensors used in food processing operations.

Sensing parameter	Sensor	Range of application
Temperature	Thermocouple	
	Type J	–320 to 1400°F
	Type T	–310 to 750°F
	Type K	–310 to 2500°F
	Resistance temperature detector (RTD)	430–1200°F
Volumetric flow	Magnetic	Down to 0.01 gal/min
	Vortex-shedding	Down to 0.1 lb/min
Mass flow	Coriolis	Down to 0.1 lb/min
	Heat loss	Down to 0.5 cc/min
Density	Vibration	Down to 0.2 g/cc
	Nuclear	Down to 0.1 g/cc
Pressure	Strain gage	Down to 2 psi
Level	Differential pressure	Down to $<$ 1 inch of water column
	Capacitance	Point level to $>$ 20 ft
	RF impedence	Point level to $>$ 20 ft
	Ultrasonic	Several inches to 100 ft
Moisture	Infrared	1–100%
	Microwave	0 to $>$ 35%
Viscosity	Vibration	0.1–106 cP

a transmitter is 4–20 mA. Often a power source of around 24 V is used as a direct current source, and any other voltage generated due to electrical noise is usually not a problem as only the change in the current is measured. Within limits of the power source, devices may be driven by including them within the 4- to 20-mA loop.

10.3.1.3 Controller

A controller reads the transmitted signal and relates it to the set point. The controllers are able to handle a variety of electrical signals such as current, voltage, or frequency. In special situations where electrical circuits may cause hazardous conditions such as explosion, pneumatic controllers are used.

Digital controllers are used to convert analog to digital signals. The digital signal is read by a digital computer that processes the data and calculates the deviation of the transmitted signal from the set point. The digital controller then converts the digital signal received from the computer into an analog signal in the form of 4–20 mA; however, other output signals are also possible. The output signal is used to adjust the control element. In case of a current to pneumatic converter, the 4- to 20-mA signal is converted into a 3- to 15-psig output signal. In addition to controlling valves, other food processing devices may also be controlled such as a variable speed motor used to drive a pump.

10.3.1.4 Sensors

There are a wide variety of sensors used in the industry, as shown in Table 10.5. Several considerations are necessary when seeking a sensor for food processing application, including type of material contacting with food, range, accuracy, and cost.

In the case of CIP applications, it is important to make sure that no dead volumes are created around the sensor. Furthermore, sensor housing may require wash down, and therefore specifications call for an appropriate National Electrical Manufacturers Association (NEMA) rating of 3 (weatherproof), 4 (watertight), or 5 (dust-tight).

10.3.2 Process dynamics

Whenever a process is to be adjusted, certain factors may cause a delaying time before the system responds. These factors causing a delay in response time include the inertia, lag, or dead time.

Inertia is often associated with mechanical systems such as those involving fluid control. In case of liquids, their incompressible nature minimizes the delay due to inertia.

Lag is quite common in many applications. For example, consider a liquid food being heated in a steam-jacketed vessel. After the steam is turned on, it takes time before the product begins to heat due to inherent resistances of the vessel and the product.

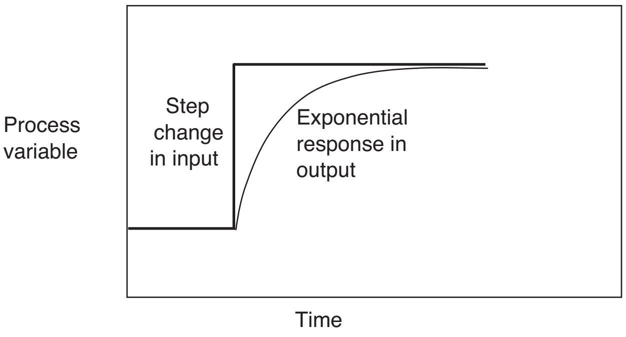

Figure 10.2 Exponential response to a step change in input.

Typically, a first order equation is used to describe the lag, as shown in the following equation:

$$\tau \frac{dy}{dt} + y = Kx \tag{10.1}$$

where

y is the output as a function of time,
x is the input as a function of time,
τ is the system time constant,
K is a constant.

First order lag is the most common type of response in process control. Figure 10.2 shows how a process responds when there is a sudden change in the input. The response curve is exponential; it approaches the new steady state value in an asymptotic manner. The response behavior of such a system is characterized by calculating the time constant. After one time constant the system responds to 63.2% of the step change in the input.

Dead time is associated with how the equipment is designed. For example, in measuring the temperature of a liquid in a tank, if the liquid is being pumped to a pipe where the temperature detector is placed then it will take time before the liquid reaches the temperature detector and this will result in a delay.

10.3.3 Modes of process control

To understand different modes of process control, consider a vessel containing a submerged heating coil (Fig. 10.3). A liquid food enters the vessel from the top and exits at the bottom. To heat the food, hot water circulates through the heating coil. A valve is installed on the pipe feeding hot water into the coil. A temperature sensor is used to measure the temperature of the food inside the vessel. It is desired that the temperature of the food inside the vessel is maintained at some constant temperature (for this example, let us assume 50°C). We will consider different modes of control that may be used to achieve this objective.

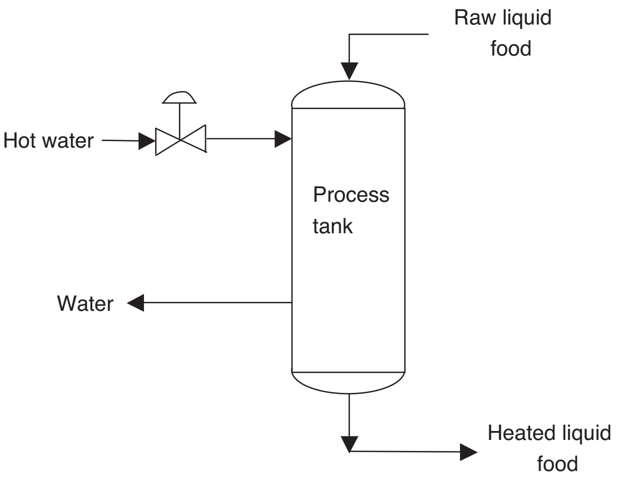

Figure 10.3 A process tank to heat liquid food using hot water.

10.3.3.1 On/off control

The on/off control is perhaps the simplest method of control. For our example, to maintain a juice temperature of 50°C, an operator would observe the temperature sensor; if the temperature falls below the set point of 50°C, the valve will be fully opened (on) to allow hot water to circulate through the coil. When the temperature of the juice goes above the set point of 50°C, the valve is fully closed (off).

The on/off control may be expressed mathematically as follows:

$$e = P_v - S_p \tag{10.2}$$

where

e is the error,
P_v is the process variable,
S_p is the set point.

This control algorithm responds to a change in the sign of the error by turning the system off or on. Although on/off control will be able to maintain an average temperature, there could be large variations in

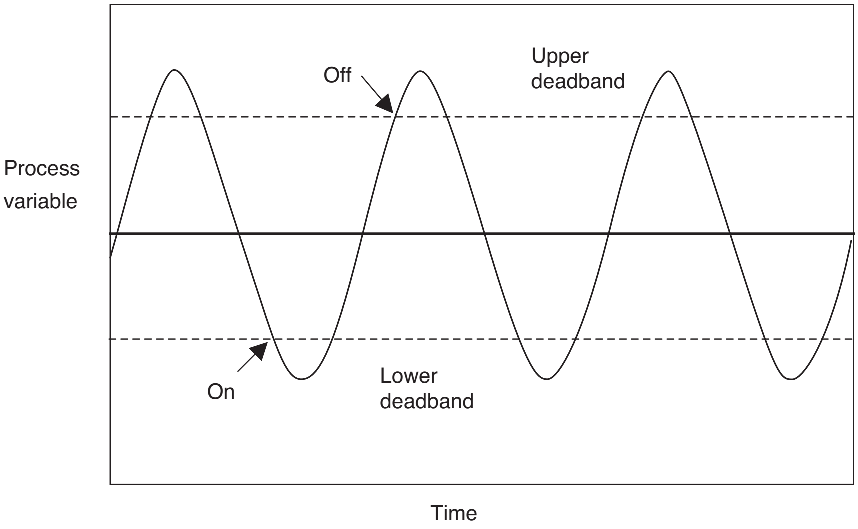

Figure 10.4 On/off control with dead bands. (Adapted from Bresnahan, 1997.)

temperature around the set point. In a batch heater, some reduction in variation in temperature may be realized by good agitation.

To prevent too quick oscillations, dead bands are used as shown in Fig. 10.4. The system is turned on prior to reaching the lower dead band and then turned off when it reaches the upper dead band.

10.3.3.2 Proportional control

In our example, if we conduct a simple energy balance on our system, we will find that there is a certain ideal steady flow rate of hot water that will maintain the juice temperature at 50°C. However, this ideal flow rate of water will be different for different flow rates of juice in and out of the vessel. Thus, to control the process we need to accomplish two tasks: (1) determine a flow rate of hot water that will maintain the juice at 50°C for some normal flow rate of juice in and out of the vessel, and (2) any increase or decrease in the error (difference in set point and temperature of the juice) must be allowed to cause a corresponding change in the flow rate of the hot water. This is the basis of proportional control. The proportional control may be thought in terms of the gain. Mathematically, in proportional control algorithm, the following calculations are used to determine the output based on the error between the set point and the measured variable:

$$C_o = Ge + m \tag{10.3}$$

where

C_o is the controller output (such as position of a control valve),
G is the proportional gain,
e is the error,
m is the controller bias.

This equation suggests that there is a direct relationship between the error and the controller output (or position of the controller valve). For our example, the valve used to control hot water must be adjustable (such as an electrically or pneumatically operated diaphragm actuator). In the case of a reverse acting controller, if there is a larger positive error then the output will decrease, and vice versa for direct acting controllers.

In many industrial controllers, the gain adjusting mechanism is expressed in terms of the proportionality band. The proportionality band represents a percent change in the output based on the change in the input. The following equation is used to calculate the proportional band:

$$B_p = \frac{100}{G} \tag{10.4}$$

where

B_p is the proportional band,
G is the proportional gain.

Thus, a gain of 1.0 corresponds to a proportional band of 100%, whereas a gain of 0.5 corresponds to a proportional band of 200%.

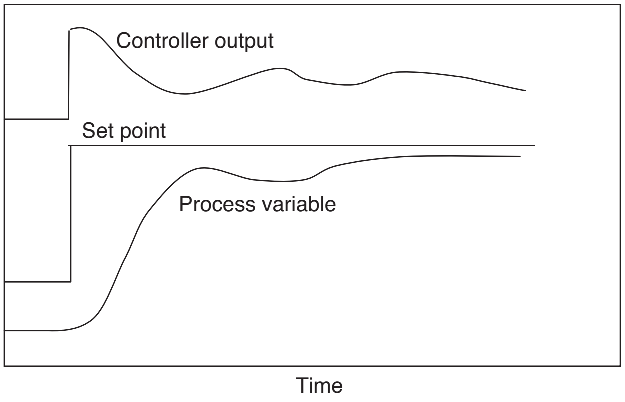

Figure 10.5 Process variable, set point and controller output in a proportional control.

Proportional-only control can rarely keep the process variable at the set point. As shown in Fig. 10.5 with a step change in the error, the controller output also experiences a step change. Due to this step change in the controller, the process variable begins to respond. This causes a decrease in the error, which results in a decrease in the controller output. After some time the error decreases and there is no change in the error. Similarly, the controller output also does not change because it is a product of the gain and change in error. No change in error results in no change in the output. This means that there will be a constant error or offset. In order to minimize it, the gain, G, may be made large. However, this can also cause excessive oscillations when there is a response lag in the system. In some applications, such as measurement of pressure, the control variable has a very fast response, and a high gain proportional controller is well suited. In case of flow measurements, due to considerable noise, these controllers are not well suited as they give erroneous response to the noise as well as to the real signal.

10.3.3.3 Proportional-plus-integral control

To eliminate the offset error, noted in the proportional control, one strategy would be to adjust the proportional controller. The manual reset may be automated by moving the valve at a rate that is proportional to the error. This means that if the deviation or the error is doubled, then the control element will move twice as fast to respond. On the other hand, if there is no deviation, the error is zero, and the control element remains stationary.

The integral action (or reset) is often combined with the proportional control and called proportional integral (PI) control.

Integral controls involve the use of a cumulative error in determining the controller output along with the instantaneous action of the proportional component of the controller. Thus only the bias term for each set point needs to be adjusted.

The following equation applies to the proportional and integral control:

$$C_o = Ge + \frac{G}{t_i}\int e\,dt \qquad (10.5)$$

where t_i is the reset time tuning parameter.

The adjustable parameter for the integral mode is t_i or the reset time (its units are time per repeat, e.g. minutes per repeat). In some controllers, $1/t_i$ is used, which is called repeats per unit of time. When using the preceding equation, the terms and units should be carefully checked.

The significance of the reset time as used in the above equations may be understood as follows. For a given error, the reset time is the time for the integral action to provide a change in output signal equal to that provided by the proportional control mode. Consider an example when t_i =1 minute; if the error at time zero undergoes a step change from 0 to 1, the output from the preceding equation will have an instantaneous magnitude of G for the first term of the right-hand side of the equation. After 1 minute if the error stays constant at 1, then the output will equal 2 G (contributions from both proportional and integral parts of the equation). After another minute, another G will be added and so on. This will continue until either the error disappears or the controller reaches saturation point of either 0 or 100%. The advantage of the PI control is the elimination of offset. However, some instability may be present due to the integral component.

10.3.3.4 Derivative control

The derivative of a controller adds to the controller output a term in proportion to the rate of change in error with respect to time. On a theoretical basis, one may consider a controller that is based only on the rate of change of the error, but in practical situations it will mean that in cases where there is a large but constant error there will be zero controller output. Therefore, one needs to incorporate proportional control to a derivative control. An equation for a proportional, integral, and derivative control (PID) may be written as

$$C_o = Ge + \frac{G}{t_i}\int edt + Gt_d\frac{de}{dt} \tag{10.6}$$

where t_d is the derivative time tuning parameter.

An additional corrective action for the PID controller is obtained by determining the slope of the error vs. the time curve and multiplying with the derivative tuning parameter. Another approach to determining the derivative term is to modify the process variable by using the slope of its change with time to predict a new value in future. The predicted value is then used in error calculation instead of the actual process variable (Bresnahan, 1997).

The derivative action in PID controllers circumvents the problems encountered by other algorithms with significant lag or large variation from set points. Consider a case of heating a viscous liquid where there is slow dynamic response. If a controller does not contain derivative action, then error will change signs and there will be considerable overshoot past the process set point; this may result in excessive burning of the product or fouling of the heat transfer surface. A PID controller reduces the oscillations. Normally, a derivative control is not employed when the system response is too fast.

A more detailed discussion on process controls used in the food industry is available in Bresnahan (1997), Murrill (2000), and Hughes (2002).

10.4 Storage vessels

10.4.1 Tanks for liquid foods

In processing liquid foods, tanks are essential for short- and long-term storage. Consider milk processing in a dairy plant. In a modern dairy plant, the size of tanks may vary from 110 to 150,000 liters. The design of a tank must adhere to the specific requirements of the process and product being handled.

Raw milk received at a dairy plant is stored in large vertical tanks with capacities varying from 25,000 to 150,000 liters. Larger tanks, generally located outdoors, are usually double-wall construction, with the interior wall made of stainless steel and the outside wall of welded sheet metal. In between the walls, a minimum of 70 mm of mineral-wool insulation is used. In raw milk tanks, gentle agitation, using a propeller agitator, is provided to prevent gravity separation of cream (Fig. 10.6). Level indicators are used to provide low-level protection to ensure that the agitator is submerged before it is turned on, and overflow protection to prevent overfilling. An empty tank indication is used to ensure that the tank is completely empty before the rinse cycle. In modern facilities, the data obtained from these indicators are transmitted directly to a central location.

Figure 10.6 A tank with a propeller agitator. (Source: *Dairy Processing Handbook*, Tetra Pak.)

The bottom of the tank slopes downwards towards the outlet with an inclination of about 6% to provide easy drainage (Fig. 10.7). Appropriate sanitary connections and vents are used to prevent backpressure buildup during filling and vacuum during emptying.

After milk is heat treated, it is often stored in intermediate storage tanks which are insulated to maintain a constant temperature. In these tanks, both inner and outer walls are made of stainless steel and the space between is filled with mineral wool to provide insulation. These intermediate tanks are also used as a buffer storage; typically a buffer capacity of a maximum of 1.5 hours of normal operation is used (Fig. 10.8).

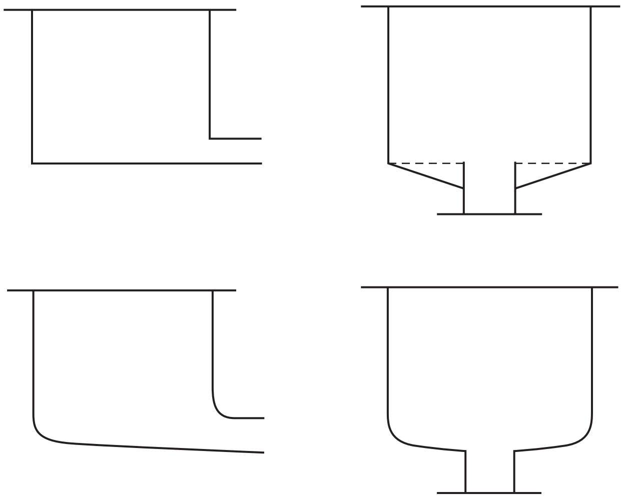

Figure 10.7 Different designs of tank floors with slope to aid drainage.

Figure 10.8 A tank used to provide buffer capacity in a processing line. (Source: *Dairy Processing Handbook*, Tetra Pak.)

In addition to storage tanks, a dairy processing plant may also use several process tanks where milk or other dairy products are processed: for example, tanks for cultured products such as yogurt, ripening tanks for butter cream, and tanks for preparing starter cultures for fermented products.

When designing a transport system for liquid foods such as milk, certain potential problems must be considered. For example, the product being pumped must be free of air for a centrifugal pump to work properly, pressure at all points of the inlet must be higher than the vapor pressure of the liquid to prevent cavitation, there should be provision for redirecting the flow if the process has been inadequate, and the suction pressure at the pump must remain constant for uniform flow. In order to avoid these types of problems, balance tanks are located along the suction side of the pump (Fig. 10.9). The liquid level in a balance tank is always maintained at a certain minimum level, using a float, to provide a constant head on the suction side of the pump.

10.5 Handling solid foods in a processing plant

The design and layout of the plant and how materials are handled between various processing equipment have a major impact on the production efficiency. In the case of transporting solid foods in a food processing plant, it is typical to consider the movement of product in any direction, horizontal or vertical. A variety of conveyors and elevators are used for this purpose. These include belt, chain, screw, gravity, and pneumatic conveyors, and bucket elevators. In some cases fork-lifts and cranes are employed. Some salient features of these different conveyors are described below.

10.5.1 Belt conveyors

An endless belt operating between two or more pulleys is one of the most ubiquitous conveyors used in transporting solid foods in a processing plant (Fig. 10.10). Between the pulleys, idlers are used to support the weight of the belt. Some key advantages and disadvantages of belt conveyors are as follows:

- High mechanical efficiency as load is carried on antifriction bearings.

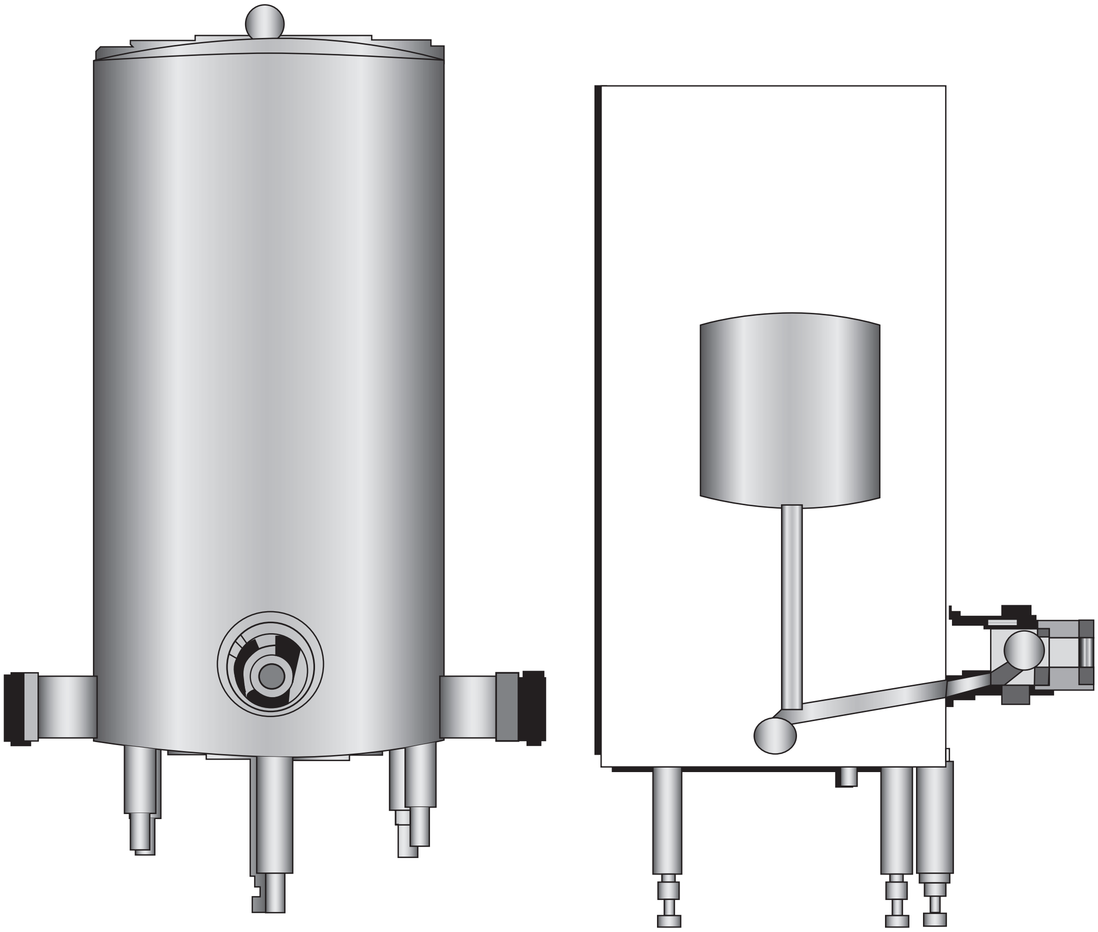

Figure 10.9 A balance tank located on the suction side of a pump. (Source: *Dairy Processing Handbook*, Tetra Pak.)

- Minimal damage to product, as no relative motion between the product and the belt.
- High carrying capacity.
- Ability to convey long distances.
- Long service life.
- High initial cost.
- Requires significant floor area.

In designing belt conveyors, the type of drive, belt, belt tension, idlers, and belt loading and discharge devices must be considered. A wide range of belt materials are used depending on the product requirements. In many cases, the belts must be washed after each shift to maintain sanitary conditions. The drive is located at the discharge end of the belt, and

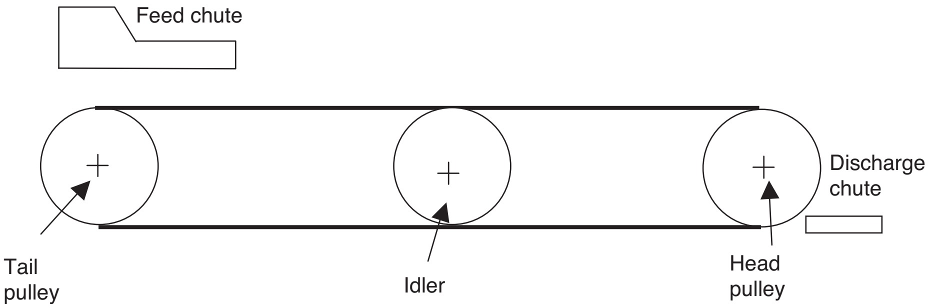

Figure 10.10 A belt conveyor.

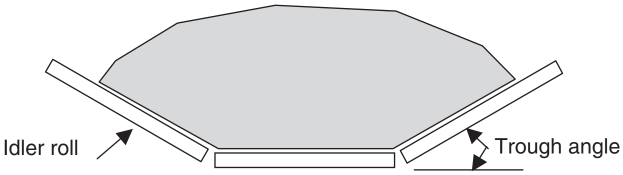

Figure 10.11 Cross-section of a troughed-belt conveyor.

sufficient contact area between the pulley and the belt is necessary to obtain a positive drive.

Belt conveyors may be either flat or troughed (Fig. 10.11). Troughed belts are suited for grains, flour, and other small particulate foods. The angle between the idler rolls and the horizontal is called the troughing angle. For conveying small particulates like grain, the troughing angle is from 20 to 45 degrees. The belt speed is kept below 2.5 m/s to minimize spillage and dust when conveying small particulates.

10.5.2 Screw conveyors

Screw conveyors consists of a helix turning inside a circular or U-shaped trough (Fig. 10.12). Screw conveyors are suited for handling powders, sticky and viscous products such as peanut butter, and granular materials. They are also useful for mixing in batch or continuous mode. Screw conveyors are useful to empty silos of flour and powder materials. Often they are used as metering devices.

The flights of screw conveyor are made of a variety of materials including stainless steel. Their operating power requirements are high, and they are used for distances less than 25 m. In a standard screw conveyor, the pitch of a screw is the same as the diameter. Screw conveyors are suitable for horizontal as well as incline up to 20 degrees. For horizontal screw conveyors an oval trough is used, whereas for a steep incline a cylindrical trough is necessary.

The power requirement of a screw conveyor depends upon a number of factors including:

- the length of the conveyor;

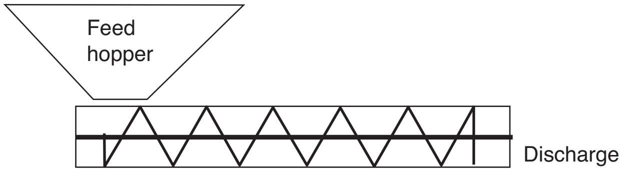

Figure 10.12 A screw conveyor.

- elevation;
- pitch;
- speed;
- type of flights and hanger brackets;
- weight and properties of the material being conveyed;
- the coefficient of friction between the product and the material of the flights and housing.

The startup power requirement of a screw conveyor is generally higher than for continuous operation.

10.5.3 Bucket elevators

The bucket elevator consists of an endless belt with buckets attached to it. The belt operates on two wheels; the top wheel is referred to as the head and the bottom is called the foot. Bucket elevators are highly efficient as there is absence of frictional loss between the product and the housing material. The bucket elevators are enclosed in a single housing referred to as a leg; in certain cases, the return is housed in a second leg. A chain or a belt is used to carry the buckets that are shaped with either rounded or sharp bottoms. The belt or chain operates between two wheels – the head and foot. For longer lengths, idlers are installed to prevent belt whip.

The product carried by the buckets is discharged at the top when the bucket turns around the head wheel, and the product is thrown out by the centrifugal force. The speed of the bucket as it goes around the head wheel must be maintained within limits to ensure that the product is discharged in a desired region (Fig. 10.13).

The conveying capacity of a bucket elevator depends on the product density, belt speed, bucket size,

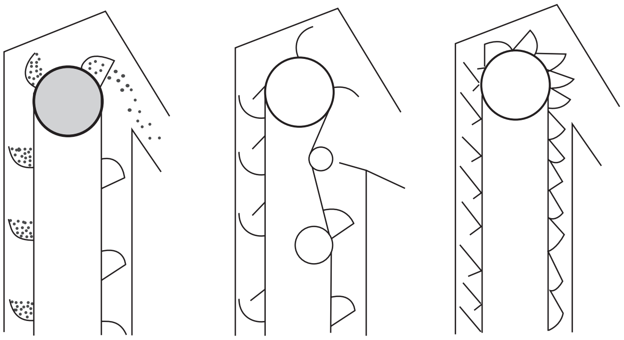

Figure 10.13 A bucket conveyor with buckets going around a head wheel.

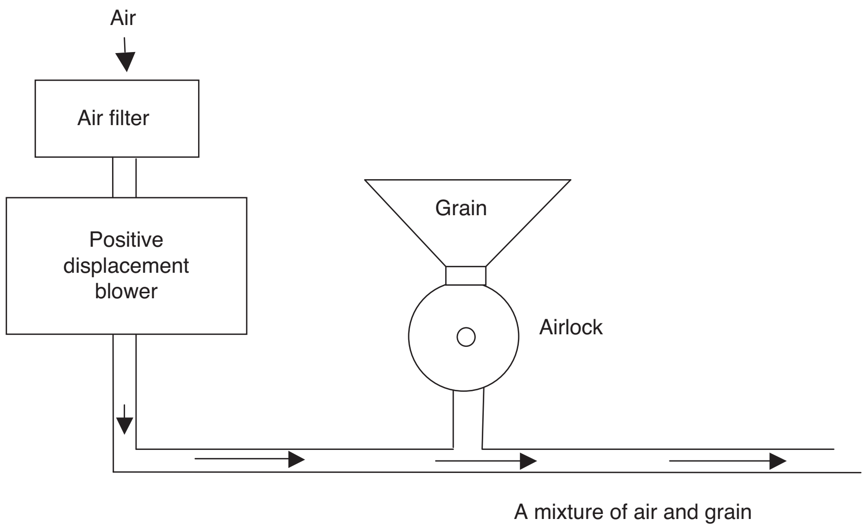

Figure 10.14 A pneumatic conveyor.

and spacing of buckets on the belt. Typical applications of bucket elevators are for handling cereal grain, animal feed, and meal. The energy requirements of bucket conveyors for cereal grains range from 0.1 to 0.2 kWh/m^3.

10.5.4 Pneumatic conveyors

A pneumatic conveyor consists of a blower, transport duct, and a device to introduce the product into the duct at the entrance and out of the duct at the exit (Fig. 10.14).

In a pneumatic conveyor, particulate food is conveyed in a closed duct by a high-velocity stream of air. The pneumatic conveyor may be operated as:

- a suction system, operating at pressures lower than atmospheric pressure;
- a low pressure suction system using high-velocity low-density air powered by a centrifugal fan;
- a high pressure system, using low-velocity high-density air powered by positive displacement blowers;
- a fluidized system that uses high-pressure, high-density air to move material with low conveying velocities.

Examples of pneumatic conveyors include the use of suction systems for unloading grain from trucks, freight cars, and pressure systems for loading freight cars or storage tanks.

Typical air velocities used in pneumatic conveying of some common products are:

- coffee beans, 3000–3500 fpm;
- corn, 500–7000 fpm;
- oats, 4500–6000 fpm;
- salt, 5500–7500 fpm;
- wheat, 5000–7000 fpm.

Empirical procedures are generally used to determine the energy requirements of pneumatic conveying. At the entrance to the conveyor, the velocity of the particle is zero, and the energy required to accelerate the product can be substantial. The mechanisms involved in moving the particulates in a pneumatic conveyor include horizontal force acting on the particulate due to the moving air and vertical force due to gravity. When particulates reach the bottom of the conduit, they slide and roll, and they are again lifted due to the action of the moving air; they may also clump with other particulates and move as a slug. These mechanisms bring complexities in developing theoretical description of the process. The power requirements of pneumatic conveyors for grains range from 0.6 to 0.7 kWh/m^3.

The key advantages and disadvantages of a pneumatic conveyor are:

- Low initial cost.
- Simple mechanical design with only one moving part (a fan).
- Random conveying path with many branches.

- Easy to change conveying path.
- Wide variety of materials can be conveyed.
- Self cleaning system.
- High power requirements.
- Possible damage to product.

More information on conveying systems used in the agricultural and food processing industry is available in Labiak and Hines (1999).

10.6 Storage of fruits and vegetables

Many fruits and vegetables are highly perishable. Therefore in post harvest management, proper techniques of handling and storage of fruits and vegetables are essential to minimize losses. The range of post harvest losses varies anywhere from 5 to 50% or even higher. In developing countries, post harvest losses are enormous often due to lack of adequate infrastructure and poor handling practices. As a result, the growers and those engaged in the food handling chain suffer major financial losses. Moreover, the shelf life of these products is severely reduced and poor quality product is delivered to the consumer. Unfortunately any gains made in increasing the production yields of fruits and vegetables are compromised by increased post harvest losses due to inadequate practices.

In industrialized countries, major progress has been made in developing proper systems for the handling of fruits and vegetables. Post harvest losses are reduced in a significant manner and the product is delivered to the consumer with minimal quality loss.

10.6.1 The respiration process

Fruits and vegetables continue to undergo physiological changes after harvest. These changes are largely the result of the respiration process. The metabolic pathways active in a respiration process are complex. As a result of the respiration process, the starch and sugars present in the plant tissue are converted into carbon dioxide and water. Oxygen plays an important role in the respiration process. The oxygen concentration within a product is very similar to that of the normal atmosphere. When sufficient amount of oxygen is available, the respiration process is called aerobic. If the surrounding atmosphere becomes deficient in oxygen then anaerobic respiration occurs. Anaerobic respiration results in the production of ketones, aldehydes, and alcohol. These products are often toxic to the plant tissue and hasten its death and decay. Therefore anaerobic respiration must be prevented. Furthermore, to extend the shelf life of fruits and vegetables, the oxygen concentration must be controlled in such a manner as to allow aerobic respiration at a reduced rate. Control of the respiration process has become one of the most important methods of storage in commercial practice.

Along with the final products of aerobic respiration, carbon dioxide and oxygen, there is also the evolution of heat. The amount of heat generated due

Table 10.6 Heat of respiration of selected fruits and vegetables.

	Watts per megagram (W/Mg)			
Commodity	**0°C**	**5°C**	**10°C**	**15°C**
Apples	10–12	15–21	41–61	41–92
Apricots	15–17	19–27	33–56	63–101
Beans, green or snap	—	101–103	161–172	251–276
Broccoli, sprouting	55–63	102–474	—	514–1000
Cabbage	12–40	28–63	36–86	66–169
Carrots, topped	46	58	93	117
Garlic	9–32	17–29	27–29	32–81
Peas, green (in pod)	90–138	163–226	—	529–599
Potatoes, mature	—	17–20	20–30	20–35
Radishes, topped	16–17	23–24	45–47	82–97
Spinach	—	136	327	529
Strawberries	36–52	48–98	145–280	210–273
Turnips, roots	26	28–30	—	63–71

Table 10.7 Classification of fruits and vegetables based on their respiration rates.

Respiration rates	Range of CO_2 production at 5°C (mg CO_2/kg h)	Commodities
Very low	< 5	Nuts, dates, dried fruits, vegetables
Low	5–10	Apple, citrus, grape, kiwifruit, garlic, onion, potato (mature), sweet potato
Moderate	10–20	Apricot, banana, cherry, peach, nectarine, pear, plum, fig (fresh), cabbage, carrot, lettuce, pepper, tomato, potato (immature)
High	20–40	Strawberry, blackberry, raspberry, cauliflower, lima bean, avocado
Very high	40–60	Artichoke, snap beans, green onion, Brussels sprouts
Extremely high	> 60	Asparagus, broccoli, mushroom, pea, spinach, sweet corn

to respiration varies with different commodities, as shown in Table 10.6. The growing parts of a plant such as a leafy vegetable have higher rates of heat generation than plant tissues where the growth has ceased such as a tuber crop. Reducing the storage temperature controls the rate of respiration process. The respiration rate is expressed in terms of the rate of carbon dioxide production per unit mass. A classification of commodities based on their respiration rates is given in Table 10.7.

An important physiological change during fruit storage is the production of ethylene gas. Based on their ethylene production, fruits are classified as either climacteric or nonclimacteric. Climacteric fruits exhibit a high production of ethylene and carbon dioxide at the ripening stage. Table 10.8 lists some of the fruits according to this classification. The rate of production of ethylene may be controlled by storage temperature, atmospheric oxygen, and carbon dioxide concentration. The results of ethylene gas on the maturation process of fruits and vegetables include change in green color due to loss of chlorophyll, browning of tissues due to changes in anthocyanin and phenolic compounds, and development of yellow and red color due to the development of anthocyanin and carotenoids, respectively.

During storage, the loss of water from a commodity causes major deteriorative changes. Not only is there a loss of weight but also the textural quality is altered causing a commodity to lose its crispness and juiciness.

Fruits and vegetables may undergo three types of physiological breakdown that may be caused by poor post harvest practices. These include chilling injury, freezing injury, and heat injury. Chilling injury occurs mostly in commodities of tropical and subtropical regions when they are stored at temperatures above their freezing point and below 5–15°C. This type of injury causes uneven ripening, decay, growth of

Table 10.8 Classification of fruits and vegetables based on their respiration behavior during ripening.

Climacteric fruits		Nonclimacteric fruits	
Apple	Muskmelon	Blackberry	Olive
Apricot	Nectarine	Cacao	Orange
Avocado	Papaya	Cashew apple	Pepper
Banana	Passion fruit	Cherry	Pineapple
Blueberry	Peach	Cucumber	Pomegranate
Breadfruit	Pear	Eggplant	Raspberry
Cherimoya	Persimmon	Grape	Satsuma mandarin
Feijoa	Plantain	Grapefruit	Strawberry
Fig	Plum	Jujube	Summer squash
Guava	Sapote	Lemon	Tamarillo
Jackfruit	Soursop	Lime	Tangerine
Kiwifruit	Tomato	Loquat	
Mango	Watermelon	Lychee	

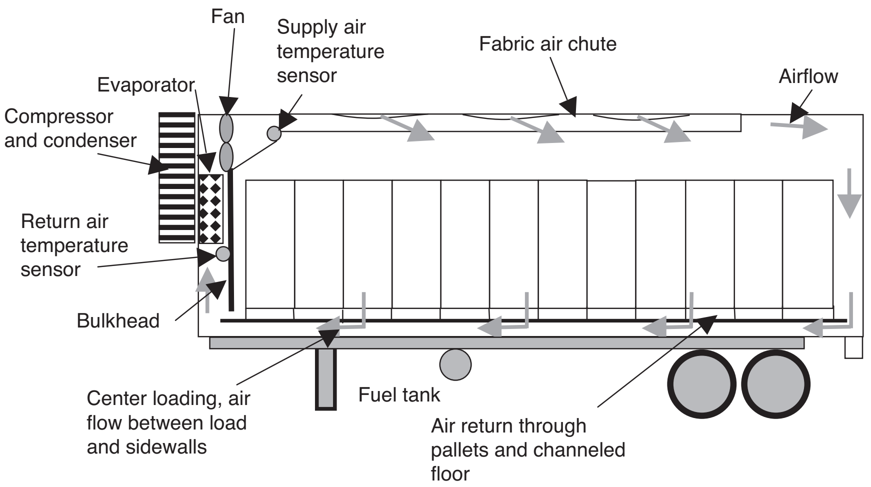

Figure 10.15 Airflow in a refrigerated trailer.

surface molds, development of off flavors, and both surface and internal discoloration.

Improper handling causes surface injuries and internal damage in fruits and vegetables. Similarly pathological breakdown caused by bacteria and fungi enhances product deterioration. Often physical damage makes it easier for the bacteria and fungi to infect plant tissues. Therefore, handling systems such as conveying and packing should be designed to minimize physical damage to the commodity being handled.

10.6.2 Controlled atmosphere storage

A large number of fruits and vegetables benefit from storage under controlled atmosphere conditions. A reduced level of oxygen and increased concentration of carbon dioxide in the immediate environment surrounding a fruit or vegetable retards its respiration rate. With a reduced respiration rate, the storage life of the product is enhanced. Considerable research has been done to determine the most suitable concentrations for oxygen and carbon dioxide that extend the storage life of fruits and vegetables. Table 10.9 is a compilation of recommended conditions for gas composition. The controlled atmosphere technology is well developed, and for certain products like apples it is used worldwide.

10.7 Refrigerated transport of fruits and vegetables

One of the most common ways to transport perishable foods such as fruits and vegetables is by using a refrigerated trailer that may be either pulled via a truck on a highway or placed in a ship for trans-ocean shipment. Any perishable product stored in the trailer must be kept refrigerated for the entire duration. A typical refrigerated trailer, shown in Fig. 10.15, includes a refrigeration system to cool air and an air handling system to distribute air within the trailer. It is vital that there is uniform air distribution within the trailer; otherwise regions with no air circulation can lead to product heating and spoilage (Thompson *et al.*, 2002).

Temperature control of the air circulating inside the trailer is vital to the shipment of perishable foods. Modern trailers are equipped with temperature sensors and controllers that automatically control the refrigeration unit based on the temperature of air exiting the refrigeration unit. The control of air temperature at the exit of the refrigeration unit is important in protecting fresh produce that is sensitive to chilling injury or freeze damage. The temperature of the thermostat in these systems is set within 0.5°C of the long-term storage temperature. In older trailers used for chilling/freeze-sensitive produce, the temperature control is typically based on the return air to the refrigeration unit, and the controllers should be set at least 1.5–2.5°C above the long-term storage temperature of the produce. For frozen products, the temperature is controlled based on the return air temperature. The trailer used for frozen products should be set at −18°C or colder. The frozen food industry generally requires that at the time frozen food is loaded into a trailer, the temperature of the product should be less than −12°C

When a trailer load contains more than one type of produce, care must be taken that these are compatible in terms of their storage temperature and ethylene

Table 10.9 Recommended conditions for controlled atmosphere (CA) storage of fruits and vegetables.

Common name	Scientific name	Storage temperature (°C)	Relative humidity (%)	Highest freezing temperature (°C)	Ethylene production	Ethylene sensitivity	Approximate shelf-life	Beneficial controlled atmosphere
Apple, nonchilling sensitive varieties		−1.1	90–95	−1.5	Vh	H	3–6 months	CA varies by cultivar
Apple, chilling sensitive	Yellow Newtown, Grimes Golden, McIntosh	4	90–95	−1.5	Vh	H	1–2 years	CA varies by cultivar
Apricot	*Prunus armeniaca*	−0.5–0.0	90–95	−1.1	M	H	1–3 weeks	2–3% O_2 + 2–3% CO_2
Artichoke, Globe	*Cynara acolymus*	0	95–100	−1.2	VL	L	2–3 weeks	2–3% O_2 + 3–5% CO_2
Asparagus, green, white	*Asparagus officinalis*	2.5	95–100	−0.6	VL	M	2–3 weeks	5–12% CO_2 in air
Avocado Cv Fuerta, Haas	*Persea americana*	3–7	85–90	−1.6	H	H	2–4 weeks	2–5% O_2 + 3–10% CO_2
Banana	*Musa paradisiaca* var. *sapientum*	13–15	90–95	−0.8	M	H	1–4 weeks	2–5% O_2 + 2–5% CO_2
Beans, snap, wax, green	*Phaseolus vulgaris*	4–7	95	−0.7	L	M	7–10 days	2–3% O_2 + 4–7% CO_2
Lima beans	*Phaseolus lunatus*	5–6	95	−0.6	L	M	5–7 days	
Strawberry	*Fragaria* spp.	0	90–95	−0.8	L	L	7–10 days	5–10% O_2 + 15–20% CO_2
Cabbage, Chinese, Napa	*Brassica campestris* var. *perkinensis*	0	95–100	−0.9	VL	H	2–3 months	1–2% O_2 + 0–5% CO_2
Carrots, topped	*Daucus carota*	0	98–100	−1.4	VL	H	6–8 months	No CA benefit
Carrots, bunched	*Daucus carota*	0	98100	−1.4	VL	H	10–14 days	Ethylene causes bitterness

(*Continued*)

Table 10.9 (*Continued*)

Common name	Scientific name	Storage temperature (°C)	Relative humidity (%)	Highest freezing temperature (°C)	Ethylene production	Ethylene sensitivity	Approximate shelf-life	Beneficial controlled atmosphere
Cauliflower	*B. oleracea* var. *botrytis*	0	95–98	−0.8	VL	H	3–4 weeks	2–5% O_2 + 2–5% CO_2
Cherimoya, Custard Apple	*Annona cherimola*	13	90–95	−2.2	H	H	2–4 weeks	3–5% O_2 + 5–10% CO_2
Citrus, lemon	*Citrus limon*	10–13	85–90	−1.4			1–6 months	5–10% O_2 + 0–10% CO_2
Citrus, orange	*Citrus sinensis*, California, dry	3–9	85–90	−0.8	VL	M	3–8 weeks	5–10% O_2 + 0–5% CO_2
Citrus, orange	*Citrus sinensis*, Florida, humid	0–2	85–90	−0.8	VL	M	8–12 weeks	5–10% O_2 + 0–5% CO_2
Cucumber	*Cucumis sativus*	10–12	85–90	−0.5	L	H	10–14 days	3–5% O_2 + 3–5% CO_2
Eggplant	*Solanum melongena*	10–12	90–95	−0.8	L	M	1–2 weeks	3–5% O_2 + 0% CO_2
Garlic	*Allium sativum*	0	65–70	−0.8	VL	L	6–7 months	0.5% O_2 + 5–10% CO_2
Ginger	*Zingiber officinale*	13	65		VL	L	6 months	No CA benefit
Grape	*Vitis vinifera*	−0.5–0	90–95	−2.7	VL	L	2–8 weeks	2–5% O_2 + 1–3% CO_2
Guava	*Psidium guajava*	5–10	90		L	M	2–3 weeks	
Lettuce	*Lactuca sativa*	0	98–100	−0.2	VL	H	2–3 weeks	2–5% O_2 + 0% CO_2
Loquat	*Eriobotrya japonica*	0	90	−1.9			3 weeks	
Lychee, litchi	*Litchi chinensis*	1–2	90–95		M	M	3–5 weeks	3–5% O_2 + 3–5% CO_2
Mango	*Mangifera indica*	13	85–90	−1.4	M	M	2–3 weeks	3–5% O_2 + 5–10% CO_2
Melon, honey dew, orange flesh	*Cucurbita melo*	5–10	85–90	−1.1	M	H	3–4 weeks	3–5% O_2 + 5–10% CO_2

Mushroom	*Agaricus*	0	90	−0.9	VL	M	7–14 days	3–21% O_2 + 5–15% CO_2
Okra	*Abelmoschus esculentus*	7–10	90–95	−1.8	L	M	7–10 days	Air + 4–10% CO_2
Papaya	*Carica papaya*	7–13	85–90		H	H	1–3 weeks	2–5% O_2 + 5–8% CO_2
Peach	*Prunus persica*	−0.5–0	90–95	−0.9	H	L	2–4 weeks	1–2% O_2 + 3–5% CO_2
Pepper, Bell	*Capsicum annuum*	7–10	95–98	−0.7	L	L	2–3 weeks	2–5% O_2 + 2–5% CO_2
Persimmon, Fuyu	*Dispyros kaki*	7–10	95–98	−0.7	L	L	2–3 weeks	2–5% O_2 + 2–5% CO_2
Persimmon, Hachiya	*Dispyros kaki*	10	90–95	−2.2	L	H	1–3 months	
Pineapple	*Ananas comosus*	5	90–95	−2.2	L	H	2–3 months	
Pomegranate	*Punica granatum*	5	90–95	−3.0			2–3 months	3–5% O_2 + 5–10% CO_2
Potato, early crop	*Solanum turbersom*	10–15	90–95	−0.8	VL	M	10–14 days	
Potato, late crop	*Solanum tubersom*	4–12	95–98	−0.8	Vl	M	5–10 months	
Spinach	*Spinacia oleracea*	0	95–100	−0.3	VL	H	10–14 days	5–10% O_2 + 5–10% CO_2
Tomato, mature-green	*Lycopersicon esculentum*	10–13	90–95	−0.5	VL	H	1–3 weeks	3–5% O_2 + 2–3% CO_2
Tomato, firm ripe	*Lycopersicon esculentum*	10	85–90	−0.5	H	L	7–10 days	3–5% O_2 + 3–5% CO_2
Watermelon	*Citrullus vulgaris*	10–15	90	−0.4	VL	H	2–3 weeks	No CA benefit

VL, very low; L, low; M, medium; H, high; VH, very high.

Table 10.10 Ethylene sensitivity of selected vegetables during storage.

Commodity	Symptoms of ethylene injury
Asparagus	Increased lignification (toughness) of spears
Beans, snap	Loss of green color
Broccoli	Yellowing, abscission of florets
Cabbage	Yellowing, abscission of leaves
Carrot	Development of bitter flavor
Cauliflower	Abscission and yellowing of leaves
Cucumber	Yellowing and softening
Eggplant	Calyx abscission, browning of pulp and seeds, accelerated decay
Leafy vegetables	Loss of green color
Lettuce	Russet spotting
Parsnip	Development of bitter flavor
Potato	Sprouting
Sweet potato	Brown flesh discoloration and off flavor detectable when cooked
Turnip	Increased lignification (toughness)
Watermelon	Reduced firmness, flesh tissue maceration resulting in thinner rind, poor flavor

sensitivity. Table 10.10 lists some of the deleterious effects on vegetables due to excessive ethylene exposure. Ethylene-sensitive vegetables should not be mixed with ethylene-producing fruits.

In a refrigerated trailer, it is usually difficult to force sufficient air through boxes. As a result, it is not generally possible to cool the stored product. In fact, in a poorly designed or managed trailer, the product may warm during transit.

Figure 10.16 shows a checklist for trailer conditions before loading food. The loading pattern of pallets inside a trailer has a marked influence on the airflow. Airflow in a typical refrigerated highway trailer is shown in Fig. 10.15. Air exiting the evaporator of the refrigeration unit is directed to the ceiling (usually through an air chute), between the walls, around the rear door, and it returns through the channeled floor to the front bulk head. For air to circulate in this manner, it is important that adequate spacing is provided between the load and the ceiling, walls, rear doors, and floor. Several types of loading arrangements for pallets are used; some

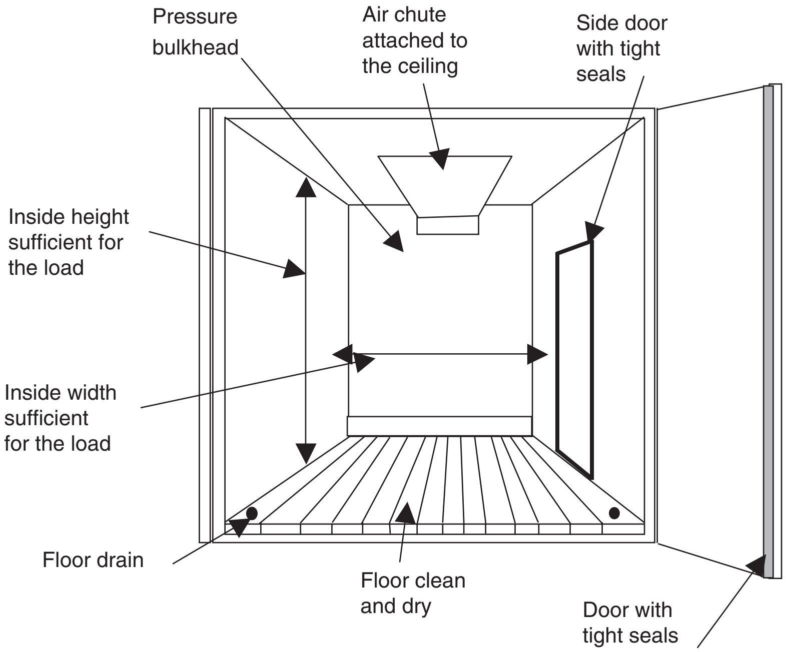

Figure 10.16 Key features of a refrigerated trailer.

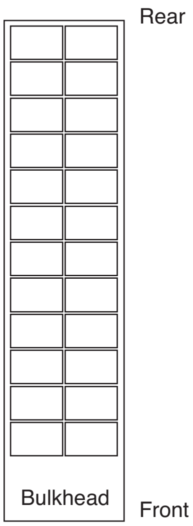

Figure 10.17 An arrangement of 24 pallet loads in a refrigerated truck.

common patterns for 24 standard pallets are shown in Fig. 10.17.

In long-distance shipping, vibration damage to the produce can be a significant factor. Vibration damage to product is more severe for trailers using steel-spring-suspended axles. Dramatic reductions in vibration damage are observed in trailers using air ride suspension. If the rear-axle of the trailer has steel springs, then vibration-sensitive products such as pears and berries should not be loaded in the rear section of the trailer.

10.8 Water quality and wastewater treatment in food processing

Water is a ubiquitous resource on our planet, yet the availability of a clean and reliable supply of water is becoming increasingly scarce. The food processing industry relies heavily on access to clean water. Water use in food processing has increased with the widespread mechanization of harvesting operations; raw agricultural products arriving at a food processing plant require large quantities of water for cleaning (Fig. 10.18). Inside the plant, water is used in a variety of processing and handling operations such as product conveying, peeling, blanching, cooling, generating steam, and washing equipment and floors (Figs 10.19 and 10.20).

The quality of water used in food processing depends on the function of water in the manufacturing process. For example, water quality for initial cleaning of raw produce has a different requirement than water required for the formulation of carbonated

Figure 10.18 Water sprays are used in washing spinach. Leafy vegetables require a considerable amount of water to remove any insects and other debris attached to the leaves.

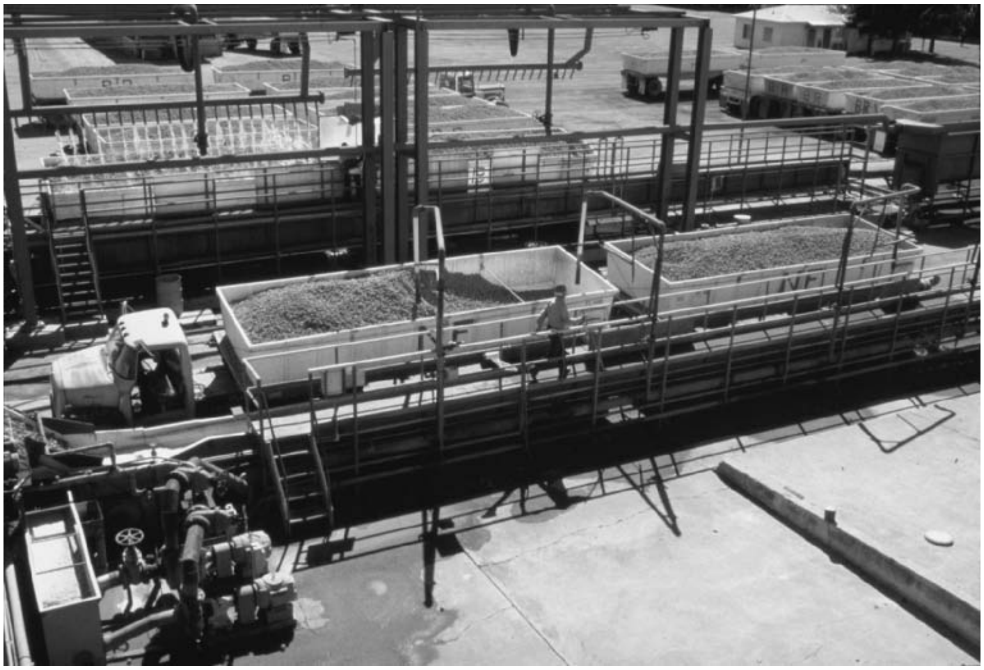

Figure 10.19 Mechanically harvested tomatoes, brought in gondola containers in trucks to a processing plant, are removed by pumping water into gondolas and transferred into water flumes.

beverages, beer, and bottled drinking water. Water obtained from ground wells or surface areas (such as lakes, rivers, and springs) may require certain treatment before its use in the food processing plant. If the water has high levels of hardness due to the presence of dissolved solids, then processes such as precipitation, ion exchange, distillation, or reverse osmosis may be used. To remove turbidity, domestic water is

Figure 10.20 A water flume is used to convey tomatoes from the receiving area to the processing equipment.

often pretreated using coagulation, flocculation, sedimentation, or filtration. The presence of dissolved organics in water causes off-flavor, odor, or color that is often removed by activated carbon adsorption.

10.8.1 Characteristics of food processing wastewater

Foods processed in a processing plant influence the composition of the discharged wastewater. For example, in a fruit and vegetable canning plant, wastewater contains the product residues generated from operations such as peeling, blanching, cutting, washing, heating and cooling, and cooking. For sanitary requirements, equipment and floors are frequently washed, creating large volumes of wastewater. Any detergents and lubricants used in the processing equipment and chemicals such as caustic solution (NaOH) for lye-peeling vegetables are also mixed in the wastewater. Other typical constituents of wastewater include emulsified oil, organic colloids, dissolved inorganics, and suspended solids.

The quantity and composition of wastewater generated by different food processing plants are highly variable. Most of the pollutants in food processing wastewater are organic in nature. Up to 80% of total organic matter in the wastewater from food processing plants may be in a dissolved form.

The quality of wastewater is expressed by two commonly measured quantities, namely biological oxygen demand and chemical oxygen demand.

10.8.1.1 Biological oxygen demand (BOD)

BOD is a measure of oxygen required to oxidize the organic content in a water sample with the action of microorganisms. The biodegradable content present in the wastewater is expressed by the 5-day (120-hour), 20°C biological oxygen demand (BOD_5). The BOD value is commonly used to determine the efficiency of the wastewater treatment. The procedure for measuring BOD_5 involves the following steps (Schroeder, 1977):

- Procure samples of wastewater ensuring that there is minimal time delay before the test is started.
- Make dilution with a nutrient solution so that a maximum BOD of <6 mg/L will be obtained.
- Add a bacterial "seed" to the sample.
- Fill the standard (300 mL) bottles with diluted wastewater and seal. Also, prepare blank samples with bottles filled with dilution water containing the "seed".
- Immediately determine oxygen content of at least two samples and two blank bottles.
- Incubate samples at 20°C for 5 days, determine the oxygen content of remaining samples and blanks.
- Calculate BOD_5 using the following equation:

$$BOD_5 = D_f[(DO_0 - DO_5)]_{sample} - [(DO_0 - DO_5)]_{blank} \tag{10.7}$$

where

DO_0 is the initial dissolved oxygen,
DO_5 is the dissolved oxygen at the end of 5 days,
D_f is dilution factor

Some typical BOD_5 values of wastewater measured in food processing plants are shown in Table 10.11.

10.8.1.2 Chemical oxygen demand (COD)

COD is a measure of oxygen (in parts per million) required to oxidize organic and inorganic matter in a sample of wastewater. A strong chemical oxidant is used to determine the COD value. Although no direct correlation exists between COD and BOD_5, COD is useful to estimate the oxygen demand because it is

Table 10.11 Typical values of BOD measured in food processing plants (Environmental Protection Service, 1979b).

Industry sector	BOD_5 (mg/L)
Dairy	
Cheese	790–5900
Fluid milk	1210–9150
Ice cream	330–230
Fruit and vegetables	
Apple products	660–3200
Carrots	640–2200
Corn	680–5300
Green beans	130–380
Peaches	750–1900
Peas	270–2400
Fish	
Herring filleting	3200–5800
Meat and poultry	
Red meat slaughtering	200–6000
Poultry processing	100–2400
Poultry slaughtering	400–600

a rapid test taking less than 2 hours compared to measurement of BOD_5 that takes 120 hours. Standard testing procedures to measure COD of wastewater are available (American Society of Testing and Materials, 2006).

10.8.2 Wastewater treatment

Wastewater treatment is often classified as primary, secondary, or tertiary. Primary treatment is often a physico-chemical process involving sedimentation; secondary treatment comprises biological treatment with sedimentation; and tertiary treatment involves removal of residual and nonbiodegradable materials.

Dissolved organic matter in the wastewater is removed using biological treatment and adsorption, whereas dissolved inorganic matter requires the use of ion exchange, reverse osmosis, evaporation, and/or distillation. Any suspended organic matter is typically removed using physico-chemical and biological treatment methods. Other suspended inorganic or organic content is removed by screening, sedimentation, filtration, and coagulation.

10.8.3 Physico-chemical methods of wastewater treatment

A variety of physico-chemical methods are used in separating solids from wastewater. In this section some of the common methods are introduced. More details on these operations are presented in Schroeder (1977) and Liu (2007).

10.8.3.1 Screening

Screens are used to separate any debris or other suspended solid materials from wastewater. Typical mesh size for coarse screens is 6 mm or larger, whereas for fine screens it is 1.5–6 mm. Screens are made of stainless steel, and they can be effective in reducing the suspended solids to levels similar to those obtained in sedimentation. To minimize clogging of screens, a scraping system is employed. Rotary drum screens are also used where the screen is formed into a cylindrical drum shape that is used to separate particulate matter.

10.8.3.2 Flotation systems

For wastewater containing oil and grease, flotation systems are frequently used. In a flotation system, air is diffused into the wastewater causing the oil and grease to float to the top. Other slowly settling particulates are also separated as they attach themselves to the air bubbles and rise to the surface, where they are skimmed off with the use of skimmers. In case there is emulsified fat present in the wastewater then the emulsion must be first destabilized by use of additives to improve the efficiency of fat removal.

10.8.3.3 Sedimentation

Sedimentation is a widely used method for treating wastewater. The process is simple, as it involves filling a tank with wastewater and letting gravity cause the settling of solid particulates with a specific gravity of >1 to the bottom of the tank. The wastewater enters from the bottom of the tank and moves either upward or in a radial direction in the tank. The solid matter that settles in a sedimentation tank is referred to as sludge. In food processing wastewater, sludge is organic in nature and it is periodically removed for further treatment.

If we conduct a force balance on a rigid sphere falling through a Newtonian liquid, we obtain the following expression for the particle velocity, v_{p}:

$$v_p = \frac{d_p^2 g(\rho_p - \rho_L)}{18\mu} \tag{10.8}$$

where

d_p is the solid particle diameter,
g is gravitational constant,
ρ_p is the density of particles,
ρ_L is the density of liquid,
μ is the viscosity of the liquid.

From Equation (10.8), the particle velocity, v_{p}, is a function of the diameter and density of the particles, and density and viscosity of the liquid. In the sedimentation tank, the density and viscosity of liquid cannot be changed, but aggregating small particles into larger ones can increase the particle size and density. According to Equation (10.8), larger particles will descend faster, and thus a coagulation step is commonly employed.

Furthermore, particles present in the wastewater are often colloidal, and they carry the same charge. As a result, they repel each other. This creates a stable suspension. However, to allow particles to grow we need to destabilize the suspension. This is accomplished by the use of coagulants such as alum ($Al_2(SO_4)$), ferric chloride ($FeCl_3$), and metal oxides or hydroxides (CaO or $Ca(OH)_2$).

10.8.3.4 Filtration

In nature, water is filtered as it moves through different layers of sand, soil, and granular materials. Analogous to the natural systems, filtration systems have been developed using materials such as sand, diatomaceous earth, powdered carbon, and perlite.

The complexity of the filtration process is evident when we consider that the movement of water through a granular bed may involve a variety of different interactions between the filter medium and the material being separated. For example, there is the influence of gravity, diffusion, and adsorption on the filter media. The variability in the composition of the feed stream adds to the complexity of the process. When a high concentration of suspended solids is present then frequent cleaning and backwashing of the filter medium is required. Any organic matter present in the wastewater results in a buildup of biological slime on the filter, causing problems with cleaning. For this reason, filtration is typically used only in the tertiary treatment of water.

Two commonly used filtration systems are pre-coat filters and depth filters.

Pre-coat filters

In a precoat filter, a coating of particulates is applied on a support medium made of cloth or finely woven wire. The support medium and the particulate coating act as the filter medium. In some cases, the solids present in the wastewater stream provide the pre-coating medium.

Depth filters

A depth filter is constructed using granular material with varying porosity supported on a gravel layer. The filtration medium is usually graded sand. Depth filters require backwashing to keep them clean. The flow of liquid in a filtration system is described using Darcy's law,

$$v = KS \tag{10.9}$$

where

v is the apparent velocity obtained by dividing flow rate by cross-sectional area,
K is the coefficient of permeability,
S is the pressure gradient.

Using Darcy's law, Kozeny proposed the following equation to calculate flow through a medium with uniform porosity (Schroeder, 1977):

$$\frac{h_L}{H} = \frac{k\mu v}{g\rho}\frac{(1-\phi)^2}{\phi^3}a_v \tag{10.10}$$

where

H is the bed depth,
h_L is the head loss through bed of depth H,
ϕ is the bed porosity,
ρ is the liquid density,
g is the gravitational constant,
a_v is the average grain surface area to volume ratio,
k is the dimensionless coefficient (typically its value is 5 for wastewater filtration).

10.8.4 Biological treatment of wastewater

Although physicochemical operations described in the preceding sections are useful in the separation and removal of suspended solids of varying dimensions, these operations are often unable or inefficient to remove dissolved and colloidal organic matter. For this purpose, biological treatment of wastewater is commonly employed. Any organic matter that does not settle or is dissolved is treated with microorganisms. In the presence of oxygen, aerobic microorganisms break down the organic matter. Anaerobic treatment involves microbial activity in the absence of oxygen.

Lagoons or ponds are widely used for the biological treatment of food processing wastewater. Lagoons cover a large surface area up to several acres. The base of these ponds is lined with impervious material such as plastic. Wastewater is held in these large ponds for a certain number of days and then pumped out. Lagoons or ponds are suitable when sufficient land is available. Two common types of lagoons used in treating food processing wastewater are anaerobic lagoons and aerobic lagoons.

In anaerobic lagoons, the breakdown of organic matter involves two steps. In the first step, acid-producing bacteria break down organic matter into compounds such as fatty acids, aldehydes, and alcohols. The second step involves bacteria that convert these compounds into methane, carbon dioxide, ammonia, and hydrogen. Anaerobic ponds are typically 3–5 m deep and mostly devoid of oxygen.

In aerobic lagoons, mechanical systems are used for complete mixing and aeration of the wastewater. With excess oxygen, the microbial growth is under aerobic conditions. High concentration of dissolved oxygen is maintained in the wastewater by aeration as well as the growth of algae. As bacteria break down the organic matter, nutrients become available for more algae to grow. The photosynthetic activity of algae helps maintain aerobic conditions. Aerobic lagoons are shallow in depth (around 1 m) so that sun rays can penetrate to the bottom of the lagoon to promote the growth of algae. Case studies involving use of lagoons in the treatment of different food processing wastewater are presented in Environmental Protection Service (1979b).

Microbial activity during biological treatment of wastewater generates solid material. Sedimentation procedures, as described in previous sections, are used to settle suspended solids. The solid material removed from the sedimentation tanks is commonly referred to as biological sludge. The role of bacteria in wastewater processing and the rate of kinetics of microbial activity are elaborated by Liu (2007).

Another commonly used method for biological treatment of food processing wastewater is a trickling filter. A trickling filter is a large tank containing the following components:

- an inert filter medium (such as gravel, stones, wood, or plastic particulates) with microorganisms attached to it forming a slime layer or biofilm;
- a water distribution system;
- a pipe that conveys incoming wastewater to a water distribution system so that water can uniformly trickle down through the filter medium;
- an under-drain system to support the filter medium and ensure that oxygen is uniformly available throughout the tank.

A trickling filter is an example of a film flow system whereby a thin film of wastewater flows over the biofilm attached to the filter medium. As the wastewater is allowed to trickle through the filter medium, the microorganisms attached to the filter medium in the biofilm utilize the organic matter. To avoid clogging of the filter medium, wastewater undergoes some primary treatment to remove suspended solids and other coarse material before it is fed to the trickling filter.

Around the world, the cost of water for food processing continues to increase due to competitive demands for water by urban areas as well as changing climatic conditions with periodic droughts. Regulations governing wastewater disposal have become stricter, adding to the cost of disposing wastewater generated by the processing plants. For both environmental and economic reasons, there is an increasing need to reduce water use in food processing plants. There are considerable opportunities to reuse water within a food processing plant. Recycling water from one operation to another, with proper treatment of water between the operations, would help achieve this goal (Maté and Singh (1993).

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