Chapter 3
Mechanical Transport and Storage Equipment

3.1 Introduction

Mechanical transport of food materials may be divided into fluid and solid transport. The mechanical transport of air, gases, and vapors is carried out by fans, blowers, compressors, vacuum pumps, and ejectors, which are discussed briefly in Appendix D (Utilities). For the transport of liquids, semifluids, and suspensions, pumps are used. The transport of fluid foods by pumping in process pipelines is a well-developed technology, based on the theory of fluid mechanics, and applied extensively in the chemical process industries (Perry and Green 1997). The mechanical transport equipment is often used in combination with other food processing equipment, such as heating and cooling of water, air or steam, and fluidization and transport of particles.

The transport of solid foods in suspension (hydraulic and pneumatic transport) is based partly on theory and partly on practical experience. Mechanical transport in conveyors is mostly empirical, based on experience, taking into consideration the physical/mechanical properties of the food materials. Furthermore, in transport of balk or packed products, mobile vehicles and cranes may be used (see vii, page 109).

Storage equipment is used extensively for liquid, semifluid, and solid food materials. The design and construction of food storage equipment is based on practical experience and economic materials of construction, taking into consideration the sensitivity of food quality to temperature and environmental conditions and the strict public health requirements for food products.

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3.2 Mechanical Transport Equipment

3.2.1 Fluid Food Transport Equipment

The transport of fluid foods (liquids, emulsions, suspensions of particles, pulps) requires special mechanical equipment, like pumps, pipes, valves, and fittings. In addition to the mechanical and engineering aspects, the food handling equipment must meet the strict hygienic (sanitary) requirements, which will insure the quality and safety of the processed food products. The nature (composition) of the liquid must also be considered, avoiding damage or disintegration (e.g., fat separation in milk).

3.2.1.1 Rheological Properties

The design of fluid piping and pumping systems requires rheological (viscometric) data for the food materials being transported (Steffe and Rao 1992; Steffe and Singh 1997; Rao 1999; Saravacos and Maroulis 2001).

For Newtonian fluids, the viscosity η (Pa s) is constant, i.e., independent of the shear rate γ (s^{-1}), according to the Newton equation of fluid flow:

$$\tau = \eta\gamma \tag{3.1}$$

where τ is the shear stress (Pa).

Most food fluids are non-Newtonian materials, for which the shear stress is a nonlinear function of shear rate. For time-independent fluid foods, the following models are commonly used:

$$\text{Bingham plastic:} \quad \tau = \tau + \eta\gamma \tag{3.2}$$

$$\text{Power law:} \quad \tau = K\gamma^n \tag{3.3}$$

$$\text{Herschel-Bulkley:} \quad \tau = \tau_o + K\gamma^n \tag{3.4}$$

where τ_o (Pa) is the yield stress, K (Pa s^n) is the consistency coefficient, and n (–) is the flow behavior index of the fluid material. The Herschel–Bulkley model is also known as the generalized Bingham fluid or the yield-power-law model.

Table 3.1 shows some examples of rheological categories of Newtonian and non-Newtonian foods. Pseudoplastic, dilatant, and Bingham-plastic foods are time-independent materials, i.e., their rheological properties (constants) are not affected by the time of shearing. Thixotropic (time-thinning) and rheopectic (time-thickening) materials are time-dependent non-Newtonian materials.

The rheological constants (τ_o, K, and n) are determined from experimental plots of rheological data log (τ) versus log(γ).

Table 3.1 Examples of rheological categories of foods

Rheological category	Food material
Newtonian food	Water, vegetable oil, honey
Non-Newtonian food	
Pseudoplastic	Concentrated juice, pulp, milk
Dilatant	Dough
Thixotropic	Ketchup
Rheopectic	Mayonnaise
Bingham plastic	Jellies

For laminar flow in a circular pipe of internal diameter (d) and length (L), the Newton equation (3.1) is equivalent to the Poiseuille equation:

$$(d\Delta P/4L) = \eta(8u/d) \tag{3.5}$$

where u (m/s) is the mean velocity of the fluid.

Thus, in a pipe, the shear rate of Newtonian fluids can be calculated from the relationships

$$\gamma = (8u/d) = \left(32Q/\pi d^3\right) = \left(32m/\pi\rho d^3\right) \tag{3.6}$$

where Q (m^3/s) is the volumetric flow rate, m (kg/s) is the mass flow rate, and ρ (kg/m^3) is the density of the fluid.

By comparing (3.1) and (3.6), it follows that the shear stress at the wall in pipe flow becomes

$$\tau_w = (d\Delta P/4L) \tag{3.7}$$

In non-Newtonian fluids, the shear rate can be calculated from the Rabinowitsch–Mooney equation (Holland and Bragg 1995):

$$\gamma = (8u/d) = [3/4 + d\ln(8u/d)4d\ln\tau_w] \tag{3.8}$$

The correction factor (in brackets) of (3.8) can be estimated graphically from a plot of experimental flow data (ΔP, Q), converted to (τ_w, γ), using (3.6) and (3.7).

The Reynolds number (Re) in pipe flow for Newtonian fluids is given by the equation

$$\mathrm{Re} = (du\rho)/\eta \tag{3.9}$$

The generalized Re number for non-Newtonian fluids is estimated from the equation (Steffe and Singh 1997):

$$Re = \left[\left(d^n u^{2-n}\rho\right)/\left(8^{n-1}K\right)\right][(4n)/(3n+1)] \tag{3.10}$$

An alternative method of calculation of the Re for non-Newtonian fluids is to estimate the apparent viscosity (η_a) from (3.11) and use it in (3.9):

$$\eta_a = K\gamma^{n-1} \quad (3.11)$$

Most fluid foods are pseudoplastic ($n < 1$), and their apparent viscosity (η_a) decreases as the shear rate (γ) is increased (shear-thinning materials). Very few fluid foods are dilatant ($n > 1$).

Temperature has a negative exponential effect (Arrhenius) on η, K, and η_a, while concentration (C, kg/m^3) has an exponential positive effect, according to equation (Saravacos and Maroulis 2001)

$$\eta = \eta_o \exp[(E_a/RT) + BC] \quad (3.12)$$

where E_a (kJ/mol) is the activation energy for flow, T is the absolute temperature, and B is a constant.

Concentration has a small negative effect on the flow behavior index, while temperature has a negligible effect. In general, clear juices and food fluids have a high activation energy (about 60 kJ/mol), while food suspensions and pulps have low (E_a) values, even below 14.4 kJ/mol, the activation energy of water.

In fluid flow applications, time-dependent non-Newtonian fluids (thixotropic or rheopectic) can be treated as power-law fluids, assuming a constant shearing time. Similarly, the flow of viscoelastic fluids can be approximated by the power-law model, using empirical rheological constants.

Table 3.2 shows some typical rheological data of fluid foods, which can be used in the design of food pumping and piping systems (Rao 1999; Saravacos and Maroulis 2001). For design calculations, most fluid foods can be approximated by the power-law model, and therefore, the rheological constants (K, n) at a given temperature can define the flow of the product. The activation energy (E_a) can be used to convert the flow data to other temperatures.

Table 3.2 Characteristic of rheological constants of fluid food at 20 °C

Fluid food	n	K (Pa s^n)	E_a (kJ/mol)
Orange juice, 12 °Brix	1.00	0.002	16
Orange juice, 42 °Brix	0.82	0.100	30
Orange juice, 65 °Brix	0.76	0.400	40
Clarified apple juice, 60 °Brix	1.00	0.060	50
Apple sauce, 12 °Brix	0.29	26.000	15
Tomato concentrate, 20 °Brix	0.33	25.000	20
Tomato concentrate, 30 °Brix	0.30	120.000	15
Vegetable oil	1.00	0.080	45

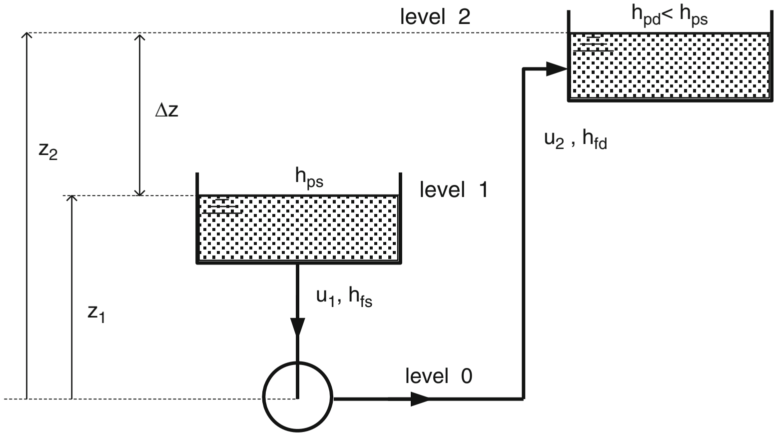


Fig. 3.1 Pumping system

3.2.1.2 Mechanical Energy Balance

The energy required for transporting a fluid through a piping system or the pump work W (J/kg) is calculated from the Bernoulli equation or the Mechanical Energy Balance Equation (MEBE). Figure 3.1 shows a simple system, in which a pump transports the fluid from a lower level z_1 (m), pressure P_1 (Pa), and velocity u_1 (m/s) to the corresponding higher levels (z_2, P_2, and u_2). The reference level here is the pump inlet. The MEBE equation for the pumping system, including pump work and friction losses, is (Holland and Bragg 1995)

$$W_\mathrm{p} = \Delta P/\rho + \Delta u^2/\alpha + g\Delta z + E_\mathrm{f} \tag{3.13}$$

where W_p is the pump work per unit mass of the fluid (J/kg), ρ is the density of the fluid (kg/m^3), and

$$\Delta P = P_1 - P_2, \quad \Delta u^2 = u_2^2 - u_1^2, \quad \Delta z = z_2 - z_1, \quad g = 9.81\,\mathrm{m/s^2}\,(\text{gravity constant}),$$
$$E_\mathrm{f} = \text{friction losses (J/kg)}, \quad \text{and} \quad \alpha = 1\ (\text{laminar flow}), \quad \alpha = 2\ (\text{turbulent flow})$$

The MEBE equation (3.13) can be written in the form of "heads," i.e., heights (elevations) of the liquid being pumped in meters (m):

$$H = h_\mathrm{p} + h_\mathrm{u} + \Delta z + h_\mathrm{f} \tag{3.14}$$

where H, h_p, h_u, h_f and Δz are, respectively, the pump (total), pressure, velocity, and friction heads (m) and Δz is the level height (Fig. 3.1) defined as

$$H = W_\mathrm{p}/g; \quad h_\mathrm{p} = \Delta P/\rho g, \quad h_\mathrm{u} = \Delta u^2/\alpha g, \quad \Delta z = z_2 - z_1 \quad \text{and} \quad h_\mathrm{f} = E_\mathrm{f}/g$$

In most food processing operations, the velocity head is small, compared to the important heads of pressure and friction losses. This is because the inlet and outlet velocities of food fluids are relatively low and usually close to each other, e.g., pumping from tank to tank. Low velocities are preferred in pumping, because of the potential mechanical damage of food quality at high velocities and shear rates.

The total head (H) of a pumping system is defined by the equation

$$H = h_{\mathrm{d}} - h_{\mathrm{s}} \tag{3.15}$$

$$h_{\mathrm{d}} = h_{\mathrm{sd}} + h_{\mathrm{pd}} + h_{\mathrm{fd}} \tag{3.16}$$

$$h_{\mathrm{s}} = h_{\mathrm{ss}} + h_{\mathrm{ps}} - h_{\mathrm{fs}} \tag{3.17}$$

where h_{d} = discharge head; h_{s} = suction head; $h_{\mathrm{sd}} = u_2^2/2g + z_2$, static discharge head; and $h_{\mathrm{ss}} = u_1^2/2g + z_1$, static suction head; $h_{\mathrm{pd}} = P_2/\rho g$, discharge surface pressure head; $h_{\mathrm{ps}} = P_1/\rho g$, suction surface pressure head; and h_{fd}, h_{fs} discharge and suction friction head, respectively.

The theoretical power (P_{o}, kW) required to pump a fluid at a rate m (kg/s) and pump work (W_{p}) is

$$P_{\mathrm{o}} = mW_{\mathrm{p}} = mHg \tag{3.18a}$$

The actual power (P_{a}), required by the electric motor to move the pump, is higher, and it can be estimated by dividing (P_{o}) by the mechanical efficiency η_1, of the pump (e.g., 70 %) and the motor efficiency η_2 (e.g., 90 %).

$$P_{\mathrm{a}} = P_{\mathrm{o}}/\eta_1\eta_2 \tag{3.18b}$$

3.2.1.3 Friction Losses

The energy losses due to friction in a pipeline (E_{f}) are estimated from the empirical equation

$$E_{\mathrm{f}} = 4f\left[\left(\sum L_{\mathrm{e}}\right)/d\right]\left(u^2/2\right) \tag{3.19}$$

where f is the friction (Fanning) factor, which is a function of the Re number and the flow behavior index of the fluid (n), and $\left(\sum L_{\mathrm{e}}\right)$ is the summation of the equivalent lengths of the pipeline, valves, and fittings. The L_{e} values of the various fittings are given in the literature (Walas 1988; Perry and Green 1997) as function of the diameter (d) of the pipeline (Table 3.3).

An alternative method of estimating E_{f} is to calculate first the friction loss of the straight pipeline, using $\sum L_{\mathrm{e}} = L$ in (3.19), and then estimate the friction losses in the various fittings, using empirical factors k_{f} from the literature (tables or nomograms) for the equation

Table 3.3 Equivalent lengths (L_e) for pipeline fittings (pipe internal diameter, d)

Pipeline fitting	L_e/d
45° Ell (L)	15
90° Standard ell (L)	32
Tee (T), line flow	60
Tee (T), branch flow	90
Gate valve, open	7
Globe valve, open	300

$$E_f = k_f\left(u^2/2\right) \quad (3.20)$$

The friction coefficient (f) of the Fanning equation (3.19) is estimated from empirical equations or diagrams of the literature. For Newtonian fluids in laminar flow ($Re < 2100$)

$$F = 16/Re \quad (3.21)$$

For Newtonian fluids in turbulent flow, the standard (f, Re) diagram of the literature is used (Perry and Green 1997). Since, for hygienic reasons, food pipes are generally smooth, the roughness factor in the diagrams is neglected. Alternatively, the factor (f) can be estimated from the simplified equation (explicit in f)

$$\left(1/f^{1/2}\right) = 3.6\log(Re/7) \quad (3.22)$$

For non-Newtonian fluid foods, in laminar flow (the usual case of fluid foods), the friction factor can be estimated from an empirical equation, analogous to (3.21)

$$F = 16/\psi Re \quad (3.23)$$

where Re is the generalized Reynolds number (3.10) and ψ is a correction factor.

In pipeline calculations, most fluid foods can be approximated by the power-law model, for which the correction factor is $\psi = 1$. For fluids described by the generalized Bingham-plastic (Herschel–Bulkley) model, the correction factor is given by empirical equations and diagrams (Walas 1988; Steffe and Singh 1997) as a function of the Re and Hedstrom (He) numbers. The (He) number is defined by the equation

$$He = \left(\tau_o d^2 \rho\right)/(\eta_B)^2 \quad (3.24)$$

where τ_o is the yield stress (Pa) and η_B is the Bingham (apparent) viscosity (Pa s).

The (f, Re) diagrams, for various He numbers, can also be used for turbulent flow of non-Newtonian fluid foods, i.e., at $Re > 3000$. The transition Re number (from laminar to turbulent flow) in Newtonian liquids is taken as 2100, while in non-Newtonian fluid foods, it depends on the flow behavior index (n), varying from 1500 to 2500 (Steffe and Singh 1997).

Table 3.4 Classification of food processing pumps

Pump category	Type of pump	
Positive displacement	Reciprocating pumps	Piston
		Diaphragm
	Rotary pumps	Progressive cavity
		Twin screw
		Gear
		Lobe
		Vane
		Peristaltic
Centrifugal	Radial flow pumps	
	Axial flow pumps	
Other	Jet pumps	
	Air-lift pumps	

3.2.1.4 Pump Characteristics

Pumps are mechanical devices used widely for transporting fluids and suspensions through piping systems in various processing and auxiliary plant operations. Main types of pumps used in food processing operations are the centrifugal and the positive displacement pumps (PDPs). Some other types of pumps, such as the injection and the air-lift pumps, are also used in special cases (Table 3.4).

As a general rule, the centrifugal pumps are used mainly for transporting large volumes of fluids, while the PDPs are more frequently used in volumetric flow (dosing) of liquids and in achieving higher pressures. The centrifugal pumps are further divided into radial flow and axial flow pumps. The distinction is based on the discharge of the fluid with respect to the axis of rotation of the pump. The PDPs are divided into reciprocating and rotary pumps. Common PDPs, used in food processing, are the progressive cavity, the eccentric screw, and the diaphragm pumps. Examples of rotary pumps are the gear, the lobe, the vane, and the peristaltic pumps.

Centrifugal Pumps

The centrifugal pumps (Fig. 3.2) are based on the conversion of velocity head into pressure head of the fluid by a rotating impeller (rotor). Most centrifugal pumps are of the radial volute type, i.e., the fluid enters the center of the impeller and it is discharged into a progressively expanding spiral.

The operation of centrifugal pumps is connected directly to an electric motor, and they operate at a fixed speed, e.g., 1750 RPM (or $1750/60 = 29.2\ s^{-1}$). They can operate at various capacities by regulating the opening of the discharge valve. The centrifugal pumps are not self-priming, unless special constructional measures

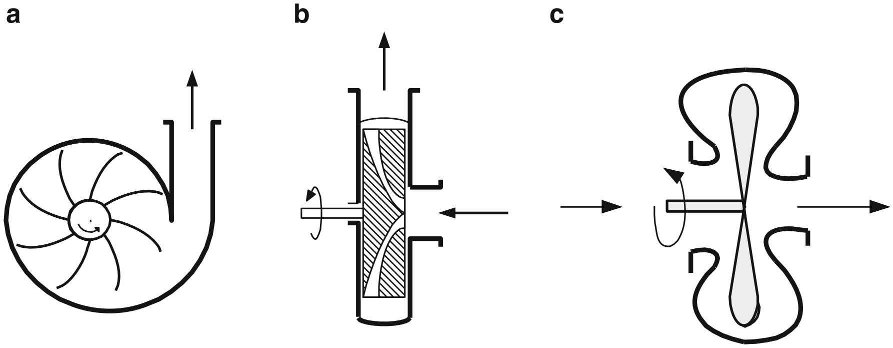
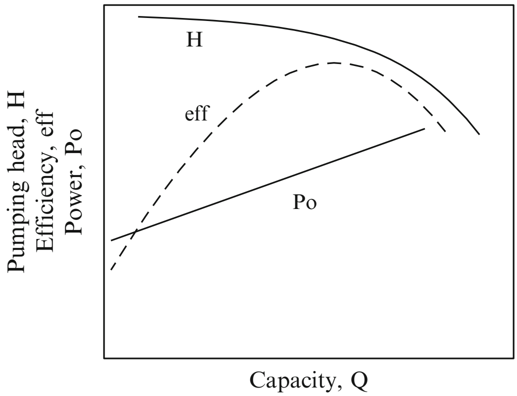


Fig. 3.2 Centrifugal pumps: (**a**, **b**) radial flow; (**c**) axial flow

Fig. 3.3 Characteristics of centrifugal pump



are taken. Such measures are, e.g., the installation of valves at the suction side of the pump and the filling of the pump with liquid before starting its operation.

The centrifugal pumps are used extensively for pumping simple (Newtonian) liquids, like water, aqueous solutions, juices, and oils, but can be also used for pumping liquids containing small particles. Pumps of special impeller and casing design can handle complex non-Newtonian fluids and suspensions of relatively low apparent viscosity. The vanes of the impellers of the centrifugal radial flow pumps usually run backwards for reducing the pump instability, which for constant speed is related to the number of intersections of the capacity curve $H = f(Q)$ with the operating curve $H =$ constant (Fig. 3.4). Centrifugal pumps are preferred, wherever applicable, because of their simple construction, easy maintenance, and low cost.

Characteristic pump curves (Fig. 3.3), provided by the manufacturer or obtained from experimental tests (AIChE 1964), show the pump head (H, m), pump efficiency (%), and pump power (P_o, kW) as functions of the volumetric pump capacity (Q, m^3/h). Note that the pump capacity is often expressed in US gallons per minute, GPM (1 GPM = 0.227 m^3/h). It should be noted that centrifugal pumps can operate

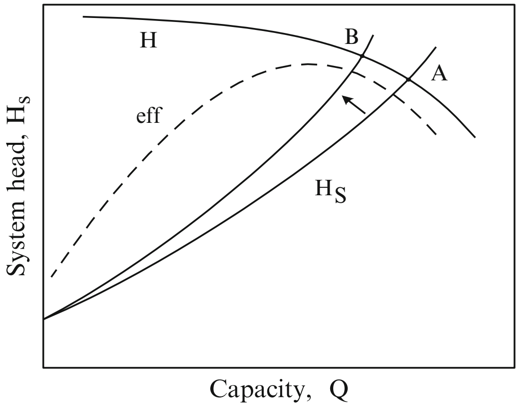


Fig. 3.4 Operation of centrifugal pump

without mechanical damage at zero capacity ($Q = 0$), i.e., with the discharge valve completely closed, obtaining the maximum head.

The head (H_s) of the pumping system is a nonlinear function of the pump capacity (Q), according to (3.14). The normal operating point (A) of a given pump is the intersection of the pump head with the system head (Fig. 3.4). In a normal operation, the operating point (A) should be to the right of the maximum efficiency, so that any reduction in pump capacity will result in increased efficiency. This effect is illustrated by a throttling operation of the centrifugal pump, i.e., partially closing the discharge valve, resulting in a shift of the operating point from (A) to (B).

The following equations (pump laws) relate the centrifugal pump characteristics, capacity (Q), head (H), pump power (P_o), speed of rotation (RPM), and impeller diameter (d):

$$(Q_1/Q_2) = (\mathrm{RPM}_1/\mathrm{RPM}_2)(d_1/d_2)^3 \tag{3.25}$$

$$(H_1/H_2) = (\mathrm{P\Pi M}/\mathrm{P\Pi M}_2)^2(\delta_1/\delta_2)^2 \tag{3.26}$$

$$(Po_1/o_2) = (\mathrm{RPM}_1/\mathrm{RPM}_2)^3(d_1/d_2)^5 \tag{3.27}$$

These relationships can be simplified for the cases of constant impeller diameter (d) and constant rotating speed (RPM).

The pumping head or the capacity of centrifugal pumps can be increased by serial or parallel assembly of pumps (Fig. 3.5). In several cases, this can be also achieved by using multiple-stage pumps. A two-stage small radial flow centrifugal pump, e.g., with a capacity 50 m^3/h at 1500 RPM, can pump up to a head of 20 m. If an 8-stage similar pump is used, the pumping capability increases to 100 m. Larger one-stage radial flow centrifugal pumps can pump, e.g., 2000 m^3/h at 30 bar, or more when more stages are used. In comparison to the radial centrifugal pumps, the axial centrifugal pumps may have up to a 40-fold capacity, at pressures not

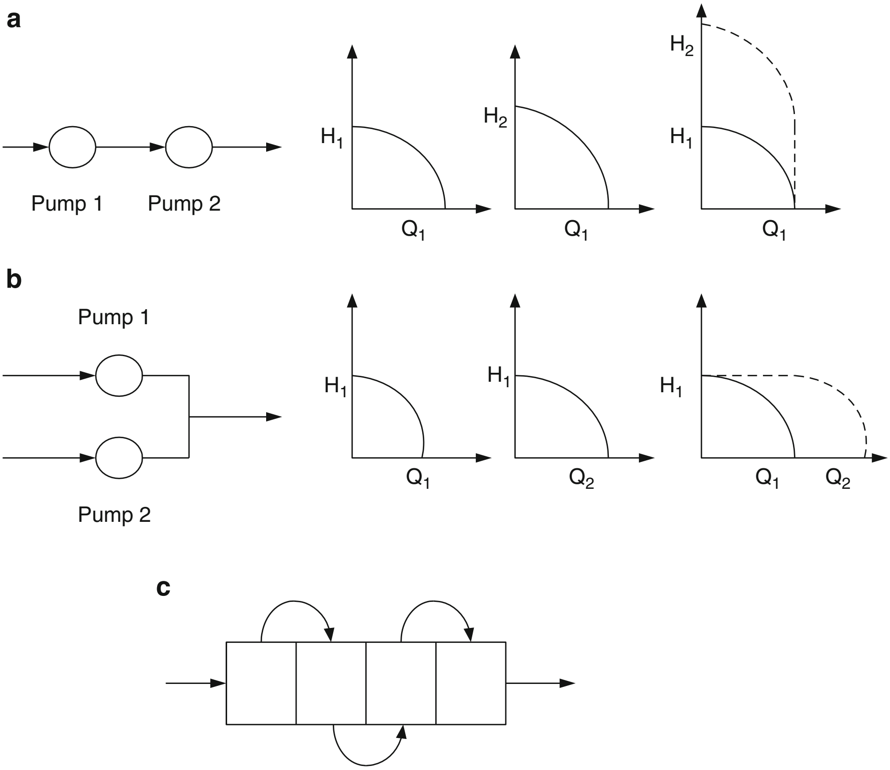


Fig. 3.5 Combination of pumps: (**a**) serial, (**b**) parallel, (**c**) multistage

exceeding 3–4 bar. The efficiency of both types of pumps increases with their capacity (Walas 1988).

The Net Positive Suction Head (NPSH) is an important characteristic of centrifugal pumps, which insures that pumped fluid is available at the suction level of the pump. NPSH is defined by the equation

$$\mathrm{NPSH} = h_s - h_{vp} \tag{3.28a}$$

where h_s is the suction head (m) and $h_{vp} = P_v/\rho g$ the vapor pressure head (m) of the liquid at the suction of the pump. P_o is the vapor pressure of the liquid at the suction temperature. It must be noted that the suction head (h_s) includes the suction velocity, pressure, elevation, and friction heads (3.17). The elevation (z_1) will be negative if the suction surface is below the suction level.

For efficient pump operation, the NSPH should be positive, i.e., $h_s > h_{vp}$, or

$$P_1/\rho g + u_1^2/2g + z_1 - h_f > h_{vp} \tag{3.28b}$$

For boiling liquids, $P_1 = P_v$ and $P_1/\rho g = h_{vp}$ and, therefore, $u_1^2/2g + z_1 > h_f$. Since the liquid velocity at the suction level (u_1) is usually low, the suction surface level

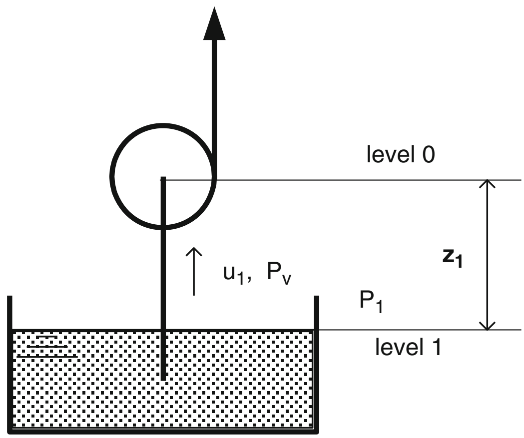


Fig. 3.6 NPSH and cavitation in a centrifugal pump

should be positive ($z_1 > 0$) and higher than the friction head ($z_1 > h_f$). Practically, this means that the suction friction head should be minimized, e.g., by using a large diameter suction entrance, without valves and fittings, and locating the pump at the bottom of the process vessel (e.g., an evaporator).

When the NPSH is negative, the operation of the pump will be difficult and erroneous, because of cavitation problems. In pumping of liquids, cavitation must be avoided. It occurs when vapor bubbles within a liquid, caused by constructional patterns, turbulence, etc., collapse suddenly due to condensation, resulting in a localized low pressure. The collapsing is followed by noise and vibration. Cavitation, besides reduction of the pumping efficiency, produces also stresses on the material of the pumping equipment, causing, in extreme cases, a breakdown.

Figure 3.6 shows diagrammatically a pumping system, in which cavitation may take place. The suction of the pump is above the liquid level ($z_1 < 0$), and the NSPH may become negative when the suction pipe is long with high friction head, when the temperature of the liquid is high or at the boiling point ($P_1 = P_v$), and when the liquid is at reduced pressure (vacuum). In these cases, the pump should be located below the liquid level ($z_1 < 0$), assuring a positive NPSH.

NPSH data for a given pump should be provided by the pump manufacturer. The NPSH in a given pumping system should be calculated in the following cases (Bhatia 1982): (1) when the pump is installed at an appreciable height above the suction liquid level, (2) when the pump suction is connected to a tank under vacuum, (3) when the liquid has a high vapor pressure (volatile liquid), (4) when the suction line is very long, and (5) when the pumping system is at an altitude considerably higher than the sea level (low atmospheric pressure).

Positive Displacement Pumps

The PDPs trap a volume of fluid, and they force it out mechanically against the existing process pressure. Their efficiency is higher than that of centrifugal pumps

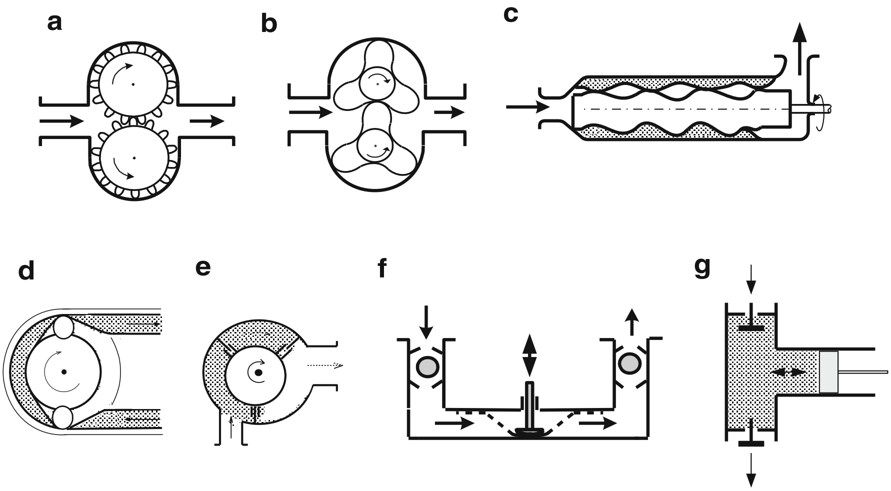


Fig. 3.7 Positive displacement pumps: (**a**) gear, (**b**) lobe, (**c**) progressive cavity, (**d**) peristaltic, (**e**) vane, (**f**) diaphragm, (**g**) piston

(Walas 1988). The most common PDPs used in food processing are the rotary pumps, with rotating gears, lobes, screws, etc. (Fig. 3.7). Reciprocating PDPs, such as piston (plunger), diaphragm, and peristaltic pumps, are used in limited applications. All PDP pumps are self-priming, with no NPSH or cavitation problems.

The rotary PDPs have no valves, and the liquid flow is continuous. The progressive cavity or eccentric screw pumps consist of a metallic screw rotor, rotating within a rubber or elastomer stator. These pumps are usually used for a gentle pumping of viscous fluids, which may also contain significant amounts of particles or pieces. They are easily disassembled for cleaning, but their weak point is the reduction of their efficiency, accompanied by stator wear. Such pumps can be used in pumping, e.g., 8 m^3/h at a pressure up to 80 bar, or 400 m^3/h at a pressure up to 6 bar. The lobe pumps are used for pumping products similar to those pumped by the progressive cavity pumps. Normally, they are used to pump 20–200 m^3/h, at pressures up to 25 bar. The lobe pumps can pump liquids in both directions. The rotation speed depends on the volume pumped, and it usually varies between 20 and 500 RPM.

The function of the gear, screw, and lobe pumps is similar. In the gear pumps, two gears rotate in counter direction as indicated in Fig. 3.7, forwarding the fluid that enters the gap between the gear teeth. The capacity of both types of pumps is similar; however, the pressure achieved by the gear pumps can be higher (up to 100 bar). In the twin-screw pumps, two rotating parallel screws forward the fluid along the axis of the screws. The twin-screw pumps can pump liquids of a wide viscosity range (1–10^5 mPa s). Their flow is similar to that of piston pump with infinite long stroke. The lobe pumps work in a similar way with the gear pumps, but they have rotating lobes instead of gears.

The advantages of the gear, lob, and progressive cavity pumps:

1. Continuous flow without turbulence and vibration.
2. High suction force.
3. Coupling with high rotation motors (up to 5000 RPM) is possible.
4. Pumping control by the rotation speed.
5. Reverse pumping is possible.

Lobe pumps are usually made of stainless steel. They can pump liquids of viscosities up to 100 Pa at capacities from 1 to 700 m^3 and differential pressures up to 30 bar. They provide pulsation-free flow and they conform to the 3-A and EHEDG hygienic standards.

The three types of rotary RDPs can be used in dosing applications. The gear and the twin-screw pumps are used in the chocolate, gelatin, fat, and molasses processing industry. At relatively low pressure (e.g., 15 bar), they can pump high volumes of fluids, e.g., 2000 m^3/h at about 15 bar, while at threefold pressure, increase of pressure will reduce the flow rate by tenfold.

The vane pumps consist of a cylindrical chamber/shell in which vanes rotate. The chamber is divided into compartments by radially placed vanes. The vanes are assembled on an eccentrically placed rotor, and they are flexible in the radial direction of the chamber, securing water tightness between the compartments. The volume of the compartments varies as the rotor moves. The sucked fluid is discharged at a higher pressure as it is compressed into smaller compartments during rotation. They can be used for pumping of high viscosity fluids containing particles against a short head. Vane pumps, containing oil at the contact surfaces between the vanes and the chamber wall, are used as vacuum pumps in laboratory and small-scale vacuum applications.

The peristaltic pumps consist of a flexible rubber or plastic, friction-resistant tube, and a rotating eccentric device, or an eccentric wheel, with 2–4 smaller wheels adjusted on its periphery. The eccentric device or the small wheels, compress the tube, pushing the liquid, while rotating. The pump is quite simple, since the only essential parts are the rotating device and the tube, which should be replaced when worn out.

The peristaltic pumps are suitable for pumping cream, since no churning takes place. They can also be used in feeding filtrates, crystalline suspensions, and extraction of liquids from vacuum tanks. Their capacity may vary according to the dimensions of the pump and the speed of rotation of the eccentric devices. For a pump of maximal diameter of the rotating parts pressurizing the tube, $d = 40$ cm and pump weight 8 kg, the pumping capacity at 20 RPM is 30 L/h and at 60 RPM is 90 L/h. A pump with a diameter $d = 1$ m (weight 380 kg), at 20 RPM pumps 8000 L/h, while at 60 RPM is 24,000 L/h.

Advantages of peristaltic pumps:

1. Resistance to corrosion
2. Self-priming up to 9 m
3. Not damaged if run dry

4. Precise dosing of liquids
5. Reverse pumping possible
6. Operation at pressures up to 6 bar

The diaphragm pumps consist of a reciprocating plastic or rubber membrane, driven by an eccentrically rotating device, which sucks and forwards of a definite liquid volume at each movement. The diaphragm pumps are used in dosing of liquids and in pumping viscous nonhomogeneous liquids that cannot be handled by centrifugal pumps. The liquid volume pumped can be higher than that of a single piston pump, but the maximal pressure is about 30 % less than the pressure developed in a single-stage piston pump.

Advantages of the diaphragm pump:

1. Pumping non-homogeneous liquids.
2. Can run dry.
3. No leakage during operation.
4. Can be used for dosing applications, the worn out parts (mainly the membrane), can be replaced easily.
5. They are self-priming.

The reciprocating positive displacement (piston) pumps transport the liquid periodically by alternating suction and discharge strokes, employing special valves. An even fluid flow supply can be achieved by using more stages. The volumetric efficiency of the piston pumps falls with shorter strokes and higher discharge pressure. Accurate regulation is possible when the fluid flow rate is larger than 20 % of the maximum value. The maximal capacity of multistage piston pumps is ten times less than that of centrifugal radial pumps, but their maximal pressure is two to three times higher. Piston pumps can be used for nonhomogeneous products. In single-stage pumps, e.g., pumping 20 m^3/h, the pressure developed may be up to 30 bar. Using multistage pumps, a tenfold increase of the pumped fluid volume can be achieved by a 50-fold increase of the pressure.

Piston pumps are used, e.g., in homogenizing equipment at pressures up to 250–300 bar (Chap. 4) and in high-pressure atomizers at pressures up to 100 bar, e.g., in spray dryers (Chap. 8).

Advantages of piston pumps:

1. Application of high discharge pressures is possible.
2. Can be used in dosing applications.
3. The volume discharged is almost pressure independent.
4. They are self-priming.

The performance characteristics of a rotary PDPs, provided by the pump manufacturer or obtained from experimental tests, are shown in Fig. 3.8. The pump characteristics (capacity Q, efficiency, and power P_o) are usually plotted as a function of the total discharge pressure (AIChE 1968). The rotary PDP should not be operated at zero capacity (completely closed discharge valve), because of the danger of mechanical damage.

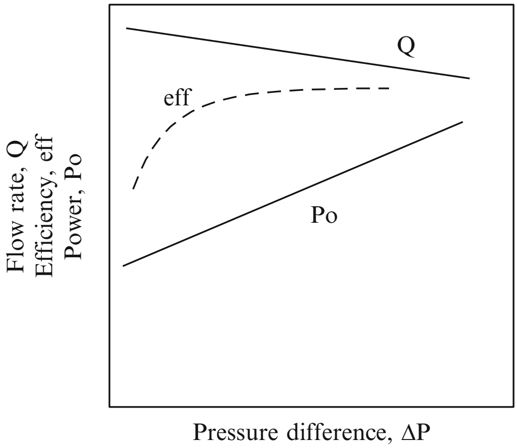


Fig. 3.8 Performance of rotary positive displacement pump

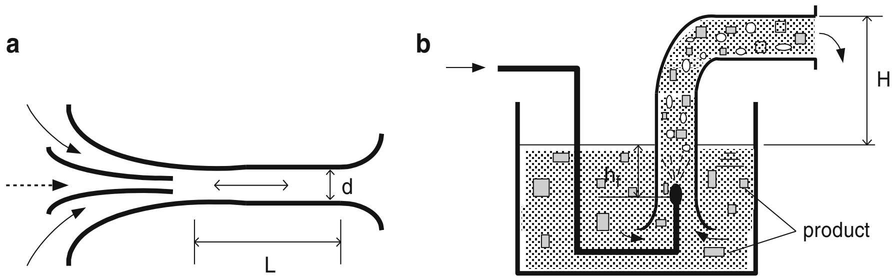


Fig. 3.9 Special pumps: (**a**) injection, (**b**) air lift

Other Pumps

Two pumps of this category are the injection pump and the air-lift or "Mammoth" pump (Fig. 3.9).

The injection pumps consist of a Venturi tube and a nozzle injecting a fluid, usually steam, at high velocity, in the center of the tube (Fig. 3.9). They are often used for feeding steam boilers with recycled hot water and for reducing the pressure (vacuum generation) in food processing equipment, e.g., evaporators (Chap. 8). For a successful operation, the length of the Venturi pump (L) must be about ten times larger than its shortest diameter (d), and the nozzle must be as close as possible to the straight section of the Venturi tube. The efficiency of injection pumps is low (2–15 %), and they can transport, e.g., about 20 m^3/h fluid at 5 bar pressure.

The air-lift pumps are used for transporting liquids or light particles to a short height. They operate with pressurized air that is blown at the lowest part of a tube, immersed in the liquid. The air reduces the specific gravity of the fluid in the tube, resulting in the upstream movement of the liquid and the entrained particles. The maximum height of transport is about 50 m. The transport height (H) depends on the distance between the edge of the air-blowing tube and the fluid level (z_f) and the density of the fluid with (ρ_m) and without air (ρ_f):

$$H = z_f(\rho_f/\rho_m - 1) \tag{3.29}$$

Since the air-lift and the injection pumps do not have mechanical moving parts, they can be used for transporting sensitive food products. The air-lift pumps are almost twice as efficient as the injection pumps.

Requirements for Food Pumps

In addition to the general design and construction requirements, food pumps must meet special requirements, dictated by hygienic (sanitary) design and good manufacturing practices, as outlined in Chaps. 1 and 2.

Stainless steel (304 and 316) is the most widely used construction material, since it meets all of these requirements. Since stainless steel is an expensive material, in several pump applications, some less expensive materials can be used. Carbon steel may be used in special pumps for some preliminary food processing operations, such as hydraulic transport of raw fruits and vegetables.

Special plastic materials are used in some pump parts, e.g., Teflon, FEP (fluorinated ethylpropylene), epoxy resins, and fiber-reinforced plastics. In special applications (e.g., high temperature, corrosive fluids), glass-lined steel and ceramics may be used. Composite construction is sometimes used, e.g., stainless steel for the wet (fluid product) side of the pump and carbon steel for the dry (auxiliary) side (Bhatia 1982).

Hygienic requirements in pump design are presented by Jowitt (1980), Troller (1993), and the various codes, like 3-A (IAMFES 1988). Pumps should be disassembled and cleaned easily. Process parts and pipes should be preferably clamped instead of bolted. Smooth curves and shapes should be used, avoiding dead ends and turbulence-promoting sections. All fluid product parts of the pump should be completely self-draining. The whole pumping system should be suitable for CIP cleaning.

Packings and mechanical seals must be fabricated from food-approved materials, and they should be readily removable for inspection and replacement. The pumps should be installed on sanitary supports, with adequate clearance space to facilitate cleaning and maintenance.

Pump Selection

Selection of the proper pump for a given food processing application is based on the pumping requirements of a particular product and the information on pump characteristics and cost, provided by the pump manufacturer. Pumping requirements include total head (m), volumetric capacity (m^3/h), and product characteristics (composition, density, rheological properties, density, temperature, etc.). Pump characteristics include performance curves (total head, efficiency, and power versus capacity), NPSH, materials of construction, pump dimensions, hygienic features, auxiliary equipment, and pump maintenance.

Pump cost is an important factor in pump selection, but hygienic design and product quality should be considered first. Pump capacity, pumping head, and efficiency are the basic pump parameters.

Centrifugal pumps are inexpensive, and they should be preferred if the food fluid is pumpable, i.e., it has low viscosity, and the product quality is not damaged by the pump impeller. They are especially efficient at high capacities ($Q > 100\ m^3/h$ or 500 GPM) and relatively low heads ($H < 100$ m) (Walas 1988). Volute-type pumps are preferred, and the ratio of the discharge to suction diameters should be about $(d_d/d_s) = 2/3$.

The centrifugal pumps usually are linked directly to electric motors, and there is no need for speed reduction equipment. They are available in several construction materials, and they have low maintenance cost. They cannot run dry (without liquid), and they need some assistance in starting (pump priming). The cost of centrifugal pumps increases linearly with the increase in capacity (Fig. 2.3).

Positive displacement (usually rotary) pumps are suitable for pumping high viscosity food fluids and suspensions. They develop high heads ($H > 100$ m), and they have relatively low capacities ($Q < 100\ m^3/h$). They operate at relatively low seeds (<1000 RPM) and they need some variable speed device (special DC motor or mechanical speed reduction). Maintenance cost is higher than for the centrifugal pumps (gears and rotors more expensive than impellers). The PDPs can run dry, and they are self-priming.

Small PDPs, like diaphragm and peristaltic pumps, are often used as metering pumps for some food ingredients into food processing streams and tanks.

3.2.1.5 Pump Auxiliaries

The main auxiliaries of interest in the design and operation of pumping equipment are the pump drives (motors) and the mechanical seals (Bhatia 1982; Walas 1988).

Electric Motors

Electric motors are used to drive the pumps in most food processing applications. In special cases of large installations, like sugar refineries, where exhaust steam is available, steam turbines may be attached to centrifugal pumps for significant energy savings. Standards and specifications for electric motors are found in special publications of engineering and electrical national and international organizations, like the American National Standards Institute (ANSI), the Institute of Electrical and Electronics Engineers (IEEE), the National Electrical Code (NEC), and the International Electrotechnical Commission (IEC).

Most centrifugal pumps are driven by AC induction-type motors, operating between 900 and 3600 RPM. For variable speed operation, e.g., for PDPs, DC motors may be used. Variable speeds can also be obtained by mechanical speed reduction units attached to constant RPM motors.

The voltage of the electric motor depends on the pump power, varying from 220 to 4000 V for motor power 1–2000 kW, respectively. The required torque for starting the pump should be considered in the selection of the electric motor. Electrical equipment is discussed briefly in Appendix D (Utilities).

Mechanical Seals

Connection of the rotating shaft of a pump to an electric motor should be protected against leaking of the pumped fluid. Two types of seals are used, the stuffing box and the mechanical seal (Bhatia 1982).

The stuffing box consists of packings of rings and sealing materials, like Teflon and graphite, attached tightly on the rotating shaft of the pump. Small amounts of process fluid may leak through the packing, lubricating the rotating shaft.

Mechanical seals, which are more expensive than stuffing boxes, allow little leakage of process fluids, and they meet the stringent rules of Environmental Protection Agency (EPA) and Occupational Safety and Health Administration (OSHA) against toxic substances. They consist of two parts, one stationary attached to the pump casing and the other attached to the rotating shaft of the motor drive. A sealing liquid in the intermediate space is used to lubricate the system. Mechanical seals utilize materials like stainless steel, Teflon, and graphite.

3.2.1.6 Process Piping and Valves

Piping, valves, and pipe fittings constitute a significant part of the investment in chemical and petrochemical plants, accounting up to 25 % of the fixed investment. Details on these large piping systems are given in Perry and Green (1997), Walas (1988), and Marks (1987). This information is especially important in large food processing plants handling liquids, such as vegetable oils, sugar syrups, and beverages, where large piping systems are installed.

In most food processing plants, handling sensitive fluid foods, like milk, juices, pulps, and soups, piping and valves, is important not only from the engineering standpoint but mostly from the hygienic and quality requirements of the food products.

Piping

The size of pipes is usually characterized by the nominal diameter (nd), which is slightly larger than the outside diameter (od) of the pipe. The thickness of the wall is expressed by the Schedule number, which thus defines the inside diameter (id) of the pipe. Pipe dimensions in literature and manufacturers' tables are given in inches or mm, and they should be converted to SI units (m) for engineering calculations.

Piping codes provide useful information on construction and dimensions of various types of pipes (Bhatia 1982), e.g., ANSI, American Society of Mechanical Engineers (ASME), and American Society for Testing and Materials (ASTM).

Pipes should be distinguished from tubes, used in heat exchangers and in refrigeration, which are identified by the outside diameter (od) and the tube wall thickness.

Stainless steel is the most widely used material of construction for pipes, valves, and fittings. Extruded plastic pipes, like PVC, can be used at temperatures up to 100 °C. In some applications, plastic-coated carbon steel or reinforced plastic pipes may be used.

For hygienic reasons, seamless (extruded) stainless steel pipes are preferred over the welded type. In long permanent pipelines, stainless steel pipes are joined usually by butt welding (without overlapping). In most food applications, the pipes must be occasionally taken apart (disassembled), and some type of joining must be used, like flanged gaskets and mechanical couplings. Mechanical couplings are preferred, because they can be disassembled for inspection and cleaning easier than the flanges. Gasket materials are made of food-grade synthetic elastomers (e.g., Neoprene) and Teflon. Screwed joints of small diameter pipes should be avoided, because they cannot be cleaned and sanitized effectively.

Valves

In the design and applications of food piping systems, an average fluid velocity of 2 m/s is recommended. The cost of pipes is usually expressed on the basis of carbon steel pipe Schedule number 40. The cost of stainless steel 304 and 316 is, respectively, 1.5 and 2.0 times higher (Perry and Green 1997).

Valves control the flow in a piping system by blocking off the flow, by throttling, or by checking the direction of flow (diversion). The gate and the globe valves are widely used in chemical processing of gases and liquids, but they are not acceptable in food pipelines, since they cannot meet the strict hygienic requirements. Special vales, designed for hygienic operation and quick cleaning, are used in food pipelines (Jowitt 1980; Troller 1993), including the diaphragm, the plug and stem, and the flow diversion valves (Fig. 3.10). The diaphragm (membrane) valve is the most

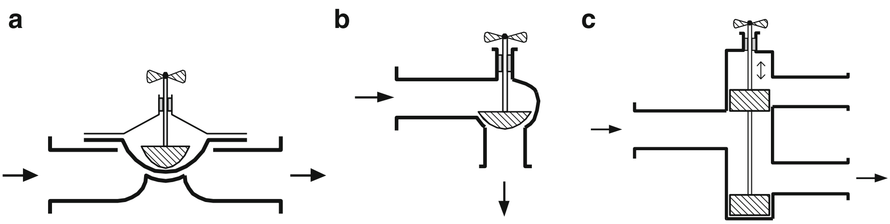


Fig. 3.10 Valves: (**a**) diaphragm, (**b**) plug and stem, (**c**) flow diversion

appropriate, since the fluid food does not come into contact with the opening mechanism of the valve. The diaphragm (membrane) is made of a food-grade plastic material, like Neoprene and Teflon, which should be replaced when worn out.

3.2.1.7 Hygienic Considerations

In addition to the general design and construction requirements, food pumps must meet special requirements, dictated by hygienic (sanitary) design and good manufacturing Practices, as outlined in Chaps. 1 and 2.

Stainless steel (304 and 316) is the most widely used construction material, since it meets all of these requirements. Since stainless steel is an expensive material, in several pump applications, some less expensive materials can be used. Carbon steel may be used in special pumps, used in some preliminary food processing operations, such as hydraulic transport of raw fruits and vegetables.

Special plastic materials are used in some pump parts, e.g., Teflon, FEP, epoxy resins, and fiber-reinforced plastics. In special applications (e.g., high temperature, corrosive fluids), glass-lined steel and ceramics may be used. Composite construction is sometimes used, e.g., stainless steel for the wet (fluid product) side of the pump and carbon steel for the dry (auxiliary) side (Bhatia 1982).

Hygienic requirements in pump design are presented by Jowitt (1980), Troller (1993), and the various codes, like 3-A (IAMFES 1988). Pumps should be disassembled and cleaned easily. Process parts and pipes should be preferably clamped instead of bolted. Smooth curves and shapes should be used, avoiding dead ends and turbulence-promoting sections. All fluid product parts of the pump should be completely self-draining. The whole pumping system should be suitable for CIP cleaning.

Packings and mechanical seals must be fabricated from food-approved materials, and they should be readily removable for inspection and replacement. The pumps should be installed on sanitary supports, with adequate clearance space to facilitate cleaning and maintenance.

Pumps used in food processing should be smooth and without dead ends and other flow obstacles to effective cleaning. The use of progressive pumps, whenever possible, facilitates often cleaning. The pipe bends should be smooth and rounded, with a centerline radius larger than the pipe diameter (Jowitt 1980). Hygienic (sanitary) couplings should be used for easy disassembling and cleaning. Cleaning of pipelines from difficult deposits can be facilitated by "pigging," i.e., pumping a plastic sponge ("pig") through the pipe.

In CIP applications, a turbulent flow of the cleaning/washing fluids is desirable, which is assured by an average fluid velocity of 1.5 m/s. The flow of the cleaning fluid should be against any dead ends in the piping system, which are cleaned by the resulting turbulence.

Pipes should be inclined by about 1 % to facilitate drainage. When not used for some time, they should be dried by passing through hot air. Pipe insulation is necessary for cold pipes, e.g., in refrigeration systems, in order to prevent moisture condensation, which may induce microbial growth.

Other fittings in pipeline systems should be of hygienic design, e.g., electromagnetic flow meters, which are installed with a smoothed bore.

Pipe hangers should be constructed so that they do not contaminate the food plant floor and they can be inspected easily for hygienic requirements (Troller 1993).

3.2.2 Pneumatic and Hydraulic Transport Equipment

Solid food materials, in the form of pieces, granules, and powder, can be transported by pneumatic or hydraulic conveying, i.e., suspending in an inert fluid medium (air or water) and using fluid transport equipment and piping. Pneumatic conveying is widely used in several food processing plants and in food transport and storage facilities. Hydraulic conveying is used for the transport of some agricultural raw materials in food plants.

3.2.2.1 Pneumatic Conveyors

Granular food solids, grains, and powders can be conveyed to long distances through ducts with high velocity air streams. Typical applications include the unloading of granular foods from railroad cars and ships and the transport of such materials within the food processing plant. Food materials handled include wheat, corn, flour, beans, coffee, and granular sugar.

Although pneumatic conveying requires more energy than mechanical conveyors, it is generally preferred for its important advantages, particularly in large, continuous food processing plants. Dilute-phase conveying is normally used in food processing, while dense-phase systems are applied to conveying of inorganic materials, e.g., coal.

Physical and mechanical properties of food materials, needed in the design of pneumatic conveying systems, include particle density, bulk density, particle size distribution, moisture content and hygroscopicity, coefficient of sliding friction (angle of repose), and flowability. Particular care should be taken to prevent fires and explosions of some sensitive food powders (Walas 1988).

Two basic systems of pneumatic conveying are applied, i.e., the air-pressure and the vacuum system (Fig. 3.11). In addition, mixed systems of air-pressure/vacuum conveyors are used (Bhatia 1982; Mills 1990; Perry and Green 1997).

The pressure conveying system receives particulate material from one source and delivers it to more than one place (bins), while the vacuum system can receive material from several sources and deliver it to one receiving bin. Vacuum conveying is more expensive than pressure conveying, but it is preferred in transporting dusty products, since it reduces air pollution and explosion hazard.

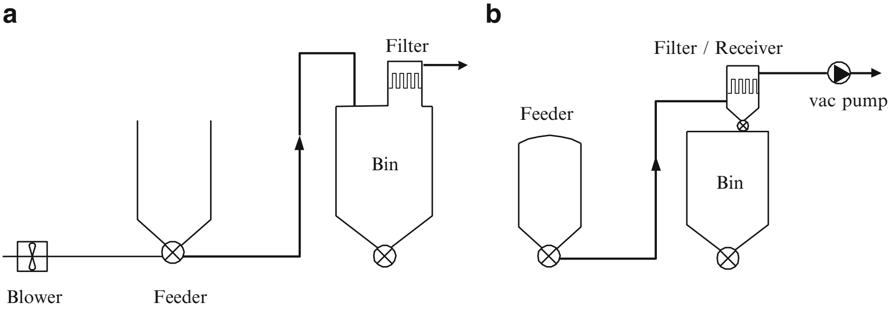


Fig. 3.11 Air-pressure (**a**) and vacuum (**b**) pneumatic conveying systems

Table 3.5 Pneumatic conveying systems for food materials: ρ_b, bulk density; u, velocity; saturation, std m^3 air/kg solids; power, kW h/t; conveying distance, 100 m

	Bulk density	Air-pressure system			Vacuum system		
Food material	ρ_b (kg/m^3)	Saturation	Power	u (m/s)	Saturation	Power	u (m/s)
Coffee beans	673	0.068	1.9	14	0.136	3.2	23
Corn	720	0.074	2.0	17	0.161	3.2	32
Flour, wheat	641	0.062	2.0	11	0.136	3.3	27
Malt	450	0.075	1.8	17	0.155	3.1	30
Oats	400	0.093	2.2	17	0.200	3.9	30
Starch powder	640	0.081	2.2	17	0.186	3.7	31
Sugar, granulated	800	0.093	2.7	18	0.186	4.6	33
Wheat	770	0.074	1.9	17	0.161	3.2	32

Empirical equations, rules, and data, based on experience and on engineering principles of fluid flow, are used in the design of pneumatic conveying systems (Bhatia 1982; Stoes 1982; Walas 1988; Perry and Green 1997). The calculations lead to the estimation of the pressure drop and the required power of the conveyor (see Example 3.2).

Table 3.5 shows typical design data of two pneumatic systems (air pressure and vacuum) for the transport of particulate food materials, such as grain, flour, and granular sugar (Stoes 1982; Walas 1988).

Required data for the design calculations are bulk density, air velocity, and length of the pipeline. The table provides estimated data for the required air saturation of the system (std m^3/kg solids) and the power (kW/t h). It should be noted that the ton in SI units is 1000 kg, while in the USA, the ton is often equal to 2000 lb, i.e., 908 kg.

Table 3.5 shows the significant effect of bulk density on the saturation (carrying air) and power requirements of pneumatic conveying. Thus, air-pressure conveying of wheat flour ($\rho_b = 641$ kg/m^3) requires a power of 2.0 kWh/t, compared to

2.7 h kW/t for granulated sugar ($\rho_b = 800$ kg/m^3). For vacuum conveying, the respective power requirements will be 3.3 and 4.6 kW/t h. It should be noted that in the SI system, the ton is 1000 kg, while ton used in the USA is often equal to 2000 lb, i.e., 908 kg.

The data of Table 3.5 indicate that the power and the carrying air requirements for vacuum conveying are almost double the requirements of air-pressure conveying, evidently due to the higher, nearly double, air velocities in the low-pressure operation. The minimum air velocity is about 15 m/s.

The pneumatic conveying systems of food particles and powders should be designed and operated so that fire and explosion are prevented and eliminated, following strict regulatory and legal requirements.

Explosion hazards exist in air conveying of particles and powders of size lower than 200 μm. Explosion of air/particle mixtures requires a suitable solid concentration and a hot surface. The solid concentration must fall within the explosibility range, e.g., from 50 to 2000 g/m^3. Solid concentrations higher than 5 kg/m^3 (i.e., air saturation lower than 0.2 m^3/kg), used in pressure and vacuum conveying (Table 3.5), are resistant to explosion (Mills 1999).

Hot surfaces, inducing explosion, include sparks, caused by mechanical, electrical, or electrostatic forces, overheated bearings, and welding of piping. The minimum ignition temperatures for sugar, coffee, and cocoa are 350, 410, and 420 °C, respectively. Explosion in closed-conveying systems or tanks can create a rapid rise of pressure up to 7 bar. The collection tanks of the air-conveying systems are the most vulnerable units to explosion damage. Special design and proper relief valves are required.

Although air is used as the normal conveying medium, an inert gas, like nitrogen, may be required for very explosive materials (more expensive operation).

The basic equipment of pneumatic conveyors includes the following units:

1. Air blower, usually of the positive displacement rotary type. The blower provides pressure drops up to 0.8 bar. A similar blower is used in vacuum conveying, with a pressure drop of 0.4 bar.
2. A solid feeder, usually of the rotating valve type.
3. A transfer line (duct), diameter 76.2–178 mm (3–7 in.) Schedule 40, or 200–305 mm (8–12 in.) Schedule 30. Length of the line 100 m or higher.
4. Smooth bends of long radius (r), e.g., $r = 12$ (pipe diameter).
5. Dust collection equipment at the receiving bin (usually filter bags).

3.2.2.2 Hydraulic Conveying

Some agricultural raw materials, transported and stored in bulk in the yard of the food processing plant, are conveyed into the processing area by open water channels and flumes. The floating food materials, e.g., tomatoes, citrus fruit, sugar beets, are transported to the juice extractors by mechanical elevators, which may act also as washing equipment.

Transportation to longer distances against a pressure drop (e.g., to higher elevation) requires pumping and piping systems, specially designed for the particular application. Volute-type centrifugal pumps, with special impellers, which can handle large food pieces, are used. Food materials, like whole fruit, beets, carrots, potatoes, and fish, can be pumped without damage to the quality of the product. The pump may be constructed of expensive stainless steel or the less expensive cast iron, when allowed.

Hydraulic conveying of concentrated slurries (suspensions) is used for the transport of coal particles to long distances (Walas 1988). Empirical equations and data, obtained from such systems, can be utilized in the design of food conveying systems.

The velocity of a suspension in the pipeline should be such that the particles will not settle due to gravity, but at the same time, it should not be too high, which could damage the product quality and require excessive power. The critical velocity (u_c) for this purpose is estimated from the equation (Walas 1988)

$$u_{\mathrm{c}} = 34.6\, C_{\mathrm{v}} d u_{\mathrm{t}} \left[g(S-1)/d_{\mathrm{p}} \right] \tag{3.30}$$

where u_t is the terminal (Stokes) velocity of the largest particle present, d is the pipe diameter, S is the ratio of suspension to liquid densities, C_v is the solid volumetric fraction, and g is the gravity constant. This equation holds for consistent units of both SI and US systems.

An important parameter in the design of hydraulic conveying is the ratio of the pressure drops of the suspension and the liquid which can be calculated from the empirical equation

$$(\Delta\Pi_{\sigma}/\Delta\Pi_{\Lambda}) = 1 + 69\ \Psi_{\omega}\left[\gamma\ \ \delta\ \ (\Sigma - 1)/\theta^{2}\Psi_{\delta}{}^{1/2}\right] \tag{3.31}$$

The drag coefficient C_d is calculated from the equation

$$C_{\mathrm{d}} = 1.333 g\, d_{\mathrm{p}}(S-1)/u_{\mathrm{t}}^{2} \tag{3.32}$$

The design velocity of the suspension (u) is a function of the terminal velocity (u_t) and the Fanning friction factor (f):

$$u = 8.41 u_{\mathrm{t}}/f \tag{3.33}$$

For approximate calculations, the design velocity can be taken as 30 % higher than the terminal (Stokes) velocity (u_t), i.e., $u = 1.3u_t$.

From empirical data, the ratio ($\Delta P_s/\Delta P_L$) is approximately equal to the ratio of the densities of suspension and liquid, i.e., ($\Delta P_s/\Delta P_L$) = ρ_s/ρ_L.

3.2.3 Mechanical Conveyors

3.2.3.1 Introduction

Mechanical conveyors can be classified into motor-driven and gravity conveyors (Table 3.6). The motor-driven conveyors are further classified into steady and vibratory motion conveyors. Mechanical conveying can be steady or time interrupted. Steady (nonstop) conveying can be continuous or pulsated. However, a continuous conveying process is steady when certain mass is transported in definite time intervals. The steady-motion conveyors are distinguished into belt, roll, skate wheel, chain, and screw equipment. The vibratory conveyors can be classified according to the vibration mechanism used, which can be either electromagnetic or eccentric. Gravity conveyors are distinguished into skate, roller, and chute equipment.

Regarding the transport direction of the products, conveyors can be classified as horizontal, inclined, vertical, and combined direction conveyors. Most conveyors are able to convey products in both directions. The vertical conveyors belong to the elevators. The combined direction conveyors carry products, placed on trays, up and down, without changing the initial horizontal position of the trays (Fig. 3.12c). In some cases, a horizontal movement of the trays may follow the up or down motion of the trays. In food processing, the conveyors can be used mainly as transport equipment, or in connection with some processing operation (e.g., freezing or drying of the transported food). When equipment is used for conveying bulk dry products (e.g., corn and cereal grains), the conveying speed must not exceed certain limits (e.g., 2–4 m/s) to avoid dusting. Several conveyors or parts of them (e.g., belt, rolls, etc.) are standardized.

Combination of mechanical and pneumatic conveying can be used in moving boxes, weighing up to 150 kg. Thus, the vacuum forklift can load/unload boxes by application of vacuum, and the vacuum hoist lifting can load and move boxes on a monorail bridge to distances up to 40 m. Pneumatic conveying is described in Sect. 3.2.2 of this chapter, and forklift transport is discussed in Chap. 13.

3.2.3.2 Selection of Conveyors

Mechanical conveying is discussed in the technical literature, e.g., Perry and Green (1997), McCabe and Smith (1976), Walas (1988), Brennan et al. (1990), Huette (1960), and Feustel and Hemendiger (1987). Details on conveyors for specific industrial applications, including materials of construction, standards, performance, and cost, are given in catalogs of equipment manufacturers.

The selection of mechanical conveyors depends on the following factors: (1) type and properties of product to be conveyed, (2) capacity, (3) conveying distance, (4) transport direction, (5) packaging of product, (6) energy required, (7) product heating requirements, (8) hygienic (sanitary) and safety requirement, (9) automation, (10) degree of standardization, (11), flexibility, and (12) environmental impact.

Table 3.6 Conveying and transport systems

Motion	Transport direction	Type of "conveyor"		Auxiliary device
Steady motion	Horizontal and inclined	Belt	Uniform belt	Plain, cross slats
			Segmented belt	Plates, boxes, flights
		Roll		
		Chain	Suspended devices	Hooks, plates, buckets
			Flights	Vertical plates, anchor
			Magnet	Permanent magnet
			Drag	Kart, rolls
		Screw	Ribbon type	
			Blade type	
	Vertical	Chain	Suspended devices	Hooks, plates, buckets
			Flights	Vertical, inclined plates
			Magnet	Permanent magnet
			Drag	Cart, rolls
			Buckets	Fixed, swinging
		Screw	Ribbon type	
			Blade type	
	Combined direction	Chain, cable	Up and down "paternoster"	Tray
		Robot	Pick place	
Vibration	Horizontal	Vertical vibration	Straight trough	Electromagnetic or eccentric drive
		Horizontal vibration		
	Inclined	Vertical vibration		
	Vertical	Vertical vibration	Circular trough	
Gravity	Inclined	Skate	Straight path, (circular)	
		Roll		
		Chute		
	Vertical	Skate	Circular path (Straight)	
		Roll		
		Chute		
Elevators	Vertical	Cable		
		Telescope mast		
Mobile media	Vertical–horizontal	Forklifts		Electric/diesel
	Horizontal	Buggers		Diesel
	Vertical–horizontal	Cranes, hoists		
Hydropneumatic	Vertical–horizontal	Push, pull system	Pumps, tubes,	Pumps, ventilators

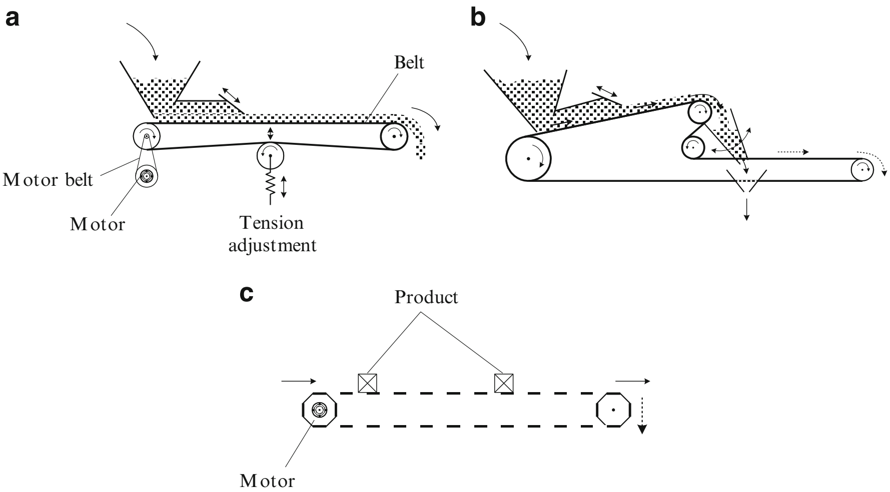


Fig. 3.12 Belt conveyors (**a**), indirect drive (**b**), product removal (**c**)

Uniform Belt Conveyors

Belt conveyors are used to convey, horizontally or inclined, granular products or larger packed or non-packed pieces. They consist of an endless belt driven by a drum (shaft) at one end of the belt, while a second drum lies at the other end (Fig. 3.12). The drum is driven either directly by a geared electrical motor (Fig. 3.12a) or indirectly by a transmission belt (Fig. 3.12b).

The belt is tensioned (stretched) by a spring mechanism, whenever necessary, due to thermal or overweight belt stresses, belt wear, or material accumulation on the shafts (drums), causing effectively an increase of their diameter. There is a wide range of belt dimensions. Belts are 0.4–2.5 m wide, they can be up to 100 m long, and their speed varies between 0 and 4.5 m/s. The length of a tensed belt can be increased by adjustment up to about 2 %. Belt loadings of various industrial products are given by Walas (1988) and conveyor manufacturers. Conveyor belts are usually standardized, e.g., DIN (Deutsch Industrie Normen) (Huette 1960).

The belts are usually made of synthetic rubber, steel, or canvass combined with steel wire and plastic materials (Perry and Green 1997). The belts can also be made of a continuous, meshed, or perforated sheet material. For hygienic reasons, plastics such as solid woven polyester and coated polyester are replacing solid woven cotton used in bakery (dough) conveyor belts. Coated solid woven polyester is resistant to stretch and to bacterial contamination, and it is cleaned and sanitized easily. The polyester is usually coated (surface of interface) with polyurethane or PVC. Its main disadvantages are edge abrasion (fraying) and difficulty in particle entrapment.

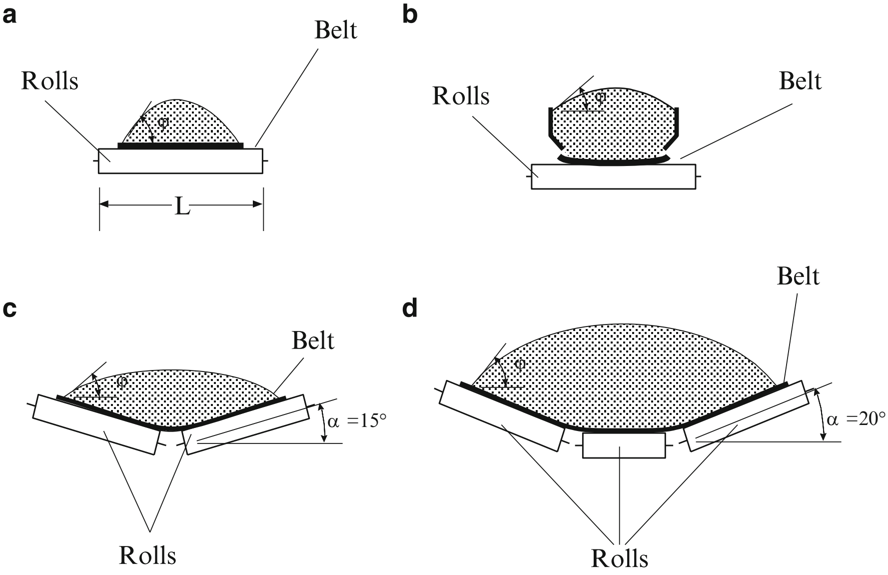


Fig. 3.13 Supporting rolls of belt conveyors

A belt may be as long as required. However, if the length of the belt and the weight conveyed are too large, supporting rolls are necessary (Fig. 3.12a). The distance between the rolls varies according to the type and to the weight of the product. Rolls may be placed in every 0.8–2.0 m (Huette 1960) material.

The inclination of a belt depends on the material transported, and it should not exceed 22°. If the belts are covered with anti-slip material, or have cross slats, the inclination may increase up to 45° (Brennan et al. 1990). If the belts convey bulk product, the material placed on the belt must not exceed the angle of repose, φ (Fig. 3.13). This angle depends on the product, and it is 10–30°. If a lager quantity of bulk product has to be conveyed, as indicated in Fig. 3.13, more rolls are used to support the bended belt. In all cases, the rolls must be 10–20 % longer than the width of the belt (Feustel and Hemendiger 1987).

In the case that conveying is part of a processing operation of bulk products, special support devices take care for the even distribution of the food on the belt. As indicated in Figs. 3.12c and 3.14, it is possible to remove part or the whole conveyed food, at any position of the belt. Short belt conveyors can be part of a continuous weighing system (Chap. 13).

A special case of uniform belts is the magnetic conveyor. It is used in conveying empty, e.g., from a storage room to the filling station. It consists of a steel belt, rolling in front of a magnetic plate. The cans remain on the belt as long as the magnetic plate is on the other side. In such a conveyor, a 2 kW motor can transport, e.g., 600 cans per minute. Besides the significant output, an additional advantage of the magnetic conveyors is the low noise during transport.

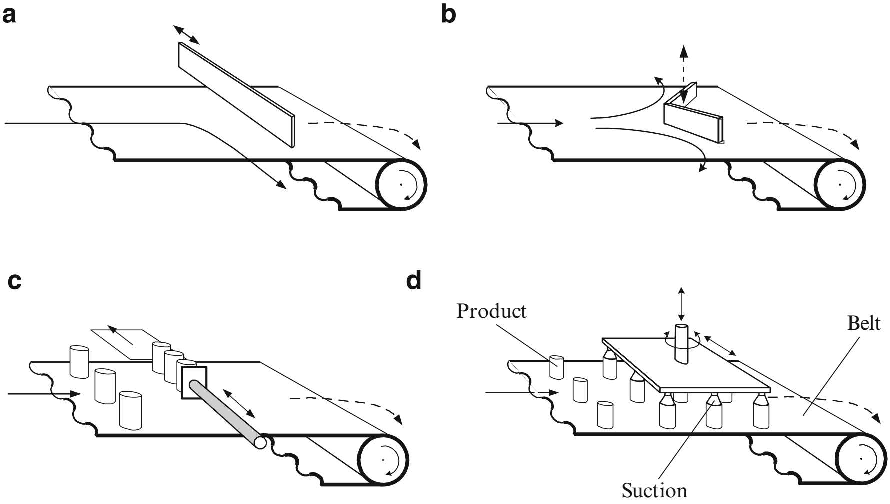


Fig. 3.14 Removal of products from belts

Advantages of the uniform belt conveyors:

1. Large capacity
2. No damage of transported material
3. Relatively low energy consumption
4. Possibility to remove the product at any place of the belt
5. Low maintenance cost
6. Low noise

The disadvantages include:

1. Not suitable for curved paths
2. Inclination restricted
3. Not suitable for dusty products (powders)
4. Increased cost when the conveying distance is reduced

Segmented Belt Conveyors

The segmented belts consist of adjoined segments, usually placed parallel to each other, as tightly as possible. Endless chains or cables, rolled on drums (shafts), drive the segments (Fig. 3.12d). As indicated in Fig. 3.15, the segments may be troughs (a), aprons (b), plates (c), or discs (d). In food processing, the most common types of segmented belts are the steel plate belts. They are used when too heavy products are to be conveyed, or when the temperature during conveying is higher than 100–120 °C, as, e.g., in belt ovens or belt can pasteurizes. The segmented belt can move on slide bars or on rolls at a maximum speed of 1.5 m/s (Huette 1960).

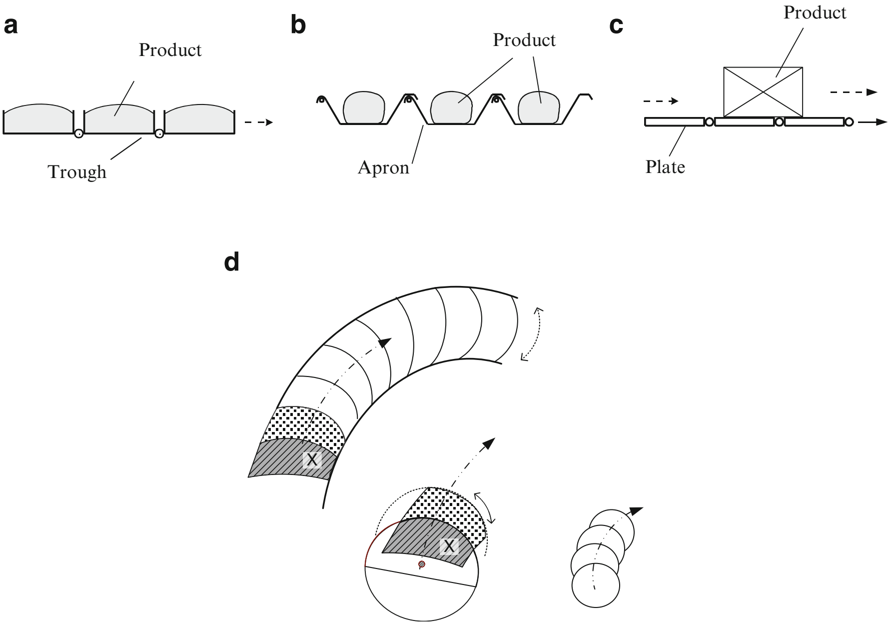


Fig. 3.15 Segmented belt conveyors. (**a**) Trough, (**b**) apron, (**c**) plate, (**d**) discs

However, in most food processing operations, lower speed is required. Therefore, when higher capacity is required (e.g., biscuit ovens), wider belts are used. Segmented belts are usually standardized, e.g., DIN (Huette 1960).

The modular system (elements and modules, joined to form a belt) is increasingly used in the food industry. Use of small modules, e.g., 20 mm long, makes the conveyor belt very flexible. Their surface can be flat, or with flush grid, raised ribs, etc., for meeting the production requirements. Such belts have quite high open area, reaching in some cases up to 45 %. Such systems are suit (a) trough, (b) apron, and (c) plate able for applications where air must flow through the conveyor during processing.

Sprockets are used to drive the belts and the conveying noise is low. Side guards and flights, made of polypropylenes or polyethylene, can be easily added to the conveyors. Polypropylene has high traction resistance, high resistance to chemical agents, and good impact resistance. Both plastic materials are suitable for several food processing operations, because of their hardness, rigidity, low density, and resistance to chemical substances and temperatures up to 104 °C. Polyethylene resists fraying caused by friction and can be used at temperatures down to −50 °C. Another advantage of the modular belts is the easy maintenance (replacement of worn or defective parts). Their main disadvantage is the difficulty in cleaning.

In belt structures, the thickness of the end rolls should be reduced as far as possible. This enables the easy transfer of conveyed products from belt to belt. In belt installations, it must be taken into consideration that the curvature of the belt is a function of its width. Usually, the radius of the curve is 1.7–2.5 times the belt width. The straight paths between two consecutive curves should be at least 2.0–2.5 times the belt width.

Roll and Skate Wheel Conveyors

The roll conveyors consist of cylindrical steel rolls, which may be powered, or idle (Fig. 3.16a). The powered roll conveyors are chain driven (Fig. 3.16b). However, in some cases, since the rolls are locally fixed, conveying occurs by the rotation of the powered single rolls (Fig. 3.16c). Free-rotating rolls are used in conveying, using gravity. Roll conveyors are often used in conveying heavy products. Furthermore, they can be part of fruit and vegetable cleaning equipment, or they can be used in size sorting of such products, when the distance between the rolls changes progressively (Chap. 4).

Roll conveyors are manufactured in various types. For example, a roll conveyor used for inspecting boxes is split into two parts, each rolling at different speed, enabling the rotation of the boxes. Another conveyor is equipped with forklift pockets, enabling unloading by forklifts, even during conveying.

The skate wheel conveyors consist of coaxial wheels (Fig. 3.16d), which are usually idle (conveying by gravity) or chain driven. The skate wheel conveyors are more flexible than the rolls. They are mainly used in interconnecting belt conveyors

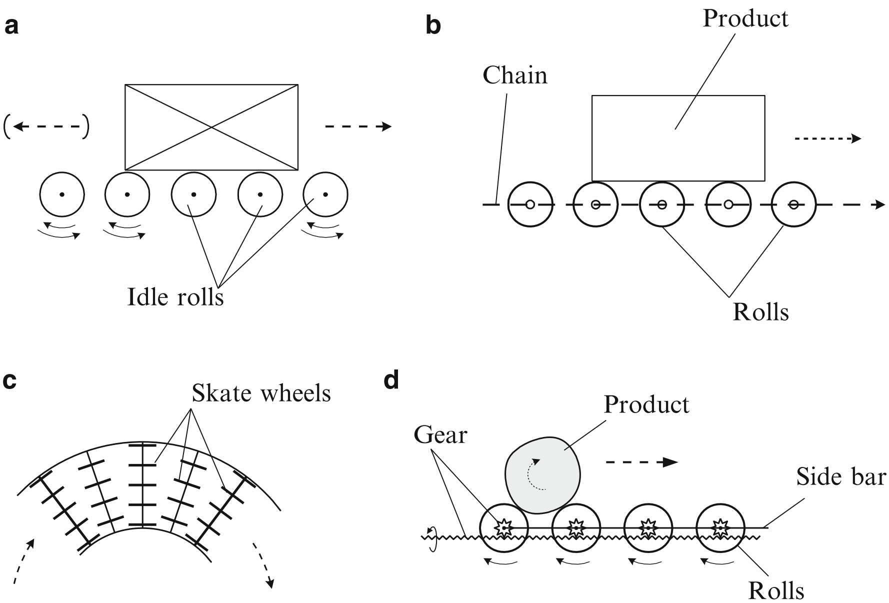


Fig. 3.16 Roll and skate wheel conveyors. (**a**) Idle rolls, (**b**) powered rolls, (**c**) skate wheel rolls, (**d**) chain-driven rolls

and in conveying products in curved paths. The speed of belt-driven roll conveyors is 13–20 m/s (Brennan et al. 1990).

Advantages of roll conveyors:

1. Conveying of heavy products.
2. They can be powered or gravity driven.
3. It is possible to separate conveying from the drive.

Their disadvantages include:

1. They are heavy with significant inertia.
2. Their use in inclined paths is limited.
3. Their wear is significant.
4. They are quite noisy.

Chain Conveyors

Chains are used to convey products horizontally, vertically, or inclined, in straight or curved paths. These paths may be "open" or "closed" (Table 3.7). In the closed paths, the conveyed product is confined in certain channels, such as tubes or troughs. Chains may be used in direct conveying of products or in conveying in connection with auxiliary devices attached to them (Table 3.6). The direct conveying is an "open conveying," e.g., parallel chains on ground paths, transporting large pieces, such as barrels, milk containers, or pallets.

In the low level transport in the open system, buckets, rolls, carts, or plates are used. These devices move on slide ways, or they are fitted on wheels moving on rails or fixed pathways, such as grooves (Fig. 3.17). The buckets are used in conveying bulk products. The other devices are used to convey small or large pieces. In the overhead transport, the auxiliary devices are hooks or buckets.

In the closed system, example auxiliary devices of the chains are flights or anchors (Fig. 3.18). The flight conveyors can be used at a maximum inclination of 30 at speeds up to 0.60 m/s (Huette 1960; Feustel and Hemendiger 1987). They need more specific energy than the belt, but less than the screw conveyors.

Advantages of flight conveyors:

Table 3.7 Classification of chain conveyors

Type of chain	Path	Device
With device	Open	Bucket
		Roll
		Plate
		Cart
		Hook
	Closed	Flight
		Bucket
Without device	Open	(Chain)

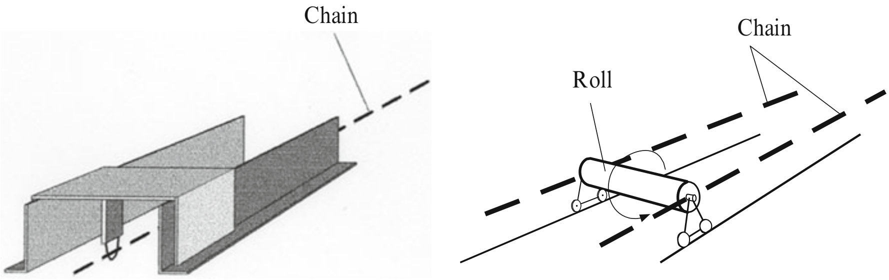


Fig. 3.17 Conveyor paths

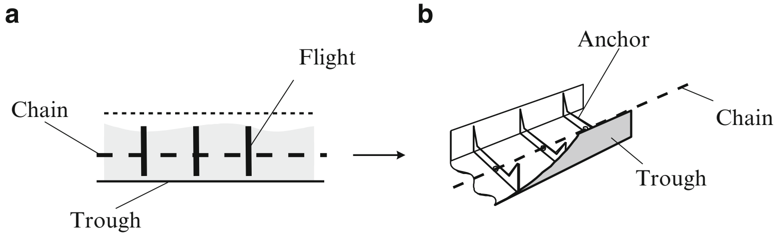


Fig. 3.18 Flight/anchor conveyors. (**a**) Flight, (**b**) anchor

1. High capacity
2. No dusting at conveying speeds lower than 0.6 m/s
3. Possibility to convey in air-tight troughs

Their disadvantages include:

1. Not suitable for sticky process.
2. They are noisy.

In the overhead chain conveyors, hooks, horizontal plates, or buckets are used (Fig. 3.19). These devices usually swing or are pivoted to the conveyor chain. Overhead hooks are often used in the meat and the poultry processing industries. Furthermore, they are used in conveying packaging materials in the fruit and vegetable processing plants. In slaughtering lines of pigs, overhead conveyors move at a speed of 12–16 cm/s. The horizontal plate conveyors ("paternoster") are used to transport products in trays up and down, maintaining the horizontal position (Fig. 3.19c). The maximum speed of bucket conveyors is 1.3 m/s, when chains are used as the driving device, or 2 m/s, when belts are used (Feustel and Hemendiger 1987).

Figure 3.20 shows the mechanism of feeding and emptying of vertical bucket conveyors (elevators). Two common methods of emptying products from buckets are the centrifugal discharge (Fig. 3.20a) and the continuous discharge (Fig. 3.20b).

The bucket conveyors have the following advantages: (1) it requires less energy than the pneumatic conveyors and less space than the trough and belt conveyors and

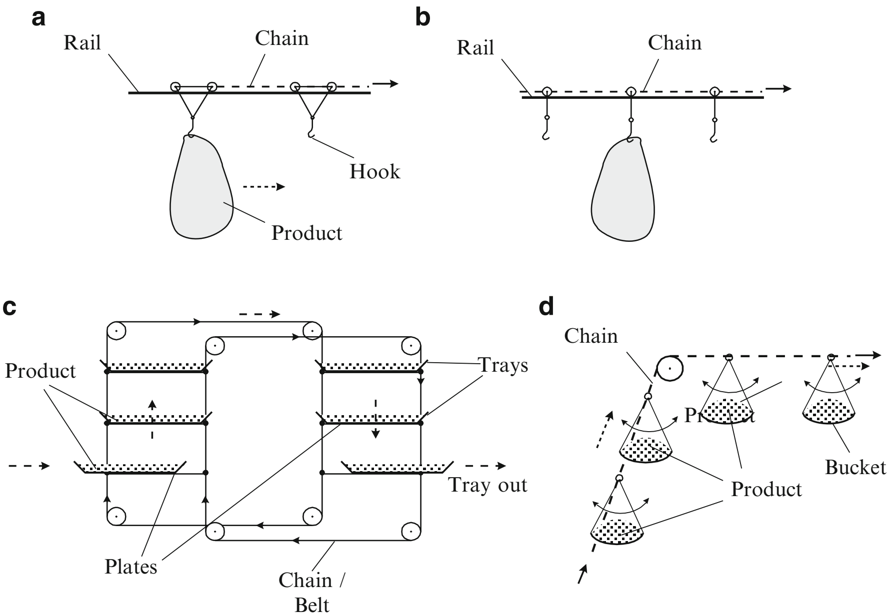


Fig. 3.19 Chain conveyors. (**a**, **b**) Hook conveyors; (**c**) up-and-down plate conveyor; (**d**) bucket conveyor

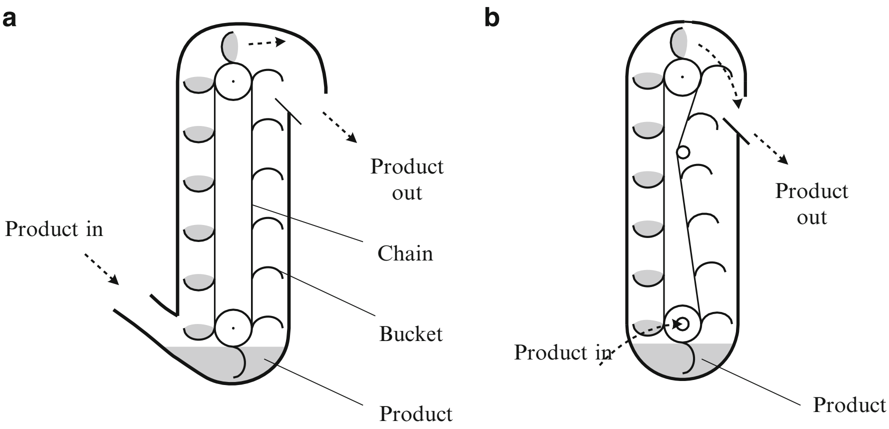


Fig. 3.20 Bucket elevator feeding and discharge systems. (**a**) Centrifugal and (**b**) continuous discharge

(2) vertical, horizontal, or inclined conveying is equally possible. Their disadvantages are (1) limited capacity and (2) fire or explosion danger, if the conveying system is defective or not clean.

Screw Conveyors

Screw conveyors are used in transporting high-consistency, non-free-flowing products in all directions. However, their capacity is reduced when conveying products in inclined direction (Walas 1988). They are also used in emptying silos (Sect. 3.3.2.4 of this chapter). They consist of a helical device (shaft), rotating along the axis of a cylindrical vessel (Fig. 3.21). The helical shaft may be a screw-type spiral (Fig. 3.21a, b), a row of individual blades (Fig. 3.21c), or a continuous ribbon (Fig. 3.21d). Seats for the two ends of the helical axis are provided, if it is longer than 2–4 m. Shorter helical axes can sit on one side (end) only. The maximum length and diameter of the common types of screw conveyors, used in the food industry, are 100–120 and 40–60 cm, respectively. This conveyor type can be transported without disassembling. Assembled (immobile) conveyors may be up to 50 times longer. The diameter (d_h) of a screw shaft depends on the diameter of the conveyed largest grain or particle (d_k), e.g., $d_h = 12d_k$ for sorted large grain and $d_h = 4d_k$ for non-sorted grain (Feustel and Hemendiger 1987). The pitch of the screw is $l_p = (0.5–1.0)d_h$. The speed of rotation of the screw varies from 16 to 140 rpm (Feustel and Hemendiger 1987; Walas 1988). Long screw conveying is avoided, because of the relatively high energy required due to friction and the problems that may arise, especially if dry, dust-containing products pack between the screw and the wall of the vessel. In this case, there is a danger of explosion if the temperature of the product is high or if some sparking (friction or electrical) occurs. In screw conveying of dry food, only 25–50 % of the vessel is filled. The capacity of food screw conveyors depends on the material and its condition, with a usual range of 25–40 m^3/h, although higher conveying capacities are possible.

Advantages of screw conveyors:

1. Effective conveying of even packed products.
2. Good control of conveying capacity.
3. Conveying in all directions is possible.

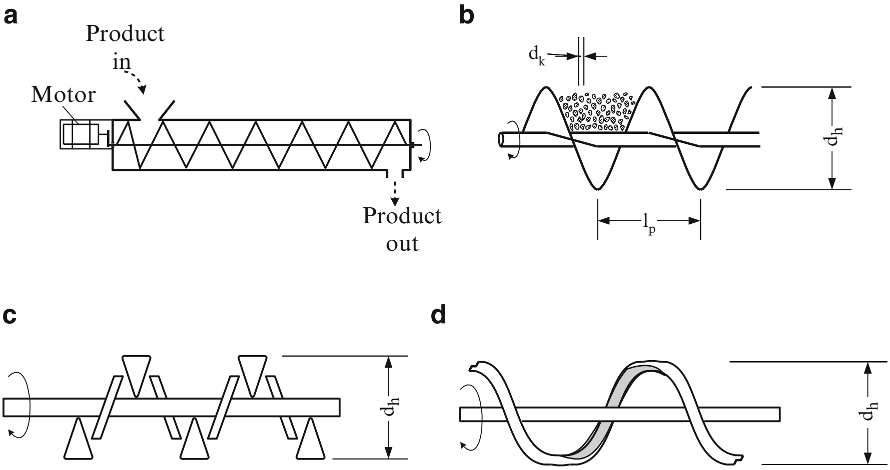


Fig. 3.21 Screw conveyors. (**a**, **b**) Screw spiral, (**c**) individual blades, (**d**) continuous ribbon

Their disadvantages include:

1. High energy consumption.
2. Products are conveyed without much care.
3. Fire and explosion danger, if dust is packed in the conveyor.

Vibratory Conveyors

The vibratory conveyors are used in transporting, horizontally or in inclined direction, bulk product ranging from loose materials to powders, placed in troughs or tubes. The product can be conveyed in straight, curved, or spiral direction and elevated to a new level (Table 3.6). The vibration can be vertical or horizontal (gliding transport). In the second case, if the size of the grains is not homogenous, some de-mixing of the product during conveying may take place (Hemming 1991). The vibration of the trough or tube is achieved electromagnetically or mechanically, e.g., by a rotating eccentric mechanism, e.g., out-of-balance rotating weights (Fig. 3.22). The trough or tube sits on springs. The frequency of vibration is high (up to 6000 min^{-1}) and the amplitude does not exceed 1 mm (Huette 1960). The capacity of vibratory conveyors depends on the size and the moisture and fat

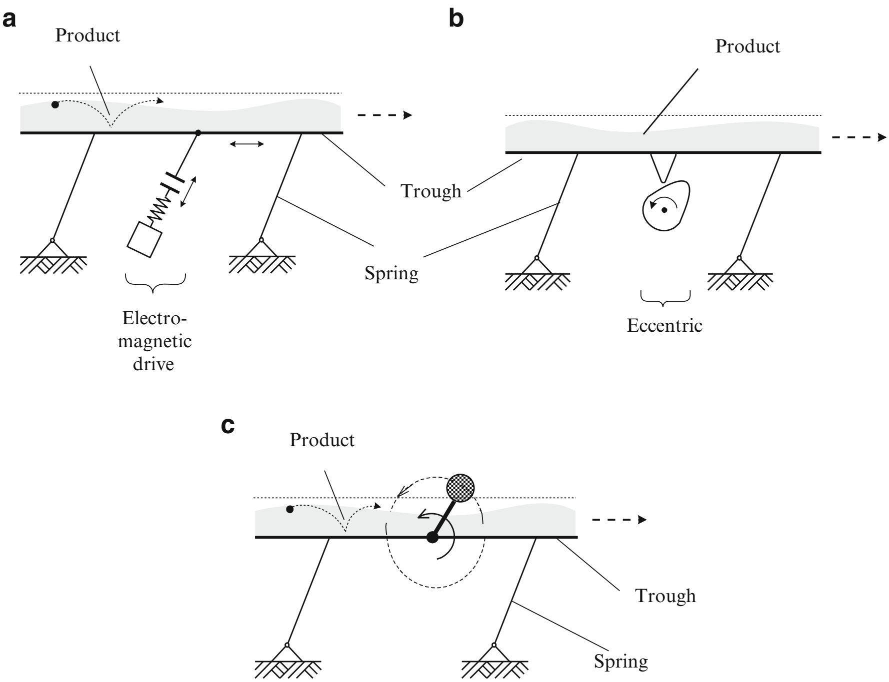


Fig. 3.22 Vibratory conveyors. (**a**) Electromagnetic drive, (**b**) eccentric drive, (**c**) out-of-balance drive

content of the grains. It increases with the size of the grains and the bulk density of the product. However, high frequency and small amplitudes are preferred to prevent dusting due to friction. The vibratory conveyors may be up to 6 m long and 1.5–1.8 m wide. For longer conveying, a system of more conveyors is used. Vibratory conveyors can transport small (kg/h) to large amounts (t/h) using a relatively small motor (e.g., 3 kW). Since this type of equipment does not cause friction, it is often used in conveying sensitive products, such as potato chips. It is also used for conveying wet or even sticky grains like raisins. Due to its accuracy, it is also used in controlled feeding, such as dosing in of weigh balances (see Chap. 13).

Advantages of the vibratory conveyor:

1. They do not damage the conveyed products.
2. Good control of the flow rate.
3. Conveying in all directions possible.
4. Conveying of wet and sticky products possible.

Their disadvantages include:

1. The conveyed product must be homogeneous.
2. Not suitable for large pieces and for long transport.
3. They are relatively noisy.

Mobile Transport Systems, Hoists Cranes, and Elevators

For transports of bulk or packed products inside and at the site of the factory, mobile vehicles may be also used. Their main advantage is their flexibility: (a) not fixed location of the devices and (b) additional possibility of a three-dimensional transport. In the processing and storage of food inside the buildings, besides using conveyors, transport is also done by electric powered *forklifts*. They operate in almost any lift and transport application. Very important is their roll in the transport and placement of already palletized products (boxes, bags, etc.) in cold stores, in other storage operations, in the transport of materials required in several processes, and in loading/unloading of lorries. The load carried and elevated by forklifts depends on the end height of the products that are moved. For 3–4 m height, the load is usually about 2–3 t. Outside of the processing area, the forklifts usually have diesel engines. In short distance, transport of not very heavy loads is done by man-moved charts, small wagons, and low-lift pallet fork trucks.

For heavier products in permanent operation, *hoists* and *cranes* may be also used (Fig. 3.23). The ceiling-mounted cranes are more seldom in food processing. They are mainly used in loading/unloading operations such as large amount of bulk products or packed products placed in large shipment containers. The transport in vertical direction may be also done by elevators. There are two main types of elevators. Those that operate using cables and those equipped with hydraulic

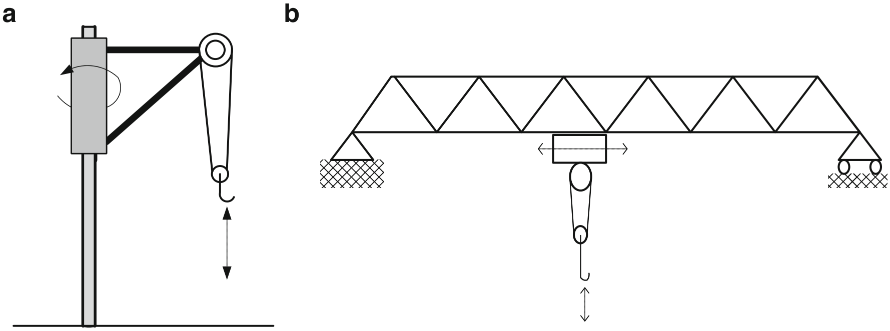


Fig. 3.23 Hoists (**a**) and cranes (**b**)

pressure telescope masts. The last ones are used in minor heights. In some cases such as storage of Swiss-type large round hard cheeses and in logistics in which the products are stored in shelves, the work is done by robots or mobile elevators operating between the shelves. In very large storages, the elevators oscillate on railways, placed in the very narrow corridors between the shelves, and the height of the storage room/shelves sometimes exits 30 m. The whole process is computer aided and full automated.

Robots

In short distance, robots are also used in transport such as pick and place operations. This is either done as part of food processing (e.g., sorting) or at the end of applications such as filing and palletizing of ready products. More about robotics is described in Chap. 12.

Hygienic Considerations

Perishable foods should be transported fast, avoiding microbial or chemical/biochemical deterioration. Fresh foods, such as fruits and vegetables, should not be bruised or damaged mechanically by the conveying equipment.

Belt conveyors are more hygienic than other mechanical transport equipment, e.g., screw conveyors. Smooth belts can be kept more hygienic than segmented, indented, or screen (perforated) belts, which can hold food residues, supporting microbial growth. Plastic and Teflon-coated belts may develop cracks, where food residues may adhere, resulting in undesirable microbial growth. Belts are cleaned and washed with detergents and water, using mechanical scrubbing devices, and installed at the return loop of the belt (Troller 1993). Antimicrobial substances, such as triclosan, could be used to sanitize the belts, provided that they are approved by public health authorities.

3.3 Food Storage Equipment

3.3.1 Introduction

In food processing and manufacturing, storage may be short or long term. Short-term storage may be a preliminary stage of processing, as in the case of milk and tomato manufacturing, or it may be involved in a later stage, as in the case of adding supplementary substances. Long-term storage is used in securing a continuous flow of raw material in manufacturing, as, e.g., in the case of grains or in the storage of aseptically filled concentrated juice in tanks. In long-term storage, measures must be undertaken for protecting the product from spoilage or degradation.

In food processing, stored food may be solid, liquid, or viscous. Furthermore, for some applications, gases may be also stored. Storage equipment of solids includes silos, bins, boxes, and bags. Storage of liquid food may be done in vats, tanks, and large pouches (Table 3.8).

Storage equipment is distinguished between large scale (silos, tanks) and small scale (pallets, boxes, vats).

There are regulations defining the maximum dimension of large equipment, e.g., mobile tanks. The Euro-pallet has been adopted as an international standard (ISO). Regulations restrict the smallest dimension of European inland containers to 7.15 m.

Small containers are very popular for in-house transport and distribution of food products in urban areas. European regulations on small containers were established recently, following the recommendations of the cooperative research project COST 339 (2001).

3.3.2 Storage of Solids

3.3.2.1 Pallets

Pallets are usually made of wood, but there are also pallets made of cardboard, metal, and plastic materials. The metallic pallets are usually made of aluminum, while plastic containers are usually injection molded. ISO recommends pallet dimensions of 0.80×1.20, 1.00×1.20, and 1.0×1.80 m (Paine 1996). With respect to the direction of entry of the forklift, pallets are usually distinguished in

Table 3.8 Basic types of food storage equipment

Product	Storage equipment
Solids (pieces, grains, powders)	Pallets, box pallets, bags, bins, silos
Liquids (low and high viscosity)	Vats, vessels, tanks, drums, pouches
Gases (air, N_2, CO_2, steam)	Tanks

two- and four-way pallets. The main factors influencing pallet selection are use, firmness, and cost.

The use and firmness determine the service life of a pallet. Two main pallet categories are used, the single use (one way) and the reusable (return) pallets. Furthermore, there are pallets that are used mainly in transport or in long-term storage. In the second case, it is important to know the storage conditions (moisture, humidity, and temperature). The firmness of pallets is affected by vibration, e.g., during transport, and by the way they are loaded. Cross positioning of boxes (as in bricklaying of a wall) causes less stress to the pallet than serial placing, since, in the second case, bending of the pallet may occur, due to divided load. Pallets must also resist puncturing, caused by forklifts. For a construction material, e.g., wood, the pallet firmness is related to its weight. However, heavy pallets add weight in transport, and in cases such as cold storage, they require more refrigeration. This can be significant, especially if pallets are wet, since the weight of, e.g., a 30-kg wood pallet may increase by more than 5 kg if it is wet (Paine 1996). Furthermore, moisture causes rotting of the pallet, by shrinking when dried, and may affect the food, if mold is formed. For reusable pallets, repair cost and cleaning should be taken into consideration.

The cost of pallets increases with their firmness. However, a detailed analysis is required for finding the most profitable pallet storage, especially when choosing between one-way and reusable pallets.

3.3.2.2 Box Pallets

Box pallets are used in short- and long-term storage (e.g., fresh fruits, raisins, beans). They are either large boxes placed on pallets (Fig. 3.24a) or boxes incorporating pallets. Compared to bulk and silo storage, their advantages include (1) control of material losses due to spoilage, (2) increased processing flexibility, (3) they can be stacked, and (4) stored material less abused by mechanical stresses, meaning it can be aerated better.

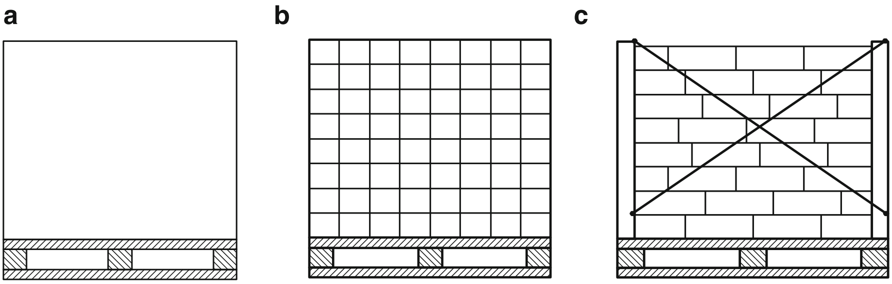


Fig. 3.24 Box pallets. (**a**) Pallet with box pallet on, (**b**) mesh wire box pallet, (**c**) pallet with superstructure

The disadvantages of box pallets are that (1) they need more floor space and more refrigeration load in cold storage, (2) they require more labor in handling, and (3) they are more expensive.

Characteristics of Box Pallets

With respect to forklift handling, box pallets are distinguished, as in the case of plain pallets, into "two-way entry" and "four-way entry" units. Furthermore, there are simple box pallets; mesh wire containers, with fixed or collapsible walls (Fig. 3.24b); and pallets with superstructure (Fig. 3.24c), which have steel posts on the four corners, allowing much higher stacking. The last ones allow much higher stacking. Smaller box pallets can have wheels when it is required to be moved around in short distances.

Box pallets are made of wood, metal, or plastic materials. They may be constructed in any size, but the popular pallet dimensions are 1.2 × 0.8 m ("Euro-Pallet"), 1.2 × 1.0 m, 1.2 × 1.2 m, and 1.0 × 1.0 m. Since the products should not be stacked very densely, the height of box pallets is usually not more than 0.7 m.

The capacity of the box pallets depends on the bulk density of the product. For example, a "Euro-pallet" may store about 200 kg of fruits (e.g., apples, oranges), 460-kg legumes/pulses, or 350-kg raisins.

Selection and Use of Box Pallets

Selection of box pallets depends on the products, firmness, transportation, available storage space, and environmental conditions.

With respect to the products, a maximum storage height should be maintained for avoiding squeezing or temperature rise. The height of food products, such as fruits, potatoes, and raisins, stored in box pallets, usually should not exceed 0.6–1.1 m. Metallic or plastic box pallets should be preferred when, e.g., sticky products like raisins are stored. If good aeration is required, as in the case of cold storage of fruits, the side walls of the boxes should be permeable, so that air may flow easily through the products.

If the frequency of handling and stacking is high, rigid box pallets (e.g., metallic or wooden) should be preferred. The kind and type of transport should be considered (forklifts, cranes). Two-way box pallets facilitate handling. When cranes are to be used, grips or other suitable handles should be provided.

The condition of room and space in which the box pallets are stored must be taken into consideration, e.g., transport corridors, easy stacking, and space for provisional storage.

Measures to reduce or avoid insect or animal (e.g., rodent) infestation and temperature and humidity control must be taken into consideration (e.g., disinfesting, covers on boxes, aeration, air conditioning, insulation, sun radiation reflecting roofs).

3.3.2.3 Bags

Bags are usually employed in short-term storage of powders or granulates. Bags are mostly square based, with one or two spouts on the top and the bottom. The larger bags may have some emptying arrangement, attached in their hopper. When transported or stored, bags may be hung from grips. Bags with only one spout may be hung from both sides (bottom and top). Very large bags may incorporate a steel frame.

Below are the advantages of bags:

1. They are easily filled, emptied, and transported, while hung.
2. The product is protected against insect/animal infestations.
3. They do not need much space for storage and emptying.
4. They increase manufacturing flexibility.

Their disadvantages include the following:

1. They are relatively delicate against external mechanical abuses.
2. They cannot be stacked very high.
3. The storage space is not utilized very efficiently.
4. Special supporting and hanging structure is required for extending their application.

Characteristics of Bags

There are simple bags or bags externally supported by a metal structure, e.g., hanging on a metallic frame (Fig. 3.25). Bags are made of simple plastics, woven plastic textiles, or multiply texture combinations, e.g., plastic/aluminum/plastic for juice concentrates.

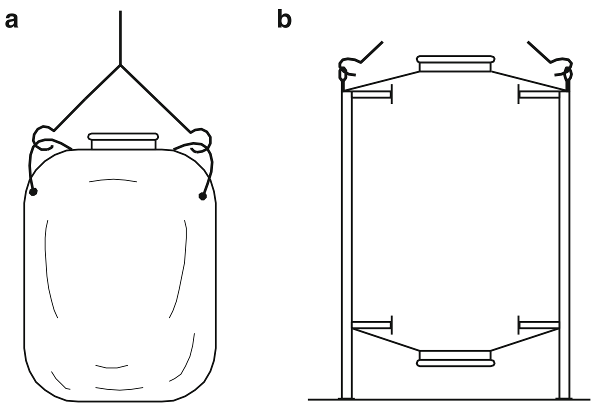


Fig. 3.25 Storage bags. (**a**) Simple bag; (**b**) metallic support structure

Depending on the type of bags, the popular dimensions, without metallic support, are 0.8–1.2 m (base) and 1.0–1.2 m (height). Bags with metal frame structure: 1.5–3.0 m (base), 2.0–7.0 m (height).

The capacity of bags depends on the type of bag and the bulk density of the product. For storage of grain (bulk density, 800 kg/m^3), simple bags have a capacity of 1–2 t. Bags with metal structure support may have capacities 2.5–25 t.

3.3.2.4 Bins and Silos

Bins and silos are used in storage of large quantities of powder and granular food (flour, grain, etc.). Table 3.9 indicates some of the commonly used bins and silos.

Bins are smaller than silos and may be stationary or movable. Transport is carried out by hoists or forklifts, when the bins are not very heavy, e.g., <2 t (Fig. 3.26). Bins are used for short-term storage, e.g., silo grains before shipment, or for blending products in powder or granular form. Silos are constructions enabling long-term storage of dry flowable food materials, such as grains. Sometimes, the silo contents are renewed steadily, as inflow and outflow of the material can take place at the same time.

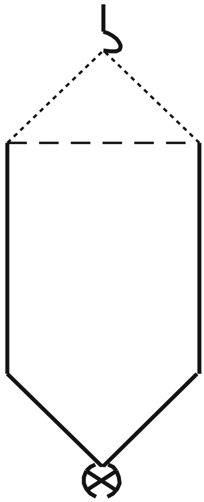
The following are the advantages of bins and silos:

1. Great variation of stored quantities.
2. The stored products are well protected (weather, rodents, etc.).
3. Reduced handling cost due to automation.

Table 3.9 Classification of bins and silos

Characteristics	Type of bin or silo			
Capacity	<2 t	2–500 t	500–3000 t	>3000 t
Installation	Elevated	Elevated or on the ground	On the ground	On the ground
	(a) Legs			
	(b) Brackets			
	(c) Hanged			
Shape	Cylindrical or rectangular	Cylindrical or rectangular	Cylindrical or rectangular	Cylindrical
Mobility	Fixed or movable	Fixed or movable	Fixed	Fixed
Lower part	Hopper	Hopper	Hopper or flat	Flat
Emptying	By gravity	Auxiliary mechanisms	Auxiliary mechanisms	Auxiliary mechanisms
Location	In buildings or shelters	In buildings or shelters	In buildings or shelters	Outside
Material of construction	Steel/aluminum/plastics	Steel/aluminum	Steel	Steel/concrete
Conditioning	Product aeration	Product aeration or circulation	Product aeration or circulation	Product circulation

Fig. 3.26 Transportable bin



4. Reduced ground/floor space requirement.
5. They may be installed outside the buildings.
6. Extension of total capacity by adding new units.

The disadvantages include:

1. Relatively low flexibility, with the exception of mobile bins.
2. Additional equipment required for filling, emptying, and aeration.
3. Significant running cost due to conditioning of stored products and maintenance cost, especially for auxiliary installations.
4. Precautions must be taken to prevent dust explosions.

Characteristics of Bins and Silos

Bins are mainly cylindrical tanks, with a hopper underneath. Silos are cylindrical or rectangular fixed constructions, with or without a hopper. Bins and silos have a hopper when they are elevated, i.e., when they stand on supporting pillars/legs or on brackets (Fig. 3.27). Depending on the way they are filled, e.g., free falling/dropping of product or product transported and filled pneumatically, their roofing can be conical or flat. Conical roofing is used when powders and granulates drop from one filling funnel into the bin, forming a product cone on the upper surface. The angle of the base of this cone is then the angle of repose (Perry and Green 1997).

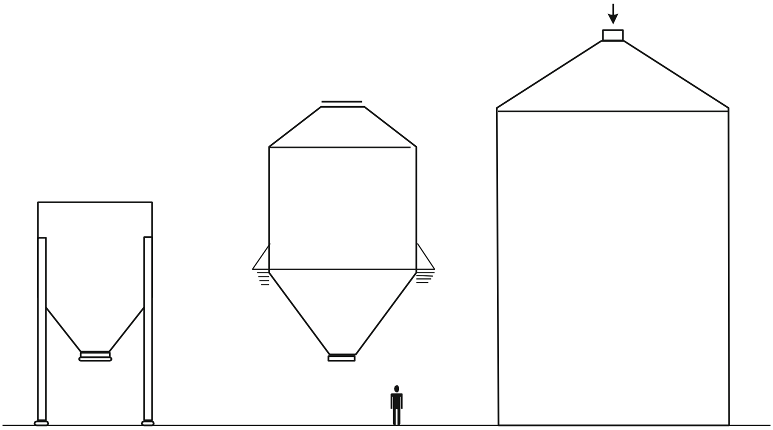


Fig. 3.27 Bins and silos

Construction Consideration

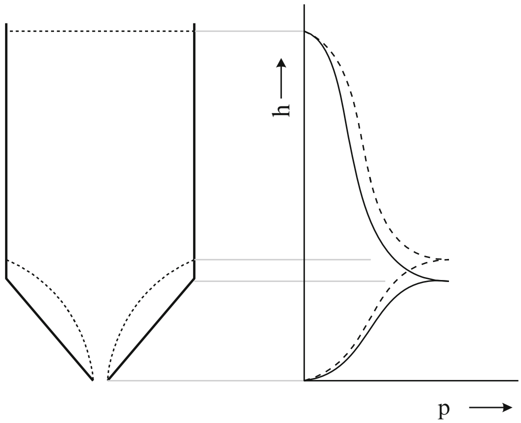
Materials of construction for bins and silos include aluminum panels, galvanized steel panels, glass fiber, and reinforced plastics (smaller bins). Panel sheet joints are bolted, riveted, or welded.

The dimensions of bins depend on their utilization. The diameter of the larger units is up to about 13 m, and the total height may be more than 18 m. An example of dimensions of a typical 500-t bin for grain is the following: cover height, 1–2 m; height of cylindrical part, 8–9 m; height of hopper, 4–5 m; and diameter, 2.7–3 m. Grain silos can be much larger, and their diameter and height may both exceed 24 m.

The capacity of bins varies from about 20 to 1000 t. Silos may be as large as 13,000 t.

Most bins last at least 20 years and most fans and motors about 5–10 years (Wilcke 1998). Since silos are installed outside of buildings, their construction materials should be corrosion resistant. Furthermore, since abrasion of silo walls, due to movement of granulates or powders, takes place, friction-resistant materials should be used. Pahl (1989) recommends for hoppers, which are more than any other silo parts affected by abrasion, the use of aluminum alloys and stainless steel. Sturdy constructions are also important because of external and internal pressures, such as wind, earthquakes, and pressure of products on the walls. Standards, e.g., the Australian Earthquake Code AS 2121 SAA for commercial silos and the Farm Silo Standard AS 2867, should be also taken into consideration, as far as possible. Side pressure on the silo wall increases from the upper surface of the product downward, reaching a maximum value at the point the hopper meets the cylindrical part of the silo. If during the emptying process, instead of mass flow, funnel flow takes place, the maximum point may be effectively moved further up (Fig. 3.28) (Stiess 1992; Pahl 1989; Dialer et al. 1984). Therefore, besides measures for avoiding funnel flow, measures for strengthening the whole construction should be considered,

Fig. 3.28 Wall pressure in silos



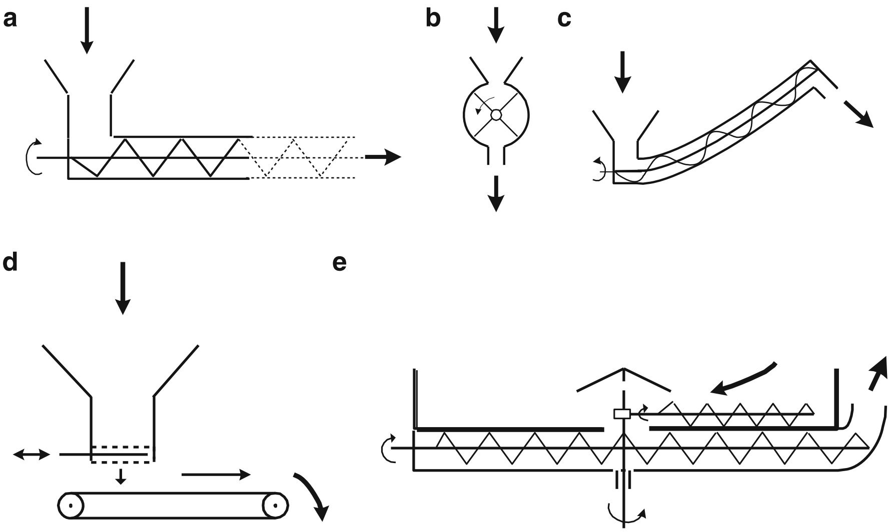


Fig. 3.29 Equipment for emptying of silos. (**a**) Screw feeder, (**b**) star feeder, (**c**) spiral feeder, (**d**) belt feeder, (**e**) planetary movement feeder

e.g., placement of metal rings in the silo circumference and use of corrugated sheets. Erection of silos and bins is easier, if the metallic sheets are screwed together. However, welded air- and dust-tight bins should be preferred, especially for short-term storage of very hygroscopic foods, such as fine sugar or flour.

Emptying of Bins and Silos

Emptying of bins and silos may be controlled through special arrangements at the lowest part of the hopper (Fig. 3.29). In some cases, these arrangements are also useful in blending operations. Examples of such mechanisms are screw feeders, flexible spiral feeders, belt feeders, and star feeders (Perry and Green 1997). The capacity of a screw feeder, used in blending, may be up to 30 kg/h, if high accuracy (e.g., 1 %) is required. For silos without hopper, screw arms of planetary movement may be installed. Such screws rotate around the main axe of the cylindrical silo, in a very short distance from its base, sweeping all material toward a funnel hole, from which the material is then discharged. A 10-kW powered screw, rotating at 5–250 rpm around its axis, is adequate for discharge. Flexible spiral feeders may discharge and at the same time transport the material to a distance of 12–30 m. A combination of more such units may extend this length up to 80 m. The capacities may vary from 20 kg/h to 10 t/h. The pipes in which the screw spiral rotates may be 20–150 mm in diameter. As an example, for transport of 6 t/h to 10 m high, a power of 3 kW is required.

Environmental Considerations

For long-term storage in silos, products must be flowable and resistant to spoilage. Therefore, products that are qualified for silo storage are low-moisture powders and granulates. The product's water activity (a_w) plays an important role in silo storage (Table 3.10). Molds and yeasts may cause damage if $a_w > 0.60$–0.70. Caking and lumping of food particles may take place, when $a_w > 0.35$–0.50. When crystalline dried products, like sugar, are stored, sugar recrystallizes if its critical a_w is reached. The presence of sugar in starch increases cohesiveness.

Temperature fluctuations due to climate changes (e.g., significant temperature differences between summer and winter, day and night) should not influence the silo contents, since they cause migration and condensation of moisture on the coldest surfaces, resulting, e.g., in growth of molds in grains, flour, and sugar (Matz 1988). During summer, moisture in silos tends to accumulate on the top, while in winter, it tends to be accumulated on the side walls of the silos (Cloud and Morey 1991). It is important to equalize temperature differences in products stored in silos. This may be achieved by means of aeration or recirculation of the product. In extreme climates, bins are sometimes insulated or put in shelters. Aeration is done by means of perforated ducts at the bottom of silos. Air is blown slowly by radial ventilators. Recommended air flow for grains is 14 $m^3/h/m^3$ of grain (Wilcke 1998; Cloud and Morey 1991). Aeration starts as soon as grains are stored and lasts

Table 3.10 Equilibrium moisture content of grain at 15.5 °C

Product	Relative humidity (%)			
Moisture	50 %	60 %	70 %	80 %
Corn	11.4	12.9	14.5	16.4
Wheat	12.3	13.7	15.2	16.9
Soybeans	8.6	10.5	12.8	15.7
Sunflowers[a]	–	8.0	10.0	12.0

Data from Cloud and Morey (1991)
[a]Estimation based on comparative storability

about 24 h. Thereafter, the frequency and duration of ventilation depends on the moisture content, the water activity of the product, and the temperature and humidity of the air. The ambient air temperature must be lower than that of air present in the grain. This way the ambient air, which is more dense, flows toward the wall of the silo displacing the warm air on its way upward. At ambient air temperature of about 15 °C and grain moisture of 16 %, a 24-h ventilation every 14 days is recommend. If moisture content rises to 18 %, a 24-h ventilation every 7 days is required. Aeration increases also the flowability of grain. For 1-year storage, the moisture content of grains should not exceed 13 %.

Material Flowability

Flow properties of products are enhanced, when they are stored in air-tight silos (reduced environmental moisture absorption) and when bins are well aerated. Furthermore, smooth or even polished material surfaces and right hopper construction reduce the danger of funnel flow during emptying of silos (Stiess 1992). The angle of hoppers is usually 45–60°. Additional measures can be applied or increase flowability (Rumpf 1975; Perry and Green 1997). Some of these measures are as follows (see also Fig. 3.30): (1) addition/mixing of anti-caking fine powders, which impede agglomeration of granulates, e.g., addition of 3 % starch to sugar (Matz 1988); (2) blowing air upstream, which reduces the bulk density of granulates; (3) use of rotating "scrapers," placed at the lower part of the hopper; and (4) use of storage "activators," consisting of a flexible vibrator and a curved baffle, attached to the lower part of the hopper. The vibrator produces horizontal thrusts, which vibrate the activator, without influencing the rest of the bin. The curved baffle of the activator resolves the horizontal thrusts into strong vertical impulses. Usually, a vibrator can be operated continuously for 20,000 h.

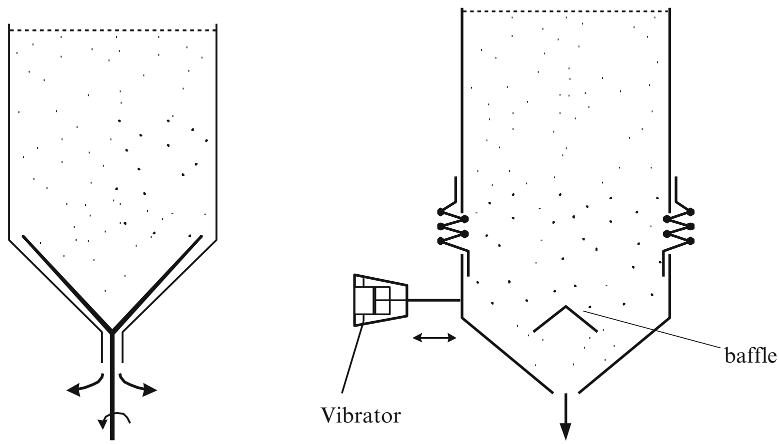


Fig. 3.30 Measures for increasing flowability

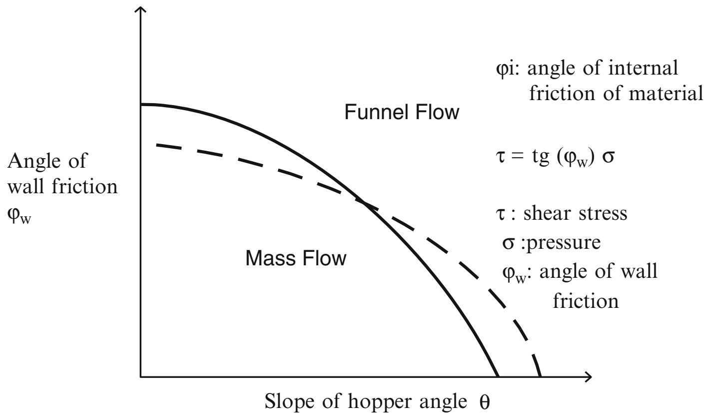
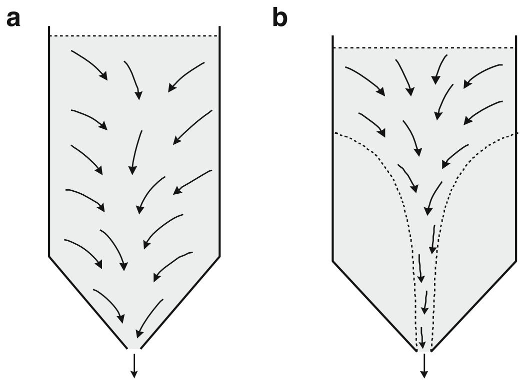


Fig. 3.31 Borders between mass and funnel flow in silos

Fig. 3.32 Mass (**a**) and funnel (**b**) flow in silos



The factors influencing the flow of powders and granulates are analyzed by Rumpf (1975), Dialer et al. (1984), Stiess (1992), and Perry and Green (1997). All these analyses are based on the fundamental work of Jenike (1970). For good material flow, it is important to establish conditions of mass flow. Figure 3.31 indicates the borders between mass and funnel flow with relation to the hopper's angle θ, the angle of friction of the material on the silo wall φ_w (kinematic friction), and the angle of the material's internal friction φ_ι.

The flowability of particles (powders) is measured by various methods, including shear stress, Hausner ratio (tapped over loose packed particles), compression tests, static and dynamic angle of repose, funnel discharge tests, fluidization index, flowability tests, and rheological measurements (flow behavior index), (de Jong et al. 1999).

If funnel instead of mass flow of product takes place (Fig. 3.32), interlocking and friction of particles may form product arches/bridges in the silo, inhibiting material flow (Perry and Green 1997). In the case that the stored food does not

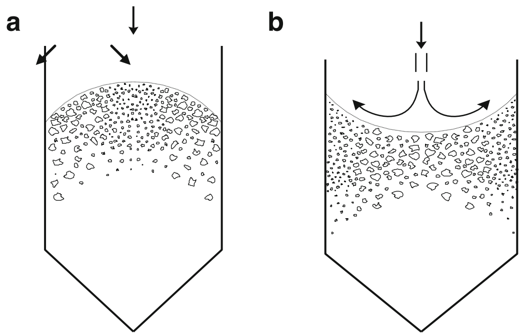


Fig. 3.33 Nonhomogeneous filling of silos. (**a**) Free flow, (**b**) pressure flow

consist of homogenous granulates, the material flow may also depend on the size distribution of the granulates. With respect to the size distribution of granulates, non-homogeneity may be developed during filling of the silo. During free dropping, e.g., when a cone with the angle of repose is formed on the top of the heap, larger granulates may roll down to the side wall of the silo (Fig. 3.33) (Pahl 1989).

Safety Considerations

Silos are one of the most dangerous equipments in the food industry. According to a report of the Health and Safety Executive UK (HSE 1994), 22 % of all fatal injuries of the food industry are caused with respect to silos. Therefore, special caution is required when personnel enters a silo. External and internal ladders must exist, and personnel should never work alone or enter silos during filling or emptying operations. Furthermore, filter respirators must be worn when presence of mold spores is suspected (Cyr and Johnson 2000). When powders are handled and stored, attention must be paid so that dust and air do not form explosive mixtures. Food belongs to weak explosion materials as its Kst value (bar m/s), which is an indicator of explosive mixtures (HSE 1996), is between 0 and 200. Nevertheless, explosion in silos may take place, if a critical fine powder-air mixture is present. Sudden collapse of product arches and bridges that may exist in silos supports such conditions. In all cases that fine dust-air mixture (e.g., higher than 20 g/m^3) and high temperatures (>200 °C) exist, a spark that may come up due to electric defects or friction between metals (e.g., handling equipment) can cause hazards. Therefore, dust collecting silos and bins must be equipped with explosion relief valves (HSE 1996) and be constructed according to appropriate standards such as BS 6467, Parts 1 and 2, for dust protected electrical equipment, and ANSI/NFPA 61-1995, referring to the prevention of dust explosions in agricultural and food product facilities.

For the storage of adhesive grain products such as dry grape raisins, the following silo has been proposed (Fig. 3.34). Such a silo protects the product up to its final processing and packaging, it allows a flexible handling of the product,

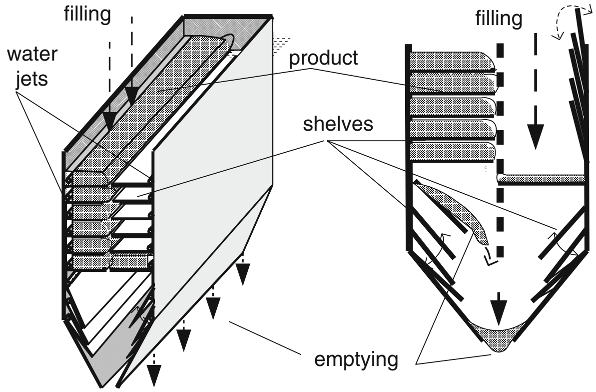


Fig. 3.34 Filling and emptying of a silo for the bulk storage of adhesive corn products (raisins)

and it contributes in full automation, from storage up to the final packaging operation, improving the final quality of the processed raisins (Kostaropoulos and Saravacos 2003).

3.3.3 Storage of Liquids

3.3.3.1 Vats and Vessels

Vats and vessels are used for temporary storage of relatively small quantities of liquid or highly viscous foods such as concentrated juice, fruit pulp, processed cheese, dough, etc. Vats and vessels are also used as auxiliary equipment in food processing. Some examples in which vats or vessels are used as auxiliary equipment are cheese processing (cutting of crude cheese), filling of marmalade, sausage processing, and several kinds of mixing. The upper ends of types of both equipments are open, but often covers are used.

The product kind, handling, and application determine the form and dimensions of a vat. If vats are used for draining processes, the relation of surface to height must be as large as possible.

The criteria of selection of vats and vessels are (1) product to be stored, (2) handling of the product, (3) environmental conditions, (4) materials of construction, and (5) hygienic considerations.

The advantages of vats/vessels are:

1. Economic storage of small quantities.
2. Flexibility, especially when mobile and the stored product can be carried to the final processing place (e.g., filling).
3. Transport of mobile units with forklifts or hoists is possible.
4. Better utilization of the processing site, e.g., elevation or hanging of vats, close to the main processing equipment.
5. Reduced risk of quality damage. For example, if some product happens to be of inferior quality, there is no risk of mixing it with the rest of the stored material.

The disadvantages of vats/vessels are as follows:

1. More costly, when large quantities are handled, e.g., a large silo costs less than three smaller units of equal total capacity.
2. Maintenance is more expensive.
3. More skilled personnel are required.
4. Danger of post contamination.
5. More space is required for large quantities, if used on the plant floor.

Basic Characteristics

Vats or vessels may be fixed or mobile. Fixed elevated vats or vessels usually stand on metallic legs. Vessels that have free space underneath are supported by brackets. Mobile vats may have wheels at the end of their legs, directly below the vat, or they may be placed on mobile frames (Fig. 3.35). Vats and vessels can be also jacketed, when their contents are cooled, heated, or maintained at a constant temperature (see also heat transfer equipment, Chap. 6). Sometimes, such equipment is also insulated. Most vats and vessels have a circular perimeter, because (a) curved surfaces withstand better mechanical or thermal stresses and (b) they are easier cleaned up. However, there are some cases in which rectangular shape is also used. This happens, e.g., in curd draining vats or vats in which salting of cheese, packed in rectangular forms, takes place. Some jacketed equipment is rectangular, but the bottom may be curved. The bottom of vats and vessels may be spherical, inclined, regular, or irregular conical (Fig. 3.36).

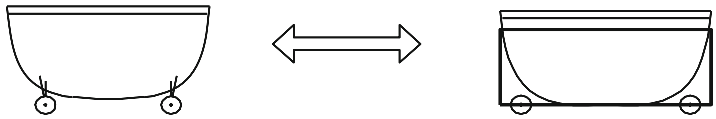


Fig. 3.35 Mobile vessels

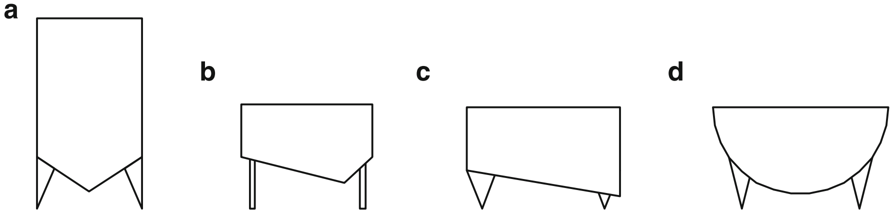


Fig. 3.36 Bottoms of vessels. (**a**) Regular conical, (**b**) irregular conical, (**c**) inclined, (**d**) spherical

Construction Considerations

Most vats and vessels used in the food industry are made of stainless steel. Since products do not stay long in such equipment, usually AISI 304 stainless steel is sufficient. In some cases, plastic materials such as glass fiber strengthened polyester or aluminum are also used. For constructions, often 2–3-mm stainless steel sheets are used. The upper edge of the vats is commonly finished with a round rod, continuously welded to the body. For lifting, tipping, and emptying the vat contents, special lugs must be provided. Whenever frames or legs are used, for hygienic reasons, they are made of tubular steel or a similar structure without corners. In some cases, adjustable, e.g., ball-type feet, is used for adjustment of the equipment height. When insulation is used, this must be adequate and protected from moisture or mechanical damage. Therefore, it usually has a moisture barrier on the outside surface and is totally enclosed between two stainless steel surfaces. The outside surface is sometimes made of aluminum. The type of insulation that may be used for vats and vessels depend on the temperature difference between product and ambient temperature. For equipment maintained in the range 5–40 °C, a 50-mm thick glass fiber or mineral wool gives adequate heat protection. The thermal conductivity of mineral wool is similar to that of glass fiber, i.e., 0.033 W/m K at 15 °C (Perry and Green 1997).

In short-time storage of several liquids or semiliquids, coated carbon steel (e.g., glass or plastic-lined surface) or aluminum may be used. A less expensive material for vessels is plastics. Polyethylene vessels of food grade (without toxic plasticizers) may be used in four-way pallet containers for liquids with capacities of 800–1300 L. Such containers are lighter than the metallic ones, although for rigidity, wall thickness up to 1.25 cm may be required. One-piece construction (pallet container) and incorporation of heavy-duty ball valves and quick couplers increase the flexibility of such vessels. In some applications, vats and vessels should enable, if required, a safe switch for additional equipment, e.g., agitators.

The capacity of large cylindrical vats varies from 1000 L to more than 5000 L. Common dimensions of such vats include: diameter, 1.2–3.0 m and height, 1.0–1.2 m. Rectangular vats of the same capacity can be 1.0–7.0 m long, 1.0–1.5 m wide, and 0.5–0.7 m high. Smaller vats can have a capacity of 250–1000 L. For example, the dimensions of a 500-L cylindrical vat include: diameter of 0.70 m and height of 1.30 m. The capacity of small vessels may vary from 150 to 1000 L.

Processing Aspects

Vats and vessels are usually elevated. Emptying takes place by gravity or pumps. Some types of vats, especially when they are used for semiliquid products (e.g., processed cheese), may be tipped over for emptying. Tipping over is done by a motor-driven gear mechanism on one side of the vat support. In equipment that is not frequently used, sometimes tipping is manual.

If the product has to be conditioned, vats or vessels must either enable good heat, and eventually mass transfer, during storage in the specially air conditioned rooms, in which they are placed (e.g., rooms for ripening of bread dough), or they must be jacketed. Insulation is required, when the product stays in a vessel a little longer, and its initial temperature must be maintained constant.

If a vat is part of a machine, as in the case of kneading equipment, then adjustment of the vat to this machine must be possible (e.g., quick coupling to pumps or pipes). If it is used for transporting meat between various stages of meat or sausage manufacturing, it must be mobile and equipped with the proper lugs that fit in the loaders and in the emptying devices. If it is used in connection with mixing or filling machines, it must have the right mechanism to allow thorough emptying (e.g., installation of scrapers in the case of marmalade and jacketing for heating of honey), adjustment for pumps, or even adjustment for dosing machines.

The surface of vats and vessels should be smooth, and corners or “dead ends” should be avoided. Furthermore, the application of effective cleaning solutions should be possible, and CIP should be foreseen. Open containers should be covered, whenever covering does not disturb processing (e.g., operation of agitators, cutting machines, etc.).

3.3.3.2 Tanks

Characteristics of Tanks

Tanks are mainly used for storage of liquid foods and fruit/vegetable concentrates and pulps. Two main categories of tanks, i.e., fixed and transportable, are used in food processing. The fixed tanks are subdivided into vertical and horizontal (Fig. 3.37). The vertical tanks are in general larger than the horizontal. Most tanks are cylindrical, but the horizontal tanks may have an elliptical cross section, for reducing their height. Product in tanks has little or no contact to the environment, as in the cases of controlled atmosphere storage (e.g., wine), or aseptic

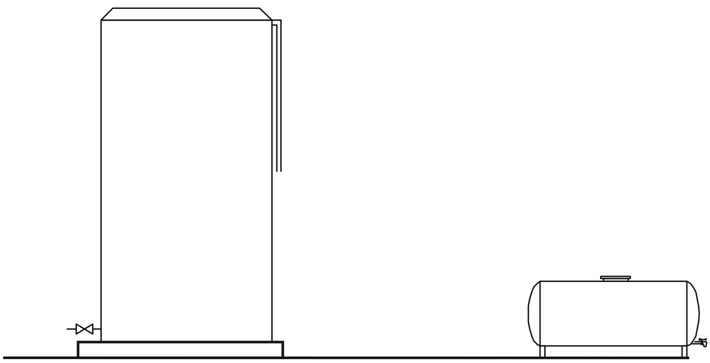


Fig. 3.37 Fixed tanks

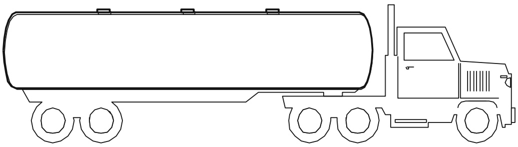


Fig. 3.38 Mobile tank

storage. Most tanks stand on the floor, although there are exceptions of smaller tanks that are elevated. Most tanks are stationary, but there are tanks that are transported by cranes, trucks (Fig. 3.38), railroads, or ships.

Tank trucks usually have (2–4) compartments and a maximum capacity of about 30 t.

They also have pumping systems for filling and discharge. The maximum capacity of rail trucks is about 130 m^3 or 120 t. The bottom of tanks must be inclined for draining (slope of 2–4°).

Larger tanks often have automation and control instruments, indicating temperature, liquid level, and actual weight.

Below are the advantages of tanks:

1. Significant quantities of liquids can be stored for a long term.
2. Full automation of filling, emptying, and product conditioning is possible.
3. Less skilled labor is required.
4. Good protection of the product (e.g., application of inert atmosphere and aseptic conditions) is possible.
5. Simultaneous filling and emptying is possible.
6. Good utilization of factory site (e.g., installation outside buildings) is possible.

The disadvantages of tanks include:

1. Susceptibility to external damage
2. Expensive, when made of stainless steel
3. Require more space than other liquid storage installations (e.g., lined concrete)

Fermentation Tanks

Special tanks are used in the processing of fermented foods, such as olives, pickles, wine, and beer. Industrial fermenters used in the production of bio-products are discussed in books of biochemical engineering and biotechnology. Figure 3.39 indicates a common fermentation tank. In such tanks, besides several additives, air can be also added if required. The product in the tank may be continuously agitated and heated. Important in fermentation tanks is to have proper measuring and automation instrumentation for achieving and maintaining the required processing conditions.

Wood and concrete (cement) are used in lactic acid fermentations of olives, pickles, and sauerkraut. Expensive stainless steel tanks are subject to corrosion by

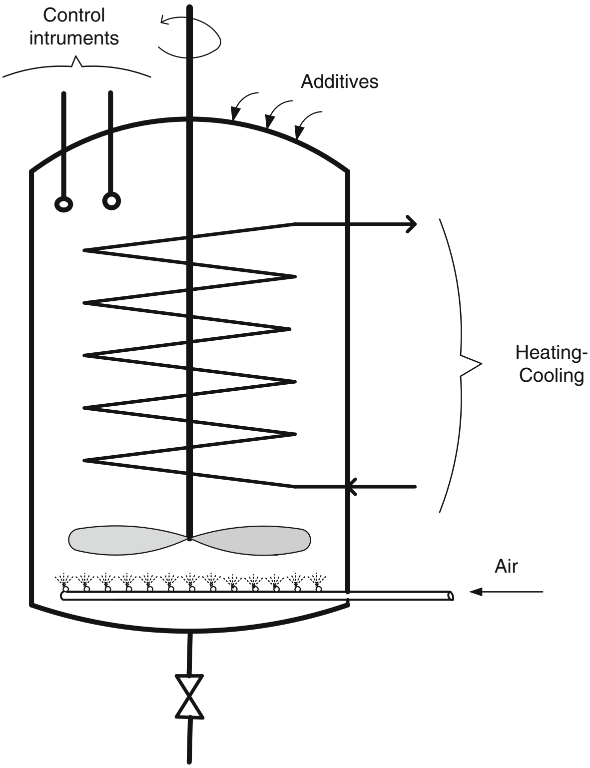


Fig. 3.39 Fermentation equipment

the brines (aqueous solutions of about 10 % sodium chloride) used in the processing of these food products.

Large wooden vats are used in the fermentation of cucumbers (pickles) and cabbage (sauerkraut). Wooden barrels (oak or chestnut) of about 200 L capacity are used in olive fermentation (Luh and Woodroof 1988).

Wine is produced by fermentation of most grape juice in either coated concrete tanks or in stainless steel vessels. Wooden barrels are used in aging and storing of wine and other fermented liquors.

Special copper (bronze) or stainless steel tanks are used in beer processing. Lautering tubs, traditionally made of copper, about 40 m^3 capacity, are used to separate the liquid (wort) from the mash. Brew kettles, made of copper or stainless steel (about 80 m^3 capacity), are used for boiling the wort.

Large vertical tanks, made of stainless steel (capacity up to 400 m^3), are used in the primary beer fermentation. Horizontal stainless steel tanks (capacity up to 200 m^3) are used in the secondary (lager) beer fermentation at relatively lower temperature.

Rectangular stainless steel vats (10–15 m^3 capacity) are used in cheese fermentation, while yogurt and other fermented milk products (e.g., sour cream) are processed in vertical temperature-controlled tanks.

Tank Regulations

In addition to the US Department of Transport (DOT) regulations, there are also the following international regulations for the transportation of food tanks:

1. EU (European Union) regulations.
2. Food Tanks-Food Hygiene Directive 93/43/EC. "Containers" for transport of bulk foods in liquid, granular, or powder form. Tanks should be marked "for foodstuffs only" in one or more European Union languages (Chapter IV, article 6 of Annex to the Directive). Put in force 14 July 1995 (EPTA 1997).

Example 3.1 Design a pumping system for transferring the concentrated orange juice (COJ) 65 °Brix of Example 1.1 from the evaporator to the freezer and bulk packing. The flow rate of COJ is 1032 kg/h.

Assumptions and Data

The 65 °Brix COJ has a density of 1320 kg/m^3 (Ting and Rouseff 1986). The COJ is assumed to be pseudoplastic fluid with rheological constants $K = 2$ Pa s^n and $n = 0.76$ at 20 °C (Table 3.1) (Saravacos and Maroulis 2001).

The COJ is transferred from the last (third) effect of the evaporator system (Example 7.1) which operates at a pressure of 0.123 bar and temperature 50 °C to the freezer/packing through a PDP. A stainless steel pipe of 20-mm internal diameter and 15 m long is assumed. Fittings: one gate valve open, one globe valve open, four standard 90° ells (bends). The freezer is a scraped surface heat exchanger.

The mean temperature of the COJ in the piping *and f*reezer is assumed to be 0 °C, and the rheological constant (K) follows the Arrhenius equation (3.12) with an energy of activation $E_a = 40$ kJ/mol. The flow behavior index (n) is assumed to be independent of temperature.

Calculations

Cross-sectional area of pipe is $A = \{3.14 \times (0.02)^2\}/4 = 3.14 \times 10^{-4}$ m^2. Mass flow rate of COJ is $m = 1032/3600 = 0.287$ kg/s. Density of the COJ 65 °Brix is $\rho = 1320$ kg/m^3. Volumetric flow rate is $Q = 0.287/1320 = 2.17 \times 10^{-4}$ m^3/s. Mean velocity in the pipe is $u = 2.17/3.14 = 0.7$ m/s.

Rheological constants are $K(20) = 2$ Pa s^n, $n = 0.76$.

Constant $K(0)$ at 0 °C calculated from Arrhenius equation (3.12), neglecting the effect of concentration, is $K(0)/K(20) = \exp\{(E_a/R)(1/273 - 1/293)\}$,

where $E_a = 40$ kJ/mol and $R = 8.314$ J/mol K

$$\ln\{K(0)/K(20)\} = 4811(3.663 - 3.413) = 1.203$$
$$K(0)/K(20) = 3.33 \quad \text{and} \quad K(0) = 3.33K(20) = 3.33 \times 2 = 6.66\,\text{Pa}\,\text{s}^n.$$

Shear rate (γ) in the pipe (laminar flow) is $\gamma = 8u/d$, or $\gamma = 32Q/(\pi d^3)$, $\gamma = 8 \times 0.7/0.02 = 280$ s^{-1}.

Apparent viscosity in pipe (3.11) is $\eta_a = K\gamma^{n-1}$, $\eta_a = 6.66 \times 280^{-0.24} = 1.7$ Pa s.

Reynolds number of COJ in the pipe is $Re = (u\rho d)/\eta_a$ $Re = (0.7 \times 1320 \times 0.02)/1.7 = 10.87$ (laminar flow).

The pump work (W_p) in the system is given by (3.13): $W_p = E_f + (\Delta P/\rho) + \Delta u^2 + g\Delta z$, where friction energy $E_f = 4f\sum(L_e/d)(u^2/2)$, pressure energy $\Delta P/\rho = (P_2 - P_1)/\rho$, and velocity energy $\Delta u^2 = 0$ (the product velocity at the entrance and exit of the piping system is assumed to be equal). It is also assumed that $\Delta z = 0$, i.e., there is no elevation in the piping system.

The total equivalent length $\left(\sum L_e\right)$ is equal to the straight pipe length (15 m) plus the equivalent lengths of the fittings and the heat exchanger. The fittings have $L_e = (7 + 300 + 4 \times 32) \times 0.02 = 8.7$ m (Table 3.2). The heat exchanger is assumed to mix and cool the product without pumping action and to have an equivalent friction length $L_e = 3$ m. Thus, $\sum L_e = 15 + 8.7 + 3 = 26.7\,\text{m}$.

The friction factor (f) of the pipe is estimated from (3.21) for laminar flow, $f = 16/Re = 16/10.87 = 1.47$. Thus, friction energy $E_f = 4 \times 1.47 \times (26.7/0.02)(0.7)^2/2$, $E_f = 1923$ J/kg.

The product (frozen slurry) is assumed to exit the piping system at a pressure 1.5 bar (0.5 bar above atmospheric). Therefore, the pressure energy will be $(\Delta P/\rho) = (1.5 - 0.123)/1320 = 104.3$ J/kg.

Thus, the pump work will be $W_p = 1923 + 104.3 = 2027.3$ J/kg

The power of the pump is estimated from (3.18a), $P_o = mW_p/\beta$, where $\beta = 0.70$ is the pump efficiency. $P_o = 0.287 \times 2027.3/0.70 = 831$ W, or $P_o = 0.83$ kW.

In practice, a pump with a motor of 1 kW can be chosen for this pumping application.

Example 3.2 Design a pressure pneumatic conveying system to transport wheat at a rate of 10 t/h from a bulk truck to a storage silo. The conveying line consists of a horizontal pipe of 20 m long, a vertical lift of 10 m, and three 90° elbows (bends).

Data and Assumptions

Bulk density of wheat $\rho_b = 770$ kg/m^3, conveying velocity $u = 30$ m/s, and coefficient of friction of bulk wheat = 0.5 (Bhatia 1982).

Assume a bend radius $R = 0.70$ m. Then, the length of the 90° bend will be $L_b = 2\pi R/4 = 2 \times 3.14 \times 0.7/4 = 1.1$ m.

Flow rate of product $m = 10{,}000/3600 = 2.78$ kg/s. Assume pipe diameter is 10 cm. The empirical equations for pneumatic conveyors, suggested by Bhatia (1982), are used. For a more detailed analysis, the fluid flow calculations suggested by Walas (1988) can be used.

The energy (E) and pressure drop (ΔP) of the conveying system are the sums of the energy losses (E) and pressure drops (ΔP) of the product and the air.

Product (*E*)

Energy to accelerate the product from zero to the conveying velocity, $E_1 = mu^2/2 = 2.78 \times (30)^2/2 = 1251$ W

Energy to convey the product in the horizontal pipe, $E_2 = mL_h fg = 2.78 \times 20 \times 0.5 \times 9.81 = 272.7$ W

Energy to move the product vertically, $E_3 = mL_v g = 2.78 \times 10 \times 9.81 = 272.7$ W

Energy to convey the product through the three bends $E_4 = (mu^2 NL_b f)/R = (2.78 \times 30^2 \times 3 \times 1.1 \times 0.5)/0.7 = 5898$ W. Total product $E = E_1 + E_2 + E_3 + E_4 = 7694$ W. Note the very high energy loss in the bends of the piping system (about 77 % of the total energy).

Air (ΔP) and (E)

Flow rate of air (20 °C) $Q = (\pi d^2/4)u = (3.14 \times (0.1)^2 \times 30)/4 = 0.235$ m^3/s.

The pressure drop of the air through the piping can be calculated from empirical tables of the literature, e.g., Bhatia (1982). For an air velocity of 30 m/s or 5900 FPM and a 10-cm (4-in.) pipe diameter, the $\Delta P = 15$ in. of water $= 15 \times 249 = 3735$ Pa per 100 ft (30 m). The energy equivalent of air flow $\Delta P/\rho = (3735)/1.19$ or $\Delta P/\rho = 3139$ J/kg, where the density of air at 20 °C is taken as 1.19 kg/m^3. The energy equivalent of air flow is $E = 0.235 \times 1.19 \times 3139 = 878$ W.

Power Requirement

The total power requirement will be $P_o = 7694 + 878 = 8572$ W $= 8.57$ kW.

A 10-kW rotary displacement blower of 15 m^3/min or 530 CFM can be chosen.

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