

Introduction

Physics, chemistry, and mathematics are essential in gaining an understanding of the principles that govern most of the unit operations commonly found in the food industry. For example, if a food engineer is asked to design a food process that involves heating and cooling, then he or she must be well aware of the physical principles that govern heat transfer. The engineer's work is often expected to be quantitative, and therefore the ability to use mathematics is essential. Foods undergo changes as a result of processing; such changes may be physical, chemical, enzymatic, or microbiological. It is often necessary to know the kinetics of chemical changes that occur during processing. Such quantitative knowledge is a prerequisite to the design and analysis of food processes. It is expected that prior to studying food engineering principles, the student will have taken basic courses in mathematics, chemistry, and physics. In this chapter, we review some selected physical and chemical concepts that are important in food engineering.

1.1 DIMENSIONS

A physical entity, which can be observed and/or measured, is defined qualitatively by a dimension. For example, time, length, area, volume, mass, force, temperature, and energy are all considered dimensions. The quantitative magnitude of a dimension is expressed by a unit; a unit of length may be measured as a meter, centimeter, or millimeter.

Primary dimensions, such as length, time, temperature, and mass, express a physical entity. Secondary dimensions involve a combination of primary dimensions (e.g., volume is length cubed; velocity is distance divided by time).

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Equations must be dimensionally consistent. Thus, if the dimension of the left-hand side of an equation is “length,” the dimension of the right-hand side must also be “length”; otherwise, the equation is incorrect. This is a good method to check the accuracy of equations. In solving numerical problems, it is also useful to write the units of each dimensional quantity within the equations. This practice is helpful to avoid mistakes in calculations.

1.2 ENGINEERING UNITS

Physical quantities are measured using a wide variety of unit systems. The most common systems include the Imperial (English) system; the centimeter, gram, second (cgs) system; and the meter, kilogram, second (mks) system. However, use of these systems, entailing myriad symbols to designate units, has often caused considerable confusion. International organizations have attempted to standardize unit systems, symbols, and their quantities. As a result of international agreements, the *Système International d’Unités*, or the SI units, have emerged. The SI units consist of seven base units, two supplementary units, and a series of derived units, as described next.

1.2.1 Base Units

The SI system is based on a choice of seven well-defined units, which by convention are regarded as dimensionally independent. The definitions of these seven base units are as follows:

1. Unit of length (meter): The *meter* (m) is the length equal to 1,650,763.73 wavelengths in vacuum of the radiation corresponding to the transition between the levels $2p_{10}$ and $5d_5$ of the krypton-86 atom.
2. Unit of mass (kilogram): The *kilogram* (kg) is equal to the mass of the international prototype of the kilogram. (The international prototype of the kilogram is a particular cylinder of platinum-iridium alloy, which is preserved in a vault at Sèvres, France, by the International Bureau of Weights and Measures.)
3. Unit of time (second): The *second* (s) is the duration of 9,192,631,770 periods of radiation corresponding to the transition between the two hyperfine levels of the ground state of the cesium-133 atom.
4. Unit of electric current (ampere): The *ampere* (A) is the constant current that, if maintained in two straight parallel conductors

Table 1.1 SI Base Units

Measurable attribute of phenomena or matter	Name	Symbol
Length	meter	m
Mass	kilogram	kg
Time	second	s
Electric current	ampere	A
Thermodynamic temperature	kelvin	K
Amount of substance	mole	mol
Luminous intensity	candela	cd

of infinite length, of negligible circular cross-section, and placed 1 m apart in vacuum, would produce between those conductors a force equal to 2×10^{-7} newton per meter length.

5. Unit of thermodynamic temperature (kelvin): The *kelvin* (K) is the fraction $1/273.16$ of the thermodynamic temperature of the triple point of water.
6. Unit of amount of substance (mole): The *mole* (mol) is the amount of substance of a system that contains as many elementary entities as there are atoms in 0.012 kg of carbon 12.
7. Unit of luminous intensity (candela): The *candela* (cd) is the luminous intensity, in the perpendicular direction, of a surface of $1/600,000 \text{ m}^2$ of a blackbody at the temperature of freezing platinum under a pressure of 101,325 newton/ m^2 .

These base units, along with their symbols, are summarized in [Table 1.1](#).

1.2.2 Derived Units

Derived units are algebraic combinations of base units expressed by means of multiplication and division. For simplicity, derived units often carry special names and symbols that may be used to obtain other derived units. Definitions of some commonly used derived units are as follows:

1. Newton (N): The *newton* is the force that gives to a mass of 1 kg an acceleration of 1 m/s^2 .

2. Joule (J): The *joule* is the work done when due to force of 1 N the point of application is displaced by a distance of 1 m in the direction of the force.
3. Watt (W): The *watt* is the power that gives rise to the production of energy at the rate of 1 J/s.
4. Volt (V): The *volt* is the difference of electric potential between two points of a conducting wire carrying a constant current of 1 A, when the power dissipated between these points is equal to 1 W.
5. Ohm (Ω): The *ohm* is the electric resistance between two points of a conductor when a constant difference of potential of 1 V, applied between these two points, produces in this conductor a current of 1 A, when this conductor is not being the source of any electromotive force.
6. Coulomb (C): The *coulomb* is the quantity of electricity transported in 1 s by a current of 1 A.
7. Farad (F): The *farad* is the capacitance of a capacitor, between the plates of which there appears a difference of potential of 1 V when it is charged by a quantity of electricity equal to 1 C.
8. Henry (H): The *henry* is the inductance of a closed circuit in which an electromotive force of 1 V is produced when the electric current in the circuit varies uniformly at a rate of 1 A/s.
9. Weber (Wb): The *weber* is the magnetic flux that, linking a circuit of one turn, produces in it an electromotive force of 1 V as it is reduced to zero at a uniform rate in 1 s.
10. Lumen (lm): The *lumen* is the luminous flux emitted in a point solid angle of 1 steradian by a uniform point source having an intensity of 1 cd.

Examples of SI-derived units expressed in terms of base units, SI-derived units with special names, and SI-derived units expressed by means of special names are given in [Tables 1.2, 1.3, and 1.4](#), respectively.

1.2.3 Supplementary Units

This class of units contains two purely geometric units, which may be regarded either as base units or as derived units.

Table 1.2 Examples of SI-Derived Units Expressed in Terms of Base Units

Quantity	SI Unit	
	Name	Symbol
Area	square meter	m ²
Volume	cubic meter	m ³
Speed, velocity	meter per second	m/s
Acceleration	meter per second squared	m/s ²
Density, mass density	kilogram per cubic meter	kg/m ³
Current density	ampere per square meter	A/m ²
Magnetic field strength	ampere per meter	A/m
Concentration (of amount of substance)	mole per cubic meter	mol/m ³
Specific volume	cubic meter per kilogram	m ³ /kg
Luminance	candela per square meter	cd/m ²

Table 1.3 Examples of SI-Derived Units with Special Names

Quantity	SI Unit			Expression in terms of SI base units
	Name	Symbol	Expression in terms of other units	
Frequency	hertz	Hz		s ⁻¹
Force	newton	N		m kg s ⁻²
Pressure, stress	pascal	Pa	N/m ²	m ⁻¹ kg s ⁻²
Energy, work, quantity of heat	joule	J	N m	m ² kg s ⁻²
Power, radiant flux	watt	W	J/s	m ² kg s ⁻³
Quantity of electricity, electric charge	coulomb	C		s A
Electric potential, potential difference, electromotive force	volt	V	W/A	m ² kg s ⁻³ A ⁻¹
Capacitance	farad	F	C/V	m ⁻² kg ⁻¹ s ⁴ A ²
Electric resistance	ohm	Ω	V/A	m ² kg s ⁻³ A ⁻²
Conductance	siemens	S	A/V	m ⁻² kg ⁻¹ s ³ A ²
Celsius temperature	degree Celsius	°C		K
Luminous flux	lumen	lm		cd sr
Illuminance	lux	lx	lm/m ²	m ⁻² cd sr

Table 1.4 Examples of SI-Derived Units Expressed by Means of Special Names

Quantity	SI Unit		Expression in terms of SI base units
	Name	Symbol	
Dynamic viscosity	pascal second	Pa s	$\text{m}^{-1} \text{kg s}^{-1}$
Moment of force	newton meter	N m	$\text{m}^2 \text{kg s}^{-2}$
Surface tension	newton per meter	N/m	kg s^{-2}
Power density, heat flux density, irradiance	watt per square meter	W/m^2	kg s^{-3}
Heat capacity, entropy	joule per kelvin	J/K	$\text{m}^2 \text{kg s}^{-2} \text{K}^{-1}$
Specific heat capacity	joule per kilogram kelvin	J/(kg K)	$\text{m}^2 \text{s}^{-2} \text{K}^{-1}$
Specific energy	joule per kilogram	J/kg	$\text{m}^2 \text{s}^{-2}$
Thermal conductivity	watt per meter kelvin	$\text{W}/(\text{m K})$	$\text{m kg s}^{-3} \text{K}^{-1}$
Energy density	joule per cubic meter	J/m^3	$\text{m}^{-1} \text{kg s}^{-2}$
Electric field strength	volt per meter	V/m	$\text{m kg s}^{-3} \text{A}^{-1}$
Electric charge density	coulomb per cubic meter	C/m^3	$\text{m}^{-3} \text{s A}$
Electric flux density	coulomb per square meter	C/m^2	$\text{m}^{-2} \text{s A}$

Table 1.5 SI Supplementary Units

Quantity	SI Unit	
	Name	Symbol
Plane angle	radian	Rad
Solid angle	steradian	Sr

1. Unit of plane angle (radian): The *radian* (rad) is the plane angle between two radii of a circle that cut off on the circumference an arc equal in length to the radius.
2. Unit of solid angle (steradian): The *steradian* (sr) is the solid angle that, having its vertex in the center of a sphere, cuts off an area of the surface of the sphere equal to that of a square with sides of length equal to the radius of the sphere.

The supplementary units are summarized in [Table 1.5](#).

Determine the following unit conversions to SI units:

Example 1.1

- a density value of $60 \text{ lb}_m/\text{ft}^3$ to kg/m^3
- an energy value of $1.7 \times 10^3 \text{ Btu}$ to kJ
- an enthalpy value of $2475 \text{ Btu}/\text{lb}_m$ to kJ/kg
- a pressure value of 14.69 psig to kPa
- a viscosity value of 20 cp to Pa s

Solution

We will use conversion factors for each unit separately from Table A.1.2.

- Although a composite conversion factor for density, $1 \text{ lb}_m/\text{ft}^3 = 16.0185 \text{ kg}/\text{m}^3$, is available in Table A.1.2, we will first convert units of each dimension separately. Since

$$1 \text{ lb}_m = 0.45359 \text{ kg}$$

$$1 \text{ ft} = 0.3048 \text{ m}$$

Thus,

$$\begin{aligned} & (60 \text{ lb}_m/\text{ft}^3)(0.45359 \text{ kg}/\text{lb}_m) \left(\frac{1}{0.3048} \text{ m}/\text{ft} \right)^3 \\ & = 961.1 \text{ kg}/\text{m}^3 \end{aligned}$$

An alternative solution involves the direct use of the conversion factor for density,

$$\frac{(60 \text{ lb}_m/\text{ft}^3)(16.0185 \text{ kg}/\text{m}^3)}{(1 \text{ lb}_m/\text{ft}^3)} = 961.1 \text{ kg}/\text{m}^3$$

- For energy

$$1 \text{ Btu} = 1.055 \text{ kJ}$$

Thus,

$$\frac{(1.7 \times 10^3 \text{ Btu})(1.055 \text{ kJ})}{(1 \text{ Btu})} = 1.8 \times 10^3 \text{ kJ}$$

- For enthalpy, the conversion units for each dimension are

$$1 \text{ Btu} = 1.055 \text{ kJ}$$

$$1 \text{ lb}_m = 0.45359 \text{ kg}$$

Thus,

$$\begin{aligned} & (2475 \text{ Btu}/\text{lb}_m)(1.055 \text{ kJ}/\text{Btu}) \left(\frac{1}{0.45359 \text{ kg}/\text{lb}_m} \right) \\ & = 5757 \text{ kJ}/\text{kg} \end{aligned}$$

Alternately, using the composite conversion factor for enthalpy of

$$1 \text{ Btu/lb}_m = 2.3258 \text{ kJ/kg}$$

$$\frac{(2475 \text{ Btu/lb}_m)(2.3258 \text{ kJ/kg})}{(1 \text{ Btu/lb}_m)} = 5756 \text{ kJ/kg}$$

d. For pressure

$$\text{psia} = \text{psig} + 14.69$$

The gauge pressure, 14.69 psig, is first converted to the absolute pressure, psia (see Section 1.9 for more discussion on gauge and absolute pressures).

$$14.69 \text{ psig} + 14.69 = 29.38 \text{ psia}$$

The unit conversions for each dimension are

$$1 \text{ lb} = 4.4483 \text{ N}$$

$$1 \text{ in} = 2.54 \times 10^{-2} \text{ m}$$

$$1 \text{ Pa} = 1 \text{ N/m}^2$$

Thus,

$$\begin{aligned} & (29.38 \text{ lb/in}^2)(4.4482 \text{ N/lb}) \left(\frac{1}{2.54 \times 10^{-2} \text{ m/in}} \right)^2 \left(\frac{1 \text{ Pa}}{1 \text{ N/m}^2} \right) \\ &= 202567 \text{ Pa} \\ &= 202.57 \text{ kPa} \end{aligned}$$

Alternatively, since

$$1 \text{ psia} = 6.895 \text{ kPa}$$

$$\frac{(29.38 \text{ psia})(6.895 \text{ kPa})}{(1 \text{ psia})} = 202.58 \text{ kPa}$$

e. For viscosity

$$1 \text{ cp} = 10^{-3} \text{ Pa s}$$

Thus,

$$\frac{(20 \text{ cp})(10^{-3} \text{ Pa s})}{(1 \text{ cp})} = 2 \times 10^{-2} \text{ Pa s}$$

Starting with Newton's second law of motion, determine units of force and weight in SI and English units.

Example 1.2

Solution

a. Force

Newton's second law of motion states that force is directly proportional to mass and acceleration. Thus,

$$F \propto ma$$

Using a constant of proportionality k ,

$$F = kma$$

where in **SI units**,

$$k = 1 \frac{N}{kg \ m/s^2}$$

Thus,

$$F = 1 \left(\frac{N}{kg \ m/s^2} \right) (kg)(m/s^2)$$

$$F = 1 \ N$$

In **English units** the constant k is defined as

$$k = \frac{1}{32.17} \frac{lb_f}{lb_m \ ft/s^2}$$

More commonly, another constant g_c is used where

$$g_c = 1/k = 32.17 \left(\frac{lb_m}{lb_f} \right) \left(\frac{ft}{s^2} \right)$$

Thus

$$F = \frac{ma}{g_c}$$

or

$$F = \frac{1}{32.17} \left(\frac{lb_f}{lb_m \ ft/s^2} \right) (lb_m)(ft/s^2)$$

$$F = \frac{1}{32.17} lb_f$$

b. Weight

Weight W' is the force exerted by the earth's gravitational force on an object. Weight of 1 kg mass can be calculated as

In **SI units**,

$$\begin{aligned} W' &= kmg \\ &= \left(1 \frac{\text{N}}{\text{kg m/s}^2}\right)(1 \text{ kg})\left(9.81 \frac{\text{m}}{\text{s}^2}\right) \\ &= 9.81 \text{ N} \end{aligned}$$

In **English units**,

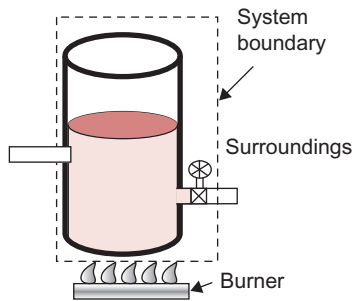
$$\begin{aligned} W' &= kmg \\ &= \frac{1}{32.17} \left(\frac{\text{lb}_f}{\text{lb}_m \text{ ft/s}^2}\right)(1 \text{ lb}_m)(32.17 \text{ ft/s}^2) \\ &= 1 \text{ lb}_f \end{aligned}$$

1.3 SYSTEM

A **system** is any region prescribed in space or a finite quantity of matter enclosed by a **boundary**, real or imaginary. The boundary of a system can be real, such as the walls of a tank, or it can be an imaginary surface that encloses the system. Furthermore, the boundary may be stationary or moveable. For example, in [Figure 1.1](#), the system boundary encloses a tank, piping, and a valve. If our analysis had concerned only the valve, we could have drawn the system boundary just around the valve.

The composition of a system is described by the components present inside the system boundary. Once we choose the boundaries of a system, then everything outside the boundary becomes the **surroundings**. The analysis of a given problem is often simplified by how we select a system and its boundaries; therefore, proper care must be exercised in so doing.

A system can be either **open** or **closed**. In a closed system, the boundary of the system is impervious to flow of mass. In other words, a closed system does not exchange mass with its surroundings. A closed system may exchange heat and work with its surroundings, which may result in a change in energy, volume, or other properties of the system, but its mass remains constant. For example, a system boundary that contains



■ **Figure 1.1** A system containing a tank with a discharge pipe and valve.

a section of the wall of a tank (Fig. 1.2) is impervious to the flow of matter, and thus in this case we are dealing with a closed system. In an open system (also called a control volume), both heat and mass can flow into or out of a system boundary (also called control surface). As shown in Figure 1.1, heat and water flow across the system boundary.

Depending on the problem at hand, the system selected may be as simple as just the wall of a tank, or several parts, such as a tank, valve, and piping as we considered in Figure 1.1. As we will see later in Section 1.14, a system boundary may even enclose an entire food processing plant.

When a system does not exchange mass, heat, or work with its surroundings, it is called an **isolated** system. An isolated system has no effect on its surroundings. For example, if we carry out a chemical reaction in an insulated vessel such that no exchange of heat takes place with the surroundings, and if its volume remains constant, then we may consider that process to be occurring in an isolated system.

If either in a closed or an open system, no exchange of heat takes place with the surroundings, it is called an **adiabatic** system. Although we are unlikely to achieve perfect insulation, we may be able to approach near adiabatic conditions in certain situations. When a process occurs at a constant temperature, often with an exchange of heat with the surroundings, then we have an **isothermal** system.

Note that the system boundaries do not have to be rigid; in fact, they can be flexible and expand or contract during a process. An example of a piston and a cylinder illustrates the moving boundaries of a system. As shown in Figure 1.3, consider a system boundary that encloses only the gas. The piston and the cylinder therefore are surrounding the system. The system boundary in this case is flexible. When the cylinder moves to the right, the system boundary expands; when it moves to the left, it contracts. This is an example of a closed system, because no transfer of mass (gas) takes place across the system boundary. As an extension of this example, we can also locate a heater under the piston; because of heat transfer across the boundary, the gas will expand and the piston will move to the right.

1.4 STATE OF A SYSTEM

Next, let us consider the **state** of a system, which refers to the equilibrium condition of the system. When a system is at equilibrium, we can

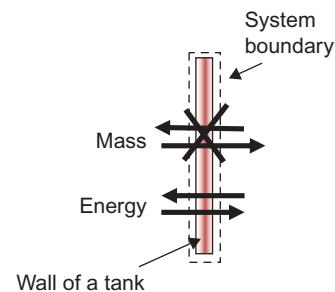


Figure 1.2 A closed system containing a wall.

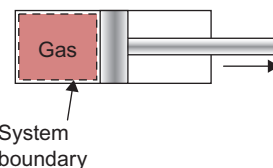
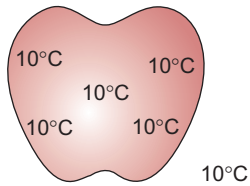
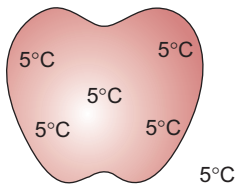


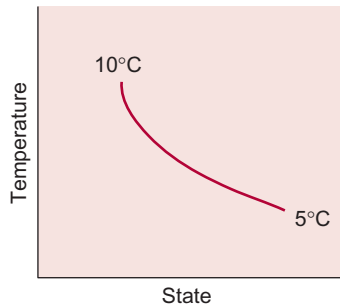
Figure 1.3 A system with a flexible boundary.



■ **Figure 1.4** An apple in a thermal equilibrium with a uniform internal temperature of 10°C .



■ **Figure 1.5** The final state of an apple when placed in a 5°C environment.



■ **Figure 1.6** A path of a process to cool an apple from 10°C to 5°C .

either measure its properties or calculate them to obtain a complete description of the state of the system. At equilibrium, all properties of a system will have fixed values. If any property value changes, then the state of the system will change. Consider an apple with a uniform internal temperature of 10°C (Fig. 1.4); it is in **thermal equilibrium**. Similarly, if the pressure in an object is the same throughout, it is in **mechanical equilibrium**. Although the pressure may vary due to a gravity-induced elevation within the system, this variation in pressure is often ignored in thermodynamic systems. When we have two phases, such as with solid crystals in a saturated liquid, and their mass remains constant, we have **phase equilibrium**. Furthermore, in situations when the chemical composition of a material remains constant with time, we have **chemical equilibrium**. This implies that there is no chemical reaction taking place. For a system to be considered in equilibrium, we must have all preceding conditions of equilibrium satisfied.

When a system undergoes a change of state, then a **process** is said to have taken place. The **path** of the process may involve many different states. A complete description of a process involves initial, intermediate, and final states along with any interactions with the surroundings. For example, when the apple shown in Figure 1.4 is placed in a 5°C environment, it will subsequently attain a final state at a uniform internal temperature of 5°C (Fig. 1.5). The apple in this example went through a cooling process that caused a change in state. In this case, its temperature was initially uniform at 10°C but was changed to a final uniform temperature of 5°C . The path of the process is shown in Figure 1.6.

The previous example of the apple illustrates that we can always describe the state of any system by its **properties**. To fix the state of a system, we specify the values of its properties.

Properties are those observable characteristics, such as pressure, temperature, or volume that define the equilibrium state of a thermo-dynamic system. Properties do not depend on how the state of a system is attained; they are only functions of the state of a system. Therefore, properties are independent of the path by which a system reaches a certain state. We can categorize properties as extensive and intensive.

1.4.1 Extensive Properties

The value of an extensive property depends on the extent or the size of a system. For example, mass, length, volume, and energy depend

on the size of a given system. These properties are additive; therefore, an extensive property of a system is the sum of respective partial property values of the system components. We can determine if a property is extensive by simply doubling the size of the system; if the property value doubles, then it is an extensive property.

1.4.2 Intensive Properties

Intensive properties do not depend on the size of a system. Examples include temperature, pressure, and density. For a homogeneous system, we can often obtain an intensive property by dividing two extensive properties. For example, mass divided by volume, both extensive properties, gives us density, which is an intensive property.

There are also specific properties of a system. Specific properties are expressed per unit mass. Thus, specific volume is volume/mass, and specific energy is energy/mass.

1.5 DENSITY

Density is defined as mass per unit volume, with dimensions (mass)/(length)³. The SI unit for density is kg/m³. Density is an indication of how matter is composed in a body. Materials with more compact molecular arrangements have higher densities. The values of density for various metals and nonmetals are given in Appendix A.3. Density of a given substance may be divided by density of water at the same temperature to obtain specific gravity.

There are three types of densities for foods: solid density, particle density, and bulk density. The values of these different types of densities depend on how the pore spaces present in a food material are considered.

If the pore spaces are disregarded, the solid density of most food particles (Table 1.6) is 1400–1600 kg/m³, except for high-fat or high-salt foods (Peleg, 1983).

Particle density accounts for the presence of internal pores in the food particles. This density is defined as a ratio of the actual mass of a particle to its actual volume.

Bulk density is defined as the mass of particles occupied by a unit volume of bed. Typical values of bulk densities for food materials are given in Table 1.7. This measurement accounts for the void space between the particles. The void space in food materials can be

Table 1.6 Solid Densities of Major Ingredients of Foods

Ingredient	kg/m ³	Ingredient	kg/m ³
Glucose	1560	Fat	900–950
Sucrose	1590	Salt	2160
Starch	1500	Citric acid	1540
Cellulose	1270–1610	Water	1000
Protein (globular)	~1400		

Source: Peleg (1983)

Table 1.7 Bulk Density of Selected Food Materials

Material	Bulk density (kg/m ³)
Beans, cocoa	1073
Beans, soy, whole	800
Coconut, shredded	320–352
Coffee beans, green	673
Coffee, ground	400
Coffee, roasted beans	368
Corn, ear	448
Corn, shelled	720
Milk, whole dried	320
Mustard seed	720
Peanuts, hulled	480–720
Peas, dried	800
Rapeseed	770
Rice, clean	770
Rice, hulled	320
Sugar, granulated	800
Wheat	770

described by determining the **porosity**, which is expressed as the volume not occupied by the solid material.

Thus,

$$\text{Porosity} = 1 - \frac{\text{Bulk density}}{\text{Solid density}} \quad (1.1)$$

The interparticle porosity may be defined as follows:

$$\text{Interparticle porosity} = 1 - \frac{\text{Bulk density}}{\text{Particle density}} \quad (1.2)$$

The solid density of a food can be predicted from the product composition using coefficients provided in Table A.2.9, and the following expression:

$$\rho = 1 / \sum (m_i / \rho_i) \quad (1.3)$$

where:

m_i = mass fraction of product components

ρ_i = density of individual product components (Table A.2.9)

Equation (1.3) can be applied for any high moisture food and where overall porosity is zero. The density values from the expression are a function of temperature based on the expressions for the individual product components.

1.6 CONCENTRATION

Concentration is a measure of the amount of substance contained in a unit volume. It may be expressed as weight per unit weight, or weight per unit volume. Normally, concentration is given in percentage when weight per unit weight measurement is used. Thus, a food containing 20% fat will contain 20 g of fat in every 100 g of food. Concentration values are also expressed as mass per unit volume—for example, mass of a solute dissolved in a unit volume of the solution.

Another term used to express concentration is **molarity**, or molar concentration. Molarity is the concentration of solution in grams per liter divided by the molecular weight of the solute. To express these units in a dimensionless form, **mole fraction** may be used; this is the

ratio of the number of moles of a substance divided by the total number of moles in the system.

Thus, for a solution containing two components, A and B, with number of moles n_A and n_B , respectively, the mole fraction of A, X_A , is

$$X_A = \frac{n_A}{n_A + n_B} \quad (1.4)$$

Concentration is sometimes expressed by **molality**. The molality of a component A in a solution is defined as the amount of a component per unit mass of some other component chosen as the solvent. The SI unit for molality is mole per kilogram.

A relationship between molality, M'_A , and mole fraction, X_A , for a solution of two components, in which the molecular weight of solvent B is M_B , is

$$X_A = \frac{M'_A}{M'_A + \frac{1000}{M_B}} \quad (1.5)$$

Both molality and mole fraction are independent of temperature.

Example 1.3

Develop a spreadsheet on a computer to calculate concentration units for a sugar solution. The sugar solution is prepared by dissolving 10 kg of sucrose in 90 kg of water. The density of the solution is 1040 kg/m³. Determine

- a. concentration, weight per unit weight
- b. concentration, weight per unit volume
- c. °Brix
- d. molarity
- e. mole fraction
- f. molality
- g. Using the spreadsheet, recalculate (a) to (f) if: (1) The sucrose solution contains 20 kg of sucrose in 80 kg of water, and density of the solution is 1083 kg/m³; (2) the sucrose solution contains 30 kg of sucrose in 70 kg of water, and density of the solution is 1129 kg/m³.

Solution

1. The spreadsheet is written using Excel™, as shown in [Figure E1.1](#).
2. The results from the spreadsheet calculation are shown in [Figure E1.2](#).

	A	B
1	Given	
2	Amount of sucrose	10
3	Amount of water	90
4	Density of solution	1040
5		
6	Volume of solution	$=(B2+B3)/B4$
7	Concentration w/w	$=B2/(B2+B3)$
8	Concentration w/v	$=B2/B6$
9	Brix	$=B2/(B2+B3)*100$
10	Molarity	$=B8/342$
11	Mole fraction	$=(B2/342)/(B3/18+B2/342)$
12	Molality	$=(B2*1000)/(B3*342)$

■ **Figure E1.1** Spreadsheet for calculation of sugar solution concentration in Example 1.3.

	A	B	C	D	E
1	Given				Units
2	Amount of sucrose	10	20	30	kg
3	Amount of water	90	80	70	kg
4	Density of solution	1040	1083	1129	kg/m ³
5					
6	Volume of solution	0.0962	0.0923	0.0886	m ³
7	Concentration w/w	0.1	0.2	0.3	kg solute/kg solution
8	Concentration w/v	104	216.6	338.7	kg solute/m ³ solution
9	Brix	10	20	30	(kg solute/kg solution)*100
10	Molarity	0.30	0.63	0.99	mole solute/liter of solution
11	Mole fraction	0.0058	0.0130	0.0221	
12	Molality	0.325	0.731	1.253	mole solute/liter of solution

■ **Figure E1.2** Results of the spreadsheet calculation in Example 1.3.

3. Once the spreadsheet is prepared according to Step (1), the given values are easily changed to calculate all other unknowns.

1.7 MOISTURE CONTENT

Moisture content expresses the amount of water present in a moist sample. Two bases are widely used to express moisture content; namely, moisture content wet basis and moisture content dry basis.

Moisture content wet basis (MC_{wb}) is the amount of water per unit mass of moist (or wet) sample.

Thus,

$$MC_{wb} = \frac{\text{mass of water}}{\text{mass of moist sample}} \quad (1.6)$$

Moisture content dry basis (MC_{db}) is the amount of water per unit mass of dry solids (bone dry) present in the sample.

Thus,

$$MC_{db} = \frac{\text{mass of water}}{\text{mass of dry solids}} \quad (1.7)$$

A relationship between MC_{wb} and MC_{db} may be developed as follows:

$$MC_{wb} = \frac{\text{mass of water}}{\text{mass of moist sample}} \quad (1.8)$$

$$MC_{wb} = \frac{\text{mass of water}}{\text{mass of water} + \text{mass of dry solids}} \quad (1.9)$$

Divide both numerator and denominator of Equation (1.9) with mass of dry solids:

$$MC_{wb} = \frac{\text{mass of water}/\text{mass of dry solids}}{\frac{\text{mass of water}}{\text{mass of dry solids}} + 1} \quad (1.10)$$

$$MC_{wb} = \frac{MC_{db}}{MC_{db} + 1} \quad (1.11)$$

This relationship is useful to calculate MC_{wb} when MC_{db} is known. Similarly, if MC_{wb} is known, then MC_{db} may be calculated from the following equation:

$$MC_{db} = \frac{MC_{wb}}{1 - MC_{wb}} \quad (1.12)$$

The moisture content values in the preceding equations are expressed in fractions. Note that moisture content dry basis may have values greater than 100%, since the amount of water present in a sample may be greater than the amount of dry solids present.

Example 1.4

Convert a moisture content of 85% wet basis to moisture content dry basis.

Solution

a. $MC_{wb} = 85\%$

b. In fractional notation, $MC_{wb} = 0.85$

c. From equation,

$$\begin{aligned} MC_{db} &= \frac{MC_{wb}}{1 - MC_{wb}} \\ &= \frac{0.85}{1 - 0.85} \\ &= 5.67 \end{aligned}$$

or

$$MC_{db} = 567\%$$

Develop a table of conversions from moisture content wet basis to moisture content dry basis between 0% MC_{wb} to 90% MC_{wb} in steps of 10%.

Example 1.5

Solution

- Since repetitive computations are involved, a spreadsheet is prepared as follows.
- In an Excel spreadsheet (Fig. E1.3), enter 0 to 90 in steps of 10 in column A.
- Enter the formula given in Equation (1.12) in cell B2, modified to account for percent values and following spreadsheet notation,

$$MC_{db} = A2/(100 - A2)*100$$

- Copy cell B2 into cells B3 to B11.
- The output is obtained as shown on the spreadsheet in Figure E1.4.
- A plot of the values in columns A and B may be obtained using the chart command of Excel. This plot (Fig. E1.5) is useful in converting moisture content values from one basis to another.

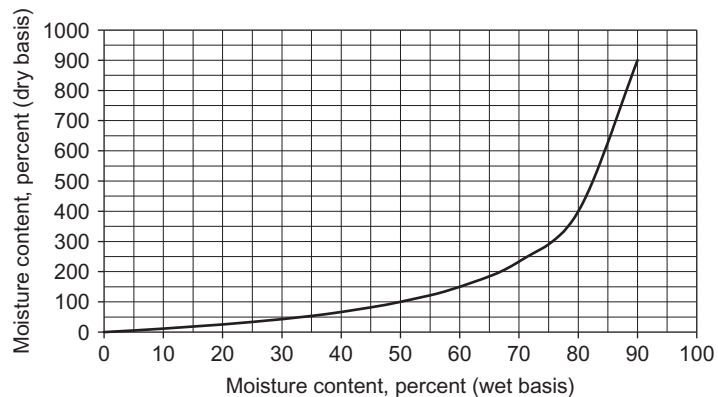
	A	B
1	Moisture content (wb)	Moisture content (db)
2	0	=A2/(100-A2)*100
3	10	=A3/(100-A3)*100
4	20	=A4/(100-A4)*100
5	30	=A5/(100-A5)*100
6	40	=A6/(100-A6)*100
7	50	=A7/(100-A7)*100
8	60	=A8/(100-A8)*100
9	70	=A9/(100-A9)*100
10	80	=A10/(100-A10)*100
11	90	=A11/(100-A11)*100

■ **Figure E1.3** Spreadsheet for converting moisture content wet basis to moisture content dry basis in Example 1.5.

■ **Figure E1.4** Results of the spreadsheet calculation in Example 1.5.

	A	B
1	Moisture content (wb)	Moisture content (db)
2	0	0.00
3	10	11.11
4	20	25.00
5	30	42.86
6	40	66.67
7	50	100.00
8	60	150.00
9	70	233.33
10	80	400.00
11	90	900.00

■ **Figure E1.5** Plot of moisture content wet basis versus moisture content dry basis.



1.8 TEMPERATURE

Temperature is one of those properties that defies a precise scientific definition. We generally perceive temperature as a measure of our physiological response to “hotness” or “coldness.” However, physiological response is subjective, and it does not provide us with an objective measure. For example, holding a block of steel at 40°C gives a much colder sensation than holding a block of wood also at 40°C. An accurate measure of temperature is possible because of the way the properties of many materials change due to heat or cold. Furthermore, these changes are both reliable and predictable—a necessary prerequisite to accurate measurement of temperature.

A thermometer is a commonly used instrument to measure temperature; simply, it gives us a numerical measure of the degree of hotness. Typically, in a glass thermometer, a material such as mercury or alcohol is present inside a glass capillary. This material expands

in response to heat. Its coefficient of expansion is much higher than that of glass. The movement of this material in the glass capillary, on a preselected scale, gives us the measure of temperature. Other instruments used in measuring temperature include thermocouple, resistance temperature detector, thermistor, and pyrometers (to be discussed later in Chapter 3).

The thermodynamic basis for the thermometer is the Zeroth Law of Thermodynamics, first described by R. H. Fowler in 1931. According to this law, "if two bodies are in thermal equilibrium with a third body, they are also in thermal equilibrium with each other." This implies that if the third body is selected as a thermometer, and the temperature of the two bodies is the same, then the two bodies are in thermal equilibrium with each other, even when they may not be in contact with each other.

The statement of the Zeroth Law of Thermodynamics appears rather trivial; however, it cannot be deduced from the other two laws of thermodynamics.

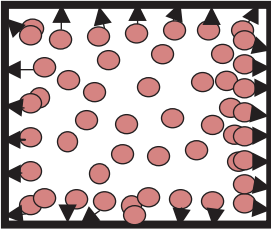
The temperature scale according to the SI units is the Celsius scale, named after a Swedish astronomer, Celsius. In the English system of units, we use the Fahrenheit scale, named after the German instrument maker G. Fahrenheit. Both these scales use two reference points. The ice point is a temperature of ice and water mixture in equilibrium with saturated air at one atmospheric pressure. The ice point for the Celsius scale is 0°C and 32°F in the Fahrenheit scale. The boiling point, when a mixture of liquid and water vapor are in equilibrium at one atmospheric pressure, is 100°C in the Celsius scale and 212°F in the Fahrenheit scale.

In addition to the temperature scales, there is a thermodynamic temperature scale that does not depend on the properties of any material. In SI units, the scale is the Kelvin scale, with a temperature unit of kelvin (K not °K, according to convention). On the Kelvin scale, the lowest temperature is 0 K, although this temperature has not actually been measured. A corresponding scale in English units is the Rankine scale, with the temperature unit expressed as R.

The Kelvin and Celsius scales are related by the following function:

$$T(\text{K}) = T(^{\circ}\text{C}) + 273.15 \quad (1.13)$$

In most engineering calculations, the number in this equation is rounded off to 273.



■ **Figure 1.7** Gas molecules exerting force on the inside of a chamber.

It is also important to recognize that the actual scale division in the Kelvin and Celsius scales is exactly the same. Therefore, if we are concerned with difference in temperature, then either the Celsius or Kelvin scales may be used. Thus,

$$\Delta T(\text{K}) = \Delta T(^{\circ}\text{C}) \quad (1.14)$$

For example, consider a liquid food whose specific heat value is reported as $3.5 \text{ kJ}/(\text{kg } ^{\circ}\text{C})$. The units of specific heat, $\text{kJ}/(\text{kg } ^{\circ}\text{C})$, suggest that 3.5 kJ of heat are required per kilogram of the liquid food to raise its temperature by 1°C . Therefore, whenever we have temperature in the denominator, we are actually considering a unit difference in temperature, since 1°C change in the Celsius scale is the same as a unit change in the Kelvin scale. Therefore, the specific heat of the given liquid food may also be reported as $3.5 \text{ kJ}/(\text{kg K})$.

1.9 PRESSURE

Figure 1.7 illustrates a gas contained in a chamber. The gas molecules strike the inside surface of the chamber and exert a force normal to the surface. When the fluid is at equilibrium, the force exerted by the fluid per unit area of the inside chamber surface is called pressure. If we take a differential section of the chamber surface area, dA , and consider that the force acting normal to it is dF , then pressure is

$$P = \frac{dF}{dA} \quad (1.15)$$

Pressure is an intensive property of a system. The pressure of a fluid contained in a chamber increases with depth, because the weight of the fluid increases with depth.

Pressure may be expressed as force per unit area. The dimensions of pressure are $(\text{mass})(\text{time})^{-2}(\text{length})^{-1}$. In the SI system, the units are N/m^2 . This unit is also called a pascal (named after Blaise Pascal¹). Since the pascal unit is small in magnitude, another unit, bar, is used, where

$$1 \text{ bar} = 10^5 \text{ Pa} = 0.1 \text{ MPa} = 100 \text{ kPa}$$

¹ Blaise Pascal (1623–1662), a French philosopher and mathematician, was the founder of the modern theory of probabilities. He studied hydrostatic and atmospheric pressure and derived Pascal's law of pressure. He is credited with inventing the first digital computer and the syringe. In addition to studying physical sciences, he became a scholar of religion, and in 1655 he wrote *Les Provinciales*, a defense of Jansenism against the Jesuits.

The standard atmospheric pressure is defined as the pressure produced by a column of mercury 760 mm high. The standard atmospheric pressure can be expressed, using different systems of units, as

$$1 \text{ atm} = 14.696 \text{ lb/in}^2 = 1.01325 \text{ bar} = 101.325 \text{ kPa}$$

Zero pressure characterizes absolute vacuum. When pressure is measured relative to absolute vacuum, it is called **absolute pressure**. However, when we use a pressure measuring device such as a pressure gauge, it is usually calibrated to read zero at one atmospheric pressure. Therefore, these devices are actually reading the difference between the absolute pressure and the local atmospheric pressure. A pressure measured by a gauge is often called **gauge pressure**, and it is related to the atmospheric pressure based on the following expression:

$$P_{\text{absolute}} = P_{\text{gauge}} + P_{\text{atmosphere}} \quad (1.16)$$

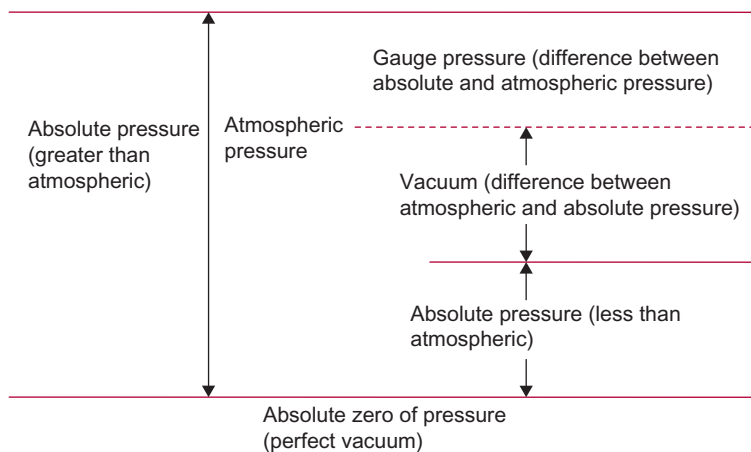
(for pressures greater than $P_{\text{atmosphere}}$)

$$P_{\text{vacuum}} = P_{\text{atmosphere}} - P_{\text{absolute}} \quad (1.17)$$

(for pressures below $P_{\text{atmosphere}}$)

A visual description of the relationships between the various terms used to define pressure is given in [Figure 1.8](#).

In expressing units for **vacuum** in the English system, the atmospheric pressure is referred to as 0 inches of mercury. Perfect vacuum is 29.92 inches of mercury. Thus, 15 inches of mercury has a higher



■ **Figure 1.8** Illustration of the relationships between the terms used to define pressure.

pressure than 20 inches of mercury. In the SI system, the convention to express vacuum is opposite from that of the English system, and the units are given in pascals. At perfect vacuum, the absolute pressure is 0 Pa (recall that one atmospheric pressure is 101.325 kPa). The relationship between the English system and the SI system for expressing vacuum can be written as

$$P_{\text{atmosphere}} = 3.38638 \times 10^3(29.92 - I) \quad (1.18)$$

where $P_{\text{atmosphere}}$ is in Pa, I is inches of mercury.

Pressure is the term used to express this property for liquids and gases. For solids, we use the term **normal stress** instead of pressure. In situations involving fluid flow, pressure is often expressed in terms of height or **head** of a fluid. The height of a fluid that can be supported by the pressure acting on it can be written mathematically as

$$P = \rho gh \quad (1.19)$$

where P is absolute pressure (Pa), ρ is fluid density (kg/m^3), g is acceleration due to gravity ($9.81 \text{ m}/\text{s}^2$), and h is height of fluid (m).

Thus, two atmospheric pressures will support

$$\frac{2 \times (101.325 \times 10^3 \text{ N}/\text{m}^2)}{(13,546 \text{ kg}/\text{m}^3)(9.81 \text{ m}/\text{s}^2)} = 1525 \text{ mm of mercury}$$

Consider a tank filled with cold water to a height of 7 m, as shown in Figure 1.9. The pressure exerted by the water at any point on the bottom of the tank is independent of the diameter of the tank but depends on the height of the water in the tank. This height or elevation of water in the tank is called the **static head**. As shown in the figure, a pressure gauge located at the bottom of the tank indicates a pressure of 0.69 bar (10 psig, i.e., a gauge pressure of $10 \text{ lb}/\text{in}^2$) exerted by a column of water of height 7 m. Thus, the static head at location 1 is 7 m of water. If there is liquid other than water in the tank, then the indicated pressure will be different because of the different specific gravity of the liquid. Thus, if the tank contained gasoline (specific gravity = 0.75), the same pressure of 0.69 bar will be exerted by a column of gasoline 9.38 m high, and the static head will be 9.38 m of gasoline. If the tank contained mercury (specific gravity = 13.6), the same pressure at location 1 will be exerted by a

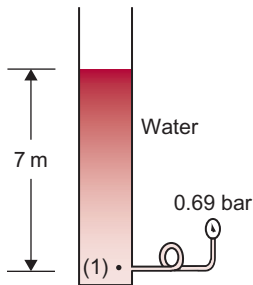
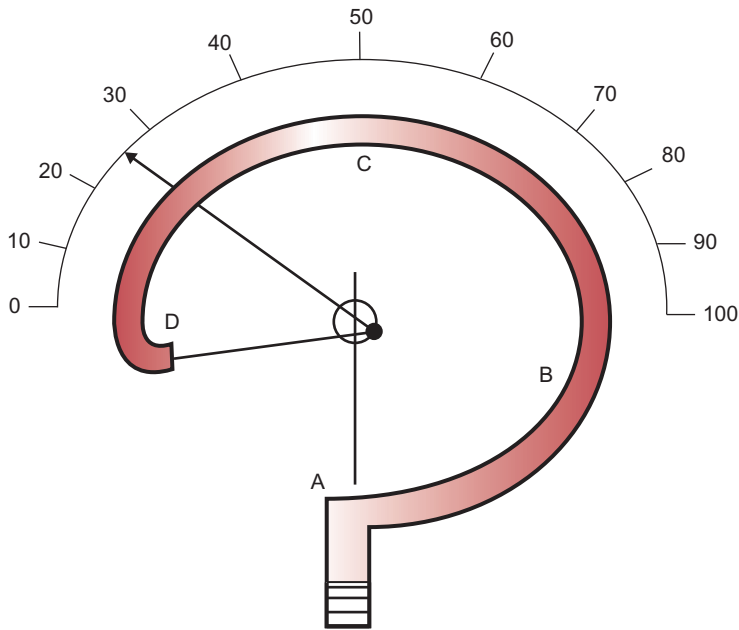


Figure 1.9 Pressure head of a column of water.



■ **Figure 1.10** A Bourdon tube pressure sensor.

column 0.518 m high and the static head designated as 0.518 m of mercury.

The static head may be converted to pressure using the following formula:

$$\text{Pressure (bar)} = \frac{\text{Static head (m)}}{10.2} \times \text{Specific gravity} \quad (1.20)$$

In fluid flow problems, two additional terms are often encountered, namely, static pressure and impact pressure. **Static pressure** is the pressure measured by a device if it is moving with the same velocity as the fluid velocity. **Impact pressure** is force per unit area perpendicular to the direction of flow when the fluid is brought reversibly to rest.

The pressure of a fluid is measured using a variety of instruments, including a Bourdon tube, a manometer, and a pressure transducer. A Bourdon tube is shown in [Figure 1.10](#). It consists of an oval-shaped arm ABCD. An increase in the internal pressure extends the arm, and the movement of the pointer on the dial is calibrated to indicate the pressure.

1.10 ENTHALPY

Enthalpy is an extensive property, expressed as the sum of internal energy and the product of pressure and volume:

$$H = E_i + PV \quad (1.21)$$

where H is enthalpy (kJ), E_i is internal energy (kJ), P is pressure (kPa), and V is volume (m^3).

Enthalpy may also be expressed per unit mass as follows:

$$H' = E'_i + PV' \quad (1.22)$$

where H' is enthalpy per unit mass (kJ/kg), E'_i is internal energy per unit mass (kJ/kg), and V' is specific volume (m^3/kg).

Note that enthalpy is an energy quantity only in special cases. For example, the enthalpy of air in a room is not an energy quantity, because the product of pressure and specific volume in this case is not an energy quantity. The only energy of the air in the room is its internal energy. When a fluid enters or leaves an open system, the product of pressure and volume represents flow energy. In this case, enthalpy of the fluid represents the sum of internal energy and flow energy.

Enthalpy value is always given relative to a reference state in which the value of enthalpy is arbitrarily selected, usually zero for convenience. For example, steam tables give enthalpy of steam, assuming that at 0°C the enthalpy of saturated liquid (i.e., water) is zero.

1.11 EQUATION OF STATE AND PERFECT GAS LAW

The thermodynamic properties of a simple system are established by any two independent properties. A functional relationship between the properties of a system is called an equation of state. Values of two properties of a system help establish the value of the third property.

For a perfect gas, an equation of state is a relationship between pressure, volume, and temperature. The equation may be written as

$$PV' = RT_A \quad (1.23)$$

or

$$P = \rho RT_A \quad (1.24)$$

where P is absolute pressure (Pa), V' is specific volume (m^3/kg), R is the gas constant ($\text{m}^3 \text{ Pa}/[\text{kg K}]$), T_A is absolute temperature (K), and ρ is density (kg/m^3).

At room temperature, real gases such as hydrogen, nitrogen, helium, and oxygen follow the perfect gas law (very closely).

The equation of state for a perfect gas may also be written on a mole basis as

$$PV = nR_0T_A \quad (1.25)$$

where V is the volume (of m kg or n mol), m^3 ; $R_0 = M \times R$ is the universal gas constant, independent of the nature of a gas, $8314.41 \text{ m}^3 \text{ Pa}/(\text{kg mol K})$; and M is the molecular weight of the substance.

1.12 PHASE DIAGRAM OF WATER

Water is considered to be a pure substance. It has a homogeneous and invariable chemical composition, even though it may undergo a change in phase. Therefore, liquid water or a mixture of ice and liquid water, and steam, a mixture of liquid water and water vapor, are pure substances.

When a substance occurs as a vapor at the saturation temperature and pressure, it is called *saturated vapor*. Saturation temperature is the temperature at which vaporization takes place at a given pressure. This pressure is called the *saturation pressure*. Thus, water at 100°C has a saturation pressure of 101.3 kPa. When the temperature of the vapor is greater than the saturation temperature at the existing pressure, it is called *superheated vapor*.

When a substance occurs in a liquid state at its saturation temperature and pressure, it is called a *saturated liquid*. If at the saturation pressure, the temperature of the liquid is lowered below the saturation temperature, it is called a *subcooled liquid*. In the case where, at the saturation temperature, a substance exists partly as liquid and partly as vapor, the ratio of the mass of water vapor to the total mass of the substance is expressed as the quality of the vapors. For example, if steam has 0.1 kg water and 0.9 kg vapor, the quality of steam is 0.9 divided by 1.0 (which represents the total mass of steam); thus steam quality equals 0.9 or 90%.

A phase diagram of water, shown in [Figure 1.11](#), is useful to study pressure–temperature relationships between various phases. This

■ **Figure 1.11** Phase diagram for water.

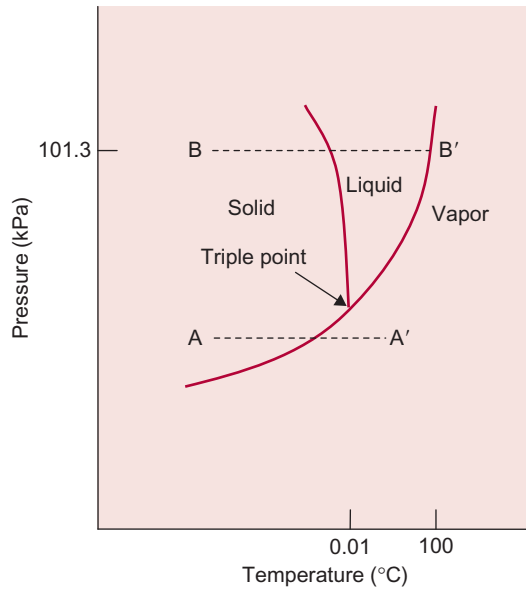


diagram gives the limiting conditions for solid, liquid, and gas (or vapor) phases. At any location within the areas separated by the curves, the pressure and temperature combination permits only one phase (solid, liquid, or vapor) to exist. Any change in temperature and pressure up to the points on the curves will not change the phase. As shown in [Figure 1.11](#), the sublimation line separates the solid phase from the vapor phase, the fusion line separates the solid phase from the liquid phase, and the vaporization line separates the liquid phase from the vapor phase. The three lines meet at a triple point. The triple point identifies a state in which the three phases—solid, liquid, and vapor—may all be present in equilibrium. The triple point for water is at 0.01°C.

The phase diagram shown in [Figure 1.11](#) is useful in examining processes conducted at constant pressure with change of phase. For example, line AA' is a constant-pressure process conducted at a low temperature, where ice sublimates into the vapor phase. There is no liquid phase in this case. Line BB' represents a heating process at or above atmospheric pressure, where initially solid ice melts into the liquid state, followed by vaporization of water at a higher temperature.

Phase diagrams are important in studying processes such as extraction, crystallization, distillation, precipitation, and freeze concentration.

1.13 CONSERVATION OF MASS

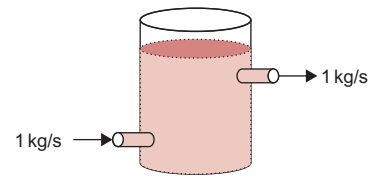
The principle of conservation of mass states that:

Mass can be neither created nor destroyed. However, its composition can be altered from one form to another.

Even in the case of a chemical reaction, the composition of mass of a reactant and the product before and after the reaction may be different, but the mass of the total system remains unaltered. When the chemical reactions are absent, the composition of a system as well as its mass remains the same for a closed system. We can express the conservation of mass principle as an equation written in words as

$$\begin{array}{l} \text{Rate of mass entering} \\ \text{through the boundary} \\ \text{of a system} \end{array} - \begin{array}{l} \text{Rate of mass exiting} \\ \text{through the boundary} \\ \text{of a system} \end{array} = \begin{array}{l} \text{Rate of mass} \\ \text{accumulation within} \\ \text{the system} \end{array} \quad (1.26)$$

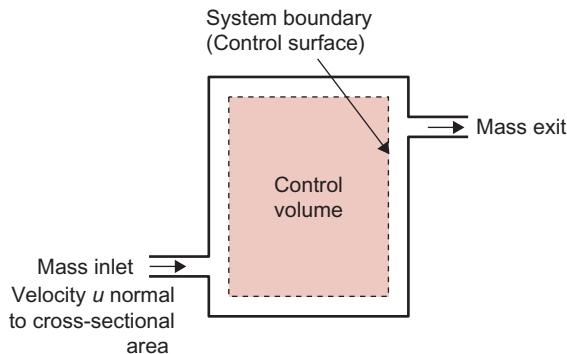
If the rate of mass accumulation within a system is zero, then the rate of mass entering must equal rate of mass leaving the system. For example, as shown in Figure 1.12, if the level of milk in a tank remains constant, and the milk flow rate at the inlet is 1 kg/s, then the flow rate of milk at the exit must also be 1 kg/s.



■ Figure 1.12 Liquid flow in and out of a tank.

Next, let us convert the previous word equation into a mathematical form. To do this, we will refer to Figure 1.13, which shows a system with mass inlet and exit streams. Although only one inlet and one exit stream is shown, there may be more than one stream entering and exiting a control volume. Therefore, for a general case, the rate of mass flow entering the system is

$$\dot{m}_{\text{inlet}} = \sum_{i=1}^n \dot{m}_i \quad (1.27)$$



■ Figure 1.13 A control volume.

where subscript i denotes the inlet, and n is the number of inlets to a system.

The rate of mass flow exiting the system is

$$\dot{m}_{\text{exit}} = \sum_{e=1}^p \dot{m}_e \quad (1.28)$$

where subscript e denotes the exit, and p is the number of exits from a system.

The rate of mass accumulation within the system boundary, expressed as a function of time, is

$$\dot{m}_{\text{accumulation}} = \frac{dm_{\text{system}}}{dt} \quad (1.29)$$

Then substituting into the word [Equation \(1.26\)](#) we obtain

$$\dot{m}_{\text{inlet}} - \dot{m}_{\text{exit}} = \frac{dm_{\text{system}}}{dt} \quad (1.30)$$

Typically, mass flow rate is easier to measure than other flow properties such as velocity. When instead of mass flow rate, we may measure velocity of the flow along with the density of the fluid, the mathematical analysis involves integral expressions, as shown in the following section.

1.13.1 Conservation of Mass for an Open System

Consider a section of a pipe used in transporting a fluid. For a control volume shown, for this open system a fluid with a velocity, u , is entering the system across a differential area dA . Recall that velocity is a vector quantity, possessing both magnitude and direction. As seen in [Figure 1.13](#), only the component of velocity vector normal to the area dA will cross the system boundary. The other component, u_{tan} , (tangent to the area) has no influence on our derivation. Thus, if the fluid particle crossing the boundary has a velocity u_n , then the rate of mass flow into the system may be expressed as

$$d\dot{m} = \rho u_n dA \quad (1.31)$$

Integrating over a finite area

$$\dot{m} = \int_A \rho u_n dA \quad (1.32)$$

The previous equation for mass flow rate will apply for inlet and exit cases.

The total mass of the system may be expressed as a product of its volume and density, or

$$m = \int_V \rho dV \quad (1.33)$$

Substituting this quantity in the word [Equation \(1.26\)](#), we obtain

$$\int_{A_{\text{inlet}}} \rho u_n dA - \int_{A_{\text{exit}}} \rho u_n dA = \frac{d}{dt} \int_V \rho dV \quad (1.34)$$

The previous equation is somewhat complicated because of the integral and differential operators. However, this expression may be simplified for two common situations encountered in engineering systems. First, if the flow is uniform, then all measurable properties of the fluid are uniform throughout the cross-sectional area. These properties may vary from one cross-sectional area to another, but at the same cross-section they are the same in the radial direction. For example, fruit juice flowing in a pipe has the same value of its properties at the center and the inside surface of the pipe. These properties may be density, pressure, or temperature. For a uniform flow, we can replace the integral signs with simple summations, or

$$\sum_{\text{inlet}} \rho u_n dA - \sum_{\text{outlet}} \rho u_n dA = \frac{d}{dt} \int_V \rho \frac{dV}{dt} \quad (1.35)$$

The second assumption we will make is that of *steady state*—that is, the flow rate does not change with time, although it may be different from one location to another. If there is no change with time, then the right-hand term must drop out. Thus, we have

$$\sum_{\text{inlet}} \rho u_n dA = \sum_{\text{outlet}} \rho u_n dA \quad (1.36)$$

Furthermore, if we are dealing with an incompressible fluid—a good assumption for most liquids—there is no change in density. Thus

$$\sum_{\text{inlet}} u_n dA = \sum_{\text{outlet}} u_n dA \quad (1.37)$$

The product of velocity and area is the volumetric flow rate. Thus, according to the conservation of mass principle, for a steady, uniform,

and incompressible flow, the volumetric flow remains unchanged. For compressible fluids such as steam and gases, the inlet mass flow rate will be the same as the exit mass flow rate.

1.13.2 Conservation of Mass for a Closed System

Recall that in a closed system, mass cannot cross system boundaries. Therefore, there is no time rate of change of mass in the system, or

$$\frac{dm_{\text{system}}}{dt} = 0 \quad (1.38)$$

or

$$m_{\text{system}} = \text{constant} \quad (1.39)$$

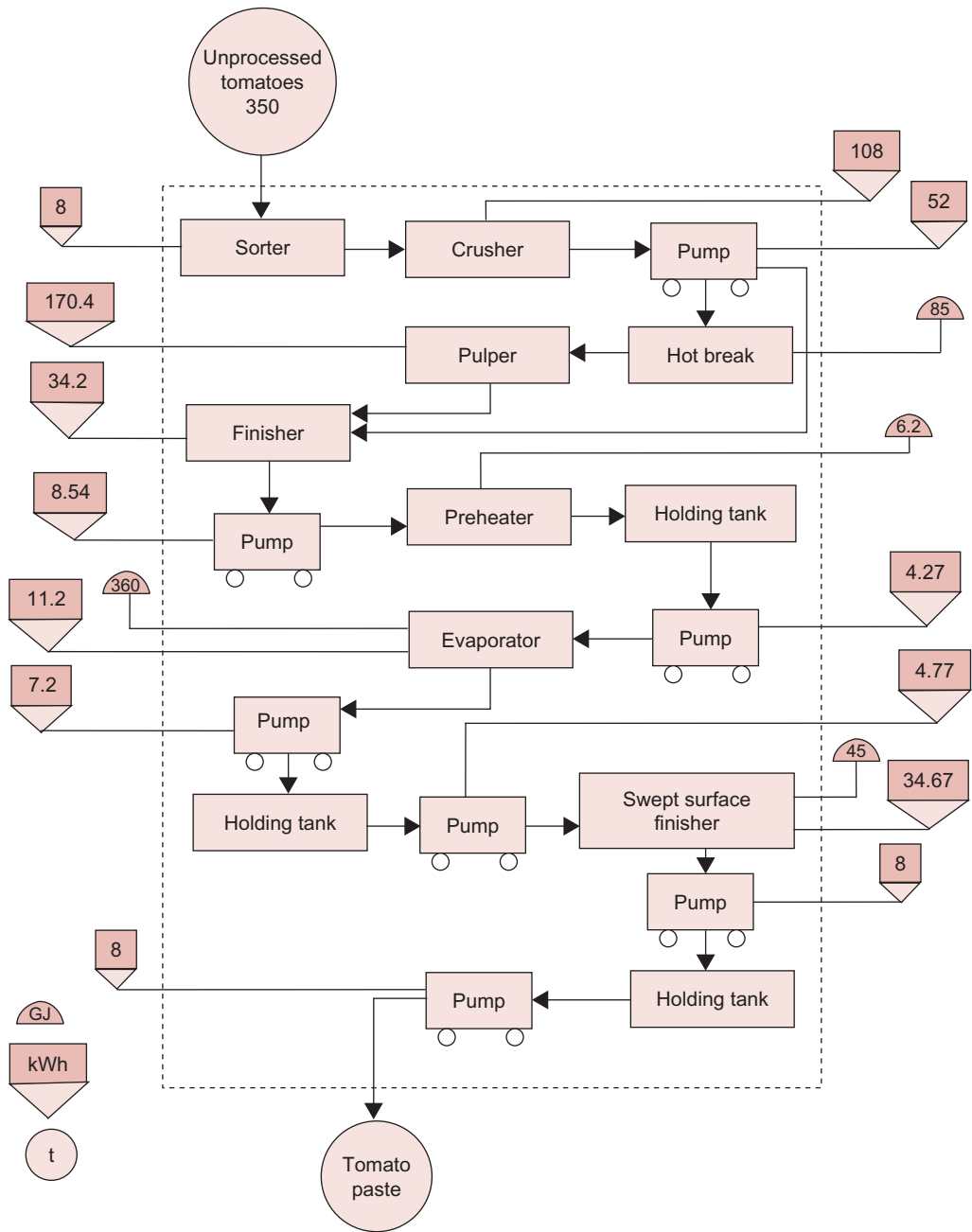
1.14 MATERIAL BALANCES

Material balances are useful in evaluating individual pieces of equipment, such as a pump or a homogenizer, as well as overall plant operations consisting of several processing units—for example, a tomato paste manufacturing line, as shown in [Figure 1.14](#). Compositions of raw materials, product streams, and by-product streams can be evaluated by using material balances.

The following steps should be useful in conducting a material balance in an organized manner.

1. Collect all known data on mass and composition of all inlet and exit streams from the statement of the problem.
2. Draw a block diagram, indicating the process, with inlet and exit streams properly identified. Draw the system boundary.
3. Write all available data on the block diagram.
4. Select a suitable basis (such as mass or time) for calculations. The selection of basis depends on the convenience of computations.
5. Using [Equation \(1.30\)](#), write material balances in terms of the selected basis for calculating unknowns. For each unknown, an independent material balance is required.
6. Solve material balances to determine the unknowns.

The use of material balances is illustrated in the following examples.



■ Figure 1.14 Energy accounting diagram of tomato paste manufacturing based on an eight-hour shift. (Singh et al., 1980)

Example 1.6

In a furnace, 95% of carbon is converted to carbon dioxide and the remainder to carbon monoxide. By material balance, predict the quantities of gases appearing in the flue gases leaving the furnace.

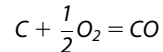
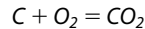
Given

Carbon converted to $\text{CO}_2 = 95\%$

Carbon converted to $\text{CO} = 5\%$

Solution

1. Basis is 1 kg of carbon
2. The combustion equations are



3. From these equations, 44 kg carbon dioxide is formed by combustion of 12 kg carbon, and 28 kg carbon monoxide is formed by combustion of 12 kg carbon.
4. Then, the amount of CO_2 produced,

$$\frac{(44 \text{ kg CO}_2)(0.95 \text{ kg C burned})}{12 \text{ kg C burned}} = 3.48 \text{ kg CO}_2$$

5. Similarly, the amount of CO produced,

$$\frac{(28 \text{ kg CO})(0.05 \text{ kg C burned})}{12 \text{ kg C burned}} = 0.12 \text{ kg CO}$$

6. Thus, the flue gases contain 3.48 kg CO_2 and 0.12 kg CO for every kilogram of carbon burned.

Example 1.7

A wet food product contains 70% water. After drying, it is found that 80% of original water has been removed. Determine (a) mass of water removed per kilogram of wet food and (b) composition of dried food.

Given

Initial water content = 70%

Water removed = 80% of original water content

Solution

1. Select basis = 1 kg wet food product
2. Mass of water in inlet stream = 0.7 kg
3. Water removed in drying = $0.8(0.7) = 0.56$ kg/kg of wet food material
4. Write material balance on water,

$$\text{Water in dried food} = 0.7(1) - 0.56 = 0.14 \text{ kg}$$

5. Write balance on solids,

$$0.3(1) = \text{solids in exit stream}$$

$$\text{Solids} = 0.3 \text{ kg}$$

6. Thus, the dried food contains 0.14 kg water and 0.3 kg solids.

Example 1.8

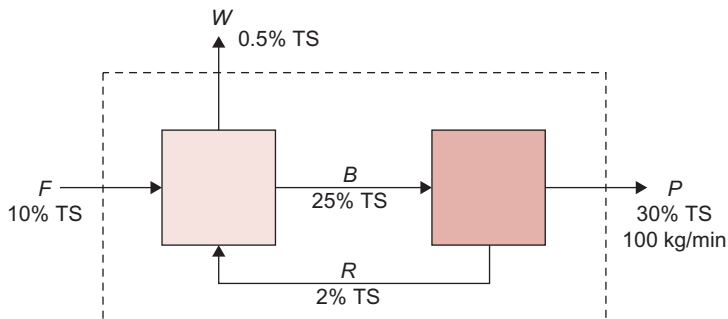
A membrane separation system is used to concentrate total solids (TS) in a liquid food from 10% to 30%. The concentration is accomplished in two stages with the first stage resulting in release of a low-total-solids liquid stream. The second stage separates the final concentration product from a low-total-solids stream, which is returned to the first stage. Determine the magnitude of the recycle stream when the recycle contains 2% TS, the waste stream contains 0.5% TS, and the stream between stages 1 and 2 contains 25% TS. The process should produce 100 kg/min of 30% TS.

Given

(Fig. E1.6)

Concentration of inlet stream = 10%

Concentration of exit stream = 30%



■ **Figure E1.6** A schematic arrangement of equipment described in Example 1.8.

Concentration of recycle stream = 2%
 Concentration of waste stream = 0.5%
 Concentration of stream between two stages = 25%
 Mass flow rate of exit stream = 100 kg/min

Solution

1. Select 1 min as a basis.
2. For the total system

$$F = P + W$$

$$F x_F = P x_P + W x_w$$

$$F = 100 + W$$

$$F(0.1) = 100(0.3) + W(0.005)$$

where x is the solids fraction.

3. For the first stage

$$F + R = W + B$$

$$F x_F + R x_R = W x_W + B x_B$$

$$F(0.1) + R(0.02) = W(0.005) + B(0.25)$$

4. From Step (2)

$$(100 + W)(0.1) = 30 + 0.005W$$

$$0.1W - 0.005W = 30 - 10$$

$$0.095W = 20$$

$$W = 210.5 \text{ kg/min}$$

$$F = 310.5 \text{ kg/min}$$

5. From Step (3)

$$310.5 + R = 210.5 + B$$

$$B = 100 + R$$

$$310.5(0.1) + 0.02R = 210.5(0.005) + 0.25B$$

$$31.05 + 0.02R = 1.0525 + 25 + 0.25R$$

$$4.9975 = 0.23R$$

$$R = 21.73 \text{ kg/min}$$

6. The results indicate that the recycle stream will be flowing at a rate of 21.73 kg/min.
-

Example 1.9

Potato flakes (moisture content = 75% wet basis) are being dried in a concurrent flow drier. The moisture content of the air entering the drier is 0.08 kg of water per 1 kg dry air. The moisture content of air leaving the drier is 0.18 kg water per 1 kg of dry air. The air flow rate in the drier is 100 kg dry air per hour. As shown in Figure E1.7, 50 kg of wet potato flakes enter the drier per hour. At steady state, calculate the following:

- a. What is the mass flow rate of “dried potatoes”?
- b. What is the moisture content, dry basis, of “dried potatoes” exiting the drier?

Given

Weight of potato flakes entering the drier $F = 50$ kg

Time = 1 h

Solution

1. Basis = 1 h
2. Mass of air entering the drier = mass of dry air + mass of water

$$I = 100 + 100 \times 0.08$$

$$I = 108 \text{ kg}$$

3. Mass of air leaving the drier = mass of dry air + mass of water

$$E = 100 + 100 \times 0.18$$

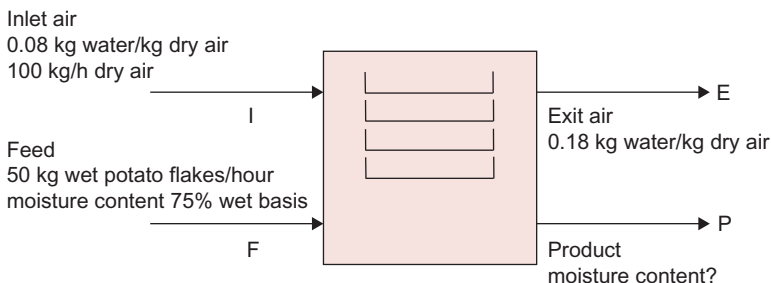
$$E = 118 \text{ kg}$$

4. Total balance on the drier

$$I + F = E + P$$

$$108 + 50 = 118 + P$$

$$P = 40 \text{ kg}$$



■ **Figure E1.7** System diagram for Example 1.9.

5. Solid balance on the drier

Solid content in feed is calculated from the definition of the wet basis moisture content (Eq. (1.6)), rewriting Equation (1.6) as

$$1 - MC_{wb} = 1 - \frac{\text{mass of water}}{\text{mass of moist sample}}$$

or

$$1 - MC_{wb} = \frac{\text{mass of dry solids}}{\text{mass of moist sample}}$$

or

$$\text{Mass of dry solids} = \text{Mass of moist sample} (1 - MC_{wb})$$

Therefore,

$$\text{Mass of solid content in feed} = F(1 - 0.75)$$

If y is the solid fraction in the product stream P , then solid balance on the drier gives

$$\begin{aligned} 0.25 F &= y \times P \\ y &= \frac{0.25 \times 50}{40} \\ &= 0.3125 \end{aligned}$$

Thus,

$$\frac{\text{mass of dry solids}}{\text{mass of moist sample}} = 0.3125$$

or

$$1 - \frac{\text{mass of dry solids}}{\text{mass of moist sample}} = 1 - 0.3125$$

Therefore, moisture content (wet basis) in the exit potato stream is

$$1 - 0.3125 = 0.6875$$

6. The wet basis moisture content is converted to dry basis moisture content

$$MC_{db} = \frac{0.6875}{1 - 0.6875}$$

$$MC_{db} = 2.2 \text{ kg water per 1 kg dry solids}$$

7. The mass flow rate of potatoes exiting the drier is 40 kg at a moisture content of 2.2 kg per 1 kg dry solids.

Example 1.10

An experimental engineered food is being manufactured using five stages, as shown in Figure E1.8. The feed is 1000 kg/h. Various streams have been labeled along with the known composition values on the diagram. Note that the composition of each stream is in terms of solids and water only. Stream C is divided equally into streams E and G. Product P, with 80% solids, is the desired final product. Stream K produces a by-product at the rate of 450 kg/h with 20% solids. Calculate the following:

- Calculate the mass flow rate of product P.
- Calculate the mass flow rate of recycle stream A.
- Calculate the mass flow rate of recycle stream R.

Given

Feed = 1000 kg/h

Solid content of P = 80%

Mass rate of stream K = 450 kg/h

Solids in stream K = 20%

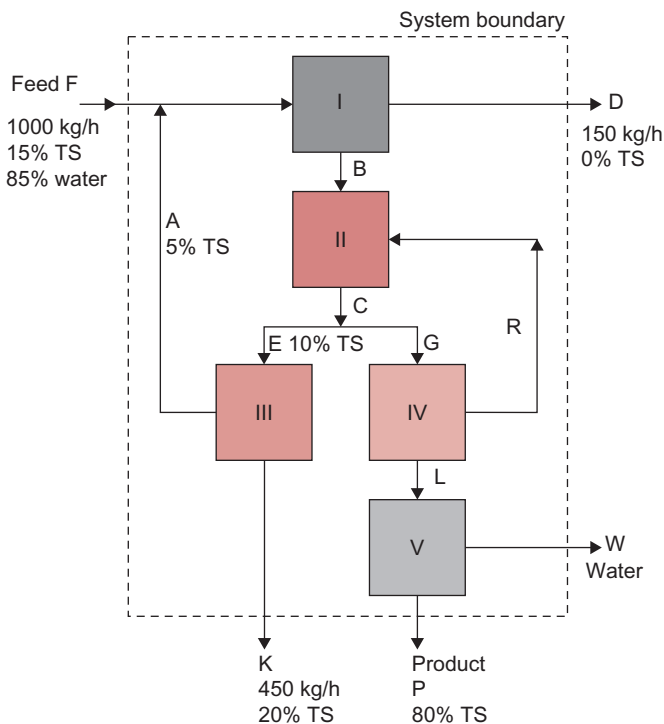
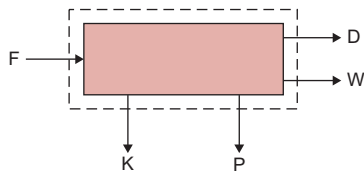
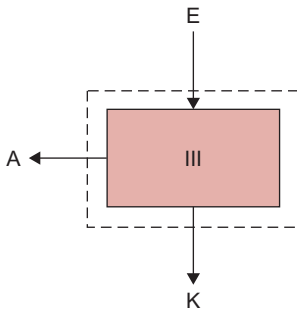


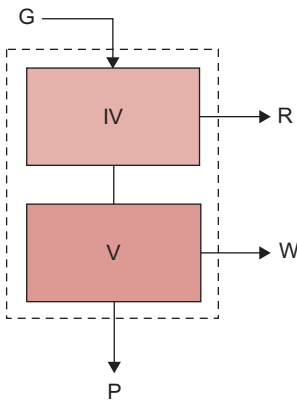
Figure E1.8 A flow sheet of an experimental food manufacturing system.



■ **Figure E1.9** Total system for Example 1.10.



■ **Figure E1.10** Illustration of stage III of the system in Example 1.10.



■ **Figure E1.11** Illustration of stages IV and V of the system in Example 1.10.

Solution

1. Basis = 1 h
2. Consider total system, solid balance (Fig. E1.9).

$$0.15 \times F = 0.2 \times K + 0.8 \times P$$

$$0.15 \times 1000 = 0.2 \times 450 + 0.8 \times P$$

$$150 = 90 + 0.8P$$

$$P = \frac{60}{0.8} = 75 \text{ kg}$$

$$P = 75 \text{ kg}$$

3. Consider Stage III (Fig. E1.10).

Total balance

$$E = A + K; \quad E = A + 450 \tag{1}$$

Solid balance

$$0.1E = 0.05A + 0.2K$$

$$0.1E = 0.05A + 0.2 \times 450 \tag{2}$$

$$0.1E = 0.05A + 90$$

Solve preceding Equations (1) and (2) simultaneously.

$$E = 1350 \text{ kg}$$

$$A = 900 \text{ kg}$$

4. Since C is divided equally into E and G,

$$G = 1350 \text{ kg with 10% solid}$$

5. For total system, conduct total balance to find W.

$$F = K + P + D + W$$

$$1000 = 450 + 75 + 150 + W$$

$$W = 325 \text{ kg}$$

6. Consider stages IV and V together (Fig. E1.11).

$$G = R + W + P$$

$$1350 = R + 325 + 75$$

$$R = 950 \text{ kg}$$

7. The mass flow rates of stream P, A, and R are 75 kg, 900 kg, and 950 kg, respectively.

1.15 THERMODYNAMICS

The science of thermodynamics gives us the foundation to study commonly occurring phenomena during processing of foods. A typical approach to studying any food process may be to first observe a phenomenon, make experimental measurements to confirm the validity of the observation, develop a mathematical basis, and then apply the knowledge gained to an engineering process at hand. This observational scheme is very similar to what is often the thermodynamic approach to examining physical systems.

In examining engineering processes, we are concerned mostly with a macroscopic view. The branch of thermodynamics that deals with this macroscopic approach is called *classical thermodynamics*. Another branch of thermodynamics, called *statistical thermodynamics*, is concerned with what happens at a molecular level, and the average behavior of a group of molecules is considered.

In food engineering, many of the processes of concern to a food engineer are applications of thermodynamics. For example, we may need to calculate heat and work effects associated with a given process. In other instances, the maximum work obtainable from a process may be the key calculation, or we may need to determine how to carry out a process with minimum work. Furthermore, we will encounter the need to determine relationships that exist between various variables of a system when it is at equilibrium.

When we conduct experiments and then want to know the behavior of a given system, the laws of thermodynamics are most useful in the analysis. Based on an experimental foundation, classical thermodynamics is concerned with the macroscopic properties of a system. These properties may be directly measured or they may be calculated from other properties that are directly measurable. For example, we can measure pressure of a gas enclosed in a chamber by attaching a pressure gauge to the chamber.

Thermodynamics also helps us in determining the potential that defines and determines the equilibrium. By knowing potential, we can determine the direction a process will undertake. Although thermodynamics may not tell us how long a process will take to arrive at its final state, it does help in determining what the final state will be. Thus, time is not a thermodynamic variable, and we will rely on other procedures to determine the rate of a process—another important area of calculations for food engineers.

1.16 LAWS OF THERMODYNAMICS

1.16.1 First Law of Thermodynamics

The first law of thermodynamics is a statement of the conservation of energy. The law states:

The energy of an isolated system remains constant.

Stated in other words,

Energy can be neither created nor destroyed but can be transformed from one form to another.

Energy can be either stored within an object or transferred to another one, such as in the form of thermal or mechanical energy. If we increase the elevation of an object, its potential energy will increase. The increased potential energy will remain stored in the object until we move it again. Similarly, we can increase the thermal energy of an object by transferring heat into it and observing an increase in temperature.

Energy can also be transformed from one form to another. For example, in a hydroelectric plant, as water falls from a high elevation onto the blades of a turbine, the potential energy of water is converted into mechanical energy in the turbine, and the generator then converts the mechanical energy into electrical energy. The electrical energy is transmitted to homes or factories where it is further converted to other useful forms such as thermal energy in electric heaters.

During the energy conversion or transmission processes, there is also generation of heat, often misstated as “loss” of energy, when it is actually conversion of energy to other forms that may not be directly useful for the intended purpose. For example, when electrical energy is converted into mechanical energy in an electric motor, the energy “loss” may be 10 to 15%. The “loss” in this case is the conversion of part of the electrical energy into heat due to friction. Although we can convert all mechanical energy into heat because all processes are assumed reversible, we cannot convert all heat into work, as will be evident when we consider the second law of thermodynamics.

1.16.2 Second Law of Thermodynamics

The second law of thermodynamics is useful in examining the direction of energy transfer or conversion. The following two statements

of the second law are by Rudolf Clausius,² and Lord Kelvin,³ respectively.

No process is possible whose sole result is the removal of heat from a reservoir (system) at one temperature and the absorption of an equal quantity of heat by a reservoir at a higher temperature.

No process is possible whose sole result is the abstraction of heat from a single reservoir and the performance of an equivalent amount of work.

The second law of thermodynamics helps explain why heat always flows from a hot object to a cold object; why two gases placed in a chamber will mix throughout the chamber, but will not spontaneously separate once mixed; and why it is impossible to construct a machine that will operate continuously while receiving heat from a single reservoir and producing an equivalent amount of work.

The second law of thermodynamics assigns both quantity and quality to energy. The importance of this law is evident in any process—the path of a process is always toward that of decreasing quality. For example, a hot bowl of soup left to itself on a table cools down. In this case, the quality of energy degrades. Energy of a higher quality (at a higher temperature) transfers from the soup to the surroundings and converts into less useful forms of energy.

1.17 ENERGY

Energy is a scalar quantity. It was first hypothesized by Newton to express kinetic and potential energies. We cannot observe energy directly, but we can measure it using indirect methods and analyze its value. Energy may be in different forms, such as potential, kinetic, chemical, magnetic, or electrical.

² Rudolf Clausius (1822–1888), a German mathematical physicist, is credited with making thermodynamics a science. In 1850, he presented a paper that stated the second law of thermodynamics. He developed the theory of the steam engine, and his work on electrolysis formed the basis of the theory of electrolytic dissociation.

³ Lord Kelvin (1824–1907) was a Scottish mathematician, physicist, and engineer. At the age of 22, he was awarded the chair of natural philosophy at the University of Glasgow. He contributed to the development of the law of conservation of energy, the absolute temperature scale (which was named after him), electromagnetic theory of light, and mathematical analysis of electricity and magnetism. A prolific writer, he published over 600 scientific papers.

Potential energy of a system is by virtue of its location with respect to the gravitational field. If an object has a mass m , located at elevation h , and acceleration due to gravity is g , then the potential energy is

$$E_{PE} = mgh \quad (1.40)$$

Kinetic energy of an object is due to its velocity. If an object is moving with a velocity u , and it has mass m , then its kinetic energy is

$$E_{KE} = \frac{1}{2}mu^2 \quad (1.41)$$

Both kinetic and potential energies are macroscopic; that is, they represent energy of a system due to its entire being. This is in contrast to internal energy, which is due to the microscopic nature of a system. At the molecular scale, the atoms of a substance are continuously in motion. They move in random direction, collide with each other, vibrate, and rotate. Energies related to all these movements, including energy of attraction between the atoms, is combined into one lump sum and is called the internal energy.

Internal energy is an extensive property, and it is independent of the path of a process. Although we cannot measure an absolute value of internal energy, we can relate changes in internal energy to other properties such as temperature and pressure.

In many engineering systems, one or two forms of energy may dominate whereas others can be neglected. For example, when a sugar beet is dropped from a conveyor into a bin, the potential and kinetic energy of the sugar beet changes, but other energy forms such as chemical, magnetic, and electrical do not change and may be neglected in the analysis. Similarly, when tomato juice is heated in a hot-break heater, the potential or kinetic energy of the juice does not change, but the internal energy will change as temperature increases.

The total energy of a system can be written in the form of an equation as

$$E_{TOTAL} = E_{KE} + E_{PE} + E_{ELECTRICAL} + E_{MAGNETIC} + E_{CHEMICAL} + \dots + E_i \quad (1.42)$$

where E_i is the internal energy, kJ.

If the magnitudes of all other energy forms are small in comparison with the kinetic, potential, and internal energies, then

$$E_{TOTAL} = E_{KE} + E_{PE} + E_i \quad (1.43)$$

1.18 ENERGY BALANCE

The first law of thermodynamics states that energy can be neither created nor destroyed. We may express this in the form of a word equation as

$$\begin{array}{r} \text{Total energy} \\ \text{entering the} \\ \text{system} \end{array} - \begin{array}{r} \text{Total energy} \\ \text{leaving the} \\ \text{system} \end{array} = \begin{array}{r} \text{Change in the} \\ \text{total energy of} \\ \text{the system} \end{array} \quad (1.44)$$

Therefore, when a system is undergoing any process, the energy entering the system minus that leaving the system must equal any change in the energy of the system, or

$$E_{\text{in}} - E_{\text{out}} = \Delta E_{\text{system}} \quad (1.45)$$

We can also write the energy balance per unit time as a rate expression:

$$\dot{E}_{\text{in}} - \dot{E}_{\text{out}} = \Delta \dot{E}_{\text{system}} \quad (1.46)$$

We use the dot above the E to note that the units are per unit time. Therefore, \dot{E}_{in} is the rate of energy at the inlet, J/s.

When applying the first law of thermodynamics to engineering problems, we need to account for all forms of energy that are important for the given system. We will consider each major form of energy that is important in the analysis of food engineering problems and discuss each based on the type of a system at hand—closed or open.

1.19 ENERGY BALANCE FOR A CLOSED SYSTEM

Recall that for a closed system, energy may transfer across the system boundaries, but the boundaries are impervious to transfer of mass. The key interactions between a system and its surroundings are due to heat transfer and different forms of work. We will first consider each of these interactions and then combine them into an energy balance, as suggested in the First Law of Thermodynamics.

1.19.1 Heat

Heat transfer between a system and its surroundings is probably the most prevalent form of energy that we observe in many food engineering systems. Heat plays a major role in cooking, preservation, and creating new food products with unique properties.

Heat is an energy form that is easy to sense because of its association with temperature. We know that heat transfers from a hot object to a cold one because of the temperature difference. Heat transfer plays a significant role in food engineering systems, and thus we will devote a separate chapter (Chapter 4) to examining heat transfer in more detail. It is sufficient to note here that heat exchange between a system and its surroundings is temperature driven.

We will denote heat with a symbol Q , with units of joule (J). A **sign convention** is used in thermodynamics regarding transfer of heat across a system boundary. If heat transfer is from a system to its surroundings, then Q is **negative**. On the other hand, if heat is transferring into a system from its surroundings (such as in heating of a potato), then heat transfer Q is **positive**.

If we consider heat transfer per unit time, then we express it as rate of heat transfer, q , with the units J/s or watts (W).

Thermal energy, Q , can be determined if the heat capacity c is known. Thus,

$$Q = m \int_{T_1}^{T_2} c dT \quad (1.47)$$

If the path for energy transfer is under constant pressure, then

$$Q = m \int_{T_1}^{T_2} c_p dT \quad (1.48)$$

where c_p is the specific heat capacity at constant pressure, J/(kg K).

Under constant volume conditions,

$$Q = m \int_{T_1}^{T_2} c_v dT \quad (1.49)$$

where c_v is the specific heat capacity at constant volume, J/(kg K).

The numeric values of c_p and c_v are similar for solids and liquids; however, they may be considerably different for gases.

1.19.2 Work

Work encompasses all interactions between a system and its surroundings that are not a result of temperature difference. There are many such interactions. Examples include the movement of a piston in an engine, an electric wire conducting electric current across a

system boundary, and a shaft transmitting energy from a motor to another piece of equipment that is enclosed in the system boundary.

The symbol used for work is W , and its units are joules (J). The **sign convention** used for work (W) is that any time work is done by a system, W is positive; when work is done on a system, W is negative. This is opposite to that of heat transfer.

A general mathematical formulation for any work interaction is developed as follows. As shown in Figure 1.15, consider a case where an object moves a small distance ds due to the application of force F . The work done on the system may then be calculated as the product of force and distance, or

$$dW = -Fds \quad (1.50)$$

The negative sign reflects the sign convention stated earlier. We can calculate the total work done in moving the object from location 1 to 2 as

$$W_{1-2} = - \int_1^2 Fds = F(s_1 - s_2) \quad (1.51)$$

The work interaction between a system and its surroundings can be attributed to several mechanisms, such as a moving boundary, gravitational forces, acceleration, and shaft rotation. We will develop mathematical expressions for each of these in the following sections.

1.19.2.1 Work Due to a Moving Boundary

A common example of an energy delivery system is an engine where gas enclosed in a cylinder moves a piston. Another case is that of compressing a gas, such as in a bicycle pump, where a piston is moved to compress a gas enclosed in the cylinder. In these examples, the system boundary moves due to application of force, and work is transferred across the system boundary.

Let us consider the case of a piston and a cylinder, as shown in Figure 1.16; the system boundary is drawn around the gas. Note that the piston and cylinder are not a part of the system, but they belong to the surroundings of the system. Next, we place the cylinder on a heater, and apply a constant pressure to the piston. As the gas heats, it expands and causes the piston to move from location 1 to 2. Since the system boundary is flexible, it expands as the piston moves outward. In this case, work is being done by the expanding gas, or by the system.

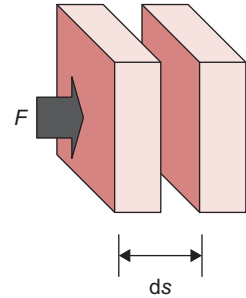
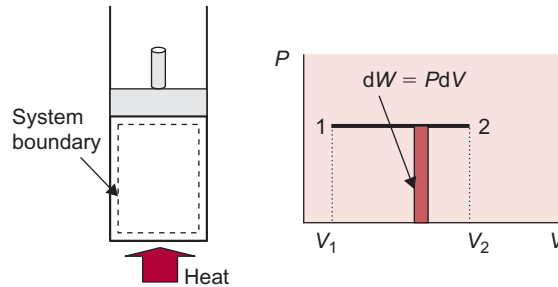


Figure 1.15 Work associated with movement of an object.

■ **Figure 1.16** Work due to moving boundary.



When the piston moves by a small distance, ds , then the differential amount of work done by the system is force, F , times the distance, ds :

$$dW = Fds \quad (1.52)$$

But, from Equation (1.15), Force/Area = Pressure. Therefore, if the cross-sectional area of the piston is A , then

$$dW = PA ds = PdV \quad (1.53)$$

If the piston moves from location 1 to 2, then

$$W_{1-2} = \int_1^2 PdV \quad (1.54)$$

According to gas laws, the relationship between pressure and volume is inversely related; when pressure increases, volume decreases (or the gas is compressed), and when pressure decreases, the volume increases (or the gas expands). Therefore, in our example, as the pressure is kept constant and the gas expands due to application of heat, then the volume V_2 will be larger than V_1 , and the work W_{1-2} will be positive. This agrees with our sign convention that the work is being done by the system; in moving the piston from location 1 to 2, the gas expands. On the other hand, if there is no heat supplied to the cylinder, and the gas is compressed by the movement of the piston with a downward stroke, then the final volume V_2 will be smaller than initial volume V_1 , and the work calculated using Equation (1.54) would be negative, indicating that work is being done on the system.

It is important to understand that the work interaction and heat transfer are mechanisms of energy transfer across a system boundary. They are not properties; therefore, they depend on the path taken

during a process. In case of the work associated with a moving boundary, as presented in this section, we need to know the pressure volume path. A typical path, shown in Figure 1.16, depicts a process from state 1 to 2. As pressure remains constant, the volume changes from V_1 to V_2 . The area under the curve is the work done.

1.19.2.2 Work Due to Gravitational Forces

The work done by or against the force of gravity may be calculated by using the definition of force according to Newton's⁴ second law of motion:

$$F = mg \quad (1.55)$$

If an object of mass m is lifted a small distance dz , as shown in Figure 1.17, the required work is

$$dW = Fdz \quad (1.56)$$

or, substituting Equation (1.55)

$$dW = mgdz \quad (1.57)$$

To lift an object from location 1 to 2:

$$\int_1^2 dW = \int_1^2 mgdz \quad (1.58)$$

or

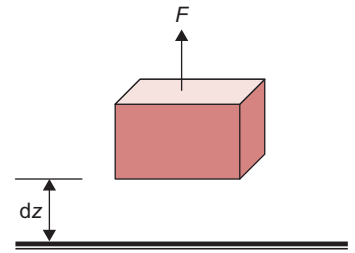
$$W = mg(z_2 - z_1) \quad (1.59)$$

From Equation (1.59), we can see that the work done due to gravitational forces is equivalent to the change in potential energy of the system.

1.19.2.3 Work Due to Change in Velocity

If an object is moving at a velocity u_1 and we want to determine the work required to change the velocity to u_2 , we will again use Newton's second law of motion. Accordingly, force is

$$F = ma \quad (1.60)$$



■ Figure 1.17 Work due to raising an object.

⁴ Sir Isaac Newton (1643–1727), an English physicist and mathematician, laid the foundation of calculus, discovered the composition of white light, studied mechanics of planetary motion, derived the inverse square law, and in 1687, authored the *Principia*.

but acceleration is expressed as

$$a = \frac{du}{dt} \quad (1.61)$$

If the object moves a small distance ds during time dt , then the velocity is

$$u = \frac{ds}{dt} \quad (1.62)$$

The definition of work is

$$W = Fds \quad (1.63)$$

Substituting [Equations \(1.61\) and \(1.62\)](#) in [Equation \(1.63\)](#)

$$W = m \frac{du}{dt} u dt \quad (1.64)$$

Simplifying and setting up integrals,

$$W = m \int_1^2 u du \quad (1.65)$$

we obtain

$$W = \frac{m}{2}(u_2^2 - u_1^2) \quad (1.66)$$

Thus, the work done in changing velocity is equal to the change in kinetic energy of the system.

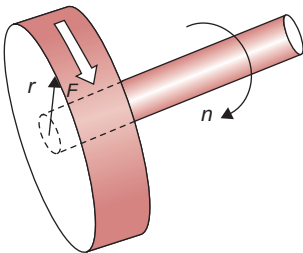
1.19.2.4 Work Due to Shaft Rotation

Transmitting energy by a rotating shaft is common in many energy delivery systems. For example, in an electric motor, a rotating shaft provides a source of mechanical energy to the connected equipment. Similarly, in an automobile, the energy from an engine is transmitted to the wheels by a rotating shaft. As shown in [Figure 1.18](#), the torque Ω applied to a shaft is determined if the force and radius are known. Thus,

$$\Omega = Fr \quad (1.67)$$

If the movement along the circumference is distance s , and the number of revolutions is n , then the distance traveled along the circumference during n revolutions is

$$s = (2\pi r)n \quad (1.68)$$



■ **Figure 1.18** Work due to a rotating shaft.

Since the product of force and distance is work, from [Equations \(1.67\) and \(1.68\)](#), we get

$$W = \frac{\Omega}{r}(2\pi r)n \quad (1.69)$$

$$W = (2\pi n)\Omega \quad (1.70)$$

1.19.2.5 Work Due to Frictional Forces

If friction is present in the system, work must be done to overcome it. If we denote frictional energy as E_f , in units of J, then work due to frictional forces is

$$W = -E_f \quad (1.71)$$

1.19.2.6 Energy Balance

According to the first law of thermodynamics, the total change in energy of a closed system is equal to the heat added to the system minus the work done by the system. Using appropriate signs based on conventions, this can be written mathematically as

$$\Delta E = Q - W \quad (1.72)$$

The total change in energy ΔE of a system is composed of internal thermal energy E_i , kinetic energy E_{KE} , and potential energy E_{PE} . Thus,

$$\Delta E_i + \Delta E_{KE} + \Delta E_{PE} = Q - W \quad (1.73)$$

Based on discussions in [Section 1.19.2](#), for the expansion of a gas in a cylinder ([Fig. 1.16](#)), a complete equation for work may be written as

$$W = \int PdV - \Delta E_{KE} - \Delta E_{PE} - E_f \quad (1.74)$$

[Equation \(1.74\)](#) may be rearranged as

$$W + E_f = \int PdV - \Delta E_{KE} - \Delta E_{PE} \quad (1.75)$$

Eliminating W , ΔE_{KE} , and ΔE_{PE} between [Equation \(1.73\)](#) and [Equation \(1.75\)](#),

$$\Delta E_i = Q + E_f - \int PdV \quad (1.76)$$

From an elementary theorem of calculus, we know that

$$d(PV) = PdV + VdP \quad (1.77)$$

Or, integrating,

$$\Delta PV = \int PdV + \int VdP \quad (1.78)$$

Thus, we can write

$$\int PdV = \Delta PV - \int VdP \quad (1.79)$$

Or substituting Equation (1.79) into Equation (1.76),

$$\Delta E_i + \Delta PV = Q + E_f + \int VdP \quad (1.80)$$

Writing Equation (1.80) in expanded form, noting that Δ for internal energy means final minus initial energy in time, and Δ for other terms means out minus in,

$$E_{i,2} - E_{i,1} + P_2V_2 - P_1V_1 = Q + E_f + \int VdP \quad (1.81)$$

$$(E_{i,2} + P_2V_2) - (E_{i,1} + P_1V_1) = Q + E_f + \int VdP \quad (1.82)$$

In Section 1.10, $E_i + PV$ was defined as enthalpy, H . Thus,

$$H_2 - H_1 = Q + E_f + \int VdP \quad (1.83)$$

Enthalpy H is used widely in process calculations. Tabulated values of enthalpy are available for many substances, such as steam, ammonia, and food products (see Tables A.4.2, A.6.2, and A.2.7).

For a heating process under constant pressure, friction is absent, and the third term on the right-hand side in Equation (1.83) is zero; thus,

$$H_2 - H_1 = Q \quad (1.84)$$

or

$$\Delta H = Q \quad (1.85)$$

Constant pressure processes are encountered most commonly in food processing applications. Thus, from Equation (1.85), the change in enthalpy is simply called the **heat content**.

The change in enthalpy, ΔH , of a system can be determined by actually measuring the change in heat content, Q , for a batch heating

process, provided the process occurs at a constant pressure. A calculation procedure may be used to determine the change in enthalpy by using either measured or tabulated properties. We will consider two cases: a process involving sensible heating/cooling, and another process where heating/cooling involves a phase change.

Sensible heating at constant pressure

If the heating process involves an increase in temperature from T_1 to T_2 , then

$$\Delta H = H_2 - H_1 = Q = m \int_{T_1}^{T_2} c_p dT \quad (1.86)$$

$$\Delta H = mc_p(T_2 - T_1) \quad (1.87)$$

where c_p is heat capacity (J/[kg °C]), m is mass, T is temperature, and 1 and 2 are initial and final values.

Heating at constant pressure involving phase change

Heating/cooling processes involving latent heat may occur where the temperature remains constant while the latent heat is added or removed. For example, when ice is melted, latent heat of fusion is required. Similarly, latent heat of vaporization must be added to water to vaporize it into steam. The latent heat of fusion for water at 0°C is 333.2 kJ/kg. The latent heat of vaporization of water varies with temperature and pressure. At 100°C, the latent heat of vaporization of water is 2257.06 kJ/kg.

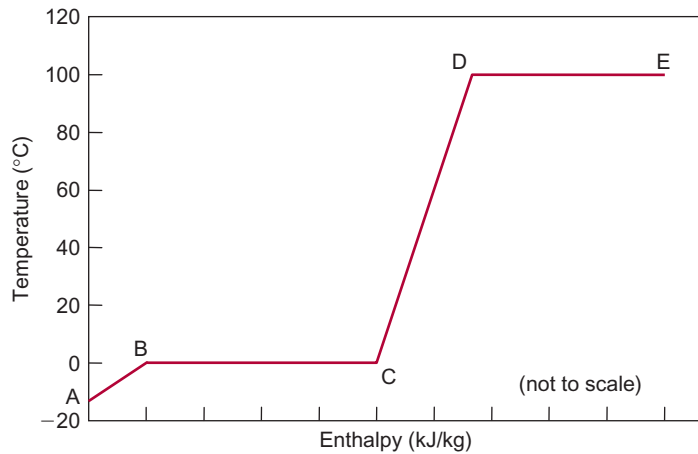
Five kilograms of ice at -10°C is heated to melt it into water at 0°C ; then additional heat is added to vaporize the water into steam. The saturated vapors exit at 100°C . Calculate the different enthalpy values involved in the process. Specific heat of ice is 2.05 kJ/(kg K). Specific heat of water is 4.182 kJ/(kg K), latent heat of fusion is 333.2 kJ/kg, and latent heat of vaporization at 100°C is 2257.06 kJ/kg.

Example 1.11

Given

Figure E1.12 shows a plot of temperature versus enthalpy. Note that temperature remains constant in regions that involve latent heat.

■ **Figure E1.12** A plot of temperature versus enthalpy for melting of ice and vaporization of water.



Solution

The enthalpy calculations are made separately for each zone in [Figure E1.12](#).

1. Zone A–B

$$\begin{aligned}\Delta H_{AB} &= \Delta Q = m \int_{-10}^0 c_p dT \\ &= 5(\text{kg}) \times 2.05 \left(\frac{\text{kJ}}{\text{kg} \cdot ^\circ\text{C}} \right) (0 + 10)^\circ\text{C} \\ &= 102.5 \frac{\text{kJ}}{\text{kg}}\end{aligned}$$

2. Zone B–C

$$\begin{aligned}\Delta H_{BC} &= mH_{\text{latent}} \\ &= 5(\text{kg}) \times 333.2 \left(\frac{\text{kJ}}{\text{kg}} \right) \\ &= 1666 \text{ kJ}\end{aligned}$$

3. Zone C–D

$$\begin{aligned}\Delta H_{CD} &= \Delta Q = m \int_0^{100} c_p dT \\ &= 5(\text{kg}) \times 4.182 \left(\frac{\text{kJ}}{\text{kg} \cdot ^\circ\text{C}} \right) \times (100 - 0)^\circ\text{C} \\ &= 2091 \text{ kJ}\end{aligned}$$

4. Zone D–E

$$\begin{aligned}\Delta H_{DE} &= mH_{\text{latent}} \\ &= 5(\text{kg}) \times 2257.06 \left(\frac{\text{kJ}}{\text{kg}} \right) \\ &= 11,285.3 \text{ kJ}\end{aligned}$$

5. Total change in enthalpy

$$\begin{aligned}\Delta H &= \Delta H_{AB} + \Delta H_{BC} + \Delta H_{CD} + \Delta H_{DE} \\ &= 102.5 + 1666 + 2091 + 11,285.3 \\ &= 15,144.8 \text{ kJ}\end{aligned}$$

It is evident that almost 70% of the enthalpy is associated with the vaporization process.

1.20 ENERGY BALANCE FOR AN OPEN SYSTEM

The transfer of mass across a system boundary, in addition to work and energy, characterizes open systems. Any mass that enters or exits the system carries a certain amount of energy into or out of the system, respectively. Therefore, we need to account for the change in the energy of the system due to mass flow. The work associated with flow sometimes is referred to as **flow work**. We can calculate flow work by determining the work involved in pushing a certain mass through the system boundary. Consider a differential element of fluid of uniform properties entering an open system (Fig. 1.19). If the cross-sectional area of the element is A and the pressure of the fluid is P , then the force required to push this element through the system boundary is

$$F = PA \quad (1.88)$$

If the element is pushed a distance L , then the work done on the fluid element is

$$W_{\text{mass flow}} = FL = PAL = PV \quad (1.89)$$

According to Equation (1.43), the total energy of the fluid element shown in Figure 1.19 includes the kinetic, potential, and internal energies. In addition, we must account for the energy associated with the flowing fluid or flow work. Therefore,

$$E = E_i + E_{KE} + E_{PE} + PV \quad (1.90)$$

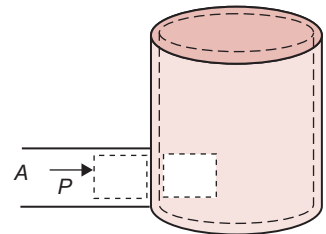


Figure 1.19 Movement of a liquid volume.

or, substituting individual terms for the energy components,

$$E = E_i + \frac{mu^2}{2} + mgz + PV \quad (1.91)$$

1.20.1 Energy Balance for Steady Flow Systems

When a system is in a steady state, its properties do not change with time. They may be different from one location to another. This is a very common situation encountered in numerous engineering systems. For a steady state system, there is no change in the energy of the system with time. Using this condition, we can modify the rate form of the energy balance as follows:

$$\dot{E}_{\text{in}} = \dot{E}_{\text{out}} = \Delta \dot{E}_{\text{system}} = 0 \quad (1.92)$$

Therefore,

$$\dot{E}_{\text{in}} = \dot{E}_{\text{out}} \quad (1.93)$$

1.21 A TOTAL ENERGY BALANCE

Substituting all the individual terms presented in the preceding sections into [Equation \(1.93\)](#), we get

$$\begin{aligned} Q_{\text{in}} + W_{\text{in}} + \sum_{j=1}^p m_i \left(E'_{i,j} + \frac{u_j^2}{2} + gz_j + P_j V'_j \right) \\ = Q_{\text{out}} + W_{\text{out}} + \sum_{e=1}^q m_e \left(E'_{i,e} + \frac{u_e^2}{2} + gz_e + P_e V'_e \right) \end{aligned} \quad (1.94)$$

In [Equation \(1.94\)](#) we have used E' for internal energy per unit mass and V' for specific volume. This general equation is for a system that may have p inlet streams or q exit streams for a fluid to flow in or out, respectively. If there is only one inlet (location 1) and exit (location 2) for a system, then

$$Q_m = \left(\frac{u_2^2}{2} + gz_2 + \frac{P_2}{\rho_2} \right) - \left(\frac{u_1^2}{2} + gz_1 + \frac{P_1}{\rho_1} \right) + (E'_{i,2} - E'_{i,1}) + W_m \quad (1.95)$$

where Q_m and W_m are the transfer of heat and work per unit mass, respectively. The specific volume V' is replaced with $1/\rho$ in [Equation \(1.95\)](#). A more detailed discussion of energy balances in steady flow systems will be presented in Chapter 2. The following examples illustrate the use of energy balances in food processing applications.

A tubular water blancher is being used to process lima beans (Fig. E1.13). The product mass flow rate is 860 kg/h. It is found that the theoretical energy consumed for the blanching process amounts to 1.19 GJ/h. The energy lost due to lack of insulation around the blancher is estimated to be 0.24 GJ/h. If the total energy input to the blancher is 2.71 GJ/h,

Example 1.12

- Calculate the energy required to reheat water.
- Determine the percent energy associated with each stream.

Given

Product mass flow rate = 860 kg/h

Theoretical energy required by product = 1.19 GJ/h

Energy lost due to lack of insulation = 0.24 GJ/h

Energy input to the blancher = 2.71 GJ/h

Approach

We will first write an energy balance and then solve for the unknowns.

Solution

- Select 1 h as a basis.
- Energy balance may be written as follows:

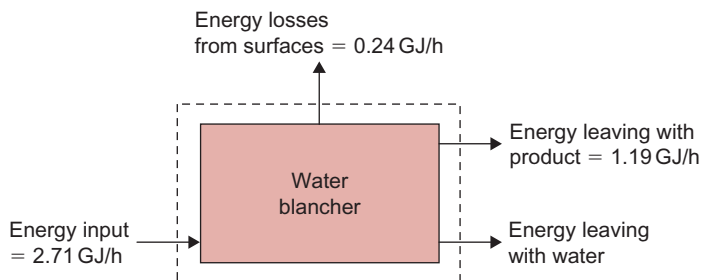
$$\text{Energy input to blancher} = \text{energy out with product} + \text{energy loss due to lack of insulation} + \text{energy out with water}$$
- Substituting appropriate values in the energy balance,

$$2.71 = 1.19 + 0.24 + E_W$$

we get

$$E_W = 1.28 \text{ GJ/h}$$

Thus, the blancher requires $2.71 - 1.28 = 1.43 \text{ GJ/h}$ to both reheat water and maintain it at conditions necessary to accomplish the blanching process.



■ **Figure E1.13** A schematic of a water blancher.

4. These values can be converted to percentage of total thermal input as follows:

$$\text{Energy out with product} = \frac{(1.19)}{2.71}(100) = 43.91\%$$

$$\text{Energy loss due to lack of insulation} = \frac{(0.24)(100)}{2.71} = 8.86\%$$

$$\text{Energy out with water} = \frac{(1.28)(100)}{2.71} = 47.23\%$$

5. The results indicate that this water blancher operates at about 44% thermal energy efficiency.

Example 1.13

Steam is used for peeling potatoes in a semicontinuous operation. Steam is supplied at the rate of 4 kg per 100 kg of unpeeled potatoes. The unpeeled potatoes enter the system with a temperature of 17°C, and the peeled potatoes leave at 35°C. A waste stream from the system leaves at 60°C (Fig. E1.14). The specific heats of unpeeled potatoes, waste stream, and peeled potatoes are 3.7, 4.2, and 3.5 kJ/(kg K), respectively. If the heat content (assuming 0°C reference temperature) of the steam is 2750 kJ/kg, determine the quantities of the waste stream and the peeled potatoes from the process.

Given

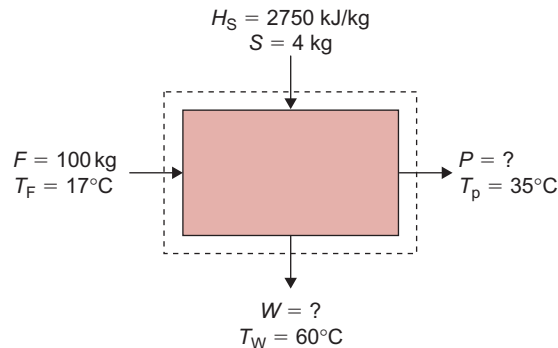
Mass flow of steam = 4 kg per 100 kg of unpeeled potatoes

Temperature of unpeeled potatoes = 17°C

Temperature of peeled potatoes = 35°C

Temperature of waste stream = 60°C

■ **Figure E1.14** A block diagram showing various streams described in Example 1.13.



Specific heat of unpeeled potatoes = 3.7 kJ/(kg K)

Specific heat of peeled potatoes = 3.5 kJ/(kg K)

Specific heat of waste stream = 4.2 kJ/(kg K)

Heat content of steam = 2750 kJ/kg

Solution

1. Select 100 kg of unpeeled potatoes as a basis.
2. From mass balance

$$F + S = W + P$$

$$100 + 4 = W + P$$

$$W = 104 - P$$

3. From energy balance

$$F c_p (T_F - 0) + S H_s = W c_p (T_w - 0) + P c_p (T_p - 0)$$

$$100(3.7)(17) + 4(2750) = W(4.2)(60) + P(3.5)(35)$$

$$6290 + 11,000 = 252W + 122.5P$$

4. From Step (3)

$$17,290 = 252(104 - P) + 122.5P$$

$$252P - 122.5P = 26,208 - 17,290 = 8918$$

$$P = 68.87 \text{ kg}$$

$$W = 35.14 \text{ kg}$$

1.22 POWER

Power is defined as the rate of doing work, using the dimensions (mass)(length)²(time)⁻³ and the SI unit of watts (W). In the English system of units, the commonly used unit for power is horsepower (hp), where 1 hp = 0.7457 kW.

1.23 AREA

Area is a quantitative measure of a plane or a curved surface. It is defined as the product of two lengths. In the SI system, the unit is square meters (m²).

The surface area of a food product is required in a number of process calculations. For example, when calculating heat and mass transfer across the surface of a food material, the surface area of the food

	Mean surface area (cm²)
Apple, Delicious	140.13
Pear, Bartlett	145.42
Plum, Monarch	35.03
Egg (60 g)	70.5

Source: *Mohsenin (1978)*

must be known. Certain physical processes increase the surface area; for example, prior to spray drying, a liquid stream is converted to spray droplets, increasing the surface area of the liquid and enhancing the drying process. The surface areas of some foods are given in [Table 1.8](#). Certain food processing applications require that the surface-area-to-volume ratio be known. For example, in the canning of foods, a higher surface-area-to-volume ratio will result in faster heating of the geometrical center of the container, thus minimizing overheating of the product. For this reason, retortable pouches are often considered better than cylindrical cans. Because of their slab shape, the pouches have high surface area per unit volume, thus resulting in a more rapid heating of the slowest heating point when compared with cylindrical cans. Among various geometric shapes, a sphere has the smallest surface-area-to-volume ratio.

PROBLEMS

- 1.1** A food product with 10 kg mass is being transported to the surface of the moon, where the acceleration due to gravity is 1.624 m/s^2 ; about $1/6$ of the value on earth. Compute the following:
- The force exerted by the product on the earth's surface; in SI units and English units.
 - The product force exerted on the surface of the moon; in SI and English units.
- 1.2** An empty metal can is heated to 90°C and sealed. It is then placed in a room to cool to 20°C . What is the pressure inside the can upon cooling? Assume that can contains air under ideal conditions.

- 1.3** Estimate the solid density of fresh carrot at 20°C.
- *1.4** A 10-kg batch of a food product has a moisture content of 175% dry basis. Calculate the amount of water to be removed from the product to reduce the moisture content to 15% wet basis.
- 1.5** Estimate the change in temperature of 5 m³ of air, due to an increase in pressure of 50 kPa. The initial temperature of the air is 15°C at atmospheric pressure.
- 1.6** A liquid product with 10% product solids is blended with sugar before being concentrated (removal of water) to obtain a final product with 15% product solids and 15% sugar solids. Determine the quantity of final product obtained from 200 kg of liquid product. How much sugar is required? Compute mass of water removed during concentration.
- 1.7** A food product is being frozen in a system with capacity remove 6000 kJ of thermal energy. Assume the product has a specific heat of 3.5 kJ/(kg °C) above the initial freezing temperature of -2°C, a latent heat of fusion of 275 kJ/kg, and a specific heat of 2.8 kJ/(kg °C) for the frozen product below -5°C. Estimate the final temperature of 15 kg of frozen product, if the initial temperature is 20°C.
- 1.8** A liquid food product is being cooled from 80°C to 30°C in an indirect heat exchanger using cold water as a cooling medium. If the product mass flow rate is 1800 kg/h, determine the water flow rate required to accomplish product cooling if the water is allowed to increase from 10°C to 20°C in the heat exchanger. The specific heat of the product is 3.8 kJ/(kg K) and the value for water is 4.1 kJ/(kg K).
- 1.9** Milk enters a heat exchanger at 15°C and at a rate of 2000 kg/h. The heating medium is the latent heat provide by steam. The outlet temperature of the product is 95°C and the specific heat of the product is 3.9 kJ/(kg °C). If the latent heat provided by the steam is 2600 kJ/kg, estimate the flow rate of steam needed to accomplish product heating.
- 1.10** A steel bucket contains 4 liters of water at 12°C. An electric immersion heater rated at 1400 Watts is placed in the

* Indicates an advanced level in solving.

bucket. Determine how long it will take for water to heat to 70°C. Assume that the empty bucket weighs 1.1 kg. The specific heat of steel is 0.46 kJ/(kg °C). Use an average specific heat of water of 4.18 kJ/(kg °C). Disregard any heat loss to the surroundings.

- *1.11** Use MATLAB[®] to plot the enthalpy versus temperature for water over the range of temperature from –40°C to 40°C using the following data taken from [Pham et al. \(1994\)](#). Find enthalpy data for water from a standard source (e.g., [Green and Perry, 2008](#)) and plot it along with the following data from Pham. Discuss possible reasons for differences in the results.

T (°C)	Enthalpy (kJ/kg)
–44.8	–7.91
–36.0	6.46
–27.6	23.2
–19.5	40.0
–11.4	56.8
–3.35	73.1
0.04	123
0.07	236
0.08	311
0.18	385
3.95	433
10.5	460
17.0	487
23.4	514
29.8	541
36.2	568
42.5	595

- *1.12** A concentrated juice is being diluted in a two-stage process. The first stage is blending juice concentrate with 40% product solids with water to create a stream of juice with 5% product solids. The second stage uses the stream with 5% product solids blended with 100 kg/min of concentrate with 40% product solids to produce the final juice at 500 kg/min. Determine the total product solids content (%) of the final product and the flow rate (kg/min) needed in the first stage.

* Indicates an advanced level in solving.

LIST OF SYMBOLS

A	area (m^2)
c	specific heat ($\text{kJ}/[\text{kg } ^\circ\text{C}]$)
c_p	specific heat at constant pressure ($\text{kJ}/[\text{kg } ^\circ\text{C}]$)
c_v	specific heat at constant volume ($\text{kJ}/[\text{kg } ^\circ\text{C}]$)
E	energy (J/kg)
E_i	internal energy (kJ)
E'_i	specific internal energy (kJ/kg)
E_{KE}	kinetic energy (kJ/kg)
E_{PE}	potential energy (kJ/kg)
F	force (N)
g	acceleration due to gravity (m/s^2)
h	height of fluid (m)
H	enthalpy (kJ)
H'	enthalpy per unit mass (kJ/kg)
I	height of mercury column (in)
m	mass (kg)
\dot{m}	mass flow rate (kg/s)
MC_{db}	moisture content, dry basis ($\text{kg water}/\text{kg dry product}$)
MC_{wb}	moisture content, wet basis ($\text{kg water}/\text{kg wet product}$)
M'	molality ($\text{mol solute}/\text{kg solvent}$)
M	molecular weight
n	number of moles
P	pressure (Pa)
q	rate of heat transfer (W)
Q	heat content (kJ/kg)
ρ	density (kg/m^3)
R	gas constant ($\text{m}^3 \text{ Pa}/[\text{kg mol K}]$)
R_0	universal gas constant, $8314.41 \text{ (m}^3 \text{ Pa}/[\text{kg mol K}]$)
τ	time constant (s)
T	temperature ($^\circ\text{C}$)
U	internal energy (kJ/kg)
u	velocity (m/s)
V'	specific volume (m^3/kg)
V	volume (m^3)
W	work (kJ)
x	mass fraction (dimensionless)
X_A	mole fraction of A
z	distance (m)
Ω	torque

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