Chapter 3

Resource Sustainability

The modern food processing plant cannot function without adequate supplies of basic utilities. The use of large quantities of water is not unexpected due to the handling of food in water and the need for water as a cleaning medium. Electricity is used as a utility to power many motors and related equipment throughout food processing. Heated air and water are used for a variety of purposes, with energy provided from several fuel sources, including natural gas, coal, or oil. Refrigeration is a much used utility throughout the food industry, with most applications involving conversion of electrical energy into cold air. Steam is a utility similar to refrigeration, in that its availability is dependent on generating facilities at a location near the point of use.

Within this chapter, three of the utilities used in food processing will be analyzed in some detail. These utilities include (1) generation and utilization of steam, (2) natural gas utilization, and (3) electric power utilization. Water utilization will not be analyzed, except as a part of steam generation, since it is not viewed as a source of energy in most applications. The subject of refrigeration will be described in a separate chapter to adequately reflect the importance of this subject.

3.1 GENERATION OF STEAM

Steam represents the vapor state of water and becomes a source of energy when the change-of-state is realized. This energy can be used for increasing the temperature of other substances, such as food products, and results in production of a water condensate as the energy is released. The vapor state of water or steam is produced by addition

All icons in this chapter refer to the author's web site, which is independently owned and operated. Academic Press is not responsible for the content or operation of the author's web site. Please direct your web site comments and questions to the author: Professor R. Paul Singh, Department of Biological and Agricultural Engineering, University of California, Davis, CA 95616, USA. Email: rps@rpaulsingh.com

of energy from a more basic source, such as fuel oil or natural gas, to convert water from a liquid to a vapor state.

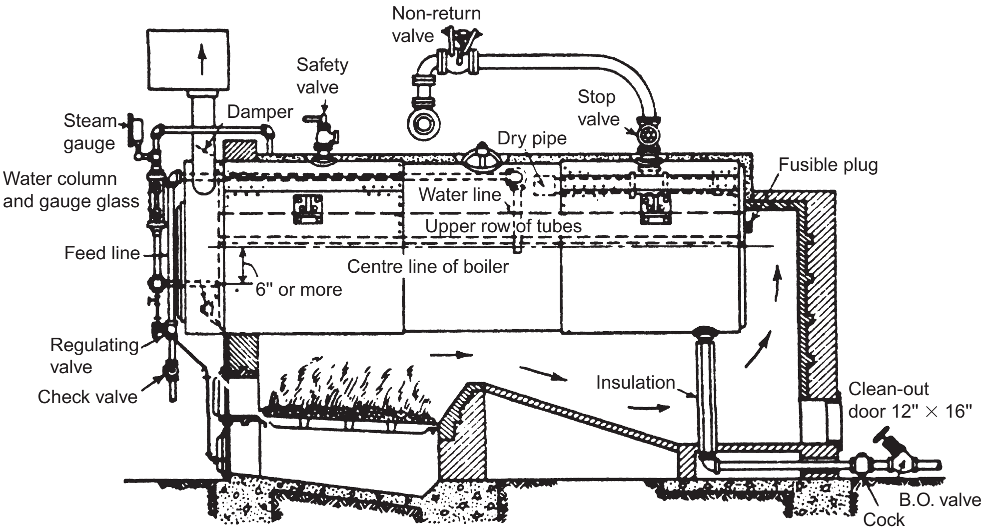
This section will first describe typical systems used in the food industry for conversion of water to steam. The thermodynamics of phase change will be discussed and will be used to explain steam tables. The values tabulated in steam tables will be used to illustrate energy requirements for steam generation, as well as availability of energy from steam to use in food processing. The efficient conversion of energy from the source used to generate steam to some food processing application will be emphasized.

3.1.1 Steam Generation Systems

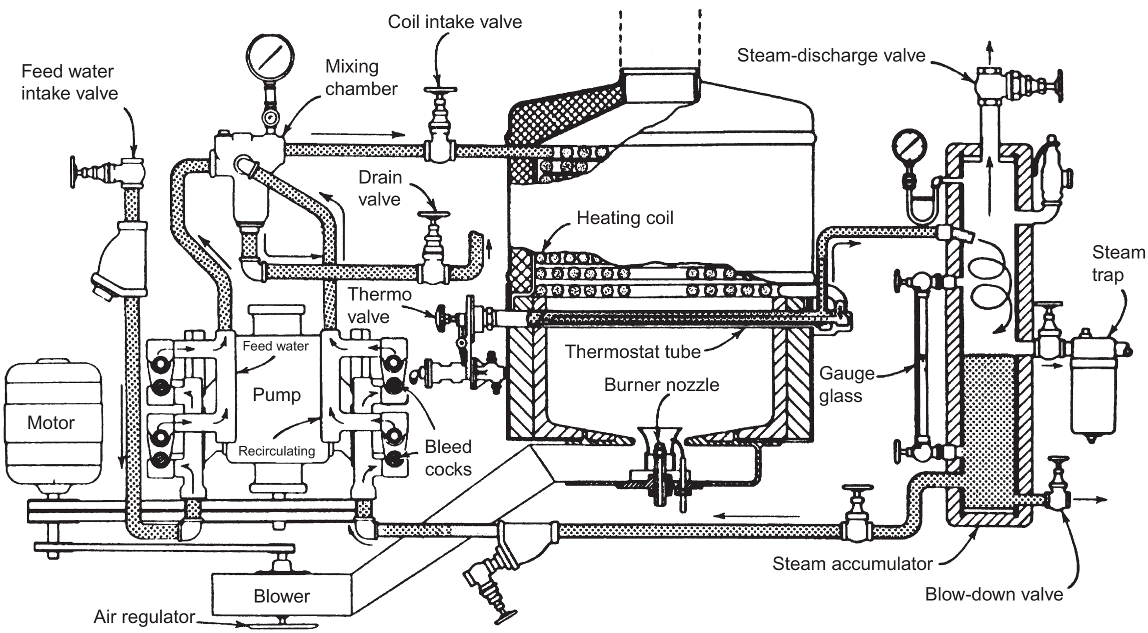
The systems for generation of steam can be divided into two major classifications: fire-tube and water-tube. Both systems are used in the food industry, but water-tube systems are designed for the more modern applications. The steam generation system or boiler is a vessel designed to bring water into contact with a hot surface, as required to convert liquid to vapor. The hot surface is maintained by using hot gases, usually combustion gases from natural gas or other petroleum products. The boiler vessel is designed to contain the steam and to withstand the pressures resulting from the change of state for water.

Fire-tube steam generators (Fig. 3.1) utilize hot gases within tubes surrounded by water to convert the water from liquid to vapor state. The resulting heat transfer causes the desired change of state, with the vapors generated contained within the vessel holding the water. A water-tube steam generator (Fig. 3.2) utilizes heat transfer from hot gas surrounding the tubes to the water flowing through the tubes to produce steam. The heat transfer in the water-tube system tends to be somewhat more rapid because of the ability to maintain turbulent flow within the liquid flow tube.

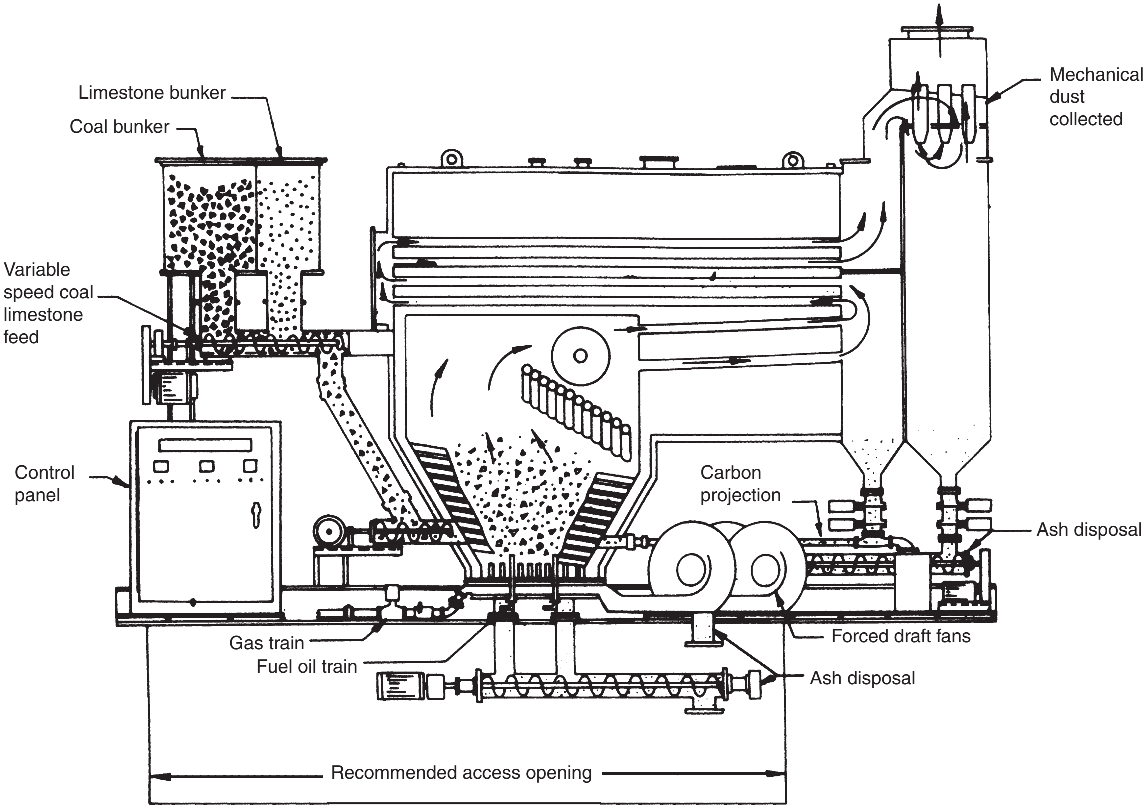
Water-tube boilers generally operate with larger capacities and at higher pressures. These systems have greater flexibility and are considered safer to operate than the counterpart fire-tube systems. The safety feature is associated most closely with the change-of-phase occurring within small tubes in a water-tube system rather than in a large vessel in a fire-tube system. The latter system does have an advantage when the load on the system varies considerably with time. Nearly all modern installations in the food industry are of the water-tube design.



■ **Figure 3.1** The horizontal return tubular (HRT) fire-tube boiler. (From Farrall, 1979)



■ **Figure 3.2** Water-tube steam generator. (Courtesy of Cherry-Burrell Corporation)



■ **Figure 3.3** Steam generation system. (Courtesy of Johnson Boiler Company)

One of the more recent developments is the utilization of alternate fuels as a source of energy for steam generation. In particular, combustible waste materials from processing operations have become a viable alternative. In many situations, these materials are available in large quantities and may present a disposal problem.

Steam generation systems do require modifications in design to accommodate different combustion processes, as illustrated in Figure 3.3. The advantage of these systems is the opportunity to establish cogeneration, as sketched in Figure 3.4. This arrangement utilizes steam generated by burning waste materials to generate electric power, as well as to provide steam for processing operations. Depending on the availability of waste materials, significant percentages of electric power demand can be met in this way.

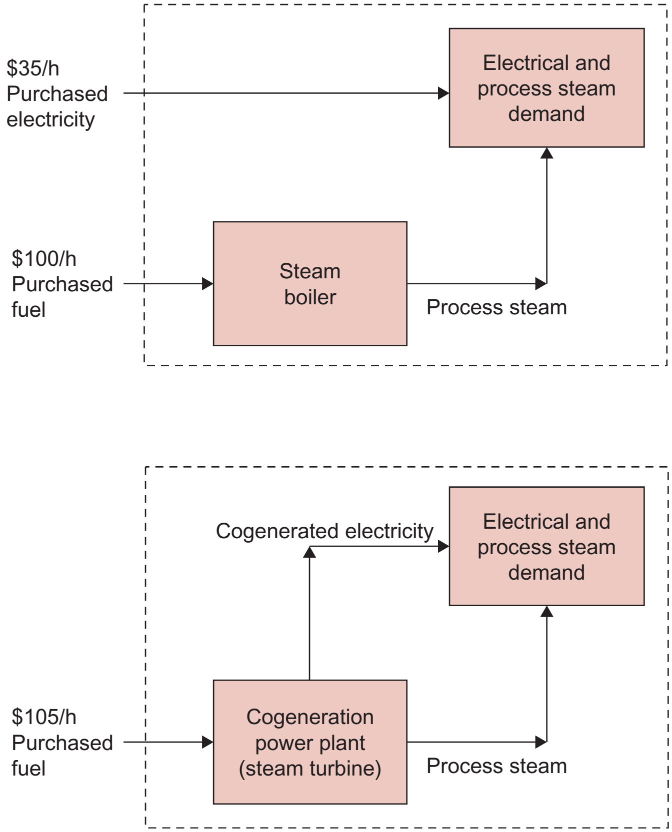
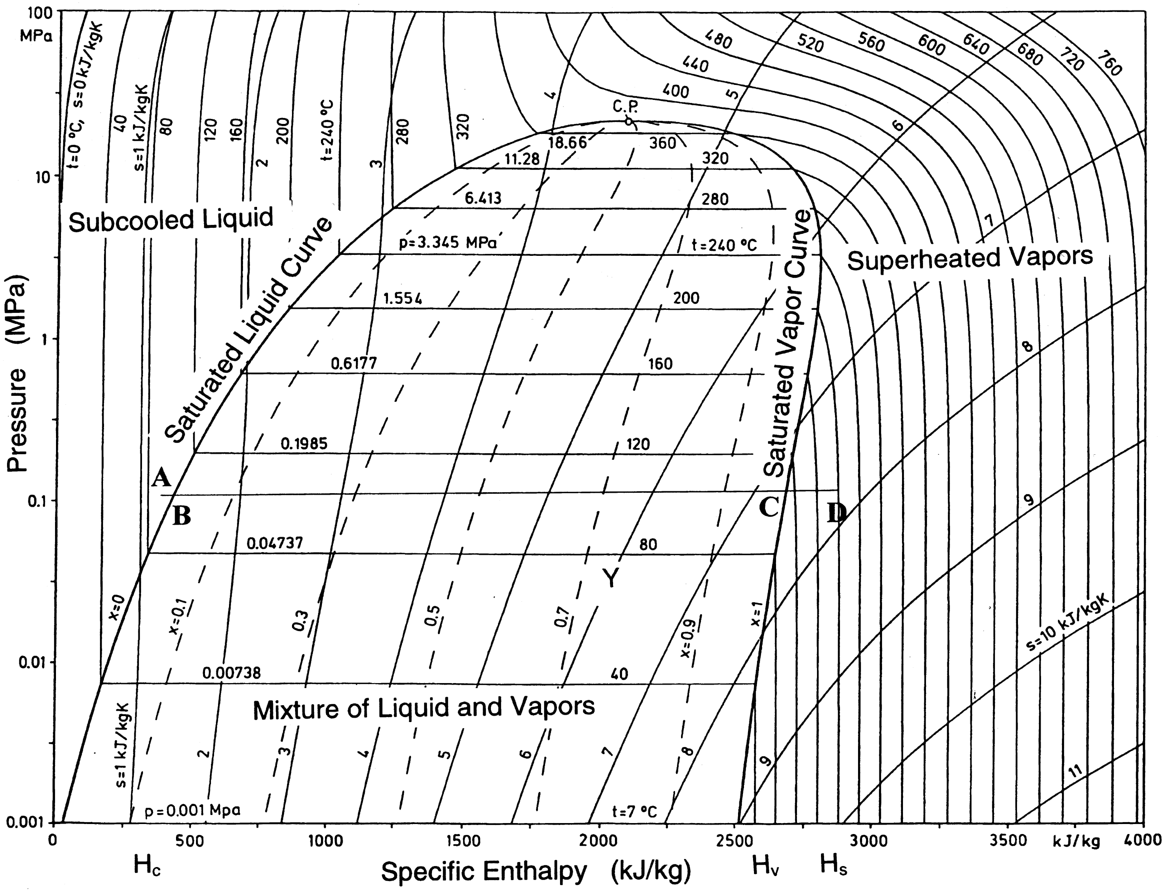


Figure 3.4 Steam generation systems with and without cogeneration. (From Teixeira, 1980)

3.1.2 Thermodynamics of Phase Change

The conversion of water from a liquid to vapor state can be described in terms of thermodynamic relationships. If the phase change for water is presented as a pressure–enthalpy relationship, it appears as shown in Figure 3.5. The bell-shaped curve represents the pressure, temperature, and enthalpy relationships of water at its different states.

The left-side curve is the saturated liquid curve, whereas the right-side curve is the saturated vapor curve. Inside the bell-shaped curve any location indicates a mixture of liquid and vapor. The region to the right side of the saturated vapor curve indicates superheated vapors. And the region to the left side of the saturated liquid curve indicates subcooled liquid. At atmospheric pressure, the addition of sensible heat increases the heat content of liquid water until it reaches the saturated liquid curve.



■ **Figure 3.5** Pressure—enthalpy diagram for steam—water and vapor. (From Straub and Scheibner, 1984)

As an illustration, consider a process ABCD on Figure 3.5. Point A represents water at 90°C and 0.1 MPa pressure. The enthalpy content is about 375 kJ/kg of water. As heat is added to the water, the temperature increases to 100°C at point B on the saturated liquid curve. The enthalpy content of saturated water at point B is H_c (referring to enthalpy of condensate), which can be read off the chart as 420 kJ/kg. Further addition of thermal energy (in the form of latent heat) causes a phase change. As additional heat is added, more liquid water changes to vapor state. At point C, all the water has changed into vapors, thus producing saturated steam at 100°C. The enthalpy of saturated steam at point C is H_v (referring to enthalpy of saturated vapors) or 2675 kJ/kg. Further addition of thermal energy results in

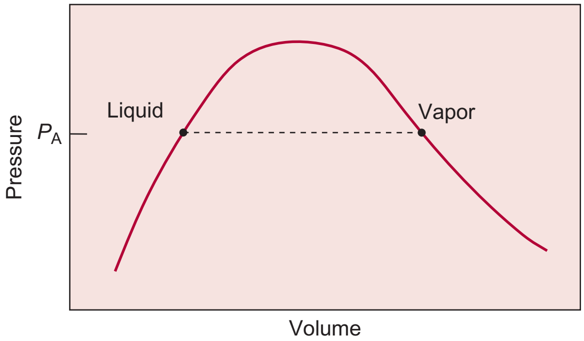


Figure 3.6 Pressure–volume relationships for water liquid and vapor during phase change.

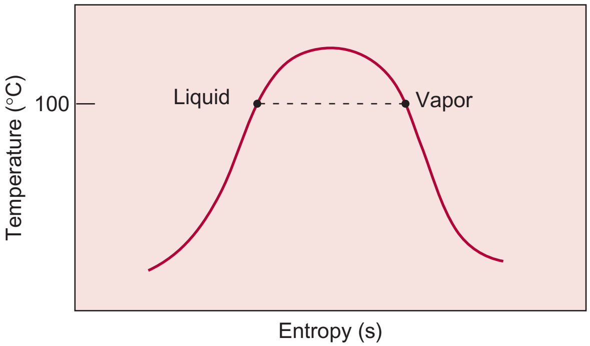


Figure 3.7 Temperature–entropy relationships for water liquid and vapor during phase change.

superheated steam at the same pressure but higher temperatures. Point D represents superheated steam at 200°C with an enthalpy content H_s (referring to superheated steam) of 2850 kJ/kg. Although Figure 3.5 provides a conceptual understanding of the steam generation processes, steam tables (to be described in the following section) give more accurate values.

By plotting the water phase-change process on pressure–volume coordinates, Figure 3.6 is obtained. This illustrates that a significant increase in volume occurs during the conversion of water from a liquid to vapor state. In practice, this conversion occurs within a constant-volume vessel, resulting in an increase in pressure as a result of the phase-change process. In a continuous steam generation process, the pressure and corresponding temperature of the steam to be used for processing operations are established by the magnitude of thermal energy added from the fuel source.

The third thermodynamic relationship would be on temperature–entropy coordinates, as illustrated in Figure 3.7. This relationship indicates that the phase change from liquid to vapor is accompanied by an increase in entropy. Although this thermodynamic property has less practical use than enthalpy, it has interesting characteristics. For example, the pressure decrease resulting in a temperature decrease (referred to as "flash cooling") is, ideally, an isoentropic or constant entropy process. In a similar manner, the compression of steam from a low to a high pressure is a constant entropy process with a corresponding increase in temperature.

There are numerous terms unique to the subject of steam generation. *Saturated liquid* is the condition when **water** is at equilibrium with its vapor. This condition exists at any pressure and corresponding temperature when the liquid is at the boiling point. *Saturated vapor* is **steam** at equilibrium with liquid water. Likewise, the condition exists at any pressure and temperature at the boiling point. *Superheated vapor* is steam at any pressure and temperature when the heat content is greater than saturated vapor. A continuous range of states exists between that of a saturated liquid and that of a saturated vapor, in which the proportions of liquid and vapor vary according to the degree of phase change transition. The extent to which the phase change has progressed is defined as *steam quality*. Normally, steam quality is expressed as a percentage indicating the heat content of the vapor–liquid mixture. In Figure 3.5, point Y indicates a mixture of liquid and vapor. The steam quality of the mixture represented by this point is 0.7 or 70%, meaning 70% of the mixture is vapor and the remaining 30% is in a liquid state. The enthalpy of steam with a steam quality less than 100% is expressed by the following equation:

$$H = H_c + x_s(H_v - H_c) \tag{3.1}$$

The preceding equation may be rearranged into the following alternative form:

$$H = (1 - x_s)H_c + x_s H_v \tag{3.2}$$

The specific volume of steam with a steam quality of x_s can be expressed by

$$V' = (1 - x_s)V'_c + x_s V'_v \tag{3.3}$$

3.1.3 Steam Tables

In the previous section, we saw the use of diagrams to obtain thermodynamic properties of steam. A more accurate procedure to obtain these values is by using tables (see Tables A.4.2 and A.4.3).

Table A.4.2 presents the properties of saturated steam. The properties include specific volume, enthalpy, and entropy, all presented as a function of temperature and pressure. Each property is described in terms of a magnitude for saturated liquid, an additional value for saturated vapor, and a value representing the difference between vapor and liquid. For example, the latent heat of vaporization, as given in Table A.4.2, is the difference between the enthalpy of saturated vapor and saturated liquid.

The properties of superheated steam are presented in Table A.4.3. The specific volume, enthalpy, and entropy are presented at several temperatures above saturation at each pressure. The property values represent the influence of temperature on the magnitude of specific volume, enthalpy, and entropy.

Another procedure to obtain thermodynamic properties of steam is with the use of mathematical equations. These mathematical equations are available in literature. When programmed into a computer, these equations allow determination of enthalpy values. A set of these empirical equations, suggested by Martin (1961) and Steltz and Silvestri (1958) are presented in Example 3.3. This example uses a spreadsheet for the determination of the thermodynamic properties.

Example 3.1

Determine the volume and enthalpy of steam at 120°C with 80% quality.

Given (from Table A.4.2)

Specific volume of liquid $(V'_c) = 0.0010603\ m^3/kg$
Specific volume of vapor $(V'_v) = 0.8919\ m^3/kg$
Enthalpy of liquid $(H_c) = 503.71\ kJ/kg$
Enthalpy of vapor $(H_v) = 2706.3\ kJ/kg$

Approach

The volume and enthalpy of the 80% quality steam can be determined from the saturation conditions using appropriate proper proportions based on steam quality expressed as a fraction.

Solution

1. *For enthalpy*

$$\begin{aligned} H &= H_c + x_s(H_v - H_c) = (1 - x_s)H_c + x_sH_v \\ &= 0.2(503.7) + 0.8(2706.3) \\ &= 2265.78\ kJ/kg \end{aligned}$$

2. *For specific volume*

$$V' = (1 - x_s)V'_c + x_s V'_v$$
$$= 0.2(0.0010603) + 0.8(0.8919)$$
$$= 0.7137\ m^3/kg$$

3. *Note that a small error results from ignoring the volume of saturated liquid.*

$$V' = x_s V'_v = 0.8(0.8919) = 0.7135\ m^3/kg$$

Example 3.2

Fluid milk is being heated from 60 to 115°C at a rate of 500 kg/h using steam as a heating medium. The heat exchanger being utilized has an efficiency of 85%, and the steam quality is 90%. The system is designed to allow condensate to be released at 115°C. The mass and volume flow rates of steam required for this process are to be determined.

Given

Product flow rate ($\dot{m}$) = 500 kg/h
Specific heat of milk (c_p) = 3.86 kJ/(kg °C) (Table A.2.1)
Initial product temperature (T_i) = 60°C
Final product temperature (T_o) = 115°C
Steam quality (x_s) = 90%
Steam temperature (T_s) = 120°C; selected to ensure a minimum temperature gradient of 5°C between steam and product
For steam temperature of 120°C, pressure will be 198.55 kPa, and (from Table A.4.2):

$$H_c = 503.71\ kJ/kg \qquad V'_c = 0.0010603\ m^3/kg$$
$$H_v = 2706.3\ kJ/kg \qquad V'_v = 0.8919\ m^3/kg$$

Approach

The thermal energy requirements for the product will be used to establish the mass flow rate of steam required. The volumetric flow rate is computed from the mass flow rate and specific volume of steam.

Solution

1. *Thermal energy requirement*

$$q = \dot{m}c_p(T_o - T_i) = (500\ kg/h)(3.86\ kJ/kg\ °C)(115°C - 60°C)$$
$$= 106{,}150\ kJ/h$$

or for 85% heat exchanger efficiency

$$q = \frac{106{,}150}{0.85} = 124{,}882\ kJ/h$$

2. *For steam quality of 90%,*

$$H = (0.1)503.71 + (0.9)2706.3 = 2486.04\ \text{kJ}/\text{kg}$$

3. *The thermal energy content of condensate leaving the heat exchanger will be (the specific heat for water is obtained from Table A.4.1)*

$$H_c = (4.228\ \text{kJ}/[\text{kg}\ °\text{C}])(115°\text{C}) = 486\ \text{kJ}/\text{kg}$$

4. *Since the thermal energy provided by steam will be*

$$q_s = \dot{m}_s(H - H_c)$$

and this magnitude must match the steam requirements, then

$$\dot{m}_s = \frac{124{,}882\ \text{kJ}/\text{h}}{(2486.04 - 486)\ \text{kJ}/\text{kg}} = 62.44\ \text{kg}/\text{h}$$

5. *For 90% quality,*

$$V' = (0.1)0.0010603 + (0.9)0.8919 = 0.8028\ \text{m}^3/\text{kg}$$

6. *Volumetric flow rate* $= (62.35\ \text{kg/h})(0.8028\ \text{m}^3/\text{kg}) = 50.05\ \text{m}^3/\text{h}$
7. *Steam generation system capacity*

$$\begin{aligned} 124{,}882\ \text{kJ}/\text{h} = 34{,}689\ \text{J}/\text{s} &= 34{,}689\ \text{W} \\ &= 34.7\ \text{kW} \\ &= 46.5\ \text{hp} \end{aligned}$$

Example 3.3

Develop a spreadsheet program for predicting enthalpy values of saturated and superheated steam.

Approach

We will use the numeric equations given by Martin (1961) and Steltz and Silvestri (1958) to program an Excel™ spreadsheet.

Solution

The spreadsheets with equations and a sample calculation for steam at a temperature of 120°C are as shown in Figures E3.1 and E3.2. The *results are given in cells B45 through B48, as follows:*

$$V_V = 0.89\ \text{m}^3/\text{kg}$$

$$H_c = 503.4\ \text{kJ/kg}$$

$$H_v = 2705.6\ \text{kJ/kg}$$

$$H_{evap} = 2202.2\ \text{kJ/kg}$$

	A	B
1	Temperature °C?	120
2		248
3		7.46908269
4		=−0.00750675994
5		−0.0000000046203229
6		−0.001215470111
7		0
8		=B2−705.398
9		=(EXP(8.0728362+B8*(B3+B4*B8+B5*B8^3+B7*B8^4)/(1+B6*B8)/(B2+459.688)))*6.89
10	Pressure kPa?	=B9
11		=B10*0.1450383
12	Temperature °C?	=B1
13		=B12*1.8+32
14		=(B13+459.688)/2.84378159
15		=0.0862139787*B14
16		=LN(B15)
17		=−B16/0.048615207
18		=0.73726439−0.0170952671*B17
19		=0.1286073*B11
20		=LN(B19)
21		=B20/9.07243502
22		=14.3582702+45.4653859*B21
23		=(B15)^2/0.79836127
24		=0.00372999654/B23
25		=186210.0562*B24
26		=EXP(B25+B20−B16+4.3342998)
27		=B26−B19
28		=B24*B27^2
29		=B28^2
30		=3464.3764/B15
31		=−1.279514846*B30
32		=B28*(B31+41.273)
33		=B29*(B15+0.5*B30)
34		=2*(B32+2*B33)
35		=B28*(B30*B28−B31)
36		=18.8131323+B22*B21
37		=B26+2*(B26*B25)
38		=B37*B34/B27+B34−B35−B37
39		−32.179105
40		1.0088084
41		−0.00011516996
42		0.00000048553836
43		−0.00000000073618778
44		9.6350315E−13
45	V_v	=(0.0302749643*(B34−B27+83.47150448*B15)/B19)*0.02832/0.45359
46	H_c	=(B39+B40*B13+B41*B2^2+B42*B2^3+B43*B2^4+B44*B2^5)*2.3258
47	H_v or H_s	=(835.417534−B17+B14+0.04355685*(B32+B23−B27+B38))*2.3258
48	H_{evap}	=B47−B46

Figure E3.1 Spreadsheet for predicting enthalpy values of saturated and superheated steam in Example 3.3.

	A	B	C
1	Temperature °C?	120	
2		248	For calculations involving saturated vapors: Enter temperature in cell B1, =B9 in cell B10, and =B1 in cell B12
3		7.46908269	
4		−0.00750676	
5		−4.62032E−09	
6		−0.00121547	
7		0	
8		−457.398	
9		198.558129	For calculations involving superheated vapors: Enter pressure in cell B10 and temperature in cell B12
10	Pressure kPa?	198.558129	
11		28.79853348	
12	Temperature °C?	120	
13		248	
14		248.8545543	
15		21.45474124	
16		3.065945658	
17		−63.06556831	
18		1.815387125	
19		3.703701635	
20		1.309332761	
21		0.144319883	
22		20.91982938	
23		576.5634419	
24		6.46936E−06	
25		1.204659912	
26		43.91899067	
27		40.21528903	
28		0.010462699	
29		0.000109468	
30		161.4736976	
31		−206.6079934	
32		−1.729850209	
33		0.011186715	
34		−3.414953557	
35		2.179353383	
36		21.83227963	
37		149.7338856	
38		−168.0431145	
39		−32.179105	
40		1.0088084	
41		−0.00011516996	
42		4.8553836E−07	
43		−7.361878E−10	
44		9.6350315E−13	
45	V_v	0.89172	For superheated vapors, Hs is given by cell B47
46	H_c	503.41	
47	H_v or H_s	2705.61	
48	H_{evap}	2202.20	

Figure E3.2 Sample calculation spreadsheet for Example 3.3.

3.1.4 Steam Utilization

The capacity of the steam generation system in a food processing plant is established by requirements of the individual operations using steam. The requirements are expressed in two ways: (1) the temperature of steam needed as a heating medium, and (2) the quantity of steam required to supply the demands of the operation. Since the temperature requirement is a function of pressure, this establishes one of the operating conditions of the system. In addition, the steam properties are a function of pressure (and temperature), which in turn influences the quantity of steam utilized.

The steps involved in determining the capacity of a steam generation system include the following. The thermal energy requirements of all operations utilizing steam from a given system are determined. In most situations, those requirements will establish maximum temperature required and therefore the pressure at which the steam generation system must operate. After the operating pressure of the system is established, the properties of steam are known and the thermal energy available from each unit of steam can be determined. This information can then be used to compute quantities of steam required for the process. An important consideration in sizing the pipe connecting the process to the steam generation system is the volume of steam required. Using the quantity of steam required as expressed in mass units, and the specific volume of the steam being used, the volumetric flow rate for steam leading to the process is computed.

The use of steam by various processes in a food processing plant requires a transport system. The steam generation system is connected by a network of pipelines to the processes using steam. The transport system must account for two factors: (1) the resistance to flow of steam to the various locations, and (2) the loss of thermal energy or heat content during transport.

The transport of steam involves many of the considerations presented in Chapter 2. The flow of steam through a processing plant pipeline can be described by factors in the mechanical energy balance equation, Equation (2.81). In many situations, the steam generation system and the process using the steam will not be at the same elevation, and the third term on each side of the equation must be considered. Since the steam velocity within the steam generation system will be essentially zero, the kinetic energy term on the left side of the equation will be zero, at least in comparison to the same term on the right side of the equation. The pressure terms in Equation (2.81) are very important, since the left side represents the pressure at the steam generation system and the right side will be the pressure at the point of use. Since no work EP is being done on the steam during transport, this term is zero; but the energy loss due to friction will be very important. In many situations, the energy loss due to friction can be translated directly into the loss of pressure between the steam generation system and the point of steam use.

Example 3.4

Steam is being transported from a steam generation system to a process at the rate of 1 kg/min through a 2-inch (nominal diameter) steel pipe. The distance is 20 m and there are five 90° standard elbows in the pipeline. If the steam is being generated at 143.27 kPa, compute the pressure of the steam at the point of use. The viscosity of steam is 10.335×10^{-6} Pa s.

Given

Steam flow rate ($\dot{m}_s$) = 1 kg/min
Steam pressure = 143.27 kPa
Pipe diameter (D) = 2 inches (nominal) = 0.0525 m (Table 2.3)
Pipe length (L) = 20 m
Fittings include five 90° standard elbows
Steam viscosity (μ) = 10.335×10^{-6} Pa s

Approach

By using the mechanical energy balance and computation of energy losses due to friction, the pressure losses for the 20-m length of pipe will be determined.

Solution

1. *To use Equation (2.51), the friction factor f must be determined from the Reynolds number and the relative roughness, for a steam density of 0.8263 kg/m^{3}obtained at 143.27 kPa.*

$$\bar{u} = \frac{(1\ \mathrm{kg/min})(1/60\ \mathrm{min/s})}{(0.8263\ \mathrm{kg/m^3})[\pi(0.0525\ \mathrm{m})^2/4]} = 9.32\ \mathrm{m/s}$$

and

$$N_{\mathrm{Re}} = \frac{(0.8263\ \mathrm{kg/m^3})(0.0525\ \mathrm{m})(9.32\ \mathrm{m/s})}{(10.335 \times 10^{-6}\ \mathrm{Pa\ s})} = 39{,}120$$

2. *For steel pipe (using Fig. 2.16),*

$$\frac{\varepsilon}{D} = \frac{45.7 \times 10^{-6}\ \mathrm{m}}{0.0525\ \mathrm{m}} = 0.00087$$

3. *The friction factor f is determined from Figure 2.16.*

$$f = 0.0061$$

4. *The energy loss due to friction is computed using Equation (2.51).*

$$\frac{\Delta P}{\rho} = 2(0.0061)\frac{(9.32\ m/s)^2(20\ m)}{(0.0525\ m)} = 403.7\ J/kg$$

5. *Energy loss due to friction in five standard elbows: From Table 2.2, for standard elbow, $C_{ff} = 1.5$.*

$$\frac{\Delta P}{\rho} = \frac{5 \times 1.5 \times (9.32)^2}{2}$$

$$\frac{\Delta P}{\rho} = 325.7\ J/kg$$

6. *Using the mechanical energy balance, Equation (2.81), without elevation and work terms and with velocity of zero at steam generation system,*

$$\frac{143{,}270\ Pa}{0.8263\ kg/m^3} = \frac{(9.32\ m/s)^2}{2} + \frac{P_2}{\rho} + (403.7 + 325.7)$$

or

$$\frac{P_2}{\rho} = 173{,}387.4 - 43.4 - 729.4 = 172{,}614.6\ J/kg$$

7. *By assuming that steam density has not changed and noting that $1Pa = 1J/m^3$*

$$P_2 = (172{,}614.6\ J/kg)(0.8263\ kg/m^3) = 142.63\ kPa$$

indicating that change in steam pressure due to friction losses during flow is relatively small.

Example 3.5

A liquid food with 12% total solids is being heated by steam injection using steam at a pressure of 232.1 kPa (Fig. E3.3). The product enters the heating system at 50°C at a rate of 100 kg/min and is being heated to 120°C. The product specific heat is a function of composition as follows:

$$c_p = c_{pw}(\text{mass fraction } H_2O) + c_{ps}(\text{mass fraction solid})$$

and the specific heat of product at 12% total solids is 3.936 kJ/(kg °C). Determine the quantity and minimum quality of steam to ensure that the product leaving the heating system has 10% total solids.

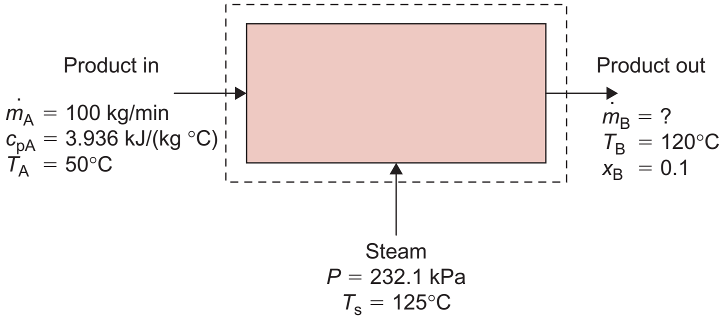


Figure E3.3 System diagram for Example 3.5.

Given

Product total solids in (X_A) = 0.12
Product mass flow rate ($\dot{m}_A$) = 100 kg/min
Product total solids out (X_B) = 0.1
Product temperature in (T_A) = 50°C
Product temperature out (T_B) = 120°C
Steam pressure = 232.1 kPa at (T_S) = 125°C
Product specific heat in (C_{PA}) = 3.936 kJ/(kg °C)

Approach

1. *Set up mass balance equations.*

$$\dot{m}_a + \dot{m}_S = \dot{m}_B$$

$$\dot{m}_A X_A = \dot{m}_B X_B$$

2. *Set up energy balance equation using reference temperature of 0°C.*

$$\dot{m}_A c_{PA}(T_A - 0) + \dot{m}_S H_S = \dot{m}_B c_{PB}(T_B - 0)$$

3. *By solving the mass balance equations for $\dot{m}_B$ and $\dot{m}_S$, the enthalpy of steam (H_s) required can be computed.*

Solution

1. *Mass and solid balance*

$$100 + \dot{m}_s = \dot{m}_B$$

$$100(0.12) + 0 = \dot{m}_B(0.1)$$

$$\dot{m}_B = \frac{12}{0.1} = 120 \text{ kg/min}$$

2. *Then*

$$\dot{m}_s = 120 - 100 = 20 \text{ kg/min}$$

3. *From energy balance*

$$(100)(3.936)(50 - 0) + (20)H_s = (120)c_{PB}(120 - 0)$$

where

$$c_{PB} = (4.232)(0.9) + c_{PS}(0.1)$$

$$3.936 = (4.178)(0.88) + c_{PS}(0.12)$$
$$c_{PS} = 2.161$$

then

$$c_{PB} = 4.025 \text{ kJ/(kg °C)}$$

4. *Solving for enthalpy (H_s),*

$$H_s = \frac{(120)(4.025)(120) - (100)(3.936)(50)}{20}$$

$$H_s = 1914.0 \text{ kJ/kg}$$

5. *From properties of saturated steam at 232.1 kPa,*

$$H_c = 524.99 \text{ kJ/kg}$$

$$H_v = 2713.5 \text{ kJ/kg}$$

then

$$\%\text{Quality} = \frac{1914 - 524.99}{2713.5 - 524.99}(100)$$

$$= 63.5\%$$

6. *Any steam quality above 63.5% will result in higher total solids in heated product.*

3.2 FUEL UTILIZATION

The energy requirements for food processing are met in a variety of ways. In general, the traditional energy sources are utilized to generate steam as well as to provide for other utilities used in the

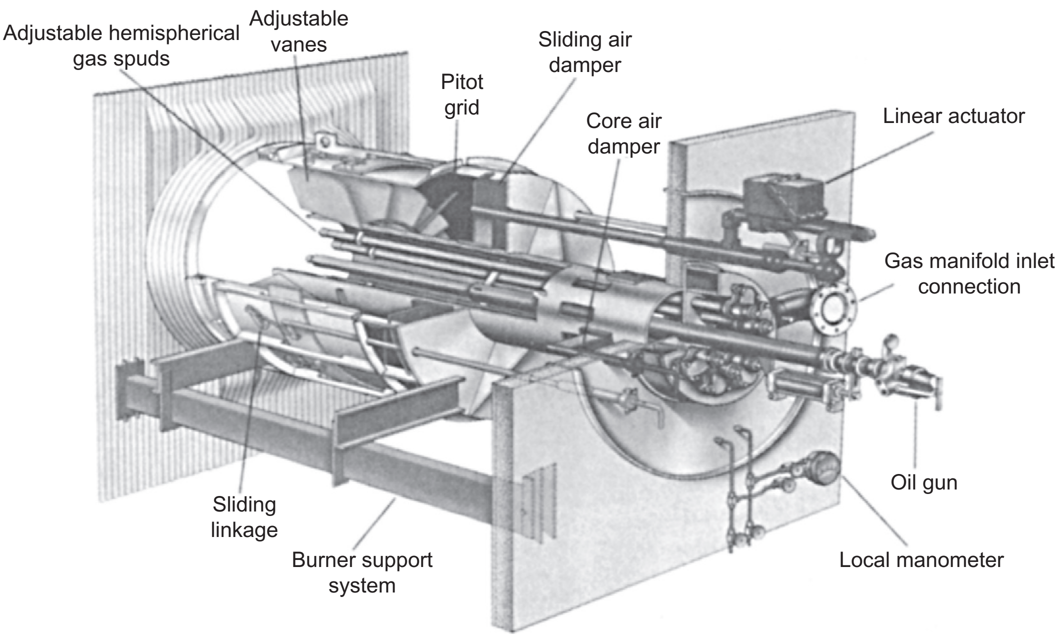
Table 3.1 Energy Use by Fuel Type for 14 Leading Energy-Using Food and Kindred Products Industries for 1973

	Energy use by type of fuel (%)				
Industry	**Natural Gas**	**Purchased Electricity**	**Petroleum Products**	**Coal**	**Other**
Meat packing	46	31	14	9	0
Prepared animal feeds	52	38	10	<1	0
Wet corn milling	43	14	7	36	0
Fluid milk	33	47	17	3	0
Beet sugar processing	65	1	5	25	4
Malt beverages	38	37	18	7	0
Bread and related products	34	28	38	0	0
Frozen fruits and vegetables	41	50	5	4	0
Soybean oil mills	47	28	9	16	0
Canned fruits and vegetables	66	16	15	3	0
Cane sugar refining	66	1	33	0	0
Sausage and other meat	46	38	15	1	0
Animal and marine fats and oils	65	17	17	1	0
Manufactured ice	12	85	3	0	0

Source: *Unger (1975)*

processing plant. As illustrated in Table 3.1, the energy types include natural gas, electricity, petroleum products, and coal. Although the information presented was collected in 1973 and percentages of natural gas utilization have declined somewhat, it seems evident that food processing has a definite dependence on petroleum products and natural gas.

To release the energy available from natural gas and petroleum products, they are exposed to a combustion process. This is a rapid chemical reaction involving fuel components and oxygen. The primary fuel components involved in the reaction include carbon, hydrogen, and sulfur, with the last being an undesirable component. The oxygen for the reaction is provided by air, which must be mixed with fuel in the most efficient manner.



■ **Figure 3.8** Circular register burner with water-cooled throat for oil and gas firing. (From the Babcock and Wilcox Handbook, 1978)

3.2.1 Systems

The burner is the primary component of the system required for combustion of natural gas or petroleum products. Burners are used to produce the hot gases required in steam generation or the heated air for space heating in a building. Burners are designed to introduce fuel and air into the combustion chamber in a manner leading to maximally efficient generation of energy.

A typical burner is illustrated by Figure 3.8, a single circular register burner for both natural gas and oil. The orientation of doors in the air register provides turbulence needed to create mixing of fuel and air, as well as producing a desirable short flame. Burners are designed to minimize maintenance by keeping exposure of the burner to a minimum and allowing the replacement of vulnerable components while the unit continues to operate.

Safety is a definite concern in operating any system involving combustion. Ignition of a burner should occur at a location close to the burner, even at much higher air flows than required. Safety precautions should apply during starting and stopping of the system, as well as during load changes and variations in fuel.

3.2.2 Mass and Energy Balance Analysis

The combustion process can be described by equations involving the reaction between methane and oxygen as follows:

$$CH_4 + 2\ O_2 + 7.52\ N_2 = CO_2 + 2\ H_2O + 7.52\ N_2 \tag{3.4}$$

where 3.76 mol N_2 per mol O_2 are included in air for combustion and in the reaction processes. Actual fuel gas will contain 85.3% CH_4 (by volume), and the reaction will appear as follows:

$$\begin{aligned} 0.853\ CH_4 &+ 0.126\ C_2H_6 + 0.001\ CO_2 \\ &+ 0.017\ N_2 + 0.003\ O_2 + 2.147\ O_2 + 8.073\ N_2 \\ &= 1.106\ CO_2 + 2.084\ H_2O + 8.09\ N_2 \end{aligned} \tag{3.5}$$

where the theoretical balance has been established to indicate that 10.22 m^3 air would be needed for each cubic meter of fuel gas.

In actual combustion reactions, as much as 10% excess air will be provided and the reaction equation will appear as

$$\begin{aligned} 0.853\ CH_4 &+ 0.126\ C_2H_6 + 0.001\ CO_2 \\ &+ 0.017\ N_2 + 0.003\ O_2 + 2.362\ O_2 + 8.88\ N_2 \\ &= 1.106\ CO_2 + 0.218\ O_2 + 2.084\ H_2O + 8.897\ N_2 \end{aligned} \tag{3.6}$$

and indicate that the excess air produces excess oxygen and nitrogen in the flue gas from the combustion process. On a dry basis, the composition of the flue gas would be 87.1% nitrogen, 10.8% carbon dioxide, and 2.1% oxygen, where percentages are in volume basis.

The use of excess air is important to ensure efficient combustion. Without sufficient oxygen, the reaction will be incomplete, resulting in the production of carbon monoxide (CO) along with associated safety hazards. In addition, the inefficient combustion has nearly 70% less heat released by the reaction. The amount of excess air must be controlled, however, since the air that is not involved in the reaction absorbs heat energy and decreases the amount of heat released by the combustion process.

The heat of combustion for a given reaction is dependent on the mixture of gases within the fuel. For the fuel previously described, the heat of combustion will be approximately 36,750 kJ/m^3. The losses with flue gas can be compared to this value, which would represent the maximum achievable from the process. The flue gas losses would be dependent on heat content of each component in the flue gas, and these values are a function of gas temperature, as indicated by Figure 3.9. Using this information, the energy losses associated with the previously described situation can be estimated (based on 1 m^3 fuel with 370°C flame gas).

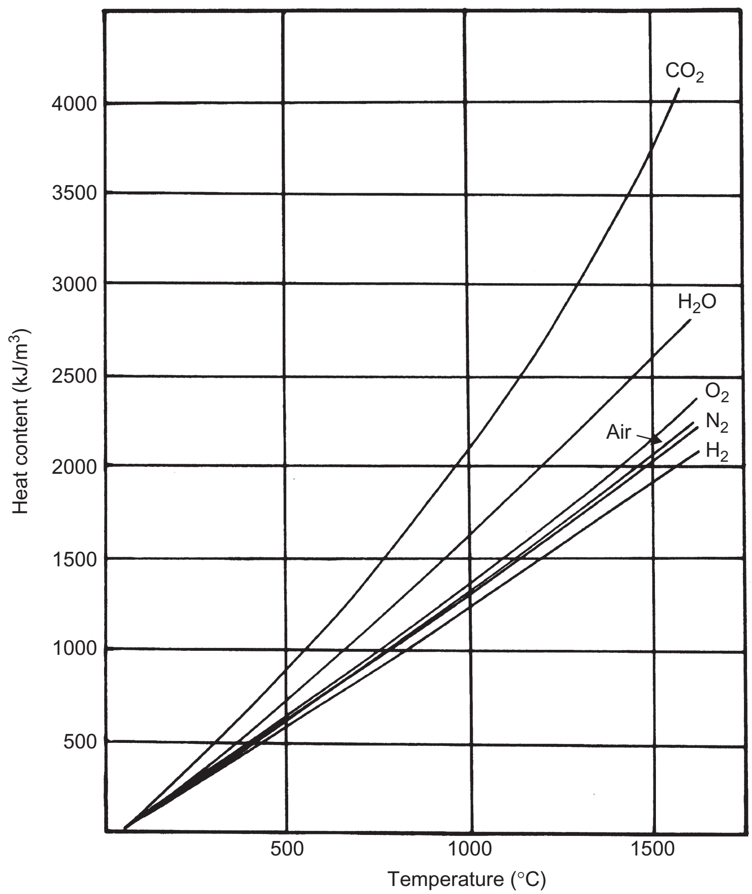


Figure 3.9 Heat content of gases found in flue products.

CO_2	$1.106\ m^3 \times 652\ kJ/m^3 = 721.1\ kJ$
O_2	$0.2147\ m^3 \times 458\ kJ/m^3 = 98.3\ kJ$
H_2O	$2.084\ m^3 \times 522\ kJ/m^3 = 1087.9\ kJ$
N_2	$8.897\ m^3 \times 428\ kJ/m^3 = \underline{3807.9\ kJ}$
	$5715.2\ kJ$

This estimate indicates that flue gas energy losses are 5715.2 kJ/m^3 of fuel gas used. This represents 15.6% of the total energy available from the combustion process.

3.2.3 Burner Efficiencies

As indicated in Section 3.2.1, one of the primary purposes of the fuel burner is to ensure optimum mixing of fuel and air. Without mixing, the combustion process will be incomplete and will produce the same results as insufficient oxygen. The burner is the key component of the combustion system in ensuring that minimum amounts of excess air are required to maintain efficient combustion while minimizing the losses of energy in flue gas.

Example 3.6

Natural gas is being burned to produce thermal energy required to convert water to steam in a steam generator. The natural gas composition is 85.3% methane, 12.6% ethane, 0.1% carbon dioxide, 1.7% nitrogen, and 0.3% oxygen. An analysis of the flue gas indicates that the composition is 86.8% nitrogen, 10.5% carbon dioxide, and 2.7% oxygen. Determine the amount of excess air being utilized and the percentage of energy loss in the flue gas leaving at 315°C.

Given

Composition of natural gas
Composition of flue gas after combustion
All CO_2 in flue must originate with natural gas: 1.106 m^3CO_2/m^3 fuel

Approach

The amount of excess air in the reaction can be evaluated by writing the reaction equation in a balanced manner and determining the extra oxygen in the reaction. The energy loss in the flue gas is based on thermal energy content in the flue gas, as determined from Figure 3.9.

Solution

1. *Based on the flue gas composition and the observation that the reaction must produce 1.106 $m^3 CO_2/m^3$ fuel,*

$$10.5\%\ CO_2 = 1.106\ m^3$$

$$2.7\%\ O_2 = 0.284\ m^3$$

$$86.8\%\ N_2 = 9.143\ m^3$$

2. *The reaction equation becomes*

$$\begin{aligned} &0.853\ CH_4 + 0.126\ C_2H_6 + 0.001\ CO_2 + 0.017\ N_2 \\ &\quad + 0.003\ O_2 + 2.428\ O_2 + 9.126\ N_2 \\ &\quad = 1.106\ CO_2 + 0.284\ O_2 + 2.084\ H_2O + 9.143\ N_2 \end{aligned}$$

3. *Based on the analysis presented,*

$$\text{Excess air} = \frac{0.284}{2.428 - 0.284} \times 100 = 13.25\%$$

where the percentage of excess air is reflected in the amount of oxygen in the flue gas as compared with oxygen associated with the air involved in the reaction.

4. *Using the composition of flue gas and the heat content of various components from Figure 3.9, the following computations are obtained:*

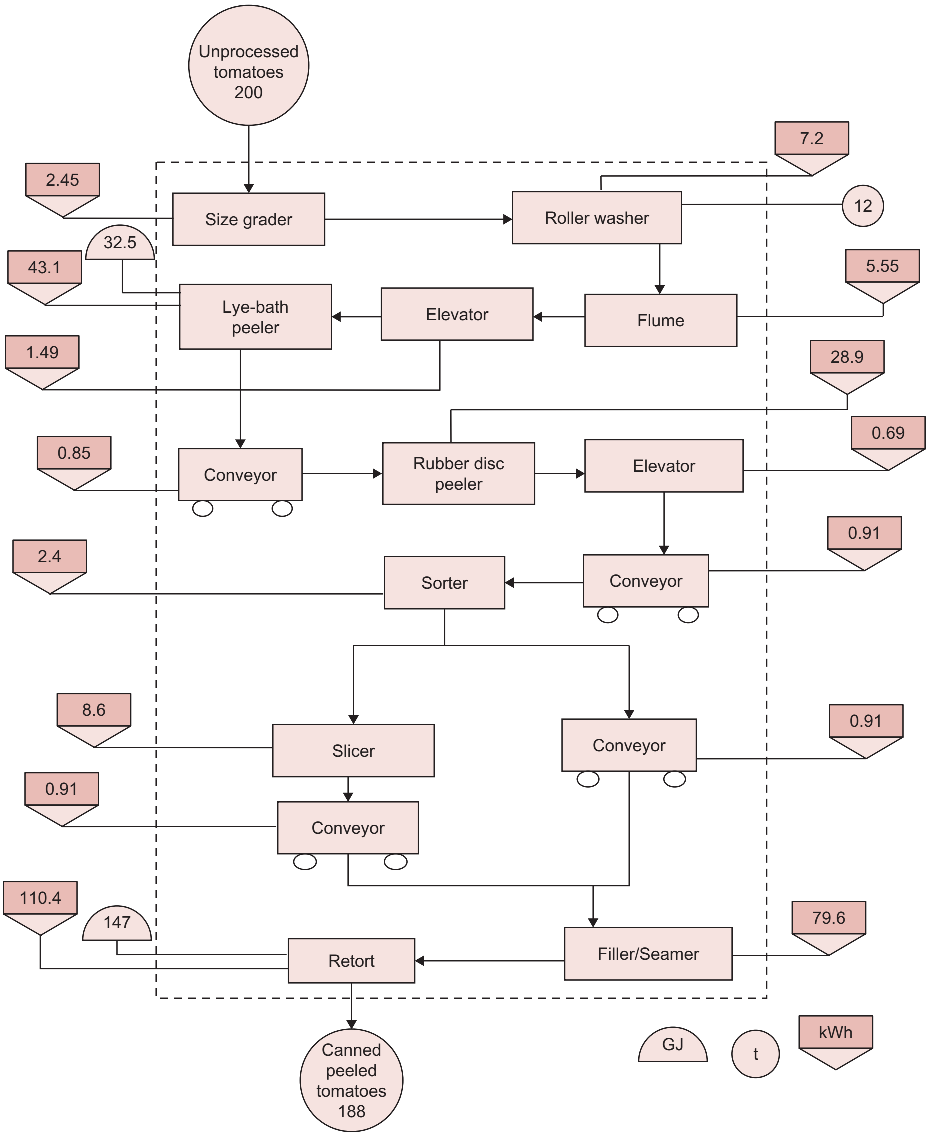
$$\begin{array}{ll} CO_2 & 1.106\ m^3 \times 577.4\ kJ/m^3 = 638.6\ kJ \\ O_2 & 0.284\ m^3 \times 409.8\ kJ/m^3 = 116.4\ kJ \\ H_2O & 2.084\ m^3 \times 465.7\ kJ/m^3 = 970.5\ kJ \\ N_2 & 9.143\ m^3 \times 372.5\ kJ/m^3 = \underline{3405.8\ kJ} \\ & \qquad\qquad\qquad\qquad\qquad\quad 5131.3\ kJ \end{array}$$

The analysis indicates that 5131.3 kJ are lost with flue gas per cubic meter of fuel used in the process.

5. *Using the heat combustion of 36,750 kJ/m^3 for the fuel, the loss of energy with flue gas represents 14% of the energy available from the fuel.*

3.3 ELECTRIC POWER UTILIZATION

Electric power has become so commonplace in the food industry that modern plants could not operate without this power source. In fact, most plants of significant size have acquired "back-up" electrical power generators to use in case disruptions occur in the primary supply. It is quite evident that electric power represents the most versatile and flexible power source available. In addition, the cost of electric power is very attractive when compared with other sources. In Figure 3.10, a tomato processing line is shown along with energy



■ **Figure 3.10** Energy accounting diagram of peeled tomato canning based on an 8-hour shift. (From Singh et al., 1980) requirements to operate each unit. As seen in this figure, most of the process equipment requires electrical energy for their operation.

3.3.1 Electrical Terms and Units

As in most physical systems, electricity has its own set of terms and units. These terms and units are entirely different from most physical systems, and it requires careful analysis to relate the terms to applications. This presentation is elementary and is intended to be a brief introduction to the subject. The following terms are essential.

Electricity can be defined as the flow of electrons from atom to atom in an electrical conductor. Most materials can be considered conductors, but will vary in the ability to conduct electricity.

Ampere is the unit used to describe the magnitude of electrical current flowing in a conductor. By definition, 1 ampere (A) is 6.06×10^{18} electrons flowing past a given point per second.

Voltage is defined as the force causing current flow in an electrical circuit. The unit of voltage is the volt (V).

Resistance is the term used to describe the degree to which a conductor resists current flow. The ohm (Ω) is the unit of electrical resistance.

Direct current is the type of electrical current flow in a simple electrical circuit. By convention, current is considered to flow from a positive to a negative terminal of a voltage generator.

Alternating current describes the type of voltage generated by an AC (alternating current) generator. Measurement of the actual voltage generated would indicate that the magnitude varies with time and a uniform frequency. The voltage ranges from positive to negative values of equal magnitudes. Most electrical service in the United States operates at 60 cycles per second (60 Hz).

Single-phase is the type of electrical current generated by a single set of windings in a generator designed to convert mechanical power to electrical voltage. The rotor in the generator is a magnet that produces magnetic lines as it rotates. These magnetic lines produce a voltage in the iron frame (stator) that holds the windings. The voltage produced becomes the source of alternating current.

Three-phase is the type of electrical current generated by a stator with three sets of windings. Since three AC voltages are generated simultaneously, the voltage can be relatively constant. This type of system has several advantages compared with single-phase electricity.

Watt is the unit used to express electrical power or the rate of work. In a direct current (DC) system, power is the product of voltage and current, whereas computation of power from an alternating current (AC) system requires use of a power factor.

Power factors are ratios of actual power to apparent power from an alternating current system. These factors should be as large as possible to ensure that excessive current is not carried through motors and conductors to achieve power ratings.

Conductors are materials used to transmit electrical energy from source to use. Ratings of conductors are on the basis of resistance to electrical flow.

3.3.2 Ohm's Law

The most basic relationship in electrical power use is Ohm's[1] law, expressed as

$$E_{\mathrm{v}} = IR_{\mathrm{E}} \tag{3.7}$$

where the voltage E_{v} is equal to the product of current I and resistance R_{E}. As might be expected, this relationship illustrates that for a given voltage, the current flow in a system will be inversely proportional to the resistance in the conductor.

As indicated earlier, the power generated is the product of voltage and current.

$$\text{Power} = E_{\mathrm{v}} I \tag{3.8}$$

or

$$\text{Power} = I^2 R_{\mathrm{E}} \tag{3.9}$$

or

$$\text{Power} = \frac{E_{\mathrm{v}}^2}{R_{\mathrm{E}}} \tag{3.10}$$

These relationships can be applied directly to direct current (DC) systems and to alternating current (AC) with slight modifications.

[1] George Simon Ohm (1789–1854). A German physicist, in 1817 he was appointed as a professor of mathematics at the Jesuit College, Cologne. In 1827, he wrote the paper *Die galvanische Kette, mathamatisch bearbeitet* (The Galvanic Circuit Investigated Mathematically), but he remained unrecognized for his contribution. He resigned from his professorship to join the Polytechnic School in Nürnberg. Finally, in 1841, he was awarded the Copley medal by the Royal Society of London.

Example 3.7

A 12-volt battery is being used to operate a small DC motor with an internal resistance of 2 Ω. Compute the current flow in the system and the power required to operate the motor.

Given

Battery with voltage $E_v = 12$ V

DC motor with resistance $R_E = 2$ Ω

Approach

The current flow in the motor can be computed using Equation (3.7), and power required can be determined from Equations (3.8), (3.9), or (3.10).

Solution

1. *Using Equation (3.7),*

$$I = \frac{E_v}{R_E} = \frac{12}{2} = 6\ A$$

indicating a current flow of 6 A in the system.

2. *The power required can be computed from Equation (3.10)*

$$Power = \frac{(12)^2}{2} = 72\ W$$

or 0.072 kW for the motor.

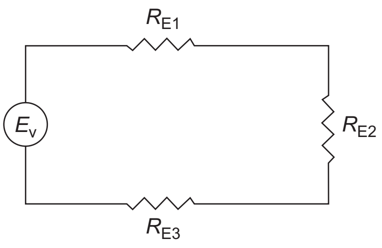


Figure 3.11 Electrical circuit with resistance in series.

3.3.3 Electric Circuits

The manner in which conductors are used to connect the electric power source to the point of use is the electrical circuit. There are three basic types of circuits, with the series circuit being the simplest. As indicated by Figure 3.11, this type of circuit is recognized as having the resistances connected in series with the power source. In this type of situation, each resistance would probably represent the points at which the electrical power is used. Often, these points are referred to as electrical loads. Application of Ohm's law to this situation leads to

$$E_v = I(R_{E1} + R_{E2} + R_{E3}) \tag{3.11}$$

indicating that resistances in series are additive. In addition, the voltage is often expressed as the sum of the voltage drop across each resistance in the circuit.

A parallel electrical circuit has the resistance or loads connected in parallel with the power source, as illustrated in Figure 3.12. When Ohm's law is applied to the parallel circuit, the following relationship applies:

$$E_v = \frac{I}{\left(\frac{1}{R_{E1}} + \frac{1}{R_{E2}} + \frac{1}{R_{E3}}\right)} \tag{3.12}$$

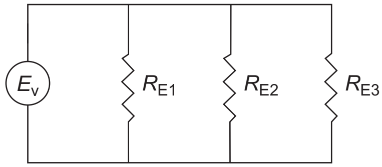


Figure 3.12 Electrical circuit with resistances in parallel.

with the inverse of each resistance being additive. The most complex basic electrical circuit has a combination of series and parallel resistances, as illustrated in Figure 3.13. To analyze relationships between voltage and resistances, the combination circuit must be treated in two parts. First, the three resistances (R_{E1}, R_{E2}, R_{E3}) must be resolved as an equivalent R_e.

$$\frac{1}{R_e} = \frac{1}{R_{E1}} + \frac{1}{R_{E2} + R_{E3}} \tag{3.13}$$

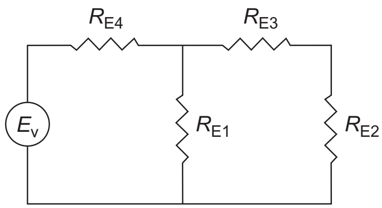


Figure 3.13 Electrical circuit with resistances in series and in parallel.

Then the circuit can be analyzed by applying Ohm's law in the following manner:

$$E_v = I(R_{E4} + R_e) \tag{3.14}$$

since in the modified circuit, the resistance R_{E4} and R_e are in series.

Example 3.8

The four resistances in Figure 3.13 are $R_{E1} = 25\ \Omega$, $R_{E2} = 60\ \Omega$, $R_{E3} = 20\ \Omega$, $R_{E4} = 20\ \Omega$. Determine the voltage source E_v required to maintain a voltage drop of 45 V across the resistance R_{E2}.

Given

Four resistances as identified in Figure 3.13.
Voltage (E_{v2}) = 45 V

Approach

The voltage source E_v required can be evaluated by analysis of the circuit in terms of individual components and equivalent resistances.

Solution

1. *By using Ohm's law, the current flow through the resistance R_{E2} will be*

$$I_2 = \frac{45}{60} = 0.75\ A$$

2. *Since the current flow through R_{E3} must be the same as R_{E2}, then*

$$E_{v3} = (0.75)(20) = 15\ V$$

3. *Due to the circuit design, the voltage drop across R_{E1} must be the same as across R_{E2} plus R_{E3}; therefore,*

$$E_{v2} + E_{v3} = 45 + 15 = 60 = I_1(25)$$

$$I_1 = \frac{60}{25} = 2.4\ A$$

4. *The current flow through R_{E4} must be the total for the circuit, or*

$$I_4 = 0.75 + 2.4 = 3.15\ A$$

which is the current drawn from the voltage source E_v as well.

5. *The equivalent resistance for the circuit will be*

$$\frac{1}{R_e} = \frac{1}{25} + \frac{1}{60 + 20}$$

$$R_e = 19.05\ \Omega$$

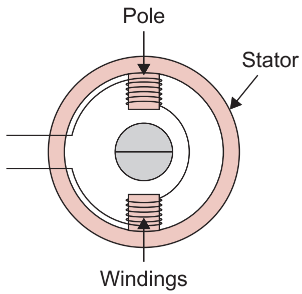
3.3.4 Electric Motors

The basic component of an electric energy utilization system is the electric motor. This component converts electrical energy into mechanical energy to be used in operation of processing systems with moving parts.

The majority of the motors used in food processing operations operate with alternating current (AC), and their operation depends on three basic electrical principles. These principles include the electromagnet, formed by winding insulated wire around a soft iron core. Current flow through the wire produces a magnetic field in the iron core; orientation of the field is dependent on the direction of current flow.

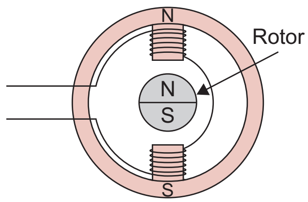
The second electrical principle involved in the operation of a motor is electromagnetic induction. This phenomenon occurs when an electric current is induced in a circuit as it moves through a magnetic force field. The induced electric current produces a voltage within the circuit, with magnitude that is a function of the strength of the magnetic field, the speed at which the current moves through the field, and the number of conductor circuits in the magnetic field.

The third electrical principle is alternating current. As indicated earlier, this term refers to a current that changes direction of flow in a consistent manner. Normal electric service in the United States is 60 Hz, indicating that the change in current flow direction occurs 60 times per second.



■ **Figure 3.14** Schematic diagram of a stator. (From Merkel, 1983)

An electric motor contains a stator: a housing that has two iron cores wound with insulated copper wire. The two cores or windings are located opposite one another, as illustrated in Figure 3.14, and the leads from the windings are connected to a 60-Hz alternating current source. With this arrangement, the stator becomes an electromagnet with reversing polarity as the current alternates.



■ **Figure 3.15** Schematic diagram of a stator with rotor. (From Merkel, 1983)

A second component of an electric motor is the rotor: a rotating drum of iron with copper bars. The rotor is placed between the two poles or windings of the stator (Fig. 3.15). The current flow to the stator and the resulting electromagnetic field produces current flow within the copper bars of the rotor. The current flow within the rotor creates magnetic poles, which in turn react with the magnetic field of the stator to cause rotation of the rotor. Due to the 60-Hz alternating current to the stator, the rotation of the rotor should be 3600 revolutions per minute (rpm), but it typically operates at 3450 rpm.

Although there are numerous types of electric motors, they operate on these same basic principles. The most popular motor in the food processing plant is the single-phase, alternating current motor. There are different types of single-phase motors; the differences are related primarily to the starting of the motor.

The selection of the proper motor for a given application is of importance when ensuring that efficient conversion of electrical to mechanical energy occurs. The selection process takes into account the type of power supply available, as well as the use of the motor. The type and size of load must be considered, along with the environmental conditions of operation and the available space.

3.3.5 Electrical Controls

The efficient use of electrical energy and the equipment that is operated by this energy source is related to the opportunity for automatic control. Since the operation of processes and equipment in a food processing plant depends on responses to physical parameters, automatic control involves conversion of the physical parameter into an electrical response or signal. Fortunately, these conversions can be achieved rather easily using a variety of electrical transducers.

The control of electrical circuits is accomplished by using several different types of transducers. A magnetic relay utilizes a coil that produces electromagnetism to move a contact mechanically and complete the primary circuit. Thermostats and humidistats are controllers that use some physical change in temperature or humidity to provide the mechanical movement required to complete an electrical circuit. A timing device utilizes movement of the clock mechanism to mechanically bring two points into contact and complete an electrical circuit. Photoelectric controls use a photocell to produce a small current required to bring the points in the primary circuit into contact and allow for current flow. Time-delay relays, pressure switches, and limit switches are other types of controls used to accomplish the same type of electrical power utilization.

3.3.6 Electric Lighting

Another primary use of electric power in food processing plants is to provide illumination of work spaces. Often the work productivity of workers within the plant will be dependent on the availability of proper lighting. The design of a lighting system for a workspace will depend on several factors. The light must be distributed properly within the space, and the light source must be of sufficient size and efficiency. The light source must be supported properly and easily replaced or serviced. Finally, the cost of the entire system will be a factor to consider.

Light can be defined as visually evaluated radiant energy. Light is a small portion of the electromagnetic spectrum and varies in color depending on the wavelength. The intensity of a light at a point location is measured in the unit *lux*: the magnitude of illumination at a distance of one meter from a standard candle. A light source can be expressed in lumens: the amount of light on one square meter of surface when the intensity is one *lux*.

Two types of light sources are used in food processing plants: the incandescent lamp and the fluorescent lamp. The incandescent lamp uses a tungsten filament through which current flows. Due to the high electrical resistance of the filament, the flow of current through it causes it to glow white-hot. These types of lamps will provide efficiencies of approximately 20 lumens per watt.

A fluorescent lamp uses an inductance coil to create a current discharge within the tube. The heat from the discharge causes electrons to be removed from mercury vapor within the tube. The return of the electrons to the shell of mercury vapor causes emission of ultra-violet rays. These rays react with phosphor crystals at the tube surface to produce light. Fluorescent lamps are two to three times more efficient than comparable incandescent lamps. Although there are other factors to consider when comparing incandescent and fluorescent lamps, the efficiency and the longer life of fluorescent lamps are the most important.

One of the basic decisions related to lighting system design is determining the number of light sources required to maintain a desired level of illumination. An expression for illumination can be

$$\text{Illumination} = \frac{(\text{lumens/lamp}) \times \text{CU} \times \text{LLF}}{\text{area/lamp}} \tag{3.15}$$

where CU is the coefficient of utilization and LLF is the light loss factor.

The preceding equation indicates that the illumination maintained in a given space is a function of the magnitude of the light source and the number of lamps in the space. The coefficient of utilization CU accounts for various factors within the space, such as room size proportions, location of lamps, and workspace light. Light loss factors (LLF) account for room surface dust, lamp dust, and lamp lumen depreciation.

Example 3.9

A work area within a food processing plant is to be maintained at a light intensity of 800 lux. The room is 10 by 25 m, and 500-watt incandescent lamps (10,600 lumens/lamp) are to be utilized. A CU of 0.6 and LLF of 0.8 have been established. Determine the number of lamps required.

Given

Desired light intensity = 800 lux

Room size = 10 m by 25 m = 250 m^2

Lamps are 500 W, or 10,600 lumens/lamp

Coefficient of utilization CU = 0.6

Light loss factor LLF = 0.8

Approach

Equation (3.15) can be used to determine area/lamp, and the result is combined with the given room area to calculate the number of lamps required.

Solution

1. *Equation (3.15) can be used to compute the area per lamp allowed for the desired illumination.*

$$Area/lamp = \frac{10{,}600 \times 0.6 \times 0.8}{800} = 6.36\ m^2$$

2. *Based on the preceding,*

$$Number\ of\ lamps = \frac{10 \times 25}{6.36} = 39.3 \quad \text{or} \quad 40$$

3.4 ENERGY, WATER AND ENVIRONMENT

Over the past 20 years, the term "sustainability" has received increased attention and has emerged with many different interpretations. The applications to agriculture and food date to the 1960s when David Pimentel and others (Pimentel and Terhune, 1977; Pimentel and Pimentel, 1979; Pimentel et al., 1975) began discussing the limitations of the planet to meet the needs of a growing world population. Today, sustainability has a close association to the impacts of all industrial practices on the environment. The United Nations (WCED, 1987) defined sustainability as "developments that meet the needs of the present without compromising the ability of future generations to meet their own needs". Recently, Bakshi and Fiksel (2003) defined a sustainable product or process as one that constrains resource consumption and waste generation to an acceptable level, makes a positive contribution to the satisfaction of human needs, and provides enduring economic value to the business enterprise. More recent interpretations suggest that sustainability should assign equal weight to *social, economic and environmental* concerns.

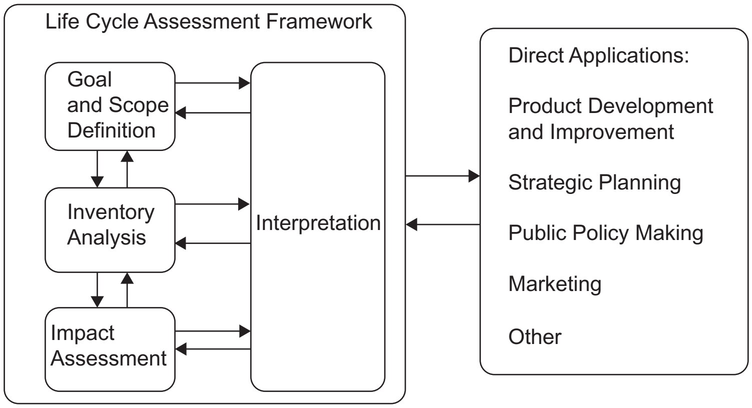
The interpretations of sustainability as applied to agriculture and the food chain are still evolving. Some of the early focus has been on energy demand for production and delivery of food to the consumer. Heller and Keoleian (2000) estimated that the annual energy demand for the food chain in the United States was 9.73×10^{15} kJ (or 10.3×10^{15} BTUs) in 1995. The same authors (2000) estimated that only 117,757 million kg of food were consumed in the U.S., from a production of 418,026 million kg of crops and 108,622 million kg of livestock and poultry products. From the total production, 165,166 million kg were exported and 111,012 million kg were lost or wasted. More recent emphasis has been on the emission of greenhouse gases, such as the 1010 g CO_2 (or equivalent) per kilogram of wheat flour. Finally, the consumption of water has been quantified for the lifecycle of a food product, with 40 liters of water for a 30-g slice of bread becoming the water footprint.

Although the quantities used to describe the demands for energy and water may indicate the overall impact on natural resources, typical values do not provide guidance on steps needed to reduce the impacts on the environment and natural resources. Likewise, the magnitudes of greenhouse and similar emissions from agriculture and the food chain do not identify specific steps to be followed in reducing these emissions. The concepts of Life Cycle Assessment (LCA) provide the framework for quantitation of the impact of individual sectors in the food chain, as well as the overall impact on the entire system.

3.4.1 Life Cycle Assessment

Life cycle assessment (LCA) is a method to quantify the impact of products, processes or activities on resource consumption or environmental burdens. In practice, LCA is the application of mass and energy balances to a process, a series of processes or an entire system of operations with the goal of establishing the quantitative impact of the processes or operations on the environment or natural resources. According to ISO (2006), the stages of LCA are illustrated in Fig. 3.16. As indicated, the framework for the assessment includes:

- Goal and scope definition—a step to define the purpose of the study, the system boundaries, the expected outcome from the study, the functional units and the assumptions.
- Inventory analysis—a phase dedicated to the collection of the data to be used as inputs to the appropriate LCA model. Databases have been established in many industrial sectors, but appropriate data for most processes associated with the food system are limited.
- Impact assessment—based on the data identified during the inventory analysis, the assessment determines the impacts on the environment and/or other goals set for the assessment. A specific series of elements have been established by ISO standards.
- Interpretation—to complete the assessment requires quantitative analysis leading to conclusions and recommendations. This phase of the overall assessment includes recommendations leading to improvements in the processes or operations.



■ **Figure 3.16** Phases and applications of Life Cycle Assessment. (From ISO, 2006)

In addition, Fig. 3.16 illustrates the typical applications of LCA, including product development and improvements, strategic planning, public policy making and marketing.

The application of Life Cycle Assessment (LCA) to the food system requires careful implementation of all four phases of the assessment.

Definition of goals and scope—the goals of the LCA define the application, the specific reasons for the study, the intended audience and how the results will be used. The scope of the LCA defines the system, the functional units, the system boundaries, assumptions, limitations and appropriate allocations. Defining the system boundaries is a critical first step. These boundaries become the locations for collection of data; as input to and outputs from a process, operations or system. Selecting boundaries for the food system depends on the goals of the LCA. The entire system could include all the processes between the farm gate and the consumer, and would include all inputs associated with production of the raw food materials. A more specific assessment would focus of specific processes or operations, and would require measurements of inputs and outputs from each process or operation.

The functional units are equally important components of the goals and scope. For food products, the functional unit should be obvious in the input data collected and in the outputs from the LCA models. Typical units for foods include the mass of final product (kg), or the size of a serving to the consumer (a liter or a cup). The portion of the functional unit expressing the impact on the environment or resources may be quite varied, such as kJ of energy or kg CO_2 emissions.

Inventory analysis—this phase of the assessment governs the collection and assembly of input data for the LCA models. A systematic approach to data collection has been established in ISO 14044 (ISO, 2006), and identifies a series of renewable and non-renewable resources to be considered. Most often, this phase involves an in-depth search of all sources of information in an effort to establish the data base needed to proceed with the assessment. Use of data from published literature and similar sources may require translation of the data in the appropriate function units. The alternative is to collect and assemble data through experimental measurement at the boundaries of actual processes and operations. Although such measurements may be time and labor intensive, the confidence in the outputs from the LCA models for those processes and operations will be enhanced. An example of the detailed inventory for several food product ingredients and components has been developed by Bevilacqua et al. (2007) as illustrated in Table 3.2. Measurement and assembly of data will involve careful attention to changes in characteristics of each stream between the input and output. During many processes and operations for food, the raw materials or ingredients change as a result of the process, and an energy input may change in form before the output from the process.

Impact assessment—after completion of the inventory, the potential impacts of the process, operation or system are analyzed. According to ISO-14040, this phase should involve a four- to six-step protocol designed to establish the appropriate impacts on the environment or natural resources. Based on the inventory of data, the outcomes are assembled in various categories. After selecting the categories, the outcomes from the assessment are placed in the appropriate categories. Typical categories include climate change, land use and water use as midpoint categories, and human health and depletion of natural resources as endpoint categories. The third step in the impact assessment involves the characterization of the impacts. During this step, the impacts are assigned to various scales, including global, regional or local. Based on characterization factors, assessment outcomes can be converted into impact indicators at the appropriate scale. After characterization, the assessment outcomes are presented in a manner that best represents the flow within the system being described. The final steps are optional and involve the appropriate normalization, grouping, or weighting of the assessment outcomes.

Table 3.2 Examples of Life Cycle Inventory for the Production of Pasta in Italy

Unit process	Inputs	Specific emissions
Durum wheat production (7.4 tons of wheat, which is the average yield in 1 hectare)	Wheat seeds 200 kg Atrazine ($C_8H_{14}ClN_5$) 1.5 kg Fertilizer (N) 500 kg as ammonium nitrate and urea Fertilizer (P) 150 kg as diammonium phosphate Truck 127.5 tons x km considering an average trip of 150 km to transport input materials Tractor I (135 kW) for 14 km of plowing Tractor II (80 kW) 42 km for application of fertilizer (three times) Combine harvester for 2 h of harvesting	Ammonia (NH_3) 27.3 kg (air) Nitrogen oxides (NO_x) 0.51 kg (air) Nitrous oxide (N_2O) 2.1 kg (air) Atrazine ($C_8H_{14}ClN_5$) 0.6 kg (soil and water) Nitrite (NO_2^-) 2.5 kg (soil and water) Use of land: 10,000 m^2/year
Semolina production (6.8 tons of semolina and 2.1 tons of subproducts)	Water 1.5 m^3 Durum wheat 9 tons Truck 450 tons x km for an average trip of 50 km to transport what from fields Natural gas 17 kg (780 MJ) Electricity 5.8 MWh	Particulate matter (PM 2.5) 1.4 kg Sulfur dioxide(SO_2) 1.5 mg (air) Nitrous oxide (N_2O) 55 mg (air) Carbon monoxide (CO) 12 mg (air) Carbon dioxide (CO_2) 40 kg (air) Hydrocarbons C_xH_y 8mg (air) 0.1-ton compostable waste (soil) Land use for industrial facility 28.5 m^2/yr
Durum wheat pasta production (1,000 kg of durum wheat pasta)	Water 310 liters Semolina 1,010 kg Truck 101 tons x km for an average trip of 100 km to transport semolina Heat gas 136 MJ for heat for services Electricity 40 kWh for services Electricity 120 kWh for productive process Natural gas 22 kg (1,012 MJ) for thermal energy for drying Crude oil 17 kg (700 MJ) for thermal energy for drying	Particulate matter (PM) 15 mg (air) Sulfur dioxide (SO_2) 460 mg (air) Nitrogen oxides (NO_x) 200 mg (air) Nitrous oxide (N_2O) 78 mg (air) Carbon monoxide (CO) 13.8 mg (air) Carbon dioxide (CO_2)106 kg (air) Hydrocarbons C_xH_y 16 mg (air) Water vapor from drying 245 kg (air) Occupation as industrial area 1.5 m^2/year Occupation as industrial area 1.5 m^2/year Occupation as rail/road area 0.2 m^2/year Compostable waste 10 kg
Plastic packages production (1,000 kg of plastic packages)	Expandable polystyrene 1,008 kg Ink 8 kg Heat oil 60.7 GJ Electricity 570 kWh	Pentane (C_5H_{12}) 37.4 kg (air) Iron (Fe) 32 mg (water) Ammonium ion (NH_+^4) 19 mg (water) Nitrate (NO_3^-) 16 mg (water) Phosphate (PO_4^{3-}) 259 mg (water) Hydrocarbons C_xH_y 8 g (water)
Cardboard packages production (167 kg of cardboard packages)	Glue 1.6 kg Ink 0.6 kg Cardboard duplex 170 kg Crude oil 1.5 kg (62 MJ) Electricity 26 kWh	Particulate matter (PM) 1.5 mg Sulfur dioxide (SO_2) 40 mg (air) Nitrogen oxides (NO_x) 11 mg (air) Nitrous oxide (N_2O) 0.9 mg (air) Carbon emissions (CO) 0.4 mg (air) Carbon dioxide (CO_2) 4.8 kg (air) Waste (paper) 5 kg (soil waste)

(Adapted from Bevilacqua et al. (2007) and Morawicki (2012))

Life cycle interpretation—the final phase in the LCA is the interpretation of the outcomes from the assessment. The interpretation must be consistent with goals and scope established during the first phase. There are three key steps associated with this phase:

- Identification of the significant issues to be addressed through recommendations.
- An evaluation of the reliability of the outcomes from the LCA through appropriate sensitivity analysis.
- The conclusions, limitations and recommendations from the overall assessment.

The guidelines provided by ISO (2006) emphasize the need for caution when reporting the outcomes from an LCA. The reports need to consider the audience receiving the outcomes and importance of avoiding misinterpretation of the outcomes in a manner beyond the goals of the assessment.

3.4.2 Food System Applications

The application of life cycle assessment to the food system is illustrated in several examples published in the research literature. In most cases, these outcomes have been established by using the procedures described in the previous section. The overall goal of these assessments has been to establish the impacts of the system on the environment and/or natural resources.

A typical illustration of LCA outcomes [Heller and Keoleian (2003)] is presented in Fig. 3.17, where the energy demands of the entire U.S. food chain are illustrated. The outcomes identify the specific demands of individual sectors of the food chain, and indicate that household storage and preparation has the largest demand for energy at 31.7%, and even larger than agricultural production at 21.4%. The energy demand of the processing sector is 16.4%. Although these outcomes provide some guidance on the comparative demand of the major sectors of the food system, the seven sectors defined are very general. The same authors (Heller and Keoleian, 2011) reported the energy demand for the entire fluid milk chain, including specific reference to production, processing and distribution, as well as for packaging and waste management (Fig. 3.18). These more detailed outcomes indicate that feed production, farm utilities, processing plant utilities, product storage and transportation, and consumer storage are the major contributors to total energy demand. The results identify the sectors of the

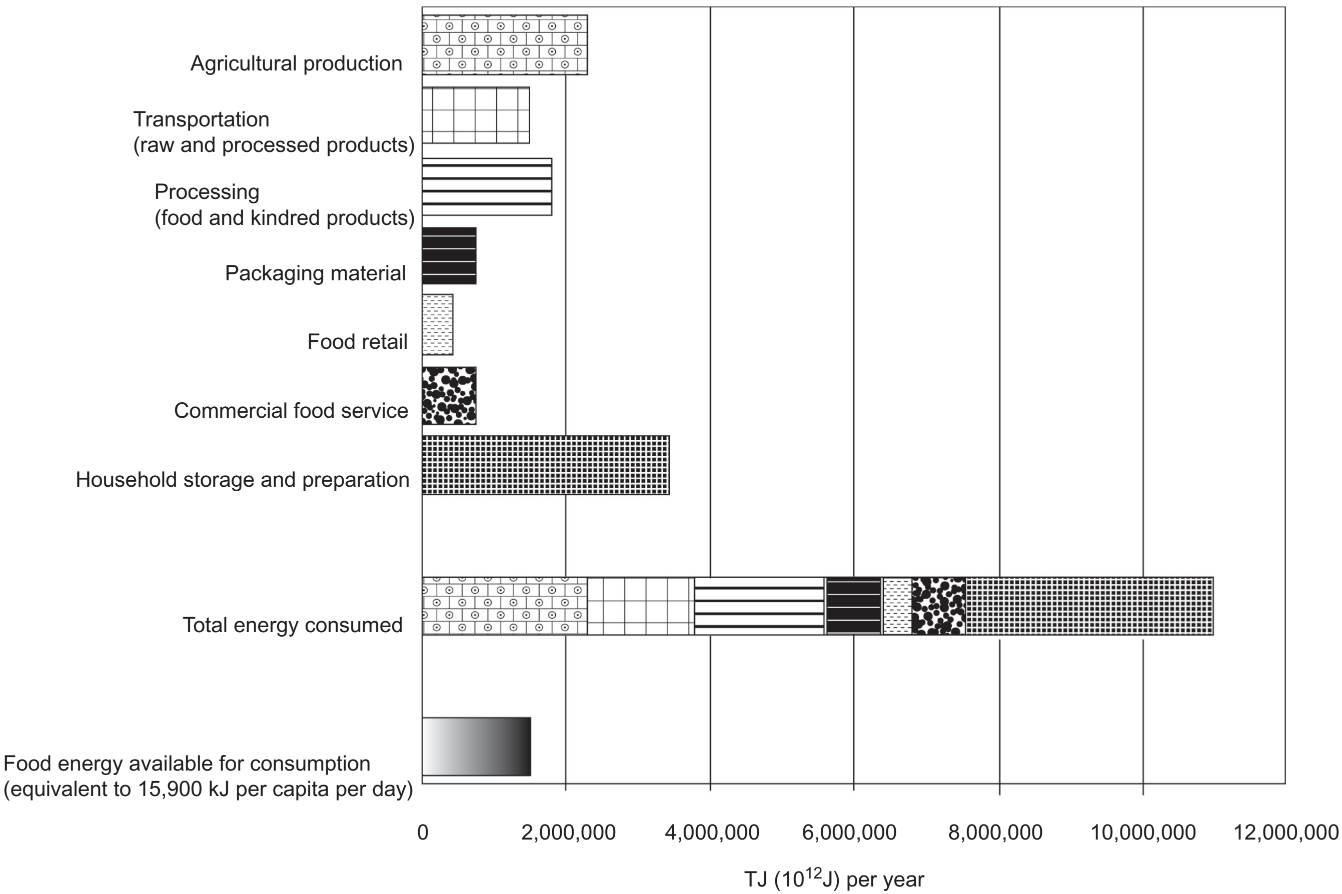


Figure 3.17 Life cycle energy use in supplying U.S. food. (Heller and Koeleian, 2003)

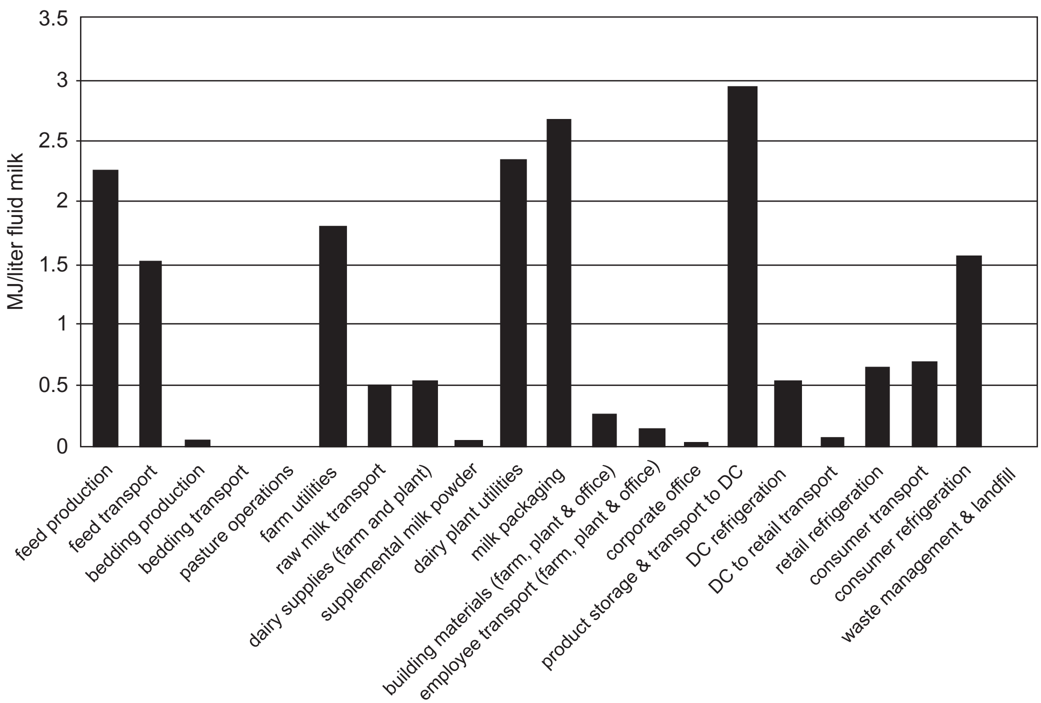
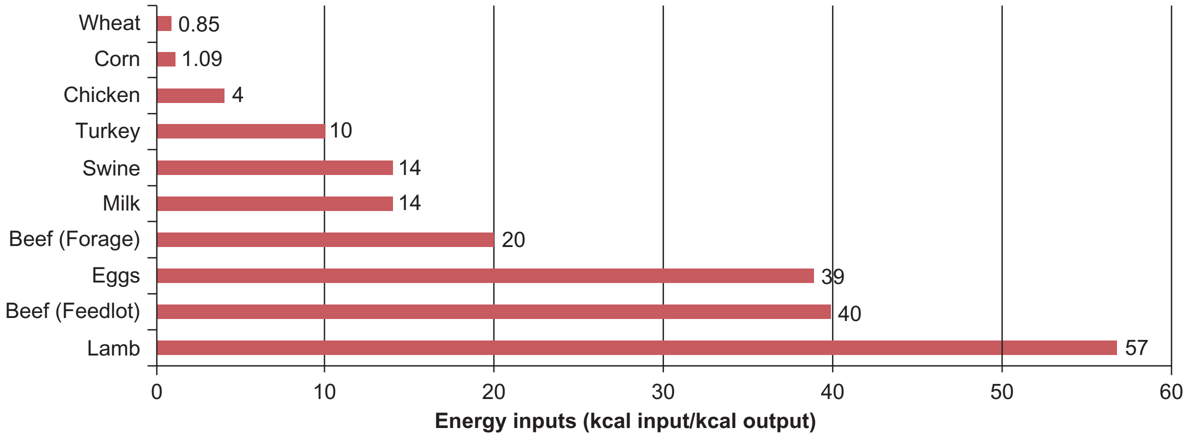


Figure 3.18 Distribution of primary energy consumption across the fluid milk life cycle on a functional unit basis. (Heller and Koeliean, 2011)

fluid milk chain where changes in practice would have the most significant impact on the overall demand. The input data were collected at six dairy farms and in a single processing faculty, but may not reflect assessment outcomes for other farms and processing facilities, and the impacts are likely to be influenced by other factors, such as region of the country or size of operations.

A different type of outcome from an LCA application is illustrated in Figure 3.19 from Pimentel and Pimentel (2008) and Pelletier and Tyedmers (2007). These results compare the energy demand for production of different food commodities, and use a base of kcal of protein. Similar outcomes for fisheries, livestock and aquaculture are presented in Table 3.3, and illustrate the energy demands for various and livestock fish species. Although these outcomes illustrate the higher energy demands associated with animal proteins, the outcomes do not provide guidance on steps needed to reduce the energy demand to produce food proteins with reduced energy.



■ **Figure 3.19** Energy inputs to produce 1 kcal of animal protein in the United States compared with two vegetable crops expressed as a ratio of kcal input/kcal output. (Adapted from Pimentel and Pimentel, 2008, and Pelletier and Tyedmers, 2007)

A more specific application of LCA to illustrate impacts on the environment is presented in Table 3.4. As indicated, the impacts on global warming, acidification, nutrient enrichment, photochemical smog and land use from frozen chicken, wheat bread and low-fat milk have been developed by Nielsen et al., 2003. These outcomes provide comparative impacts per kilogram of product for the three products. Overall, the results suggest that frozen chicken has the most impact on global warming and nutrient enrichment, although the three products are not interchangeable in terms of human nutrition. Again, the outcomes are not sufficiently specific to use in developing recommendations on the steps required to reduce the impacts on the environment or natural resources. The global warming impacts from several foods have been assembled by Morawicki (2012) as illustrated in Fig. 3.20. The outcomes from the LCA indicate the contributions of five different sectors from production to consumption of the product. For pork meat, a significant amount of the carbon emissions occurs during production, while processing and packaging are major contributors for tomato ketchup. Production and transportation are significant contributors to the gas emissions from bread, and production is the primary contributor to gas emissions for milk. The latter results are similar to those for milk from Heller and Koeleian (2011) in

Table 3.3 Energy Intensity of Selected Fisheries, Livestock and Aquaculture Production Systems Expressed as Edible Protein Energy Return on the Investment (EROI%)

Production System (Location)	EROI (%)
Herring/mackerel, Purse seine (NE Atlantic)	56
Chicken (USA)	25
Redfish spp.,Trawl (N. Atlantic)	11
Mussel, longline culture (Scandinavia)	5 - 10
Turkey (USA)	10
Global Fisheries	8
Milk (USA)	7.1
Swine (USA)	7.1
Salmon spp., Gillnet (NE Pacific)	6.8
Tilapia, pond culture (Zimbabwe)	6.0
Beef, pasture-based (USA)	5.0
Catfish, intensive pond culture (USA)	4.0
Norway lobster, Trawl (NE Atlantic)	2.6
Eggs (USA)	2.5
Beef, feedlot (USA)	2.5
Atlantic salmon, intensive cage (Canada)	2.5
Shrimp, semi-intensive culture (Ecuador)	2.5
Chinook salmon, intensive culture (Canada)	2.0
Atlantic salmon, intensive cage (Sweden)	2.0
Lamb (USA)	1.8
Sea bass, intensive culture (Thailand)	1.5
Shrimp, intensive culture (Thailand)	1.4

(From Tyedmers (2004) and Tyedmers et al. (2005))

Table 3.4 Cradle-to-Retail Environmental Impacts for the Production of 1 Kilogram of Selected Foods

Impact category	Units	Frozen Chicken	Wheat Bread (fresh)	Low fat milk
Global warming	g CO_2 equivalent	3650	840	1.1
Acidification	g SO_2 equivalent	48.3	5	0.3
Nutrient enrichment	g NO, equivalent	208	59	0.51
Photochemical smog	g ethene equivalent.	0.672	0.27	0.07
Land use	m^2 year	5	0.98	0

(Adapted from Nielsen et al. (2003))

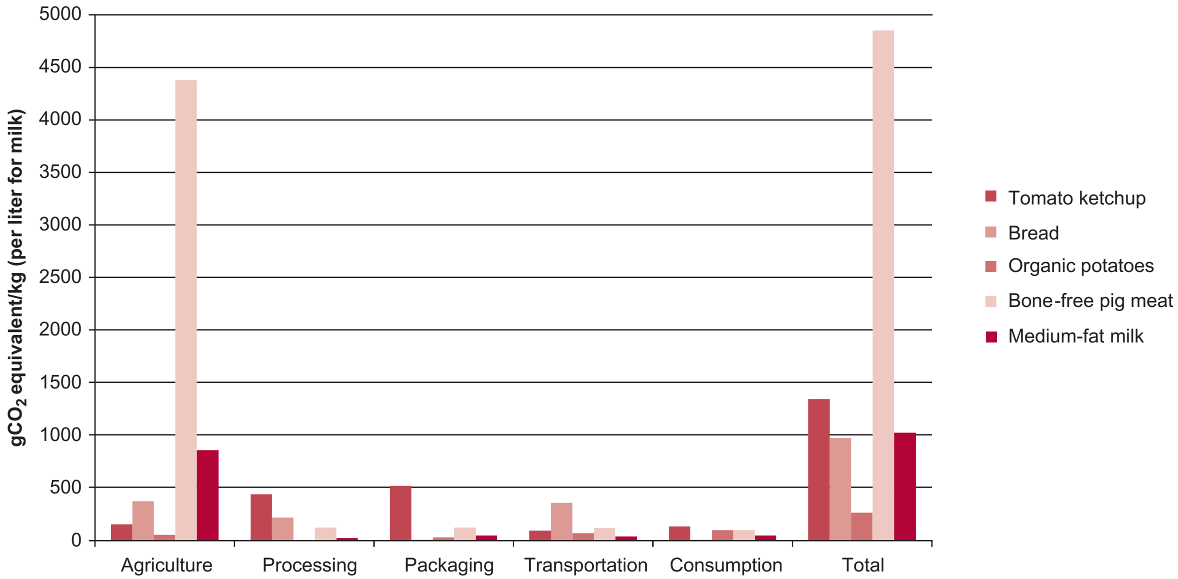


Figure 3.20 Carbon emissions expressed as grams of carbon dioxide per kilogram of product at different stages of the supply chain of selected food products. (From Morawicki, 2012)

Fig. 3.18, but waste management during production is a major contributor to emissions from fluid milk.

The applications of LCA to water demand are illustrated by Table 3.5 from Hoekstra and Chapagain (2007). These virtual water magnitudes describe the amounts of water required to produce, process and deliver a given quantity of a product to the consumer. The outcomes presented in the table provide comparisons among food and non-food commodities, but do not provide insight into the steps needed to reduce the demand for water. More in-depth assessment of the food system should reveal sectors and specific processes where changes in practice would lead to significant reductions in the water footprint.

Heller and Koeleian (2000) provided an in-depth evaluation of material flows in the U.S. food system as illustrated by Figure 3.21. The outcomes from the analysis provide evidence of the significant losses occurring between production and the point of consumption. These outcomes indicate that 26% of edible food is wasted by the consumers. A recent study by Gunders (2012) confirms the

Table 3.5 Average Virtual Water for Selected Consumer Products

Product	Virtual water content (liter)
1 cup of coffee (125 mL)	140
1 cup of tea (250 mL)	35
1 glass of beer (250 mL)	75
1 glass of milk (200 mL)	200
1 glass of wine (125 mL)	120
1 glass of apple juice (200 mL)	190
1 glass of orange juice (200 mL)	170
1 tomato (70 g)	13
1 orange (100 g)	50
1 potato (100 g)	25
1 apple (100 g)	70
1 slice of bread (30 g)	40
1 bag of potato chips (200 g)	185
1 egg (40 g)	135
1 hamburger (150 g)	2400
1 cotton T-shirt (250 g)	2000
1 pair of shoes (bovine leather)	8000

(Adapted from Hoekstra and Chapagain (2007) and Morawicki (2012))

significant losses associated with various food commodities as illustrated by Figure 3.22. These more recent outcomes suggest that the losses range from as low as 20% for milk to as high as 52% for fruits and vegetables.

All of the outcomes from life cycle assessment for the food system describe opportunities for improvements in efficiency of the food system. Much of the literature associated with sustainability emphasize that wastes and losses throughout the food systems compound the losses of energy and water, and indirectly impact all of the LCA indicators being used to quantify the impacts of the food system on the environment and natural resources.

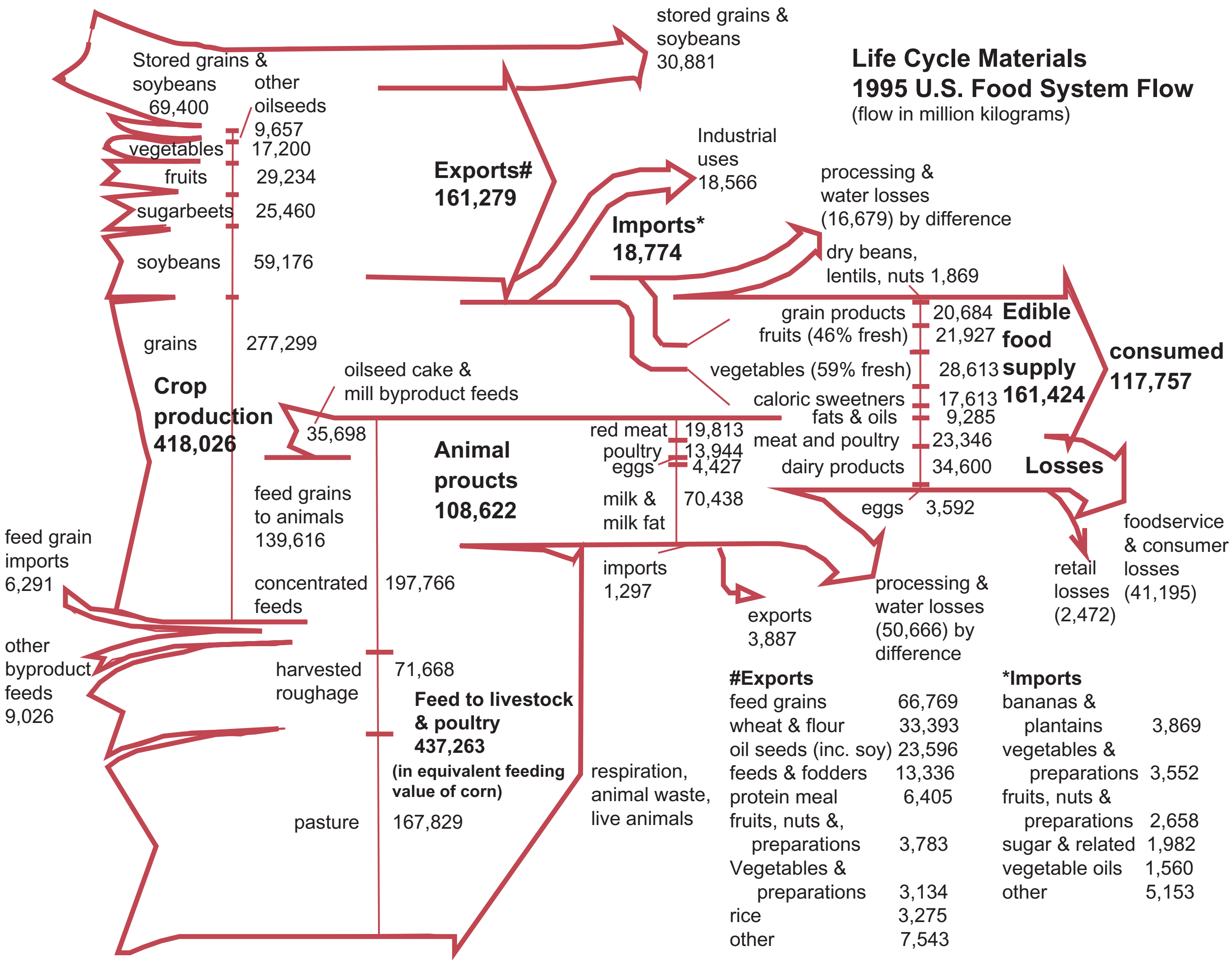


Figure 3.21 Life cycle materials flow for the U.S. food system in 1995. (From Heller and Koelian, 2000)

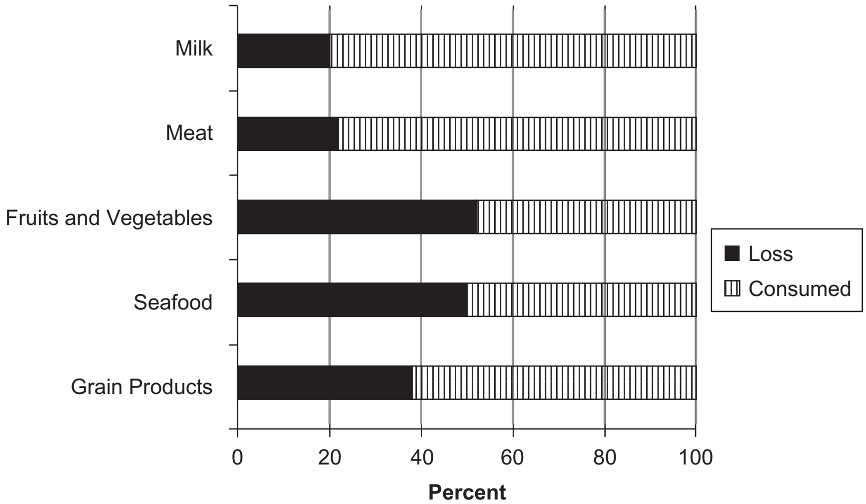


Figure 3.22 Food consumed versus food loss. (From Gunders, 2012)

3.4.3 Sustainability Indicators

A significant challenge for the food system is to identify an appropriate indicator to best describe the impacts of processes and operations within the system on the environment and natural resources. Most outcomes from LCA indicate that energy demand, water use and wastes are the most significant contributors to the outcomes. Although the Sustainability Process Index (SPI) proposed by Narodoslawsky and Niederi (2006) may provide a starting point as an overall indicator, additional analysis of the various inputs will be needed to provide an appropriate index for the food system.

PROBLEMS

3.1 Compute the thermal energy requirements to convert water at 60°C to superheated steam at 150°C when the pressure is 150 kPa.

3.2 Determine the quality of steam at 198.53 kPa when 470 kJ/kg of energy are lost from saturated steam. What is the steam temperature?

3.3 Calculate the amount of energy (kJ/kg) required to convert saturated water at 150 kPa to superheated steam at 180°C and at the same pressure.

3.4 Thermal energy is being added to steam at 475.8 kPa and 75% quality. Determine the amount of thermal energy to be added to create saturated steam. What is the temperature of the 75% quality steam.

3.5 A fruit juice is being heated in an indirect heat exchanger using steam as a heating medium. The product flows through the heat exchanger at a rate of 1000 kg/h and the inlet temperature is 30°C. Determine the quantity of steam required to heat the product to 100°C when only latent heat of vaporization (2230.2 kJ/kg) from steam at 110°C is used for heating. The specific heat of the product is 4 kJ/(kg °C).

3.6 Saturated steam at 232.1 kPa and 80% quality is being used to heat a liquid food by direct steam injection. The product enters the heating system at 200 kg/min and 15°C, and leaves at 105°C. The specific heat of the product is 3.85 kJ/kgK and does not change significantly during the heating process. Estimate the steam requirement.

***3.7** Steam with 80% quality is being used to heat a 40% total solids tomato purée as it flows through a steam injection heater at a rate of 400 kg/h. The steam is generated at 169.06 kPa and is flowing to the heater at a rate of 50 kg/h. Assume that the heat exchanger efficiency is 85%. If the specific heat of the product is 3.2 kJ/(kg K), determine the temperature of the product leaving the heater when the initial temperature is 50°C. Determine the total solids content of the product after heating. Assume the specific heat of the purée is not influenced by the heating process.

3.8 Natural gas combustion is being used for steam generation and 5% excess air is incorporated into the combustion. Estimate the composition of the flue gas and compute the percent thermal energy loss if the flue gas temperature is 20°C.

3.9 An electrical circuit includes a voltage source and two resistances (50 and 75 Ω) in parallel. Determine the voltage source required to provide 1.6 A of current flow through

* Indicates an advanced level of difficulty in solving.

the 75 Ω resistance and compute current flow through the 50 Ω resistance.

3.10 Compute the current flow in an electric circuit with a 0.1-kW motor and internal resistance of 4 Ω. How much voltage is required.

***3.11** The manufacturing of pie filling involves blending of concentrated product with liquid sugar and heating by steam injection. The product being manufactured will contain 25% product solids and 15% sugar solids and will be heated to 115°C. The process has input streams of concentrated product with 40% product solids at 40°C and 10 kg/s and liquid sugar with 60% sugar solids at 50°C. Heating is accomplished using steam at 198.53 kPa. The concentrated product entering the process and the final product have specific heats of 3.6 kJ/(kg °C), whereas the liquid sugar has a specific heat of 3.8 kJ/(kg °C). Determine (a) the rate of product manufacturing; (b) the flow rate of liquid sugar into the process; (c) the steam requirements for the process; and (d) the quality of steam required for the process.

***3.12** Steam injection is used to heat a liquid food with a composition of 10% protein and 5% carbohydrate (85% water) from 20°C and 80°C. Steam with 80% quality and 232.1 kPa is being used and the input product flow rate is 200 kg/min. Compute the following: (a) specific heat of product into the system, mass flow rate of steam required for the process, (c) composition of the final product, and (d) specific heat of the final product.

3.13 Let us determine how long it takes to heat water in an electric kettle and the cost of heating. Water (1.5 liters) initially at 10°C is to be heated to 95°C in a kettle equipped with a 1500-W electric heating element inside. The mass of the empty kettle is 0.5 kg and it has an average specific heat of 0.7 kJ/kg °C. Taking the specific heat of water to be 4.18 kJ/kg °C and disregarding any heat loss from the kettle, (a) determine how long it will take for water to be heated. (b) If the cost of electricity is $0.18/kWh, what is the cost of heating water in this kettle?

---

* Indicates an advanced level of difficulty in solving.

***3.14** Balan et al. (1991) present an empirical equation for the enthalpy of saturated steam vapor:

$$H_v = -484.836273 + 3.741550922T + 1.3426566 \times 10^{-3}T^2 + 97.21546936(647.3 - T)^{1/2} - 1.435427715(1.0085)^T$$

The enthalpy is in (kJ/kg) and the temperature, T, is in degrees K. Write a MATLAB® script to compare the results predicted by this equation to those for saturated steam from a set of steam tables (see Table A.4.2).

3.15 Irvine and Liley (1984) present equations for the estimation of vapor enthalpy, H_v, of saturated steam given the temperature in degrees K, T_{sat}.

$$Y = A + BT_C^{1/3} + CT_C^{5/6} + DT_C^{7/8} + \sum_{N=1}^{7} E(N)T_C^N$$

$$Y = \frac{H_v}{H_{v\ CR}} \qquad H_{v\ CR} = 2099.3\ \mathrm{kJ/kg}$$

$$T_C = \frac{T_{CR} - T_{sat}}{T_{CR}} \qquad T_{CR} = 647.3\ \mathrm{K}$$

	273.16 ≤ T ≤ 647.3 K
A	1.0
B	0.457874342
C	5.08441288
D	−1.48513244
E(1)	−4.81351884
E(2)	2.69411792
E(3)	−7.39064542
E(4)	10.4961689
E(5)	−5.46840036
E(6)	0.0
E(7)	0.0
$H_{v\ CR}$	2099.3

Write a MATLAB® script to evaluate the enthalpy and compare them to values given in saturated steam tables such as in Table A.4.2.

* Indicates an advanced level of difficulty in solving.

***3.16** Irvine and Liley (1984) present equations for the estimation of liquid enthalpy, H_c, of saturated steam given the temperature in degrees K, T_{sat}.

$$Y = A + BT_C^{1/3} + CT_C^{5/6} + DT_C^{7/8} + \sum_{N=1}^{7} E(N)T_C^N$$

$$Y = \frac{H_C}{H_{c\ CR}} \qquad H_{c\ CR} = 2099.3\ \text{kJ/kg}$$

$$T_C = \frac{T_{CR} - T_{sat}}{T_{CR}} \qquad T_{CR} = 647.3\ \text{K}$$

The parameter values (A, B, C, D, E(N)) vary with temperature.

	273.16 ≤ *T*, 300 K	**300 ≤ *T*, 600 K**	**600 ≤ *T* ≤ 647.3 K**
A	0.0	0.8839230108	1.0
B	0.0	0.0	−0.441057805
C	0.0	0.0	−5.52255517
D	0.0	0.0	6.43994847
E(1)	624.698837	−2.67172935	−1.64578795
E(2)	−2343.85369	6.22640035	−1.30574143
E(3)	−9508.12101	−13.1789573	0.0
E(4)	71628.7928	−1.91322436	0.0
E(5)	−163535.221	68.7937653	0.0
E(6)	166531.093	−124.819906	0.0
E(7)	−64785.4585	72.1435404	0.0
$H_{f\ CR}$	2099.3	2099.3	2099.3

Write a MATLAB® script to evaluate the enthalpy and compare results to values given in saturated steam tables such as in Table A.4.2.

LIST OF SYMBOLS

c_p	specific heat (kJ/[kg K])
CU	coefficient of utilization
D	diameter (m)
ΔP	pressure drop (Pa)
ε	surface roughness factor (m) in Example 3.4
E_v	voltage (V)
f	friction factor

* Indicates an advanced level of difficulty in solving.

h	height, (m)
H	enthalpy (kJ/kg)
H_{evap}	latent heat of evaporation (kJ/kg)
I	current (A)
L	length (m)
L_e	equivalent length (m)
LLF	light loss factor
$\dot{m}$	mass flow rate
μ	viscosity (Pa s)
N_{Re}	Reynolds number, dimensionless
P	pressure (Pa)
q	heat transfer rate (kJ/s)
Q	heat energy, (kJ)
ρ	density
R_E	electrical resistance (Ω)
R_e	equivalent electrical resistance (Ω)
s	entropy (kJ/[kg K])
T	temperature (°C or K)
$\bar{u}$	average fluid velocity (m/s)
V'	specific volume (m^3/kg)
x_s	steam quality

Subscripts: c, liquid/condensate; e, exit; v, vapor; i, initial or inlet; o, outer; s, steam.

BIBLIOGRAPHY

Bakshi, B.R., Fiksel, J., 2003. The quest for sustainability: Challenges for process systems engineering. AIChE Journal 49 (6), 1350–1359.

Babcock & Wilcox Handbook, 1978. Steam—Its Generation and Use. Babcock & Wilcox Co., New York, New York.

Balan, G.P., Hariarabaskaran, A.N., Srinivasan, D., 1991. Empirical formulas calculate steam properties quickly. Chem. Eng. Jan, 139–140.

Bevilacqua, M., Braglia, M., Carmignani, G., Zammori, F.A., 2007. Life cycle assessment for pasta production in Italy. J. Food Quality 30 (6), 932–952.

Farrall, A.W., 1979. Food Engineering Systems, vol. 2. AVI Publ. Co., Westport, Connecticut.

Grigull, U., Straub, U.G., Scheibner, G., 1990. Steam Tables in SI Units, third ed. Springer-Verlag, Berlin.

Gunders, D., 2012. Wasted: How America is Losing up to 40 Percent of its Food from Farm to Fork to Landfill. NRDC Issue Paper IP:12-06-B. Natural Resources Defense Council. Washington, DC.

Gustafson, R.J., Morgan, M.T., 2004. Fundamentals of Electricity for Agriculture, third ed. American Society of Agricultural and Biological Engineers, St. Joseph, Michigan.

Heller, M.C., G.A., Keoleian, 2000. Life Cycle Based Sustainability Indicators for Assessment of the U.S. food System. The University of Michigan—Center for Sustainable Systems. Ann Arbor, MI. I-60, CSS00–04.

Heller, M.C., Keoleian, G.A, 2003. Assessing the sustainability of the U.S. food system: a life cycle perspective. Agric. Syst. 76, 1007–1041.

Heller, M.C, Koeleian, G.A., 2011. Life cycle energy and greenhouse gas analysis of a large-scale vertically integrated organic dairy in the United States. Eviron. Sci. Technol. 45, 1903–1911.

Hoekstra, A.Y., Chapagain., A.K., 2007. Water footprints of nations: Water use by people as a function of their consumption pattern. Water Resour. Manag. 21 (1), 35–48.

International Organization for Standardization (ISO), 2006. Environmental Management – Life Cycle Assessment – Principles and framework. Geneva: ISO.

Irvine, T.F., Liley, P.E., 1984. Steam and Gas Tables with Computer Equations. Academic Press, Inc., Orlando, Florida.

Martin, T.W., 1961. Improved computer oriented methods for calculation of steam properties. J. Heat Transf. 83, 515–516.

Merkel, J.A., 1983. Basic Engineering Principles, second ed. AVI Publ. Co., Westport, Connecticut.

Morawicki, R.O., 2012. Handbook of Sustainability for the Food Sciences. John Wiley & Sons, Inc., Ames, IA.

Narodoslawsky, M., Niederl., A, 2006. The Sustainable Process Index (SPI). In: Dewulf, J., van Langenhove, H. (Eds.), Renewable-based Technology. John Wiley & Sons, Hoboken, NJ.

Nielsen, P.H., et al., 2003. LCA food data base. Available at: <www.lcafood.dk>.

Pelletier, N., Tyedmers, P., 2007. Feeding farmed salmon; Is organic better? Aquaculture 272, 399–416.

Pimentel, D, Terhune., E.C., 1977. Energy and food. Ann. Rev. Energy 2, 171–195.

Pimentel, D., Pimentel, M., 1979. Food, Energy and Society. Edward Arnold (Publishers) Ltd., London.

Pimentel, D., Dritschilo, W., Krummel, J., Kutzman, J., 1975. Energy and land constraints in food-protein production. Science 190, 754–761.
Singh, R.P., Carroad, P.A., Chinnan, M.S., Rose, W.W., Jacob, N.L., 1980. Energy accounting in canning tomato products. J. Food Sci. 45, 735–739.
Steltz, W.G., Silvestri, G.J., 1958. The formulation of steam properties for digital computer application. Trans. ASME 80, 967–973.
Stultz, S.C., Kitto, J.B., 2005. Steam—Its Generation and Use. Babcock & Wilcox Handbook. Babcock & Wilcox Co., New York, New York.
Straub, U.G., Scheibner, G., 1984. Steam Tables in SI Units, second ed. Springer-Verlag, Berlin.
Teixeira, A.A., 1980. Cogeneration of electricity in food processing plants. Agric. Eng. 61 (1), 26–29.
Tyedmers, P.H., 2004. Fisheries and energy use. In: Cleveland, C. (Ed.), In Encyclopedia of Energy, vol. 2. Elsevier. Inc., Amsterdam.
Tyedmers, P.H., Watson, R, Pauly, D., 2005. Fueling global fishing fleets. AMBIO: A J. Hum. Environ. 34 (8), 635–638.
Unger, S.G., 1975. Energy utilization in the leading energy-consuming food processing industries. Food Technol. 29 (12), 33–43.
Watson, E.L., Harper, J.C., 1988. Elements of Food Engineering, second ed. Van Nostrand Reinhold, New York, New York.
WCED, 1987. Report of the World Commission on Environment and development: Our common future. United Nations General Assembly, New York.