الجامعة التكنولوجية

قسم الهندسة الكيمياوية

المرحلة الثانية

موازنة الطاقة

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4 CHAPTER FOUR

Unsteady-State Material and Energy Balances

This chapter focuses briefly on unsteady-state processes in which the value of the state, dependent variable, as a function of time is of interest. The term "unsteady state" refers to processes in which quantities or operating conditions within the system change with time. The word transient state applies to such processes. A wide variety of important industrial problems fall into this category, such as start-up/shut-down of process equipment, batch processing, the change from one set of operating conditions to another, and the perturbations that develop as process conditions fluctuate. The following items outline the principal learning objectives of this chapter.

Learning Objectives

1. Develop unsteady-state material balance equations and solve simultaneous First-order ordinary differential material balance equations
2. Develop unsteady-state energy balance equations and explain the rational changes in concentration or temperature versus time (Section 4.2).

4.1 Unsteady-State Material Balance

Unsteady or transient state refers to processes in which quantities or operating conditions within the system change with time [1–3]. For such processes, the accumulation term in the mass balance equation cannot be neglected and must be accounted for (Figure 4.1).

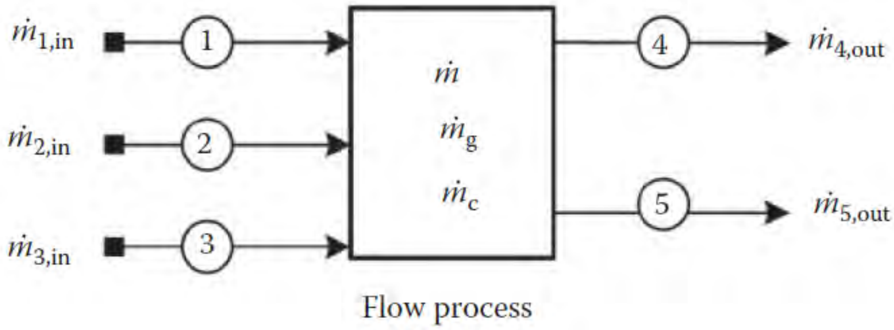


FIGURE 4.1: Open system with multiple input and output streams.

The general material balance equation takes the following form:

$$\frac{dm}{dt} = \dot{m}_{\text{in}} - \dot{m}_{\text{out}} + \dot{m}_{\text{g}} - \dot{m}_{\text{c}} \qquad \text{...............................(4-1)}$$

where

m is the mass accumulated in the system [mass]
$\dot{m}_{\text{in}}$ is the inlet mass flow rate [mass/time]
$\dot{m}_{\text{out}}$ is the outlet mass flow rate [mass/time]
$\dot{m}_{\text{g}}$ is the generated mass flow rate [mass/time]
$\dot{m}_{\text{c}}$ is the consumed mass flow rate [mass/time]

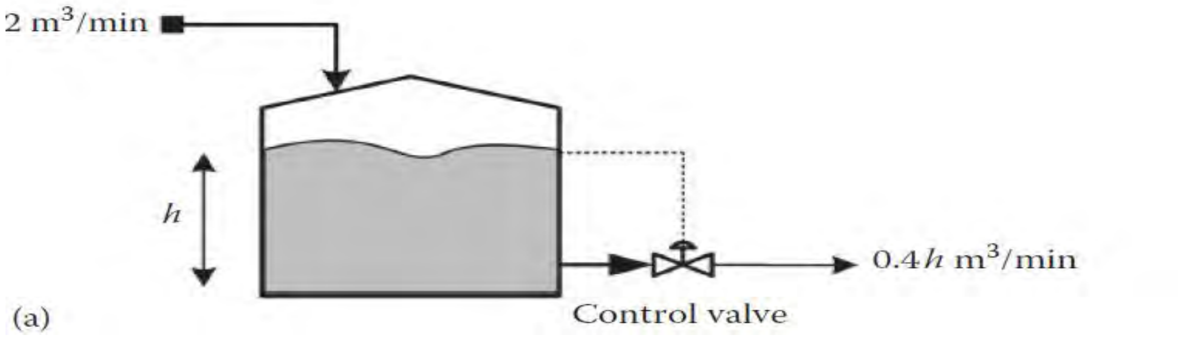
$$\dot{m}_{\text{in}} = \sum_{\text{in}} \dot{m}_{i,\text{in}}$$

$$\dot{m}_{\text{out}} = \sum_{\text{out}} \dot{m}_{i,\text{out}}$$

Example 4.1 Filling Controlled Level Storage Tank

Problem

A storage tank that is 2.0 m in diameter is filled at a rate of 2.0 m^3/min. When the height of the liquid is 2 m in the tank, a control valve installed on the exit stream at the bottom of the tank opens up, and the fluid flows at a rate proportional to the head of the fluid, that is, 0.4*h* m3/min, where *h* is the height of fluid in meters. Plot the height of the liquid as a function of time. What is the steady-state height of the fluid in the tank?



EXAMPLE FIGURE 4.1.1: (a) Schematic of a storage tank.

Solution

Known quantities: Inlet and exit tank volumetric flow rate.

Find: Plot the height of the tank as a function of time.

Analysis: The tank flowchart is shown in Example Figure 4.1a.1. Unsteady-state mass balance:

Neither generation nor consumption occurs in the process:

$$\frac{dm}{dt} = \dot{m}_{in} - \dot{m}_{out}$$

$$m = \rho V = \rho(Ah), \quad A = \pi D^2/4$$

where
A is the cross-sectional area of the tank
V is the volume of the system
$\dot{V}$ is the volumetric flow rate

$$\dot{m} = \rho \times \dot{V}$$

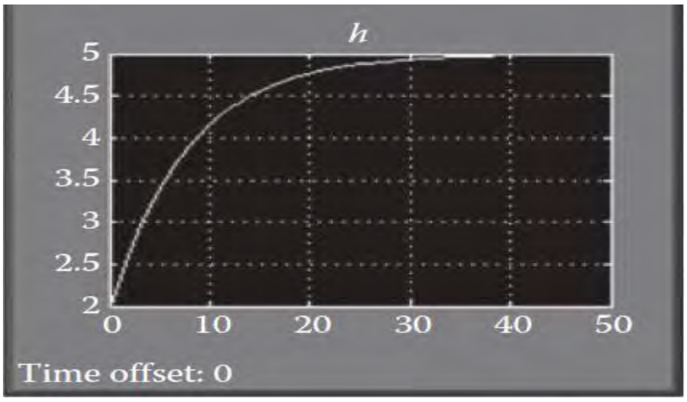
$\dot{V}_{in}$ and $\dot{V}_{out}$ are the volumetric flow rates of inlet and exit streams, respectively. Simplifying the material balance equations in terms of one variable (h) with time gives

$$\frac{d(\rho Ah)}{dt} = \rho\dot{V}_{in} - \rho\dot{V}_{out}$$

Assume density is constant; the equation is then simplified to

$$A\frac{dh}{dt} = \dot{V}_{in} - \dot{V}_{out}$$

where
$\dot{V}_{in}$ = constant = 2 m³/min
$\dot{V}_{out}$ is a function of the height of fluid in the tank, which is $0.4h$

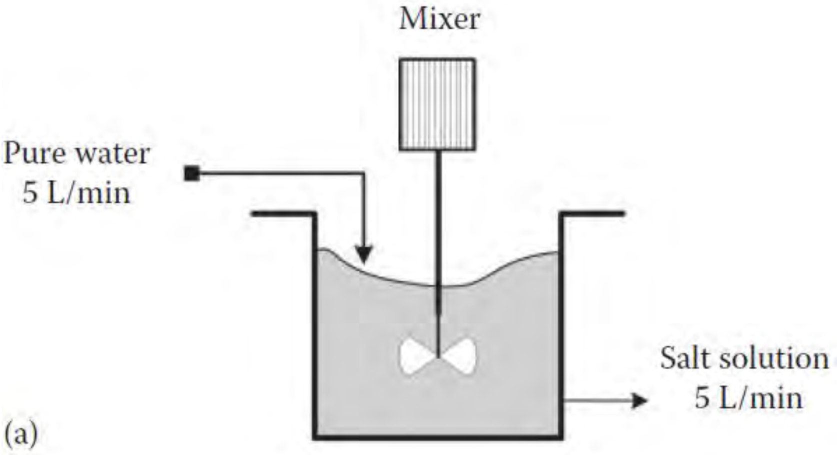


It can be seen that the height of the tank increases sharply with time at the very beginning of the process and slowly with time later on until it reaches the steady state, which is at approximately 5 m. The steady-state height is calculated by setting the differential term to zero. The height is found to be approximately 5 m.

Example 4.2 Dilution of a Salt Solution

Problem

A tank holds 100 L of a salt–water solution in which 5.0 kg of salt is dissolved. Water runs into the tank at a rate of 5 L/min, and salt solution overflows at the same rate. Plot the concentration of the salt versus time. How much salt is in the tank at the end of 10 min?



EXAMPLE FIGURE4.2.1: (a) Dilution of salt–water solution.

Solution

Known quantities: Volume, mass, and inlet flow rate are known.

Find: The amount of salt in the tank at the end of 10 min.

Analysis: Assume that the solution in the tank is well mixed and the density of the salt solution is essentially the same as that of pure water. The process flow sheet is shown in Example Figure 11.2a.1. The general unsteady-state mass balance is

$$\frac{dm}{dt} = \dot{m}_{in} - \dot{m}_{out} + \dot{m}_g - \dot{m}_c$$

Since there are no reactions, generation and consumption terms are dropped and the general material balance equation is reduced to

$$\frac{dm}{dt} = \dot{m}_{in} - \dot{m}_{out}$$

The inlet mass flow rate as a function of salt concentration is

$$\dot{m}_{\text{in}} = \dot{V}_{\text{in}}C_{\text{in}}[=]\frac{\cancel{L}}{\text{min}}\left|\frac{\text{kg}}{\cancel{L}}\right| = \frac{\text{kg}}{\text{min}}$$

The outlet mass flow rate is

$$\dot{m}_{\text{out}} = \dot{V}_{\text{out}}C_{\text{out}}[=]\frac{\cancel{L}}{\text{min}}\left|\frac{\text{kg}}{\cancel{L}}\right| = \frac{\text{kg}}{\text{min}}$$

Accumulated mass (note that, in the accumulated mass, V is the volume of the fluid in the tank) is

$$\frac{\text{d}(m)}{\text{d}t} = \frac{\text{d}(VC)}{\text{d}t}[=]\frac{\cancel{L}\,\frac{\text{kg}}{\cancel{L}}\,|}{\text{min}} = \frac{\text{kg}}{\text{min}}$$

Substitution of these terms in the simplified material balance equation yields the following equation:

$$\frac{\text{d}(VC)}{\text{d}t} = \left(\dot{V}_{\text{in}}C_{\text{in}}\right) - \left(\dot{V}_{\text{out}}C_{\text{out}}\right)$$

Assuming the tank is well mixed, the outlet salt concentration equals the concentration in the tank:

$$\frac{\text{d}(VC)}{\text{d}t} = \left(\dot{V}_{\text{in}}C_{\text{in}}\right) - \left(\dot{V}_{\text{out}}C\right)$$

The inlet is pure water, which means inlet salt concentration is zero $\Rightarrow C_{\text{in}} = 0$.

Inlet and outlet volumetric flow rates are equal $\Rightarrow \dot{V}_{\text{in}} = \dot{V}_{\text{out}}$.

Volume of fluid in the tank is constant $\Rightarrow V = \text{constant}$:

$$V\frac{\text{d}(C)}{\text{d}t} = 0 - \dot{V}_{\text{out}}C$$

Solving the resulting differential equation requires an initial condition, which is the concentration of salt in the tank at time zero:

$$C\,|_{\text{at } t=0} = \frac{5\text{ kg}}{100\text{ L}} = 0.05\text{ kg/L}$$

Integrating the developed ordinary differential equation and solving for concentration at time equal to 10 min will give the analytical solution as follows:

$$\frac{dC}{C} = -\frac{\dot{V}_{out}}{V}dt$$

Integrating,

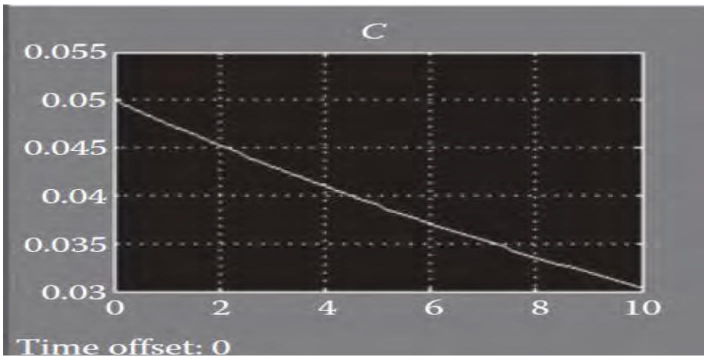
$$\ln\frac{C}{C_o} = -\frac{\dot{V}_{out}}{V}t$$

Substituting known quantities,

$$\ln\frac{C}{0.05} = -\frac{5\ \mathrm{L/min}}{1\ \mathrm{L}} \times 10\ \mathrm{min}$$

Rearranging,

$$C = 0.05\exp\left(-\frac{5\ \mathrm{L/min}}{100\ \mathrm{L}} \times 10\ \mathrm{min}\right) = 0.03\ \mathrm{kg/L}$$

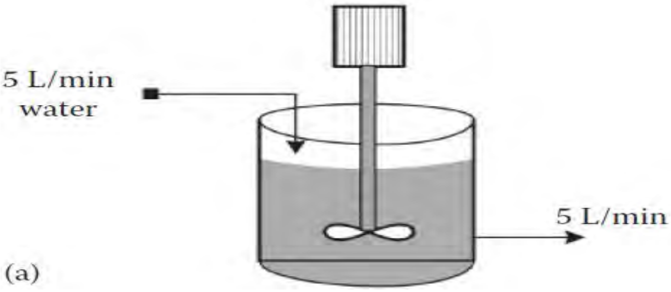


the salt concentration in the tank decreases with time. At the end of 10 min the salt concentration in the tank is 0.03 kg/L.

Example 4.3 Dilution of Salt Solution

Problem

The average ocean water of salinity 35 ppt flows into a 100 L tank containing 1.5 kg salt at a rate of 5 L/min. The salt solution overflows out of the tank at 5 L/min. How much salt remains in the tank at the end of 15 min?



EXAMPLE FIGURE4.3.1(a) Schematic of a salt dilution tank.

Solution

Known quantities: Water concentration, exit flow rate are known.

Find: The amount of salt in the tank at the end of 15 min.

Analysis: The dilution process flow sheet is shown in Example Figure 4.3a.1. Assume the fluid in the tank is well mixed and the density of salt solution is constant and equal to that of water. If we have 1 g of salt and 1000 g of water, the salinity is 1 ppt.The general unsteady-state material balance is

$$\frac{dm}{dt} = \dot{m}_{in} - \dot{m}_{out} + \dot{m}_g - \dot{m}_c$$

Since there are no reactions, generation and consumption terms are dropped and the general material balance equation is reduced to the following form:

$$\frac{dm}{dt} = \dot{m}_{in} - \dot{m}_{out}$$

Replacing mass flow rates in terms of concentration, as done in Example 11.2, yields

$$\frac{d(VC)}{dt} = \left(\dot{V}_{in}C_{in}\right) - \left(\dot{V}_{out}C_{out}\right)$$

Assuming the solution in the tank is well mixed, the outlet salt concentration equals the concentration in the tank; this assumption reduces the earlier equation to the following form:

$$\frac{d(VC)}{dt} = \left(\dot{V}_{in}C_{in}\right) - \left(\dot{V}_{out}C\right)$$

Inlet and outlet volumetric flow rates are equal $\Rightarrow \dot{V}_{in} = \dot{V}_{out}$.
Volume of fluid in the tank is constant $\Rightarrow V =$ constant:

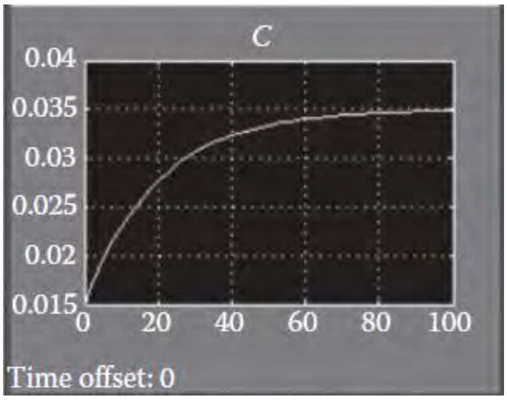
$$V\frac{dC}{dt} = \dot{V}_{in}C_{in} - \dot{V}_{out}C$$

Solving the resultant differential equation requires an initial condition, which is the concentration of salt in the tank at time zero:

$$C\,|_{at\,t=0} = \frac{1.5\text{ kg}}{100\text{ L}} = 0.015\text{ kg/L}$$

The ocean salt concentration in kilograms per liter is

$$C_{in} = 35\text{ ppt}\left|\frac{\frac{1\text{ g salt}}{1000\text{ g water}}}{1\text{ ppt}}\right|\frac{1000\text{ g water}}{\text{L}}\left|\frac{1\text{ kg}}{1000\text{ g}}\right. = 0.035\text{ kg/L}$$

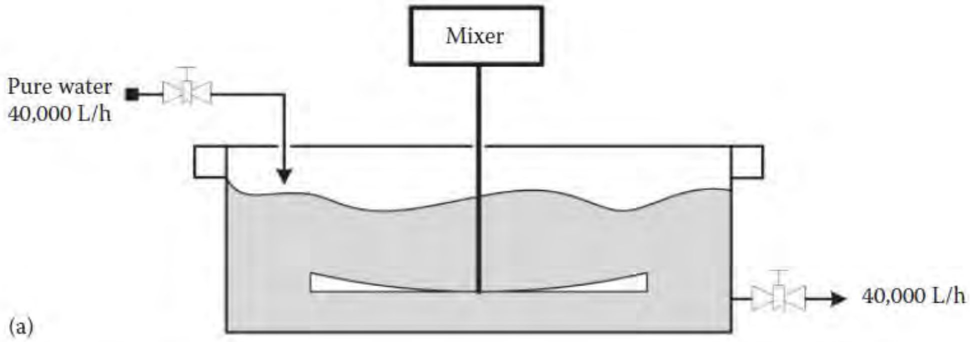


The concentration of salt in the tank after 15 min (90 s) is approximately 0.035 kg/L. Since the volume of the tank is 100 L, accordingly, the amount of salt is 3.5 kg.

Example 4.4 Sewage Treatment

Problem

In a sewage treatment plant, a large concrete tank initially contains 440,000 L liquid and 10,000 kg fine suspended solids. To flush this material out of the tank, water is pumped into the vessel at a rate of 40,000 L/h, and liquid containing solids leave at the same rate. Estimate the concentration of suspended solids in the tank at the end of 4 h.



EXAMPLE FIGURE 4.4.1: (a) Sewage treatment tank.

Solution

Known quantities: Tank volume, initial fine solid concentration, flow rates.

Find: The concentration of suspended solids in the tank at the end of 4 h.

Analysis: The process flow diagram is shown in Example Figure 11.4a.1. The general unsteady-state material balance equation is

$$\frac{dm}{dt} = \dot{m}_{in} - \dot{m}_{out} + \dot{m}_g - \dot{m}_c$$

Since there are no reactions, generation and consumption terms are dropped, and the general material balance equation is reduced to the following form:

$$\frac{dm}{dt} = \dot{m}_{in} - \dot{m}_{out}$$

Replacing mass flow rates in terms of concentration, as done in Example 4.3, yields

$$\frac{d(VC)}{dt} = \left(\dot{V}_{in}C_{in}\right) - \left(\dot{V}_{out}C_{out}\right)$$

Assuming the solution in the tank is well mixed, the outlet suspended solid concentration equals the concentration in the tank; this assumption reduces the preceding equation to the following form:

$$\frac{d(VC)}{dt} = \left(\dot{V}_{in}C_{in}\right) - \left(\dot{V}_{out}C\right)$$

Inlet and outlet volumetric flow rates are equal $\Rightarrow \dot{V}_{in} = \dot{V}_{out} = 40{,}000\ \text{L/h}$.
Volume of fluid in the tank is constant $\Rightarrow V = \text{constant} = 440{,}000\ \text{L}$.

Pure water is pumped into the vessel at a rate of 40,000 L/h; concentration of solids in the inlet pure water is zero, $C_{in} = 0$, accordingly, solid component balance is

$$V\frac{d(C)}{dt} = 0 - \left(\dot{V}_{out}C\right)$$

Solving the resultant differential equation requires an initial condition, which is the concentration of solids in the sewage tank at time zero:

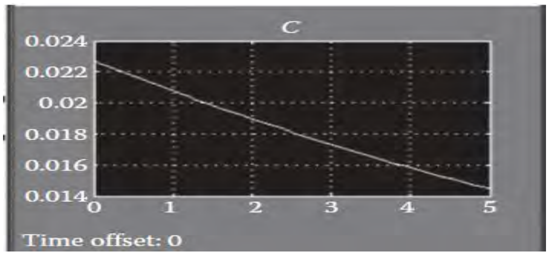
$$C\,|_{\text{at } t=0} = \frac{10{,}000\ \text{kg}}{440{,}000\ \text{L}} = 0.023\ \text{kg/L}$$

The analytical solution shows the following results:

$$\frac{d(C)}{C} = -\frac{\dot{V}_{out}}{V}, \quad \ln\frac{C_f}{C_o} = -\frac{\dot{V}_{out}}{V}t \Rightarrow C_f = C_o \exp\left(-\frac{\dot{V}_{out}}{V}t\right)$$

Substitute known quantities:

$$C_f = 0.023\frac{\text{kg}}{\text{L}}\exp\left(-\frac{40{,}000\ \text{L/h}}{440{,}000\ \text{L}}4h\right) = 0.016\ \text{kg/L}$$

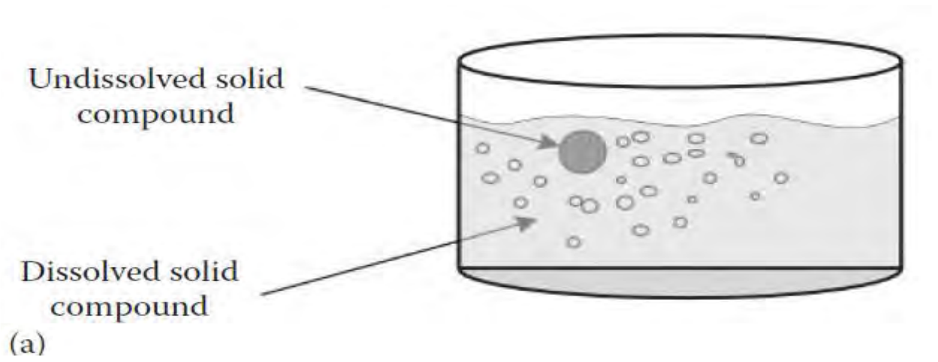


The concentration of suspended solids in the tank after 4 h of operation is approximately 0.016 kg/L, which is the same as the values of the concentration obtained analytically.

Example 4.5 Diffusion of a Solid into a Liquid

Problem

A compound dissolves in water at a rate proportional to the product of the amount of undissolved solid and the difference between the concentration in a saturated solution and the actual solution, that is, *C*sat − *C*(*t*). The dissolution rate is 0.257 h−1. A saturated solution of this compound contains 0.4 g solid/g water. In a test run starting with 20 kg of undissolved compound in 100 kg of water, how many kilograms of compound will remain undissolved after 10 h? Assume that the system is isothermal.



EXAMPLE FIGURE 4.5.1: (a) Diffusion of solid into water.

Solution

Known quantities: The dissolution rate is 0.257 h−1. A saturated solution of this compound contains 0.2 g solid/g water.

Find: The kilograms of solid compound that will remain undissolved after 10 h.

Analysis: Example Figure 11.5a.1 is a schematic of the process of diffusion of solids in water. Let us assign *m* for the mass of the undissolved compound at any time, m_0 is the initial mass of the undissolved compound at time zero, and *C* is the concentration of the dissolved compound in water.

General material balance on the undissolved compound is

$$\frac{dm}{dt} = \dot{m}_{in} - \dot{m}_{out} + \dot{m}_g - \dot{m}_c$$

There is no inlet or outlet mass flow rate to the tank: $\dot{m}$ in = $\dot{m}$ out = 0.

There is no generation of the undissolved solid: $\dot{m}$ g = 0.

The rate of consumption: *m*c = *k*m (*C*sat−*C*)

Rearranging the general material balance equation leads to the following equation:

$$\frac{dm}{dt} = -k_m(C_{sat} - C)$$

Mass of solids in the tank as a function of concentration is

$$C = \frac{m_0 - m}{W} \Rightarrow m = m_0 - C \times W$$

$$C = \frac{m_0}{W} - \frac{1}{W}m$$

Differentiation of this relation leads to

$$\frac{dC}{dt} = -\frac{1}{W}\frac{dm}{dt}$$

Rearranging so as to replace mass by solid concentration yields

$$\frac{dm}{dt} = -W\frac{dC}{dt}$$

$$\frac{dC}{dt} = \frac{k_m}{W}(C_{sat} - C)$$

Substituting concentration instead of mass of undissolved compound,

$$\frac{dC}{dt} = \frac{k_m(m_0 - C \cdot W)}{W}(C_{sat} - C)$$

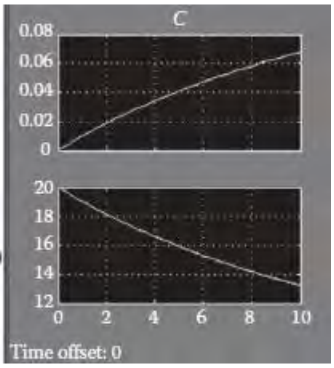
With the following data, solve the earlier equations using Simulink:

$$k = 0.257\, h^{-1}$$

$$W = 100\ \text{kg}\left|\frac{1000\ \text{g}}{1\ \text{kg}}\right. = 100{,}000\ \text{g}$$

$$C_{sat} = 0.2\frac{\text{g solid}}{\text{g water}}$$

Initial undissolved solid: $m_0 = 20\ \text{kg}\left|\frac{1000\ \text{g}}{1\ \text{kg}}\right. = 20{,}000\ \text{g}$



The diagram reveals the solid concentration is increasing with time. The amount of undissolved solid after 10 h is around 13.21 kg (13,210 g).

4.2 Unsteady-State Energy Balance

Consider the mixing tank shown in Figure 4.2 where heat is added or removed from the tank through jacketed inlet and exit streams [4, 5]. The general form of the energy balance under unsteady-state condition takes the form

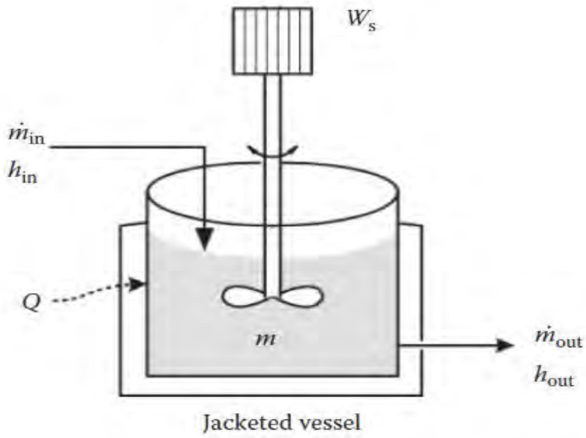


FIGURE 4.2: Energy balance on unsteady state process.

$$\frac{d(U)}{dt} = \sum \dot{m}_{in} h_{in} - \sum \dot{m}_{out} h_{out} + \dot{Q} - \dot{W}_s$$

where

U is the internal energy; $U = mC_vT$
h_{in} is the specific enthalpy of the inlet stream
h_{out} is the specific enthalpy of the exit stream
Q is the heat added to the system (+). If the heat is lost or transferred from the system to the surroundings, then the sign is negative.
W_s is the work done by the system on the surroundings (+). If the work is done on the system, then the sign is negative (–).

For liquids and solids $C_v \approx C_p$ because $\frac{d(PV)}{dt} \oplus 0$:

$$H = U + PV$$

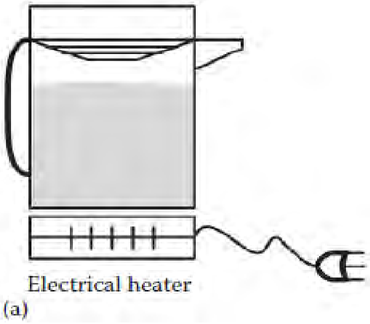
$$\frac{dH}{dt} = \frac{dU}{dt} + \cancel{\frac{d(PV)}{dt}}$$

This leads to $\frac{dH}{dt} = \frac{dU}{dt}$

Example 4.6 Heating of a Closed System

Problem

A kettle used to boil water containing 1.00 L of water at 20°C is placed on an electric heater ($Q = 2200$ J/s). Find out the time at which water begins to boil.



EXAMPLE FIGURE 4.6.1: (a) Schematic of an electrical heater kettle.

Solution
Known quantities: Kettle volume, initial water temperature, heat supplied.
Find: The time at which water begins to boil.
Analysis: The tank flowchart is shown in Example Figure 4.1a.1. The normal boiling water temperature is 100oC. The kettle heater diagram is shown in Example Figure 4.6a.1. The general energy balance equation is

$$\frac{d(U)}{dt} = \Sigma \dot{m}_{in} h_{in} - \Sigma \dot{m}_{out} h_{out} + \dot{Q} - \dot{W}_s$$

The kettle is batch; inlet and outlet mass flow rates are zero; $\dot{m}$ in = $\dot{m}$ out = 0.
No shaft work: *W*s = 0 , For liquids: *C*p ≈ *Cv,* Specific heat of water: *C*p = 4.18 J/g°C

The general energy balance equation is simplified to the following equation:

$$\frac{d(mC_pT)}{dt} = \dot{Q}$$

The mass of liquid water inside the kettle is

$$m = \rho V$$

Substituting m in the simplified energy balance equation gives

$$\frac{d\left(mC_pT\right)}{dt} = \dot{Q}$$

Rearranging,

$$\frac{dT}{dt} = \frac{\dot{Q}}{\rho V C_p}$$

Solve this ordinary differential equation using the following data:

Heat added to the kettle: $\dot{Q}$ = 2200 J/s , Specific heat of water: *C*p = 4.18 J/g°C
Volume of the kettle: *V* = 1.0 L, Density of the water in the kettle: *ρ* = 1000 g/L

The analytical solution is obtained by integrating the first-order energy balance equation:

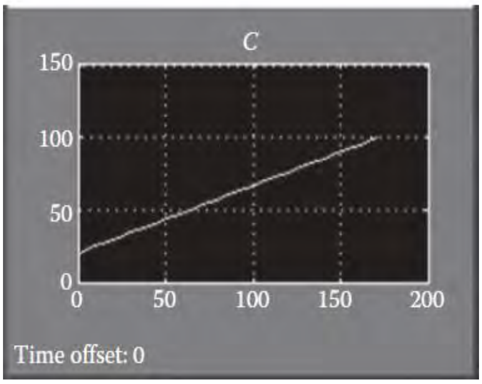
$$T_2 - 20 = \frac{\dot{Q}}{\rho V C_p} t$$

Since water boils at 100°C, accordingly $T_2 = 100$. Substitute known values and solve for time:

$$200 - 20 = \frac{2200\,\mathrm{J/s}}{\frac{1000\,\mathrm{g}}{\mathrm{L}} \times 1\,\mathrm{L}\ 4.18\,\mathrm{J/gC)}} t$$

$$\frac{80 \times 1000 \times 4.18}{2200} s = t$$

t = time = 152 s (2.53 min)



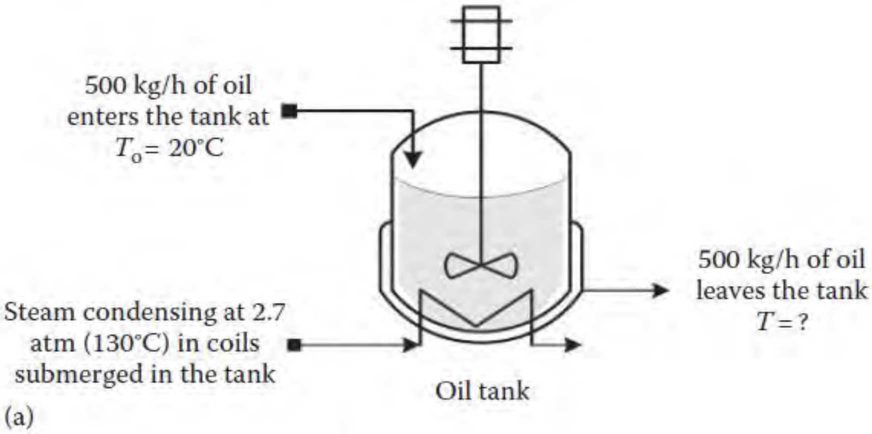
The time required to heat the water to its boiling temperature in the mentioned kettle is 171.5 s (2.86 min).

Example 4.7 Heating of a Stirred Tank
Problem

Oil at 20°C is being heated in a stirred tank. Oil enters the tank at a rate of 500 kg/h at 20°C and leaves at temperature *T*. The tank holds 2300 kg of oil, which is initially at 20°C. The heat is provided by steam condensing at 130°C in coils submerged in the tank. The rate of heat transfer is given by

$$Q = h\,(T\mathrm{steam} - T\mathrm{oil})$$

The heat capacity of the oil is given by *C*p = 2.1 J/(g °C) and the heat transfer coefficient is *h* = 115 J/s °C. The shaft work of the stirrer is 560 W. Once the process is started, how long does it take before the oil leaving the tank is at 30°C?



EXAMPLE FIGURE 4.7.1: (a) Schematic of an oil heating tank.

Solution

Known quantities: Inlet and exit tank volumetric flow rate.
Find: Plot the height of the tank as a function of time.
Analysis: The tank flowchart is shown in Example Figure 4.1a.1. The general energy balance equation is

$$\frac{d(u)}{dt} = \sum \dot{m}_{in}h_{in} - \sum \dot{m}_{out}h_{out} + \dot{Q} - \dot{W}_s$$

Reference: Inlet oil temperature (i.e., *T*ref = *T*0 = 20°C).
System: Oil in the tank (Example Figure 4.7a.1).
For liquids, *C*p and *Cv* are approximately equal.
Specific heat of oil: *C*p = 2.1 J/g °C.
The shaft work of the stirrer is 560 W.
The work done on the system *W*s = −560 *W* = −560 J/s.
The heat added to the oil from the steam is *Q* = *h* (*T*steam − *T*).
The heat transfer coefficient is *h* = 115 J/(s°C).

$$\text{Mass of oil in the tank } m = 2300\text{ kg}\left|\frac{1000\text{ g}}{1\text{ kg}}\right. = 2.3\times10^6\text{g}$$

$$\text{Inlet and exit mass flow rates: } \dot{m} = \frac{500\text{ kg}}{\text{h}}\left|\frac{1000\text{ g}}{1\text{ kg}}\right|\frac{\text{h}}{3600\text{ s}} = 139\text{ g/s}$$

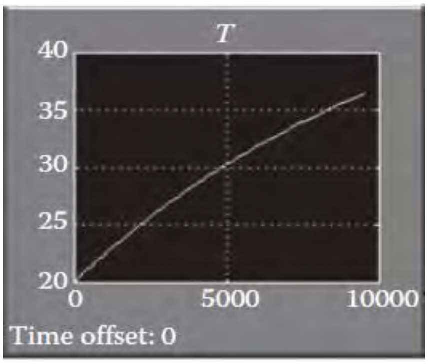
The general energy balance equation is simplified to the following equation:

$$\frac{d(mC_pT)}{dt} = \sum \dot{m}_{in}\hat{H}_{in} - \sum \dot{m}_{out}\hat{H}_{out} + \dot{Q} - \dot{W}_s$$

Rearranging the equation in order to collect and separate variables leads to

$$mC_p\frac{d(T)}{dt} = 0 - \dot{m}C_p(T - T_0) + h(T_{steam} - T) - \dot{W}_s$$

$$\frac{dT}{dt} = \frac{[0 - \dot{m}C_p(T - T_0) + h(T_{steam} - T) - \dot{W}_s]}{mC_p}$$



The result reveals that the temperature of oil reaches 35°C in approximately 123 min.

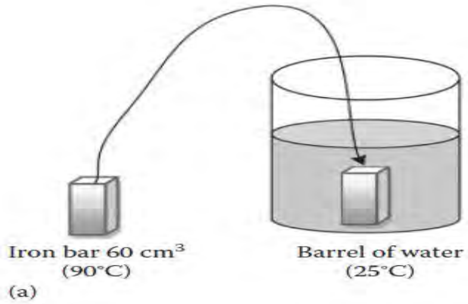
Example 4.8 Quenching of an Iron Bar

Problem

The volume of a cubic iron bar is 60 cm3 at a temperature of 95°C, the heat transfer area of the block is 112 cm^2. The iron bar is dropped into a barrel of water at 25°C. Density of the iron bar is 11.34 g/cm^3. The barrel is large enough so that the water temperature rise is negligible as the bar cools down. The rate at which heat is transferred from the bar to the water is given by the expression

Q (J/min) $= UA\,(T - T_w)$

where U is the heat transfer coefficient, which is 0.050 J/(min cm2 °C). The heat capacity of the iron bar is 0.460 J/ (g °C). Plot the temperature of the bar as a function of time, and calculate the time for the bar to cool to 30°C.



EXAMPLE FIGURE 4.8.1: (a) Schematic of cooling of iron bar block in a large tank of water.

Solution

Known quantities: Inlet and exit tank volumetric flow rate.

Find: Plot the height of the tank as a function of time.

Analysis: The tank flowchart is shown in Example Figure 4.8a.1. Assume the heat conduction in iron is rapid enough for the temperature of the bar to be uniform throughout. This latter concept is an important approximation called lumped capacitance, and it allows us to considerably simplify the problem because we do not have to worry about heat transfer within the solid bar itself. Assume also temperature of water to remain constant.

System: Iron block.

Reference temperature: 25°C

Schematic of the process is shown in Example Figure 4.8a.1.

The general energy balance equation is

$$\frac{\mathrm{d}(mC_pT)}{\mathrm{d}t} = \sum \dot{m}_{\mathrm{in}}\hat{H}_{\mathrm{in}} - \sum \dot{m}_{\mathrm{out}}\hat{H}_{\mathrm{out}} + \dot{Q} - \dot{W}_s$$

Note that for solids and liquids C_p and C_v are equal.

No inlet or exit flowing streams: $\sum \dot{m}_{\mathrm{in}}h_{\mathrm{in}} = \sum \dot{m}_{\mathrm{out}}h_{\mathrm{out}} = 0.$

The barrel is large enough so that the water temperature rise is negligible as the bar cools; this means the water temperature remains constant, T_w = constant.

No stirrer or shaft work: $W_s = 0$.

The heat transfer from the iron block: $Q(\mathrm{J/s}) = -UA(T - T_w)$

Heat transfer coefficient, $U = \dfrac{0.050\ \mathrm{J}}{\mathrm{min}\cdot\mathrm{cm}^2\cdot{}^\circ\mathrm{C}}\left|\dfrac{1\ \mathrm{min}}{60\ \mathrm{s}}\right. = 8.33\times 10^{-4}\dfrac{\mathrm{J}}{\mathrm{s}\cdot\mathrm{cm}^2\cdot{}^\circ\mathrm{C}}.$

The heat capacity of the bar: $C_{\mathrm{P_b}} = 0.460\ \mathrm{J/(g\,{}^\circ C)}$.

Heat conduction in iron is rapid enough for the temperature of the bar to be uniform throughout.

Density of the iron bar: $\rho_b = 11.34\ \mathrm{g/cm^3}$

Mass of the block: $m = \rho_b V_b$

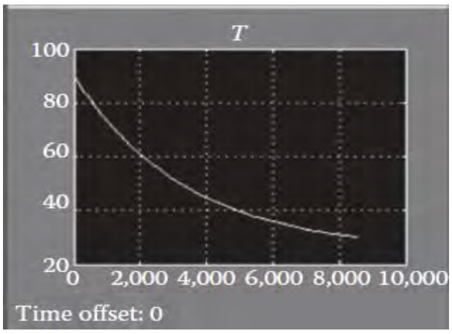
Heat transfer area of the block: $A = 112\ \mathrm{cm^2}$

We now rearrange the equation to obtain it in terms of the two variables T and t (T dependent variable, t independent variable):

$$\frac{\mathrm{d}T}{\mathrm{d}t} = \frac{\dot{Q}}{mC_p}$$

Substituting the heat transferred from the block (i.e., $Q = -UA(T-T_w)$),

$$\frac{\mathrm{d}T}{\mathrm{d}t} = \frac{-UA(T - T_w)}{mC_p}$$



the time required to cool the block to 30°C, which is around 2.39 h

Example 4.9 Heating of a Solution

Problem

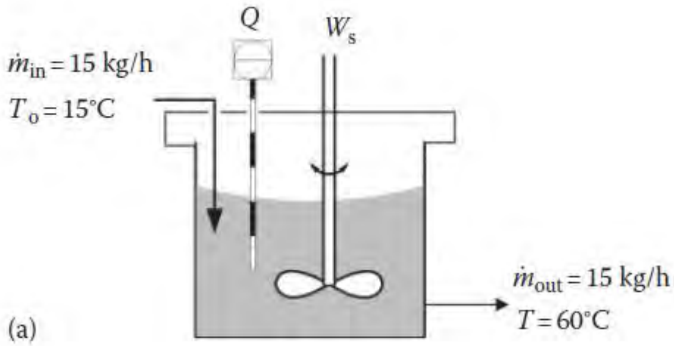
An electric heating coil is immersed in a stirred tank. The shaft work of the stirrer is 560 W. A solvent at 15°C with a heat capacity of 2.1 J/g °C is fed into the tank at a rate of 15 kg/h. Heated solvent is discharged at the same flow rate. The tank is filled initially with 125 kg cold solvent at 10°C. The rate of heating the electric coil is 2000 W. Calculate the time required for the temperature of the solvent to reach 60°C.

Solution

Known quantities: Inlet and exit flow rate, initial tank temperature.

Find: The time required for the temperature of the solvent to reach 60°C.

Analysis: The tank flowchart is shown in Example Figure 4.9a.1. Assume the tank reference temperature is 15°C. The general energy balance equation is simplified to the following equation:



EXAMPLE FIGURE 4.9.1: (a) Schematic of a heating tank.

Solution

Known quantities: Inlet and exit flow rate, initial tank temperature.

Find: The time required for the temperature of the solvent to reach 60°C.

Analysis: The tank flowchart is shown in Example Figure 4.9a.1.

Assume the tank reference temperature is 15°C. The general energy balance equation is simplified to the following equation:

$$\frac{d(mC_pT)}{dt} = \sum \dot{m}_{in}h_{in} - \sum \dot{m}_{out}h_{out} + \dot{Q} - \dot{W}_s$$

Rearranging the equation in order to collect and separate variables gives

$$mC_p\frac{d(T)}{dt} = 0 - \dot{m}C_p(T - T_0) + \dot{Q} - \dot{W}_s$$

$$\frac{dT}{dt} = \frac{\left[0 - \dot{m}C_p(T - T_0) + \dot{Q} - \dot{W}_s\right]}{mC_p}$$

The schematic diagram is shown in Example Figure 11.9a.1.

Solving the earlier equation necessitates the units to be consistent.

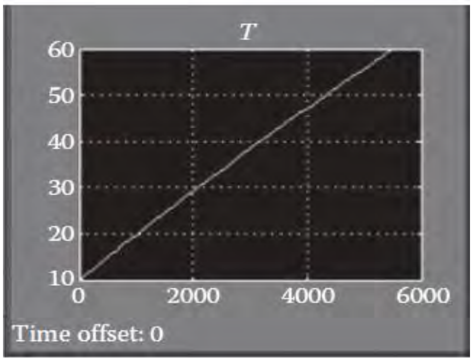
Mass of oil: $m = 125\text{ kg}\left|\frac{1000\text{ g}}{1\text{ kg}}\right. = 1.25\times 10^5$ g.

Inlet and exit oil flow rates: $\dot{m} = \frac{15\text{ kg}}{\text{h}}\left|\frac{1000\text{ g}}{1\text{ kg}}\right|\frac{\text{h}}{3600\text{ s}} = 4.17\text{ g/s}.$

Heat capacity: $C_p = 2.1$ J/g °C.

Heat added to the oil from the cooling coil: $Q = 2000$ J/s.

Work applied on the system from the stirrer: $W_s = -560$ J/s.



The time required for temperature to reach 60oC is around 5521 s (1.53 h).

Example 4.10 Heating a Glycol Solution

Problem

An adiabatic stirred tank is used to heat 100 kg of a 45 wt% glycol solution in water (mass heat capacity 3.54 J/g °C). An electrical coil delivers 2.5 kJ/s of power to the tank; 88% of the energy delivered by the coil goes into heating the vessel contents. The shaft work of the stirrer is 500 W. The glycerol solution is initially at 15°C. How long will the solution take to reach 90°C?

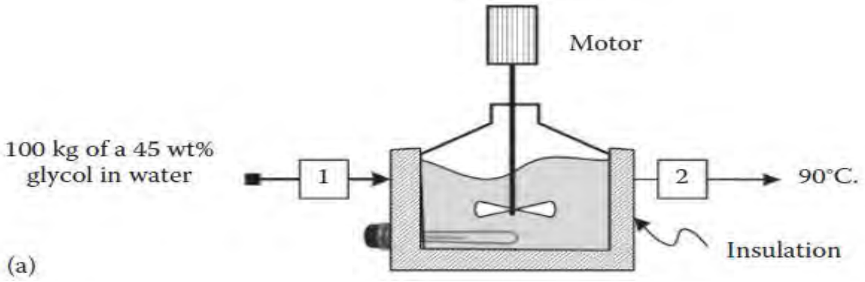


FIGURE4.10: (a) Schematic of a glycol heating tank.

Solution

Known quantities: Mass of glycol in the tank, heat capacity, heat supplied from coil.
Find: The time taken for the glycol solution to reach 90°C.
Analysis: Assume a reference temperature of 15°C. The schematic diagram of the adiabatic stirred tank heater is shown in Figure 4.10a.
The general energy balance equation is simplified to the following equation:

$$\frac{d(u)}{dt} = \sum \dot{m}_{in} h_{in} - \sum \dot{m}_{out} h_{out} + \dot{Q} - \dot{W}_s$$

$$\frac{d(mC_v T)}{dt} = \sum \dot{m}_{in} h_{in} - \sum \dot{m}_{out} h_{out} + \dot{Q} - \dot{W}_s$$

Note that for solids and liquids C_p and C are equal:

$$\frac{d(mC_p T)}{dt} = \sum \dot{m}_{in} h_{in} - \sum \dot{m}_{out} h_{out} + \dot{Q} - \dot{W}_s$$

The system is adiabatic, that is, no heat is transferred to or from the surroundings, but still there is heat added by the electrical coil:

$$\dot{Q}_{net} = \dot{Q}_e + \dot{Q}_{sur}$$

Since the system is adiabatic, $\dot{Q}_{sur} = 0$. Heat added to the glycol solution is 88% of that of the heating coil:

$$\dot{Q}_e = 0.88 \times 2.5\ \text{kJ/s} = 2.2\ \text{kJ/s}$$

The mass of the glycol solution in the heated tank: $m = 100$ kg.

The heat capacity of the glycol solution: $C_p = 3.54$ J/g °C.

Rearranging the equation in order to collect and separate variables gives

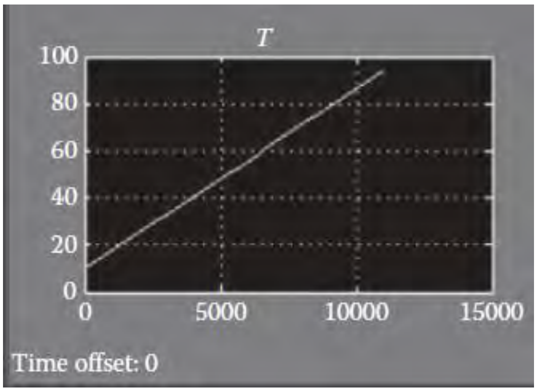
$$\frac{dT}{dt} = \frac{[\dot{Q} - \dot{W}_s]}{mC_p}$$

Use the following data:

$$\dot{Q} = \frac{2.2\text{ kJ}}{\text{s}}\left|\frac{1000\text{ J}}{\text{kJ}}\right. = 2200\text{ J/s}$$

$$W_s = -500\text{ J/s},\quad m = 100\text{ kg}$$

$$C_p = 3.54\text{ J/g °C}$$



the solution shows that it will take around 10,000 s (2.78 h) for the glycol solution to reach the temperature of 90°C.

Homework Problems

4.1 A storage tank that is 2.0 m in diameter is filled at a rate of 2.0 m^3/ min. The exit fluid flow rate is proportional to the head of the fluid (0.5*h* m^3/min), where *h* is the height of fluid in meters. Plot the height of the liquid as a function of time. What is the steady-state height of the fluid in the tank? (4 m)

4.2 A boiler used to boil water, containing 100 L of water at a temperature of 25°C, is placed on an electric heater (Q = 3000 J/s). Find the time at which water begins to boil. (100 min)

4.3 A tank containing 1000 kg water at 25°C is heated using saturated steam at 130°C. The rate of heat transfer from the steam is given by the following equation:

$$\dot{Q} = UA\,(T - T)$$

$\dot{Q}$ is the rate of heat transfer to the system. *U* is the overall heat transfer coefficient, *A* is the surface area for heat transfer, and *T* is the temperature. The heat transfer area provided by the coil is 0.3 m^2, and the heat transfer coefficient is 220 (kcal)/m^2 h°C. The condensate leaves the coil as saturated steam.

a. The tank has a surface area of 0.9 m2 exposed to the ambient air. The tank exchanges heat through this exposed surface at a rate given by an equation similar to

that given earlier. For heat transfer to or from the surrounding air, the heat transfer coefficient is 25 (kcal)/m^2 h°C. If the air temperature is 20°C, calculate the time required to heat the water to 80°C. (5.9 h)
b. How much time can be saved if the tank is insulated? (4.2 h)

4.4 A stirred tank is used to heat 100 kg of a solvent (mass heat capacity 2.5 J/g°C). An electrical coil delivers 2.0 kJ/s of power to the tank; the shaft work of the stirrer is 560 W. The solvent is initially at 25°C. The heat lost from the walls of the tank is 200 J/s.
a. Write a differential equation for the energy balance.
b. Solve the equation using the available software package.
c. How long will the solution take to reach 70°C? (1.33 h)

4.5 The following series reaction takes place in a constant volume batch reactor:

$$A \xrightarrow{k_1} B \xrightarrow{k_2} C$$

Each reaction is of first order and is irreversible. If the initial concentration of A is 1 mol/L and if only A is present initially, find an expression for the concentrations of A, B, and C as a function of time ($k1 = 0.1/s$, $k2 = 0.2/s$).

References

1. Himmelblau, D.M. (1996) *Basic Principles and Calculations in Chemical Engineering*, 6th edn., Prentice-Hall, Upper Saddle River, NJ.

2. Doran, P. (1995) *Bioprocess Engineering Principles*, Academic Press, San Diego, CA.

3. Reklaitis, G.V. (1983) *Introduction to Material and Energy Balances*, John Wiley & Sons, New York.

4. Felder, R.M. and R.W. Rousseau (1999) *Elementary Principles of Chemical Processes*, 3rd edn., John Wiley, New York.

5. Atkinson, B. and F. Mavituna (1991) *Biochemical Engineering and Biotechnology Handbook*, 2nd edn., Macmillan, Basingstoke, UK.

Appendix

Physical properties (Appendix A.1), heat capacities (Appendix A.2), and saturated and superheated steam table (Appendix A.3) are adapted with permission from the following references:

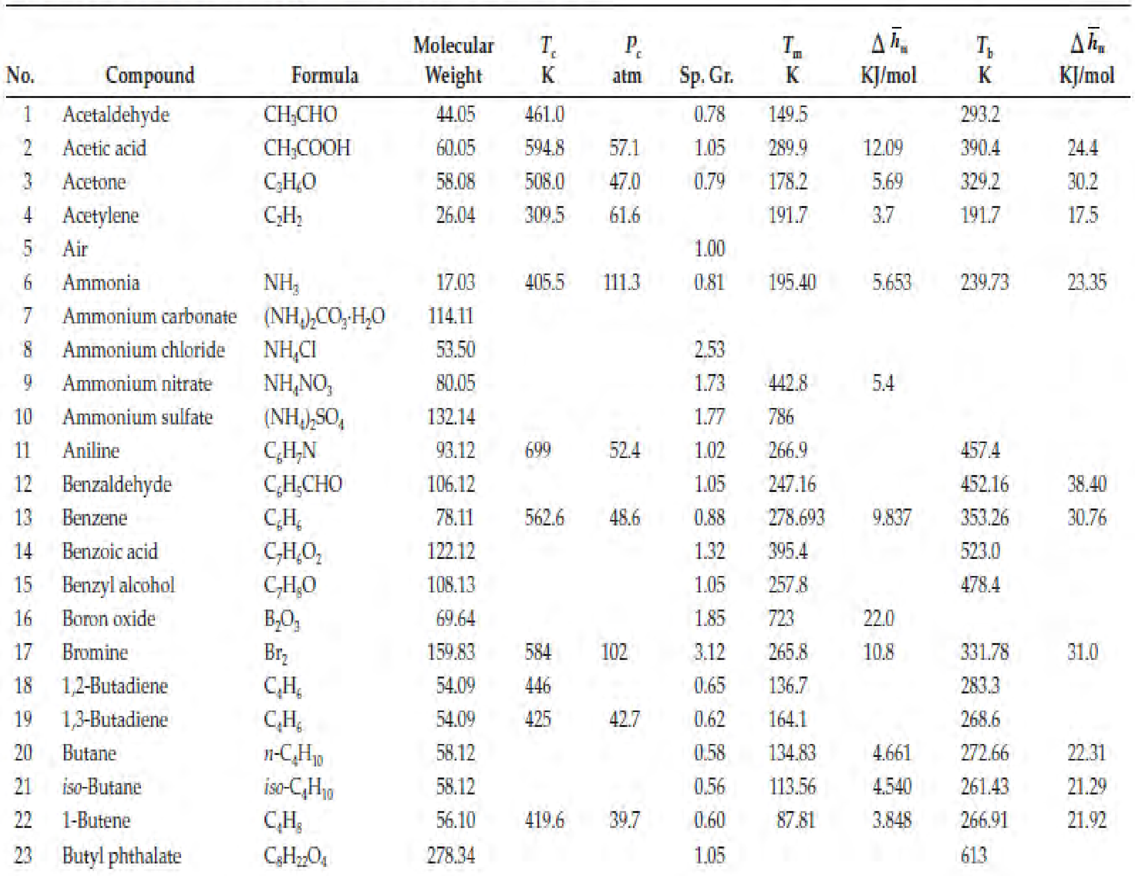
1. Himmelblau, D.M. (1996) *Basic Principles and Calculations in Chemical Engineering*, 6th edn., Prentice-Hall, Upper Saddle River, NJ (Appendices A.1 and A.2)
2. Haywood, R.W. (1968) *Thermodynamic Tables in SI (Metric) Units*, Cambridge University Press, London, U.K. (Appendix A.3).

Appendix A.1

Table A.1 contains physical properties of various organic and inorganic substances such as molecular weight, critical temperature, critical pressure, specific gravity, melting temperature, heat of fusion, boiling temperature, and heat of vaporization. Table A.2 contains standard heats of formation and standard heats of combustion.

TABLE A.1

Physical Properties of Various Organic and Inorganic Substances



No.	Compound	Formula	Molecular Weight	T_c K	P_c atm	Sp. Gr.	T_m K	$\Delta \bar{h}_u$ KJ/mol	T_b K	$\Delta \bar{h}_u$ KJ/mol
1	Acetaldehyde	CH_3CHO	44.05	461.0		0.78	149.5		293.2	
2	Acetic acid	CH_3COOH	60.05	594.8	57.1	1.05	289.9	12.09	390.4	24.4
3	Acetone	C_3H_6O	58.08	508.0	47.0	0.79	178.2	5.69	329.2	30.2
4	Acetylene	C_2H_2	26.04	309.5	61.6		191.7	3.7	191.7	17.5
5	Air					1.00				
6	Ammonia	NH_3	17.03	405.5	111.3	0.81	195.40	5.653	239.73	23.35
7	Ammonium carbonate	$(NH_4)_2CO_3{\cdot}H_2O$	114.11							
8	Ammonium chloride	NH_4Cl	53.50			2.53				
9	Ammonium nitrate	NH_4NO_3	80.05			1.73	442.8	5.4		
10	Ammonium sulfate	$(NH_4)_2SO_4$	132.14			1.77	786			
11	Aniline	C_6H_7N	93.12	699	52.4	1.02	266.9		457.4	
12	Benzaldehyde	C_6H_5CHO	106.12			1.05	247.16		452.16	38.40
13	Benzene	C_6H_6	78.11	562.6	48.6	0.88	278.693	9.837	353.26	30.76
14	Benzoic acid	$C_7H_6O_2$	122.12			1.32	395.4		523.0	
15	Benzyl alcohol	C_7H_8O	108.13			1.05	257.8		478.4	
16	Boron oxide	B_2O_3	69.64			1.85	723	22.0		
17	Bromine	Br_2	159.83	584	102	3.12	265.8	10.8	331.78	31.0
18	1,2-Butadiene	C_4H_6	54.09	446		0.65	136.7		283.3	
19	1,3-Butadiene	C_4H_6	54.09	425	42.7	0.62	164.1		268.6	
20	Butane	$n\text{-}C_4H_{10}$	58.12			0.58	134.83	4.661	272.66	22.31
21	*iso*-Butane	$iso\text{-}C_4H_{10}$	58.12			0.56	113.56	4.540	261.43	21.29
22	1-Butene	C_4H_8	56.10	419.6	39.7	0.60	87.81	3.848	266.91	21.92
23	Butyl phthalate	$C_8H_{22}O_4$	278.34			1.05			613	

24	*n*-Butyric acid	*n*-$C_4H_8O_2$	88.10			0.96	267		437.1	
25	*iso*-Butyric acid	*iso*-$C_4H_8O_2$	88.10			0.95	226		427.7	
26	Calcium arsenate	$Ca_3(AsO_4)_2$	398.06				1723			
27	Calcium carbide	CaC_2	64.10			2.22	2573			
28	Calcium carbonate	$CaCO_3$	100.09			2.93				
29	Calcium chloride	$CaCl_2$	110.99			2.15	1055	28.4		
		$CaCl_2{\cdot}H_2O$	129.01							
		$CaCl_2{\cdot}2H_2O$	147.03							
		$CaCl_2{\cdot}6H_2O$	219.09			1.78	303.4	37.3		
30	Calcium cyanamide	$CaCN_2$	80.11			2.29				
31	Calcium cyanide	$Ca(CN)_2$	92.12							
32	Calcium hydroxide	$Ca(OH)_2$	74.10			2.24				
33	Calcium oxide	CaO	56.08			2.62	2873	50	3123	
34	Calcium phosphate	$Ca_3(PO_4)_2$	310.19			3.14	1943			
35	Calcium silicate	$CaSiO_3$	117.17			2.92	1803	48.62		
36	Calcium sulfate	$CaSO_4{\cdot}2H_2O$	172.18			2.32				
37	Carbon	C	12.010			2.26	3873	46.0	4473	
38	Carbon dioxide	CO_2	44.01	304.2	72.9		217.0	8.32		
39	Carbon disulfide	CS_2	76.14			1.26	161.1	4.39	319.41	26.8
40	Carbon monoxide	CO	28.01	133.0	34.5		68.10	0.837	81.66	6.04
41	Carbon tetrachloride	CCl_4	153.84	556.4	45.0	1.60	250.3	2.5	349.9	30.0
42	Chlorine	Cl_2	70.91	417.0	76.1		172.16	6.406	239.10	20.41
43	Chlorobenzene	C_6H_5Cl	112.56	632.4	44.6	1.11	228		405.26	36.5
44	Chloroform	$CHCl_3$	119.39	536.0	54.0	1.49	209.5		334.2	
45	Chromium	Cr	52.01			7.1				
46	Copper	Cu	63.54			8.92	1356.2	13.0	2855	305
47	Cumene	C_9H_{12}	120.19			0.86	177.125	7.1	425.56	37.5

(Continued)

TABLE A.1 *(Continued)*

Physical Properties of Various Organic and Inorganic Substances

No.	Compound	Formula	Molecular Weight	T_c K	P_c atm	Sp. Gr.	T_m K	$\Delta \bar{h}_m$ KJ/mol	T_b K	$\Delta \bar{h}_m$ KJ/mol
48	Cupric sulfate	$CuSO_4$	159.61			3.61				
49	Cyclohexane	C_6H_{12}	84.16	553.7	40.4	0.78	279.83	2.677	353.90	30.1
50	Cyclopentane	C_5H_{10}	70.13	511.8	44.55	0.75	179.71	0.6088	322.42	27.30
51	Decane	$C_{10}H_{22}$	142.28	619.0	20.8	0.73	243.3		447.0	
52	Dibutyl phthalate	$C_8H_{22}O_4$	278.34			1.05			613	
53	Diethyl ether	$(C_2H_5)_2O$	74.12	467	35.6	0.71	156.86	7.301	307.76	26.05
54	Ethane	C_2H_6	30.07	305.4	48.2		89.89	2.860	184.53	14.72
55	Ethanol	C_2H_5OH	46.07	516.3	63.0	0.79	158.6	5.021	351.7	38.6
56	Ethyl acetate	$C_4H_8O_2$	88.10	523.1	37.8	0.90	189.4		350.2	
57	Ethyl benzene	C_8H_{10}	106.16	619.7	37.0	0.87	178.185	9.163	409.35	36.0
58	Ethyl bromide	C_2H_5Br	108.98	504	61.5	1.46	154.1		311.4	
59	Ethyl chloride	C_2H_5Cl	64.52	460.4	52.0	0.90	134.83	4.452	285.43	25
60	3-Ethyl hexane	C_8C_{18}	114.22	567.0	26.4	0.72			391.69	34.3
61	Ethylene	C_2H_4	28.05	283.1	50.5		103.97	3.351	169.45	13.54
62	Ethylene glycol	$C_2H_6O_2$	62.07			1.11	260	11.23	470.4	56.9
63	Ferric oxide	Fe_2O_3	159.70			5.12	1833			
64	Ferric sulfide	Fe_2S_3	207.90			4.30				
65	Ferrous sulfide	FeS	87.92			4.84	1466			
66	Formaldehyde	H_2CO	30.03			0.81	154.9		253.9	24.5
67	Formic acid	CH_2O_2	46.03			1.22	281.46	12.7	373.7	22.3
68	Glycerol	$C_3H_8O_3$	92.09			1.26	291.36	18.30	563.2	
69	Helium	He	4.00	5.26	2.26		3.5	0.02	4.216	0.084
70	Heptane	C_7H_{16}	100.20	540.2	27.0	0.68	182.57	14.03	371.59	31.69
71	Hexane	C_6H_{14}	86.17	507.9	29.9	0.66	177.84	13.03	341.90	28.85

72	Hydrogen	H_2	2.016	33.3	12.8		13.96	0.12	20.39	0.904
73	Hydrogen chloride	HCl	36.47	324.6	81.5		158.94	1.99	188.11	16.15
74	Hydrogen fluoride	HF	20.01	503.2	—	1.15	238		293	
75	Hydrogen sulfide	H_2S	34.08	373.6	88.9		187.63	2.38	212.82	18.67
76	Iodine	I_2	253.8	826.0	—	4.93	386.5		457.4	
77	Iron	Fe	55.85	—	—	7.70	1808	15	3073	353
78	Iron oxide	Fe_3O_4	231.55			5.20	1867	138		
79	Lead	Pb	207.21			11.34	600.6	5.10	2023	180
80	Lead oxide	PbO	223.21			9.50	1159	11.7	1745	213
81	Magnesium	Mg	24.32			1.74	923	9.2	1393	132
82	Magnesium chloride	$MgCl_2$	95.23			2.33	987	43.1	1691	137
83	Magnesium hydroxide	$Mg(OH)_2$	58.34			2.40				
84	Magnesium oxide	MgO	40.32			3.65	3173	77.4	3873	
85	Mercury	Hg	200.61			13.54				
86	Methane	CH_4	16.04	190.70	45.8		90.68	0.941	111.67	8.180
87	Methanol	CH_3OH	32.04			0.79	175.26	3.17	337.9	35.3
88	Methyl acetate	$C_3H_6O_2$	74.08	506.7	46.30	0.93	174.3		330.3	
89	Methyl amine	CH_5N	31.06	429.9	73.60	0.70	180.5		266.3	
90	Methyl chloride	CH_3Cl	50.49	416.1	65.80		175.3		249	
91	Methyl ethyl ketone	C_4H_8O	72.10			0.81	186.1		352.6	
92	Methyl cyclohexane	C_7H_{14}	98.18			0.77	146.58	6.751	374.10	31.7
93	Molybdenum	Mo	95.95			10.2				
94	Napthalene	$C_{10}H_8$	128.16			1.15	353.2		491.0	
95	Nickel	Ni	58.69			8.90	1725		3173	
96	Nitric acid	HNO_3	63.02			1.50	231.56	10.47	359	30.30
97	Nitrobenzene	$C_6H_5O_2N$	123.11			1.20	278.7		483.9	
98	Nitrogen	N_2	28.02	126.20	33.5		63.15	0.720	77.34	5.577
99	Nitrogen dioxide	NO_2	46.01	431.0	100.0		263.86	7.334	294.46	14.73

(Continued)

TABLE A.1 (*Continued*)

Physical Properties of Various Organic and Inorganic Substances

No.	Compound	Formula	Molecular Weight	T_c K	P_c atm	Sp. Gr.	T_m K	$\Delta \bar{h}_m$ KJ/mol	T_b K	$\Delta \bar{h}_v$ KJ/mol
100	Nitrogen (nitric) oxide	NO	30.01	179.20	65.0		109.51	2.301	121.39	13.78
101	Nitrogen pentoxide	N_2O_5	108.02			1.63	303		320	
102	Nitrogen tetraoxide	N_2O_4	92	431.0	99.0	1.45	263.7		294.3	
103	Nitrogen trioxide	N_2O_3	76.02			1.45	171		276.5	
104	Nitrous oxide	N_2O	44.02	309.5	71.70	1.23	182.1		184.4	
105	*n*-Nonane	C_9H_{20}	128.25	595	23.0	0.72	219.4		423.8	
106	*n*-Octane	C_8H_{18}	114.22	595.0	22.5	0.70	216.2		398.7	
107	Oxalic acid	$C_2H_2O_4$	90.04			1.90				
108	Oxygen	O_2	32.00	154.4	49.7		54.40	0.443	90.19	6.820
109	*n*-Pentane	C_5H_{12}	72.15	469.80	33.3	0.63	143.49	8.393	309.23	25.77
110	*iso*-Pentane	*iso*-C_5H_{12}	72.15	461.0	32.9	0.62	113.1		300.9	
111	1-Pentane	C_5H_{10}	70.13	474	39.9	0.64	107.96	4.937	303.13	
112	Phenol	C_6H_5OH	94.11	692.1	60.5	1.07	315.66	11.43	454.56	
113	Phenyl hydrazine	$C_6H_8N_2$	108.14			1.10	292.76	16.43	51.66	
114	Phosphoric acid	H_3PO_4	98.00			1.83	315.51	10.5		
115	Phosphorus (red)	P_4	123.90			2.20	863	81.17	863	41.84
116	Phosphorus (white)	P_4	123.90			1.82	317.4	2.5	553	49.71
117	Phosphorus pentoxide	P_2O_5	141.95			2.39				
118	Propane	C_3H_8	44.09	369.9	42.0		85.47	3.524	231.09	18.77
119	Propene	C_3H_6	42.08	365.1	45.4		87.91	3.002	225.46	18.42
120	Propionic acid	$C_3H_6O_2$	74.08			0.99	252.2		414.4	

121	*n*-Propyl alcohol	C_3H_5OH	60.09	536.7	49.95	0.80	146		370.2	
122	*iso*-Propyl alcohol	C_3H_8O	60.09	508.8	53.0	0.79	183.5		355.4	
123	*n*-Propyl benzene	C_9H_{12}	120.19	638.7	31.3	0.86	173.660	8.54	432.38	38.2
124	Silicon dioxide	SiO_2	60.09			2.25	1883	8.54	2503	
125	Sodium bisulfate	$NaHSO_4$	120.07			2.74	455			
126	Sodium carbonate	$Na_2CO_3{\cdot}10H_2O$	286.15			1.46	306.5			
127	Sodium carbonate	Na_2CO_3	105.99			2.53	1127	33.4		
128	Sodium chloride	$NaCl$	58.45			2.16	1081	28.5	1738	171
129	Sodium cyanide	$NaCN$	49.01				835	16.7	1770	155
130	Sodium hydroxide	$NaOH$	40.00			2.13	592	8.4	1663	
131	Sodium nitrate	$NaNO_3$	85.00			2.26	583	15.9		
132	Sodium nitrite	$NaNO_2$	69.00			2.17	544			
133	Sodium sulfate	Na_2SO_4	142.05			2.70	1163	24.3		
134	Sodium sulfide	Na_2S	78.05			1.86	1223	6.7		
135	Sodium sulfite	Na_2SO_3	126.05			2.63				
136	Sodium thiosulfate	$Na_2S_2O_3$	158.11			1.67				
137	Sulfur (rhombic)	S_8	256.53			2.07	386	10.0	717.76	84
138	Sulfur (monoclinic)	S_8	256.53			1.96	392	14.17	717.76	84
139	Sulfur chloride (mono)	S_2C_{12}	135.05			1.69	193.0		411.2	36.0
140	Sulfur dioxide	SO_2	64.07	430.7	77.8		197.68	7.402	263.14	24.92
141	Sulfur trioxide	SO_3	80.07	491.4	83.8		290.0	24.5	316.5	41.8
142	Sulfuric acid	H_2SO_4	98.08			1.83	283.51	9.87		
143	Toluene	$C_6H_5CH_3$	92.13	593.9	40.3	0.87	178.169	6.619	383.78	33.5
144	Water	H_2O	18.016	647.4	218.3	1.00	273.16	6.009	373.16	40.65
145	*m*-Xylene	C_8H_{10}	106.16	619	34.6	0.86	225.288	11.57	412.26	34.4
146	*o*-Xylene	C_8H_{10}	106.16	631.5	35.7	0.88	247.978	13.60	417.58	36.8
147	*p*-Xylene	C_8H_{10}	106.16	619	33.9	0.86	286.423	17.11	411.51	36.1
148	Zinc	Zn	65.38			7.14	692.7	6.673	1180	114.8
149	Zinc sulfate	$ZnSO_4$	161.44			3.74				

TABLE A.2

Heats of Formation and Combustion

No.	Compound	Formula	Molecular Weight	State	Δh_f^o KJ/mol	Δh_c^o KJ/mol
1	Acetic acid	CH_3COOH	60.05	l	−486.2	−871.69
				g		−919.73
2	Acetaldehyde	CH_3CHO	40.052	g	−166.4	−1192.36
3	Acetone	C_3H_6O	58.08	aq	−410.03	
				g	−216.69	−1821.38
4	Acetylene	C_2H_2	26.04	g	226.75	−1299.61
5	Ammonia	NH_3	17.032	l	−67.20	
				g	−46.191	−382.58
6	Ammonium carbonate	$(NH_4)_2CO_3$	96.09	c		
				aq	−941.86	
7	Ammonium chloride	NH_4Cl	53.50	c	−315.4	
8	Ammonium hydroxide	NH_4OH	35.05	aq	−366.5	
9	Ammonium nitrate	NH_4NO_3	80.05	c	−366.1	
				aq	−339.4	
10	Ammonium sulfate	$(NH_4)SO_4$	132.15	c	−1179.3	
				aq	−1173.1	
11	Benzaldehyde	C_6H_5CHO	106.12	l	−88.83	
				g	−40.0	
12	Benzene	C_6H_6	78.11	l	48.66	−3267.6
				g	82.927	−3301.5
13	Boron oxide	B_2O_3	69.64	c	−1263	
					−1245.2	
14	Bromine	Br_2	159.832	l	0	
				g	30.7	
15	*n*-Butane	C_4H_{10}	58.12	l	−147.6	−2855.6
				g	−124.73	−2878.52
16	Isobutane	C_4H_{10}	58.12	l	−158.5	−2849.0
				g	−134.5	−2868.8
17	1-Butene	C_4H_8	56.104	g	1.172	−2718.58
18	Calcium arsenate	$Ca_3(AsO_4)_2$	398.06	c	−3330.5	
19	Calcium carbide	CaC_2	64.10	c	−62.7	
20	Calcium carbonate	$CaCO_3$	100.09	c	−1206.9	
21	Calcium chloride	$CaCl_2$	110.99	c	−794.9	
22	Calcium cyanamide	$CaCN_2$	80.11	c	−352	
23	Calcium hydroxide	$Ca(OH)_2$	74.10	c	−986.56	
24	Calcium oxide	CaO	56.08	c	−635.6	
25	Calcium phosphate	$Ca_3(PO_4)_2$	310.19	c	−4137.6	
26	Calcium silicate	$CaSiO_3$	116.17	c	−1584	

(Continued)

TABLE A.2 (*Continued*)

Heats of Formation and Combustion

No.	Compound	Formula	Molecular Weight	State	Δh_f° KJ/mol	Δh_c° KJ/mol
27	Calcium sulfate	$CaSO_4$	136.15	c	–1432.7	
				aq	–1450.5	
28	Calcium sulfate (gypsum)	$CaSO_4 \cdot 2H_2O$	172.18	c	–2021.1	
29	Carbon	C	12.01	c	0	–393.51
30	Carbon dioxide	CO_2	44.01	g	–393.51	
				l	–412.92	
31	Carbon disulfide	CS_2	76.14	l	87.86	–1075.2
				g	115.3	–1102.6
32	Carbon monoxide	CO	28.01	g	–110.52	–282.99
33	Carbon tetrachloride	CCl_4	153.838	l	–139.5	–352.2
				g	–106.69	–384.9
34	Chloroethane	C_2H_5Cl	64.52	g	–105.0	–1421.1
				l	–41.20	–5215.44
35	Cumene (isopropylbenzene)	$C_6H_5CH(CH_3)_2$	120.19	g	3.93	–5260.59
				g	–769.86	
36	Cupric sulfate	$CuSO_4$	159.61	aq	–843.12	
				c	–751.4	
37	Cyclohexane	C_6H_{12}	84.16	g	–123.1	–3953.0
38	Cyclopentane	C_5H_{10}	70.130	l	–105.8	–3290.9
				g	–77.23	–3319.5
39	Ethane	C_2H_6	30.07	g	–84.667	–1559.9
40	Ethyl acetate	$CH_3CO_2C_2H_5$	88.10	l	–442.92	–2274.48
41	Ethyl alcohol	C_2H_5OH	46.068	l	–277.63	–1366.91
				g	–235.31	–1409.25
42	Ethyl benzene	$C_6H_5 \cdot C_2H_5$	106.16	l	–12.46	–4564.87
				g	29.79	–4607.13
43	Ethyl chloride	C_2H_5Cl	64.52	g	–105	
44	Ethylene	C_2H_4	28.052	g	52.283	–1410.99
45	Ethylene chloride	C_2H_3Cl	62.50	g	31.38	–1271.5
46	3-Ethyl hexane	C_8H_{18}	114.22	l	–250.5	–5470.12
				g	–210.9	–5509.78
47	Ferric chloride	$FeCl_3$		g	–403.34	
48	Ferric oxide	Fe_2O_3	159.70	g	–822.156	
49	Ferric sulfide	FeS_2	119.98	g	–177.9	
50	Ferrosoferric oxide	Fe_3O_4	231.55	c	–1116.7	
51	Ferrous chloride	$FeCl_2$		c	–342.67	–303.76

(Continued)

TABLE A.2 ***(Continued)***

Heats of Formation and Combustion

No.	Compound	Formula	Molecular Weight	State	Δh_f° KJ/mol	Δh_c° KJ/mol
52	Ferrous oxide	FeO	71.85	c	–267	
53	Ferrous sulfide	FeS	87.92	c	–95.06	
54	Formaldehyde	H_2CO	30.026	g	–115.89	–563.46
55	*n*-Heptane	C_7H_{16}	100.20	l	–224.4	–4816.91
				g	–187.8	–4853.48
56	*n*-Hexane	C_6H_{14}	86.17	l	–198.8	–4163.1
				g	–167.2	–4194.753
57	Hydrogen	H_2	2.016	g	0	–285.84
58	Hydrogen bromide	HBr	80.924	g	–36.23	
59	Hydrogen chloride	HCl	36.465	g	–92.311	
60	Hydrogen cyanide	HCN	27.026	g	130.54	
61	Hydrogen sulfide	H_2S	34.082	g	–20.15	–562.589
62	Iron sulfide	FeS_2	119.98	c	–177.9	
63	Lead oxide	PbO	223.21	c	–219.2	
64	Magnesium chloride	$MgCl_2$	95.23	c	–641.83	
65	Magnesium hydroxide	$Mg(OH)_2$	58.34	c	–924.66	
66	Magnesium oxide	MgO	40.32	c	–601.83	
67	Methane	CH_4	16.041	g	–74.84	–890.4
68	Methyl alcohol	CH_3OH	32.042	l	–238.64	–726.55
				g	–201.25	–763.96
69	Methyl chloride	CH_3Cl	50.49	g	–81.923	–766.63
70	Methyl cyclohexane	C_7H_{14}	98.182	l	–190.2	–4565.29
				g	–154.8	–4600.68
71	Methyl cyclopentane	C_6H_{12}	84.156	l	–138.4	–3937.7
				g	–106.7	–3969.4
72	Nitric acid	HNO_3	63.02	l	–173.23	
				aq	–206.57	
73	Nitric oxide	NO	30.01	g	90.374	
74	Nitrogen dioxide	NO_2	46.01	g	33.85	
75	Nitrous oxide	N_2O	44.02	g	81.55	
76	*n*-Pentane	C_5H_{12}	72.15	l	–173.1	–3509.5
				g	–146.4	–3536.15
77	Phosphoric acid	H_3PO_4	98.00	c	–1281	
				aq	–1278	
78	Phosphorus	P_4	123.90	c	0	
79	Phosphorus pentoxide	P_2O_5	141.95	c	–1506	

TABLE A.2 ***(Continued)***

Heats of Formation and Combustion

No.	Compound	Formula	Molecular Weight	State	Δ h_f^o KJ/mol	Δ h_c^o KJ/mol
80	Propane	C_3H_8	44.09	l	−119.84	−2204.0
				g	−103.85	−2220.0
81	Propene	C_3H_6	42.078	g	20.41	−2058.47
82	*n*-Propyl alcohol	C_3H_8O	60.09	g	−255	−2068.6
83	*n*-Propylbenzene	$C_6H_5{\cdot}CH_2{\cdot}C_2H_5$	120.19	l	−38.40	−5218.2
				g	7.824	−5264.5
84	Silicon dioxide	SiO_2	60.09	c	−851.0	
85	Sodium bicarbonate	$NaHCO_3$	84.01	c	−945.6	
86	Sodium bisulfate	$NaHSO_4$	120.07	c	−1126	
87	Sodium carbonate	Na_2CO_3	105.99	c	−1130	
88	Sodium chloride	$NaCl$	58.45	c	−411.00	
89	Sodium cyanide	$NaCN$	49.01	c	−89.79	
90	Sodium nitrate	$NaNO_3$	85.00	c	−466.68	
91	Sodium nitrite	$NaNO_2$	69.00	c	−359	
92	Sodium sulfate	Na_2SO_4	142.05	c	−1384.5	
93	Sodium sulfide	Na_2S	78.05	c	−373	
94	Sodium sulfite	Na_2SO_3	126.05	c	−1090	
95	Sodium thiosulfate	$Na_2S_2O_3$	158.11	c	−1117	
96	Sulfur	S	32.07	c	0	
97	Sulfur chloride	S_2Cl_2	135.05	l	−60.3	
98	Sulfur dioxide	SO_2	64.066	g	−296.90	
99	Sulfur trioxide	SO_3	80.066	g	−395.18	
100	Sulfuric acid	H_2SO_4	98.08	l	−811.32	
				aq	−907.51	
101	Toluene	$C_6H_5CH_3$	92.13	l	11.99	−3909.9
				g	50.000	−3947.9
102	Water	H_2O	18.016	l	−285.840	
				g	−241.826	
103	*m*-Xylene	$C_6H_4(CH_3)_2$	106.16	l	−25.42	−4551.86
				g	17.24	−4594.53
104	*o*-Xylene	$C_6H_4(CH_3)_2$	106.16	l	−24.44	−4552.86
				g	19.00	−4596.29
105	*p*-Xylene	$C_6H_4(CH_3)_2$	106.16	l	−24.43	−4552.86
				g	17.95	−4595.25
106	Zinc sulfate	$ZnSO_4$	161.45	c	−978.55	
				aq	−1059.93	

Note: Heats of formation and combustion of compounds at 25°C. Standard states of products for $\hat{H}_c^0$ are CO_2 (g), H_2O (l), N_2 (g), SO_2 (g), and HCl (aq).

Appendix A.2

Table A.3 contains heat capacity equations for organic and inorganic compounds as a function of temperature.

Forms	Heat Capacity
1.	C_p J/(mol)(K or °C) $= a + bT + cT^2 + dT^3$
2.	C_p J/(mol)(K or °C) $= a + bT + cT^{-2}$

TABLE A.3

Heat Capacity Equations for Organic and Inorganic Compounds (at Low Pressures)

No.	Compound	Formula	Mol. Wt.	State	Form	*T*	*a*	*b*	*c*	*d*	Temp. Range
1	Acetone	CH_3COCH_3	58.08	l	1	°C	123.0	0.186			–30 to 60
			58.08	g	1	°C	71.96	0.201	-1.278×10^{-4}	3.476×10^{-8}	0–1200
2	Acetylene	C_2H_2	26.04	g	1	°C	42.43	0.06053	-5.033×10^{-5}	1.820×10^{-8}	0–1200
3	Air		29.0	g	1	°C	28.94	0.004147	0.3191×10^{-5}	-1.965×10^{-9}	0–1500
				g	1	K	28.09	0.001965	0.4799×10^{-5}	-1.965×10^{-9}	273–1800
4	Ammonia	NH_3	17.03	g	1	°C	35.15	0.02954	0.4421×10^{-5}	-6.686×10^{-9}	0–1200
5	Ammonium sulfate	$(NH_4)_2SO_4$	132.15	c	1	K	215.9		0		275–328
6	Benzene	C_6H_6	78.11	l	1	°C	126.5	0.234			6–67
				g	1	°C	74.06	0.3295	-2.520×10^{-4}	7.757×10^{-8}	0–1200
7	Isobutane	C_4H_{10}	58.12	g	1	°C	89.46	0.3013	-1.891×10^{-4}	4.987×10^{-8}	0–1200
8	*n*-Butane	C_4H_{10}	58.12	g	1	°C	92.30	0.2788	-1.547×10^{-4}	3.498×10^{-8}	0–1200
9	Isobutene	C_4H_8	56.10	g	1	°C	82.88	0.2564	-1.727×10^{-4}	5.050×10^{-8}	0–1200
10	Calcium carbide	CaC_2	64.10	c	2	K	68.62	0.0119	-8.66×10^{-5}	—	298–720
11	Calcium carbonate	$CaCO_3$	100.09	c	2	K	82.34	0.04975	-1.287×10^{-4}	—	273–1033
12	Calcium hydroxide	$Ca(OH)_2$	74.10	c	1	K	89.5				276–373
13	Calcium oxide	CaO	56.08	c	2	K	41.84	0.0203	-4.52×10^{-5}		10273–1173
14	Carbon	C	12.01	c[a]	2	K	11.18	0.01095	-4.891×10^{-5}		273–1373
15	Carbon dioxide	CO_2	44.01	g	1	°C	36.11	0.04233	-2.887×10^{-5}	7.464×10^{-9}	0–1500
16	Carbon monoxide	CO	28.01	g	1	°C	28.95	0.00411	0.3548×10^{-5}	-2.220×10^{-9}	0–1500
17	Carbon tetrachloride	CCl_4	153.84	l	1	K	12.285	0.0001095	-3.1826×10^{-3}	3.4252×10^{-6}	273–343
18	Chlorine	Cl_2	70.91	g	1	°C	33.60	0.01367	-1.607×10^{-5}	6.473×10^{-9}	0–1200
19	Copper	Cu	63.54	c	1	K	22.76	0.0006117			273–1357
20	Cumene	C_9H_{12}	120.19	g	1	°C	139.2	0.5376	-3.979×10^{-4}	1.205×10^{-7}	0–1200

(Continued)

TABLE A.3 (*Continued*)

Heat Capacity Equations for Organic and Inorganic Compounds (at Low Pressures)

No.	Compound	Formula	Mol. Wt.	State	Form	*T*	*a*	*b*	*c*	*d*	Temp. Range
21	Cyclohexane	C_6H_{12}	84.16	g	1	°C	94.140	0.4962	-3.190×10^{-4}	8.063×10^{-8}	0–1200
22	Cyclopentane	C_5H_{10}	70.13	g	1	°C	73.39	0.3928	-2.554×10^{-4}	6.866×10^{-8}	0–1200
23	Ethane	C_2H_6	30.07	g	1	°C	49.37	0.1392	-5.816×10^{-5}	7.280×10^{-9}	0–1200
24	Ethyl alcohol	C_2H_6O	46.07	l	1	°C	158.8				100
				g	1	°C	61.34	0.1572	-8.749×10^{-5}	1.983×10^{-8}	0–1200
25	Ethylene	C_2H_4	28.05	g	1	°C	40.75	0.1147	-6.891×10^{-5}	1.766×10^{-8}	0–1200
26	Ethylbenzene	$C_2H_4Cl_2$	98.96	l	1	°C	182.0				
				g	1	°C	118	0.30			
27	Ethylene oxide	C_2H_4O	44.05	g	1	K	–4.69	0.206	-9.995×10^{-5}		
28	Ferric oxide	Fe_2O_3	159.70	g	2	K	103.4	0.06711	-17.72×10^{-5}	—	273–1097
29	Formaldehyde	CH_2O	30.03	g	1	°C	34.28	0.04268	0.0000	-8.694×10^{-9}	0–1200
30	Helium	He	4.00	g	1	°C	20.8				All
31	*n*-Hexane	C_6H_{14}	86.17	l	1	K	31.421	0.0097606	-2.3537×10^{-3}	3.0927×10^{-6}	273–400
				g	1	°C	137.44	0.4085	-2.392×10^{-4}	5.766×10^{-8}	0–1200
32	Hydrogen	H_2	2.016	g	1	°C	28.84	0.0000765	0.3288×10^{-5}	-0.8698×10^{-9}	0–1500
33	Hydrogen bromide	HBr	80.92	g	1	°C	29.10	–0.000227	0.9887×10^{-5}	-4.858×10^{-9}	0–1200
34	Hydrogen chloride	HCl	36.47	g	1	°C	29.13	–0.001341	0.9715×10^{-5}	-4.335×10^{-9}	0–1200
35	Hydrogen cyanide	HCN	27.03	g	1	°C	35.3	0.02908	1.092×10^{-5}		0–1200

36	Hydrogen sulfide	H_2S	34.08	g	1	°C	33.51	0.01547	0.3012×10^{-5}	-3.292×10^{-9}	0–1500
37	Magnesium chloride	$MgCl_2$	95.23	c	1	K	72.4	0.0158			273–991
38	Magnesium oxide	MgO	40.32	c	2	K	45.44	0.005008	-8.732×10^{-5}		273–2073
39	Methane	CH_4	16.04	g	1	°C	34.31	0.05469	0.3661×10^{-5}	-1.100×10^{-8}	0–1200
				g	1	K	19.87	0.05021	1.268×10^{-5}	-1.100×10^{-8}	273–1500
40	Methyl alcohol	CH_3OH	32.04	l	1	°C	75.86	0.1683			0–65
				g		°C	42.93	0.08301	-1.87×10^{-5}	-8.03×10^{-9}	0–700
41	Methyl cyclohexane	C_7H_{14}	98.18	g	1	°C	121.3	0.5653	-3.772×10^{-4}	1.008×10^{-7}	0–1200
42	Methyl cyclopentane	C_6H_{12}	84.16	g	1	°C	98.83	0.45857	-3.044×10^{-4}	8.381×10^{-8}	0–1200
43	Nitric acid	HNO_3	63.02	l	1	°C	110.0				25
44	Nitric oxide	NO	30.01	g	1	°C	29.50	0.008188	-0.2925×10^{-5}	0.3652×10^{-9}	0–3500
45	Nitrogen	N_2	28.02	g	1	°C	29.00	0.002199	0.5723×10^{-5}	-2.871×10^{-9}	0–1500
46	Nitrogen dioxide	NO_2	46.01	g	1	°C	36.07	0.0397	-2.88×10^{-5}	7.87×10^{-9}	0–1200
47	Nitrogen tetraoxide	N_2O_4	92.02	g	1	°C	75.7	0.125	-1.13×10^{-4}		0–300
48	Nitrous oxide	N_2O	44.02	g	1	°C	37.66	0.04151	-2.694×10^{-5}	1.057×10^{-8}	0–1200
49	Oxygen	O_2	32.00	g	1	°C	29.10	0.01158	-0.6076×10^{-5}	1.311×10^{-9}	0–1500
50	*n*-Pentane	C_5H_{12}	72.15	l	1	K	33.24	1.9241	-2.3687×10^{-3}	1.7944×10^{-5}	270–350
				g	1	°C	114.8	0.3409	-1.899×10^{-4}	4.226×10^{-8}	0–1200
51	Propane	C_3H_8	44.09	g	1	°C	68.032	0.2259	-1.311×10^{-4}	3.171×10^{-8}	0–1200
52	Propylene	C_3H_6	42.08	g	1	°C	59.580	0.1771	-1.017×10^{-4}	2.460×10^{-8}	0–1200
53	Sodium carbonate	Na_2CO_3	105.99	c	1	K	121				288–371

(Continued)

TABLE A.3 (*Continued*)

Heat Capacity Equations for Organic and Inorganic Compounds (at Low Pressures)

No.	Compound	Formula	Mol. Wt.	State	Form	*T*	*a*	*b*	*c*	*d*	Temp. Range
54	Sodium carbonate	$Na_2CO_3 \cdot 10H_2O$	286.15	c	1	K	535.6				298
55	Styrene	C_8H_8	104.2	l	1	°C	209.0				
				g		°C	115.0	0.270			
56	Sulfur	S	32.07	c[b]	1	K	15.2	0.0268			273–368
				c[c]	1	K	18.5	0.0184			368–392
57	Sulfuric acid	H_2SO_4	98.08	l	1	°C	139.1	0.1559			10–45
58	Sulfur dioxide	SO_2	64.07	g	1	°C	38.91	0.03904	-3.104×10^{-5}	8.606×10^{-9}	0–1500
59	Sulfur trioxide	SO_3	80.07	g	1	°C	48.50	0.09188	-8.540×10^{-5}	3.240×10^{-8}	0–1000
60	Toluene	C_7H_8	92.13	l	1	K	1.8083	0.81222	-151.27×10^{-5}	1.630×10^{-6}	270–370
				g	1	°C	94.18	0.3800	-27.86×10^{-5}	8.033×10^{-8}	0–1200
61	Water	H_2O	18.016	l	1	K	18.2964	0.47212	-133.88×10^{-5}	1.3142×10^{-6}	273–373
				g	1	°C	33.46	0.00688	0.7604×10^{-5}	-3.593×10^{-9}	0–1500

[a] Graphite.

[b] Rhombic.

[c] Monoclinic (at 1 atm).

Appendix A.3: Steam Table

Table A.4 contains properties of saturated steam, specific volume, specific internal energy, and specific enthalpy. Table A.5 contains properties of superheated steam.

TABLE A.4

Properties of Saturated Steam

		v (m^3/kg)		u (kJ/kg)		h (kJ/kg)		
P (bar)	T (°C)	Water, v_f	Steam, v_g	Water, u_f	Steam, u_g	Water, h_f	Evap. h_{fg}	Steam, h_g
0.00611	0.01	0.001000	206.2	0.0	2375.6	0.0	2501.6	2501.6
0.008	3.8	0.001000	159.7	15.8	2380.7	15.8	2492.6	2508.5
0.010	7.0	0.001000	129.2	29.3	2385.2	29.3	2485.0	2514.4
0.012	9.7	0.001000	108.7	40.6	2388.9	40.6	2478.7	2519.3
0.014	12.0	0.001000	93.9	50.3	2392.0	50.3	2473.2	2523.5
0.016	14.0	0.001001	82.8	58.9	2394.8	58.9	2468.4	2527.3
0.018	15.9	0.001001	74.0	66.5	2397.4	66.5	2464.1	2530.6
0.020	17.5	0.001001	67.0	73.5	2399.6	73.5	2460.2	2533.6
0.022	19.0	0.001002	61.2	79.8	2401.7	79.8	2456.6	2536.4
0.024	20.4	0.001002	56.4	85.7	2403.6	85.7	2453.3	2539.0
0.026	21.7	0.001002	52.3	91.1	2405.4	91.1	2450.2	2541.3
0.028	23.0	0.001002	48.7	96.2	2407.1	96.2	2447.3	2543.6
0.030	24.1	0.001003	45.7	101.0	2408.6	101.0	2444.6	2545.6
0.035	26.7	0.001003	39.5	111.8	2412.2	111.8	2438.5	2550.4
0.040	29.0	0.001004	34.8	121.4	2415.3	121.4	2433.1	2554.5
0.045	31.0	0.001005	31.1	130.0	2418.1	130.0	2428.2	2558.2
0.050	32.9	0.001005	28.2	137.8	2420.6	137.8	2423.8	2561.6
0.060	36.2	0.001006	23.74	151.5	2425.1	151.5	2416.0	2567.5
0.070	39.0	0.001007	20.53	163.4	2428.9	163.4	2409.2	2572.6
0.080	41.5	0.001008	18.10	173.9	2432.3	173.9	2403.2	2577.1

0.090	43.8	0.001009	16.20	183.3	2435.3	183.3	2397.9	2581.1
0.10	45.8	0.001010	14.67	191.8	2438.0	191.8	2392.9	2584.8
0.11	47.7	0.001011	13.42	199.7	2440.5	199.7	2388.4	2588.1
0.12	49.4	0.001012	12.36	206.9	2442.8	206.9	2384.3	2591.2
0.13	51.1	0.001013	11.47	213.7	2445.0	213.7	2380.4	2594.0
0.14	52.6	0.001013	10.69	220.0	2447.0	220.0	2376.7	2596.7
0.15	54.0	0.001014	10.02	226.0	2448.9	226.0	2373.2	2599.2
0.16	55.3	0.001015	9.43	231.6	2450.6	231.6	2370.0	2601.6
0.17	56.6	0.001015	8.91	236.9	2452.3	236.9	2366.9	2603.8
0.18	57.8	0.001016	8.45	242.0	2453.9	242.0	2363.9	2605.9
0.19	59.0	0.001017	8.03	246.8	2455.4	246.8	2361.1	2607.9
0.20	60.1	0.001017	7.65	251.5	2456.9	251.5	2358.4	2609.9
0.22	62.2	0.001018	7.00	260.1	2459.6	260.1	2353.3	2613.5
0.24	64.1	0.001019	6.45	268.2	2462.1	268.2	2348.6	2616.8
0.26	65.9	0.001020	5.98	275.6	2464.4	275.7	2344.2	2619.9
0.28	67.5	0.001021	5.58	282.7	2466.5	282.7	2340.0	2622.7
0.30	69.1	0.001022	5.23	289.3	2468.6	289.3	2336.1	2625.4
0.35	72.7	0.001025	4.53	304.3	2473.1	304.3	2327.2	2631.5
0.40	75.9	0.001027	3.99	317.6	2477.1	317.7	2319.2	2636.9
0.45	78.7	0.001028	3.58	329.6	2480.7	329.6	2312.0	2641.7
0.50	81.3	0.001030	3.24	340.5	2484.0	340.6	2305.4	2646.0
0.55	83.7	0.001032	2.96	350.6	2486.9	350.6	2299.3	2649.9
0.60	86.0	0.001033	2.73	359.9	2489.7	359.9	2293.6	2653.6
0.65	88.0	0.001035	2.53	368.5	2492.2	368.6	2288.3	2656.9
0.70	90.0	0.001036	2.36	376.7	2494.5	376.8	2283.3	2660.1
0.75	91.8	0.001037	2.22	384.4	2496.7	384.5	2278.6	2663.0
0.80	93.5	0.001039	2.087	391.6	2498.8	391.7	2274.1	2665.8

(Continued)

TABLE A.4

Properties of Saturated Steam

		v (m³/kg)		u (kJ/kg)		h (kJ/kg)		
P (bar)	T (°C)	Water, v_f	Steam, v_g	Water, u_f	Steam, u_g	Water, h_f	Evap. h_{fg}	Steam, h_g
0.00611	0.01	0.001000	206.2	0.0	2375.6	0.0	2501.6	2501.6
0.008	3.8	0.001000	159.7	15.8	2380.7	15.8	2492.6	2508.5
0.010	7.0	0.001000	129.2	29.3	2385.2	29.3	2485.0	2514.4
0.012	9.7	0.001000	108.7	40.6	2388.9	40.6	2478.7	2519.3
0.014	12.0	0.001000	93.9	50.3	2392.0	50.3	2473.2	2523.5
0.016	14.0	0.001001	82.8	58.9	2394.8	58.9	2468.4	2527.3
0.018	15.9	0.001001	74.0	66.5	2397.4	66.5	2464.1	2530.6
0.020	17.5	0.001001	67.0	73.5	2399.6	73.5	2460.2	2533.6
0.022	19.0	0.001002	61.2	79.8	2401.7	79.8	2456.6	2536.4
0.024	20.4	0.001002	56.4	85.7	2403.6	85.7	2453.3	2539.0
0.026	21.7	0.001002	52.3	91.1	2405.4	91.1	2450.2	2541.3
0.028	23.0	0.001002	48.7	96.2	2407.1	96.2	2447.3	2543.6
0.030	24.1	0.001003	45.7	101.0	2408.6	101.0	2444.6	2545.6
0.035	26.7	0.001003	39.5	111.8	2412.2	111.8	2438.5	2550.4
0.040	29.0	0.001004	34.8	121.4	2415.3	121.4	2433.1	2554.5
0.045	31.0	0.001005	31.1	130.0	2418.1	130.0	2428.2	2558.2
0.050	32.9	0.001005	28.2	137.8	2420.6	137.8	2423.8	2561.6
0.060	36.2	0.001006	23.74	151.5	2425.1	151.5	2416.0	2567.5
0.070	39.0	0.001007	20.53	163.4	2428.9	163.4	2409.2	2572.6
0.080	41.5	0.001008	18.10	173.9	2432.3	173.9	2403.2	2577.1

TABLE A.4 ***(Continued)***

Properties of Saturated Steam

		v (m³/kg)		u (kJ/kg)		h (kJ/kg)		
P (bar)	T (°C)	Water, v_f	Steam, v_g	Water, u_f	Steam, u_g	Water, h_f	Evap. h_{fg}	Steam, h_g
0.85	95.2	0.001040	1.972	398.5	2500.8	398.6	2269.8	2668.4
0.90	96.7	0.001041	1.869	405.1	2502.6	405.2	2265.6	2670.9
0.95	98.2	0.001042	1.777	411.4	2504.4	411.5	2261.7	2673.2
1.00	99.6	0.001043	1.694	417.4	2506.1	417.5	2257.9	2675.4
1.01325	100.0	0.001044	1.673	419.0	2506.5	419.1	2256.9	2676.0
1.1	102.3	0.001046	1.549	428.7	2509.2	428.8	2250.8	2679.6
1.2	104.8	0.001048	1.428	439.2	2512.1	439.4	2244.1	2683.4
1.3	107.1	0.001049	1.325	449.1	2514.7	449.2	2237.8	2687.0
1.4	109.3	0.001051	1.236	458.3	2517.2	458.4	2231.9	2690.3
1.5	111.4	0.001053	1.159	467.0	2519.5	467.1	2226.2	2693.4
1.6	113.3	0.001055	1.091	475.2	2521.7	475.4	2220.9	2696.2
1.7	115.2	0.001056	1.031	483.0	2523.7	483.2	2215.7	2699.0
1.8	116.9	0.001058	0.977	490.5	2525.6	490.7	2210.8	2701.5
1.9	118.6	0.001059	0.929	497.6	2527.5	497.8	2206.1	2704.0
2.0	120.2	0.001061	0.885	504.5	2529.2	504.7	2201.6	2706.3
2.2	123.3	0.001064	0.810	517.4	2532.4	517.6	2193.0	2710.6
2.4	126.1	0.001066	0.746	529.4	2535.4	529.6	2184.9	2714.5
2.6	128.7	0.001069	0.693	540.6	2538.1	540.9	2177.3	2718.2
2.8	131.2	0.001071	0.646	551.1	2540.6	551.4	2170.1	2721.5
3.0	133.5	0.001074	0.606	561.1	2543.0	561.4	2163.2	2724.7
3.2	135.8	0.001076	0.570	570.6	2545.2	570.9	2156.7	2727.6
3.4	137.9	0.001078	0.538	579.6	2547.2	579.9	2150.4	2730.3
3.6	139.9	0.001080	0.510	588.1	2549.2	588.5	2144.4	2732.9
3.8	141.8	0.001082	0.485	596.4	2551.0	596.8	2138.6	2735.3
4.0	143.6	0.001084	0.462	604.2	2552.7	604.7	2133.0	2737.6
4.2	145.4	0.001086	0.442	611.8	2554.4	612.3	2127.5	2739.8
4.4	147.1	0.001088	0.423	619.1	2555.9	619.6	2122.3	2741.9
4.6	148.7	0.001089	0.405	626.2	2557.4	626.7	2117.2	2743.9
4.8	150.3	0.001091	0.389	633.0	2558.8	633.5	2112.2	2745.7
5.0	151.8	0.001093	0.375	639.6	2560.2	640.1	2107.4	2747.5
5.5	155.5	0.001097	0.342	655.2	2563.3	655.8	2095.9	2751.7
6.0	158.8	0.001101	0.315	669.8	2566.2	670.4	2085.0	2755.5
6.5	162.0	0.001105	0.292	683.4	2568.7	684.1	2074.7	2758.9
7.0	165.0	0.001108	0.273	696.3	2571.1	697.1	2064.9	2762.0
7.5	167.8	0.001112	0.2554	708.5	2573.3	709.3	2055.5	2764.8
8.0	170.4	0.001115	0.2403	720.0	2575.5	720.9	2046.5	2767.5
8.5	172.9	0.001118	0.2268	731.1	2577.1	732.0	2037.9	2769.9
9.0	175.4	0.001121	0.2148	741.6	2578.8	742.6	2029.5	2772.1
9.5	177.7	0.001124	0.2040	751.8	2580.4	752.8	2021.4	2774.2
10	179.9	0.001127	0.1943	761.5	2581.9	762.6	2013.6	2776.2
11	184.1	0.001133	0.1774	779.9	2584.5	781.1	1998.5	2779.7
12	188.0	0.001139	0.1632	797.1	2586.9	798.4	1984.3	2782.7
13	191.6	0.001144	0.1511	813.2	2589.0	814.7	1970.7	2785.4
14	195.0	0.001149	0.1407	828.5	2590.8	830.1	1957.7	2787.8
15	198.3	0.001154	0.1317	842.9	2592.4	844.7	1945.2	2789.9
16	201.4	0.001159	0.1237	856.7	2593.8	858.6	1933.2	2791.7
17	204.3	0.001163	0.1166	869.9	2595.1	871.8	1921.5	2793.4
18	207.1	0.001168	0.1103	882.5	2596.3	884.6	1910.3	2794.8
19	209.8	0.001172	0.1047	894.6	2597.3	896.8	1899.3	2796.1
20	212.4	0.001177	0.0995	906.2	2598.2	908.6	1888.6	2797.2

(Continued)

TABLE A.4 ***(Continued)***

Properties of Saturated Steam

		v (m^3/kg)		u (kJ/kg)		h (kJ/kg)		
P (bar)	T (°C)	Water, v_f	Steam, v_g	Water, u_f	Steam, u_g	Water, h_f	Evap. h_{fg}	Steam, h_g
21	214.9	0.001181	0.0949	917.5	2598.9	920.0	1878.2	2798.2
22	217.2	0.001185	0.0907	928.3	2599.6	931.0	1868.1	2799.1
23	219.6	0.001189	0.0868	938.9	2600.2	941.6	1858.2	2799.8
24	221.8	0.001193	0.0832	949.1	2600.7	951.9	1848.5	2800.4
25	223.9	0.001197	0.0799	959.0	2601.2	962.0	1839.0	2800.9
26	226.0	0.001201	0.0769	968.6	2601.5	971.7	1829.6	2801.4
27	228.1	0.001205	0.0740	978.0	2601.8	981.2	1820.5	2801.7
28	230.0	0.001209	0.0714	987.1	2602.1	990.5	1811.5	2802.0
29	232.0	0.001213	0.0689	996.0	2602.3	999.5	1802.6	2802.2
30	233.8	0.001216	0.0666	1004.7	2602.4	1008.4	1793.9	2802.3
32	237.4	0.001224	0.0624	1021.5	2602.5	1025.4	1776.9	2802.3
34	240.9	0.001231	0.0587	1037.6	2602.5	1041.8	1760.3	2802.1
36	244.2	0.001238	0.0554	1053.1	2602.2	1057.6	1744.2	2801.7
38	247.3	0.001245	0.0524	1068.0	2601.9	1072.7	1728.4	2801.1
40	250.3	0.001252	0.0497	1082.4	2601.3	1087.4	1712.9	2800.3
42	253.2	0.001259	0.0473	1096.3	2600.7	1101.6	1697.8	2799.4
44	256.0	0.001266	0.0451	1109.8	2599.9	1115.4	1682.9	2798.3
46	258.8	0.001272	0.0430	1122.9	2599.1	1128.8	1668.3	2797.1
48	261.4	0.001279	0.0412	1135.6	2598.1	1141.8	1653.9	2795.7
50	263.9	0.001286	0.0394	1148.0	2597.0	1154.5	1639.7	2794.2
52	266.4	0.001292	0.0378	1160.1	2595.9	1166.8	1625.7	2792.6
54	268.8	0.001299	0.0363	1171.9	2594.6	1178.9	1611.9	2790.8
56	271.1	0.001306	0.0349	1183.5	2593.3	1190.8	1598.2	2789.0
58	273.3	0.001312	0.0337	1194.7	2591.9	1202.3	1584.7	2787.0
60	275.6	0.001319	0.0324	1205.8	2590.4	1213.7	1571.3	2785.0
62	277.7	0.001325	0.0313	1216.6	2588.8	1224.8	1558.0	2782.9
64	279.8	0.001332	0.0302	1227.2	2587.2	1235.7	1544.9	2780.6
66	281.8	0.001338	0.0292	1237.6	2585.5	1246.5	1531.9	2778.3
68	283.8	0.001345	0.0283	1247.9	2583.7	1257.0	1518.9	2775.9
70	285.8	0.001351	0.0274	1258.0	2581.8	1267.4	1506.0	2773.5
72	287.7	0.001358	0.0265	1267.9	2579.9	1277.6	1493.3	2770.9
74	289.6	0.001364	0.0257	1277.6	2578.0	1287.7	1480.5	2768.3
76	291.4	0.001371	0.0249	1287.2	2575.9	1297.6	1467.9	2765.5
78	293.2	0.001378	0.0242	1296.7	2573.8	1307.4	1455.3	2762.8
80	295.0	0.001384	0.0235	1306.0	2571.7	1317.1	1442.8	2759.9
82	296.7	0.001391	0.0229	1315.2	2569.5	1326.6	1430.3	2757.0
84	298.4	0.001398	0.0222	1324.3	2567.2	1336.1	1417.9	2754.0
86	300.1	0.001404	0.0216	1333.3	2564.9	1345.4	1405.5	2750.9
88	301.7	0.001411	0.0210	1342.2	2562.6	1354.6	1393.2	2747.8
90	303.3	0.001418	0.02050	1351.0	2560.1	1363.7	1380.9	2744.6
92	304.9	0.001425	0.01996	1359.7	2557.7	1372.8	1368.6	2741.4
94	306.4	0.001432	0.01945	1368.2	2555.2	1381.7	1356.3	2738.0
96	308.0	0.001439	0.01897	1376.7	2552.6	1390.6	1344.1	2734.7
98	309.5	0.001446	0.01849	1385.2	2550.0	1399.3	1331.9	2731.2
100	311.0	0.001453	0.01804	1393.5	2547.3	1408.0	1319.7	2727.7
105	314.6	0.001470	0.01698	1414.1	2540.4	1429.5	1289.2	2718.7
110	318.0	0.001489	0.01601	1434.2	2533.2	1450.6	1258.7	2709.3
115	321.4	0.001507	0.01511	1454.0	2525.7	1471.3	1228.2	2699.5
120	324.6	0.001527	0.01428	1473.4	2517.8	1491.8	1197.4	2689.2
125	327.8	0.001547	0.01351	1492.7	2509.4	1512.0	1166.4	2678.4

(Continued)

TABLE A.4 (*Continued*)

Properties of Saturated Steam

		v (m³/kg)		u (kJ/kg)		h (kJ/kg)		
P (bar)	T (°C)	Water, v_f	Steam, v_g	Water, u_f	Steam, u_g	Water, h_f	Evap. h_{fg}	Steam, h_g
130	330.8	0.001567	0.01280	1511.6	2500.6	1532.0	1135.0	2667.0
135	333.8	0.001588	0.01213	1530.4	2491.3	1551.9	1103.1	2655.0
140	336.6	0.001611	0.01150	1549.1	2481.4	1571.6	1070.7	2642.4
145	339.4	0.001634	0.01090	1567.5	2471.0	1591.3	1037.7	2629.1
150	342.1	0.001658	0.01034	1586.1	2459.9	1611.0	1004.0	2615.0
155	344.8	0.001683	0.00981	1604.6	2448.2	1630.7	969.6	2600.3
160	347.3	0.001710	0.00931	1623.2	2436.0	1650.5	934.3	2584.9
165	349.8	0.001739	0.00883	1641.8	2423.1	1670.5	898.3	2568.8
170	352.3	0.001770	0.00837	1661.6	2409.3	1691.7	859.9	2551.6
175	354.6	0.001803	0.00793	1681.8	2394.6	1713.3	820.0	2533.3
180	357.0	0.001840	0.00750	1701.7	2378.9	1734.8	779.1	2513.9
185	359.2	0.001881	0.00708	1721.7	2362.1	1756.5	736.6	2493.1
190	361.4	0.001926	0.00668	1742.1	2343.8	1778.7	692.0	2470.6
195	363.6	0.001977	0.00628	1763.2	2323.6	1801.8	644.2	2446.0
200	365.7	0.00204	0.00588	1785.7	2300.8	1826.5	591.9	2418.4
205	367.8	0.00211	0.00546	1810.7	2274.4	1853.9	532.5	2386.4
210	369.8	0.00220	0.00502	1840.0	2242.1	1886.3	461.3	2347.6
215	371.8	0.00234	0.00451	1878.6	2198.1	1928.9	366.2	2295.2
220	373.7	0.00267	0.00373	1952	2114	2011	185	2196
221.2	374.15	0.00317	0.00317	2038	2038	2108	0	2108

TABLE A.5

Properties of Superheated Steam

P (bar) (T_{sat} °C)		Saturated Water	Saturated Steam	Temperature (°C)							
				50	75	100	150	200	250	300	350
0.0	h	—	—	2595	2642	2689	2784	2880	2978	3077	3177
(—)	u	—	—	2446	2481	2517	2589	2662	2736	2812	2890
	v	—	—	—	—	—	—	—	—	—	—
0.1	h	191.8	2584.8	2593	2640	2688	2783	2880	2977	3077	3177
(45.8)	u	191.8	2438.0	2444	2480	2516	2588	2661	2736	2812	2890
	v	0.00101	14.7	14.8	16.0	17.2	9.5	21.8	24.2	26.5	28.7
0.5	h	340.6	2646.0	209.3	313.9	2683	2780	2878	2979	3076	3177
(81.3)	u	340.6	2484.0	209.2	313.9	2512	2586	2660	2735	2811	2889
	v	0.00103	3.24	0.00101	0.00103	3.41	3.89	4.35	4.83	5.29	5.75
1.0	h	417.5	2675.4	209.3	314.0	2676	2776	2875	2975	3074	3176
(99.6)	u	417.5	2506.1	209.2	313.9	2507	2583	2658	2734	2811	2889
	v	0.00104	1.69	0.00101	0.00103	1.69	1.94	2.17	2.40	2.64	2.87
5.0	h	640.1	2747.5	209.7	314.3	419.4	632.2	2855	2961	3065	3168
(151.8)	u	639.6	2560.2	209.2	313.8	418.8	631.6	2643	2724	2803	2883
	v	0.00109	0.375	0.00101	0.00103	0.00104	0.00109	0.425	0.474	0.522	0.571
10	h	762.6	2776.2	210.1	314.7	419.7	632.5	2827	2943	3052	3159
(179.9)	u	761.5	2582	209.1	313.7	418.7	631.4	2621	2710	2794	2876
	v	0.00113	0.194	0.00101	0.00103	0.00104	0.00109	0.206	0.233	0.258	0.282
20	h	908.6	2797.2	211.0	315.5	420.5	633.1	852.6	2902	3025	3139
(212.4)	u	906.2	2598.2	209.0	313.5	418.4	603.9	850.2	2679	2774	2862
	v	0.00118	0.09950	0.00101	0.00102	0.00104	0.00109	0.00116	0.111	0.125	0.139

(Continued)

TABLE A.5 (*Continued*)

Properties of Superheated Steam

P (bar) (T_{sat} °C)		Saturated Water	Saturated Steam	Temperature (°C)							
				50	75	100	150	200	250	300	350
40	*h*	1087.4	2800.3	212.7	317.1	422.0	634.3	853.4	1085.8	2962	3095
(250.3)	*u*	1082.4	2601.3	208.6	313.0	417.8	630.0	848.8	1080.8	2727	2829
	v	0.00125	0.04975	0.00101	0.00102	0.00104	0.00109	0.00115	0.00125	0.0588	0.0665
60	*h*	1213.7	2785.0	214.4	318.7	423.5	635.6	854.2	1085.8	2885	3046
(275.6)	*u*	1205.8	2590.4	208.3	312.6	417.3	629.1	847.3	1078.3	2668	2792
	v	0.00132	0.0325	0.00101	0.00103	0.00104	0.00109	0.00115	0.00125	0.0361	0.0422
80	*h*	1317.1	2759.9	216.1	320.3	425.0	636.8	855.1	1085.8	2787	2990
(295.0)	*u*	1306.0	2571.7	208.1	312.3	416.7	628.2	845.9	1075.8	2593	2750
	v	0.00139	0.0235	0.00101	0.00102	0.00104	0.00109	0.00115	0.00124	0.0243	0.0299
100	*h*	1408.0	2727.7	217.8	322.9	426.5	638.1	855.9	1085.8	1343.4	2926
(311.0)	*u*	1393.5	2547.3	207.8	311.7	416.1	627.3	844.4	1073.4	1329.4	2702
	v	0.00145	0.0181	0.00101	0.00102	0.001049	0.00109	0.00115	0.00124	0.00140	0.0224
150	*h*	1611.0	2615.0	222.1	326.0	430.3	641.3	858.1	1086.2	1338.2	2695
(342.1)	*u*	1586.1	2459.9	207.0	310.7	414.7	625.0	841.0	1067.7	1317.6	2523
	v	0.00166	0.0103	0.00101	0.00102	0.00104	0.00108	0.00114	0.00123	0.00138	0.0115
200	*h*	1826.5	2418.4	226.4	330.0	434.0	644.5	860.4	1086.7	1334.3	1647.1
(365.7)	*u*	1785.7	2300.8	206.3	309.7	413.2	622.9	837.7	1062.2	1307.1	1613.7
	v	0.00204	0.005875	0.00100	0.00102	0.00103	0.00108	0.00114	0.00122	0.00136	0.00167
221.2(Pc)	*h*	2108	2108	228.2	331.7	435.7	645.8	861.4	1087.0	1332.8	1635.5
(374.15)(Tc)	*u*	2037.8	2037.8	206.0	309.2	412.8	622.0	836.3	1060.0	1302.9	1600.3
	v	0.00317	0.00317	0.00100	0.00102	0.00103	0.00108	0.00114	0.00122	0.00135	0.00163
250	*h*	—	—	230.7	334.0	437.8	647.7	862.8	1087.5	1331.1	1625.0
(—)	*u*	—	—	205.7	308.7	412.1	620.8	834.4	1057.0	1297.5	1585.0
	v	—	—	0.00100	0.00101	0.00103	0.00108	0.00113	0.00122	0.00135	0.00160
300	*h*	—	—	235.0	338.1	441.6	650.9	865.2	1088.4	1328.7	1609.9
(—)	*u*	—	—	205.0	307.7	410.8	618.7	831.3	1052.1	1288.7	1563.3
	v	—	—	0.0009990	0.00101	0.00103	0.00107	0.00113	0.00121	0.00133	0.00155
500	*h*	—	—	251.9	354.2	456.8	664.1	875.4	1093.6	1323.7	1576.3
(—)	*u*	—	—	202.4	304.0	405.8	611.0	819.7	1034.3	1259.3	1504.1
	v	—	—	0.0009911	0.00100	0.00102	0.00106	0.00111	0.00119	0.00129	0.00144
1000	*h*	—	—	293.9	394.3	495.1	698.0	903.5	1113.0	1328.7	1550.5
(—)	*u*	—	—	196.5	295.7	395.1	594.4	795.3	999.0	1207.1	1419.0
	v	—	—	0.0009737	0.0009852	0.00100	0.00104	0.00108	0.00114	0.00122	0.00131

P (bar) (T_{sat} °C)		Saturated Water	Saturated Steam	Temperature (°C)							
				400	450	500	550	600	650	700	750
0.0	*h*	—	—	3280	3384	3497	3597	3706	3816	3929	4043
	u	—	—	2969	3050	3132	3217	3303	3390	3480	3591
	v	—	—	—	—	—	—	—	—	—	—
0.1	*h*	191.8	2584.8	3280	3384	3489	3596	3706	3816	3929	4043
(45.8)	*u*	191.8	2438.0	2969	3050	3132	3217	3303	3390	3480	3571
	v	0.00101	14.7	21.1	33.3	35.7	38.0	40.3	42.6	44.8	47.2
0.5	*h*	340.6	2646.0	3279	3383	3489	3596	3705	3816	3929	4043
(81.3)	*u*	340.6	2484.0	2969	3049	3132	3216	3302	3390	3480	3571
	v	0.00103	3.24	6.21	6.67	7.14	7.58	8.06	8.55	9.01	9.43
1.0	*h*	417.5	2675.4	3278	3382	3488	3596	3705	3816	3928	4042
(99.6)	*u*	417.5	2506.1	2968	3049	3132	3216	3302	3390	3479	3570
	v	0.00104	1.69	3.11	3.33	3.57	3.80	4.03	4.26	4.48	4.72

(Continued)

TABLE A.5 (*Continued*)

Properties of Superheated Steam

P (bar) (T_{sat} °C)		Saturated Steam	Saturated Steam	Temperature (°C)							
				400	450	500	550	600	650	700	750
5.0	*h*	640.1	2747.5	3272	3379	3484	3592	3702	3813	3926	4040
(151.8)	*u*	639.6	2560.2	2964	3045	3128	3213	3300	3388	3477	3569
	v	0.00109	0.375	0.617	0.664	0.711	0.758	0.804	0.850	0.897	0.943
10	*h*	762.6	2776.2	3264	3371	3478	3587	3697	3809	3923	4038
(179.9)	*u*	761.5	2582	2958	3041	3124	3210	3296	3385	3475	3567
	v	0.00113	0.194	0.307	0.330	0.353	0.377	0.402	0.424	0.448	0.472
20	*h*	908.6	2797.2	3249	3358	3467	3578	3689	3802	3916	4032
(212.4)	*u*	906.2	2598.2	2946	3031	3115	3202	3290	3379	3470	3562
	v	0.00118	0.09950	0.151	0.163	0.175	0.188	0.200	0.211	0.223	0.235
40	*h*	1087.4	2800.3	3216	3331	3445	3559	3673	3788	3904	4021
(250.3)	*u*	1082.4	2601.3	2922	3011	3100	3188	3278	3368	3460	3554
	v	0.00125	0.04975	0.0734	0.0799	0.0864	0.0926	0.0987	0.105	0.111	0.117
60	*h*	1213.7	2785.0	3180	3303	3422	3539	3657	3774	3892	4011
(275.6)	*u*	1205.8	2590.4	2896	2991	3083	3174	3265	3357	3451	3545
	v	0.00132	0.0325	0.0474	0.0521	0.0566	0.0609	0.0652	0.0693	0.0735	0.0776
80	*h*	1317.1	2759.9	3142	3274	3399	3520	3640	3759	3879	4000
(295.0)	*u*	1306.0	2571.7	2867	2969	3065	3159	3252	3346	3441	3537
	v	0.00139	0.0235	0.0344	0.0382	0.0417	0.0450	0.0483	0.0515	0.0547	0.0578
100	*h*	1408.0	2727.7	3100	3244	3375	3500	3623	3745	3867	3989
(311.0)	*u*	1393.5	2547.3	2836	2946	3047	3144	3240	3335	3431	3528
	v	0.00145	0.0181	0.0264	0.0298	0.0328	0.0356	0.0383	0.0410	0.0435	0.0461
150	*h*	1611.0	2615.0	2975	3160	3311	3448	3580	3708	3835	4962
(342.1)	*u*	1586.1	2459.9	2744	2883	2999	3105	3207	3307	3407	3507
	v	0.00166	0.0103	0.0157	0.0185	0.0208	0.0229	0.0249	0.0267	0.6286	0.0304
200	*h*	1826.5	2418.4	2820	3064	3241	3394	3536	3671	3804	3935
(365.7)	*u*	1785.7	2300.8	2622	2810	2946	3063	3172	3278	3382	3485
	v	0.00204	0.005875	0.009950	0.0127	0.0148	0.0166	0.0182	0.0197	0.0211	0.0225
221.2(Pc)	*h*	2108	2108	2733	3020	3210	3370	3516	3655	3790	3923
(374.15)(Tc)	*u*	2037.8	2037.8	2553	2776	2922	3045	3157	3265	3371	3476
	v	0.00317	0.00317	0.008157	0.0110	0.0130	0.0147	0.0162	0.0176	0.0190	0.0202
250	*h*	—	—	2582	2954	3166	3337	3490	3633	3772	3908
(—)	*u*	—	—	2432	2725	2888	3019	3137	3248	3356	3463
	v	—	—	0.006013	0.009174	0.0111	0.0127	0.0141	0.0143	0.0166	0.0178
300	*h*	—	—	2162	2826	3085	3277	3443	3595	3740	3880
(—)	*u*	—	—	2077	2623	2825	2972	3100	3218	3330	3441
	v	—	—	0.002830	0.006734	0.008680	0.0102	0.0114	0.0126	0.0136	0.0147
500	*h*	—	—	1878	2293	2723	3021	3248	3439	3610	3771
(—)	*u*	—	—	1791	2169	2529	2765	2946	3091	3224	3350
	v	—	—	0.001726	0.002491	0.003882	0.005112	0.006112	0.007000	0.007722	0.008418
1000	*h*	—	—	1798	2051	2316	2594	2857	3105	3324	3526
(—)	*u*	—	—	1653	1888	2127	2369	2591	2795	2971	3131
	v	—	—	0.001446	0.00162	0.001893	0.00224	0.00266	0.00310	0.003536	0.00395

Systems of Units

Systems of units are defined with reference to Newton's second law for a system of constant mass: $F = ma$ (mass–length/time^2)

where F is the force required to accelerate a body of mass, m, at a rate a (length/time^2)

System	Length	Time	Mass	Force	g_c
SI	Meter m	Second s	Kilogram kg	Newton N	1.0 (kg.m)/(N · s^2)
CGS	Centimeter cm	Second s	Gram g	dyne	1.0 (g.cm)/(dyne.s^2)
AES	Foot ft	Second s	Pound mass lb_m	Pound force lb_f	32.17 (lb_m.ft)/(lb_f.s^2)

1.0 N = Force that will accelerate a mass of 1.0 kg by 1.0 m/s^2
1.0 dyne = Force that will accelerate a mass of 1.0 g by 1.0 cm/s^2
1.0 lb_f = Force that will accelerate a mass of 1.0 lb_m by 32.174 ft/s^2

Metric prefixes

10^{12}	T	Tera	Trillion	10^{-1}	d	Deci	Tenths
10^{9}	G	Giga	Billion	10^{-2}	c	Centi	Hundredths
10^{6}	M	Mega	Million	10^{-3}	m	Milli	Thousandths
10^{3}	k	Kilo	Thousand	10^{-6}	μ	Micro	Millionths
10^{2}	h	Hector	Hundred	10^{-9}	n	Nano	Billionths
10^{1}	da	Deca	Ten	10^{-12}	p	Pico	Trillionths

Acceleration of gravity	$g = 9.8066$ m/s^2 (sea level, 45° latitude) $g = 32.174$ ft/s^2
Gas constant	$R = 10.731$ psia-ft^3/lbmol = 0.7302 atm-ft^3/lbmol $R = 0.082056$ atm-L/mol-K = 8.3143 Pa-m^3/mol-K $R = 0.08314$ L-bar/mol-K = 1.987 Btu/lb mol = 8314.3 J/kg mol-K $R = 8.3143$ J/mol-K = 62.36 L-mmHg/mol-K = 1.987 cal/mol-K
Density of water at 4°C	ρ (H_2O, 4°C) = 1.0 g/cm^3 = 1.0 kg/L = 10^3 kg/m^3 ρ(H_2O, 4°C) = 8.34 lb_m/gal = 62.43 lb_m/ft^3
Specific gravity of water	= 1.0
Specific gravity of Hg	= 13.6

Conversion Factors

Mass	1 $\text{lb}_m = 5 \times 10^{-4}$ t = 0.453593 kg = 453.593 g = 16 oz
	1 kg = 1000 g = 2.20462 lb_m = 0.001 t
	1 t = 2000 lb_m; 1 t = 1000 kg
Length	1 ft = 12 in.; 1 ft = 0.3048 m = 30.48 cm; 1 in. = 2.54 cm; 1 mile = 5280 ft
	1 m = 10^{10} Å = 39.37 in. = 3.2808 ft = 1.0936 yd = 0.0006214 mi
Volume	1 ft^3 = 7.481 gal = 1728 in.^3 = 28.317 L = 28,317 cm^3
	1 gal = 231 in.^3; 1 in.^3 = 16.387 cm^3
	1 cc = 1 cm^3 = 1 mL; 1000 mL = L
	1000 L = 1 m^3 = 35.3145 ft^3 = 220.83 imperial gallons = 264.17 gal = 1056.68 qt
	8 fl oz = 1 cup; 4 cup = 1 quart; 4 quart = 1 gal = 128 fl oz
Density	1 g/cm^3 = 1 kg/L = 1000 kg/m^3 = 62.428 lb/ft^3 = 8.345 lb_m/gal
Force	1 lb_f = 32.174 lb_m-ft/s^2 = 4.448222 N = 4.4482 × 10^5 dynes
	1 N = 1 kg-m/s^2 = 10^5 dynes = 10^5 g-cm/s^2 = 0.22481 lb_f
Pressure	1 bar = 10^5 Pa = 100 kPa = 10^5 N/m^2
	Pascal (Pa) is defined as 1 N/m^2 = 1 kg/m-s^2
	1 atm = 1.01325 bar = 14.696 lb_f/in.^2 = 760 mmHg at 0°C (torr) = 29.92 in Hg at 0°C
	1 psi = 1 lb_f/in.^2; psia (absolute) = psig (gauge) + 14.696
Temperature	1 K = 1.8°R (absolute temperature)
	T (°C) = T (K) − 273.15
	T (°F) = T (°R) − 459.67
	T (°F) = 1.8T (°C) + 32
Energy	1 J = 1 N-m = 1 kg-m^2/s^2 = 10^7 ergs = 10^7 dyne-cm = 2.778 × 10^{-7} kW-h
	= 0.23901 cal = 0.7376 ft-lb_f = 9.486 × 10^{-4} Btu
	1 cal = 4.1868 J; 1 Btu = 778.17 ft-lb_f = 252.0 cal
	1 Btu/lb_m-F = 1 cal/g-°C
Power	1 hp = 550 ft-lb/s = 0.74570 kW
	1 W = 1 J/s = 0.23901 cal/s = 0.7376 ft-lb_f/s = 9.486 × 10^{-4} Btu/s
	1 kW = 1000 J/s = 3412.1 Btu/h = 1.341 hp