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المرحلة الثانية

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Energy and Energy Balances

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3. Simultaneous Material and Energy Balances.......................................

4. Unsteady-State Material and Energy Balances....................................

Appendix

CHAPTER ONE (1)

This chapter illustrates the fundamental theory of energy balance without reactions. The concept of energy conservation as expressed by an energy balance equation is essential to chemical engineering calculations. Similar to material balances studied in previous chapters, a balance of energy is important to solving many problems. The chapter begins with definitions of the first law of thermodynamics, each term in the first law, and application for closed and open systems. Next, the three forms of energy, that is, kinetic, potential, and internal, are explained. Mechanical energy balance and Bernoulli's equations are also covered in this chapter. The following items outline the principal learning objectives of this chapter.

Learning Objectives

1. Calculate energy balance for closed and open systems (Section 1.1).
2. Write mechanical energy balance for a non reacting system (Section 1.2).
3. Use Bernoulli's equation to solve mechanical energy problems involving flowing fluids with no work input/output (Section 1.3).
4. Use heat capacities to calculate enthalpy changes (Section 1.4).
5. Use latent heats within energy balances for systems involving phase changes (Section 1.5).
6. Use psychrometric charts (Section 1.6).

1.1 Energy Balance for Closed and Open Systems

A system is an object or a collection of objects that an analysis is carried out on. The system has a definite boundary, called the system boundary, which is chosen and specified at the beginning of the analysis. Once a system is defined, through the choice of a system boundary, everything external to it is called the surroundings. All energy and material that are transferred out of the system enter the surroundings, and vice versa. ***An isolated system*** is a system that does not exchange heat, work, or material with the surroundings. A ***closed system*** is a system in which heat and work are exchanged across its boundary, but material is not. ***An open system*** can exchange heat, work, and material with the surroundings.

1.1.1 Forms of Energy: The First Law of Thermodynamics

Energy is often categorized as kinetic energy, potential energy, and internal energy. The first law of thermodynamics is a statement of energy conservation. Although energy cannot be created or destroyed, it can be converted from one form to another. Energy can also be transferred from one point to another or from one body to another one. Energy transfer can occur by flow of heat, by transport of mass, or by performance of work [1]. The general energy balance for a thermodynamic process can be expressed in words as the accumulation of energy in a system equals the input of energy into the system minus the output of energy from the system.

1.1.2 Energy Balance for a Closed System

Energy can cross the boundaries of a closed system in the form of heat and work (Figure1.1). The energy balance of a system is used to determine the amount of energy that flows into or out of each process unit, calculate the net energy requirement for the process, and assess ways of reducing energy requirements in order to improve process profitability and efficiency [2]. The energy balance for a closed system takes the form

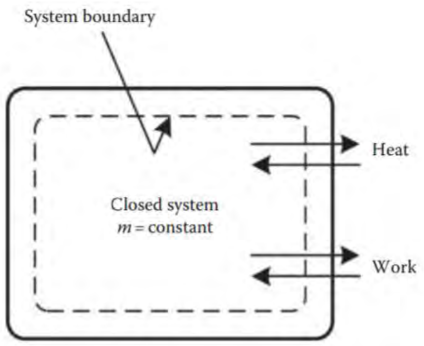


FIGURE1.1 Energy balance for a closed system.

$$Q - W = \Delta U + \Delta KE + \Delta PE \quad \ldots\ldots (1.1)$$

where heat (Q), work (W), internal energy (U), kinetic energy (KE), and potential energy (PE) are defined as follows.

Heat is the energy that flows due to a temperature difference between the system and its surroundings and always flows from regions at high temperatures to regions at low temperatures. By convention, heat is defined to be positive if it flows to a system (i.e., gained). For systems with no significant heat exchange with the surroundings, Q = 0. Such a system is said to be ***adiabatic***. The absence of any heat transfer can be due to perfect thermal insulation or the fact that the system and surroundings are at the same temperature. ***Work*** is the energy that flows in response to any driving force (e.g., applied force, torque) other than temperature, and is defined as positive if it flows from the system (i.e., work done by the system). In chemical processes, work may, for instance, come from pumps, compressors, moving pistons, and moving turbines. Heat or work only refers to energy that is being transferred to or from the system. If there is no motion along the system boundary, then W=0. ***Internal Energy*** is all the energy associated with a system that does not fall under the earlier definitions of kinetic or potential energy. More specifically, internal energy is the energy due to all molecular, atomic, and subatomic motions, and interactions. Usually, the complexity of these various contributions means that no simple analytical expression is available from which internal energy can be readily calculated. An ***isothermal*** system is one where the temperature does not change with time and in space. This does not mean that no heat crosses the boundaries. ***Kinetic Energy*** is associated with directed motion of the system. Translation refers to straight line motion. If the system is not accelerating, then ΔKE=0. ***Potential Energy*** of a system is due to the position of the system in a potential field. There are various forms of potential energy, but only gravitational potential energy will be considered in this course. If the system is not experiencing a displacement in the direction of the gravitational field, then ΔPE=0.

1.1.2.1 ***Kinetic Energy***

Kinetic energy is the energy carried by a moving system because of its velocity. The kinetic energy KE of a moving object of mass m, traveling with speed υ, is given by

$$KE = \frac{1}{2}\dot{m}v^2 \Rightarrow \left(\frac{\mathrm{kg}}{\mathrm{s}}\right)\left(\frac{\mathrm{m}}{\mathrm{s}}\right)^2 \left|\frac{\mathrm{N}}{\mathrm{kg\ m/s^2}}\right|\frac{\mathrm{J}}{\mathrm{N\cdot m}}\left|\frac{\mathrm{W}}{\mathrm{J/s}}\right. = \mathrm{W} \quad \ldots\ldots\ldots\ldots\ldots\ (1.2)$$

KE has units of energy, *m* has units of mass flow rate (mass/time), and υ has units of velocity (length/time).

Example1.1 Kinetic Energy Calculations

Water flows from a large lake into a process unit through a 0.02 m inside diameter pipe at a rate of 2.0 m^3 /h. calculate the change in kinetic energy for this stream in joules per second.

Solution

Known quantities: Pipe diameter (0.02 m), water volumetric flow rate (2.0 m^3 /h), density of water (1000 kg/m^3).

Find: Change in kinetic energy

Analysis: First, calculate the mass flow rate from the density and volumetric flow rate, and, next, determine the velocity as the volumetric flow rate divided by the pipe inner cross-sectional area. The rate of change in kinetic energy is calculated by

$$\Delta KE = \frac{1}{2}\dot{m}\Delta \upsilon^2 = \frac{1}{2}\dot{m}(\upsilon_2^2 - \upsilon_1^2) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(1.3)}$$

The mass flow rate, m, is the density (ρ) multiplied by volumetric flow rate (*V*):

$$\dot{m} = \rho\dot{V} = \frac{1000\ \text{kg}}{\cancel{\text{m}}^3}\left|\frac{2\ \cancel{\text{m}}^3}{\cancel{\text{h}}}\right|\frac{\cancel{\text{h}}}{3600\ \text{s}}\right| = 0.56\ \text{kg/s}$$

The water exit velocity (υ_2) is calculated from the volumetric flow rate (*V*) divided by pipe inner cross-sectional area of the exit of the pipe (A). The surface of the lake being large, the water surface can be assumed to be almost stagnant. Accordingly, the initial velocity is negligible (υ_1=0):

$$\upsilon_2 = \frac{\dot{V}}{A = \dfrac{\pi D^2}{4}} = \left(\frac{2.00\ \dfrac{\text{m}^3}{\text{h}}\left|\dfrac{\text{h}}{3600\ \text{s}}\right.}{\dfrac{3.14 \times (0.02\ \text{m})^2}{4}}\right) = 1.77\ \text{m/s}$$

Substituting the values of mass flow rate and velocities in the kinetic energy equation,

$$\Delta KE = \frac{1}{2}\dot{m}(v_2^2 - v_1^2) = \frac{1}{2}\left(0.56\,\frac{\text{kg}}{\text{s}}\right)\left(\left(1.77\,\frac{\text{m}}{\text{s}}\right)^2 - 0\right)\left(\frac{1\,\text{N}}{\frac{\text{kg m}}{\text{s}^2}}\right)$$

$$\times\left(\frac{1\,\text{J}}{1\,\text{N m}}\right) = 0.88\ \text{J/s}$$

1.1.2.2 *Potential Energy*

Potential energy is the energy due to the position of the system in a potential field (e.g., earth's gravitational field, g=9.81 m/s^2). The gravitational potential energy (ΔPE) of an object of mass m at an elevation z in a gravitational field, relative to its gravitational potential energy at a reference elevation z_0, is given by

$$\Delta PE = mg(z - z_0) \Rightarrow m(\text{kg})g(\text{m/s}^2)\Delta z(\text{m}) = \text{N}\cdot\text{m} = \text{J} \quad \text{……….. (1.4)}$$

To calculate the change in the rate of potential energy (ΔPE), often, the earth's surface is used as the reference, assigning z_0=0:

$$\Delta PE = \dot{m}g(z - z_0) \quad \text{……………………….. (1.5)}$$

The unit of the change in transport rate of potential energy is obtained as follows:

$$\Delta PE = \dot{m}(\text{kg/s})g(\text{m/s}^2)\Delta z(\text{m}) = \text{N}\cdot\text{m/s} = \text{J/s} = \text{W} \quad \text{………… (1.6)}$$

Example1.2 Potential Energy Calculation

Water is pumped at a rate of 10.0 kg/s from a point 200.0 m below the earth's surface to a point 100.0 m above the ground level. Calculate the rate of change in potential energy.

Solution

Known quantities: Water mass flow rate (10.0 kg/s), initial location of water below the earth's surface (−200.0 m), and final location of water above the earth's surface (100 m).

Find: The rate of change in potential energy.

Analysis: Use the definition of potential energy.

Taking the surface of the earth as a reference, the distance below the earth's surface is negative (z_1=–200.0) and above the surface is positive (z_2=100):

$$\Delta PE = \dot{m}g(z_2 - z_1)$$

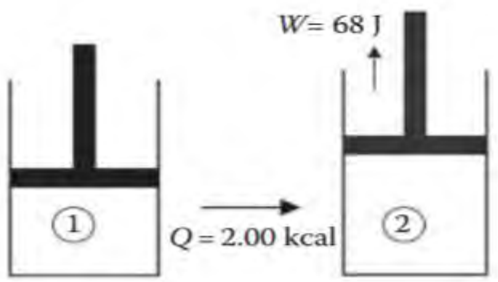
Substituting the values of the mass flow rate, gravitational acceleration, and change in inlet and exit pipe elevation from the surface of the earth,

$$\Delta PE = \left(10.0\,\frac{\text{kg}}{\text{s}}\right)\times\left(9.81\,\frac{\text{m}}{\text{s}^2}\right)\times\left(100.0-(-200.0)\right)\text{m}\left|\frac{\text{J}}{\text{kg}\cdot\text{m}^2/\text{s}^2}\right. = 29{,}430\ \text{J/s}$$

The rate of change in potential energy ΔPE = = 29. . 43 29 43 KJ/ s= Kw

Example1.3 Internal Energy Calculation

A cylinder fitted with a movable piston is filled with gas. An amount of 2.00 kcal of heat is transferred to the gas to raise the gas temperature 100°C higher. The gas does 68 J of work in moving the piston to its new equilibrium position. Calculate the change in internal energy of the system (Example Figure 1.3.1).



EXAMPLE FIGURE 1.3.1 Heat added to a cylinder fitted with a piston.

Solution

Known quantities: The difference in gas temperature (100°C), work done by the system (+68 J), and heat added to the system (+2.00 kcal).

Find: Change in internal energy.

Analysis: Use the energy balance equation for a closed system.

System: Gas in the system, closed system

$$\Delta U+\Delta KE+\Delta PE=Q - W$$

Assumption: No change in kinetic and potential energy; accordingly, both are set to zero. The equation is reduced to

$$\Delta U= Q - W$$

Substitute the values of Q and W to calculate the change in internal energy (make sure units are consistent). The heat is added to the system (positive value) and the work is done by the system (positive value as well):

$$\Delta U = \left(2.0\ \cancel{\text{kcal}}\right)\left[\frac{1000\ \cancel{\text{cal}}}{\cancel{\text{kcal}}}\,\frac{1\ \text{J}}{0.239\ \text{cal}}\right] - 68\ \text{J} = 8300\ \text{J}$$

The change in internal energy ΔU=8.30 kJ. The specific enthalpy (h=H/m) can be calculated using the following equation:

$$H = u+Pv \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \ (1.7)$$

Substituting the values of specific internal energy (u=U/m), pressure (P), and specific volume (v) in the earlier equations gives the specific enthalpy h.

Example1.4 Enthalpy from Internal Energy

The specific internal energy of helium at 25°C and 1 atm is 3.80 kJ/mol, and the specific molar volume under the same conditions is 25 L/mol. Calculate the specific enthalpy of helium at this temperature and pressure, and the rate at which enthalpy is transported by a stream with a molar flow rate of 250 kmol/h.

Solution

Known quantities: Internal energy, pressure, temperature, molar volume, molar flow.

Find: Specific molar enthalpy (h), rate of enthalpy transport (H).

Analysis: Follow the specific enthalpy definition. The specific enthalpy of helium is given by

$$h= u+Pv$$

Substituting the values of specific internal energy, pressure (P), and specific volume (v) in the earlier equations,

$$h = \left(3800\ \frac{\mathrm{J}}{\mathrm{mol}}\right) + (1\ \mathrm{atm})\left(25\ \frac{\mathrm{L}}{\mathrm{mol}}\right)\left[\frac{1\ \mathrm{m}^3}{1000\ \mathrm{L}}\ \frac{1.01325\times10^5\ \frac{\mathrm{N}}{\mathrm{m}^2}}{1\ \mathrm{atm}}\ \frac{\mathrm{J}}{\mathrm{N}\cdot\mathrm{m}}\right]$$

$$= 6333\ \mathrm{J/mol}$$

The enthalpy transport rate (H&) is calculated by multiplying the molar flow rate (n&) with the specific molar enthalpy (h):

$$H = n \times h$$

Substitute the values of molar flow rate (n) and specific enthalpy (h) to find the enthalpy transport rate (H):

$$\dot{H} = \left(250\ \frac{\mathrm{kmol}}{\mathrm{h}}\right)\times\left(6333\ \frac{\mathrm{J}}{\mathrm{mol}}\right)\left[\frac{1000\ \mathrm{mol}}{\mathrm{kmol}}\ \frac{\mathrm{kJ}}{1000\ \mathrm{J}}\right] = 1.58\times10^6\ \mathrm{kJ/h}$$

1.1.3 Energy Balance for an Open System

In open systems, material crosses the system boundary as the process occurs (e.g., continuous process at steady state). In an open system, work must be

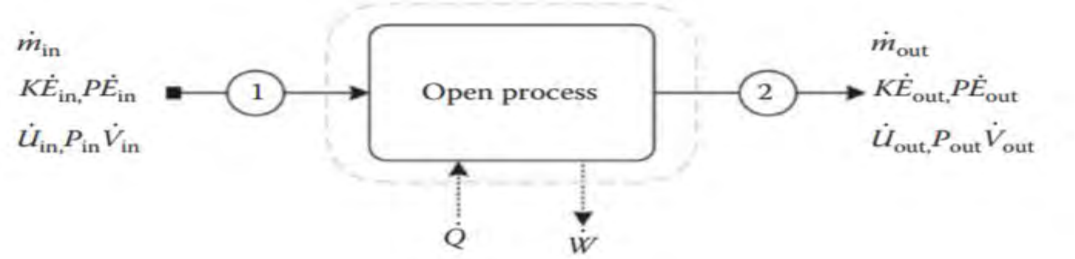


FIGURE 1.2 Energy balance for an open system.

done on the system to push input fluid streams at a pressure Pin into the system, and work is done on the surroundings to push output fluid streams at a pressure Pout out of the system, as shown in the schematic diagram in Figure 8.2 [3].

Net rate of work done by the system is

$$\dot{W}_f = \dot{W}_{out} - \dot{W}_{in} = P_{out}\dot{V}_{out} - P_{in}\dot{V}_{in} \quad \text{.........................} \quad (1.8)$$

For several input and output streams,

$$\dot{W}_f = \sum_{output} P_j\dot{V}_j - \sum_{input} P_j\dot{V}_j \quad \text{..} \quad (1.9)$$

The total rate of work (W) done by a system on its surroundings is divided into two parts:

$$\dot{W} = \dot{W}_s + \dot{W}_f \quad \text{...} \quad (1.10)$$

where shaft work (Ws) is the rate of work done by the fluid on a moving part within the system (e.g., piston, turbine, and rotor), and flow work (W_f) is the rate of work done by the fluid at the system outlet minus the rate of work done on the fluid at the system inlet. The general balance equation for an open continuous system (Figure 1.2) under steady state in the absence of generation/consumption term is

$$\text{Energy input} = \dot{U}_{in} + K\dot{E}_{,in} + P\dot{E}_{,in} + P_{in}\dot{V}_{in} \quad \text{.........} (1.11)$$

$$\text{Energy output} = \dot{U}_{out} + K\dot{E}_{,out} + P\dot{E}_{,out} + P_{out}\dot{V}_{out} \quad \text{.........} (1.12)$$

$$\text{Energy transferred} = \dot{Q} - \dot{W}_s \quad \text{.........} (1.13)$$

Under steady state, the accumulation term is set to zero and the following equation is valid:

Energy input=Energy output

$$\dot{Q} - W_s = \Delta\dot{U} + \Delta K\dot{E} + \Delta P\dot{E} + \Delta\left(P\dot{V}\right) \quad \text{.......... ....} (1.14)$$

Enthalpy (H) is the sum of the internal energy (U) of fluid volume added to the system plus the flow work (PV) performed on the system in order to push the fluid in/out of the system:

$$H = U + PV \quad \text{.....................................} (1.15)$$

The change in enthalpy transport rate is given by

$$\Delta\dot{H} = \Delta\dot{U} + \Delta\left(P\dot{V}\right) \quad \text{...} (1.16)$$

Rearranging the earlier equations leads to the first law of thermodynamics for an open system under steady state:

$$\dot{Q} - \dot{W}_s = \Delta\dot{H} + \Delta K\dot{E} + \Delta P\dot{E} \quad \text{...................................} (1.17)$$

Steam turbine is an example of an open system. Electrical generating plants operate by generating steam at elevated temperatures and pressures, then reducing the pressure in a turbine. As the pressure is reduced, the high pressure, high temperature steam expands (and cools down), driving the turbine. The shaft work produced by the turbine is transferred to a generator to produce electricity. One limitation on steam turbines is that they cannot tolerate small amounts of water in its liquid state in the gases passing through the turbine. If the liquid content of the steam is above the threshold limit (a few percentage points), the liquid droplets damage the turbine blades and lead to failure of the turbine. The steam tables in Appendix A.3 are used to determine the temperature, specific internal energy, and specific enthalpy of saturated steam and superheated steam.

Example 1.5 Energy Balance for an Open System: The Steam Turbine

Steam flowing at a rate of 10 kg/h enters a steam turbine at a velocity of 50 m/s and leaves at a point 5 m below the inlet at a velocity of 300 m/s. The heat loss from the turbine is estimated to be 10 kW, and the turbine delivers shaft work at a rate of 70 kW. Calculate the change in enthalpy transport rate of the process.

Solution

Known quantities: Steam flow rate, inlet and exit velocity, heat loss, and work delivered.

Find: Change in enthalpy transport rate.

Analysis: Use the general energy balance equation for an open system.

System: Steam turbine as open system

The energy balance for an open system has been derived as

$$\dot{Q} - \dot{W}_s = \Delta\dot{H} + \Delta\dot{KE} + \Delta\dot{PE}$$

In this example, heat is lost (negative value) from the system:

$$Q = -10\ \mathrm{kW} = -10\ \mathrm{kJ/s}$$

The shaft work is delivered (positive value) by the system:

$$W_s = 70\ \mathrm{kW} = 70\ \mathrm{kJ/s}$$

The change in kinetic energy

$$\Delta KE = \frac{1}{2}\dot{m}\left(\upsilon_2^2 - \upsilon_1^2\right)$$

Substitute the values of mass flow rate (m), inlet (υ_1), and exit (υ_2) velocities,

and use conversion factors (make sure units are consistent):

$$\Delta KE = \frac{1}{2}\left(10\ \frac{\mathrm{kg}}{\mathrm{h}}\ \frac{\mathrm{h}}{3600\ \mathrm{s}}\right)\left(300^2 - 50^2\right)$$
$$\times\left(\frac{\mathrm{m}}{\mathrm{s}}\right)^2 \bigg|\frac{\mathrm{N}}{\mathrm{kg\ m/s^2}}\bigg|\frac{\mathrm{J}}{\mathrm{N \cdot m}}\bigg|\frac{\mathrm{kJ}}{1000\ \mathrm{J}} = 0.12\ \mathrm{kJ}$$

Change in potential energy $\Delta PE = \dot{m}g\left(z_2 - z_1\right)$

Substitute the values of mass flow rate (m), and inlet and exit heights from the surface of the earth (z_1,z_2):

$$\Delta PE = 10\ \frac{\mathrm{kg}}{\mathrm{h}}\ \frac{\mathrm{h}}{3600\ \mathrm{s}} \times 9.81\ \frac{\mathrm{m}}{\mathrm{s^2}}$$
$$\times(\text{-}5\text{-}0)\mathrm{m}\bigg|\frac{\mathrm{N}}{\mathrm{kg\ m/s^2}}\bigg|\frac{\mathrm{J}}{\mathrm{N \cdot m}}\bigg|\frac{\mathrm{kJ}}{1000\ \mathrm{J}} = -0.00014\ \mathrm{kJ}$$

The change in potential energy is almost negligible compared to the magnitudes of heat and work. Substitute the values of Q, Ws, and changes in kinetic and potential

energies in the energy balance equation for an open system:

$$\Delta\dot{H} + \Delta KE + \Delta PE = Q - W_s$$

$$\Delta\dot{H} + 0.12\,\frac{\text{kJ}}{\text{s}} - 0.00014\,\frac{\text{kJ}}{\text{s}} = -10\,\frac{\text{kJ}}{\text{s}} - \left(70\,\frac{\text{kJ}}{\text{s}}\right)$$

The change in enthalpy transport $\Delta\dot{H} = -80.12\ \text{kJ/s}$ rate is

Example 1.6 Use of a Steam Table

Use steam tables in the appendix to determine the temperature, specific Internal energy and specific enthalpy of saturated steam at 3.0 bar. What is the state of the steam at 10 bar and 400°C? (i.e., is it saturated or superheated steam?)

Solution

Known quantities: *Case 1*: 3 bar, saturated steam, *Case 2*: 10 bar, 400°C.

Find: Specific enthalpy (h) and specific internal energy (u), specific volume (v). The state of steam at 10 bar and 400°C.

Analysis: Two properties are needed to be able to use saturated steam table and superheated steam table in the appendix.

Case 1: At 3 bar, steam is saturated: use saturated steam table (Appendix A.3). The temperature is 133.5°C, specific enthalpy is 2724.7 kJ/kg, and specific internal energy is 2543 kJ/kg.

Case 2: At 10 bar and 400°C: At 10 bar the saturated temperature is 179.9°C, and since the steam is at 400°C, this temperature is higher than the saturated temperature at 10 bar. Therefore, the state of water is superheated steam, and hence, the superheated steam table (Table A.5) is used. Specific enthalpy is 3264 kJ/kg, specific internal energy is 2958 kJ/kg, and specific volume is 0.307 m^3/kg.

1.1.4 Steam Turbine

Steam turbines are open systems used to generate electricity; in most cases, the turbine operates adiabatically. The exit pressure of turbine is lower than the inlet pressure. Turbines produce work; by contrast, work should be provided to a compressor or a pump. The following examples explain the possible operations for a steam turbine.

Example 1.7 Steam Table and Turbine Work

Steam at a rate of 1500 kg/s enters a turbine at 40 bar and 400°C. It comes out of the turbine as wet steam at 4 bar. The turbine operates adiabatically and produces 1000 MW of work. What is the temperature of the steam leaving the turbine? What is the mass fraction of vapor in the stream leaving the turbine?

Solution

Known quantities: Steam mass flow rate (1500 kg/s), inlet conditions (40 bar and 400°C), exit steam conditions (4 bar, wet steam).

Find: Mass fraction of vapor in the stream leaving the turbine.

Assumptions: No change in kinetic and potential energy.

Analysis: Use steam tables to find inlet and exit enthalpy and the first law for an open system. Inlet and exit steam enthalpies: Saturated steam (Table A.4), superheated steam (Table A.5).

Inlet steam conditions: at 40 bar and 400°C: the enthalpy of the incoming steam is 3216 kJ/kg (Table A.5). Exit steam conditions: at 4 bar: steam is either wet or saturated (Table A.4). Since the steam leaving the turbine is a vapor–liquid mixture,

it must be saturated. From Table A.4, for saturated steam at 4 bar the enthalpies of the liquid and vapor are 604.7 and 2737.6 kJ/kg,

$$\Delta \dot{H} = -\dot{W}_s$$

respectively, and the temperature is 143.6°C. The general energy balance applied to this process, after neglecting the potential and kinetic energy terms and bearing in mind that the turbine is adiabatic, can be expressed as

Rearranging the earlier equation,

$$-\dot{W}_s = \Delta \dot{H} = \dot{H}_{\text{out}} - \dot{H}_{\text{in}} = \dot{m}(h_{\text{out}} - h_{\text{in}})$$

Substituting known values of shaft work, mass flow rate, and inlet specific enthalpy, since the turbine is producing work, the sign of *W*s is +:

$$-W_s = -1000 \text{ MW} = -1 \times 10^6 \frac{\text{kJ}}{\text{s}} = 1500 \frac{\text{kg}}{\text{s}}(h_{\text{out}} - 3216)\frac{\text{kJ}}{\text{kg}}$$

The specific enthalpy of the exit steam is *h* out = 2549.3 kJ/kg

Let *x* be the mass fraction of the steam that is in the vapor phase, then

$$h_{\text{out}} = 2549.3 \frac{\text{kJ}}{\text{kg}} = h_f + x h_{fg} = 604.7 \frac{\text{kJ}}{\text{kg}} + x(2133.0 \text{ kJ/kg})$$

The steam quality is $x = 0.912$ → The wet steam is 91.2 wt% vapor. The wet contains 91.2% water vapor and 8.80 wt% liquid water.

Example 1.8 Steam Turbine

Steam enters a turbine at a pressure of 10.0 bar (absolute) and a temperature of 600°C. The steam leaving the turbine is at 1 atm (absolute) pressure and is of 90% quality (90 wt% steam, 10 wt% liquid). How much steam has to go into the turbine to yield 1.5 × 106 kW of shaft work?

Solution

Known quantities: Steam inlet conditions (10 bar, 600°C), exit steam conditions (1 atm, 90% quality), shaft work is 1.5 × 106 kW.

Find: Amount of steam that has to go into the turbine.

Assumptions: No change in kinetic and potential energy, turbine is adiabatic.

Analysis: Use steam tables to find inlet and exit enthalpy and the first law for an open system. From the first law,

$$\Delta H + \Delta KE + \Delta PE = Q - W_s$$

After applying the earlier assumptions, the equation is reduced to

$$\Delta \dot{H} = \dot{m}\left(h_{\text{out}} - h_{\text{in}}\right) = -W_s$$

To find the enthalpy of the steam leaving the turbine, use Table A.4. At 1 atm the enthalpies of saturated water and steam are 419.1 and 2676.0 kJ/kg, respectively.

Thus, the enthalpy of the steam leaving the turbine is

$$h_{\text{out}} = h_{\text{f}} + xh_{\text{fg}} = 419.1 + 0.9\left(2676.0 - 419.1\right) = 2450.3 \text{ kJ/kg}$$

The enthalpy of the input steam can be found from Table A.5 to be 3697 kJ/kg.

Substitute the values of inlet and outlet specific enthalpy and shaft work in the first law:

$$\dot{m}\left(2450.3 - 3697\right) = -\left(1.5 \times 10^6 \text{ kJ/s}\right)$$

The required steam mass flow rate is $m = 1.20 \times 103$ kg/s

1.1.5 Heaters and Coolers

Heaters and coolers such as shell and tube heat exchangers are open systems employed to cool down or heat up certain fluid streams. In most cases, the external surface of heaters and coolers is insulated and heat is just transferred between the cold and hot streams across the walls of the exchanger tubes. The following example illustrates the use of heat exchangers for cooling and heating purposes.

Example 1.9 Heat Exchanger

Steam at a rate of 60 kg/h, at 200°C, and 1 bar enters the tube side of a shell and tube heat exchanger. The steam is used to heat cold water flowing on the shell side; the steam leaves as saturated liquid. Neglect pressure drop of the steam on the tube side and the water on the shell side of the heat exchanger. How much heat must be transferred from the steam to the water side?

Solution

Known quantities: Mass flow rate (60 kg/h), inlet temperature and pressure (200°C, 1 bar), exit conditions (saturated water, 1 bar).

Find: Heat transfer rate from steam to water.

Assumptions: Pressure drop across the boiler is neglected, so exit pressure is at 1 bar.

Analysis: Use steam tables to find inlet and exit enthalpy.

Basis: 60 kg/h of feed steam. The schematic diagram of the problem is shown in Example Figure 8.9.1. From the superheated steam table (Table A.5),

Inlet: (1 bar, 200°C): $h_1 = 2875$ kJ/kg Using saturated steam table (Table A.4), Outlet: (1 bar, saturated water): $h_2 = h_f$ at 1 bar = 417 5. KJ/kg

No change in steam mass flow rate: $m = m$ in $= m$ out $= 60$ kg/h

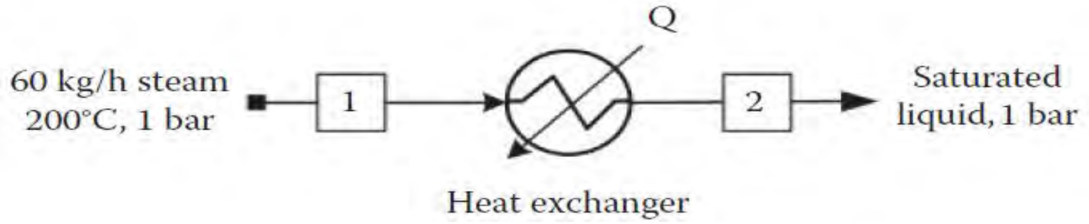
The general energy balance equation for an open system is

$$\Delta\dot{H} + \Delta KE + \Delta PE = \dot{Q} - \dot{W}_s$$

The following simplifying assumptions for the condenser are used:
No shaft work: Ws = 0.

No change in elevation. The inlet and outlet lines are at the same level: $\Delta PE = 0$.

Since we do not know anything about the diameters of the inlet and exit pipes, same pipe diameters are used for inlet and exit streams; accordingly, there is no change in velocity, and change in kinetic energy is negligible: $\Delta KE = 0$.



EXAMPLE FIGURE 1.9.1 Schematic of a heat exchanger system.

The simplified form of the energy balance is therefore

$$\dot{Q} = \Delta\dot{H} = \dot{H}_{\text{out}} - \dot{H}_{\text{in}}$$

The rate of enthalpy transport (H) as a function of specific enthalpy (h),

$$\Delta\dot{H} = \dot{m}\Delta h$$

Replacing enthalpy change rate (ΔH) with specific enthalpy (Δh) at constant mass flow rate,

$$Q = \dot{m}\Delta h = \dot{m}(h_{\text{out}} - h_{\text{in}})$$

Substituting the values of mass flow rate and exit and inlet specific enthalpy in the earlier equation,

$$Q = \left(60\ \frac{\text{kg}}{\text{h}}\right)(417.5 - 2875)\ \frac{\text{kJ}}{\text{kg}} = -147,450\ \text{kJ/h}$$

The value of heat transfer is negative; that is, heat is transferred from the system (steam) to the surrounding (cold water).

1.1.6 Compressors

Compressors are open systems utilized to raise the pressure of gas steams. The exit pressure is higher than the inlet pressure. Work is required for the compressor to operate. The following example illustrates the use of a compressor to pressurize a vapor steam.

Example 1.10 Compressor

The feed to a compressor is superheated steam at 300°C and 20 bar absolute pressure. It enters the compressor at a velocity of 20 m/s. The pipe inlet inside diameter is 0.10 m. The discharging pipe, after the compressor, has a smaller inside diameter and the discharge velocity is 170 m/s. The exit of the compressor is superheated steam at 350°C and 60 bar absolute. Heat loss from the compressor to the surroundings is 5 kW. Determine the compressor horsepower.

Solution

Known quantities: Inlet and exit steam temperature and pressure, inlet and exit velocities, heat loss from the compressor, inlet pipe diameter.

Find: Compressor horsepower.

Assumption: The system is located on a horizontal plane and no change in elevation between inlet and exit of the compressor; hence change in potential energy is negligible.

Analysis: The compressor is an open system. The steady-state energy balance can be used to describe the compressor system:

$$\Delta\dot{H} + \Delta KE + \Delta PE = \dot{Q} - \dot{W}_s$$

The general energy balance reduces to

$$\Delta H + \Delta KE = \dot{Q} - W_s$$

Determination of the specific enthalpy and specific volume from the superheated steam table (Appendix A.3):

Inlet stream at $P_1 = 20$ bar, $T_1 = 300°\mathrm{C}$, $h_1 = 3025$ kJ/kg, $v_1 =$ 0.125m3/kg

Exit stream at $P_2 = 60$ bar, $T_2 = 350°\mathrm{C}$, $h_2 = 3046$ kJ/kg, $v_2 =$ 0.0422m3/kg

Mass flow rate of the inlet steam is equal to density multiplied by volumetric flow rate; the steam density is the inverse of steam specific

$$\dot{m} = \rho \times \dot{V} = \rho \times (\upsilon \times A) = \rho \times \left(\upsilon \times \frac{\pi D^2}{4}\right) = \frac{1}{\upsilon} \times \left(\upsilon \times \frac{\pi D^2}{4}\right)$$

volume:

Substitute the values of density, velocity, and diameter:

$$\dot{m} = \frac{1}{0.125\ \mathrm{m^3/kg}} \times \left(\frac{20\ \mathrm{m}}{\mathrm{s}} \times \frac{\pi (0.1m)^2}{4}\right) = 1.25\ \mathrm{kg/s}$$

The change in enthalpy transport rate H is given by

$$\Delta\dot{H} = \dot{m}(h_2 - h_1) = 1.25\ \frac{\mathrm{kg}}{\mathrm{s}}(3046 - 3025)\frac{\mathrm{kJ}}{\mathrm{kg}} = 26.5\ \frac{\mathrm{kJ}}{\mathrm{s}} = 26.25\ \mathrm{kW}$$

The change in kinetic energy $\Delta KE = \frac{1}{2}\dot{m}\left(\upsilon_2^2 - \upsilon_1^2\right)$ is

Substitute the values of mass and inlet and exit velocity:

$$\Delta KE = \frac{1}{2} \times 1.25\ \frac{\mathrm{kg}}{\mathrm{s}}\left\{\left(\frac{170\ \mathrm{m}}{\mathrm{s}}\right)^2 - \left(\frac{20\ \mathrm{m}}{\mathrm{s}}\right)^2\right\}$$

$$\times \frac{\mathrm{N}}{\mathrm{kg\ m/s^2}}\left|\frac{\mathrm{J}}{\mathrm{N \cdot m}}\right|\frac{\mathrm{kJ}}{1000\ \mathrm{J}} = 18\ \mathrm{kJ/s}$$

$$\Delta KE = 18\ \mathrm{kW}$$

The change in the kinetic energy is

The heat loss from the system to the surroundings is 5 kW. Since heat is transferred from the system to the surroundings, $Q = -5$ kW.

The general energy balance equation $\Delta H + \Delta E_k = Q - W_s$ reduces to

Substituting the values of change in enthalpy, kinetic energy, and heat loss,

$$26.25\ \text{kW} + 18\ \text{kW} = -5\ \text{kW} - W_s$$

Rearranging and solving for the shaft work,

$$W_s = -49.25\ \text{kW}$$

$$\text{Power} = 49.25\ \text{kW}\left(\frac{1.341\ \text{hp}}{1\ \text{kW}}\right) = 66.04\ \text{hp}$$

The sign of the shaft work is negative since work is done on the system by compressor blades. To convert the shaft work to horsepower, use the proper conversion factor.

1.2 Mechanical Energy Balance

The mechanical energy balance is most useful for processes in which changes in the potential and kinetic energies are of primary interest, rather than changes in internal energy or heat associated with the process. Thus, the mechanical energy balance is mainly used for purely mechanical flow problems—that is, problems in which heat transfer, chemical reactions, or phase changes are not present. First, we assume the steady-state condition so that all terms on the left hand side become zero. Second, we assume that the system has only a single inlet and a single outlet. Moreover, steady state implies that the inlet mass flow rate must equal the outlet mass flow rate, in order to avoid accumulation of material in the system. Let us start with the general energy balance equation:

Energy transferred = Energy out − Energy in

$$\dot{Q} - \dot{W}_s = \left(\dot{U}_{\text{out}} + K\dot{E}_{,\text{out}} + P\dot{E}_{,\text{out}} + P_{\text{out}}\dot{V}_{\text{out}}\right) - \left(\dot{U}_{\text{in}} + K\dot{E}_{,\text{in}} + P\dot{E}_{,\text{in}} + P_{\text{in}}\dot{V}_{\text{in}}\right) \quad ..(1.17)$$

Rearrange the earlier equation by taking the mass flow rate (*m*) as a common factor. In this case, the internal energy and volumetric flow rate will become specific internal energy and specific volumetric flow rate, respectively:

$$\dot{Q} - W_s = \dot{m}\left(u_{\text{out}} + \frac{\upsilon_{\text{out}}^2}{2} + gz_{\text{out}} + P_{\text{out}}\upsilon_{\text{out}} - u_{\text{in}} - \frac{\upsilon_{\text{in}}^2}{2} - gz_{\text{in}} - P_{\text{in}}\upsilon_{\text{in}}\right) \quad \ldots (1.18)$$

In this equation, subscript “in” refers to the inlet section, and subscript “out” to the outlet port. Now, we divide the entire equation by *m*, and express the specific volume (volume/mass) as $v = 1/\rho$, where ρ is the density (mass/volume) of the flowing material. Assuming incompressible flow rate, so that the density is constant, $v_{\text{in}} = v_{\text{out}} = 1/\rho$. Also, we define Δu = *u*out − *u*in and ΔP = *P*out − *P*in. With these changes, the general energy balance equation becomes

$$\frac{-W_s}{\dot{m}} = \frac{\Delta P}{\rho} + \frac{\Delta \upsilon^2}{2} + g\Delta z + \Delta u - \frac{\dot{Q}}{\dot{m}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1.19)$$

The term (_*u* −*Q* /*m*) in the absence of chemical reactions, phase changes, or other sources of large amounts of heat transfer will generally represent heat generated due to the viscous friction in the fluid. In such situations, this term is called the friction loss and we will write it as *F*. With this last change, the general energy balance represents the usual form of the mechanical energy balance

$$\frac{-\dot{W}_s}{\dot{m}} = \frac{\Delta P}{\rho} + \frac{\Delta v^2}{2} + g\Delta z + F \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1.20)$$

where W $/m$ is the shaft work performed by the system on the surroundings, per unit mass of material passing through the system. The following example illustrates the use of the mechanical energy balance equation.

Example 1.11 Mechanical Energy Balance Equation

A water supply tank is capable of delivering 0.3 m^3/s of water for firefighting purposes in a chemical plant. The water supply is to come from a lake, the elevation of the surface of the lake is 800 m and the elevation of the factory is 852 m from sea level. The water discharge pipe is located at a depth of 100 m from the surface of the lake. The frictional losses in the water line to the plant are given by the relation (0.01 m/s^2) L, where L is the length of the pipe line. The water line to the supply tank has an inner diameter of 0.15 m and a length of 8000 m. How much energy must a pump deliver to the water?

Solution

Known quantities: Discharge line volumetric flow rate, initial and final elevation, friction losses, length and diameter of the pipe.

Find: Pump horsepower.

Assumption: Pressure drop is neglected because the pressure at both ends of line is atmospheric.

Analysis: Use the mechanical energy balance equation:

$$\frac{\Delta P}{\rho}+\frac{\Delta \upsilon^2}{2}+g\Delta z+F=\frac{-\dot{W}_s}{\dot{m}}$$

The pressure at both ends of the line is atmospheric, so $\Delta P = 0$. The velocity at the inlet of the lake is zero but the velocity out of the discharge end of the pipe is

$$\upsilon_2=\dot{V}\times\frac{1}{\frac{\pi D^2}{4}}=\left(0.3\ \frac{\mathrm{m}^3}{\mathrm{s}}\right)\times\frac{1}{\frac{\pi(0.15m)^2}{4}}=17\ \mathrm{m/s}$$

The mass flow rate .The

$$\dot{m}=\dot{V}\times\rho=\frac{0.3\ \mathrm{m}^3}{\mathrm{s}}\times\frac{1000\ \mathrm{kg}}{m^3}=300\ \mathrm{kg/s}$$

$$\frac{0}{\rho}+\frac{\left(17\ \frac{\mathrm{m}}{\mathrm{s}}\right)^2-0}{2}+9.81\ \frac{\mathrm{m}}{\mathrm{s}^2}(152\ \mathrm{m})+0.01\ \frac{\mathrm{m}}{\mathrm{s}^2}(8000\ \mathrm{m})=\frac{-\dot{W}_s}{300\ \mathrm{kg/s}}$$

elevation change is from 800 m (800–100 to the lake) to 852 to the factory, or the difference is equivalent to 152 m. So the mechanical energy balance becomes

Solving for shaft

$$-\dot{W}_s=514,686\ \mathrm{W}\times\frac{\mathrm{hp}}{746}=690\ \mathrm{hp}$$

work,

The minus sign indicates that the energy is going into the system.

Example 1.12 Fire Extinguishment Process

A large tank filled with water and open to atmosphere is used for fire extinguishment in an ethylene production plant. The water is taken from the tank, passed through a pump, and then delivered to hoses. It is desired to deliver 1890 L of water per minute at a pressure of 15 bar (gauge). If there is a negligible elevation change between the water level in the tank and the discharge of the pump, no changes in the diameter of the pipes and hoses, and if the pump has an efficiency of 70.0%, how much work must be supplied to the pump in order to meet the pressure and discharge rate specifications?

Solution

Known quantities: Discharge line volumetric flow rate, initial and final elevation, friction losses, length and diameter of the pipe.

Find: Pump horsepower.

Assumption: Pressure drop is neglected because the pressure at both ends of the line is atmospheric.

Analysis: Use the mechanical energy balance to solve this problem:

$$\frac{\Delta P}{\rho} + \frac{\Delta v^2}{2} + g\Delta z + F = \frac{-\dot{W}_s}{\dot{m}}$$

Because there is no change in elevation or velocity (no change in pipe/ hose diameter) and no frictional losses are given, the earlier equation reduces to

$$\frac{\Delta P}{\rho} = \frac{-\dot{W}_s}{\dot{m}}$$

The water mass flow rate is

$$\dot{m} = \dot{V} \times \rho = 1890 \frac{\text{L}}{\text{min}} \frac{1\ \text{min}}{60\ \text{s}} \times \frac{1\ \text{kg}}{\text{L}} = 31.5\ \text{kg/s}$$

The discharge pressure is given as 15 bar (gauge). This means that the absolute pressure is this pressure plus the ambient pressure. Substitute the known values to get

$$\frac{\left[\left(15\text{ bar}+P_{\text{ambient}}\right)-P_{\text{ambient}}\right]\left.\frac{10^5\text{ Pa}}{\text{bar}}\right|\frac{1\text{ N/m}^2}{\text{Pa}}}{1000\,\frac{\text{kg}}{\text{m}^3}}=\frac{-\dot{W}_s}{31.5\,\frac{\text{kg}}{\text{s}}}$$

Simplifying,

$$-\dot{W}_s=47{,}250\left.\frac{\text{N}\cdot\text{m}}{\text{s}}\right|\left.\frac{\text{J}}{\text{N}\cdot\text{m}}\right|\frac{\text{kJ}}{1000\text{ J}}=47.25\,\frac{\text{kJ}}{\text{s}}=47.25\text{ kW}$$

The pump has an efficiency of 70.0%; accordingly, the actual work (W s.a) that must be supplied to the pump in order to meet the pressure and discharge rate specifications is

$$-\dot{W}_{\text{s.a}}=\frac{62.7\text{ hp}}{0.7}=89.5\text{ hp}$$

The sign of the work is negative, which means that the work is done on the system. The actual work that must be supplied to the pump in order to meet the pressure and discharge rate specifications is higher than the theoretical work.

1.3 Bernoulli's Equation

In many instances, the amount of energy lost to viscous dissipation in the fluid is small compared to magnitudes of the other terms in the general energy balance equation. In such a case, $F = 0$. Moreover, many common flows such as fluid flow through a pipe do not have any appreciable shaft work associated with them; accordingly, $W = 0$. For such frictionless flows with no shaft work, the mechanical energy balance simplifies to *Bernoulli's equation*:

$$\frac{\Delta P}{\rho}+\frac{\Delta v^2}{2}+g\Delta z=0 \quad \text{……………………………………… (1.21)}$$

Bernoulli's equation has a wide range of applications, despite its simplified assumptions. The following example illustrates the use of Bernoulli's equation.

Example 1.13 Bernoulli's Equation

The pressure difference between the underside of the wing and the top of the wing that is necessary to lift the weight of an aircraft is 0.08 atm. At an elevation of approximately 10,000 m, the aircraft velocity is 275 m/s and the density of air is 0.45 kg/m^3. Assume that the velocity of the air on the underside of the wing is the plane velocity of 275 m/s. What is the velocity of the air on the topside of the wing, which is necessary to generate the pressure difference needed to lift the plane?

Solution

Known values: Pressure drop around the wing, velocity of air on the underside of the wing

Find: Velocity of air on the topside of the wing

Analysis: Use Bernoulli's equation around the wing (1: topside of the wing, 2: underside of the wing). Use Bernoulli's Equation to relate the pressure difference to a velocity difference so that

$$\frac{P_2 - P_1}{\rho} + \frac{\upsilon_2^2 - \upsilon_1^2}{2} + g(z_2 - z_1) = 0$$

Neglect the effect of wing thickness on change in potential energy. The equation is reduced to

$$\frac{P_2 - P_1}{\rho} + \frac{\upsilon_2^2 - \upsilon_1^2}{2} + 0 = 0$$

Substituting the values of pressure drop, air density, and velocity under the wing,

$$\frac{0.08\ \text{atm}\left|\frac{101{,}325\ \text{Pa}}{1\ \text{atm}}\right.}{0.45\ \text{kg/m}^3}+\frac{275^2-v_1^2}{2}=0$$

Solving for velocity on the topside of the wing,

$$v_1 = 334\ \frac{\text{m}}{\text{s}}$$

The velocity on the topside of the wing is higher than that on the underside of the wing.

1.4 Enthalpy Calculations

Change in enthalpy can occur because of change in temperature, change in phase, or mixing of solutions and reactions.

1.4.1 Enthalpy Change as a Result of Temperature

Sensible heat is the heat transferred to raise or lower the temperature of a material in the absence of phase change. In the energy balance calculations, sensible heat change is determined by using a property of matter called the heat capacity at constant pressure, or just heat capacity (CP). Units for CP are (J/mol/K) or (cal/g/°C). Appendix A.2 lists CP values for several organic and inorganic compounds. There are several methods for calculating enthalpy change using CP values. When CP is constant, the change in the enthalpy of a substance due to change in temperature at constant pressure is given by

$$\Delta H = mC_P(T - T_{\text{ref}}) \quad \ldots\ldots\ldots\ldots\ldots (1.22)$$

Heat capacities for most substances vary with temperature where the values of *C*P vary for the range of the change in temperature. Heat capacities are tabulated as polynomial functions of temperature such as

$$C_P = a + bT + cT^2 + dT^3 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(1.23)}$$

Coefficients *a*, *b*, *c*, and *d* for a number of substances are given in Appendix A.2 In this case, the enthalpy change is

$$\Delta \dot{H} = \dot{m} \int_{T_{\text{ref}}}^{T} C_P \, dT = \dot{m} \int_{T_{\text{ref}}}^{T} \left(a + bT + cT^2 + dT^3 \right) dT \quad \ldots. \text{(1.24)}$$

Sometimes, you need an estimate of specific enthalpy, specific internal energy, or specific volume at a temperature and a pressure that is between tabulated values. In this case, one can use a linear interpolation. The following example demonstrates the determination of internal energy from heat capacity.

Example 1.14 Internal Energy and Heat Capacity

A closed rigid vessel that contains 200 kg of a fluid is heated from 20°C to 150°C. Calculate the heat required for this purpose. The constant volume heat capacity of the fluid is given by the following relation:

$$C_v \left(\frac{\text{kJ}}{\text{kg} \cdot {}^\circ\text{C}} \right) = a + bT = 0.855 + 9.42 \times 10^{-4} T$$

Solution

Known quantities: Mass of fluid, initial (20°C) and final temperature (150°C), heat capacity at constant volume as a function of temperature.

Find: Heat required to heat the content of the closed vessel.

Analysis: Use the general energy balance for a closed system, no change in kinetic and potential energies as the system is a rigid vessel:

$$Q - W = \Delta U$$

$W = 0.0$ (rigid vessel; no moving part), the change in internal energy is

$$Q = \Delta U$$

The change in internal energy is a function of heat capacity at constant volume; since the heat capacity is a function of temperature and mass, we

$$\Delta U = m\int_{T_1}^{T_2} C_V \, dT$$

multiply mass by heat capacity as follows:

Substitute the heat capacity at constant volume:

$$\Delta U = m\int_{T_1}^{T_2} (0.855 + 9.42 \times 10^{-4} T) dT$$

Integrating the earlier equation as a function of initial and final temperature, we obtain

$$\Delta U = m\left[0.855(T_2 - T_1) + 9.42 \times 10^{-4}\left(\frac{T_2^2 - T_1^2}{2}\right)\right]$$

Substituting the values of initial (20°C) and final temperature (150°C),

$$Q = \Delta U = 200 \text{ kg}\left[0.855(150 - 20) + 9.42 \times 10^{-4}\frac{(150^2 - 20^2)}{2}\right]$$

$$\times \left[\frac{\text{kJ}}{\text{kg} \cdot {}^\circ\text{C}}\right] = 24{,}312 \text{ kJ}$$

Example 1.15 Use of Data from Tables and Reference State

The data shown in Table E1.15 are for a saturated fluid. Calculate Δh and Δu for the transition of saturated vapor from 10°C to −20°C.

Solution

Known quantities: Enthalpy, pressure, and temperature.

Find: Change of specific enthalpy and specific internal energy.

Analysis: The reference is liquid at −40°C, because the enthalpy at this temperature is zero. Change in specific enthalpy (Δh) and change in specific internal energy (Δu) for the transition of saturated CH_3Cl vapor from 10°C to −20°C can be calculated as

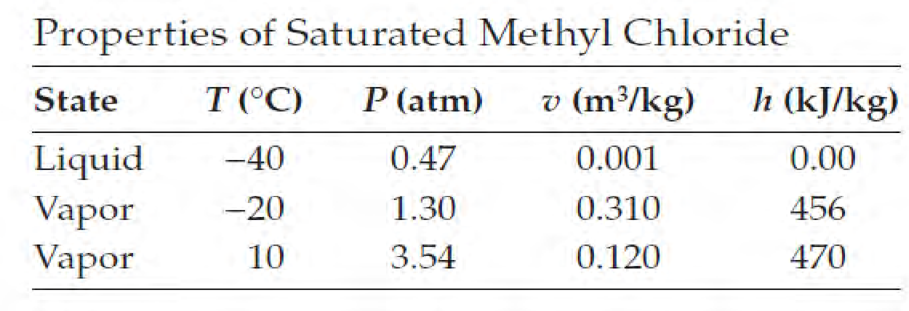
$$\Delta h = h_{-20^\circ C} - h_{10^\circ C} = 456 - 470 = -14 \text{ kJ/kg}$$

The change in specific internal energy starts using $h = u + Pv$ and $\Delta h = \Delta u + \Delta(Pv)$.

Rearranging for Δu,

$$\Delta u = \Delta h - \Delta(Pv) = \Delta h - \left\{(Pv)_{-20} - (Pv)_{10}\right\}$$

TABLE E1.15



Properties of Saturated Methyl Chloride

State	T (°C)	P (atm)	v (m³/kg)	h (kJ/kg)
Liquid	−40	0.47	0.001	0.00
Vapor	−20	1.30	0.310	456
Vapor	10	3.54	0.120	470

To calculate the change in internal energy,

$$\Delta u = -14\,\frac{\text{kJ}}{\text{kg}} - \{1.30 \times 0.312 - 3.54 \times 0.12\}\left(\text{atm} \times \frac{\text{m}^3}{\text{kg}}\right) \times \left(\frac{101.325\ \text{kN}/\text{m}^2}{1\ \text{atm}}\right)\left(\frac{\text{kJ}}{\text{kN}\cdot\text{m}}\right)$$

The rounded result of change in internal energy is $\Delta u = -12$ kJ/kg

1.4.2 Constant Heat Capacity

Keeping P constant and letting T change, we can get the expression for the constant P part as $\Delta h = \int C\text{P}\ \text{d}T \approx C\text{P}\Delta T$ (at constant P). It is not necessary to know the reference state to calculate $\Delta H\_$ for the transition from one state to another. Δh from state 1 to state 2 equals $h2 - h1$ regardless of the reference state upon which $h1$ and $h2$ were based. If different tables are used, one must make sure they have the same reference state. h and u are state properties; their values depend only on the state of the species, temperature, and pressure and not on how the species reached its state. When a species passes from one state to another, both Δu and Δh for the process are independent of the path taken from the first state to the second one.

Example 1.16 Constant Heat Capacity

What is the change in the enthalpy of 100 g/s acid heated in a double pipe heat exchanger from 20°C to 80°C, if the average heat capacity at constant pressure is 0.50 cal/g°C?

Solution

Known quantities: Mass of acid, constant heat capacity, initial and final temperatures.

Find: Change in enthalpy.

Analysis: Use change in enthalpy with constant heat capacity. The change in enthalpy as a function of specific heat is given by

$$\Delta \dot{H} = \int_{T_1}^{T_2} \dot{m} C_P \, dT$$

Since the heat capacity (CP) is constant, the earlier equation is simplified to

$$\Delta \dot{H} = \dot{m} C_P (T_2 - T_1)$$

Substitute the values of mass flow rate, heat capacity at constant pressure, and difference in temperature (the reference temperature is 20°C):

$$\Delta \dot{H} = \left(100 \frac{g}{s}\right)\left(0.5 \frac{cal}{g°C}\right)(80 - 20)°C = 3000 \ cal/s$$

The change in enthalpy transport rate is $H = 3.0$ kcal/s

Example 1.17 Heat Added to a Boiler

Liquid water is fed to a boiler at 23°C under a pressure of 10 bar, and is converted at constant pressure to saturated steam. Calculate Δh for this process and the heat input required for producing 15,000 m^3/h of steam at the exit conditions. Assume that the inlet velocity of liquid entering the boiler is negligible and that the steam is discharged through a 0.15 m ID (inner diameter) pipe (Example Figure 1.17.1). Inlet and exit pipes are at the same level.

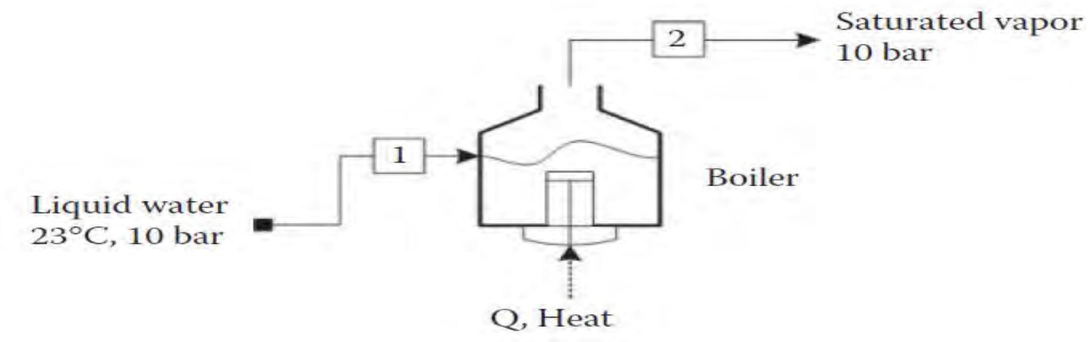
Solution

Known quantities: Water inlet conditions (23°C under a pressure of 10 bar), exit steam conditions (10 bar, saturated steam), exit steam volumetric flow rate (15,000 m^3/h), exit pipe diameter (0.15 m).

Find: Change in specific enthalpy (Δh).

Analysis: The reboiler is an open system, and the general energy balance equation is

$$Q - W_s = \dot{m}\Delta h + \Delta KE + \Delta PE$$



EXAMPLE FIGURE 1.17.1 Production of saturated steam.

Since the reboiler does not deliver shaft work, no change is seen in elevation between inlet and exit steams (change in potential energy is zero); the energy balance equation reduces to $Q_s = \dot{m}\Delta h + \Delta KE$ The change in specific enthalpy: Since no value of specific enthalpy is available at 23°C and 10 bar, the value is taken at 23°C (saturated water):

$$h_1\big|_{\text{at } 23°\text{C, 10 bar}} = 96.2 \text{ kJ/kg}$$

The specific enthalpy value for the exit conditions at 10 bar, saturated steam is

$h_2\big|_{\text{at 10 bar, sat'd steam}} = 2776.2 \text{ kJ/kg}$ The change in specific enthalpy

is $\Delta h = h_2 - h_1$ Substitute the values of inlet and exit specific enthalpy:

$$\Delta h = 2776.2 \frac{\text{kJ}}{\text{kg}} - 96.2 \frac{\text{kJ}}{\text{kg}} = 2680 \text{ kJ/kg}$$

The discharge mass flow rate (m_2) is calculated at the exit steam because exit steam volumetric flow rate and diameter of discharge pipe are given. The density is calculated from the inverse of specific volume ($\rho = 1/v$).

The specific volume (v) at 10 bar, saturated steam is 0.1943 m3/kg (used saturated steam table, Appendix A.3):

$$\dot{m}_2 = \rho \times \dot{V} = \frac{1}{0.1943\ \mathrm{m^3/kg}} \times 15{,}000\ \frac{\mathrm{m^3}}{\mathrm{h}} \times \frac{\mathrm{h}}{3600\ \mathrm{s}} = 21.45\ \mathrm{kg/s}$$

The inlet velocity is negligible as given in the problem statement. The exit velocity is calculated from the discharge volumetric flow rate divided by pipe cross sectional area:

$$\upsilon_2 = \frac{\dot{V}_2}{\frac{\pi D^2}{4}} = \frac{15{,}000\ \mathrm{m^3/h}}{\frac{\pi (0.15)^2}{4}\ \mathrm{m^2}} \times \frac{\mathrm{h}}{3600\ \mathrm{s}} = 235.79\ \mathrm{m/s}$$

The simplified general energy balance equation becomes

$$Q = \dot{m}\Delta h + \Delta KE = \dot{m}\Delta h + \frac{1}{2}\dot{m}(\upsilon_2^2 - \upsilon_1^2)$$

Substitute the values of mass flow rate, specific enthalpy, and velocity:

$$Q = 21.45\ \frac{\mathrm{kg}}{\mathrm{s}} \times \left(2680\ \frac{\mathrm{kJ}}{\mathrm{kg}}\right) + \frac{1}{2} \times 21.45\ \frac{\mathrm{kg}}{\mathrm{s}} \left\{\left(235.79\ \frac{\mathrm{m}}{\mathrm{s}}\right)^2 - 0\right\} \times \frac{\mathrm{kJ}}{1000\ \mathrm{J}} = 58{,}082\ \ \mathrm{kJ/s}$$

The sign of the heat transfer across system boundaries is positive; that is, heat is transferred from the surroundings to the system.

1.5 Enthalpy Calculations with Phase Changes

The state of a system can be changed, for example, by increasing its temperature or changing its composition. Properties of the system whose change depends only on the initial and final states of the system but not on the manner used to realize the change from the initial to the final state are referred to as state properties [4].

Phase changes, such as evaporation and melting, are accompanied by relatively large changes in internal energy and enthalpy, as bonds between molecules are broken and reformed. Heat transferred to or from a system, causing change of phase at constant temperature and pressure, is known as latent heat. The types of latent heats are latent heat of vaporization, which is the heat required to vaporize a liquid; latent heat of fusion, which is the heat required to melt a solid; and latent heat of sublimation, which is the heat required to directly vaporize a solid. Heat is released during condensation, and heat is required to vaporize a liquid or melt a solid. Table A.1 reports these two latent heats for substances at their normal melting and boiling points (i.e., at a pressure of 1 atm). Sensible heat refers to heat that must be transferred to raise or lower the temperature of a substance without change in phase as defined earlier. The quantity of sensible heat required to produce a temperature change in a system can be determined from the appropriate form of the first law of thermodynamics. The heat capacity at constant pressure, $C\text{P}$, for most incompressible liquids and solids is equal; $C\text{P} \approx Cv$ and for ideal gases, $C\text{P} = Cv + R$.

Example 1.18 Enthalpy of Phase Change

Steam at a rate of 100 kg/h is used to heat a stream of gas flowing on the tube side of a heat exchanger. The steam enters the shell side of the heat exchanger as saturated vapor at 10 bar of 90% quality, and exits as saturated liquid water at 10 bar. Calculate the rate of heat transfer to the gas side.

Solution

Known quantities: Inlet (10 bar, 90% quality) and exit (10 bar, saturated water) steam conditions.

Find: The change in enthalpy transport rate.

Assumption: No change in potential and kinetic energy, no shaft work.

Analysis: Use the general energy balance equation for an open system around the heat exchanger. The simplified energy balance is obtained as follows.

Energy balance for an open system is

$$\Delta \dot{H} + \Delta KE + \Delta PE = \dot{Q} - \dot{W}_s$$

After including the assumptions, the equation is reduced to

$$\Delta \dot{H} = Q$$

Setting enthalpy transport rate (H) in terms of specific enthalpy h,

$$\Delta \dot{H} = \dot{m}_s(h_2 - h_1) = Q$$

The change in specific enthalpy of $\Delta h_s = h_{s,2} - h_{s,1}$ steam is

The inlet steam specific enthalpy (hs,1) of saturated vapor at 10 bar and 90% quality is

$$h_{s,1}\Big|_{10\text{ bar},\, x=0.9} = h_f + x h_{fg} = 762.6 + 0.9 \times 213.6 = 2574.84 \text{ kJ/kg}$$

The exit steam specific enthalpy at 10 bar, saturated water is

$$h_{s,2}\Big|_{10\text{ bar, sat'd water}} = 762.6 \text{ kJ/kg}$$

$$\Delta h_s = h_{s,2} - h_{s,1} = 762.6 - 2574.84 = -1812.24 \text{ kJ/kg}$$

The rate of heat transfer from condensed steam to gas stream is

$$Q = m_s \Delta h_s = 100 \frac{\text{kg}}{\text{h}}\left(-1812.24 \frac{\text{kJ}}{\text{kg}}\right)\frac{\text{h}}{3600 \text{ s}} = -50.34 \text{ kJ/s}$$

The sign of Q value is negative; that is, heat is transferred from the condensed steam to gas stream.

1.5.1 Energy Balance for Open Systems with Multiple Inputs and Multiple Outputs

The general energy balance for an open system is

$$Q - \dot{W}_s = \Delta \dot{H} + \Delta KE + \Delta PE \quad \text{..............................} \quad (1.25)$$

The change in the rate of enthalpy for multiple streams is

$$\Delta \dot{H} = \sum \dot{H}_{\text{out}} - \sum \dot{H}_{\text{in}} \quad \text{................................} \quad (1.26)$$

Setting enthalpy transport rate (H□) in terms of specific enthalpy h,

$$\Delta \dot{H} = \sum \dot{m}_{\text{out}} h_{\text{out}} - \sum \dot{m}_{\text{in}} h_{\text{in}} \quad \text{.........................} \quad (1.27)$$

Example 1.19 Enthalpy Change of Mixtures and Phase Change

Thousand kilomoles per hour of a liquid mixture of 70 mol% acetone and 30 mol% benzene is heated from 10°C to 50°C in a shell-and-tube heat exchanger using steam as the heating medium. The steam enters the heat exchanger in the shell as a saturated vapor at 16 bar of 90% quality, and exits as saturated liquid water at 16 bar. Calculate the mass flow rate of the inlet steam required for this purpose.

Solution

Known quantities: Inlet mixture flow rate and composition, inlet and exit temperature, steam inlet and outlet conditions.

Find: The mass flow rate of inlet steam.

Assumptions: The boiler is adiabatic, no shaft work, no change in inetic and potential energy, inlet and exit pipe is at the same diameter and level.

Analysis: Use energy balance for an open system around the heat exchanger. Energy balance for an open system is given by

$$\Delta \dot{H} + \Delta KE + \Delta PE = \dot{Q} - \dot{W}_s$$

After including the assumptions, the equation is reduced to $\Delta \dot{H} = 0$

Since the system is of multiple inputs and multiple outputs, the change in enthalpy around the heat exchanger is $\Delta \dot{H} = 0 = \sum \dot{H}_{out} - \sum \dot{H}_{in}$

Setting the enthalpy transport rate (H) in terms of specific enthalpy h,

$\Delta \dot{H} = 0 = \sum \dot{m}_{out} h_{out} - \sum \dot{m}_{in} h_{in}$ In more detail,

$$\Delta \dot{H} = 0 = \left\{\dot{m}_{s,out} h_{s,out} + \dot{m}_{a,out} h_{a,out} + \dot{m}_{b,out} h_{b,out}\right\} - \left\{\dot{m}_{s,in} h_{s,in} + \dot{m}_{a,in} h_{a,in} + \dot{m}_{b,in} h_{b,in}\right\}$$

where

$m_{s,in}$, $m_{s,out}$ are the inlet and exit mass flow rates of steam which are equal

$\dot{m}_{a,in}$, $\dot{m}_{a,out}$ are the inlet and exit mass flow rates of acetone

$\dot{m}_{b,in}$, $\dot{m}_{b,out}$ are the inlet and exit mass flow rates of benzene

Rearranging the earlier equation,

$$\Delta \dot{H} = 0 = \dot{m}_s \left(h_{s,out} - h_{s,in}\right) + \dot{m}_a \left(h_{a,out} - h_{a,in}\right) + \dot{m}_b \left(h_{b,out} - h_{b,in}\right)$$

where

$\dot{m}_a = \dot{m}_{a,in} = \dot{m}_{a,out}$ is the mass flow rate of acetone

$\dot{m}_b = \dot{m}_{b,in} = \dot{m}_{b,out}$ is the mass flow rate of benzene

Rearranging,

$$\Delta \dot{H} = 0 = \dot{m}_s \Delta h_s + \dot{m}_a \Delta h_a + \dot{m}_b \Delta h_b$$

where

Δh_s is the change in the specific enthalpy of steam

Δh_a is the change in the specific enthalpy of acetone

Δh_b is the change in the specific enthalpy of benzene

Since the mixture contains 70% acetone and 30% benzene, the mixture mass flow rate and change of mixture enthalpy can be written as

$$m_{mix} = 0.7\dot{m}_a + 0.3\dot{m}_b$$

The change in mixture specific enthalpy is given by

$$\Delta h_{mix} = 0.7\Delta h_a + 0.3\Delta h_b$$

The change in the specific enthalpy of steam, Δhs, is given by $\Delta h_s = h_{s,2} - h_{s,1}$

The inlet steam specific enthalpy (hs,1) of saturated vapor at 16 bar and 90% quality is

$$h_{s,1}\Big|_{16\text{ bar},\, x=0.9} = h_f + x h_{fg} = 858.6 + 0.9 \times 1933.2 = 2598.5\ \text{kJ/kg}$$

The exit steam specific enthalpy at 16 bar, saturated water is

$$h_{s,2}\Big|_{16\text{ bar, sat'd water}} = 858.6\ \text{kJ/kg}$$

Substituting the values of the specific enthalpies of steam,

$$\Delta h_s = h_{s,2} - h_{s,1} = 858.6 - 2598.5 = -1740\ \text{kJ/kg}$$

The change in specific enthalpy of acetone and benzene mixture, Δhmix, is given by

$$\Delta h_{\text{mix}} = 0.7\Delta h_a + 0.3\Delta h_b = \int_{10^\circ\text{C}}^{50^\circ\text{C}} C_{P,\text{mix}}\, dT$$

The specific heat capacity of the mixture is given by

$$C_{P,\text{mix}} = \sum y_i C_{Pi} = 0.7 C_{P,\text{acetone}} + 0.3 C_{P,\text{benzene}}$$

The heat capacity at constant pressure as a function of temperature:

$$\text{Acetone (liquid): } C_{Pa}\left(\frac{\text{J}}{\text{mol}\ {}^\circ\text{C}}\right) = 123 + 0.186T$$

$$\text{Benzene (liquid): } C_{Pb}\left(\frac{\text{J}}{\text{mol}\ {}^\circ\text{C}}\right) = 126.5 + 0.234T$$

Substitute the heat capacities of acetone and benzene:

$$C_{P,\text{mix}} = \{0.7(123) + 0.3(126.5)\} + \{0.7(0.186) + 0.3(0.234)\}T$$

Rearranging,

$$C_{P,\text{mix}} = 124 + 0.20T$$

Substituting the mixture heat capacity,

$$\Delta h_{\text{mix}} = \int_{10^\circ\text{C}}^{50^\circ\text{C}} C_{P,\text{mix}}\, dT = \int_{10^\circ\text{C}}^{50^\circ\text{C}} (124 + 0.20T)\, dT$$

Integrating,

$$\Delta h_{\text{mix}} = \int_{10^\circ\text{C}}^{50^\circ\text{C}} (124 + 0.20T)\,\mathrm{d}T = \left(124T + 0.20T^2\right)\Big|_{10}^{50}$$

The change in enthalpy of the acetone–benzene mixture, Δhmix, is given by

$$\Delta h_{\text{mix}} = 124(50 - 10) + \frac{0.20}{2}\left(50^2 - 10^2\right) = 5200\ \text{J/mol}$$

Substituting the values of change in steam enthalpy and mixture enthalpy,

$$0 = \dot{m}_{\text{s}}\Delta h_{\text{s}} + \dot{m}_{\text{mix}}\Delta h_{\text{mix}}$$

$$= \dot{m}_{\text{s}}\left(-1740\ \frac{\text{kJ}}{\text{kg}}\right) + 1000\ \frac{\text{kmol}}{\text{h}}\left(\frac{1000\ \text{mol}}{\text{kmol}}\right)\left(5200\ \frac{\text{J}}{\text{mol}}\bigg|\frac{\text{kJ}}{1000\ \text{J}}\right)$$

Solving for $\dot{m}_{\text{s}}$, $\dot{m}_{\text{s}}\left(1740\ \frac{\text{kJ}}{\text{kg}}\right) = \left(5.20 \times 10^6\ \text{kJ/h}\right)$.

The rounded value of the steam mass flow rate is ms = 2990 kg/h. The amount of steam required for heating the acetone–benzene mixture is 2990 kg/h.

1.5.2 Enthalpy Change because of Mixing

The thermodynamic property of an ideal mixture is the sum of the contributions from the individual compounds. The following example illustrates the thermodynamic property of an ideal mixing.

Example 1.20 Mixing

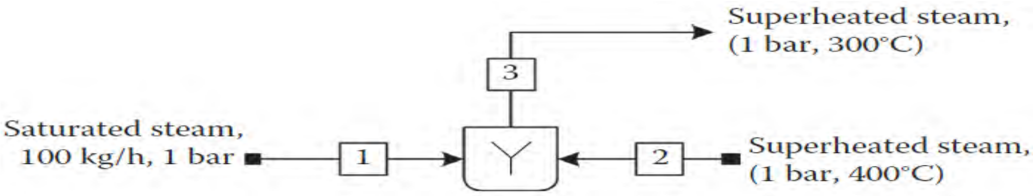
Hundred kilograms per hour of a saturated steam at 1 bar is mixed with superheated steam available at 400°C and 1 bar to produce superheated steam at 300°C and 1 bar. Calculate the amount of superheated steam produced at 300°C, and the required mass flow rate of the 400°C steam.

Solution

Known quantities: Stream 1: mass flow rate, saturated steam, 1 bar. Stream 2: 400°C and 1 atm. Stream 3: superheated steam produced at 300°C, 1 bar.

Find: Volumetric flow rate of stream 2.

Assumptions: No change in kinetic and potential energy, no shaft work.



EXAMPLE FIGURE 1.20.1 Mixing of saturated and superheated steam.

Analysis: Use open system energy balance with multiple inputs, single output. The process flow sheet is shown in Example Figure 1.20.1. The general energy balance for an open system after applying the assumptions is reduced to

$$\Delta H = 0$$

For two inputs, single output,

$$\Delta \dot{H} = \dot{H}_3 - \dot{H}_1 - \dot{H}_2 = 0$$

Putting the equation in terms of mass flow rate and specific enthalpy,

$$\Delta \dot{H} = \dot{m}_3 h_3 - \dot{m}_1 h_1 - \dot{m}_2 h_2 = 0$$

Overall mass balance for the mixing system is

$$\dot{m}_1 + \dot{m}_2 = \dot{m}_3 \Rightarrow 100 \frac{\text{kg}}{\text{h}} + \dot{m}_2 = \dot{m}_3$$

The specific enthalpy of stream 1 is

$$h_1\big|_{1\,\text{bar, sat'd steam}} = 2675.4\ \text{kJ/kg}$$

The specific enthalpy of stream 2 is

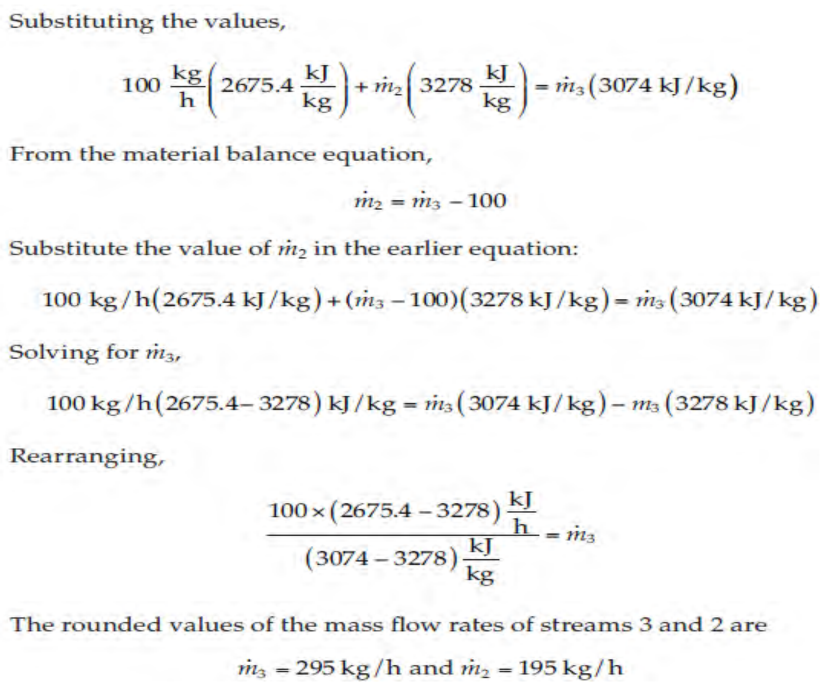
$$h_2\big|_{1\,\text{bar, }400^\circ\text{C}} = 3278\ \text{kJ/kg}$$

The specific enthalpy of stream 3 is

$$h_3\big|_{1\,\text{bar, }300^\circ\text{C}} = 3074\ \text{kJ/kg}$$

The general energy balance for the mixing process is

$$\dot{m}_1 \hat{H}_1 + \dot{m}_2 \hat{H}_2 = \dot{m}_3 \hat{H}_3$$



Substituting the values,

$$100\,\frac{\text{kg}}{\text{h}}\left(2675.4\,\frac{\text{kJ}}{\text{kg}}\right)+\dot{m}_2\left(3278\,\frac{\text{kJ}}{\text{kg}}\right)=\dot{m}_3\left(3074\ \text{kJ/kg}\right)$$

From the material balance equation,

$$\dot{m}_2=\dot{m}_3-100$$

Substitute the value of $\dot{m}_2$ in the earlier equation:

$$100\ \text{kg/h}\left(2675.4\ \text{kJ/kg}\right)+(\dot{m}_3-100)\left(3278\ \text{kJ/kg}\right)=\dot{m}_3\left(3074\ \text{kJ/kg}\right)$$

Solving for $\dot{m}_3$,

$$100\ \text{kg/h}\left(2675.4-3278\right)\text{kJ/kg}=\dot{m}_3\left(3074\ \text{kJ/kg}\right)-m_3\left(3278\ \text{kJ/kg}\right)$$

Rearranging,

$$\frac{100\times\left(2675.4-3278\right)\dfrac{\text{kJ}}{\text{h}}}{\left(3074-3278\right)\dfrac{\text{kJ}}{\text{kg}}}=\dot{m}_3$$

The rounded values of the mass flow rates of streams 3 and 2 are

$$\dot{m}_3=295\ \text{kg/h and}\ \dot{m}_2=195\ \text{kg/h}$$

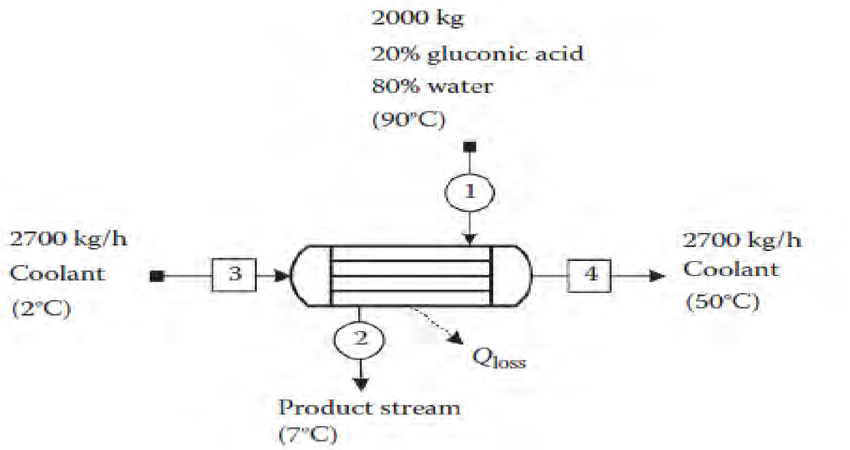
1.5.3 Energy Balance for Bioprocesses

Bioprocesses are unlike many chemical processes. Bioprocesses are not particularly energy intensive. Fermentation and enzyme reactors are operated at temperatures and pressures close to ambient conditions, and energy input for downstream processing is minimized to avoid damaging heat-labile products. Nevertheless, energy effects are important because biological catalysts are very sensitive to heat and changes in temperature. In large-scale processes, heat released during biochemical reactions can cause cell death of enzymes, if heat is not properly removed. The law of conservation of energy means that an energy accounting system can be set up to determine the amount of steam or cooling water required to maintain optimum process temperature [4].

Examples 1.21 Cooling of Fatty Acids

Problem

A liquid at the rate of 2000 kg/h fat (20 wt% acid, 80 wt% water) at 90°C is to be cooled to 7°C. Cooling is achieved by heat exchange with



EXAMPLE FIGURE 1.21.1
Shell and tube heat exchanger.

2700 kg/h coolant fluid initially at 2°C. The final temperature of the coolant liquid is 50°C. The fat is flowing on the shell side and coolant liquid is on the tube side. The heat exchanger is not adiabatic, so part of the heat is lost through the exchanger walls and the rest to coolant fluid. What is the rate of heat loss from the acid solution to the surroundings? Assume the heat capacity of acid is 1.463 (kJ/kg°C). The process flow sheet is shown in Example Figure 1.21.1.

Solution

Known quantities: Inlet and exit conditions of cooling water, inlet and exit temperature liquid stream.

Assumptions: No change in kinetic and potential energy, no shaft work.

Find: Heat loss through surroundings.

Analysis: Use the first law for an open system:

$$Q - W_s = \Delta \dot{H} + \Delta KE + \Delta PE$$

The simplified equation is

$$Q - 0 = \Delta \dot{H} + 0 + 0$$

For multiple input and multiple outputs, this equation is written as follows:

$$Q = \Delta \dot{H} = \sum_{\text{out}} \dot{m}_i h_i - \sum_{\text{in}} \dot{m}_i h_i$$

Let the subscript "c" be for coolant, "a" be for acid, and "w" be for water associated with the fat:

$$Q_{\text{loss}} = \{m_c h_{c,4} + m_a h_{a,2} + m_w h_{w,2}\}_{\text{out}} - \{m_c h_{c,3} + m_a h_{a,1} + m_w h_{w,1}\}_{\text{in}}$$

The mass flow rates of coolant, acid, and water are constant. Rearranging,

$$Q_{\text{loss}} = m_c\left(h_{c,4} - h_{c,3}\right) + m_a\left(h_{a,2} - h_{a,1}\right) + m_w\left(h_{w,2} - h_{w,1}\right)$$

The enthalpy of water is found from the steam table as saturated liquid water. The specific enthalpy of coolant medium at 2°C is 8.124 kJ/kg and at 50°C is 209.5 kJ/kg. Use the saturated steam table (Table A.4) to find the specific enthalpy of the water associated with the fat:

$$h_{w,1}\big|_{@90^\circ\text{C}} = 376.8\ \frac{\text{kJ}}{\text{kg}},\quad h_{w,1}\big|_{@7^\circ\text{C}} = 29.3\ \frac{\text{kJ}}{\text{kg}}$$

Substituting the values of mass flow rates and specific enthalpies of coolant, and water associated with steam and acid,

$$Q = 2700\ \frac{\text{kg}}{\text{h}} \times \frac{\text{h}}{3600\ \text{s}}\left(209.5\ \frac{\text{kJ}}{\text{kg}} - 8.124\ \frac{\text{kJ}}{\text{kg}}\right) + \left(2000\ \frac{\text{kg}}{\text{h}}\ \frac{\text{h}}{3600\ \text{s}}\right)$$
$$\times\left(29.3 - 376.8\ \frac{\text{kJ}}{\text{kg}}\right) + \left(400\ \frac{\text{kg}}{\text{h}}\ \frac{\text{h}}{3600\ \text{s}}\right)\left(1.463\ \frac{\text{kJ}}{\text{kg}^\circ\text{C}}\right)(7^\circ\text{C} - 90^\circ\text{C})$$

Solving for the heat loss Q,

$$Q = 151\ \text{kJ/s} - 193\ \text{kJ/s} - 13.49\ \text{kJ/s} = -55.49\ \text{kJ/s}$$

The sign for the heat transfer through the exchanger's wall is negative; that is, heat is lost from the fatty acid to the surroundings.

1.6 Psychrometric Chart

The psychrometric chart (Figure 1.3) displays the relationship between dry-bulb, wet-bulb, and dew point temperatures and specific and relative humidity. Given any two properties, the others can be calculated. To use the chart, take the point of intersection of the lines of any two known factors (interpolate if necessary), and, from that intersection point, follow the lines

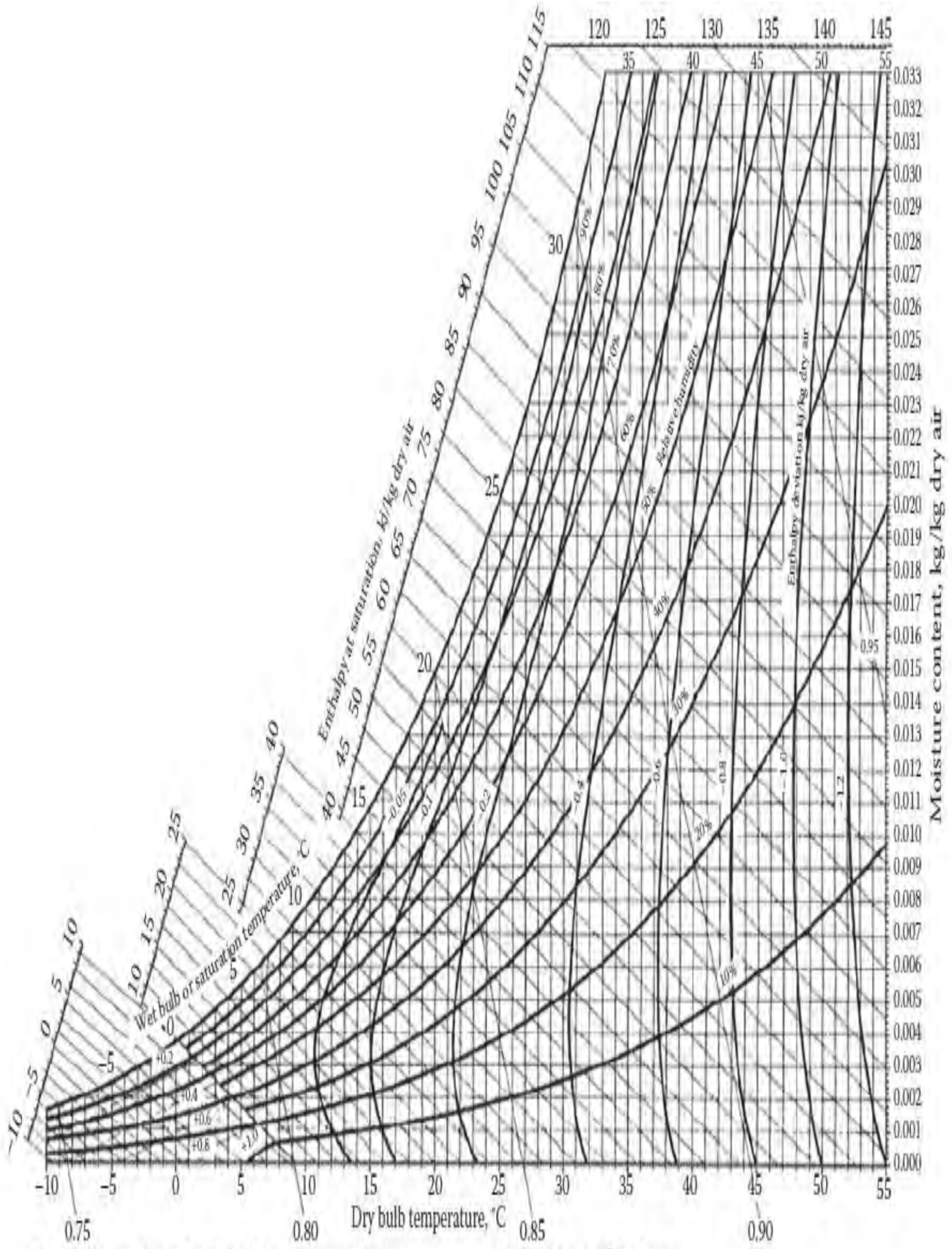


FIGURE 1.3

Psychrometric chart.

of the unknown factors to their numbered scales to obtain the corresponding values. The thermo-physical properties found on most psychrometric charts are as follows.

Dry-Bulb Temperature

Dry-bulb temperature is the temperature of an air sample, as determined by an ordinary thermometer, the thermometer bulb being dry. It is typically the abscissa or horizontal axis of the graph. The SI unit for temperature is Celsius, the other unit is Fahrenheit.

Wet-Bulb Temperature

Wet-bulb temperature is the temperature of an air sample after it has passed through a constant-pressure, ideal, adiabatic saturation process, that is, after the air has passed over a large surface of liquid water in an insulated channel. In practice, this is the reading of a thermometer whose sensing bulb is covered with a wet sock evaporating into a rapid stream of the air sample. The wet-bulb temperature is the same as the dry-bulb temperature when the air sample is saturated with water.

Dew Point Temperature

Dew point temperature is that temperature at which a moist air sample at the same pressure would reach water vapor saturation. At this saturation point, water vapor would begin to condense into liquid water fog.

Relative Humidity

Relative humidity is the ratio of the mole fraction of water vapor to the mole fraction of saturated moist air at the same temperature and pressure. Relative humidity is dimensionless, and is usually expressed as a percentage.

Humidity Ratio

Humidity ratio, also known as moisture content, mixing ratio, or specific humidity, is the proportion of mass of water vapor per unit mass of dry air at the given conditions. For a given dry-bulb temperature, there will be a particular humidity ratio for which the air sample is at 100% relative humidity. Humidity ratio is dimensionless, but is sometimes expressed as grams of water per kilogram of dry air.

Specific Enthalpy

Specific enthalpy, also called heat content per unit mass, is the sum of the internal (heat) energy of the moist air in question, including the heat of the air and water vapor within. In the approximation of ideal gases, lines of constant enthalpy are parallel to lines of constant wet-bulb temperature.

Specific Volume

Specific volume, also called inverse density, is the volume per unit mass of the air sample. The SI unit is cubic meters per kilogram of air; the other unit is cubic feet per pound of dry air.

Example 1.22 Psychrometric Chart

Humid air at 28°C has a dew point of 8°C. Using the psychrometric chart provided, determine the following: relative humidity, absolute humidity, wet-bulb temperature, dry-bulb temperature, humid volume, specific enthalpy, and mass of air that contains 2 kg of water, and volume occupied by air that contains 2 kg of water.

Solution

Known quantities: Humid air at 28°C has a dew point of 8°C. Air contains 2 kg of water, and volume occupied by air that contains 2 kg of water.

Find: Relative humidity, absolute humidity, wet-bulb temperature, dry bulb temperature, humid volume, specific enthalpy.

Analysis: Use psychrometric chart. Humid air at 28°C has a dew point of 8°C. Using the psychrometric chart provided, determine the following:

1. Relative humidity = 30% (Example Figure 1.22a.1).
2. Absolute humidity = 0.007 kg water/kg dry air (Example Figure 1.22b.1).

3. Wet-bulb temperature = 16.5°C (Example Figure 1.22c.1). Follow the constant enthalpy line from the intersection of the dry-bulb and dew point temperatures.

4. Dry-bulb temperature = 28°C.

5. Humid volume = 0.86 m3/kg (Example Figure 1.22d.1).

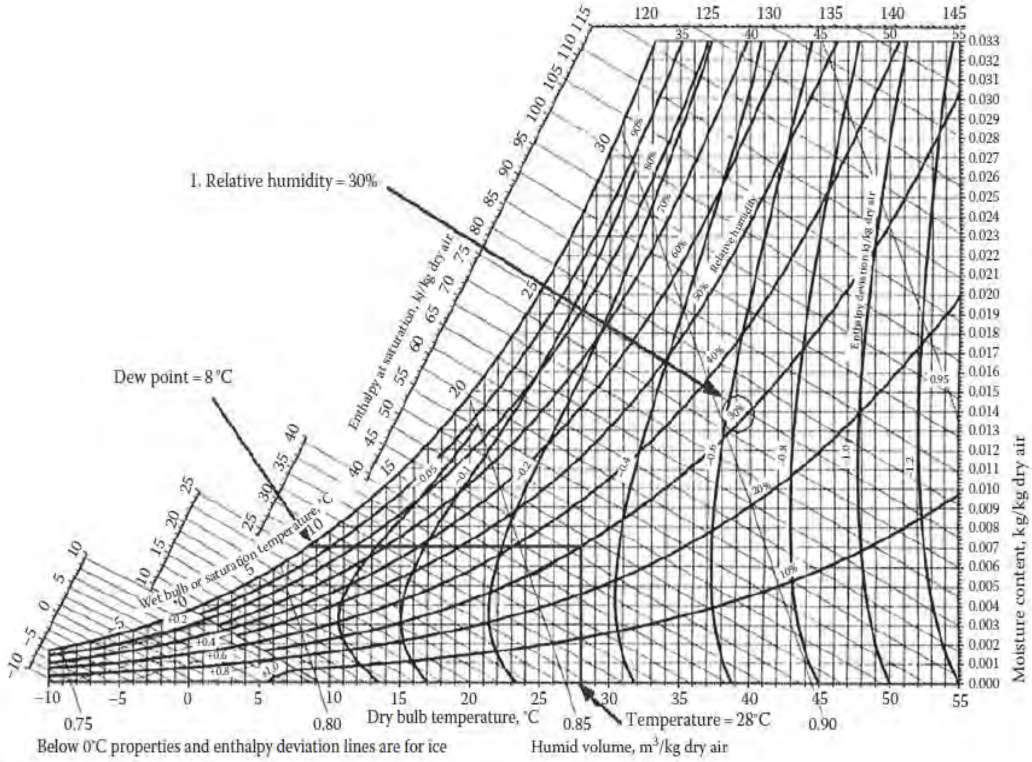
6. Specific enthalpy = 46 kJ/kg − 0.3 kJ/kg = 45.7 kJ/kg (Example Figure 1.22e.1).

7. Mass of air that contains 2 kg of water:

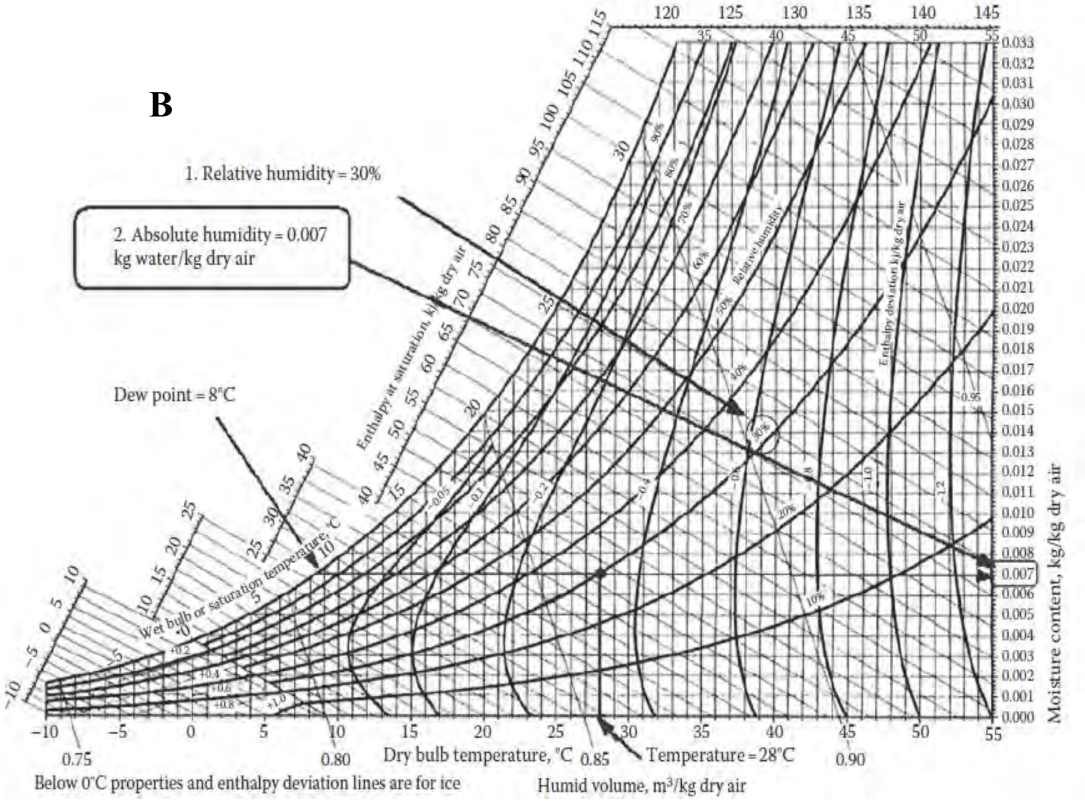
$$2\ \text{kg H}_2\text{O}\,\frac{\text{kg dry air}}{0.007\ \text{kg H}_2\text{O}} = 285.7\ \text{kg dry air}$$

8. Volume occupied by air that contains 2 kg of water:

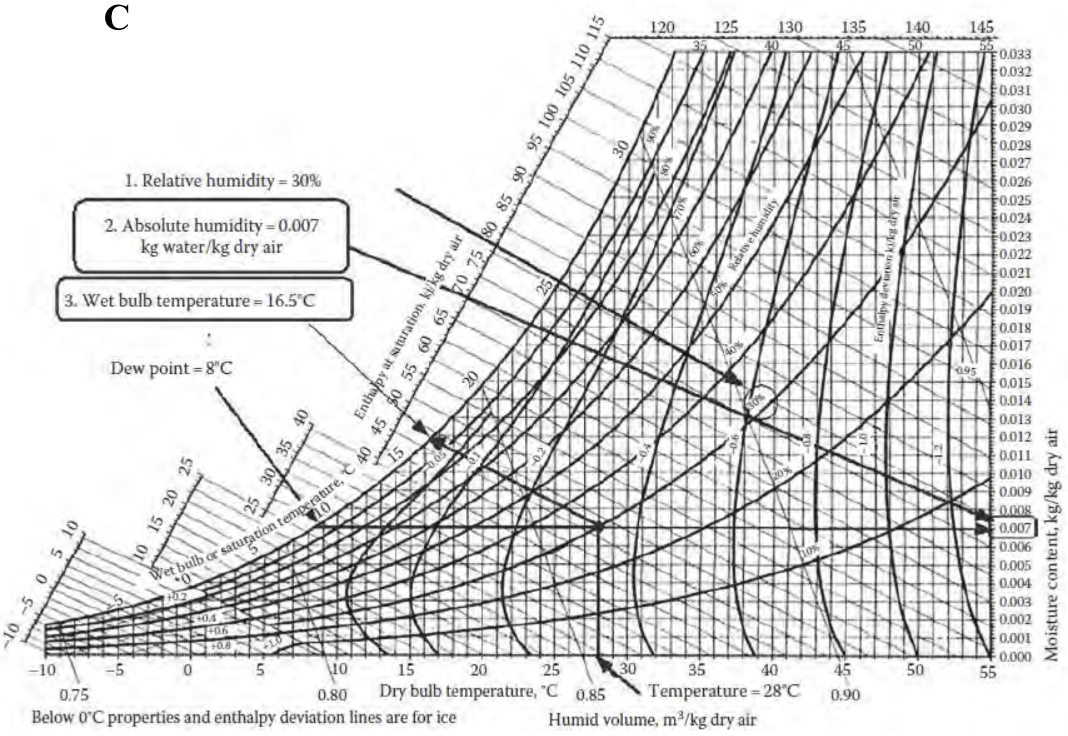
$$\frac{0.86\ \text{m}^3}{\text{kg dry air}}\,\frac{\text{kg dry air}}{0.007\ \text{kg H}_2\text{O}}\,2\ \text{kg H}_2\text{O} = 245.7\ \text{m}^3$$



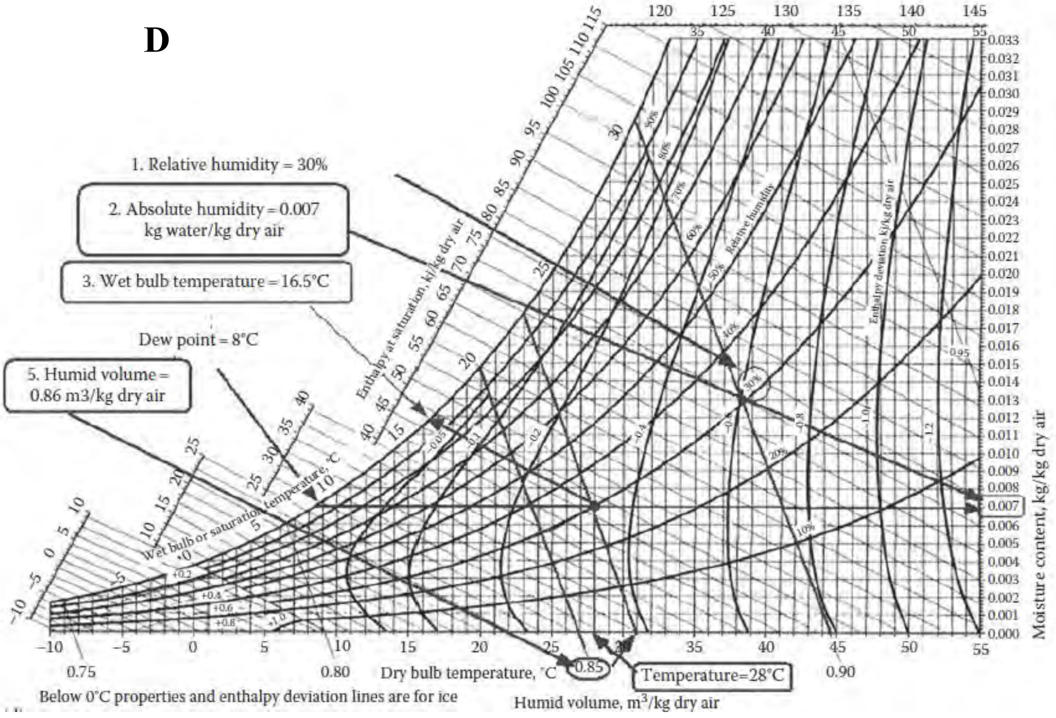
(a)


B
1. Relative humidity = 30%
2. Absolute humidity = 0.007 kg water/kg dry air
Dew point = 8°C
Temperature = 28°C
Enthalpy at saturation, kJ/kg dry air
Wet bulb or saturation temperature, °C
Relative humidity
Enthalpy deviation kJ/kg dry air
Dry bulb temperature, °C
Humid volume, m³/kg dry air
Moisture content, kg/kg dry air
Below 0°C properties and enthalpy deviation lines are for ice
0.75
0.80
0.85
0.90
0.95

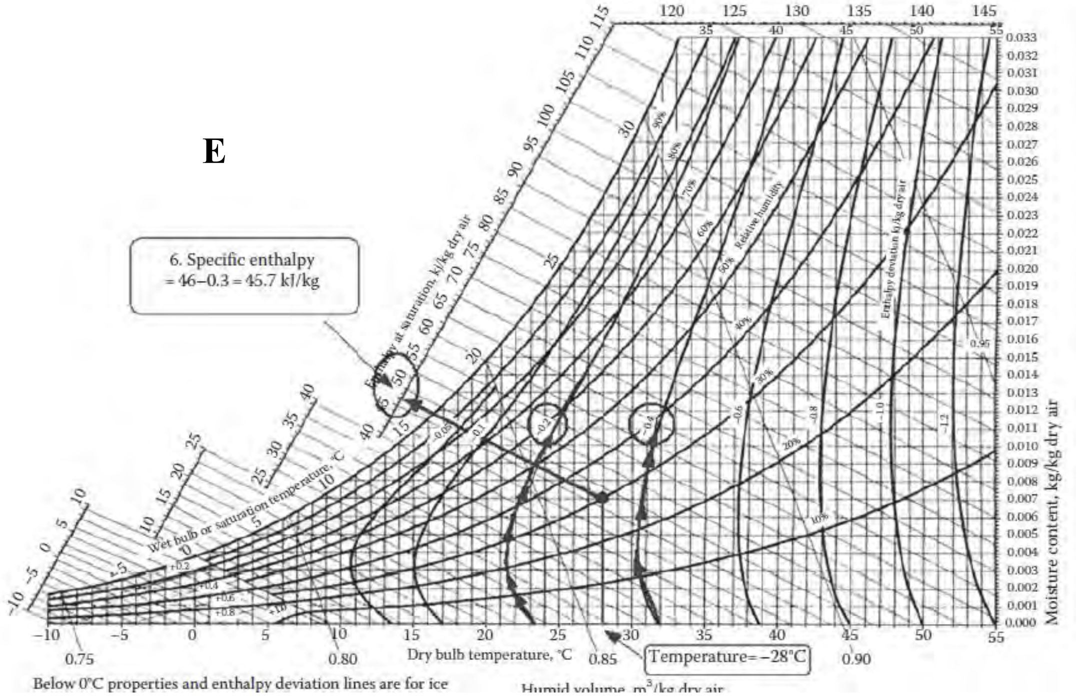
C


1. Relative humidity = 30%
2. Absolute humidity = 0.007 kg water/kg dry air
3. Wet bulb temperature = 16.5°C
Dew point = 8°C
Temperature = 28°C
Dry bulb temperature, °C
Humid volume, m³/kg dry air
Moisture content, kg/kg dry air
Enthalpy at saturation, kJ/kg dry air
Wet bulb or saturation temperature, °C
Relative humidity
Enthalpy deviation kJ/kg dry air
Below 0°C properties and enthalpy deviation lines are for ice

D


1. Relative humidity = 30%
2. Absolute humidity = 0.007 kg water/kg dry air
3. Wet bulb temperature = 16.5°C
Dew point = 8°C
5. Humid volume = 0.86 m3/kg dry air
Temperature=28°C
Dry bulb temperature, °C
Humid volume, m³/kg dry air
Moisture content, kg/kg dry air
Enthalpy at saturation, kJ/kg dry air
Wet bulb or saturation temperature, °C
Relative humidity
Enthalpy deviation kJ/kg dry air
Below 0°C properties and enthalpy deviation lines are for ice

E



Solution

Known quantities: Inlet air flow rate temperature and pressure.

Find: The molar flow rates of water, dry air, and oxygen entering the process.

Analysis: First, we calculate the partial pressure of water by using the definition of relative humidity:

$$0.8 = \frac{p_{H_2O}}{p^*_{H_2O}}$$

The vapor pressure at 25°C is 0.03 bar:

$$0.8 = \frac{p_{H_2O}}{0.03}$$

The partial pressure of water (p_{H_2O}) is 0.025 bar:

$$p_{H_2O} = y_{H_2O}P$$

Substitute values of partial pressure and total pressure:

$$0.025 = y_{H_2O}(3.0)$$

The mole fraction of water is 0.008 mol water/mole humid air, and the mole fraction of dry air is 0.992. The molar flow rate of air can be obtained using ideal gas equation of state using the volumetric flow rate given in the problem statement. After substituting the known information into this equation, we have

$$n = \frac{PV}{RT} = \frac{(3\ \mathrm{bar})(0.8\ \mathrm{m^3/h})}{\left(8.314\times10^{-5}\ \frac{\mathrm{m^3\cdot bar}}{\mathrm{mol\ K}}\right)(298\ \mathrm{K})} = 96.87\ \mathrm{mol/h}$$

The number of moles of dry air is

$$n_{\text{dry-air}} = y_{\text{dry-air}} \times \dot{n} = 0.992\times96.87\ \frac{\mathrm{mol}}{\mathrm{h}} = 96.1\ \mathrm{mol/h}$$

Example 1.25 Relative and Absolute Humidity

The dry-bulb temperature is measured as 20°C and the wet-bulb temperature as 15°C. If the total pressure is 1 atm, what are the relative humidity and the absolute humidity? Use the humidity chart.

Solution

Known quantities: Dry-bulb and wet-bulb temperatures of air.

Find: Relative and absolute humidity

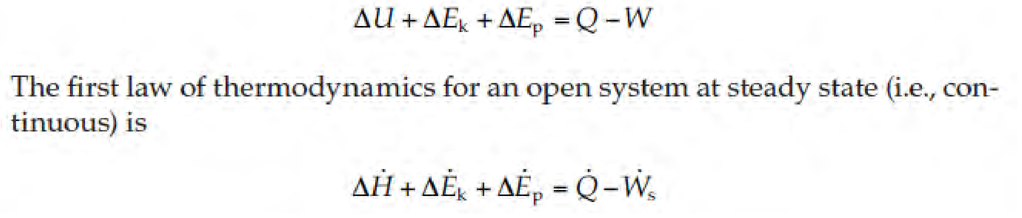
Analysis: Use the psychrometric chart.

Relative humidity = 59%

Absolute humidity = 0.0087 kg water/kg dry air

1.7 Summary

The first law of thermodynamics for a closed system is



$$\Delta U + \Delta E_k + \Delta E_p = Q - W$$

The first law of thermodynamics for an open system at steady state (i.e., continuous) is

$$\Delta \dot{H} + \Delta \dot{E}_k + \Delta \dot{E}_p = \dot{Q} - \dot{W}_s$$

Procedure for energy balance calculations:

1. Draw and completely label a process flowchart.
2. Perform all material balance calculations.
3. Write the appropriate form of the energy balance equation and remove any negligible terms.
4. Choose a reference state (phase-gas/liquid, T, P) for each species involved. If using enthalpy tables, use reference state to generate table. If no tables are available, choose one inlet or outlet condition as the reference state for the species.
5. Construct an inlet–outlet enthalpy table.
6. Calculate all required values of ui or hi and insert the values into the table.
7. Calculate ΔU or ΔH (e.g., $\Delta H = \Sigma mihi - \Sigma mihi$).
8. Calculate any other terms in the energy balance equation (i.e., W, ΔEk, ΔEp).
9. Solve for the unknown quantity in the energy balance equation.

Homework Problems

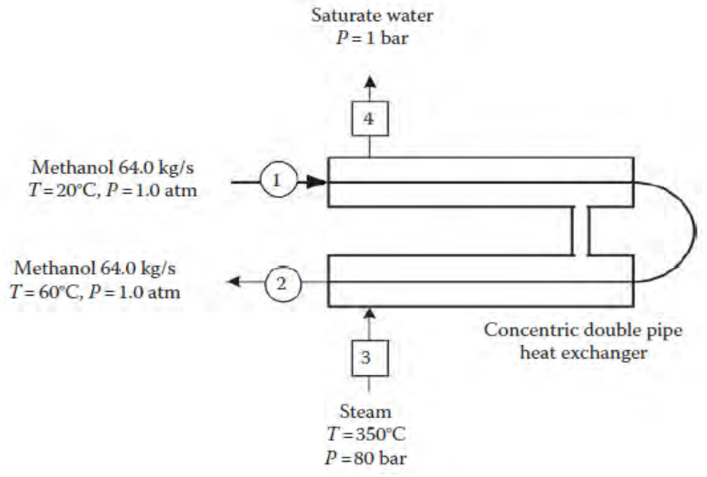
1.1 Liquid methanol at 25°C is heated and vaporized for use in a chemical reaction. How much heat is required to heat and vaporize 10 mol/s of methanol to 600°C. (744 kJ/s)

1.2 Propane gas at 40°C and 250 kPa enters an adiabatic heat exchanger and exits the heat exchanger at 240°C. The flow rate of propane is 100 mol/min. The saturated steam with a flow rate of 6 kg/min at 5 bar (absolute) enters the heat exchanger. The discharge wet steam (contains vapor and liquid) is at 3 bar. Calculate the exit steam quality and temperature. (0.86, 133.5°C)

1.3 Wet steam at 20 bar with 97% quality is passed through a throttling valve and expands to 1 bar pressure. Calculate the temperature of the steam that departs from the adiabatic expansion valve. (132.25°C)

1.4 Hundred kilograms per hour of wet steam at 20 bar with 97% quality is passed through a throttling valve and expands to 10 bar pressure. Calculate the temperature of the steam that departs from the adiabatic expansion valve and the quality of steam. (179.9°C, 0.982)

1.5 Methanol is heated by condensing steam in a concentric double pipe heat exchanger as depicted in Problem Figure 1.5.1. Methanol flowing through the inner pipe at 64.0 kg/s enters at 20°C and exits at 60°C. Steam enters the outer pipe at 350°C and 80 bar (absolute) and leaves the heat exchanger as saturated water at 1.0 bar. Assume that the outer pipe is well insulated and no heat is lost to the surroundings. Determine the mass flow rate of the steam. (2.57 kg/s)



PROBLEM FIGURE 1.5.1
Schematic of double pipe heat exchanger.

1.6 Calculate the heat rate required to heat 32.04 kg/s of liquid methyl alcohol (CH3OH) at 5°C and 1 atm to vapor at 500°C and 1 atm. The heat of vaporization of methanol at 64.7°C and 1 atm is 35.27 kJ/mol. (69.0 MW)

1.7 Determine the total amount of heat required to convert 2.00 mol of liquid *n*-hexane (C6H14) at 10°C to vapor at 55°C in a closed container. Assume that hexane vapor behaves as an ideal gas at the system pressure. Neglect any effect of a change in pressure on the liquid enthalpy. The heat of vaporization of hexane at 68.74°C and 1 atm is 28.85 kJ/mol. (63.26 kJ)

1.8 A volume of 734 cm3 of liquid acetone is contained in a closed cylinder fitted with a movable frictionless piston at 10°C. The acetone is heated via heating coil inserted inside the cylinder to vapor at 500°C. The piston area is 50.0 cm2, and the piston weighs 200 kg. The heat of vaporization of acetone at its normal boiling point (56.0°C) is 30.2 kJ/mol. Assume the cylinder is perfectly insulated and no heat is lost to the surroundings. Calculate the heat transferred from the heating process. (929 kJ)

1.9 A volume of 734 cm3 of liquid acetone is contained in a closed (vertical) cylinder fitted with a movable frictionless piston at 10°C. The acetone is heated via heating coil inserted inside the cylinder to vapor at 500°C. The piston area is 50.0 cm2, and the piston weighs 200 kg. The heat of vaporization of acetone at its normal boiling point (56.0°C) is 30.2 kJ/mol. Assume the cylinder is perfectly insulated and no heat is lost to the surroundings. If the heat is provided by superheated steam at 550°C and 1.0 bar, the final condition of the steam is saturated at 100°C. How much steam is needed? (1.0 kg)

1.10 A hydroelectric project has a volumetric flow rate of 1.2 m^3/s. The water flowing in the river at atmospheric pressure and 20.4°C falls vertically for 300 m and then passes through a turbine. The water exits the turbine at atmospheric pressure and 19°C. What is the power output of the turbine? (10.1 kW)

1.11 Air at 100 kPa and 10°C enters a compressor and is brought to 1000 kPa and 50°C. The constant pressure heat capacity of air is 1.01 kJ/kg K. If 15 kg/min of air are to be compressed, determine the power requirement of the compressor. State your assumptions. (12.625 kW)

1.12 A gasoline engine has an efficiency of 25%. If the engine consumes 0.75 L/h of gasoline with a heating value of 3.0 × 104 kJ/L, how much power does it provide? Express the answer in kilowatts. (1.56 kW) **1.13** A liquid stream (10 kg/min) flows through a heat exchanger in which it is heated from 25°C to 80°C. The liquid specific heat is 4.18 kJ/kg K. The inlet and outlet pipes have the same diameter, and there is no change in elevation between these points. Calculate the heat required. (38.3 kW)

1.14 Water (100 kg/s) passes through the gate of a dam and falls on a turbine 10 m below, which turns a shaft connected to a generator. The fluid velocity on both sides of the dam is negligible, and the water undergoes insignificant pressure and temperature changes between the inlet and outlet. Calculate the work generated by the turbine. (9.81 kW)

1.15 Crude oil is to be pumped at 1000 kg/min through a pipeline 2 km in length. The pipe inlet is 200 m below the outlet, the pipe diameter is constant. Neglect the pipe frictional losses. Calculate the work required by the pump. (32.7 kW)

1.16 A cylinder is fitted with a frictionless floating piston and contains 24.8 L of air at 25°C and 1 bar. The system is then heated to 250°C. ($C_v = 5R/2$). How much work was done by the system on the surroundings? (1.871 kJ)

1.17 A power plant (800 MW) burns natural gas to boil water producing saturated steam (100% quality) at 70 bar. This steam is expanded in a turbine to steam at 100°C and 1 bar. The steam enters the turbine at 10 m/s and exits 5 m below the entrance point level at 100 m/s. The turbine is connected to an electrical generator by a shaft. The efficiency of the turbine is 60%. What is the mass flow rate of steam to the turbine (kg/h)? (5.05×107 kg/h)

1.18 A large tank that is filled with water is open to the atmosphere. Water is taken from the tank, passed through a pump, and then delivered to the hoses of a firefighting extinguisher in a chemical factory. It is desired to deliver 69.5 lbm of water per second at a pressure of 200 psi (gauge). If there is a negligible elevation change between the water level in the tank and the discharge of the pump, no changes in the diameter of the pipes and hoses, and if the pump has an efficiency of 65.0%, how much work must be supplied to the pump in order to meet the pressure and discharge rate specifications? (89.7 hp)

1.19 Suppose you are operating a steam turbine where the steam leaving the turbine is at 5 bar (absolute). This steam contains 95 wt% vapors. If the shaft work produced by the turbine is 1100 kJ/kg and the high pressure, high temperature steam enters the turbine at 100 bar (abs), what is the temperature of the steam entering the turbine? If water at 10°C is supplied to the steam boiler to generate steam, how much heat is required per kilogram of steam produced? You may assume that heat losses from the turbine are negligible. (3700 kJ/kg)

1.20 Steam at 60 bar and 500°C enters an adiabatic turbine at a steady flow rate of 1 kg/s; the turbine outlet stream is at 1 bar and 400°C. The inlet and exit streams of the turbine are at the same height and the pipes have the same diameter of 0.15 m. How much work can be obtained from an adiabatic, continuous-flow turbine? (−144 kJ/s)

1.21 Consider taking 1000.0 kg of outside air, which is then heated to make your apartment comfortable in the winter. The outside air has a dry bulb temperature of 10.0°C and a wet-bulb temperature of 5°C. You want the air in your apartment to be at a dry-bulb temperature of 25°C and a relative humidity of 60.0%. (a) How much water must be added to the 1000.0 kg of outside air to reach the desired humidity level? (8.57 kg) (b) If the water you are using to alter the humidity of the air is coming from a tap (assume its temperature is 10°C), how much heat must be added to just the water to attain the desired temperature and humidity level in your apartment? (2.15 × 104kJ)

1.22 For healthy air quality, it is recommended that a 200 m2 house have an air exchange rate of 60.0 ft3 bone-dry air/min with the outside. It is also suggested that the relative humidity in the house be 65%. Suppose the outside air is at 30°F and a relative humidity of 40%. If this air is brought into the house and heated to 75°F without addition of water, what is the relative humidity? If you desire to maintain a relative humidity of 65%, how much water must be added to the air inside the house (g/min)? (24.3 g/min)

References

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

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

3. Himmelblau, D.M. (1974) *Basic Principles and Calculations in Chemical Engineering*, 3rd edn., Prentice-Hall, Englewood Cliffs, NJ.

4. Whirwell, J.C. and R.K. Toner (1969) *Conservation of Mass and Energy*, Blaisdell,
Waltham, MA.