turbine only? If the CV is the turbine plus the upstream flow up to the top of the lake, which terms in the energy equation are then important?

i. If you compress air, the temperature goes up. Why? When the hot air, at high P, flows in long pipes, it eventually cools to ambient T. How does that change the flow?

j. A mixing chamber has all flows at the same P, neglecting losses. A heat exchanger has separate flows exchanging energy, but they do not mix. Why have both kinds?

6.5 THE TRANSIENT PROCESS

In Sections 6.3 and 6.4 we considered the steady-state process and several examples of its application. Many processes of interest in thermodynamics involve unsteady flow and do not fit into this category. A certain group of these—for example, filling closed tanks with a gas or liquid, or discharge from closed vessels—can be reasonably represented to a first approximation by another simplified model. We call this process the transient process, for convenience, recognizing that our model includes specific assumptions that are not always valid. Our transient model assumptions are as follows:

1. The control volume remains constant relative to the coordinate frame.
2. The state of the mass within the control volume may change with time, but at any instant of time the state is uniform throughout the entire control volume (or over several identifiable regions that make up the entire control volume).
3. The state of the mass crossing each of the areas of flow on the control surface is constant with time, although the mass flow rates may vary with time.

Let us examine the consequence of these assumptions and derive an expression for the first law that applies to this process. The assumption that the control volume remains stationary relative to the coordinate frame has already been discussed in Section 6.3. The remaining assumptions lead to the following simplifications for the continuity equation and the first law.

The overall process occurs during time t. At any instant of time during the process, the continuity equation is

$$\frac{dm_{\text{C.V.}}}{dt} + \sum \dot{m}_e - \sum \dot{m}_i = 0$$

where the summation is over all areas on the control surface through which flow occurs. Integrating over time t gives the change of mass in the control volume during the overall process:

$$\int_0^t \left(\frac{dm_{\text{C.V.}}}{dt}\right) dt = (m_2 - m_1)_{\text{C.V.}}$$

The total mass leaving the control volume during time t is

$$\int_0^t \left(\sum \dot{m}_e\right) dt = \sum m_e$$

and the total mass entering the control volume during time t is

$$\int_0^t \left(\sum \dot{m}_i\right) dt = \sum m_i$$

Therefore, for this period of time t, we can write the continuity equation for the transient process as

$$(m_2 - m_1)_{\text{C.V.}} + \sum m_e - \sum m_i = 0 \tag{6.15}$$

In writing the first law of the transient process we consider Eq. 6.7, which applies at any instant of time during the process:

$$\dot{Q}_{\text{C.V.}} + \sum \dot{m}_i\left(h_i + \frac{\mathbf{V}_i^2}{2} + gZ_i\right) = \frac{dE_{\text{C.V.}}}{dt} + \sum \dot{m}_e\left(h_e + \frac{\mathbf{V}_e^2}{2} + gZ_e\right) + \dot{W}_{\text{C.V.}}$$

Since at any instant of time the state within the control volume is uniform, the first law for the transient process becomes

$$\dot{Q}_{\text{C.V.}} + \sum \dot{m}_i\left(h_i + \frac{\mathbf{V}_i^2}{2} + gZ_i\right) = \sum \dot{m}_e\left(h_e + \frac{\mathbf{V}_e^2}{2} + gZ_e\right) + \frac{d}{dt}\left[m\left(u + \frac{\mathbf{V}^2}{2} + gZ\right)\right]_{\text{C.V.}} + \dot{W}_{\text{C.V.}}$$

Let us now integrate this equation over time t, during which time we have

$$\int_0^t \dot{Q}_{\text{C.V.}}\, dt = Q_{\text{C.V.}}$$

$$\int_0^t \left[\sum \dot{m}_i\left(h_i + \frac{\mathbf{V}_i^2}{2} + gZ_i\right)\right] dt = \sum m_i\left(h_i + \frac{\mathbf{V}_i^2}{2} + gZ_i\right)$$

$$\int_0^t \left[\sum \dot{m}_e\left(h_e + \frac{\mathbf{V}_e^2}{2} + gZ_e\right)\right] dt = \sum m_e\left(h_e + \frac{\mathbf{V}_e^2}{2} + gZ_e\right)$$

$$\int_0^t \dot{W}_{\text{C.V.}}\, dt = W_{\text{C.V.}}$$

$$\int_0^t \frac{d}{dt}\left[m\left(u + \frac{\mathbf{V}^2}{2} + gZ\right)\right]_{\text{C.V.}} dt = \left[m_2\left(u_2 + \frac{\mathbf{V}_2^2}{2} + gZ_2\right) - m_1\left(u_1 + \frac{\mathbf{V}_1^2}{2} + gZ_1\right)\right]_{\text{C.V.}}$$

Therefore, for this period of time t, we can write the first law for the transient process as

$$Q_{\text{C.V.}} + \sum m_i\left(h_i + \frac{\mathbf{V}_i^2}{2} + gZ_i\right) = \sum m_e\left(h_e + \frac{\mathbf{V}_e^2}{2} + gZ_e\right) + \left[m_2\left(u_2 + \frac{\mathbf{V}_2^2}{2} + gZ_2\right) - m_1\left(u_1 + \frac{\mathbf{V}_1^2}{2} + gZ_1\right)\right]_{\text{C.V.}} + W_{\text{C.V.}} \tag{6.16}$$

As an example of the type of problem for which these assumptions are valid and Eq. 6.16 is appropriate, let us consider the classic problem of flow into an evacuated vessel. This is the subject of Example 6.11.

EXAMPLE 6.11

Steam at a pressure of 1.4 MPa and a temperature of 300°C is flowing in a pipe (Fig. 6.14). Connected to this pipe through a valve is an evacuated tank. The valve is opened and the tank fills with steam until the pressure is 1.4 MPa, and then the valve is closed. The process takes place adiabatically, and kinetic energies and potential energies are negligible. Determine the final temperature of the steam.

Control volume: Tank, as shown in Fig. 6.14.
Initial state (in tank): Evacuated, mass $m_1 = 0$.
Final state: P_2 known.
Inlet state: P_i, T_i (in line) known.
Process: Transient.
Model: Steam tables.

Analysis

From the first law, Eq. 6.16, we have

$$Q_{\text{C.V.}} + \sum m_i \left(h_i + \frac{\mathbf{V}_i^2}{2} + gZ_i \right)$$
$$= \sum m_e \left(h_e + \frac{\mathbf{V}_e^2}{2} + gZ_e \right)$$
$$+ \left[m_2 \left(u_2 + \frac{\mathbf{V}_2^2}{2} + gZ_2 \right) - m_1 \left(u_1 + \frac{\mathbf{V}_1^2}{2} + gZ_1 \right) \right]_{\text{C.V.}} + W_{\text{C.V.}}$$

We note that $Q_{\text{C.V.}} = 0$, $W_{\text{C.V.}} = 0$, $m_e = 0$, and $(m_1)_{\text{C.V.}} = 0$. We further assume that changes in kinetic and potential energy are negligible. Therefore, the statement of the first law for this process reduces to

$$m_i h_i = m_2 u_2$$

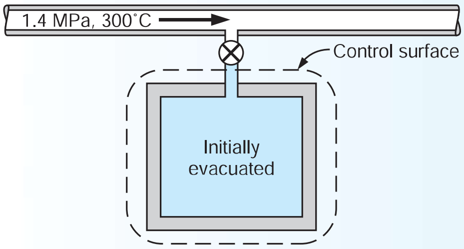

FIGURE 6.14 Flow into an evacuated vessel—control volume analysis.

From the continuity equation for this process, Eq. 6.15, we conclude that

$$m_2 = m_i$$

Therefore, combining the continuity equation with the first law, we have

$$h_i = u_2$$

That is, the final internal energy of the steam in the tank is equal to the enthalpy of the steam entering the tank.

Solution

From the steam tables we obtain

$$h_i = u_2 = 3040.4 \text{ kJ/kg}$$

Since the final pressure is given as 1.4 MPa, we know two properties at the final state and therefore the final state is determined. The temperature corresponding to a pressure of 1.4 MPa and an internal energy of 3040.4 kJ/kg is found to be 452°C.

This problem can also be solved by considering the steam that enters the tank and the evacuated space as a control mass, as indicated in Fig. 6.15.

The process is adiabatic, but we must examine the boundaries for work. If we visualize a piston between the steam that is included in the control mass and the steam that flows behind, we readily recognize that the boundaries move and that the steam in the pipe does work on the steam that comprises the control mass. The amount of this work is

$$-W = P_1 V_1 = mP_1 v_1$$

Writing the first law for the control mass, Eq. 5.11, and noting that kinetic and potential energies can be neglected, we have

$$_1Q_2 = U_2 - U_1 + {_1W_2}$$

$$0 = U_2 - U_1 - P_1 V_1$$

$$0 = mu_2 - mu_1 - mP_1 v_1 = mu_2 - mh_1$$

Therefore,

$$u_2 = h_1$$

which is the same conclusion that was reached using a control volume analysis.

The two other examples that follow illustrate further the transient process.

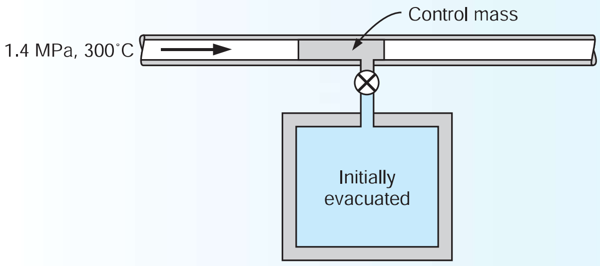

FIGURE 6.15 Flow into an evacuated vessel—control mass.

EXAMPLE 6.12 Let the tank of the previous example have a volume of 0.4 m^3 and initially contain saturated vapor at 350 kPa. The valve is then opened, and steam from the line at 1.4 MPa and 300°C flows into the tank until the pressure is 1.4 MPa.

Calculate the mass of steam that flows into the tank.

Control volume: Tank, as in Fig. 6.14.
Initial state: P_1, saturated vapor; state fixed.
Final state: P_2.
Inlet state: P_i, T_i; state fixed.
Process: Transient.
Model: Steam tables.

Analysis

The situation is the same as in Example 6.11, except that the tank is not evacuated initially. Again we note that $Q_{\text{C.V.}} = 0$, $W_{\text{C.V.}} = 0$, and $m_e = 0$, and we assume that changes in kinetic and potential energy are zero. The statement of the first law for this process, Eq. 6.16, reduces to

$$m_i h_i = m_2 u_2 - m_1 u_1$$

The continuity equation, Eq. 6.15, reduces to

$$m_2 - m_1 = m_i$$

Therefore, combining the continuity equation with the first law, we have

$$(m_2 - m_1) h_i = m_2 u_2 - m_1 u_1$$

$$m_2 (h_i - u_2) = m_1 (h_i - u_1) \qquad \text{(a)}$$

There are two unknowns in this equation—m_2 and u_2. However, we have one additional equation:

$$m_2 v_2 = V = 0.4 \text{ m}^3 \qquad \text{(b)}$$

Substituting (b) into (a) and rearranging, we have

$$\frac{V}{v_2}(h_i - u_2) - m_1 (h_i - u_1) = 0 \qquad \text{(c)}$$

in which the only unknowns are v_2 and u_2, both functions of T_2 and P_2. Since T_2 is unknown, it means that there is only one value of T_2 for which Eq. (c) will be satisfied, and we must find it by trial and error.

Solution

We have

$$v_1 = 0.5243 \text{ m}^3/\text{kg}, \qquad m_1 = \frac{0.4}{0.5243} = 0.763 \text{ kg}$$

$$h_i = 3040.4 \text{ kJ/kg}, \qquad u_1 = 2548.9 \text{ kJ/kg}$$

Assume that

$$T_2 = 300°\text{C}$$

For this temperature and the known value of P_2, we get

$$v_2 = 0.1823 \text{ m}^3/\text{kg}, \qquad u_2 = 2785.2 \text{ kJ/kg}$$

Substituting into (c), we obtain

$$\frac{0.4}{0.1823}(3040.4 - 2785.2) - 0.763(3040.4 - 2548.9) = +185.0 \text{ kJ}$$

Now assume instead that

$$T_2 = 350°\text{C}$$

For this temperature and the known P_2, we get

$$v_2 = 0.2003 \text{ m}^3/\text{kg}, \qquad u_2 = 2869.1 \text{ kJ/kg}$$

Substituting these values into (c), we obtain

$$\frac{0.4}{0.2003}(3040.4 - 2869.1) - 0.763(3040.4 - 2548.9) = -32.9 \text{ kJ}$$

and we find that the actual T_2 must be between these two assumed values in order that (c) be equal to zero. By interpolation,

$$T_2 = 342°\text{C} \quad \text{and} \quad v_2 = 0.1974 \text{ m}^3/\text{kg}$$

The final mass inside the tank is

$$m_2 = \frac{0.4}{0.1974} = 2.026 \text{ kg}$$

and the mass of steam that flows into the tank is

$$m_i = m_2 - m_1 = 2.026 - 0.763 = 1.263 \text{ kg}$$

EXAMPLE 6.13

A tank of 2 m^3 volume contains saturated ammonia at a temperature of 40°C. Initially the tank contains 50% liquid and 50% vapor by volume. Vapor is withdrawn from the top of the tank until the temperature is 10°C. Assuming that only vapor (i.e., no liquid) leaves and that the process is adiabatic, calculate the mass of ammonia that is withdrawn.

Control volume: Tank.
Initial state: T_1, V_{liq}, V_{vap}; state fixed.
Final state: T_2.
Exit state: Saturated vapor (temperature changing).
Process: Transient.
Model: Ammonia tables.

Analysis

In the first law, Eq. 6.16, we note that $Q_{\text{C.V.}} = 0$, $W_{\text{C.V.}} = 0$, and $m_i = 0$, and we assume that changes in kinetic and potential energy are negligible. However, the enthalpy of saturated vapor varies with temperature, and therefore we cannot simply assume that the enthalpy of the vapor leaving the tank remains constant. However, we note that at 40°C, $h_g = 1470.2$ kJ/kg and at 10°C, $h_g = 1452.0$ kJ/kg. Since the change in h_g during this process is small, we may accurately assume that h_e is the average of the two values given above. Therefore,

$$(h_e)_{\text{av}} = 1461.1 \text{ kJ/kg}$$

and the first law reduces to

$$m_e h_e + m_2 u_2 - m_1 u_1 = 0$$

and the continuity equation (from Eq. 6.15) becomes

$$(m_2 - m_1)_{\text{C.V.}} + m_e = 0$$

Combining these two equations, we have

$$m_2(h_e - u_2) = m_1 h_e - m_1 u_1$$

Solution

The following values are from the ammonia tables:

$$v_{f1} = 0.001\,725 \text{ m}^3/\text{kg}, \qquad v_{g1} = 0.083\,13 \text{ m}^3/\text{kg}$$

$$v_{f2} = 0.001\,60, \qquad v_{fg2} = 0.203\,81$$

$$u_{f1} = 368.7 \text{ kJ/kg}, \qquad u_{g1} = 1341.0 \text{ kJ/kg}$$

$$u_{f2} = 226.0, \qquad u_{fg2} = 1099.7$$

Calculating first the initial mass, m_1, in the tank, we find that the mass of the liquid initially present, m_{f1}, is

$$m_{f1} = \frac{V_f}{v_{f1}} = \frac{1.0}{0.001\,725} = 579.7 \text{ kg}$$

Similarly, the initial mass of vapor, m_{g1}, is

$$m_{g1} = \frac{V_g}{v_{g1}} = \frac{1.0}{0.083\,13} = 12.0 \text{ kg}$$

$$m_1 = m_{f1} + m_{g1} = 579.7 + 12.0 = 591.7 \text{ kg}$$

$$m_1 h_e = 591.7 \times 1461.1 = 864\,533 \text{ kJ}$$

$$m_1 u_1 = (mu)_{f1} + (mu)_{g1} = 579.7 \times 368.7 + 12.0 \times 1341.0$$

$$= 229\,827 \text{ kJ}$$

Substituting these into the first law, we obtain

$$m_2(h_e - u_2) = m_1 h_e - m_1 u_1 = 864\,533 - 229\,827 = 634\,706 \text{ kJ}$$

There are two unknowns, m_2 and u_2, in this equation. However,

$$m_2 = \frac{V}{v_2} = \frac{2.0}{0.001\,60 + x_2(0.203\,81)}$$

and

$$u_2 = 226.0 + x_2(1099.7)$$

and thus both are functions only of x_2, the quality at the final state. Consequently,

$$\frac{2.0(1461.1 - 226.0 - 1099.7x_2)}{0.001\,60 + 0.203\,81x_2} = 634\,706$$

Solving for x_2, we get

$$x_2 = 0.011\,057$$

Therefore,

$$v_2 = 0.001\,60 + 0.011\,057 \times 0.203\,81 = 0.003\,853\,5\ \text{m}^3/\text{kg}$$

$$m_2 = \frac{V}{v_2} = \frac{2}{0.003\,853\,5} = 519\ \text{kg}$$

and the mass of ammonia withdrawn, m_e, is

$$m_e = m_1 - m_2 = 591.7 - 519 = 72.7\ \text{kg}$$

EXAMPLE 6.13E

A tank of 50 ft^3 volume contains saturated ammonia at a temperature of 100 F. Initially the tank contains 50% liquid and 50% vapor by volume. Vapor is withdrawn from the top of the tank until the temperature is 50 F. Assuming that only vapor (i.e., no liquid) leaves and that the process is adiabatic, calculate the mass of ammonia that is withdrawn.

Control volume: Tank.
Initial state: T_1, V_{liq}, V_{vap}; state fixed.
Final state: T_2.
Exit state: Saturated vapor (temperature changing).
Process: Transient.
Model: Ammonia tables.

Analysis

In the first law, Eq. 6.16, we note that $Q_{\text{C.V.}} = 0$, $W_{\text{C.V.}} = 0$, and $m_i = 0$, and we assume that changes in kinetic and potential energy are negligible. However, the enthalpy of saturated vapor varies with temperature, and therefore we cannot simply assume that the enthalpy of the vapor leaving the tank remains constant. We note that at 100 F, $h_g = 631.8$ Btu/lbm and at 50 F, $h_g = 624.26$ Btu/lbm. Since the change in h_g during this process is small, we may accurately assume that h_e is the average of the two values given above. Therefore

$$(h_e)_{\text{avg}} = 628 \text{ Btu/lbm}$$

and the first law reduces to

$$m_e h_e + m_2 u_2 - m_1 u_1 = 0$$

and the continuity equation (from Eq. 6.15) is

$$(m_2 - m_1)_{\text{C.V.}} + m_e = 0$$

Combining these two equations, we have

$$m_2(h_e - u_2) = m_1 h_e - m_1 u_1$$

The following values are from the ammonia tables:

$$v_{f1} = 0.0274\,7 \text{ ft}^3/\text{lbm}, \qquad v_{g1} = 1.4168 \text{ ft}^3/\text{lbm}$$

$$v_{f2} = 0.025\,64 \text{ ft}^3/\text{lbm} \qquad v_{fg2} = 3.264\,7 \text{ ft}^3/\text{lbm}$$

$$u_{f1} = 153.89 \text{ Btu/lbm}, \qquad u_{g1} = 576.23 \text{ Btu/lbm}$$

$$u_{f2} = 97.16 \text{ Btu/lbm}, \qquad u_{fg2} = 472.78 \text{ Btu/lbm}$$

Calculating first the initial mass, m_1, in the tank, the mass of the liquid initially present, m_{f1}, is

$$m_{f1} = \frac{V_f}{v_{f1}} = \frac{25}{0.027\,47} = 910.08 \text{ lbm}$$

Similarly, the initial mass of vapor, m_{g1}, is

$$m_{g1} = \frac{V_g}{v_{g1}} = \frac{25}{1.416\,8} = 17.65 \text{ lbm}$$

$$m_1 = m_{f1} + m_{g1} = 910.08 + 17.65 = 927.73 \text{ lbm}$$

$$m_1 h_e = 927.73 \times 628 = 582\,614 \text{ Btu}$$

$$m_1 u_1 = (mu)_{f1} + (mu)_{g1} = 910.08 \times 153.89 + 17.65 \times 576.23 = 150\,223 \text{ Btu}$$

Substituting these into the first law,

$$m_2(h_e - u_2) = m_1 h_e - m_1 u_1 = 582\,614 - 150\,223 = 432\,391 \text{ Btu}$$

There are two unknowns, m_2 and u_2, in this equation. However,

$$m_2 = \frac{V}{v_2} = \frac{50}{0.025\,64 + x_2(3.264\,7)}$$

and

$$u_2 = 97.16 + x_2(472.78)$$

both functions only of x_2, the quality at the final state. Consequently,

$$\frac{50(628 - 97.16 - x_2\,472.78)}{0.025\,64 + 3.2647\,x_2} = 432\,391$$

Solving,

$$x_2 = 0.010\,768$$

Therefore,

$$v_2 = 0.025\,64 + 0.010\,768 \times 3.264\,7 = 0.060\,794 \text{ ft}^3/\text{lbm}$$

$$m_2 = \frac{V}{v_2} = \frac{50}{0.060\,794} = 822.4 \text{ lbm}$$

and the mass of ammonia withdrawn, m_e, is

$$m_e = m_1 - m_2 = 927.73 - 822.4 = 105.3 \text{ lbm}$$

In-Text Concept Question

k. An initially empty cylinder is filled with air from 20°C, 100 kPa until is is full. Assuming no heat transfer, is the final temperature larger than, equal to, or smaller than 20°C? Does the final T depend on the size of the cylinder?

6.6 ENGINEERING APPLICATIONS

Flow Systems and Flow Devices

The majority of devices and technical applications of energy conversions and transfers involve the flow of a substance. They can be passive devices like valves and pipes to active devices like turbans and pumps that involve work or heat exchangers that involve a heat transfer in or out of the flowing fluid.

Passive Devices as Nozzles, Diffusers, and Valves or Throttles

A nozzle is a passive (no moving parts) device that increases the velocity of a fluid stream at the expense of its pressure. Its shape, smoothly contoured, depends on whether the flow is subsonic or supersonic. The large nozzle of the NASA space shuttle's main engine was shown in Fig. 1.12*b*. A diffuser, basically the opposite of a nozzle, is shown in Fig. 6.16, in connection with flushing out a fire hydrant without having a high-velocity stream of water.

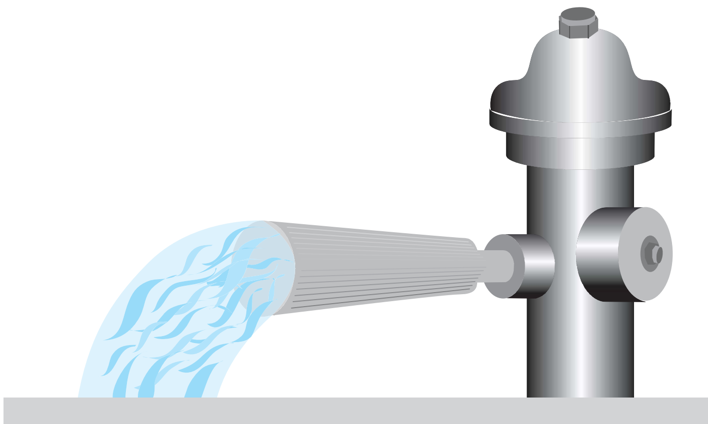

FIGURE 6.16 Diffuser.