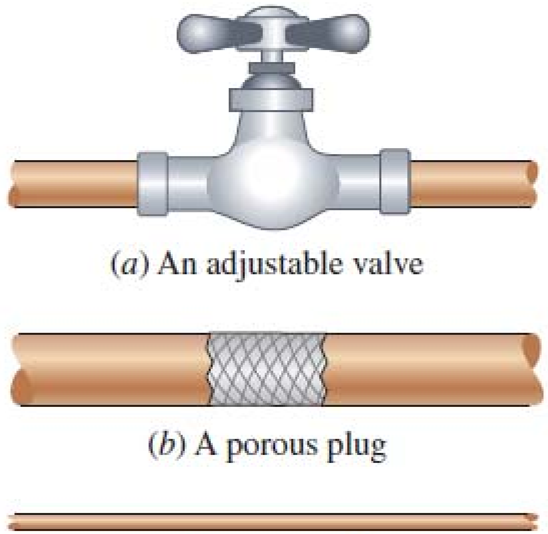
Throttling valves :



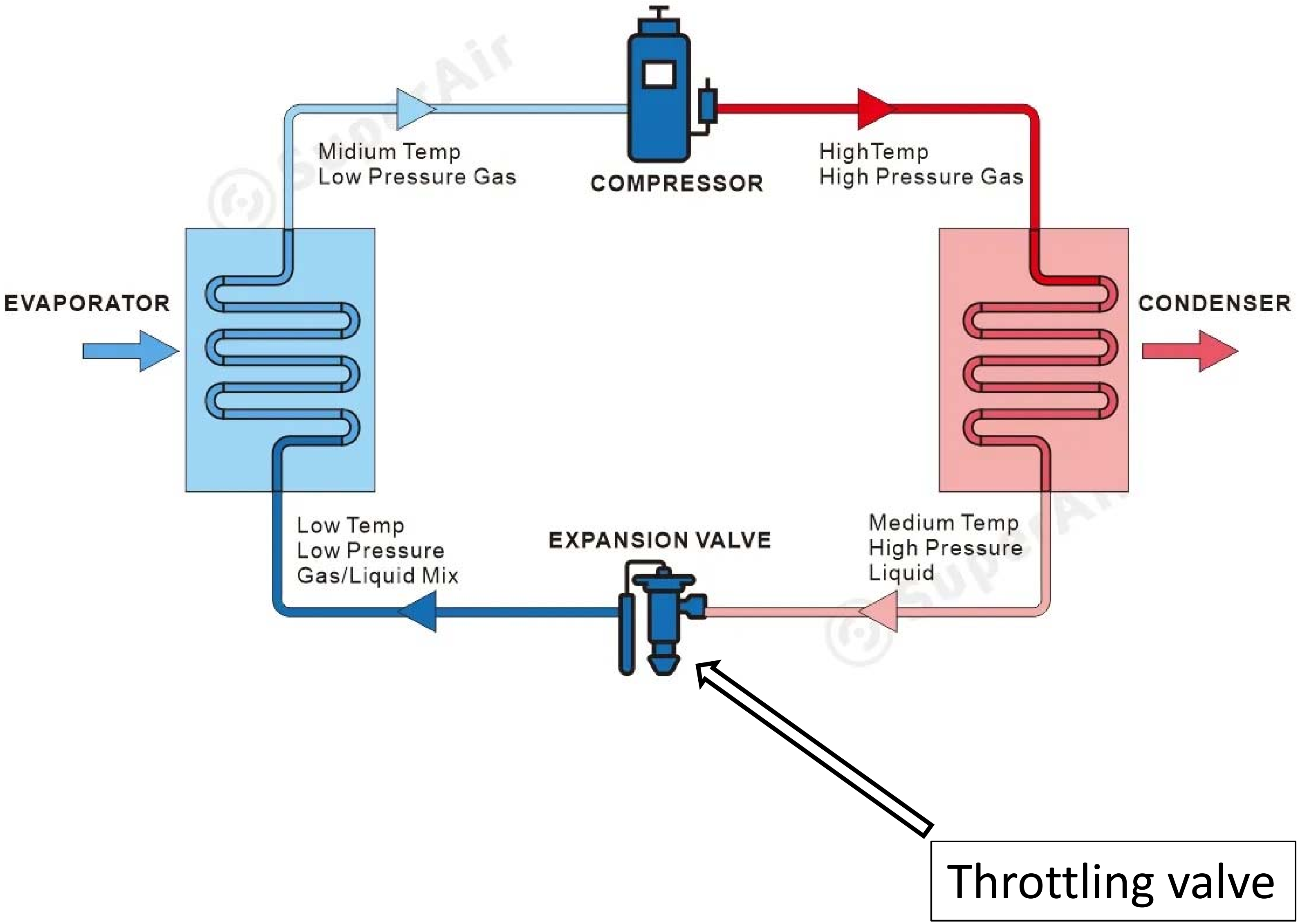
(*a*) An adjustable valve

(*b*) A porous plug

(*c*) A capillary tube

Throttling valves are *any kind of flow-restricting devices* that cause a significant pressure drop in the fluid. Some familiar examples are ordinary adjustable valves, capillary tubes, and porous plugs . Unlike turbines, they produce a pressure drop without involving any work. The pressure drop in the fluid is often accompanied by a *large drop in temperature,* and for that reason throttling devices are commonly used in refrigeration and air-conditioning applications. The magnitude of the temperature drop (or, sometimes, the temperature rise) during a throttling process is governed by a property called the *Joule-Thomson coefficient,* This property will be discussed later in the course

Use of Throttling (or expansion) valves in refrigeration :



Throttling valves :

Throttling valves are usually small devices, and the flow through them may be assumed to be adiabatic ($q \cong 0$) since there is neither sufficient time nor large enough area for any effective heat transfer to take place. Also, there is no work done ($w = 0$), and the change in potential energy, if any, is very small ($\Delta pe \cong 0$). Even though the exit velocity is often considerably higher than the inlet velocity, in many cases, the increase in kinetic energy is insignificant ($\Delta ke \cong 0$).

Thus neglecting the terms as described above, the first law equation reduces to

$$h_2 \cong h_1 \quad \text{(kJ/kg)}$$

Throttling valves :

Refrigerant-134a enters the capillary tube of a refrigerator as saturated liquid at 0.8 MPa and is throttled to a pressure of 0.12 MPa. Determine the quality of the refrigerant at the final state and the temperature drop during this process.

SOLUTION Refrigerant-134a that enters a capillary tube as saturated liquid is throttled to a specified pressure. The exit quality of the refrigerant and the temperature drop are to be determined.

Assumptions **1** Heat transfer from the tube is negligible. **2** Kinetic energy change of the refrigerant is negligible.

Analysis A capillary tube is a simple flow-restricting device that is commonly used in refrigeration applications to cause a large pressure drop in the refrigerant. Flow through a capillary tube is a throttling process; thus, the enthalpy of the refrigerant remains constant (Fig. 5–34).

Throttling valves :

$$\text{At inlet: } \left.\begin{array}{l} P_1 = 0.8 \text{ MPa} \\ \text{sat. liquid} \end{array}\right\} \begin{array}{l} T_1 = T_{\text{sat @ 0.8 MPa}} = 31.31°\text{C} \\ h_1 = h_{f\,@\,0.8\text{ MPa}} = 95.48 \text{ kJ/kg} \end{array} \quad \text{(Table A–12)}$$

$$\text{At exit: } \begin{array}{l} P_2 = 0.12 \text{ MPa} \\ (h_2 = h_1) \end{array} \longrightarrow \begin{array}{l} h_f = 22.47 \text{ kJ/kg} \quad T_{\text{sat}} = -22.32°\text{C} \\ h_g = 236.99 \text{ kJ/kg} \end{array}$$

Obviously $h_f < h_2 < h_g$; thus, the refrigerant exists as a saturated mixture at the exit state. The quality at this state is

$$x_2 = \frac{h_2 - h_f}{h_{fg}} = \frac{95.48 - 22.47}{236.99 - 22.47} = \mathbf{0.340}$$

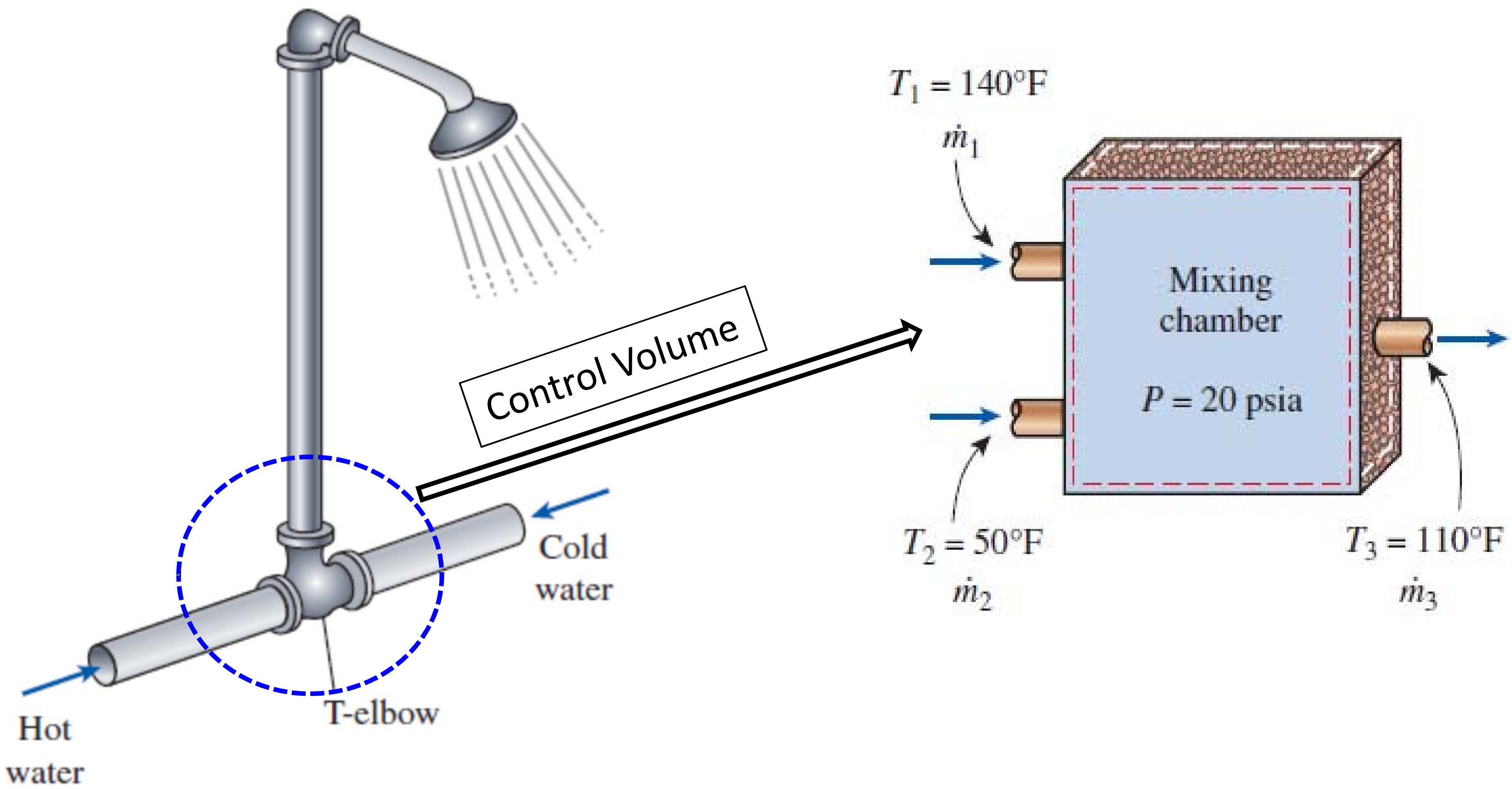
Since the exit state is a saturated mixture at 0.12 MPa, the exit temperature must be the saturation temperature at this pressure, which is −22.32°C. Then the temperature change for this process becomes

$$\Delta T = T_2 - T_1 = (-22.32 - 31.31)°\text{C} = \mathbf{-53.63°C}$$

Discussion Note that the temperature of the refrigerant drops by 53.63°C during this throttling process. Also note that 34.0 percent of the refrigerant vaporizes during this throttling process, and the energy needed to vaporize this refrigerant is absorbed from the refrigerant itself.

Mixing chambers : example

Consider an ordinary shower where hot water at 140°F is mixed with cold water at 50°F. If it is desired that a steady stream of warm water at 110°F be supplied, determine the ratio of the mass flow rates of the hot to cold water. Assume the heat losses from the mixing chamber to be negligible and the mixing to take place at a pressure of 20 psia.



Mixing chambers : example

SOLUTION In a shower, cold water is mixed with hot water at a specified temperature. For a specified mixture temperature, the ratio of the mass flow rates of the hot to cold water is to be determined.

Assumptions **1** This is a steady-flow process since there is no change with time at any point and thus $\Delta m_{CV} = 0$ and $\Delta E_{CV} = 0$. **2** The kinetic and potential energies are negligible, ke $\cong$ pe $\cong$ 0. **3** Heat losses from the system are negligible and thus $\dot{Q} \cong 0$. **4** There is no work interaction involved.

Analysis We take the *mixing chamber* as the system (Fig. 5–36). This is a *control volume* since mass crosses the system boundary during the process. We observe that there are two inlets and one exit.

Under the stated assumptions and observations, the mass and energy balances for this steady-flow system can be expressed in the rate form as follows:

Mass balance:

$$\dot{m}_{\text{in}} = \dot{m}_{\text{out}} \rightarrow \dot{m}_1 + \dot{m}_2 = \dot{m}_3$$

Mixing chambers : example

Energy balance:

$$\dot{m}_1 h_1 + \dot{m}_2 h_2 = \dot{m}_3 h_3 \quad (\text{since } \dot{Q} \cong 0, \dot{W} = 0, \text{ke} \cong \text{pe} \cong 0)$$

Combining the mass and energy balances,

$$\dot{m}_1 h_1 + \dot{m}_2 h_2 = (\dot{m}_1 + \dot{m}_2) h_3$$

Dividing this equation by $\dot{m}_2$ yields

$$y h_1 + h_2 = (y + 1) h_3$$

where $y = \dot{m}_1 / \dot{m}_2$ is the desired mass flow rate ratio.

The saturation temperature of water at 20 psia is 227.92°F. Since the temperatures of all three streams are below this value ($T < T_{sat}$), the water in all three streams exists as a compressed liquid A compressed liquid can be approximated as a saturated liquid at the given temperature.

Mixing chambers : example

Energy balance:

Thus,

$$h_1 \cong h_{f\,@\,140°F} = 107.99\ \text{Btu/lbm}$$

$$h_2 \cong h_{f\,@\,50°F} = 18.07\ \text{Btu/lbm}$$

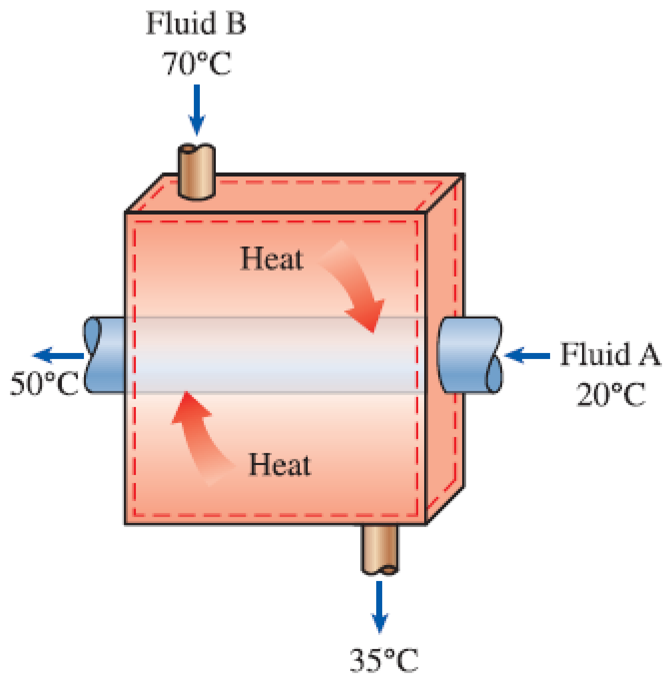
$$h_3 \cong h_{f\,@\,110°F} = 78.02\ \text{Btu/lbm}$$

Solving for y and substituting yields

$$y = \frac{h_3 - h_2}{h_1 - h_3} = \frac{78.02 - 18.07}{107.99 - 78.02} = \mathbf{2.0}$$

Discussion Note that the mass flow rate of the hot water must be twice the mass flow rate of the cold water for the mixture to leave at 110°F.

Heat exchangers :



As the name implies, **heat exchangers** are devices where two moving fluid streams exchange heat without mixing. Heat exchangers are widely used in various industries, and they come in various designs.

The simplest form of a heat exchanger is a *double-tube* (also called *tube-and-shell*) *heat exchanger*, shown in Fig. It is composed of two concentric pipes of different diameters. One fluid flows in the inner pipe, and the other in the annular space between the two pipes. Heat is transferred from the hot fluid to the cold one through the wall separating them. Sometimes the inner tube makes a couple of turns inside the shell to increase the heat transfer area, and thus the rate of heat transfer. The mixing chambers discussed earlier are sometimes classified as *direct-contact* heat exchangers.

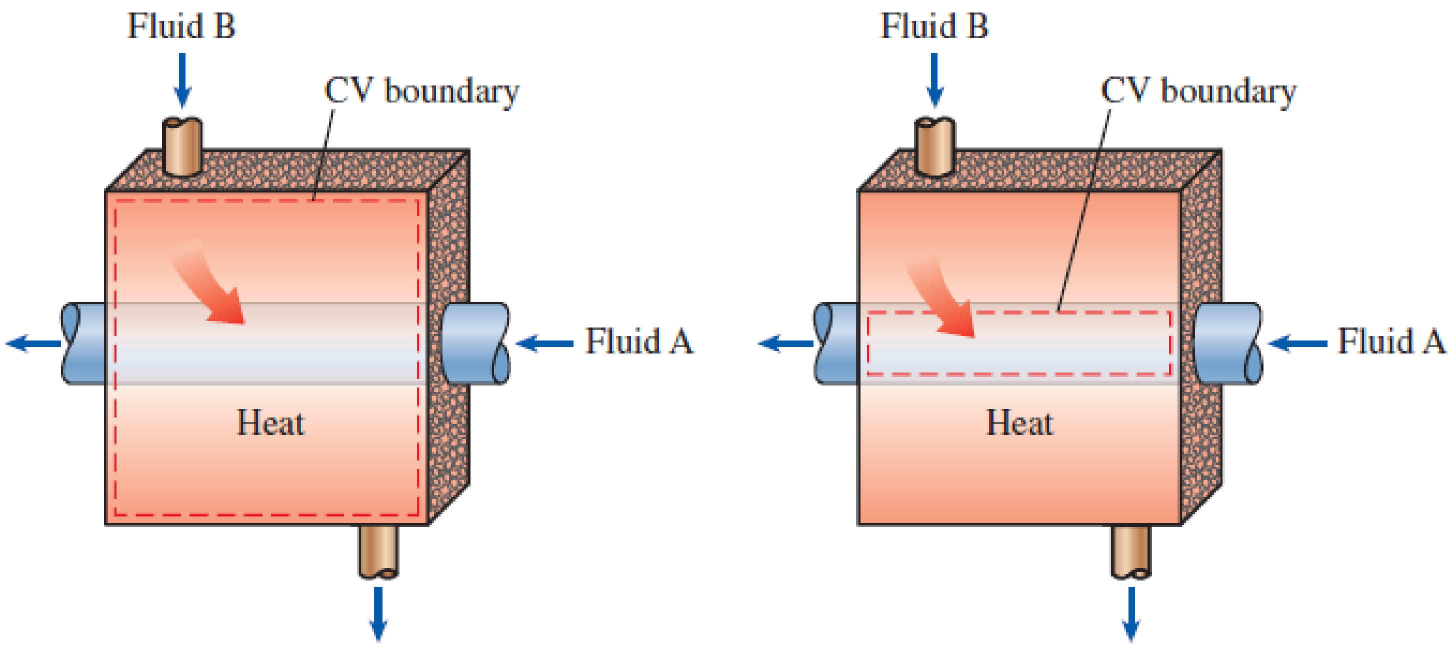
Heat exchangers :

The conservation of mass principle for a heat exchanger in steady operation requires that the sum of the inbound mass flow rates equal the sum of the outbound mass flow rates. This principle can also be expressed as follows: *Under steady operation, the mass flow rate of each fluid stream flowing through a heat exchanger remains constant.*

Heat exchangers typically involve no work interactions ($w = 0$) and negligible kinetic and potential energy changes ($\Delta ke \cong 0$, $\Delta pe \cong 0$) for each fluid stream. The heat transfer rate associated with heat exchangers depends on how the control volume is selected. Heat exchangers are intended for heat transfer between two fluids *within* the device, and the outer shell is usually well insulated to prevent any heat loss to the surrounding medium.

Heat exchangers :

Choice of control volume for a heat exchanger :



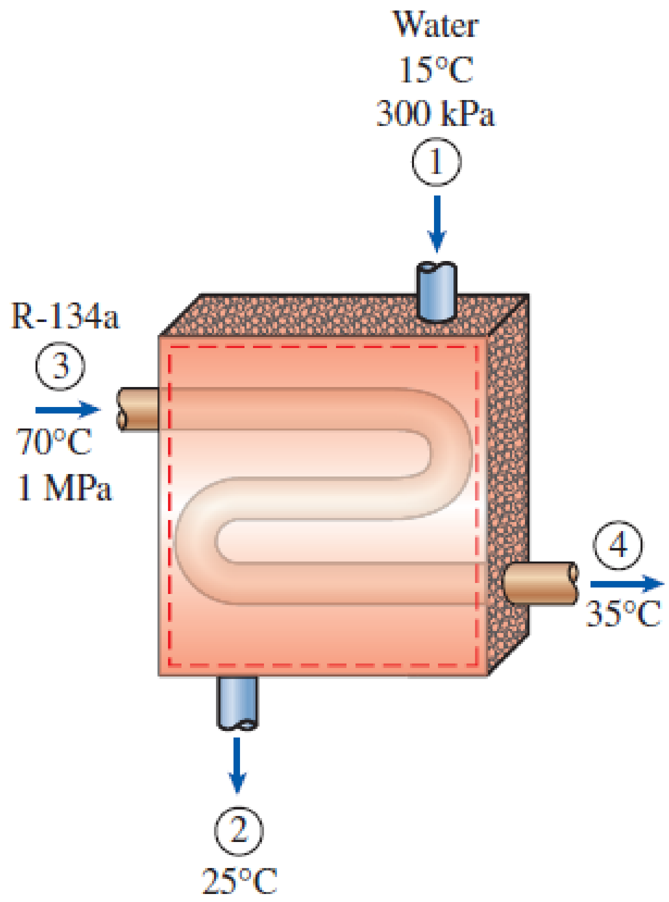
(*a*) System: Entire heat exchanger ($Q_{CV} = 0$)

(*b*) System: Fluid A ($Q_{CV} \neq 0$)

When the entire heat exchanger is selected as the control volume, $\dot{Q}$ becomes zero, since the boundary for this case lies just beneath the insulation and little or no heat crosses the boundary (Fig. 5–39). If, however, only one of the fluids is selected as the control volume, then heat will cross this boundary as it flows from one fluid to the other and $\dot{Q}$ will not be zero. In fact, $\dot{Q}$ in this case will be the rate of heat transfer between the two fluids.

Example : heat exchanger

Refrigerant-134a is to be cooled by water in a condenser. The refrigerant enters the condenser with a mass flow rate of 6 kg/min at 1 MPa and 70°C and leaves at 35°C. The cooling water enters at 300 kPa and 15°C and leaves at 25°C. Neglecting any pressure drops, determine (*a*) the mass flow rate of the cooling water required and (*b*) the heat transfer rate from the refrigerant to water.



Example : heat exchanger

SOLUTION Refrigerant-134a is cooled by water in a condenser. The mass flow rate of the cooling water and the rate of heat transfer from the refrigerant to the water are to be determined.

Assumptions **1** This is a steady-flow process since there is no change with time at any point and thus $\Delta m_{CV} = 0$ and $\Delta E_{CV} = 0$. **2** The kinetic and potential energies are negligible, ke $\cong$ pe $\cong$ 0. **3** Heat losses from the system are negligible and thus $\dot{Q} \cong 0$. **4** There is no work interaction.

Analysis We take the *entire heat exchanger* as the system This is a *control volume* since mass crosses the system boundary during the process. In general, there are several possibilities for selecting the control volume for multiple-stream steady-flow devices, and the proper choice depends on the situation at hand. We observe that there are two fluid streams (and thus two inlets and two exits) but no mixing.

Mass balance: $$\dot{m}_{\text{in}} = \dot{m}_{\text{out}}$$

for each fluid stream since there is no mixing. Thus,

$$\dot{m}_1 = \dot{m}_2 = \dot{m}_w$$

$$\dot{m}_3 = \dot{m}_4 = \dot{m}_R$$

Example : heat exchanger

Energy balance:

$$\dot{m}_1 h_1 + \dot{m}_3 h_3 = \dot{m}_2 h_2 + \dot{m}_4 h_4 \quad (\text{since } \dot{Q} \cong 0,\ \dot{W} = 0,\ \text{ke} \cong \text{pe} \cong 0)$$

Combining the mass and energy balances and rearranging give

$$\dot{m}_w (h_1 - h_2) = \dot{m}_R (h_4 - h_3)$$

Now we need to determine the enthalpies at all four states. Water exists as a compressed liquid at both the inlet and the exit since the temperatures at both locations are below the saturation temperature of water at 300 kPa (133.52°C). Approximating the compressed liquid as a saturated liquid at the given temperatures, we have

$$h_1 \cong h_{f\,@\,15^\circ\text{C}} = 62.982 \text{ kJ/kg}$$

(Table A–4)

$$h_2 \cong h_{f\,@\,25^\circ\text{C}} = 104.83 \text{ kJ/kg}$$

Example : heat exchanger

Energy balance:

The refrigerant enters the condenser as a superheated vapor and leaves as a compressed liquid at 35°C. From refrigerant-134a tables,

$$\left.\begin{aligned} P_3 &= 1\ \text{MPa} \\ T_3 &= 70^\circ\text{C} \end{aligned}\right\} \quad h_3 = 303.87\ \text{kJ/kg} \qquad \text{(Table A–13)}$$

$$\left.\begin{aligned} P_4 &= 1\ \text{MPa} \\ T_4 &= 35^\circ\text{C} \end{aligned}\right\} \quad h_4 \cong h_{f\,@\,35^\circ\text{C}} = 100.88\ \text{kJ/kg} \qquad \text{(Table A–11)}$$

Substituting, we find

$$\dot{m}_w(62.982 - 104.83)\ \text{kJ/kg} = (6\ \text{kg/min})[(100.88 - 303.87)\ \text{kJ/kg}]$$

$$\dot{m}_w = \mathbf{29.1\ kg/min}$$

Example : heat exchanger

Energy balance:

(*b*) To determine the heat transfer from the refrigerant to the water, we have to choose a control volume whose boundary lies on the path of heat transfer. We can choose the volume occupied by either fluid as our control volume. For no particular reason, we choose the volume occupied by the water. All the assumptions stated earlier apply, except that the heat transfer is no longer zero. Then assuming heat to be transferred to water, the energy balance for this single-stream steady-flow system reduces to

$$\dot{Q}_{w,\,in} + \dot{m}_w h_1 = \dot{m}_w h_2$$

Rearranging and substituting,

$$\dot{Q}_{w,in} = \dot{m}_w(h_2 - h_1) = (29.1\ \text{kg/min})[(104.83 - 62.982)\ \text{kJ/kg}]$$
$$= \mathbf{1218\ kJ/min}$$

Unsteady flow problems :

The following are the equations we shall use for solving unsteady flow problems.

Mass balance :

$$\frac{dM_{CV}}{dt} = \sum_{in} \dot{m} - \sum_{out} \dot{m}$$

First law (or energy balance) :

$$\frac{dE_{CV}}{dt} = \sum_{in} \dot{m}\left(h + \frac{1}{2}V^2 + gZ\right) - \sum_{out} \dot{m}\left(h + \frac{1}{2}V^2 + gZ\right)$$

$$+ \dot{Q}_{in} - \dot{W}_{out}$$

Unsteady flow problems :

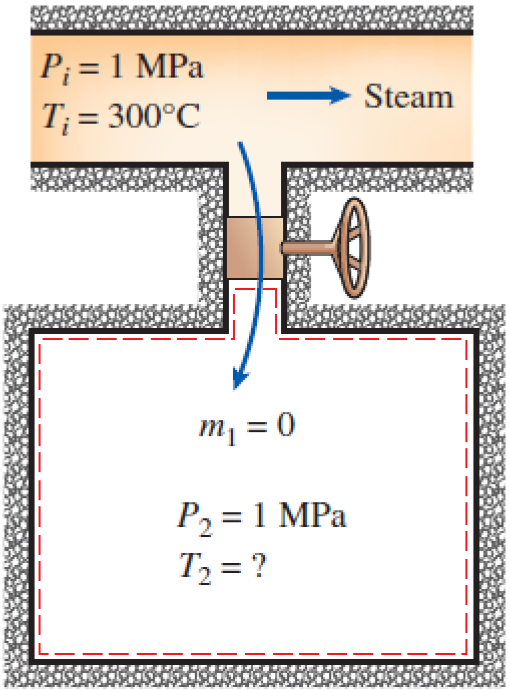
In order to simplify the unsteady-flow problems, we often make the following assumptions with respect to inlets and outlets. These assumptions are sometimes called as Uniform flow assumptions

(i) As in the case of steady flow problems, these properties are assumed to be constant over the cross sectional area of any inlet or outlet . This assumption is already taken into account in arriving at the equations on the last slide.

(ii) The fluid properties at any inlet or outlet do not change with time. In case properties at inlet or outlet change with time, the average values of these properties are considered and then this averages are treated as constants.

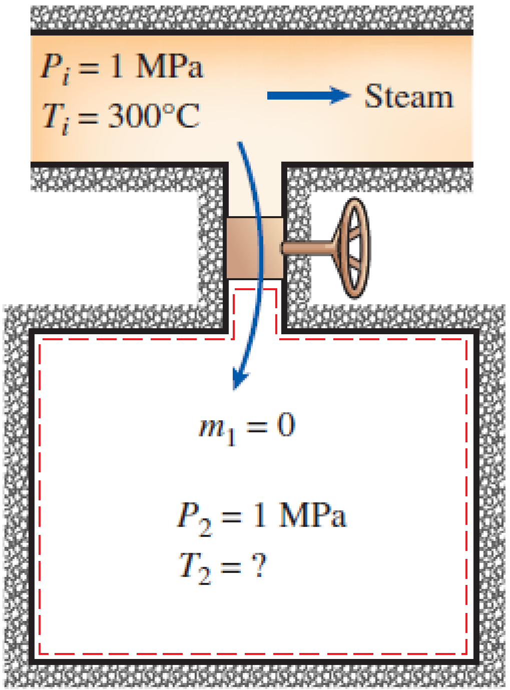
Unsteady flow problems :

A rigid, insulated tank that is initially evacuated is connected through a valve to a supply line that carries steam at 1 MPa and 300°C. Now the valve is opened, and steam is allowed to flow slowly into the tank until the pressure reaches 1 MPa, at which point the valve is closed. Determine the final temperature of the steam in the tank.



Unsteady flow problems :

We consider tank as our control volume (denoted by dotted red line in the figure below). We make uniform flow assumption for the flow through the inlet to the tank. Further we neglect changes in potential and kinetic energies.



Since there is only a single inlet and no outlet, mass balance equation reduces to:

$$\frac{dM_{CV}}{dt} = \dot{m}_{in}$$

Integrating both sides with respect to time, we get

$$m_2 - m_1 = m_{in}$$

Since tank is empty initially, $m_1 = 0$

Therefore, mass balance equation yields

$$m_2 = m_{in}$$

Unsteady flow problems :

Since there is a single inlet and no outlet, neglecting kinetic and potential energies at inlet, energy balance yields

$$\frac{dE_{CV}}{dt} = (\dot{m}h)_{in}$$

Neglecting changes in kinetic and potential energies

of the mass of the fluid in the tank, we get

$$\frac{d(mu)_{CV}}{dt} = \dot{m}_{in}h_{in}$$

Integrating with respect to time while considering

h(inlet) to be constant, we get

$(mu)_2 - (mu)_1 = m_{in}h_{in}$

Since as per mass balance $m_1 = 0$ and $m_{in} = m_2$, we get

$m_2u_2 = m_2h_{in}$

Cancelling m_2 from both sides, we get

$u_2 = h_{in}$

Unsteady flow problems :

To find out the inlet enthalpy, the relevant portion of Table A-6 is reproduced below :

TABLE A–6

Superheated water (*Concluded*)

T °C	v m^3/kg	u kJ/kg	h kJ/kg	s kJ/kg·K
	P = 1.00 MPa (179.88°C)			
Sat.	0.19437	2582.8	2777.1	6.5850
200	0.20602	2622.3	2828.3	6.6956
250	0.23275	2710.4	2943.1	6.9265
300	0.25799	2793.7	3051.6	7.1246
350	0.28250	2875.7	3158.2	7.3029
400	0.30661	2957.9	3264.5	7.4670
500	0.35411	3125.0	3479.1	7.7642

From this table, h_{in} (1 MPa, 300 ^{0}C) = 3051.6 kJ/kg

Therefore as per energy balance, $u_2 = h_{in}$ = 3051.6 kJ/kg.

If we check the third column in the above table,

$$u\,(1\text{ MPa}, 500\,^0\text{C}) > u_2 > u\,(1\text{ MPa}, 400\,^0\text{C})$$

We therefore use **linear interpolation** to find T_2 as follows :

$$T_2 = 400 + \left(\frac{500\text{-}400}{3125\text{-}2957.9}\right)(3051.6\text{-}2957.9) = 456.1\ ^0\text{C}$$

Unsteady flow problems :

Discussion : Note that the temperature of the steam in the tank is higher than the temperature of the steam in the supply line. This is because flow work is being done in pushing the steam into the tank and as a result of this energy transfer the temperature of the steam in the tank increases.