Chapter 5

MASS AND ENERGY ANALYSIS OF OPEN SYSTEMS (Control Volumes)

Thermodynamics: An Engineering Approach

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McGraw-Hill

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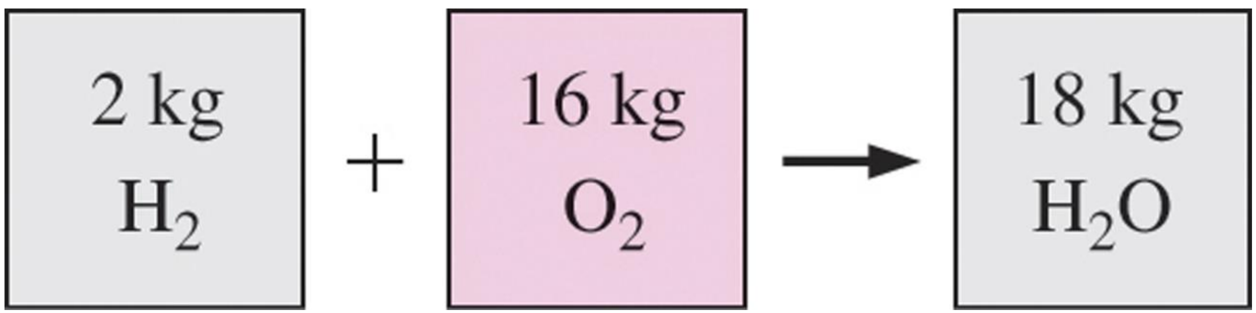
October 2023

CONSERVATION OF MASS

- **Conservation of mass**: Mass, like energy, is a conserved property, and it cannot be created or destroyed during a process.
- ***Closed systems***: The mass of the system remain constant during a process.
- ***Control volumes***: Mass can cross the boundaries, and so we must keep track of the amount of mass entering and leaving the control volume.



Mass is conserved even during chemical reactions.

- Mass *m* and energy *E* can be converted to each other according to:

$$E = mc^2$$

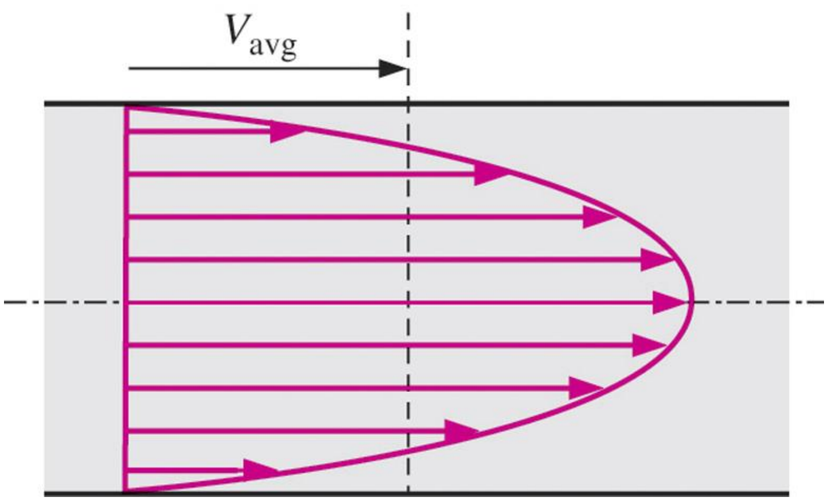
where *c* is the speed of light in a vacuum, which is $c = 2.9979 \times 10^8$ m/s.

Mass and Volume Flow Rates

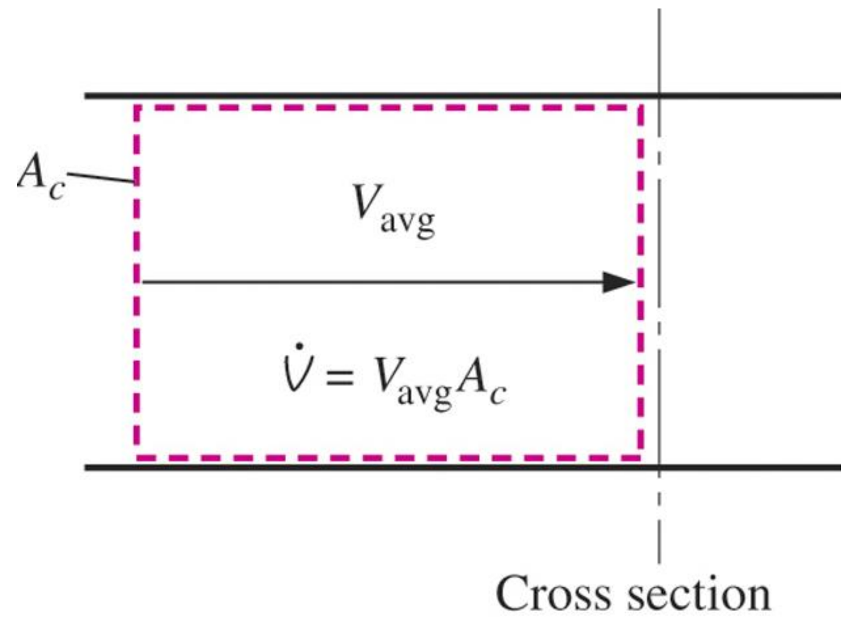
Volume flow rate $\dot{V} = V_{avg}A_c = VA_c$ $(\mathrm{m^3/s})$

Mass flow rate $\dot{m} = \rho V_{avg} A_c$ $(\mathrm{kg/s})$

$$\dot{m} = \rho \dot{V} = \frac{\dot{V}}{v}$$



The average velocity V_{avg} is defined as the average speed through a cross section.



The volume flow rate is the volume of fluid flowing through a cross section per unit time.

Conservation of Mass Principle

- The conservation of mass principle for a control volume:

$$\begin{pmatrix}\text{Total mass entering}\\ \text{the CV during } \Delta t\end{pmatrix} - \begin{pmatrix}\text{Total mass leaving}\\ \text{the CV during } \Delta t\end{pmatrix} = \begin{pmatrix}\text{Net change in mass}\\ \text{within the CV during } \Delta t\end{pmatrix}$$

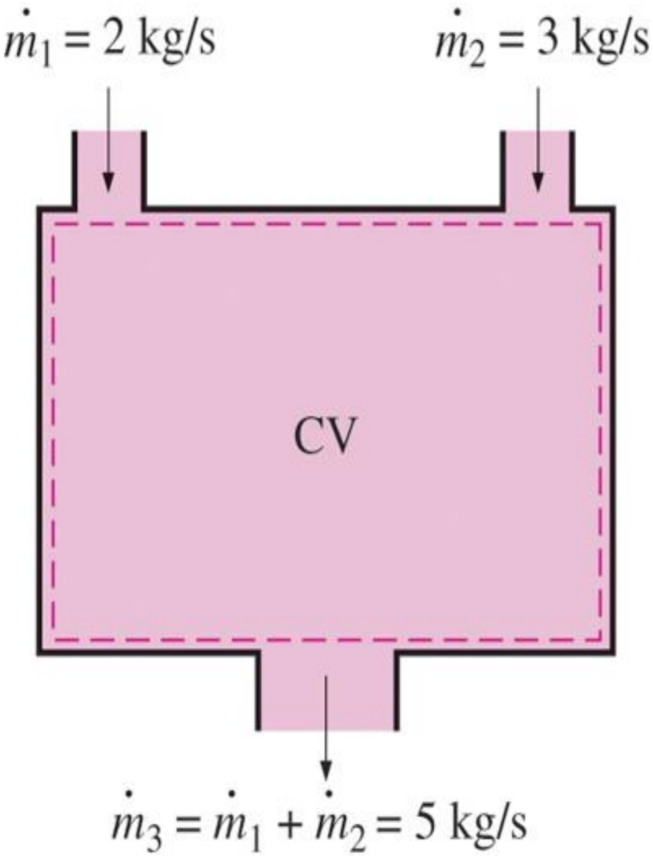
Mass Balance for Steady-Flow Processes

- During a ***steady-flow process***, the total amount of mass contained within a control volume does not change with time (**m_{CV} = constant**).
- The conservation of mass principle requires that *the total amount of mass entering a control volume equal the total amount of mass leaving it.*

or

Mass Balance for Steady-Flow Processes

- For steady-flow processes, we are interested in the amount of mass flowing per unit time, that is, *the* ***mass flow rate.***



Conservation of mass principle for a two-inlet–one-outlet steady-flow system.

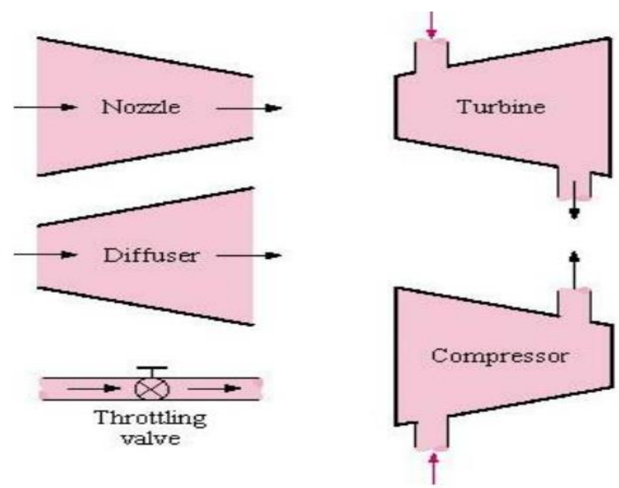
Multiple inlets and exits:

$$\sum_{\text{in}} \dot{m} = \sum_{\text{out}} \dot{m} \qquad (\text{kg/s})$$

Single stream:

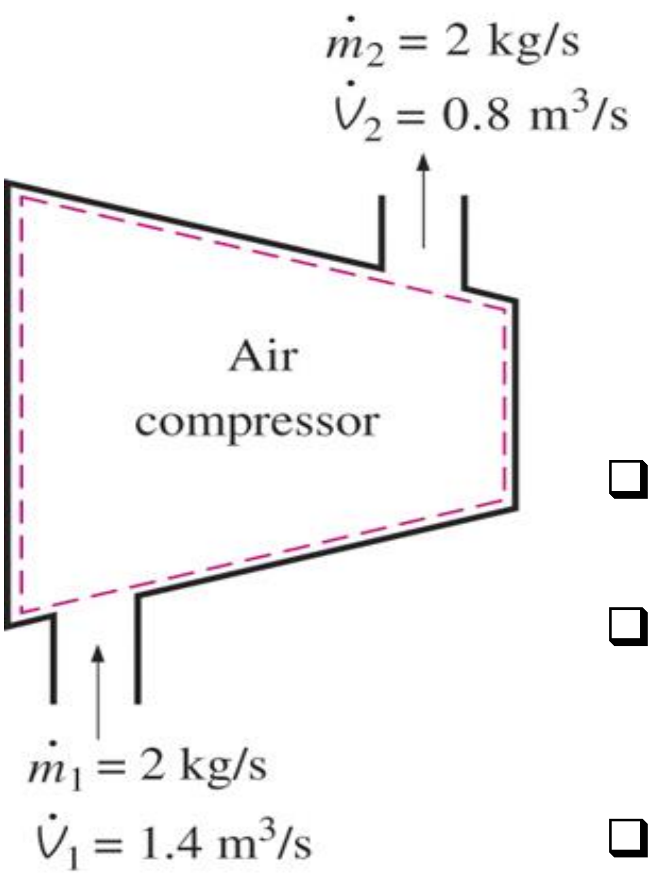
$$\dot{m}_1 = \dot{m}_2 \quad \rightarrow \quad \rho_1 V_1 A_1 = \rho_2 V_2 A_2$$

- **Many engineering devices such as nozzles, diffusers, turbines, compressors, and pumps involve a single stream (*only one inlet and one outlet*).**



Special Case: *Incompressible Flow*

- The conservation of mass relations can be **simplified** even further when the fluid is *incompressible*, which is usually the case for **liquids.**



$$\sum_{in} \dot{V} = \sum_{out} \dot{V} \qquad (m^3/s)$$

Steady, incompressible

$$\dot{V}_1 = \dot{V}_2 \rightarrow V_1 A_1 = V_2 A_2$$

Steady, incompressible flow (single stream)

- **There is no such thing as a "conservation of volume" principle.**
- **During a steady-flow process (constant fluid mass flow rates), volume flow rates are not necessarily conserved for Gases (compressible fluids).**
- **For steady flow of liquids, both volume flow rates AND mass flow rates, remain constant (liquids are incompressible fluids).**

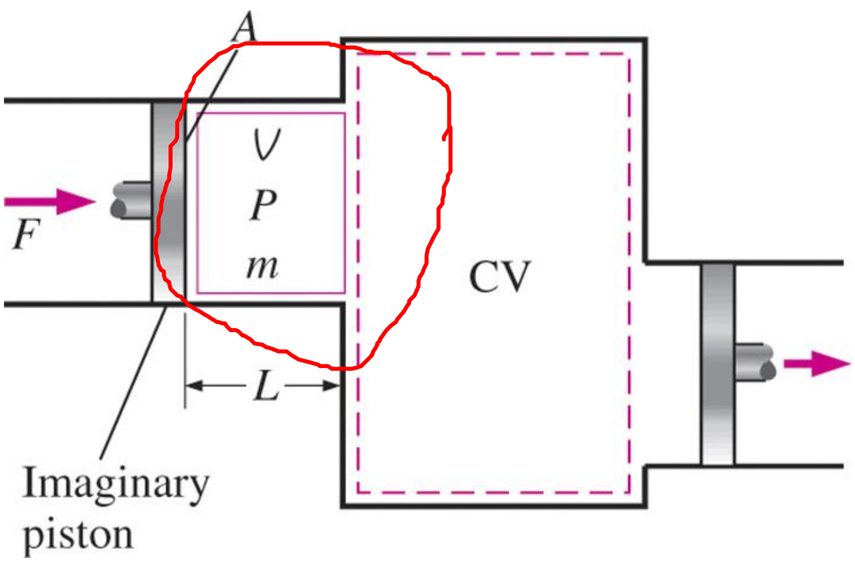
FLOW WORK AND THE ENERGY OF A FLOWING FLUID

- **Flow work, or flow energy**: The work (or energy) required to push the mass into or out of the control volume. This work is necessary for maintaining a continuous flow through a control volume.

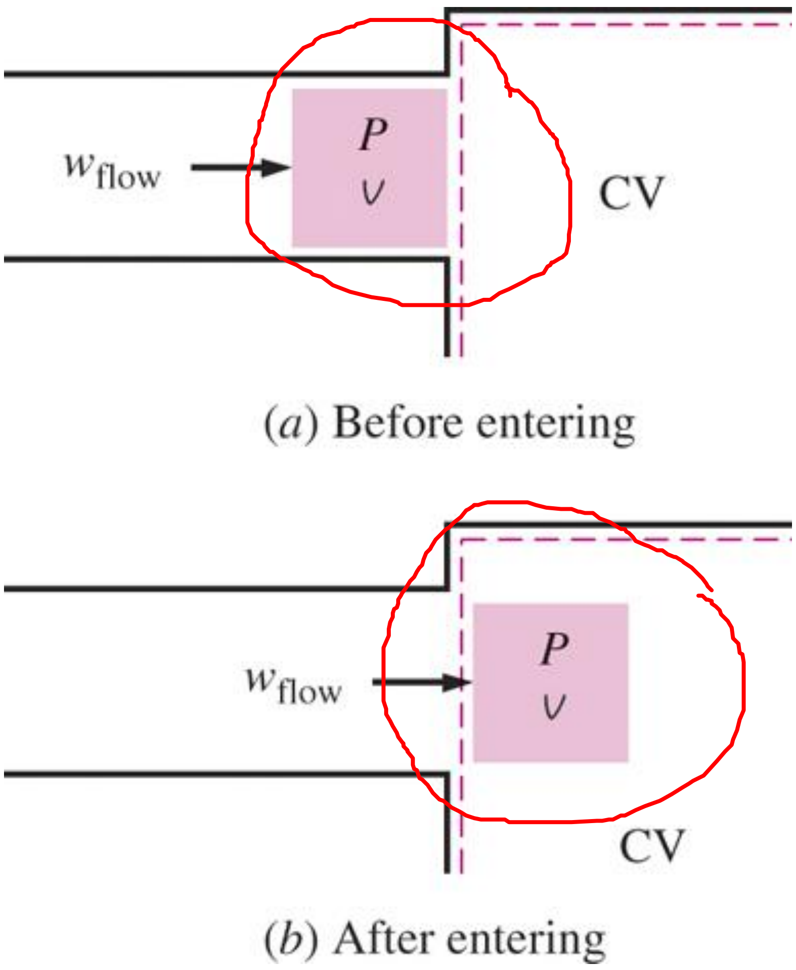
$$F = PA$$

$$W_{flow} = FL = PAL = PV \qquad \text{(kJ)}$$

$$w_{flow} = Pv \qquad \text{(kJ/kg)}$$



Schematic for flow work.



Closed vs. Open systems

- The **flow energy** is automatically taken care of by **enthalpy.**

$$h = u + Pv$$

1) ***Pv*** is known as boundary work (***Wb)*** in closed systems.
2) In open (flow) systems, ***Pv is known as*** flow work (**Wflow).**

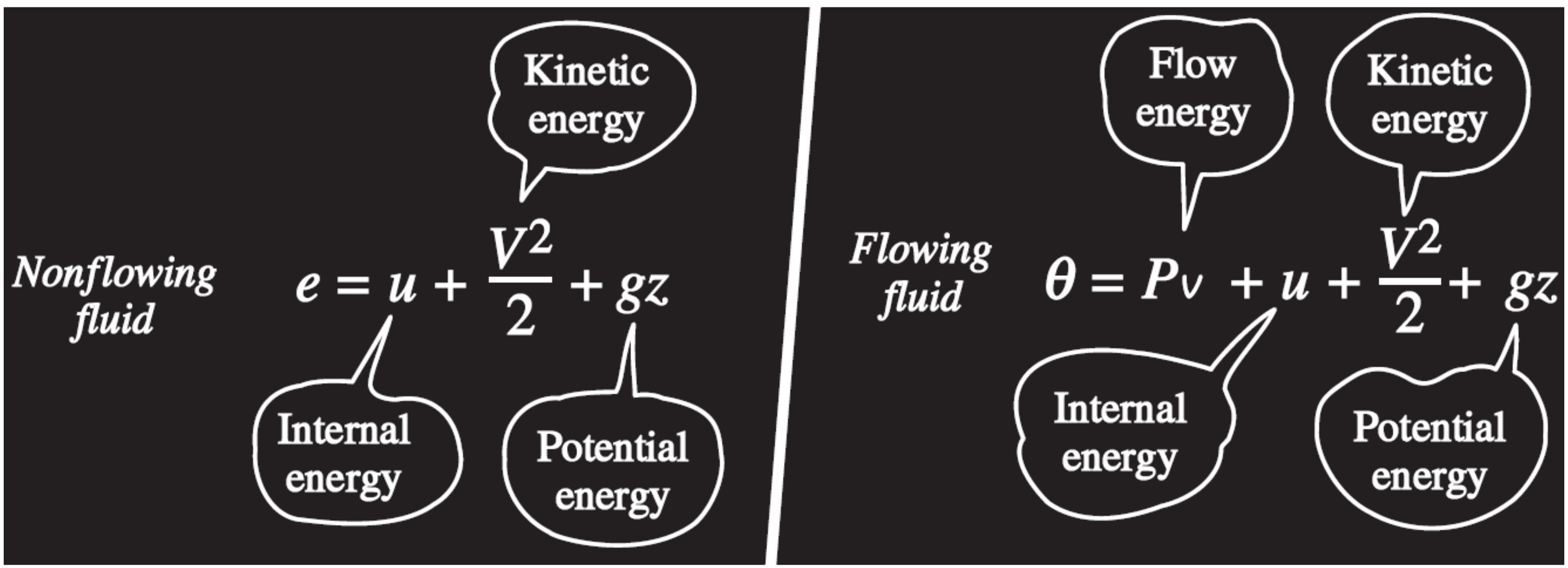
- Reminder of closed systems (see Chapter 4):
  - A closed system may have kinetic and/or potential energy due to its movement or position, e.g. in cyclic processes.
  - It is distinguished from an open system by its fixed amount of mass (no mass flow in or out of the system).

Total Energy of a Flowing Fluid

$$e = u + \mathrm{ke} + \mathrm{pe} = u + \frac{V^2}{2} + gz \qquad (\mathrm{kJ/kg})$$

$$\theta = P\mathrm{v} + e = P\mathrm{v} + (u + \mathrm{ke} + \mathrm{pe})$$

$$\theta = h + \mathrm{ke} + \mathrm{pe} = h + \frac{V^2}{2} + gz \qquad (\mathrm{kJ/kg})$$



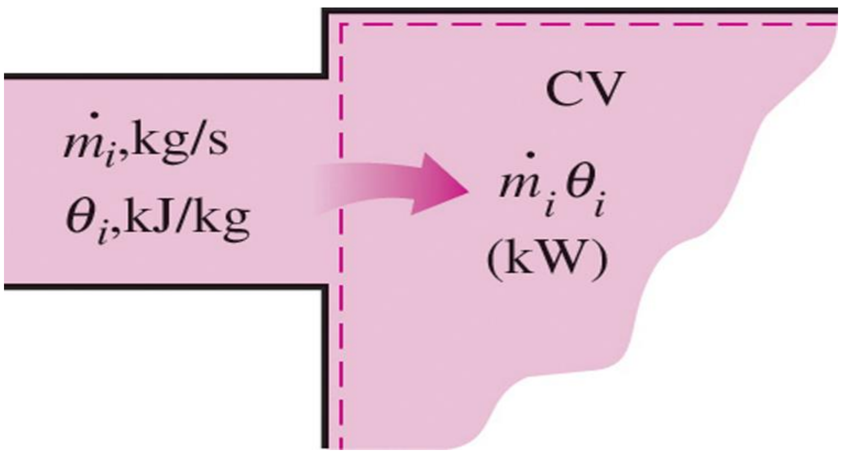
The total energy consists of three parts for a nonflowing fluid, and four parts for a flowing fluid.

Energy Transport by Mass

$$\theta = h + \text{ke} + \text{pe} = h + \frac{V^2}{2} + gz \qquad (\text{kJ/kg})$$

Amount of energy transport: $$E_{\text{mass}} = m\theta = m\left(h + \frac{V^2}{2} + gz\right) \qquad (\text{kJ})$$

Rate of energy transport: $$\dot{E}_{\text{mass}} = \dot{m}\theta = \dot{m}\left(h + \frac{V^2}{2} + gz\right) \qquad (\text{kW})$$



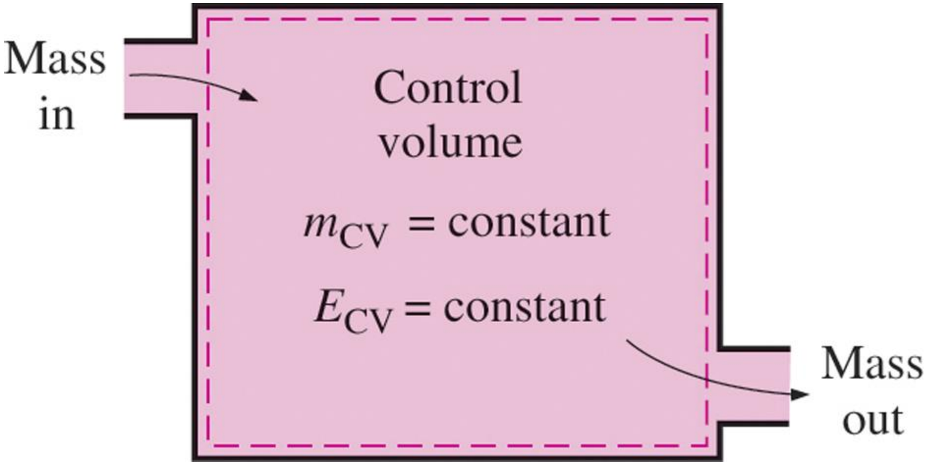
The product $\dot{m}_i\theta_i$ is the energy transported into control volume by mass per unit time.

- When the kinetic and potential energies of a fluid stream are *negligible:*

$$E_{\text{mass}} = mh$$

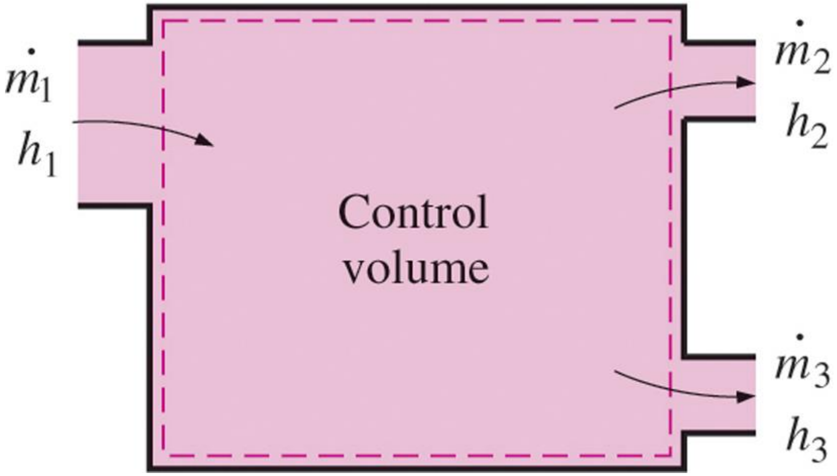
$$\dot{E}_{\text{mass}} = \dot{m}h$$

ENERGY ANALYSIS OF STEADY-FLOW SYSTEMS



Many engineering systems such as power plants operate under steady conditions.

Under steady-flow conditions, the mass and energy contents of a control volume remain ***constant.***



Under steady-flow conditions, the fluid properties at an inlet or exit *remain constant* (*do not change with time*).

Mass and Energy balances for a steady-flow process

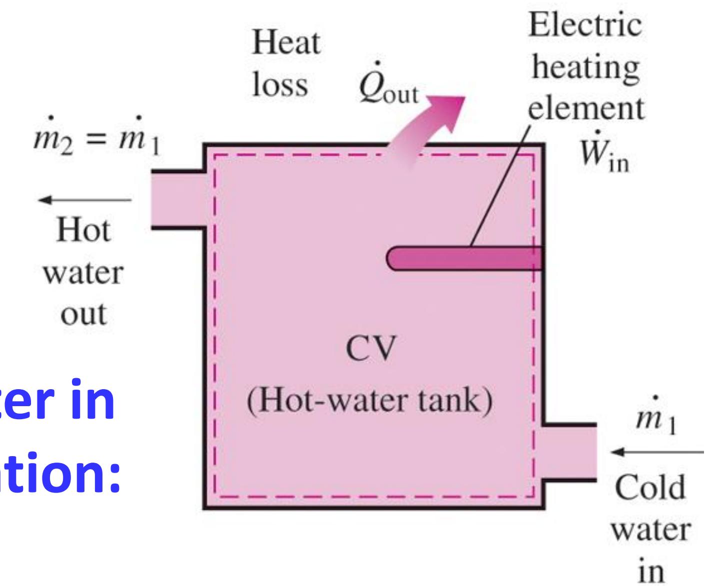
Mass balance

$$\sum_{in} \dot{m} = \sum_{out} \dot{m} \qquad (kg/s)$$

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

$$\rho_1 V_1 A_1 = \rho_2 V_2 A_2$$

A water heater in steady operation:



Energy balance

$$\underbrace{\dot{E}_{in} - \dot{E}_{out}}_{\text{Rate of net energy transfer by heat, work, and mass}} = \underbrace{dE_{system}/dt}_{\text{Rate of change in internal, kinetic, potential, etc., energies}} \xrightarrow{} 0 \text{ (steady)} = 0$$

$$\underbrace{\dot{E}_{in}}_{\text{Rate of net energy transfer in by heat, work, and mass}} = \underbrace{\dot{E}_{out}}_{\text{Rate of net energy transfer out by heat, work, and mass}} \qquad (kW)$$

$$\dot{Q}_{in} + \dot{W}_{in} + \sum_{in} \underbrace{\dot{m}\left(h + \frac{V^2}{2} + gz\right)}_{\text{for each inlet}} = \dot{Q}_{out} + \dot{W}_{out} + \sum_{out} \underbrace{\dot{m}\left(h + \frac{V^2}{2} + gz\right)}_{\text{for each exit}}$$

❑ Energy balance relations with sign conventions *(heat input and work output are positive):*

$$\dot{Q} - \dot{W} = \sum_{\text{out}} \underbrace{\dot{m}\left(h + \frac{V^2}{2} + gz\right)}_{\text{for each exit}} - \sum_{\text{in}} \underbrace{\dot{m}\left(h + \frac{V^2}{2} + gz\right)}_{\text{for each inlet}}$$

$$\dot{Q} - \dot{W} = \dot{m}\left[h_2 - h_1 + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1)\right]$$

$$q - w = h_2 - h_1 + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1)$$

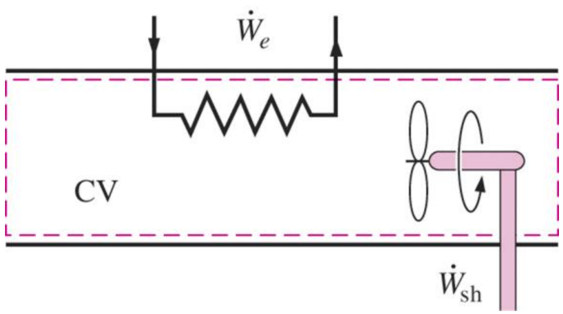
❑ When the kinetic and potential energies of a fluid stream are *negligible:*

$$q - w = h_2 - h_1$$

$$q = \dot{Q}/\dot{m}$$

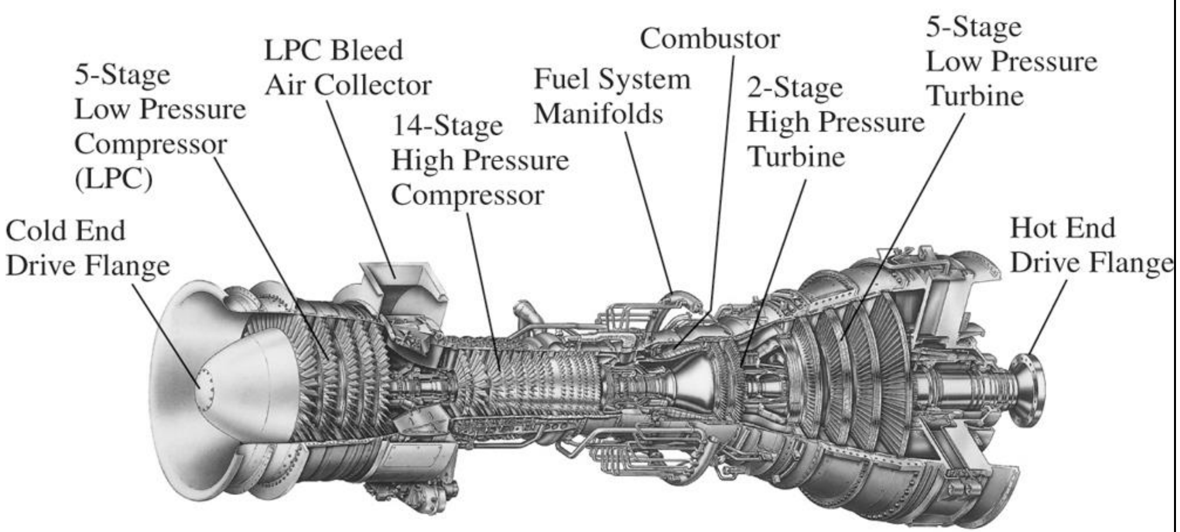
$$w = \dot{W}/\dot{m}$$

❑ **Under steady operation, *shaft work and electrical work* are the only forms of work a simple compressible system may involve.**



SOME STEADY-FLOW ENGINEERING DEVICES

- Many engineering devices operate essentially under the same conditions for long periods of time.
- The components of a steam power plant (e.g., turbines, compressors, heat exchangers, and pumps) operate nonstop for months before the system is shut down for maintenance.
- Therefore, these devices can be conveniently analyzed as steady-flow devices.

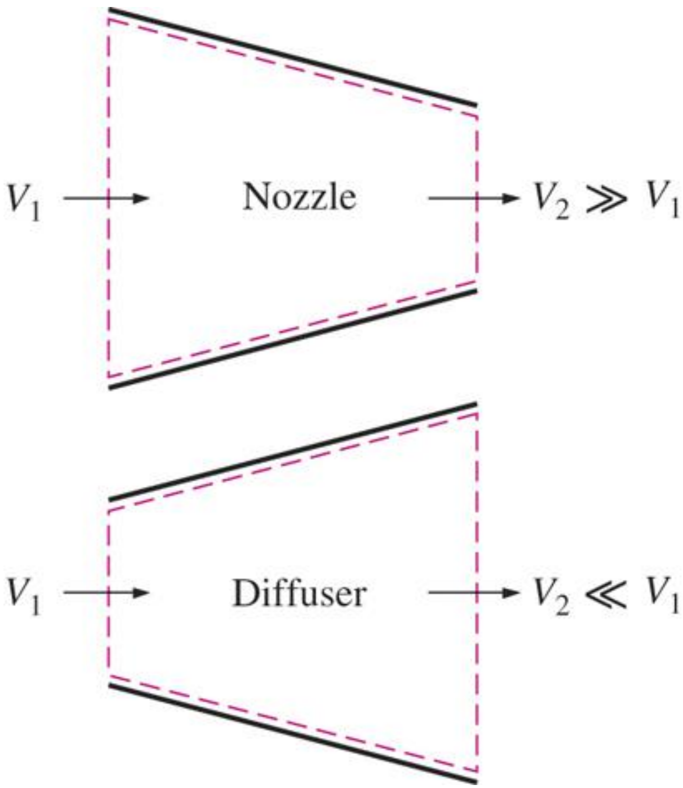


A modern gas turbine used for electric power production.

V_1 m/s	V_2 m/s	Δke kJ/kg
0	45	1
50	67	1
100	110	1
200	205	1
500	502	1

At very high velocities, even small changes in velocities can cause significant changes in the kinetic energy of the fluid

Nozzles and Diffusers



- Nozzles and diffusers are commonly utilized in jet engines, rockets, spacecraft, and even garden hoses.
- A **nozzle** is a device that *increases the velocity of a fluid* at the expense of pressure.
- A **diffuser** is a device that *increases the pressure of a fluid* by slowing it down.
- The cross-sectional area of a nozzle decreases in the flow direction for *subsonic* flows and increases for *supersonic* flows. The reverse is true for diffusers.

Nozzles and diffusers are shaped so that they cause large changes in fluid velocities and thus kinetic energies.

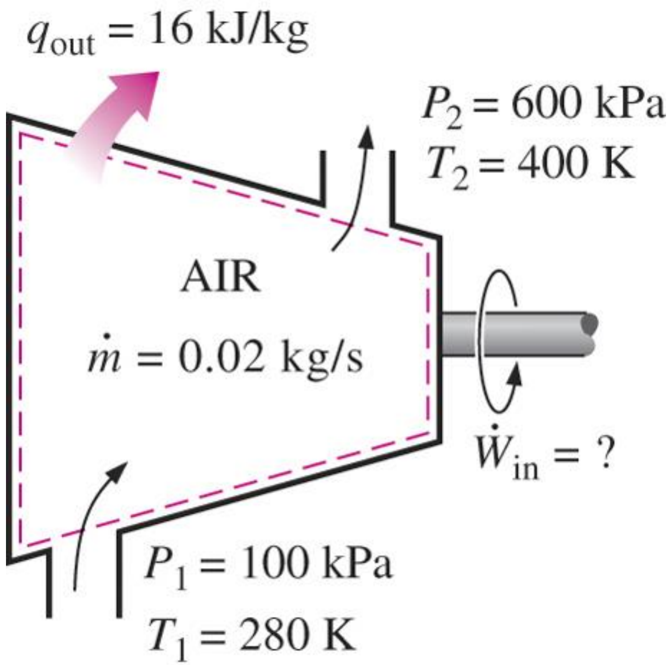
Energy balance for a nozzle or diffuser:

$$\dot{E}_{in} = \dot{E}_{out}$$

$$\dot{m}\left(h_1 + \frac{V_1^2}{2}\right) = \dot{m}\left(h_2 + \frac{V_2^2}{2}\right)$$

$$(\text{since } \dot{Q} \cong 0,\ \dot{W} = 0, \text{ and } \Delta\text{pe} \cong 0)$$

Turbines and Compressors



Energy balance for the compressor in this figure:

$$\dot{E}_{in} = \dot{E}_{out}$$

$$\dot{W}_{in} + \dot{m}h_1 = \dot{Q}_{out} + \dot{m}h_2$$

$$(\text{since } \Delta\text{ke} = \Delta\text{pe} \cong 0)$$

Turbine: drives the electric generator In steam, gas, or hydroelectric power plants.

As the fluid passes through the turbine, work is done against the blades, which are attached to the shaft. As a result, the shaft rotates, and the turbine produces work.

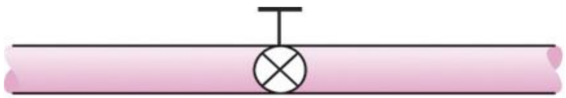
Compressors *as well as* ***pumps*** *and* ***fans,*** *are devices used to increase the pressure of a fluid. Work is supplied to these devices from an external source through a rotating shaft.*

Fan: increases the pressure of a gas slightly and is mainly used to mobilize a gas.

Compressor: capable of compressing the gas to very high pressures.

Pump: works very much like compressor, except that it handles liquids not gases.

Throttling valves



(*a*) An adjustable valve

(*b*) A porous plug

(*c*) A capillary tube

$$h_2 \cong h_1$$

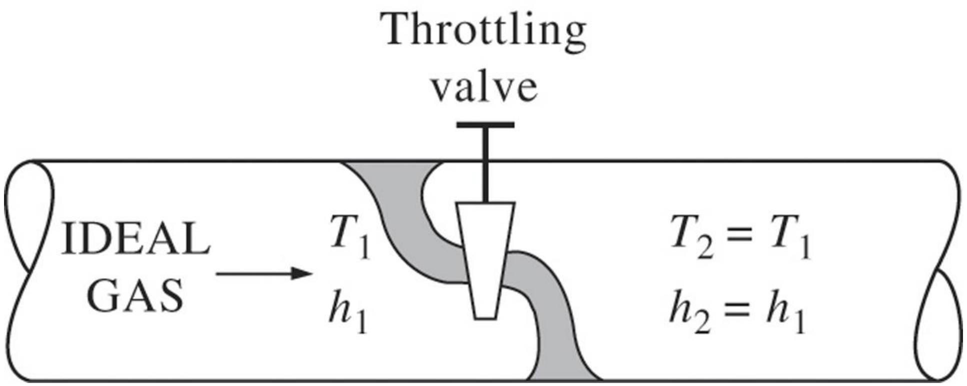
1) **Throttling valves** are any kind of flow-restricting devices that cause a significant *pressure drop* in the fluid.
2) Enthalpy remains constant since no heat or work transfer.
3) **The pressure** drop in the fluid, due to gas expansion, is often accompanied by a large drop in temperature (for non-ideal gas), and for that reason **throttling devices** are commonly used in refrigeration and air-conditioning applications.

Energy balance:

$$u_1 + P_1 v_1 = u_2 + P_2 v_2$$

$$\text{Internal energy} + \text{Flow energy} = \text{Constant}$$

Throttling valves

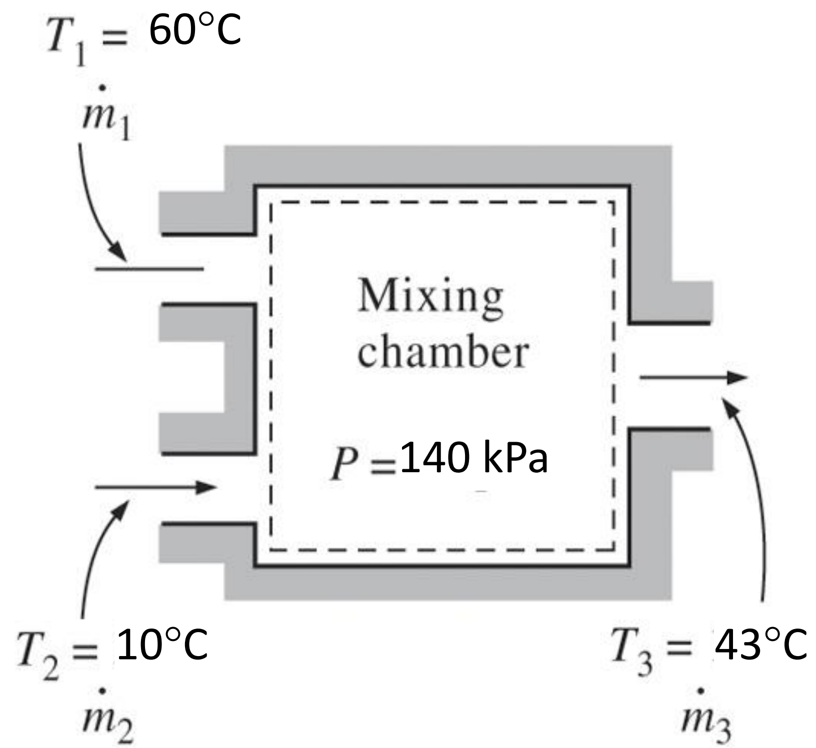


- The temperature of an ideal gas *does not change* during a throttling (h = constant) process since $h = h(T)$.

- During a throttling process, the *enthalpy of a fluid remains constant*. But internal and flow energies may be converted to each other.

Mixing chambers

- In engineering applications, the section where the mixing process takes place is commonly referred to as a ***mixing chamber.***



Energy balance for the <u>adiabatic</u> mixing chamber in the figure is:

$$\dot{E}_{in} = \dot{E}_{out}$$

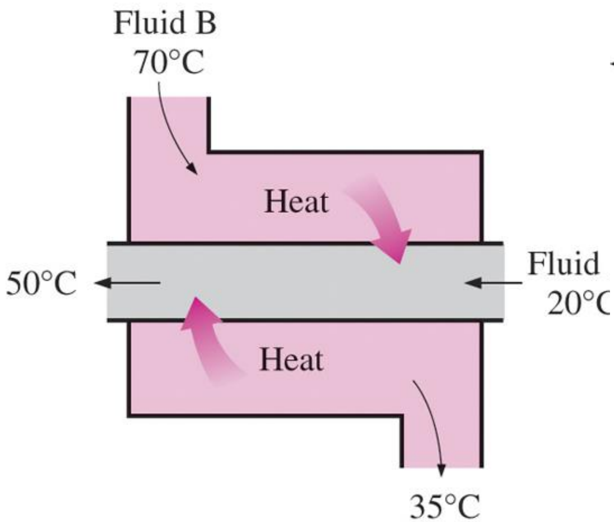
$$\dot{m}_1 h_1 + \dot{m}_2 h_2 = \dot{m}_3 h_3$$

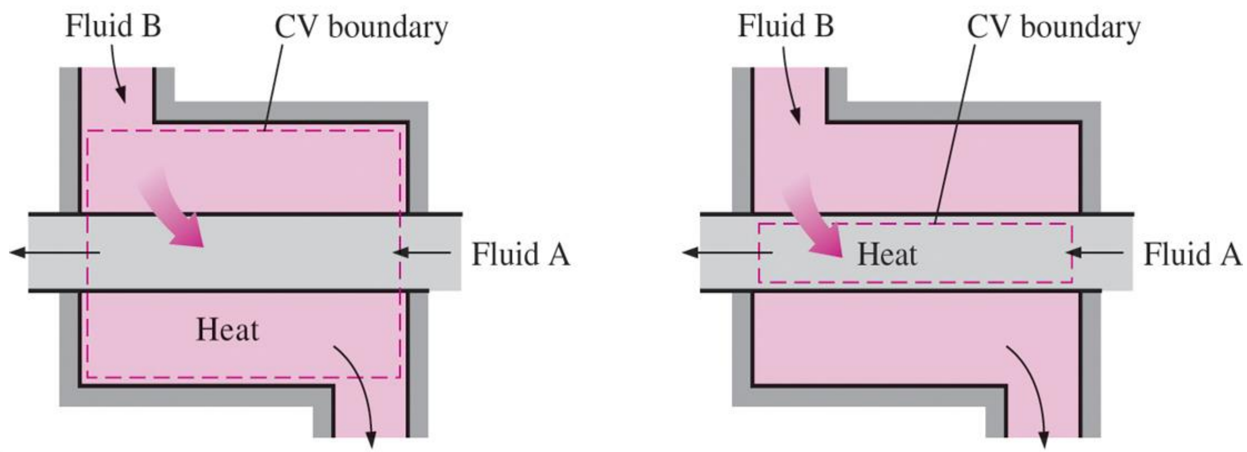
$$(\text{since } \dot{Q} \cong 0, \dot{W} = 0, \text{ke} \cong \text{pe} \cong 0)$$

Heat exchangers

Heat exchangers

- Devices where two moving fluid streams exchange heat *without mixing*.
- Widely used in various industries; they come in various designs.





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

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

(a): Heat transfer within system, not across CV boundary

A heat exchanger can be as simple as two concentric pipes.

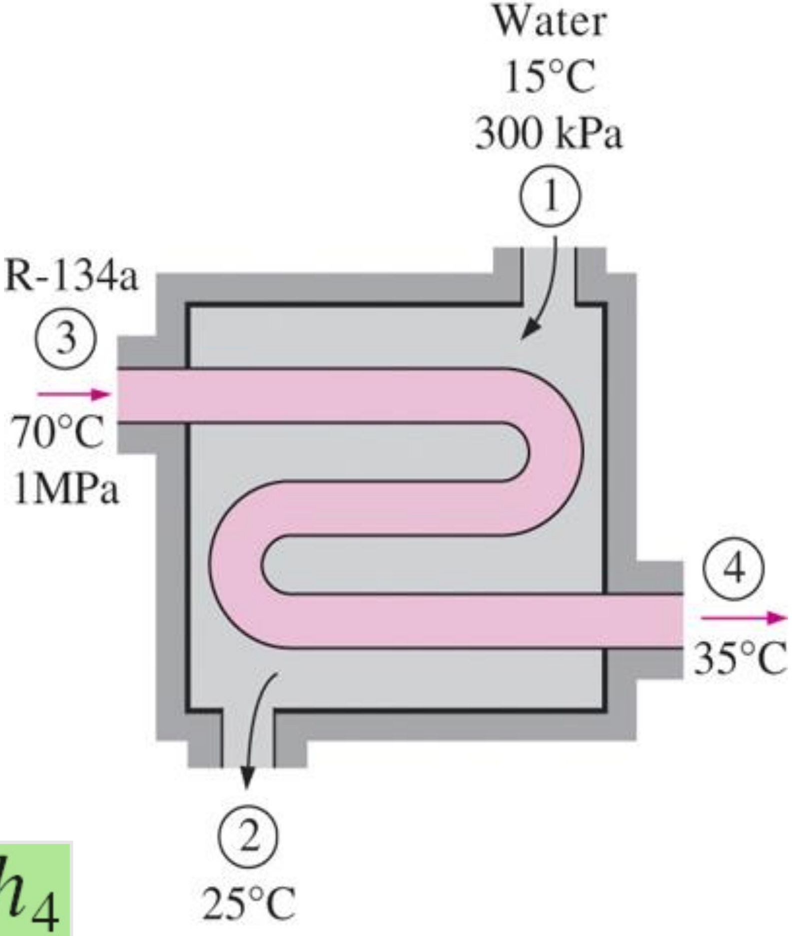
The heat transfer associated with a heat exchanger may be *zero or nonzero* depending on how the <u>control volume</u> is selected.

Heat exchangers

- Mass and energy balances for the adiabatic heat exchanger in the figure is:

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

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

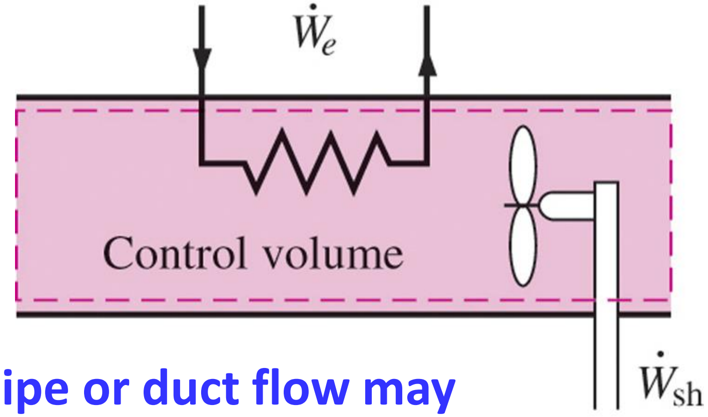


$$\dot{E}_{\text{in}} = \dot{E}_{\text{out}}$$

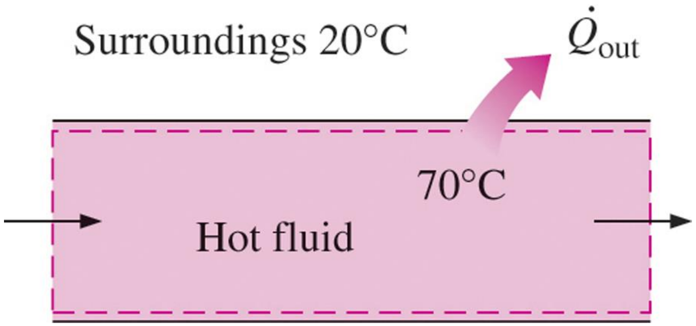
$$\dot{m}_1 h_1 + \dot{m}_3 h_3 = \dot{m}_2 h_2 + \dot{m}_4 h_4$$

Pipe and duct fow

- The <u>transport of liquids or gases</u> in *pipes and ducts* is of great importance in many engineering applications.
- Flow through a pipe or a duct usually satisfies the <u>steady-flow</u> conditions.



Pipe or duct flow may involve *<u>more than one form</u>* of work at the same time.



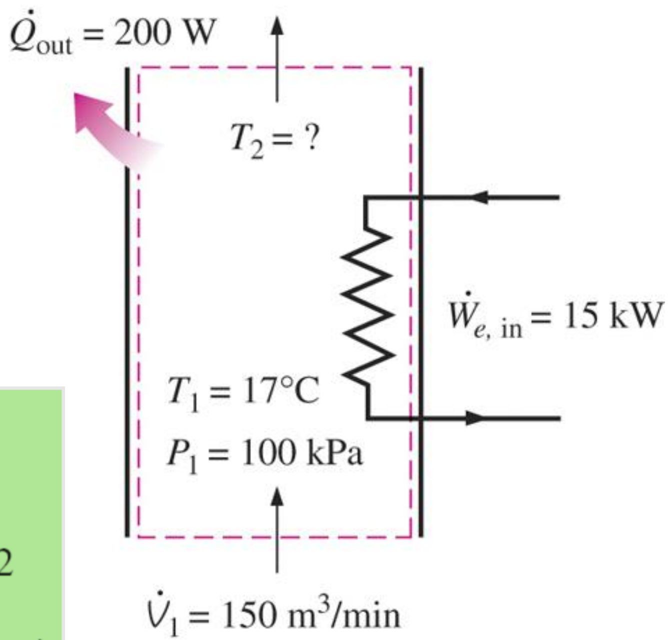
Heat losses from a hot fluid flowing through an <u>uninsulated</u> pipe or duct to the cooler environment *<u>may be very significant.</u>*

Energy balance for the pipe flow shown in the figure is:

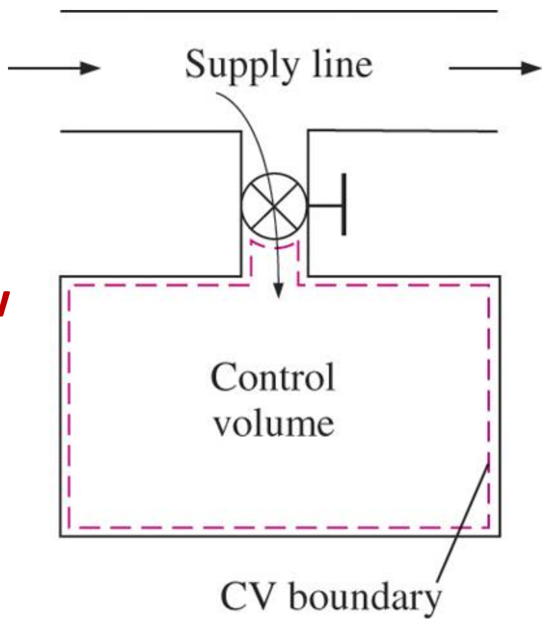
$$\dot{E}_{in} = \dot{E}_{out}$$

$$\dot{W}_{e,in} + \dot{m}h_1 = \dot{Q}_{out} + \dot{m}h_2$$

$$\dot{W}_{e,in} - \dot{Q}_{out} = \dot{m}c_p(T_2 - T_1)$$



ENERGY ANALYSIS OF UNSTEADY-FLOW PROCESSES



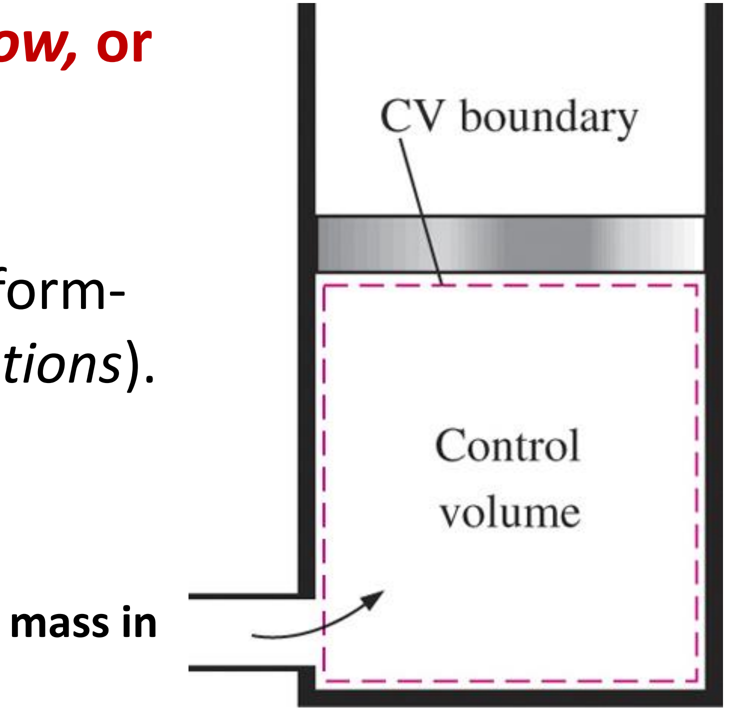
Example-1:

Charging of a rigid tank from a supply line is unsteady-flow process. It involves changes within the control volume.

- Many processes of interest, involve ***changes*** *within the control volume* ***with time.***
- Such processes are called ***unsteady-flow, or transient-flow,*** processes.
- Most unsteady-flow processes, can be represented reasonably well by the uniform-flow process (*steady at inlet or exit locations*).

Example-2:

The shape and size of a control volume may change during unsteady -flow process.



ENERGY ANALYSIS OF UNSTEADY-FLOW PROCESSES

Mass balance

$$m_{in} - m_{out} = \Delta m_{system} \qquad \Delta m_{system} = m_{final} - m_{initial}$$

$$m_i - m_e = (m_2 - m_1)_{CV}$$

i = inlet, e = exit, 1 = initial state, and 2 = final state

Energy balance:

$$\underbrace{E_{in} - E_{out}}_{\substack{\text{Net energy transfer}\\ \text{by heat, work, and mass}}} = \underbrace{\Delta E_{system}}_{\substack{\text{Change in internal, kinetic,}\\ \text{potential, etc., energies}}}$$

$$\left(Q_{in} + W_{in} + \sum_{in} m\theta\right) - \left(Q_{out} + W_{out} + \sum_{out} m\theta\right) = (m_2e_2 - m_1e_1)_{system} \qquad \textbf{(5–45)}$$

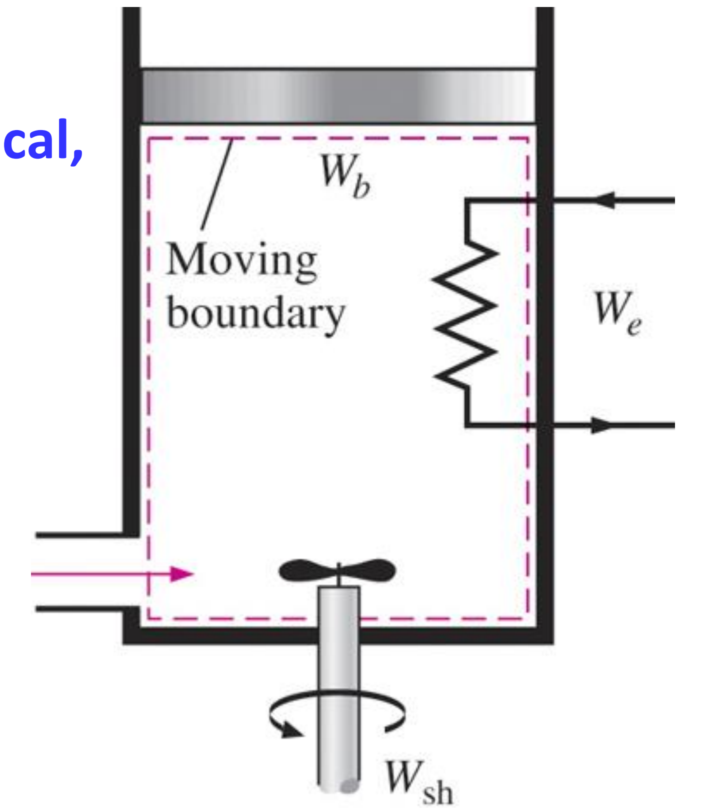
$$\theta = h + \text{ke} + \text{pe} \qquad e = u + \text{ke} + \text{pe}$$

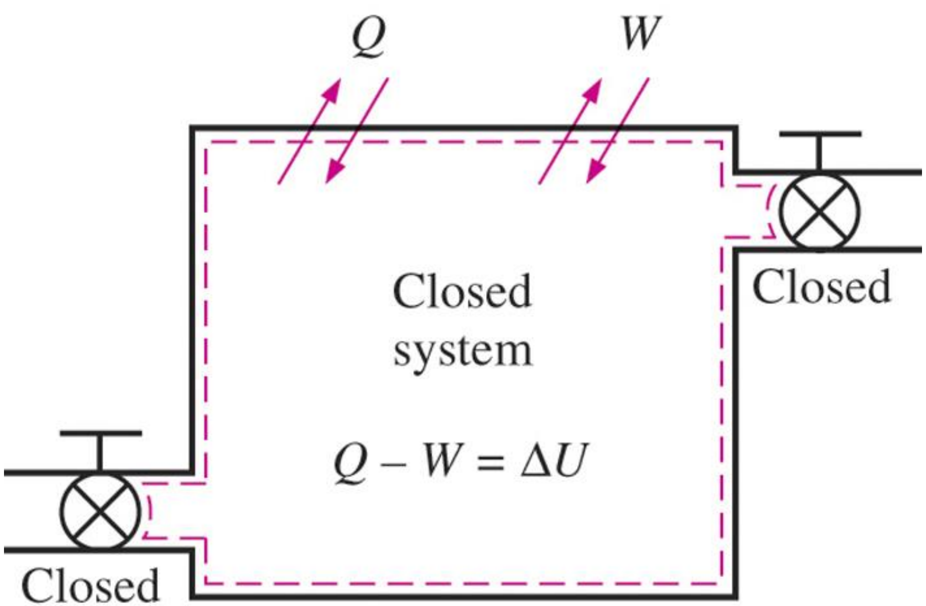
Pe, ke negligible:

$$Q - W = \sum_{out} mh - \sum_{in} mh + (m_2u_2 - m_1u_1)_{system} \qquad \textbf{(5–46)}$$

ENERGY ANALYSIS OF UNSTEADY-FLOW PROCESSES

A uniform-flow system may involve electrical, shaft, and boundary work all at once.





The energy equation of a uniform-flow system reduces to that of a closed system when all the inlets and exits are closed.

EXAMPLE 5–4 **Deceleration of Air in a Diffuser**

Air at 10°C and 80 kPa enters the diffuser of a jet engine steadily with a velocity of 200 m/s. The inlet area of the diffuser is 0.4 m^2. The air leaves the diffuser with a velocity that is very small compared with the inlet velocity. Determine (*a*) the mass flow rate of the air and (*b*) the temperature of the air leaving the diffuser.

SOLUTION Air enters the diffuser of a jet engine steadily at a specified velocity. The mass flow rate of air and the temperature at the diffuser exit 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** Air is an ideal gas since it is at a high temperature and low pressure relative to its critical-point values. **3** The potential energy change is zero, $\Delta pe = 0$. **4** Heat transfer is negligible. **5** Kinetic energy at the diffuser exit is negligible. **6** There are no work interactions.

Analysis We take the *diffuser* as the system (Fig. 5–27). This is a *control volume* since mass crosses the system boundary during the process. We observe that there is only one inlet and one exit and thus $\dot{m}_1 = \dot{m}_2 = \dot{m}$.

(*a*) To determine the mass flow rate, we need to find the specific volume of the air first. This is determined from the ideal-gas relation at the inlet conditions:

$$v_1 = \frac{RT_1}{P_1} = \frac{(0.287 \text{ kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(283 \text{ K})}{80 \text{ kPa}} = 1.015 \text{ m}^3/\text{kg}$$

Then,

$$\dot{m} = \frac{1}{v_1}V_1A_1 = \frac{1}{1.015\ \text{m}^3/\text{kg}}(200\ \text{m/s})(0.4\ \text{m}^2) = \mathbf{78.8\ kg/s}$$

Since the flow is steady, the mass flow rate through the entire diffuser remains constant at this value.

(*b*) Under stated assumptions and observations, the energy balance for this steady-flow system can be expressed in the rate form as

$$\underbrace{\dot{E}_{in} - \dot{E}_{out}}_{\substack{\text{Rate of net energy transfer}\\ \text{by heat, work, and mass}}} = \underbrace{dE_{system}/dt}_{\substack{\text{Rate of change in internal, kinetic,}\\ \text{potential, etc., energies}}}\overset{\nearrow 0\ \text{(steady)}}{} = 0$$

$$\dot{E}_{in} = \dot{E}_{out}$$

$$\dot{m}\left(h_1 + \frac{V_1^2}{2}\right) = \dot{m}\left(h_2 + \frac{V_2^2}{2}\right) \quad (\text{since } \dot{Q} \cong 0,\ \dot{W} = 0,\ \text{and } \Delta\text{pe} \cong 0)$$

$$h_2 = h_1 - \frac{V_2^2 - V_1^2}{2}$$

The exit velocity of a diffuser is usually small compared with the inlet velocity ($V_2 << V_1$); thus, the kinetic energy at the exit can be neglected. The enthalpy of air at the diffuser inlet is determined from the air table (Table A–17) to be

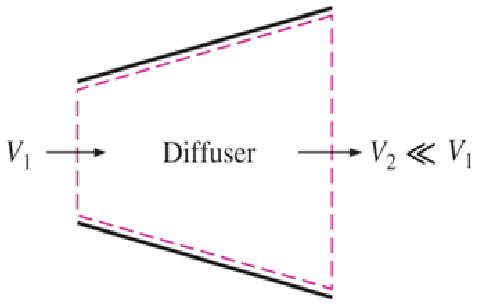
$$h_1 = h_{@\ 283\ K} = 283.14\ \text{kJ/kg}$$

Substituting, we get

$$h_2 = 283.14\ \text{kJ/kg} - \frac{0 - (200\ \text{m/s})^2}{2}\left(\frac{1\ \text{kJ/kg}}{1000\ \text{m}^2/\text{s}^2}\right)$$
$$= 303.14\ \text{kJ/kg}$$

From Table A–17, the temperature corresponding to this enthalpy value is

$$T_2 = \mathbf{303\ K}$$



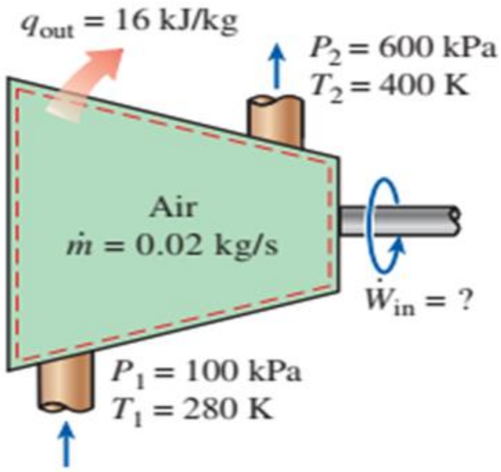
Compare with nozzle

EXAMPLE 5–6 Compressing Air by a Compressor

Air at 100 kPa and 280 K is compressed steadily to 600 kPa and 400 K. The mass flow rate of the air is 0.02 kg/s, and a heat loss of 16 kJ/kg occurs during the process. Assuming the changes in kinetic and potential energies are negligible, determine the necessary power input to the compressor.

SOLUTION Air is compressed steadily by a compressor to a specified temperature and pressure. The power input to the compressor 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** Air is an ideal gas since it is at a high temperature and low pressure relative to its critical-point values. **3** The kinetic and potential energy changes are zero, $\Delta ke = \Delta pe = 0$.



$$\dot{E}_{in} = \dot{E}_{out}$$

$$\dot{W}_{in} + \dot{m}h_1 = \dot{Q}_{out} + \dot{m}h_2 \quad (\text{since } \Delta\text{ke} = \Delta\text{pe} \cong 0)$$

$$\dot{W}_{in} = \dot{m}q_{out} + \dot{m}(h_2 - h_1)$$

The enthalpy of an ideal gas depends on temperature only, and the enthalpies of the air at the specified temperatures are determined from the air table (Table A–17) to be

$$h_1 = h_{@\,280\,\text{K}} = 280.13 \text{ kJ/kg}$$

$$h_2 = h_{@\,400\,\text{K}} = 400.98 \text{ kJ/kg}$$

Substituting, the power input to the compressor is determined to be

$$\dot{W}_{in} = (0.02 \text{ kg/s})(16 \text{ kJ/kg}) + (0.02 \text{ kg/s})(400.98 - 280.13) \text{ kJ/kg}$$

$$= \mathbf{2.74\ kW}$$

Discussion Note that the mechanical energy input to the compressor manifests itself as a rise in enthalpy of air and heat loss from the compressor.

EXAMPLE 5–7 **Power Generation by a Steam Turbine**

The power output of an adiabatic steam turbine is 5 MW, and the inlet and the exit conditions of the steam are as indicated in Fig. 5–31.

(*a*) Compare the magnitudes of Δh, Δke, and Δpe.
(*b*) Determine the work done per unit mass of the steam flowing through the turbine.
(*c*) Calculate the mass flow rate of the steam.

SOLUTION The inlet and exit conditions of a steam turbine and its power output are given. The changes in kinetic energy, potential energy, and enthalpy of steam, as well as the work done per unit mass and the mass flow rate of steam 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 system is adiabatic and thus there is no heat transfer.

Analysis We take the *turbine* as the system. This is a *control volume* since mass crosses the system boundary during the process. We observe that there is only one inlet and one exit and thus $\dot{m}_1 = \dot{m}_2 = \dot{m}$. Also, work is done by the system. The inlet and exit velocities and elevations are given, and thus the kinetic and potential energies are to be considered.

(*a*) At the inlet, steam is in a superheated vapor state, and its enthalpy is

$$\left.\begin{matrix} P_1 = 2\text{ MPa} \\ T_1 = 400^\circ\text{C} \end{matrix}\right\} \quad h_1 = 3248.4\text{ kJ/kg} \qquad \text{(Table A–6)}$$

At the turbine exit, we obviously have a saturated liquid–vapor mixture at 15-kPa pressure. The enthalpy at this state is

$$h_2 = h_f + x_2 h_{fg} = [225.94 + (0.9)(2372.3)]\text{ kJ/kg} = 2361.01\text{ kJ/kg}$$

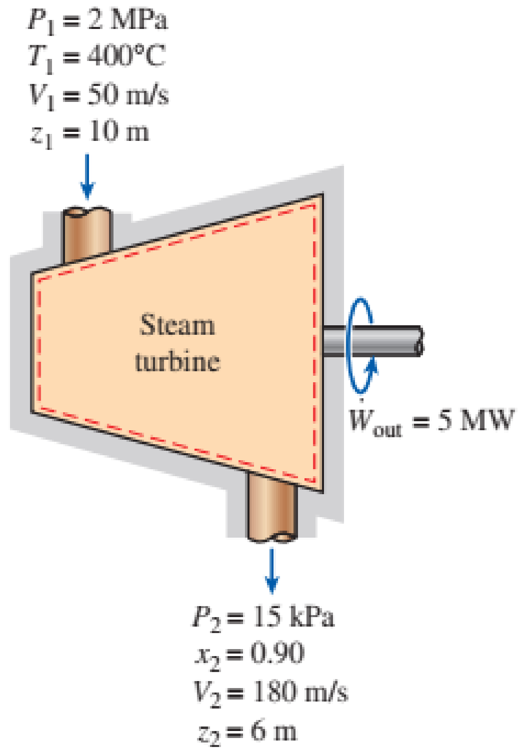


FIGURE 5–31
Schematic for Example 5–7.

Then

$$\Delta h = h_2 - h_1 = (2361.01 - 3248.4)\text{ kJ/kg} = \mathbf{-887.39\ kJ/kg}$$

$$\Delta ke = \frac{V_2^2 - V_1^2}{2} = \frac{(180\text{ m/s})^2 - (50\text{ m/s})^2}{2}\left(\frac{1\text{ kJ/kg}}{1000\text{ m}^2/\text{s}^2}\right) = \mathbf{14.95\ kJ/kg}$$

$$\Delta pe = g(z_2 - z_1) = (9.81\text{ m/s}^2)[(6 - 10)\text{ m}]\left(\frac{1\text{ kJ/kg}}{1000\text{ m}^2/\text{s}^2}\right) = \mathbf{-0.04\ kJ/kg}$$

(*b*) The energy balance for this steady-flow system can be expressed in the rate form as

$$\underbrace{\dot{E}_{in} - \dot{E}_{out}}_{\substack{\text{Rate of net energy transfer} \\ \text{by heat, work, and mass}}} = \underbrace{dE_{system}/dt}_{\substack{\text{Rate of change in internal, kinetic,} \\ \text{potential, etc., energies}}}^{\nearrow 0\text{ (steady)}} = 0$$

$$\dot{E}_{in} = \dot{E}_{out}$$

$$\dot{m}\left(h_1 + \frac{V_1^2}{2} + gz_1\right) = \dot{W}_{out} + \dot{m}\left(h_2 + \frac{V_2^2}{2} + gz_2\right) \quad (\text{since } \dot{Q} = 0)$$

Dividing by the mass flow rate $\dot{m}$ and substituting, the work done by the turbine per unit mass of the steam is determined to be

$$w_{out} = -\left[(h_2 - h_1) + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1)\right] = -(\Delta h + \Delta ke + \Delta pe)$$

$$= -[-887.39 + 14.95 - 0.04]\text{ kJ/kg} = \mathbf{872.48\ kJ/kg}$$

(*c*) The required mass flow rate for a 5-MW power output is

$$\dot{m} = \frac{\dot{W}_{out}}{w_{out}} = \frac{5000\text{ kJ/s}}{872.48\text{ kJ/kg}} = \mathbf{5.73\ kg/s}$$

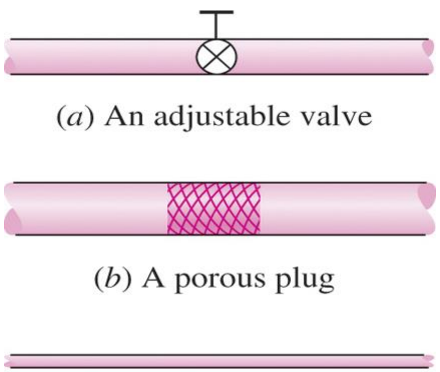
EXAMPLE 5–8 **Expansion of Refrigerant-134a in a Refrigerator**

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.

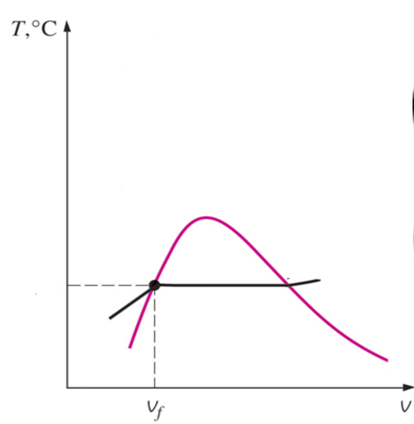
Analysis A capillary tube is a simple flow-restricting device that is commonly used in refrigeration applications to cause a large pressure drop in the

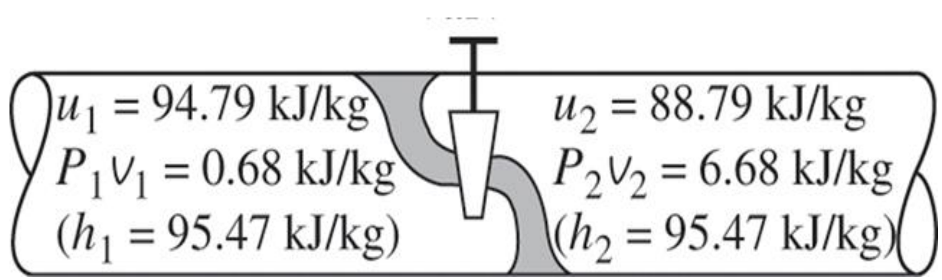


(*a*) An adjustable valve

(*b*) A porous plug

(*c*) A capillary tube





refrigerant. Flow through a capillary tube is a throttling process; thus, the enthalpy of the refrigerant remains constant (Fig. 5–34).

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

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

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

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

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.

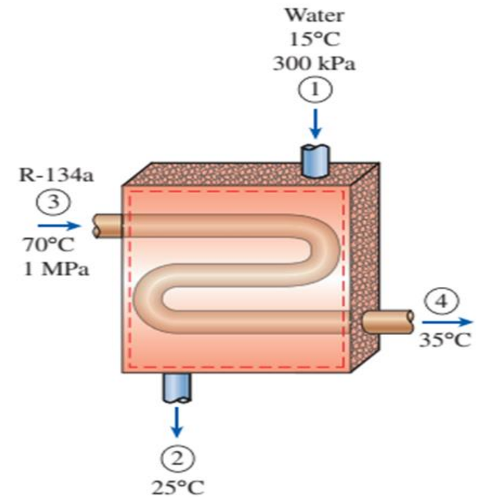
EXAMPLE 5–10 Cooling of Refrigerant-134a by Water

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.

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 ≅ pe ≅ 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 (Fig. 5–40). 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.



(a)

$$\dot{E}_{in} = \dot{E}_{out}$$

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

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

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

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

(Table A–4)

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

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

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

Substituting, we find

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

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

(*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

$$\underbrace{\dot{E}_{in} - \dot{E}_{out}}_{\substack{\text{Rate of net energy transfer} \\ \text{by heat, work, and mass}}} = \underbrace{dE_{system}/dt^{\nearrow 0 \text{ (steady)}}}_{\substack{\text{Rate of change in internal, kinetic,} \\ \text{potential, etc., energies}}} = 0$$

$$\dot{E}_{in} = \dot{E}_{out}$$

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

Rearranging and substituting,

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

$$= \mathbf{1218 \text{ kJ/min}}$$

EXAMPLE 5–12 Charging of a Rigid Tank by Steam

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.

SOLUTION A valve connecting an initially evacuated tank to a steam line is opened, and steam flows in until the pressure inside rises to the line level. The final temperature in the tank is to be determined.

Assumptions **1** This process can be analyzed as a *uniform-flow process* since the properties of the steam entering the control volume remain constant during the entire process. **2** The kinetic and potential energies of the streams are negligible, ke ≅ pe ≅ 0. **3** The tank is stationary and thus its kinetic and potential energy changes are zero; that is, $\Delta KE = \Delta PE = 0$ and $\Delta E_{system} = \Delta U_{system}$. **4** There are no boundary, electrical, or shaft work interactions involved. **5** The tank is well insulated and thus there is no heat transfer.

Analysis We take the *tank as the system* (Fig. 5–50). This is a *control volume* since mass crosses the system boundary during the process. We observe that this is an unsteady-flow process since changes occur within the control volume. The control volume is initially evacuated and thus $m_1 = 0$ and $m_1u_1 = 0$. Also, there is one inlet and no exits for mass flow.

Noting that microscopic energies of flowing and nonflowing fluids are represented by enthalpy h and internal energy u, respectively, the mass and energy balances for this uniform-flow system can be expressed as

Mass balance: $$m_{in} - m_{out} = \Delta m_{system} \rightarrow m_i = m_2 - \cancelto{0}{m_1} = m_2$$

Energy balance:

$$\underbrace{E_{in} - E_{out}}_{\substack{\text{Net energy transfer} \\ \text{by heat, work, and mass}}} = \underbrace{\Delta E_{system}}_{\substack{\text{Change in internal, kinetic,} \\ \text{potential, etc., energies}}}$$

$$m_i h_i = m_2 u_2 \quad (\text{since } W = Q = 0,\ \text{ke} \cong \text{pe} \cong 0,\ m_1 = 0)$$

Combining the mass and energy balances gives

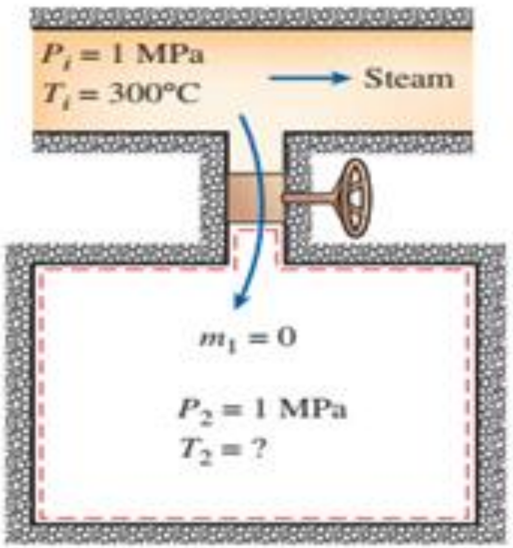
$$u_2 = h_i$$

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

$$\left.\begin{matrix} P_i = 1 \text{ MPa} \\ T_i = 300°\text{C} \end{matrix}\right\} \quad h_i = 3051.6 \text{ kJ/kg} \qquad \text{(Table A–6)}$$

which is equal to u_2. Since we now know two properties at the final state, it is fixed and the temperature at this state is determined from the same table to be

$$\left.\begin{matrix} P_2 = 1 \text{ MPa} \\ u_2 = 3051.6 \text{ kJ/kg} \end{matrix}\right\} \quad T_2 = \mathbf{456.1°C}$$



(*a*) Flow of steam into an evacuated tank