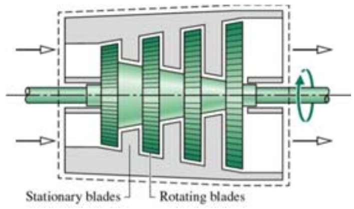
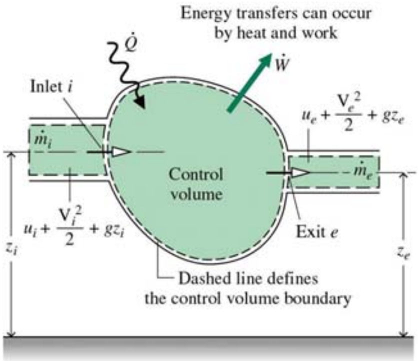
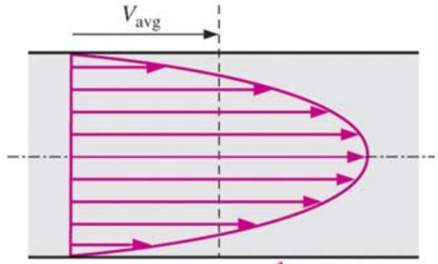
$$\sum_{\text{in}} \dot{m} = \sum_{\text{out}} \dot{m}$$

Thermodynamics I



Mass and Energy Analysis Control Volume





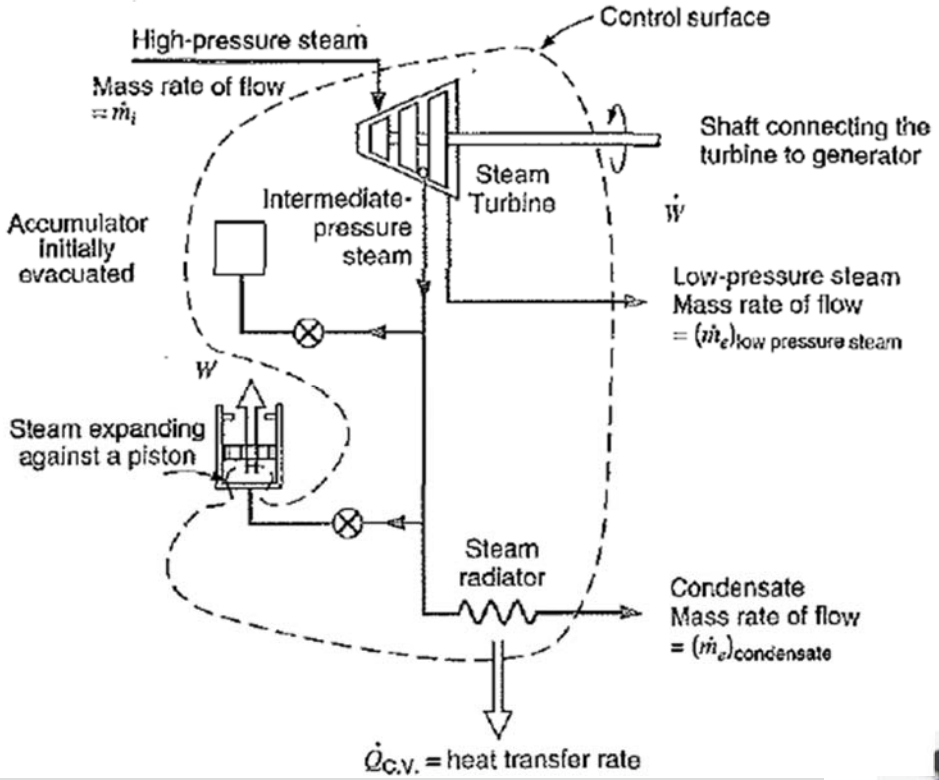
Dr.-Eng. Zayed Al-Hamamre

$$V_{avg} = \frac{1}{A_c} \int_{A_c} V_n \, dA_c$$

Content

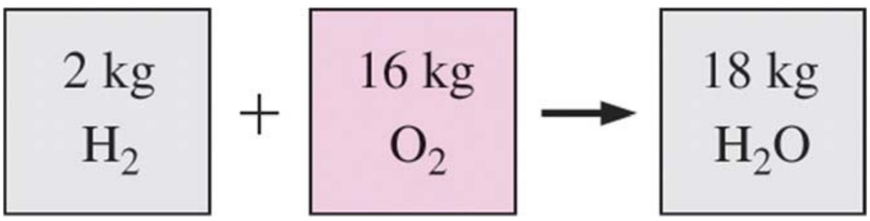
- Conservation of mass
  - ✓ Mass and volume flow rates
  - ✓ Mass balance for a steady-flow process
  - ✓ Mass balance for incompressible flow
- Flow work and the energy of a flowing fluid
  - ✓ Energy transport by mass
- Energy analysis of steady-flow systems
- Some steady-flow engineering devices
  - ✓ Nozzles and Diffusers
  - ✓ Turbines and Compressors
  - ✓ Throttling valves
  - ✓ Mixing chambers and Heat exchangers
  - ✓ Pipe and Duct flow
- Energy analysis of unsteady-flow processes

Introduction



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.

The mass change due to energy change is absolutely negligible.

Mass and Volume Flow Rates

$$\delta \dot{m} = \rho V_n \, dA_c$$

$$\dot{m} = \int_{A_c} \delta \dot{m} = \int_{A_c} \rho V_n \, dA_c \qquad \text{(kg/s)}$$

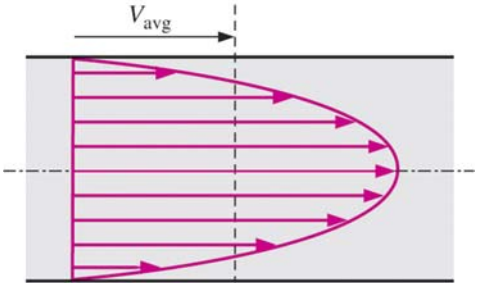
$$\dot{m} = \rho V_{avg} A_c \qquad \text{(kg/s)}$$

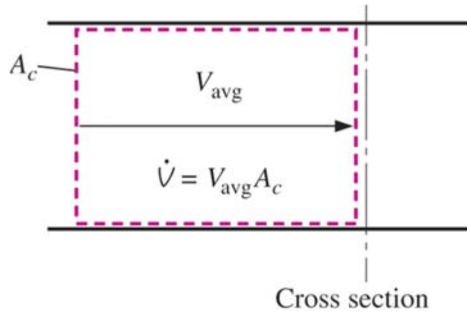
$$\dot{m} = \rho \dot{V} = \frac{\dot{V}}{v}$$ Mass flow rate

$$V_{avg} = \frac{1}{A_c} \int_{A_c} V_n \, dA_c$$ Definition of average velocity

Volume flow rate

$$\dot{V} = \int_{A_c} V_n \, dA_c = V_{avg} A_c = V A_c \qquad (\text{m}^3/\text{s})$$





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**: The net mass transfer to or from a control volume during a time interval Δt is equal to the net change (increase or decrease) in the total mass within the control volume during Δt.

$$\begin{bmatrix} \text{time } rate \text{ of change of} \\ \text{mass contained within} \\ \text{the control volume } at\ time\ t \end{bmatrix} = \begin{bmatrix} \text{time } rate \text{ of flow} \\ \text{of mass } in \text{ across} \\ \text{inlet } i\ at\ time\ t \end{bmatrix} - \begin{bmatrix} \text{time } rate \text{ of flow} \\ \text{of mass } out \text{ across} \\ \text{exit } e\ at\ time\ t \end{bmatrix}$$

$$m_{in} - m_{out} = \Delta m_{CV} \qquad \text{(kg)}$$

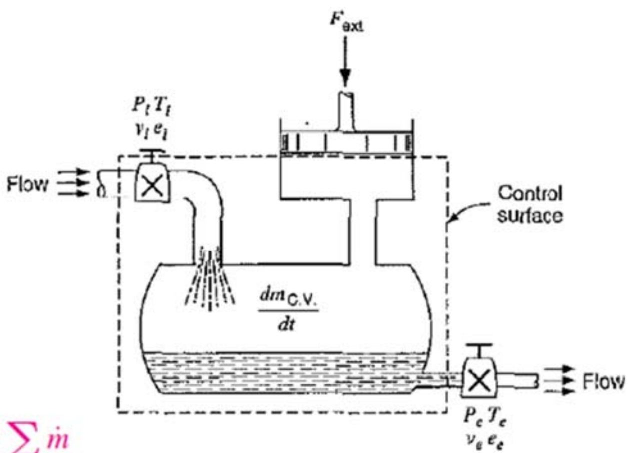
$$\dot{m}_{in} - \dot{m}_{out} = dm_{CV}/dt \qquad \text{(kg/s)}$$

General conservation of mass

$$\frac{d}{dt} \int_{CV} \rho \, dV + \int_{CS} \rho (\vec{V} \cdot \vec{n}) \, dA = 0$$

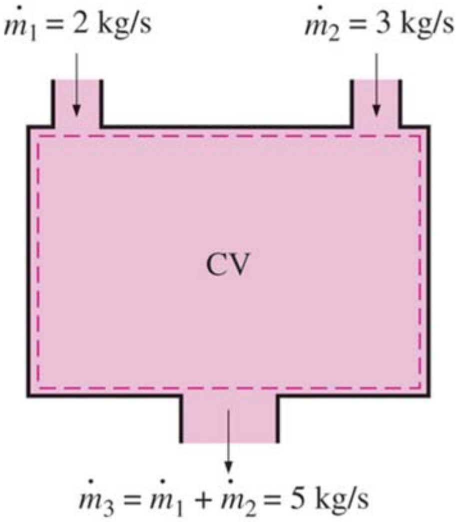
General conservation of mass in rate form

$$\frac{d}{dt} \int_{CV} \rho \, dV = \sum_{in} \dot{m} - \sum_{out} \dot{m} \quad \text{or} \quad \frac{dm_{CV}}{dt} = \sum_{in} \dot{m} - \sum_{out} \dot{m}$$



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).
- Then the conservation of mass principle requires that the total amount of mass entering a control volume equal the total amount of mass leaving it.



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

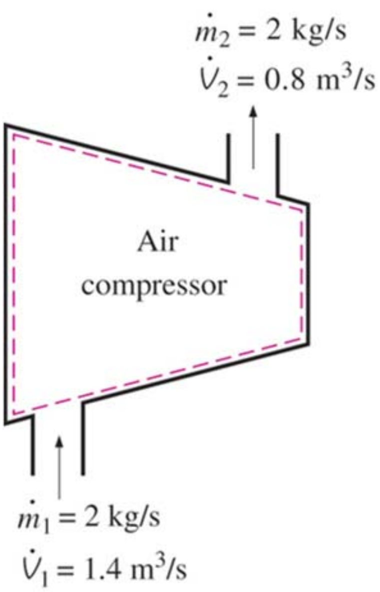
$$\sum_{in} \dot{m} = \sum_{out} \dot{m} \qquad (\text{kg/s})$$ Multiple inlets and exits

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

- 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.



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

$$\dot{V}_1 = \dot{V}_2 \rightarrow V_1 A_1 = V_2 A_2$$ Steady, incompressible flow (single stream)

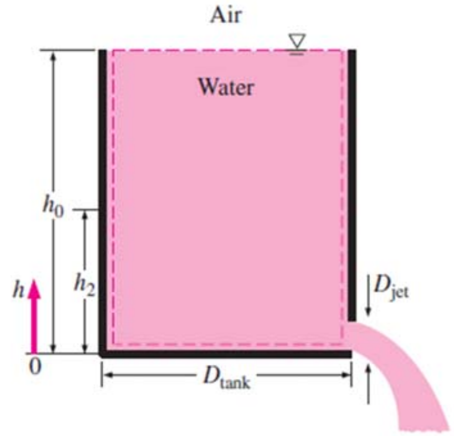
- There is no such thing as a "conservation of volume" principle.
- However, for steady flow of liquids, the volume flow rates, as well as the mass flow rates, remain constant since liquids are essentially incompressible substances.
  - During a steady-flow process, volume flow rates are not necessarily conserved although mass flow rates are.

Example

A 4-ft-high, 3-ft-diameter cylindrical water tank whose top is open to the atmosphere is initially filled with water. Now the discharge plug near the bottom of the tank is pulled out, and a water jet whose diameter is 0.5 in streams out (Fig. 5–10). Determine how long it will take for the water level in the tank to drop to 2 ft from the bottom.

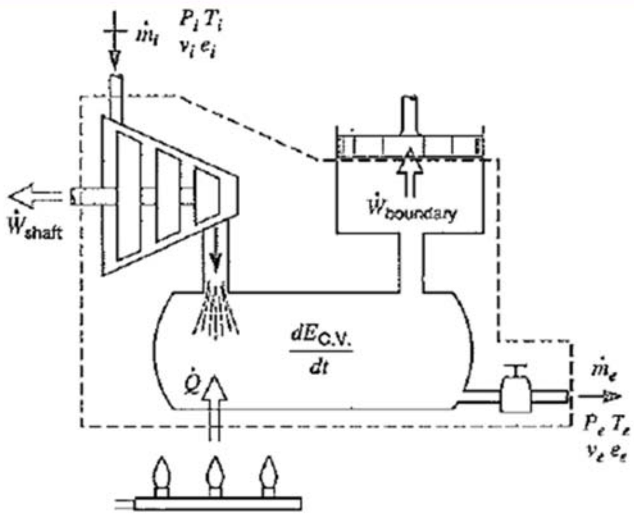
The average velocity of the jet is given by $V = \sqrt{2gh},$ **Show this**

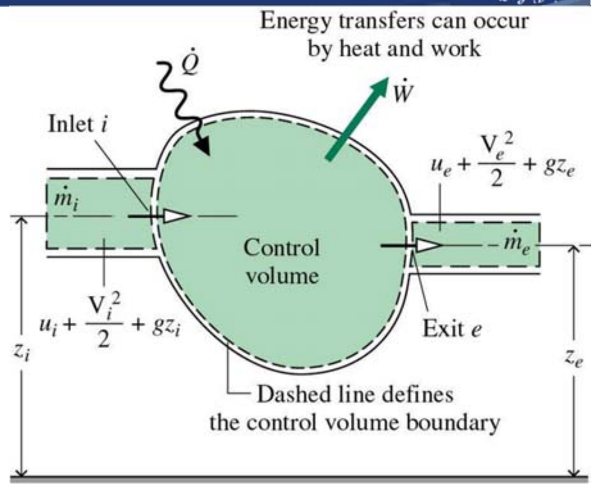
where h is the height of water in the tank measured from the center of the hole (a variable) and g is the gravitational acceleration



Example Cont.

Conservation of Energy for a Control Volume





[time *rate of change* of the energy contained within the control volume *at time t*] = [net *rate* at which energy is being transferred *in* by heat transfer *at time t*] − [net *rate* at which energy is being transferred *out* by work *at time t*] + [net *rate* of energy transfer *into* the control volume accompanying mass flow]

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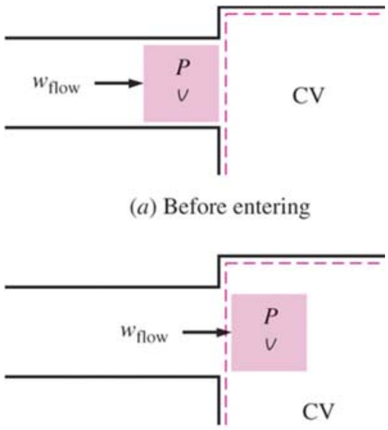
F low Work and Energy of a Flowing Fluid

- **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.

$$F = PA$$

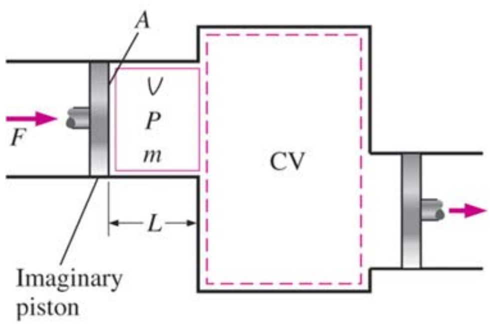
$$W_{flow} = FL = PAL = PV \qquad \text{(kJ)}$$

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



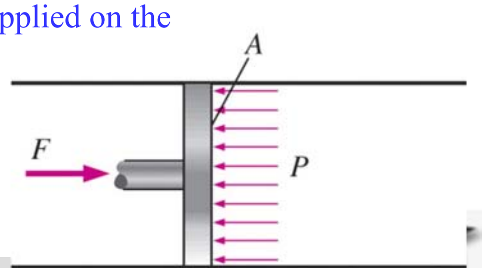
(*a*) Before entering

(*b*) After entering



Schematic for flow work.

In the absence of acceleration, the force applied on a fluid by a piston is equal to the force applied on the piston by the fluid.



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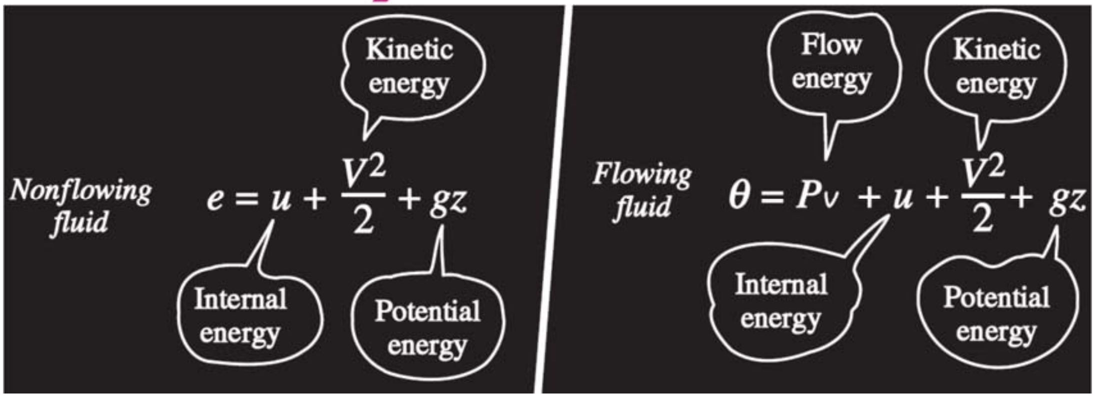
Total Energy of a Flowing Fluid

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

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

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

- The flow energy is automatically taken care of by enthalpy. In fact, this is the main reason for defining the property enthalpy.

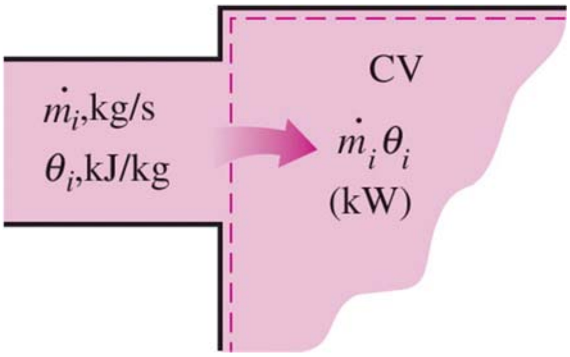


- The total energy consists of three parts for a nonflowing fluid and four parts for a flowing fluid.

Energy Transport by Mass

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



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

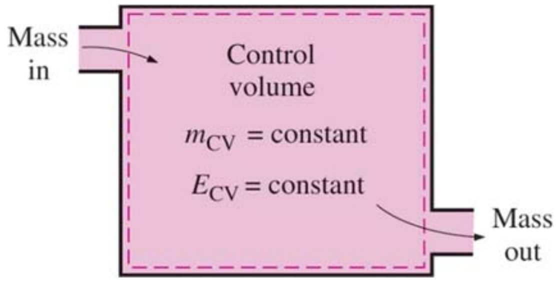
$$E_{\text{mass}} = mh \qquad \dot{E}_{\text{mass}} = \dot{m}h$$

- When the properties of the mass at each inlet or exit change with time as well as over the cross section

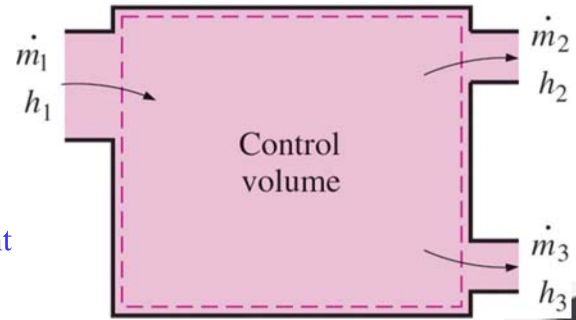
$$E_{\text{in,mass}} = \int_{m_i} \theta_i \,\delta m_i = \int_{m_i} \left(h_i + \frac{V_i^2}{2} + gz_i\right) \delta m_i$$

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

Energy Analysis of Steady Flow Systems



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



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

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

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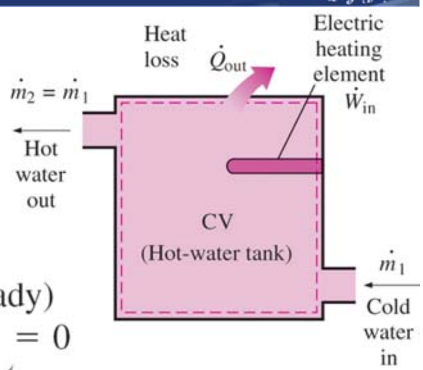
Mass and Energy balances for a steady-flow process

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 balanc

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

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

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

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Energy Balance Relations Q_{in} &W_{out} Output Are Positive

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

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

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

$$q - w = h_2 - h_1 \quad q = \dot{Q}/\dot{m} \quad w = \dot{W}/\dot{m}$$

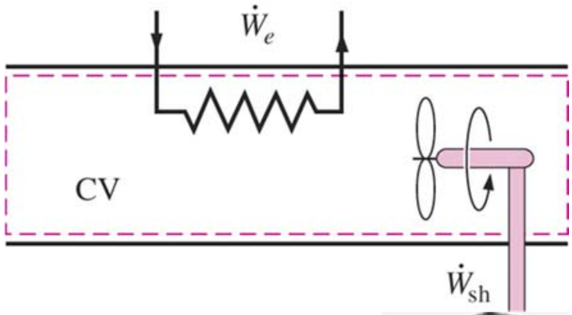
when kinetic and potential energy changes are negligible

$$\frac{\text{J}}{\text{kg}} \equiv \frac{\text{N}\cdot\text{m}}{\text{kg}} \equiv \left(\text{kg}\frac{\text{m}}{\text{s}^2}\right)\frac{\text{m}}{\text{kg}} \equiv \frac{\text{m}^2}{\text{s}^2}$$

$$\left(\text{Also, } \frac{\text{Btu}}{\text{lbm}} \equiv 25{,}037\ \frac{\text{ft}^2}{\text{s}^2}\right)$$

Some energy unit equivalents

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



Example

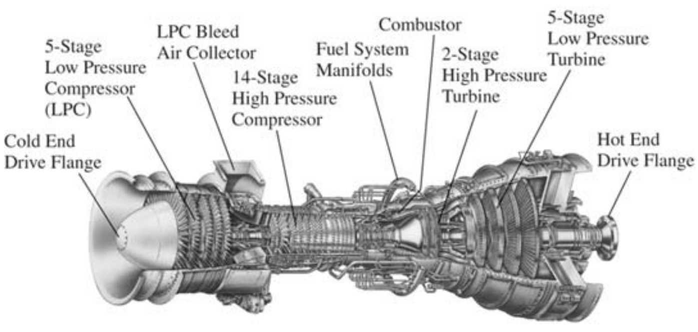
Steam is leaving a 4-L pressure cooker whose operating pressure is 150 kPa. It is observed that the amount of liquid in the cooker has decreased by 0.6 L in 40 min after the steady operating conditions are established, and the cross-sectional area of the exit opening is 8 mm^2. Determine (*a*) the mass flow rate of the steam and the exit velocity, (*b*) the total and flow energies of the steam per unit mass, and (*c*) the rate at which energy leaves the cooker by steam.

Example Cont.

Steady Flow Devices

- ➢ Many engineering devices operate essentially under the same conditions for long periods of time (the components of a steam power plant: turbines, compressors, heat exchangers, and pumps).

Can be conveniently analyzed as steady-flow devices.

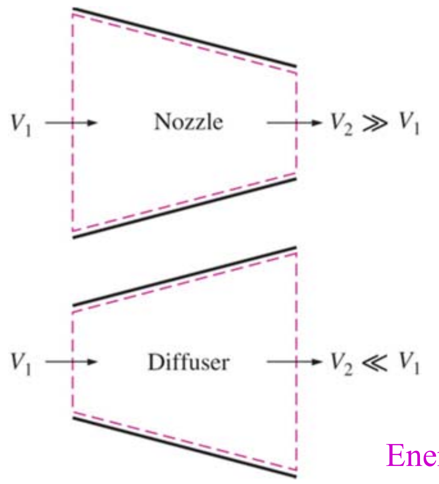


- ➢ A modern land-based gas turbine used for electric power production. This is a General Electric LM5000 turbine. It has a length of 6.2 m, it weighs 12.5 tons, and produces 55.2 MW at 3600 rpm with steam injection.

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.

Energy balance for a nozzle or diffuser:

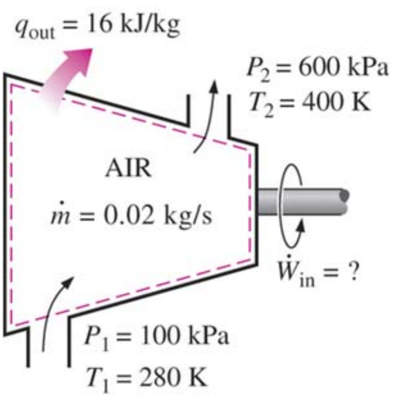
- Nozzles and diffusers are shaped so that they cause large changes in fluid velocities and thus kinetic energies.

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

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

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

Turbines and Compressors



- **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.
- A ***fan*** increases the pressure of a gas slightly and is mainly used to mobilize a gas.
- A ***compressor*** is capable of compressing the gas to very high pressures.
- ***Pumps*** work very much like compressors except that they handle liquids instead of gases.

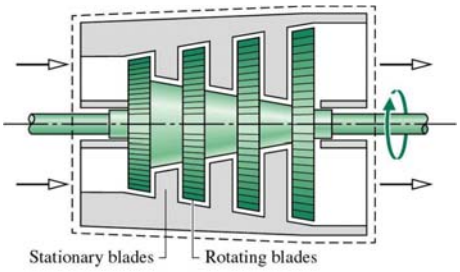
Energy balance for the compressor in this figure:

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

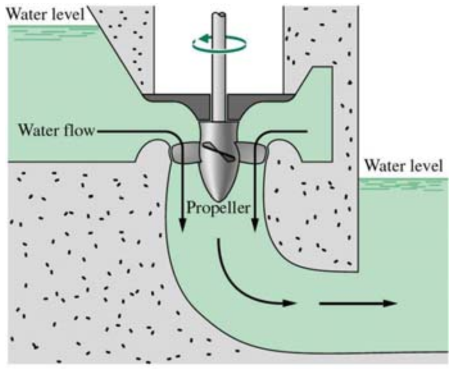
$$\dot{W}_{in} + \dot{m}h_1 = \dot{Q}_{out} + \dot{m}h_2$$

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

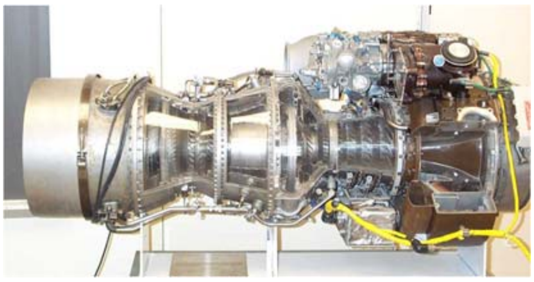
Turbines



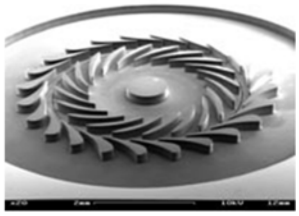
Schematic of an axial flow turbine



Hydraulic turbine installed in a dam.

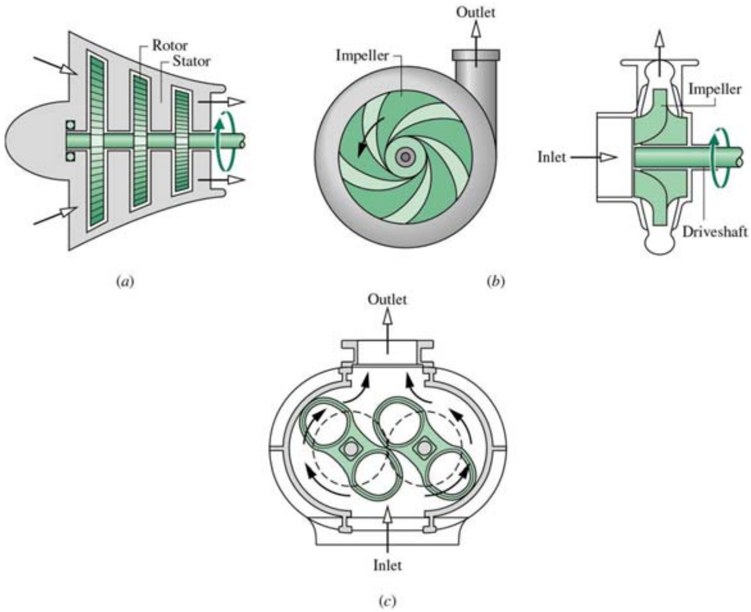


1100kW Helicopter Engine

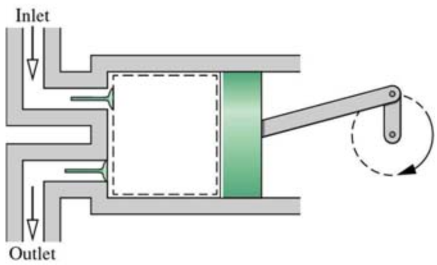


50 watt Microturbine

Compressors and Pumps

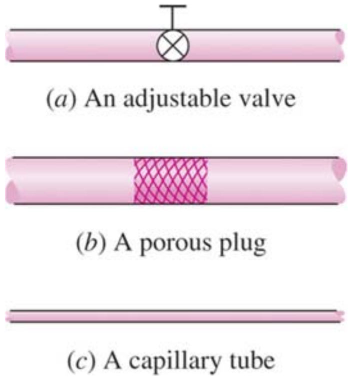


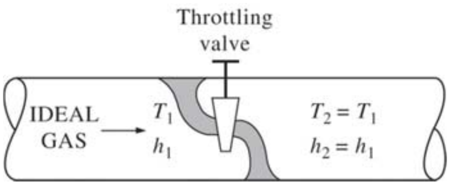
Rotating compressors. (*a*) Axial flow. (*b*) Centrifugal. (*c*) Roots type.



Reciprocating compressor

Throttling Valves





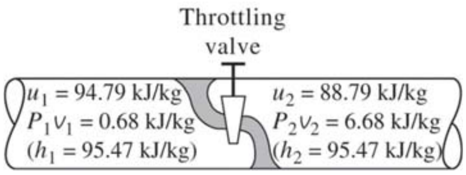
- **Throttling valves** are *any kind of flow-restricting devices* that cause significant pressure drop in the fluid.
- ***What is the difference between a turbine and a throttling valve?***
- The pressure drop in the fluid is often accompanied by a *large drop in temperature*, and for that reason throttling devices are commonly used in refrigeration and air-conditioning applications.

Energy balance

$$h_2 \cong h_1$$

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

Internal energy + Flow energy = Constant



- 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.

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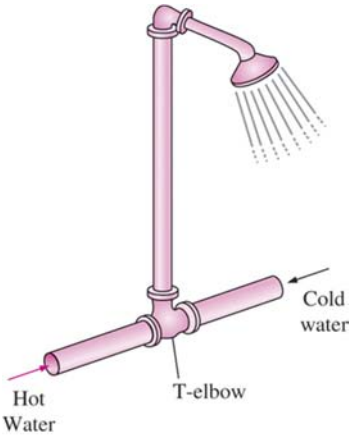
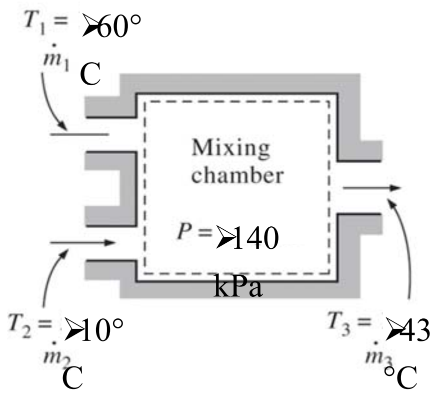
Mixing Chambers

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



- The T-elbow of an ordinary shower serves as the mixing chamber for the hot- and the cold-water streams.



- Energy balance for the adiabatic mixing chamber in the figure is:

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

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

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

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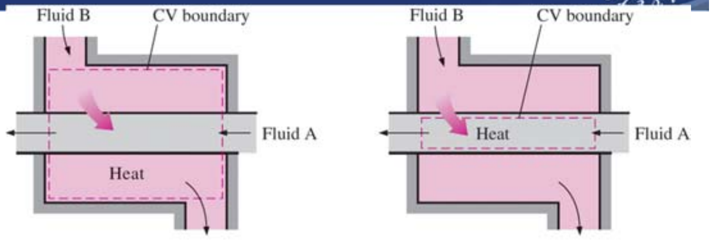
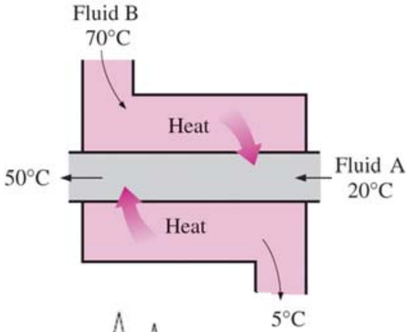
Heat Exchangers

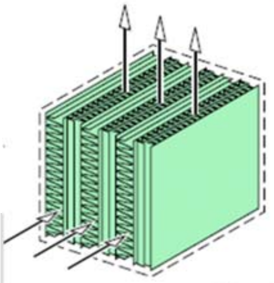
- **Heat exchangers** are devices where two moving fluid streams exchange heat without mixing. Heat exchangers are widely used in various industries, and they come in various designs.



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

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





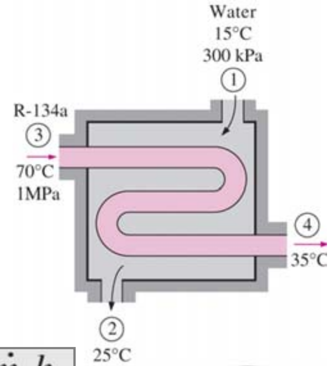
- The heat transfer associated with a heat exchanger may be zero or nonzero depending on how the control volume is selected.
- Mass and energy balances for the adiabatic heat exchanger

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

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

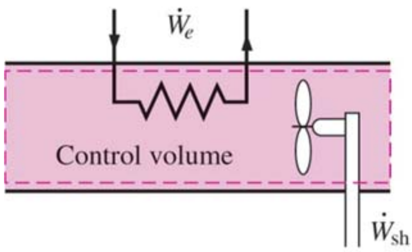
$$\dot{E}_{in} = \dot{E}_{out}$$

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

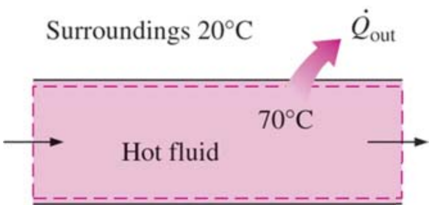


Pipe and duct flow

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



Pipe or duct flow may involve more than one form of work at the same time.



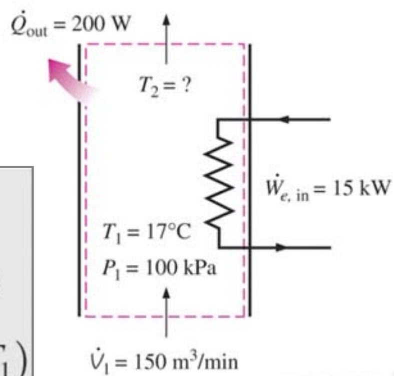
- Heat losses from a hot fluid flowing through an uninsulated pipe or duct to the cooler environment may be very significant.

Energy balance for the pipe flow shown in the figure is

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

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

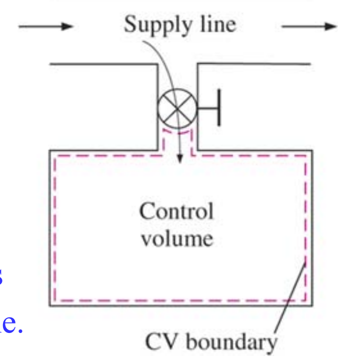
$$\dot{W}_{e,in} - \dot{Q}_{out} = \dot{m}c_p(T_2 - T_1)$$



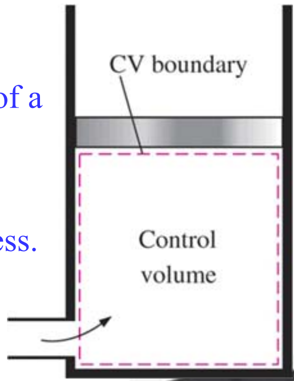
Energy Analysis of Unsteady Processes

- Many processes of interest, however, 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.*
- **Uniform-flow process:** The fluid flow at any inlet or exit is uniform and steady, and thus the fluid properties do not change with time or position over the cross section of an inlet or exit. If they do, they are averaged and treated as constants for the entire process.

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



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



Mass Balance

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

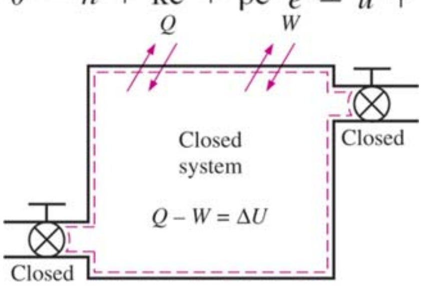
$$m_i - m_e = (m_2 - m_1)_{CV} \quad i = \text{inlet},\ e = \text{exit},\ 1 = \text{initial state, and } 2 = \text{final state}$$

Energy balance

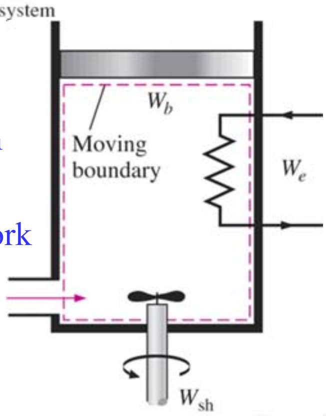
$$\underbrace{E_{in} - E_{out}}_{\substack{\text{Net energy transfer}\\ \text{by heat, work, and mass}}} = \underbrace{\Delta E_{system}}_{\substack{\text{Change in internal, kinetic,}\\ \text{potential, etc., energies}}}$$

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

$$\theta = h + ke + pe \quad e = u + ke + pe$$



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

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.

Example Cont.

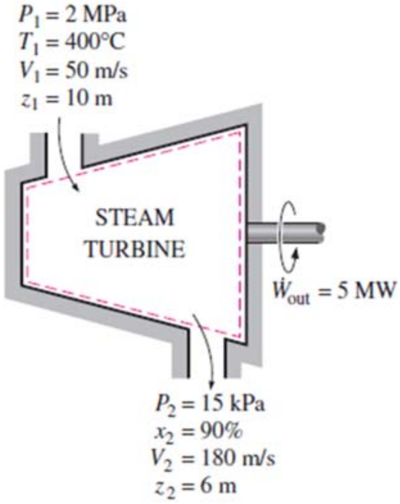
Example

The power output of an adiabatic steam turbine is 5 MW, and the inlet and the exit conditions of the steam are as shown

a. Compare the magnitudes of Δh, Δ ke, and Δ pe.

b. Determine the work done per unit mass of the steam flowing through the turbine.

c. Calculate the mass flow rate of the steam.



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Example Cont.

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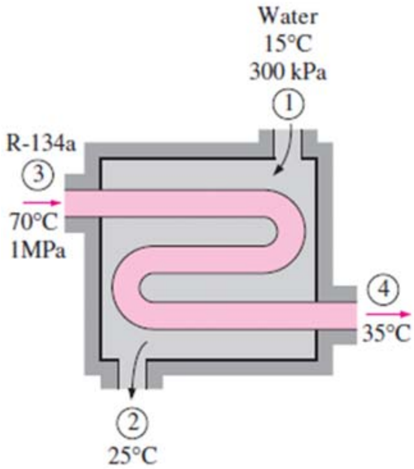
Example

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.

Example Cont.

Example

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.



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Example Cont.

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