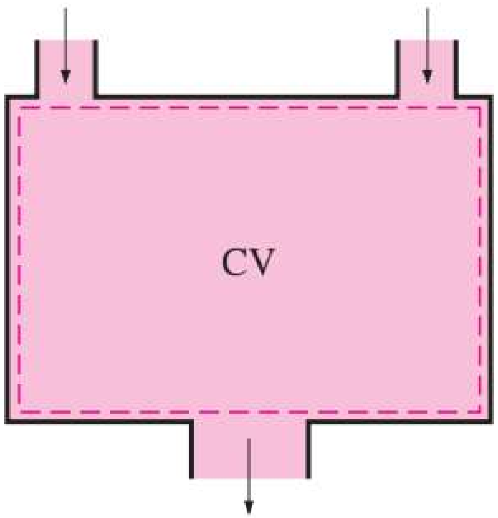
First Law Applied to Open Systems – Steady Flow Energy Equation

Conservation of mass

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



Conservation of Energy

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

For steady flow systems,

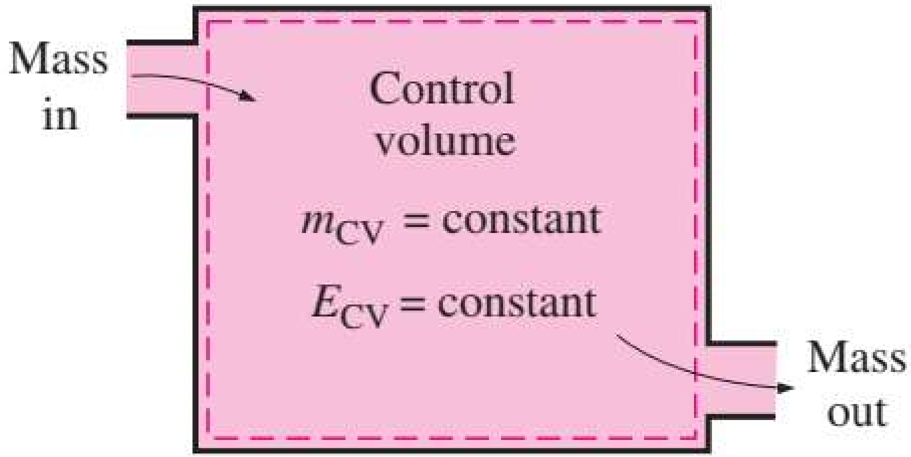


FIGURE 5–18

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

Conservation of mass - For steady flow systems

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.

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

It states that *the total rate of mass entering a control volume is equal to the total rate of mass leaving it*

- Many engineering devices such as nozzles, diffusers, turbines, compressors, and pumps involve a single stream (only one inlet and one outlet).
- For these cases, we denote the inlet state by the subscript 1 and the outlet state by the subscript 2, and drop the summation signs.
- For *single-stream steady-flow systems*, to

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

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

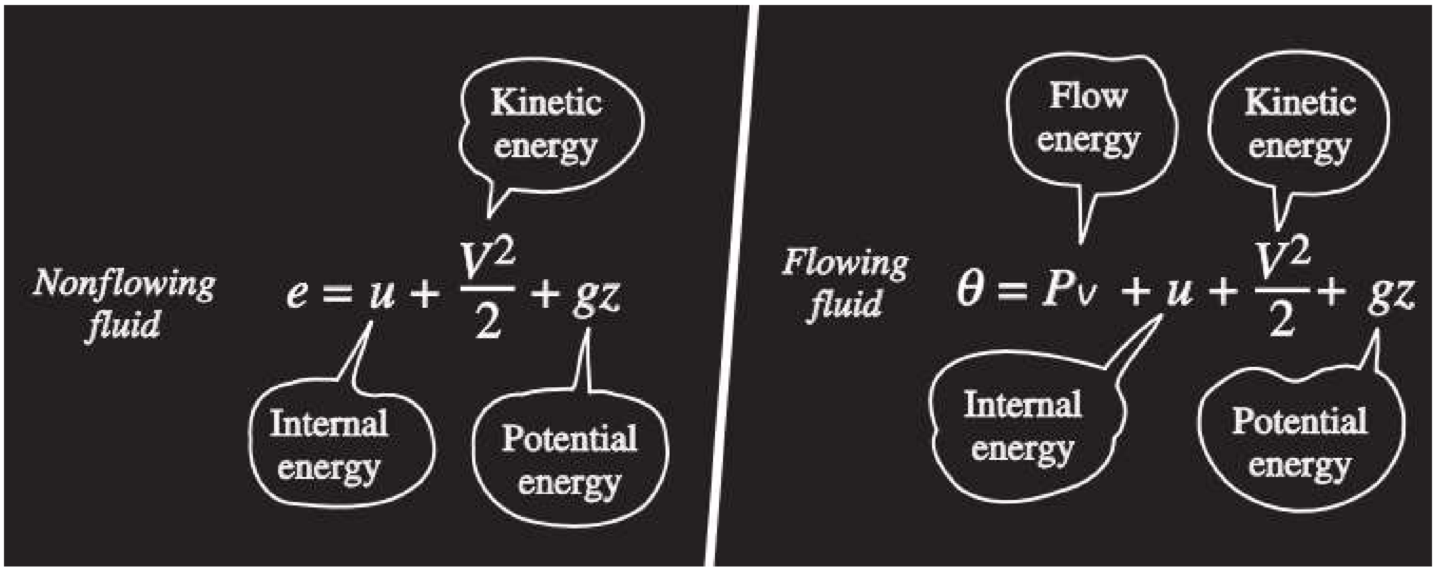
- For the special case of incompressible flow (density of the flow ρ is constant i.e., $\rho_1 = \rho_2$)

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

$$\rightarrow V_1 A_1 = V_2 A_2$$

Conservation of Energy - For steady flow systems

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



Flow Work (or) Flow Energy

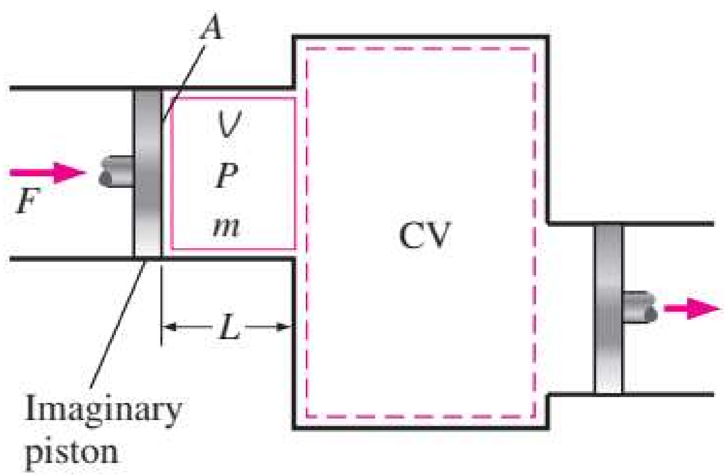


FIGURE 5–11

Schematic for flow work.

The work done in pushing the fluid element across the boundary (i.e., the flow work) is

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

The flow work per unit mass is obtained by dividing both sides of this equation by the mass of the fluid element:

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

The flow work relation is the same whether the fluid is pushed into or out of the control volume

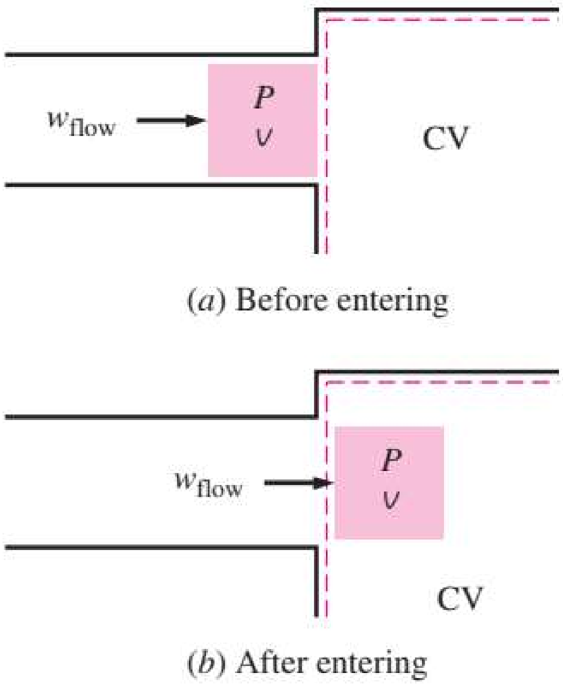


FIGURE 5–13

Flow work is the energy needed to push a fluid into or out of a control volume, and it is equal to Pv.

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

The fluid entering or leaving a control volume possesses an additional form of energy—the *flow energy* Pv, as already discussed. Then the total energy of a **flowing fluid** on a unit-mass basis (denoted by u) becomes

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

But the combination $Pv + u$ has been previously defined as the enthalpy h.

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

Conservation of energy – Steady Flow Energy Equation

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

Noting that energy can be transferred by heat, work, and mass only, the energy balance for a general steady-flow system can also be written more explicitly as

$$\dot{Q}_{\text{in}} + \dot{W}_{\text{in}} + \sum_{\text{in}} \dot{m}\theta = \dot{Q}_{\text{out}} + \dot{W}_{\text{out}} + \sum_{\text{out}} \dot{m}\theta$$

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

By applying standard sign conventions for heat and work interactions

Heat to be transferred *into the system* (heat input) at a rate of $\dot{Q}$, and work produced *by the system* (work output) at a rate of $\dot{W}$ are considered to be positive.

The first-law or energy balance relation in that case for a general steady-flow system becomes

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

For single-stream devices, the steady-flow energy balance equation becomes

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

$\dot{Q}$ = rate of heat transfer between the control volume and its surroundings.

$\dot{W}$ = power.

- Many steady-flow devices, such as turbines, compressors, and pumps, transmit power through a shaft, and $\dot{W}$ simply becomes the shaft power for those devices.
- If the control surface is crossed by electric wires (as in the case of an electric water heater), $\dot{W}$ represents the electrical work done per unit time.
- If neither is present, then $\dot{W} = 0$.

$$\Delta h = h_2 - h_1 = c_{p,\text{avg}}(T_2 - T_1)$$

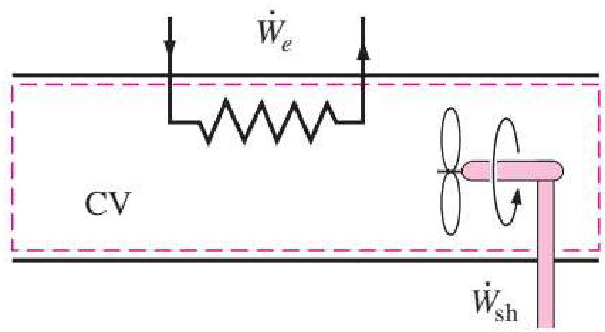


FIGURE 5–21

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

Applications of SFEE to Nozzles, Diffusers, turbines, compressor, boiler, pump. Heat exchanger and Throttling process

1. Nozzles and Diffusers

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. That is, nozzles and diffusers perform opposite tasks.

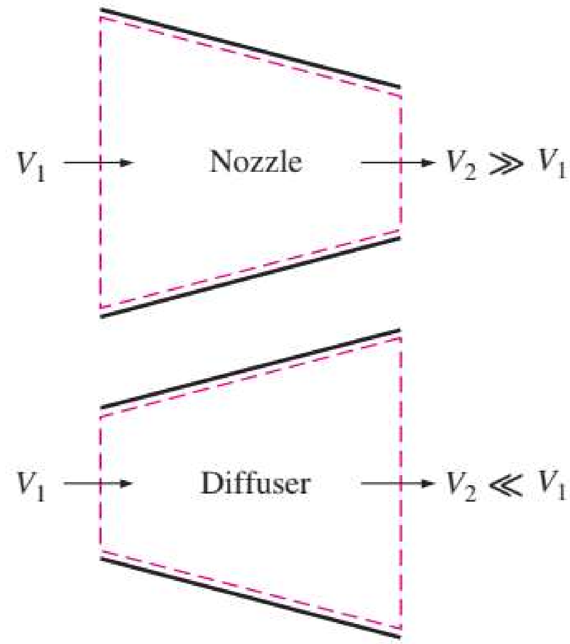


FIGURE 5–25

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

$$\cancelto{0}{\dot{Q}} - \cancelto{0}{\dot{W}} = \dot{m}\left[h_2 - h_1 + \frac{V_2^2 - V_1^2}{2} + \cancelto{\approx 0}{g(z_2 - z_1)}\right]$$

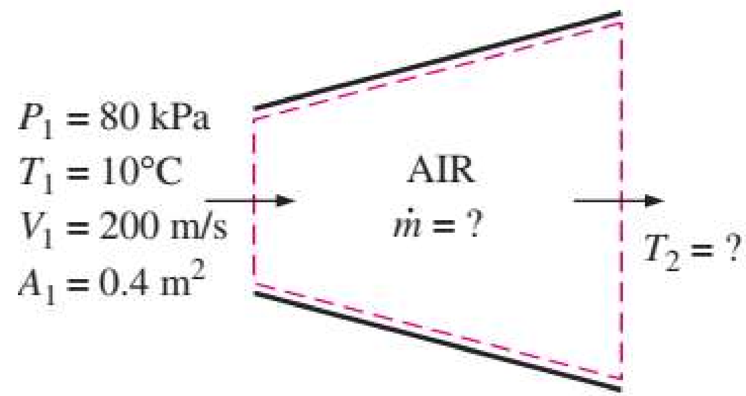
No heat Transfer

No work Transfer

No datum difference

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

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.



2 Turbines and Compressors

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. Therefore, compressors involve work inputs.

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

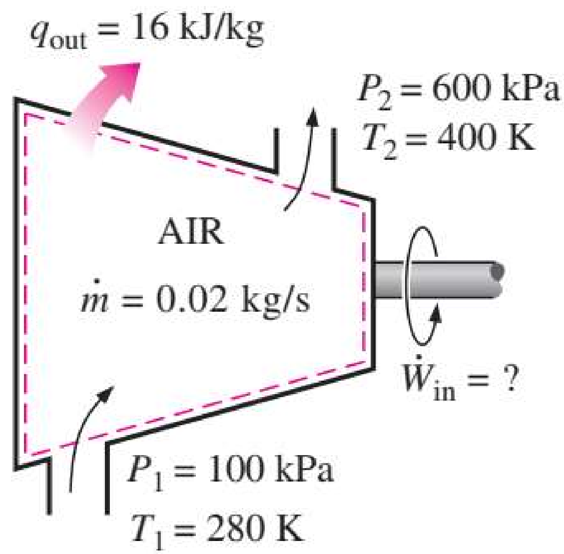
no heat transfer

$V_1 \approx V_2$ (For compressors)

$z_1 \approx z_2$

$$\Rightarrow \boxed{\dot{W} = \dot{m}\,(h_1 - h_2)} \Rightarrow \dot{W} = \dot{m}\, c_p (T_1 - T_2)$$

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.



3 Throttling Valves

- 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
- 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.

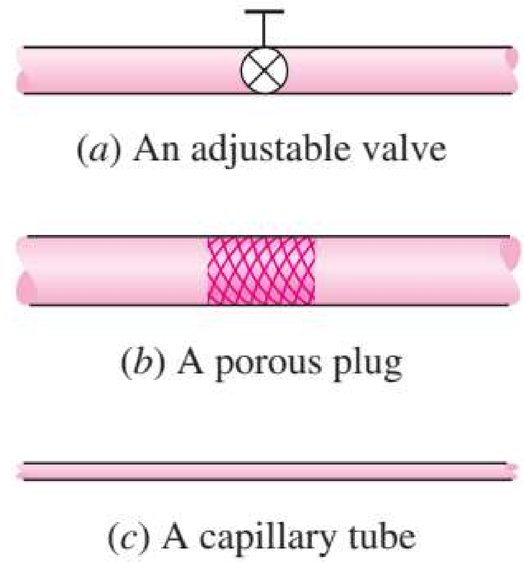


FIGURE 5–29

Throttling valves are devices that cause large pressure drops in the fluid.

$$\underbrace{\cancel{\dot{Q}}}_{\dot{Q}\approx 0} - \underbrace{\cancel{\dot{W}}}_{\dot{W}\approx 0} = \dot{m}\left[h_2 - h_1 + \underbrace{\cancel{\frac{V_2^2 - V_1^2}{2}}}_{0,\ V_1 \approx V_2} + g(\underbrace{\cancel{z_2 - z_1}}_{0,\ z_1 \approx z_2})\right]$$

$$\Rightarrow \boxed{h_1 = h_2}$$

the conservation of energy equation for this single-stream steady-flow device reduces to

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

That is, enthalpy values at the inlet and exit of a throttling valve are the same. For this reason, a throttling valve is sometimes called an *isenthalpic device*.

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

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

For an ideal gas:-

$$h_1 = h_2$$

$$\Rightarrow \quad C_p T_1 = C_p T_2$$

$$\Rightarrow \quad \boxed{T_1 = T_2}$$

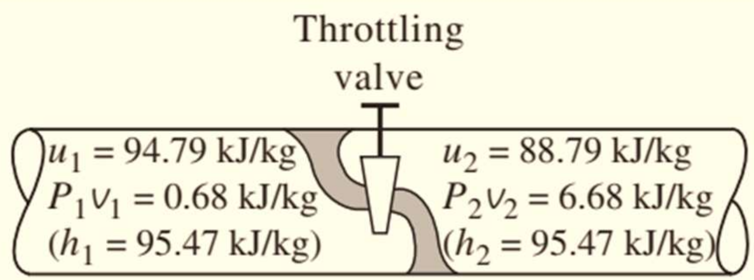


FIGURE 5–31

During a throttling process, the enthalpy (flow energy + internal energy) of a fluid remains constant. But internal and flow energies may be converted to each other.

5–70E Air at 200 psia and 90°F is throttled to the atmospheric pressure of 14.7 psia. Determine the final temperature of the air.

4 Heat Exchangers

heat exchangers are devices where two moving fluid streams exchange heat without mixing.

The simplest form of a heat exchanger is a *double-tube* (also called *tube and-shell*) *heat exchanger*

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

no work transfer

0 $V_1 \approx V_2$

0 $z_1 \approx z_2$

$\Rightarrow \boxed{\dot{Q} = \dot{m}(h_2 - h_1)}$

$\Rightarrow \dot{Q} = \dot{m}\, c_p (T_2 - T_1)$

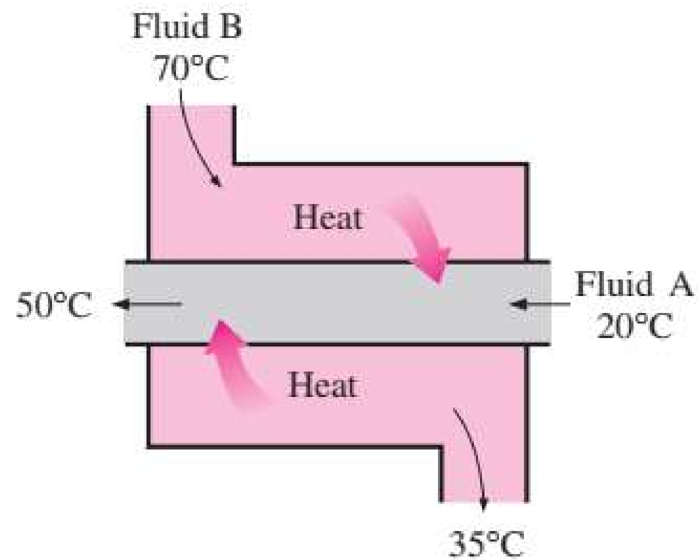


FIGURE 5–35

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

5–91 A thin-walled double-pipe counter-flow heat exchanger is used to cool oil (c_p = 2.20 kJ/kg · °C) from 150 to 40°C at a rate of 2 kg/s by water (c_p = 4.18 kJ/kg · °C) that enters at 22°C at a rate of 1.5 kg/s. Determine the rate of heat transfer in the heat exchanger and the exit temperature of water.

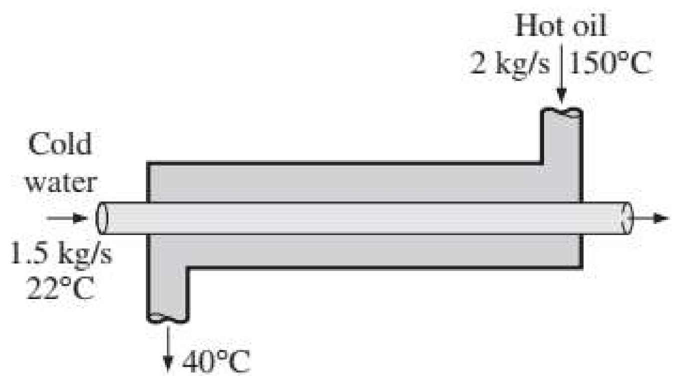


FIGURE P5–91