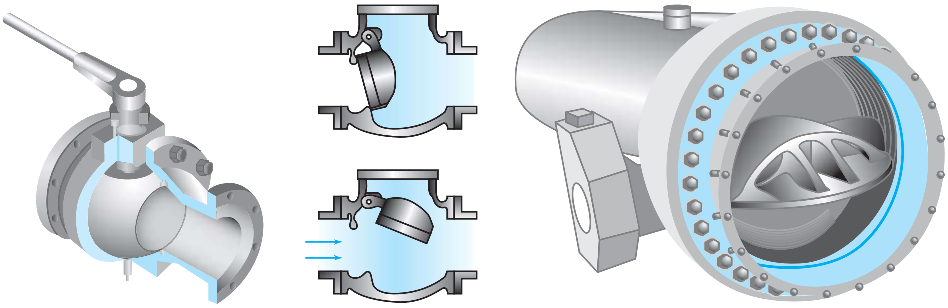
A flow is normally controlled by operating a valve that has a variable opening for the flow to pass through. With a small opening it represents a large restriction to the flow leading to a high pressure drop across the valve, whereas a large opening allows the flow to pass through freely with almost no restriction. There are many different types of valves in use, several of which are shown in Fig. 6.17.

## Heaters/Coolers and Heat Exchangers

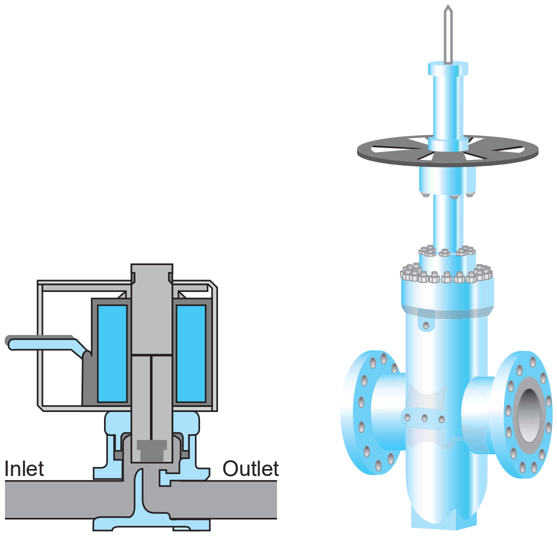
Two examples of heat exchangers are shown in Fig. 6.18. The aftercooler reduces the temperature of the air coming out of a compressor before it enters the engine. The purpose of the heat exchanger in Fig. 6.18*b* is to cool a hot flow or to heat a cold flow. The inner tubes act as the interphase area between the two fluids.

## Active Flow Devices and Systems

A few air compressors and fans are shown in Fig. 6.19. These devices require a work input so the compressor can deliver air flow at a higher pressure and the fan can provide an air flow with some velocity.

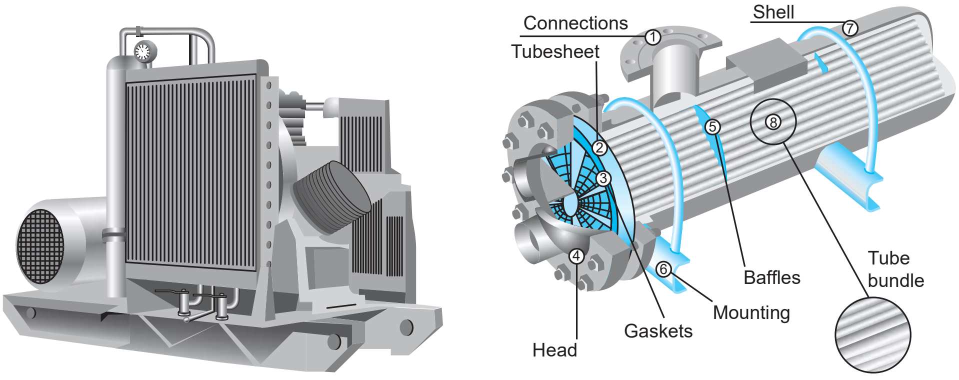


(*a*) Ball valve (*b*) Check valve (*c*) Large butterfly valve



(*d*) Solenoid valve (*e*) Pipeline gate valve

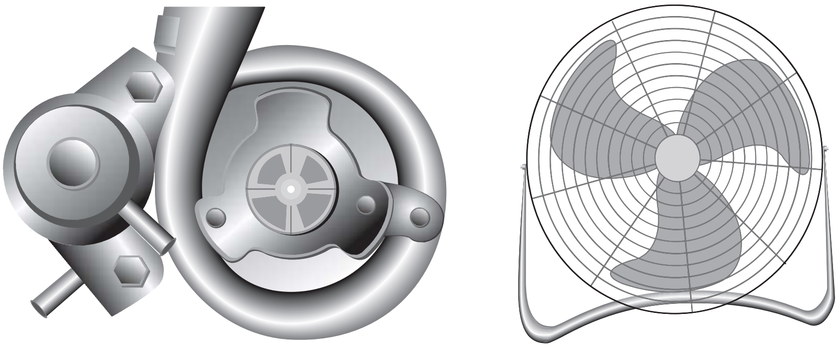
**FIGURE 6.17** Several types of valves.



(*a*) An after cooler for a diesel engine

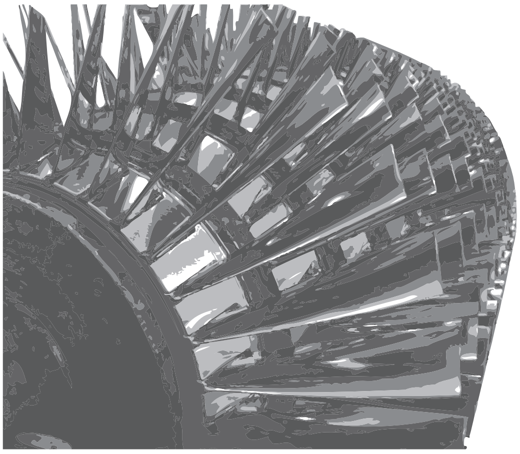
(*b*) A shell and tube heat exchanger

**FIGURE 6.18** Heat exchangers.



(*a*) Centrifugal air compressor for a car

(*b*) A simple fan



(*c*) Large axial-flow gas turbine compressor rotor

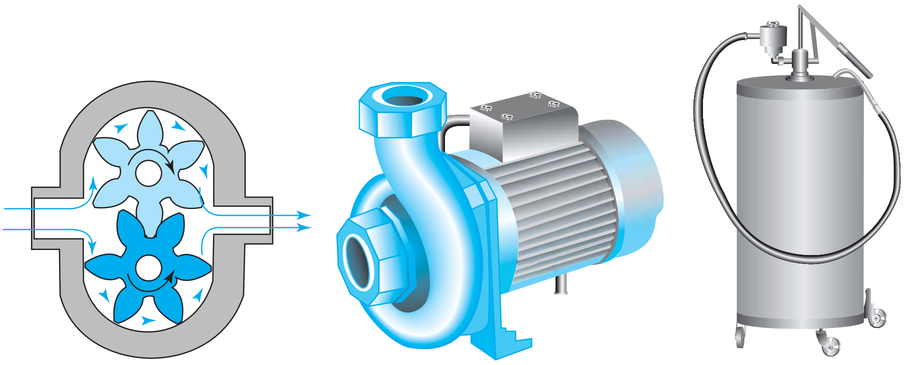
**FIGURE 6.19** Air compressors and fans.

Different types of liquid pumps are shown in Fig. 6.20.

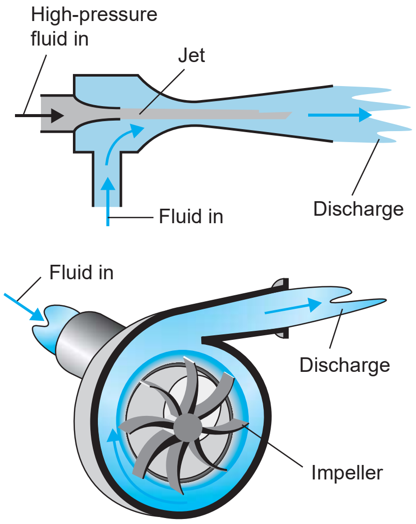
Three different types of turbines are shown in Fig. 6.21. The steam turbine's outer stationary housing also has blades that turn the flow. These are not shown in Fig. 6.21*b*.

Figure 6.22 shows an air conditioner in cooling mode. It has two heat exchangers: one inside that cools the inside air and one outside that dumps energy into the outside atmosphere. This is functionally the same as what happens in a refrigerator. The same type of system can be used as a heat pump. In heating mode, the flow is switched so that the inside heat exchanger is the hot one (condenser and heat rejecter) and the outside is the cold one (evaporator).

There are many types of power-producing systems. A coal-fired steam power plant was shown schematically in Figs. 1.1 and 1.2. A schematic of a shipboard nuclear-powered propulsion system was shown in Fig. 1.3, and other types of engines were also described in Chapter 1. This subject will be developed in detail in Chapters 11 and 12.

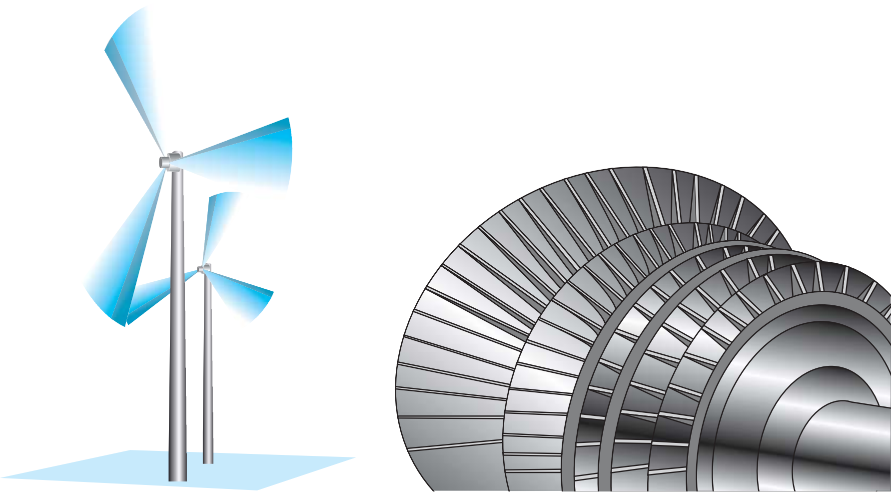


(*a*) Gear pump (*b*) Irrigation pump (*c*) Manual oil pump



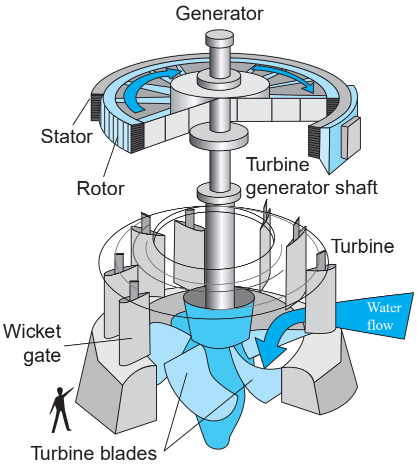
(*d*) Jet pump and rotating pump

**FIGURE 6.20** Liquid pumps.



(*a*) Large wind turbine

(*b*) Steam turbine shaft with rotating blades



(*c*) A turbine in a dam

**FIGURE 6.21**
Examples of turbines.

## SUMMARY

Conservation of mass is expressed as a rate of change of total mass due to mass flows into or out of the control volume. The control mass energy equation is extended to include mass flows that also carry energy (internal, kinetic, and potential) and the flow work needed to push the flow in or out of the control volume against the prevailing pressure. The conservation of mass (continuity equation) and the conservation of energy (first law) are applied to a number of standard devices.

A steady-state device has no storage effects, with all properties constant with time, and constitutes the majority of all flow-type devices. A combination of several devices forms a complete system built for a specific purpose, such as a power plant, jet engine, or refrigerator.

A transient process with a change in mass (storage) such as filling or emptying of a container is considered based on an average description. It is also realized that the startup or shutdown of a steady-state device leads to a transient process.

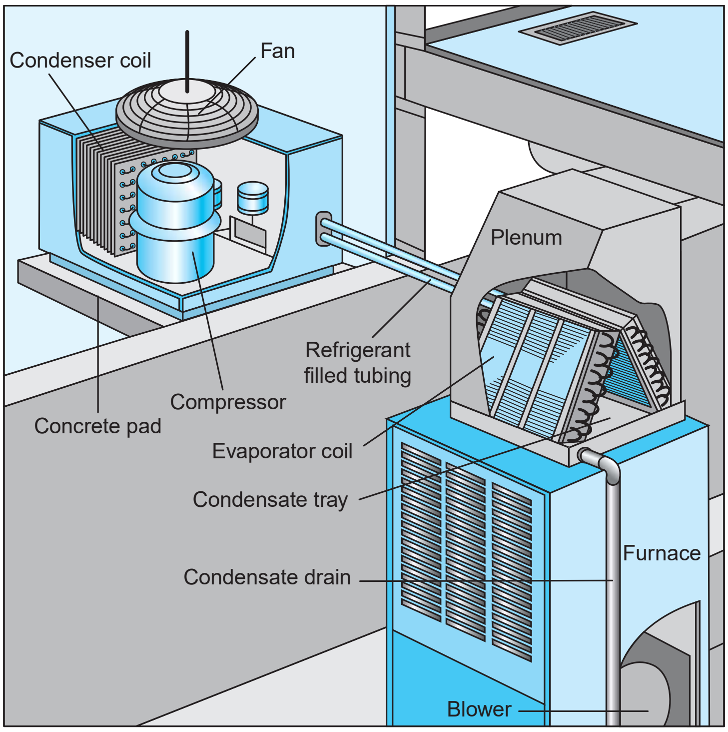


**FIGURE 6.22**
Household air-conditioning system.

You should have learned a number of skills and acquired abilities from studying this chapter that will allow you to

- Understand the physical meaning of the conservation equations. Rate $= +\text{in} - \text{out}$.
- Understand the concepts of mass flow rate, volume flow rate, and local velocity.
- Recognize the flow and nonflow terms in the energy equation.
- Know how the most typical devices work and if they have heat or work transfers.
- Have a sense about devices where kinetic and potential energies are important.
- Analyze steady-state single-flow devices such as nozzles, throttles, turbines, or pumps.
- Extend the application to a multiple-flow device such as a heat exchanger, mixing chamber, or turbine, given the specific setup.
- Apply the conservation equations to complete systems as a whole or to the individual devices and recognize their connections and interactions.
- Recognize and use the proper form of the equations for transient problems.
- Be able to assume a proper average value for any flow term in a transient.
- Recognize the difference between storage of energy ($dE/dt$) and flow ($\dot{m}h$).

A number of steady-flow devices are listed in Table 6.1 with a very short statement of the device's purpose, known facts about work and heat transfer, and a common assumption if appropriate. This list is not complete with respect to the number of devices or with respect to the facts listed but is meant to show typical devices, some of which may be unfamiliar to many readers.

TABLE 6.1

*Typical Steady-Flow Devices*

| Device | Purpose | Given | Assumption |
|---|---|---|---|
| Aftercooler | Cool a flow after a compressor | $w = 0$ | $P =$ constant |
| Boiler | Bring substance to a vapor state | $w = 0$ | $P =$ constant |
| Combustor | Burn fuel; acts like heat transfer in | $w = 0$ | $P =$ constant |
| Compressor | Bring a substance to higher pressure | $w$ in | $q = 0$ |
| Condenser | Take $q$ out to bring substance to liquid state | $w = 0$ | $P =$ constant |
| Deaerator | Remove gases dissolved in liquids | $w = 0$ | $P =$ constant |
| Dehumidifier | Remove water from air | | $P =$ constant |
| Desuperheater | Add liquid water to superheated vapor steam to make it saturated vapor | $w = 0$ | $P =$ constant |
| Diffuser | Convert KE energy to higher $P$ | $w = 0$ | $q = 0$ |
| Economizer | Low-$T$, low-$P$ heat exchanger | $w = 0$ | $P =$ constant |
| Evaporator | Bring a substance to vapor state | $w = 0$ | $P =$ constant |
| Expander | Similar to a turbine, but may have a $q$ | | |
| Fan/blower | Move a substance, typically air | $w$ in, KE up | $P = C$, $q = 0$ |
| Feedwater heater | Heat liquid water with another flow | $w = 0$ | $P =$ constant |
| Flash evaporator | Generate vapor by expansion (throttling) | $w = 0$ | $q = 0$ |
| Heat engine | Convert part of heat into work | $q$ in, $w$ out | |
| Heat exchanger | Transfer heat from one medium to another | $w = 0$ | $P =$ constant |
| Heat pump | Move a $Q$ from $T_{\text{low}}$ to $T_{\text{high}}$; requires a work input, refrigerator | $w$ in | |
| Heater | Heat a substance | $w = 0$ | $P =$ constant |
| Humidifier | Add water to air–water mixture | $w = 0$ | $P =$ constant |
| Intercooler | Heat exchanger between compressor stages | $w = 0$ | $P =$ constant |
| Nozzle | Create KE; $P$ drops<br>Measure flow rate | $w = 0$ | $q = 0$ |
| Mixing chamber | Mix two or more flows | $w = 0$ | $q = 0$ |
| Pump | Same as compressor, but handles liquid | $w$ in, $P$ up | $q = 0$ |
| Reactor | Allow reaction between two or more substances | $w = 0$ | $q = 0$, $P = C$ |
| Regenerator | Usually a heat exchanger to recover energy | $w = 0$ | $P =$ constant |
| Steam generator | Same as boiler; heat liquid water to superheat vapor | $w = 0$ | $P =$ constant |
| Supercharger | A compressor driven by engine shaft work to drive air into an automotive engine | $w$ in | |
| Superheater | A heat exchanger that brings $T$ up over $T_{\text{sat}}$ | $w = 0$ | $P =$ constant |
| Throttle | Same as valve | | |
| Turbine | Create shaft work from high $P$ flow | $w$ out | $q = 0$ |
| Turbocharger | A compressor driven by an exhaust flow turbine to charge air into an engine | $\dot{W}_{\text{turbine}} = -\dot{W}_C$ | |
| Valve | Control flow by restriction; $P$ drops | $w = 0$ | $q = 0$ |

## KEY CONCEPTS AND FORMULAS

| | | |
|---|---|---|
| Volume flow rate | $\dot{V} = \int \mathbf{V}\, dA = A\mathbf{V}$ | (using average velocity) |
| Mass flow rate | $\dot{m} = \int \rho\mathbf{V}\, dA = \rho A\mathbf{V} = A\mathbf{V}/v$ | (using average values) |
| Flow work rate | $\dot{W}_{\text{flow}} = P\dot{V} = \dot{m}Pv$ | |
| Flow direction | From higher $P$ to lower $P$ unless significant KE or PE | |

**Instantaneous Process**

| | |
|---|---|
| Continuity equation | $\dot{m}_{\text{C.V.}} = \sum \dot{m}_i - \sum \dot{m}_e$ |
| Energy equation | $\dot{E}_{\text{C.V.}} = \dot{Q}_{\text{C.V.}} - \dot{W}_{\text{C.V.}} + \sum \dot{m}_i h_{\text{tot }i} - \sum \dot{m}_e h_{\text{tot }e}$ |
| Total enthalpy | $h_{\text{tot}} = h + \frac{1}{2}\mathbf{V}^2 + gZ = h_{\text{stagnation}} + gZ$ |

**Steady State**

No storage: $\dot{m}_{\text{C.V.}} = 0;$ $\dot{E}_{\text{C.V.}} = 0$

| | | |
|---|---|---|
| Continuity equation | $\sum \dot{m}_i = \sum \dot{m}_e$ | (in = out) |
| Energy equation | $\dot{Q}_{\text{C.V.}} + \sum \dot{m}_i h_{\text{tot }i} = \dot{W}_{\text{C.V.}} + \sum \dot{m}_e h_{\text{tot }e}$ | (in = out) |
| Specific heat transfer | $q = \dot{Q}_{\text{C.V.}}/\dot{m}$ | (steady state only) |
| Specific work | $w = \dot{W}_{\text{C.V.}}/\dot{m}$ | (steady state only) |
| Steady-state, single-flow energy equation | $q + h_{\text{tot }i} = w + h_{\text{tot }e}$ | (in = out) |

**Transient Process**

| | |
|---|---|
| Continuity equation | $m_2 - m_1 = \sum m_i - \sum m_e$ |
| Energy equation | $E_2 - E_1 = {}_1Q_2 - {}_1W_2 + \sum m_i h_{\text{tot }i} - \sum m_e h_{\text{tot }e}$ |
| | $E_2 - E_1 = m_2(u_2 + \frac{1}{2}\mathbf{V}_2^2 + gZ_2) - m_1(u_1 + \frac{1}{2}\mathbf{V}_1^2 + gZ_1)$ |
| | $h_{\text{tot }e} = h_{\text{tot exit average}} \approx \frac{1}{2}(h_{\text{hot }e1} + h_{\text{tot }e2})$ |

## CONCEPT-STUDY GUIDE PROBLEMS

**6.1** A temperature difference drives a heat transfer. Does a similar concept apply to $\dot{m}$?

**6.2** What effect can be felt upstream in a flow?

**6.3** Which of the properties ($P, v, T$) can be controlled in a flow? How?

**6.4** Air at 500 kPa is expanded to 100 kPa in two steady flow cases. Case one is a nozzle and case two is a turbine; the exit state is the same for both cases. What can you say about the specific turbine work relative to the specific kinetic energy in the exit flow of the nozzle?

**6.5** Pipes that carry a hot fluid like steam in a power plant, exhaust pipe for a diesel engine in a ship, etc., are often insulated. Is that done to reduce heat loss or is there another purpose?

**6.6** A windmill takes out a fraction of the wind kinetic energy as power on a shaft. How do the temperature and wind velocity influence the power? Hint: write the power term as mass flow rate times specific work.

**6.7** An underwater turbine extracts a fraction of the kinetic energy from the ocean current. How do the temperature and water velocity influence the power? Hint: write the power term as mass flow rate times specific work.

**6.8** A liquid water turbine at the bottom of a dam takes energy out as power on a shaft. Which term(s) in the energy equation are changing and important?

**6.9** You blow a balloon up with air. What kinds of work terms, including flow work, do you see in that case? Where is energy stored?

**6.10** A storage tank for natural gas has a top dome that can move up or down as gas is added to or subtracted from the tank, maintaining 110 kPa, 290 K inside. A pipeline at 110 kPa, 290 K now supplies some natural gas to the tank. Does its state change during the filling process? What happens to the flow work?

## HOMEWORK PROBLEMS

### Continuity Equation and Flow Rates

**6.11** Carbon dioxide at 200 kPa, 10°C flows at 1 kg/s in a 0.25-$\mathrm{m}^2$ cross-sectional area pipe. Find the velocity and the volume flow rate.

**6.12** Air at 35°C, 105 kPa flows in a 100-mm × 150-mm rectangular duct in a heating system. The volumetric flow rate is 0.015 $\mathrm{m}^3/\mathrm{s}$. What is the velocity of the air flowing in the duct and what is the mass flow rate?

**6.13** An empty bath tub has its drain closed and is being filled with water from the faucet at a rate of 10 kg/min. After 10 min the drain is opened and 4 kg/min flows out; at the same time, the inlet flow is reduced to 2 kg/min. Plot the mass of the water in the bathtub versus time and determine the time from the very beginning when the tub will be empty.

**6.14** Saturated vapor R-134a leaves the evaporator in a heat pump system at 10°C with a steady mass flow rate of 0.1 kg/s. What is the smallest diameter tubing that can be used at this location if the velocity of the refrigerant is not to exceed 7 m/s?

**6.15** A boiler receives a constant flow of 5000 kg/h liquid water at 5 MPa and 20°C, and it heats the flow such that the exit state is 450°C with a pressure of 4.5 MPa. Determine the necessary minimum pipe flow area in both the inlet and exit pipe(s) if there should be no velocities larger than 20 m/s.

**6.16** A hot-air home heating system takes 0.25 $\mathrm{m}^3/\mathrm{s}$ air at 100 kPa, 17°C into a furnace, heats it to 52°C, and delivers the flow to a square duct 0.2 m by 0.2 m at 110 kPa (see Fig. P6.16). What is the velocity in the duct?

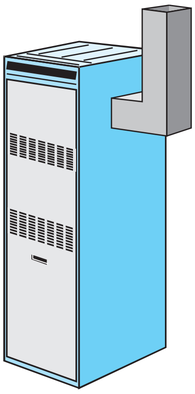


FIGURE P6.16

**6.17** A flat channel of depth 1 m has a fully developed laminar flow of air at $P_0$, $T_0$ with a velocity profile of: $\mathbf{V} = 4\,\mathbf{V}_c \times (H - x)/\mathrm{H}_2$, where $\mathbf{V}_c$ is the velocity on the centerline and $x$ is the distance across the channel, as shown in Fig. P6.17. Find the total mass flow rate and the average velocity both as functions of $\mathbf{V}_c$ and $H$.

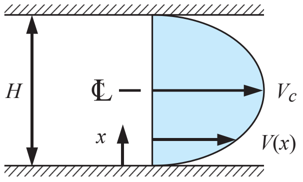


FIGURE P6.17

**6.18** Nitrogen gas flowing in a 50-mm-diameter pipe at 15°C and 200 kPa, at the rate of 0.05 kg/s, encounters a partially closed valve. If there is a pressure drop of 30 kPa across the valve and essentially no temperature change, what are the velocities upstream and downstream of the valve?

**6.19** A household fan of diameter 0.75 m takes air in at 98 kPa, 22°C and delivers it at 105 kPa, 23°C with a velocity of 1.5 m/s (see Fig. P6.19). What are the mass flow rate (kg/s), the inlet velocity, and the outgoing volume flow rate in $\mathrm{m}^3/\mathrm{s}$?

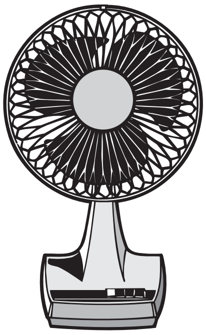


FIGURE P6.19

### Single-Flow, Single-Device Processes

#### Nozzles, Diffusers

**6.20** Liquid water at 15°C flows out of a nozzle straight up 15 m. What is nozzle $\mathbf{V}_{\text{exit}}$?

**6.21** Nitrogen gas flows into a convergent nozzle at 200 kPa, 400 K and very low velocity. It flows out of the nozzle at 100 kPa, 330 K. If the nozzle is insulated, find the exit velocity.

**6.22** A nozzle receives 0.1 kg/s of steam at 1 MPa, 400°C with negligible kinetic energy. The exit is at 500 kPa, 350°C, and the flow is adiabatic. Find the nozzle exit velocity and the exit area.

**6.23** In a jet engine a flow of air at 1000 K, 200 kPa, and 30 m/s enters a nozzle, as shown in Fig. P6.23, where the air exits at 850 K, 90 kPa. What is the exit velocity, assuming no heat loss?

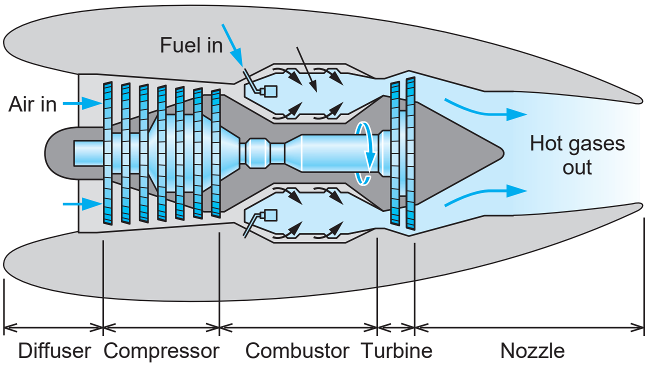


FIGURE P6.23

**6.24** In a jet engine a flow of air at 1000 K, 200 kPa, and 40 m/s enters a nozzle, where the air exits at 500 m/s, 90 kPa. What is the exit temperature, assuming no heat loss?

**6.25** Superheated vapor ammonia enters an insulated nozzle at 20°C, 800 kPa, as shown in Fig. P6.25, with a low velocity and at a steady rate of 0.01 kg/s. The ammonia exits at 300 kPa with a velocity of 450 m/s. Determine the temperature (or quality, if saturated) and the exit area of the nozzle.

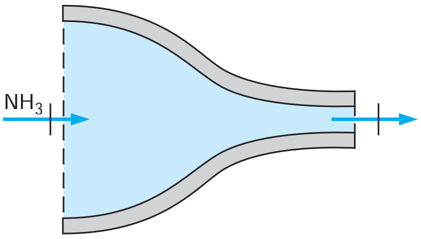


FIGURE P6.25

**6.26** Air flows into a diffuser at 300 m/s, 300 K, and 100 kPa. At the exit, the velocity is very small but the pressure is high. Find the exit temperature, assuming zero heat transfer.

**6.27** A sluice gate dams water up 5 m. A 1-cm-diameter hole at the bottom of the gate allows liquid water at 20°C to come out. Neglect any changes in internal energy and find the exit velocity and mass flow rate.

**6.28** A diffuser, shown in Fig. P6.28, has air entering at 100 kPa and 300 K with a velocity of 200 m/s. The inlet cross-sectional area of the diffuser is 100 $\mathrm{mm}^2$. At the exit the area is 860 $\mathrm{mm}^2$, and the exit velocity is 20 m/s. Determine the exit pressure and temperature of the air.

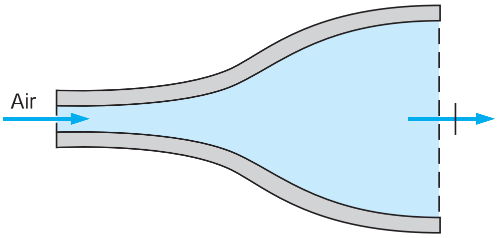


FIGURE P6.28

**6.29** A diffuser receives an ideal-gas flow at 100 kPa, 300 K with a velocity of 250 m/s, and the exit velocity is 25 m/s. Determine the exit temperature if the gas is argon, helium, or nitrogen.

**6.30** The front of a jet engine acts as a diffuser, receiving air at 900 km/h, −5°C, and 50 kPa, bringing it to 80 m/s relative to the engine before entering the compressor (see Fig. P6.30). If the flow area is reduced to 80% of the inlet area, find the temperature and pressure in the compressor inlet.

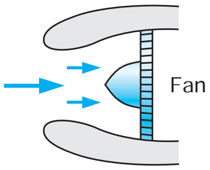


FIGURE P6.30

## Throttle Flow

**6.31** Carbon dioxide used as a natural refrigerant flows out of a cooler at 10 MPa, 40°C, after which it is throttled to 1.4 MPa. Find the state ($T$, $x$) for the exit flow.

**6.32** R-134a at 30°C, 800 kPa is throttled so that it becomes cold at −10°C. What is exit $P$?

**6.33** Helium is throttled from 1.2 MPa, 20°C to a pressure of 100 kPa. The diameter of the exit pipe is so much larger than that of the inlet pipe that the inlet and exit velocities are equal. Find the exit temperature of the helium and the ratio of the pipe diameters.

**6.34** Saturated vapor R-134a at 500 kPa is throttled to 200 kPa in a steady flow through a valve. The kinetic energy in the inlet and exit flows is the same. What is the exit temperature?

**6.35** Saturated liquid R-410a at 25°C is throttled to 400 kPa in a refrigerator. What is the exit temperature? Find the percent increase in the volume flow rate.

**6.36** Carbon dioxide is throttled from 20°C, 2000 kPa to 800 kPa. Find the exit temperature, assuming ideal gas, and repeat for real gas behavior.

**6.37** Liquid water at 180°C, 2000 kPa is throttled into a flash evaporator chamber having a pressure of 500 kPa. Neglect any change in the kinetic energy. What is the fraction of liquid and vapor in the chamber?

**6.38** R-134a is throttled in a line flowing at 25°C, 750 kPa with negligible kinetic energy to a pressure of 165 kPa. Find the exit temperature and the ratio of the exit pipe diameter to that of the inlet pipe ($D_{ex}/D_{in}$) so that the velocity stays constant.

**6.39** Water is flowing in a line at 400 kPa, and saturated vapor is taken out through a valve to 100 kPa. What is the temperature as it leaves the valve, assuming no changes in kinetic energy and no heat transfer?

## Turbines, Expanders

**6.40** A steam turbine has an inlet of 2 kg/s water at 1000 kPa and 350°C with a velocity of 15 m/s. The exit is at 100 kPa, 150°C and velocity is very low. Find the specific work and the power produced.

**6.41** Air at 20 m/s, 260 K, 75 kPa with 5 kg/s flows into a jet engine and flows out at 500 m/s, 800 K, 75 kPa. What is the change (power) in flow of kinetic energy?

**6.42** A liquid water turbine receives 2 kg/s water at 2000 kPa, 20°C with a velocity of 15 m/s. The exit is at 100 kPa, 20°C, and very low velocity. Find the specific work and the power produced.

**6.43** A windmill with a rotor diameter of 30 m takes 40% of the kinetic energy out as shaft work on a day with a temperature of 20°C and a wind speed of 30 km/h. What power is produced?

**6.44** Hoover Dam across the Colorado River dams up Lake Mead 200 m higher than the river downstream (see Fig. P6.44). The electric generators driven by water-powered turbines deliver 1300 MW of power. If the water is 17.5°C, find the minimum amount of water running through the turbines.

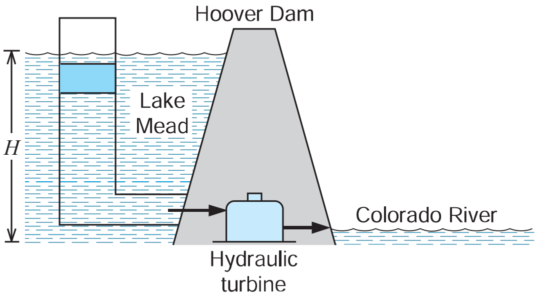


FIGURE P6.44

**6.45** A small expander (a turbine with heat transfer) has 0.05 kg/s helium entering at 1000 kPa, 550 K and leaving at 250 kPa, 300 K. The power output on the shaft measures 55 kW. Find the rate of heat transfer, neglecting kinetic energies.

**6.46** A small turbine, shown in Fig. P6.46, is operated at part load by throttling a 0.25-kg/s steam supply at 1.4 MPa and 250°C down to 1.1 MPa before it enters the turbine, and the exhaust is at 10 kPa. If the turbine produces 110 kW, find the exhaust temperature (and quality if saturated).

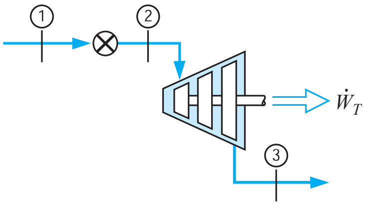


FIGURE P6.46

**6.47** A small, high-speed turbine operating on compressed air produces a power output of 100 W. The inlet state is 400 kPa, 50°C, and the exit state is 150 kPa, −30°C. Assuming the velocities to be low and the process to be adiabatic, find the required mass flow rate of air through the turbine.

## Compressors, Fans

**6.48** A compressor in a commercial refrigerator receives R-410a at −25°C and $x = 1$. The exit is at 1200 kPa and 60°C. Neglect kinetic energies and find the specific work.

**6.49** A refrigerator uses the natural refrigerant carbon dioxide where the compressor brings 0.02 kg/s from 1 MPa, −20°C to 6 MPa using 2 kW of power. Find the compressor exit temperature.

**6.50** A compressor brings R-134a from 150 kPa, −10°C to 1200 kPa, 50°C. It is water cooled, with heat loss estimated as 40 kW, and the shaft work input is measured to be 150 kW. What is the mass flow rate through the compressor?

**6.51** An ordinary portable fan blows 0.2 kg/s of room air with a velocity of 18 m/s (see Fig. P6.19). What is the minimum power electric motor that can drive it? Hint: Are there any changes in $P$ or $T$?

**6.52** The compressor of a large gas turbine receives air from the ambient surroundings at 95 kPa, 20°C with low velocity. At the compressor discharge, air exits at 1.52 MPa, 430°C with a velocity of 90 m/s. The power input to the compressor is 5000 kW. Determine the mass flow rate of air through the unit.

**6.53** A compressor in an industrial air conditioner compresses ammonia from a state of saturated vapor at 150 kPa to a pressure of 800 kPa. At the exit, the temperature is 100°C and the mass flow rate is 0.5 kg/s. What is the required motor size (kW) for this compressor?

**6.54** An air compressor takes in air at 100 kPa, 17°C, and delivers it at 1 MPa, 600 K to a constant-pressure cooler, which the air exits at 300 K (see Fig. P6.54). Find the specific compressor work and the specific heat transfer in the cooler.

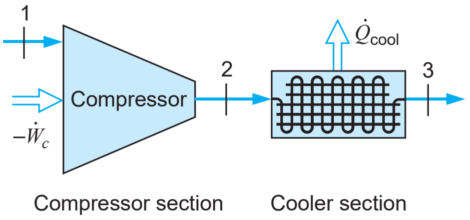


FIGURE P6.54

**6.55** An exhaust fan in a building should be able to move 2.5 kg/s of air at 98 kPa, 20°C through a 0.4-m-diameter vent hole. How high a velocity must it generate, and how much power is required to do that?

**6.56** How much power is needed to run the fan in Problem 6.19?

**6.57** A compressor in an air conditioner receives saturated vapor R-410a at 400 kPa and brings it to 1.8 MPa, 60°C in an adiabatic compression. Find the flow rate for a compressor work of 2 kW.

## Heaters, Coolers

**6.58** Carbon dioxide enters a steady-state, steady-flow heater at 300 kPa, 300 K and exits at 275 kPa, 1500 K, as shown in Fig. P6.58. Changes in kinetic and potential energies are negligible. Calculate the required heat transfer per kilogram of carbon dioxide flowing through the heater.

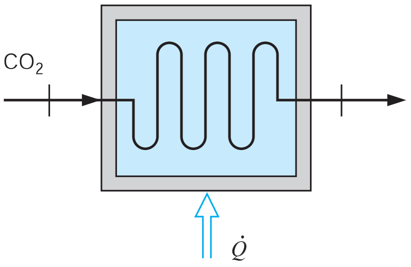


FIGURE P6.58

**6.59** A condenser (cooler) receives 0.05 kg/s of R-410a at 2000 kPa, 60°C and cools it to 15°C. Assume the exit properties are as for saturated liquid and the same *T*. What cooling capacity (kW) must the condenser have?

**6.60** Saturated liquid nitrogen at 600 kPa enters a boiler at a rate of 0.005 kg/s and exits as saturated vapor (see Fig. P6.60). It then flows into a superheater also at 600 kPa, where it exits at 600 kPa, 280 K. Find the rate of heat transfer in the boiler and the superheater.

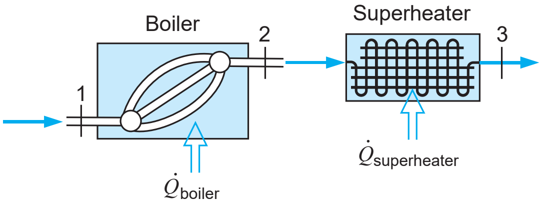


FIGURE P6.60

**6.61** The air conditioner in a house or a car has a cooler that brings atmospheric air from 30°C to 10°C with both states at 101 kPa. If the flow rate is 0.5 kg/s, find the rate of heat transfer.

**6.62** A chiller cools liquid water for air-conditioning purposes. Assume that 2.5 kg/s water at 20°C, 100 kPa is cooled to 5°C in a chiller. How much heat transfer (kW) is needed?

**6.63** Carbon dioxide used as a natural refrigerant flows through a cooler at 10 MPa, which is supercritical so that no condensation occurs. The inlet is at 200°C and the exit is at 40°C. Find the specific heat transfer.

**6.64** Liquid glycerine flows around an engine, cooling it as it absorbs energy. The glycerine enters the engine at 60°C and receives 19 kW of heat transfer. What is the required mass flow rate if the glycerine should come out at a maximum temperature of 95°C?

**6.65** In a steam generator, compressed liquid water at 10 MPa, 30°C enters a 30-mm-diameter tube at a rate of 3 L/s. Steam at 9 MPa, 400°C exits the tube. Find the rate of heat transfer to the water.

**6.66** In a boiler you vaporize some liquid water at 100 kPa flowing at 1 m/s. What is the velocity of the saturated vapor at 100 kPa if the pipe size is the same? Can the flow then be constant *P*?

**6.67** Liquid nitrogen at 90 K, 400 kPa flows into a probe used in a cryogenic survey. In the return line the nitrogen is then at 160 K, 400 kPa. Find the specific heat transfer to the nitrogen. If the return line has a cross-sectional area 100 times larger than that of the inlet line, what is the ratio of the return velocity to the inlet velocity?

## Pumps, Pipe and Channel Flows

**6.68** A steam pipe for a 300-m-tall building receives superheated steam at 200 kPa at ground level. At the top floor the pressure is 125 kPa, and the heat loss in the pipe is 110 kJ/kg. What should the inlet temperature be so that no water will condense inside the pipe?

**6.69** A small stream with water at 20°C runs out over a cliff, creating a 100-m-tall waterfall. Estimate the downstream temperature when you neglect the horizontal flow velocities upstream and downstream from the waterfall. How fast was the water dropping just before it splashed into the pool at the bottom of the waterfall?

**6.70** An irrigation pump takes water from a river at 10°C, 100 kPa and pumps it up to an open canal, where it flows out 100 m higher at 10°C. The pipe diameter in and out of the pump is 0.1 m, and the motor driving the unit is 5 hp. What is the flow rate, neglecting kinetic energy and losses?

**6.71** Consider a water pump that receives liquid water at 15°C, 100 kPa and delivers it to a same-diameter short pipe having a nozzle with an exit diameter of 1 cm (0.01 m) to the atmosphere at 100 kPa (see Fig. P6.71). Neglect the kinetic energy in the pipes and assume constant *u* for the water. Find the exit velocity and the mass flow rate if the pump draws 1 kW of power.

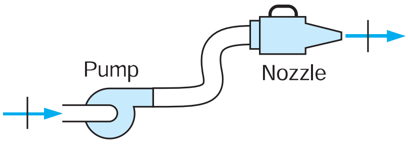


FIGURE P6.71

**6.72** A cutting tool uses a nozzle that generates a high-speed jet of liquid water. Assume an exit velocity of 500 m/s of 20°C liquid water with a jet diameter of 2 mm (0.002 m). What is the mass flow rate? What size (power) pump is needed to generate this from a steady supply of 20°C liquid water at 200 kPa?

**6.73** A small water pump is used in an irrigation system. The pump takes water in from a river at 10°C, 100 kPa at a rate of 5 kg/s. The exit line enters a pipe that goes up to an elevation 20 m above the pump and river, where the water runs into an open channel. Assume that the process is adiabatic and that the water stays at 10°C. Find the required pump work.

**6.74** The main water line into a tall building has a pressure of 600 kPa at 5 m below ground level, as shown in Fig. P6.74. A pump brings the pressure up so that the water can be delivered at 200 kPa at the top floor 150 m above ground level. Assume a flow rate of 10 kg/s liquid water at 10°C and neglect any difference in kinetic energy and internal energy *u*. Find the pump work.

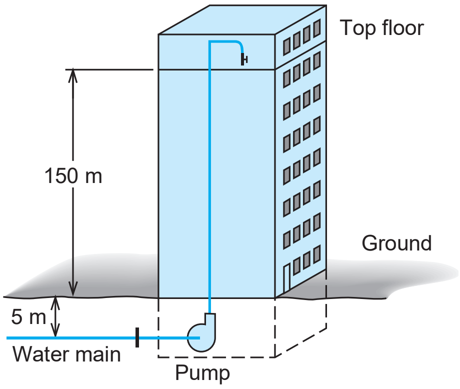


FIGURE P6.74

**6.75** A pipe flows water at 15°C from one building to another. In the winter the pipe loses an estimated 500 W of heat transfer. What is the minimum required mass flow rate that will ensure that the water does not freeze (i.e., reach 0°C)?

## Multiple-Flow, Single-Device Processes

### Turbines, Compressors, Expanders

**6.76** A steam turbine receives steam from two boilers (see Fig. P6.76). One flow is 5 kg/s at 3 MPa, 700°C and the other flow is 15 kg/s at 800 kPa, 500°C. The exit state is 10 kPa, with a quality of 96%. Find the total power out of the adiabatic turbine.

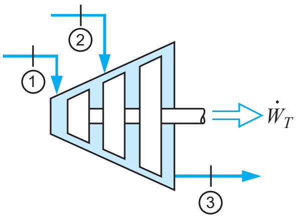


FIGURE P6.76

**6.77** A compressor receives 0.05 kg/s R-410a at 200 kPa, −20°C and 0.1 kg/s R-410a at 400 kPa, 0°C. The exit flow is at 1000 kPa, 60°C, as shown in Fig. P6.77. Assume it is adiabatic, neglect kinetic energies, and find the required power input.

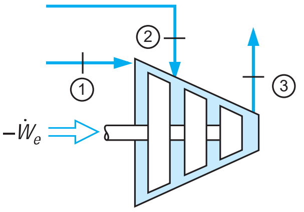


FIGURE P6.77

**6.78** Two steady flows of air enter a control volume, as shown in Fig. P6.78. One is a 0.025 kg/s flow at 350 kPa, 150°C, state 1, and the other enters at 450 kPa, 15°C, state 2. A single flow exits at 100 kPa, −40°C, state 3. The control volume ejects 1 kW heat to the surroundings and produces 4 kW of power output. Neglect kinetic energies and determine the mass flow rate at state 2.

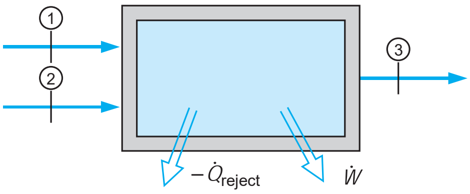


FIGURE P6.78

**6.79** A steam turbine receives water at 15 MPa, 600°C at a rate of 100 kg/s, as shown in Fig. P6.79. In the middle section 20 kg/s is withdrawn at 2 MPa, 350°C and the rest exits the turbine at 75 kPa, with 95% quality. Assuming no heat transfer and no changes in kinetic energy, find the total turbine power output.

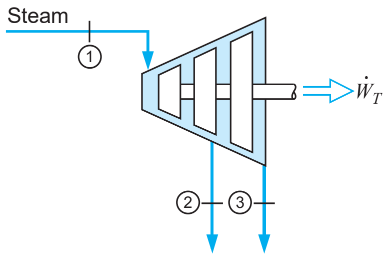


FIGURE P6.79

**6.80** Cogeneration is often used where a steam supply is needed for industrial process energy. Assume that a supply of 5 kg/s steam at 0.5 MPa is needed. Rather than generating this from a pump and boiler, the setup in Fig. P6.80 is used to extract the supply from the high-pressure turbine. Find the power the turbine now cogenerates in this process.

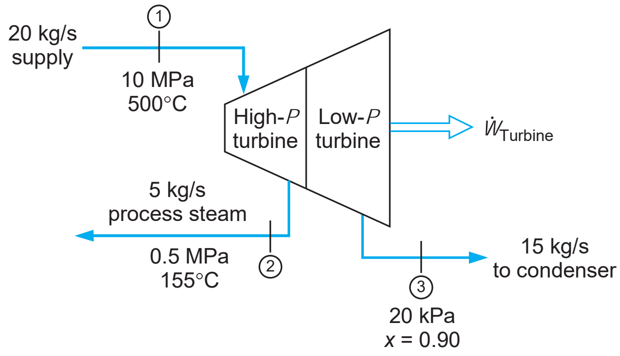


FIGURE P6.80

**6.81** A compressor receives 0.1 kg/s of R-134a at 150 kPa, −10°C and delivers it at 1000 kPa, 40°C. The power input is measured to be 3 kW. The compressor has heat transfer to air at 100 kPa coming in at 20°C and leaving at 25°C. What is the mass flow rate of air?

**6.82** A large, steady expansion engine has two low-velocity flows of water entering. High-pressure steam enters at point 1 with 2.0 kg/s at 2 MPa, 500°C, and 0.5 kg/s of cooling water at 120 kPa, 30°C centers at point 2. A single flow exits at point 3, with 150 kPa and 80% quality, through a 0.15-m-diameter exhaust pipe. There is a heat loss of 300 kW. Find the exhaust velocity and the power output of the engine.

## Heat Exchangers

**6.83** A condenser (heat exchanger) brings 1 kg/s water flow at 10 kPa from 300°C to saturated liquid at 10 kPa, as shown in Fig. P6.83. The cooling is done by lake water at 20°C that returns to the lake at 30°C. For an insulated condenser, find the flow rate of cooling water.

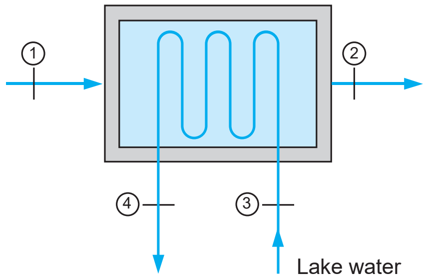


FIGURE P6.83

**6.84** In a co-flowing (same-direction) heat exchanger, 1 kg/s air at 500 K flows into one channel and 2 kg/s air flows into the neighboring channel at 300 K. If it is infinitely long, what is the exit temperature? Sketch the variation of $T$ in the two flows.

**6.85** A heat exchanger, shown in Fig. P6.85, is used to cool an air flow from 800 to 360 K, with both states at 1 MPa. The coolant is a water flow at 15°C, 0.1 MPa. If the water leaves as saturated vapor, find the ratio of the flow rates $\dot{m}_{\text{water}}/\dot{m}_{\text{air}}$.

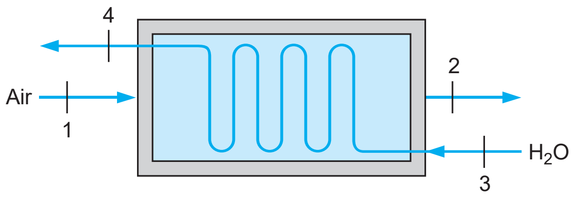


FIGURE P6.85

**6.86** Air at 600 K flows with 3 kg/s into a heat exchanger and out at 100°C. How much (kg/s) water coming in at 100 kPa, 20°C can the air heat to the boiling point?

**6.87** An automotive radiator has glycerine at 95°C enter and return at 55°C as shown in Fig. P6.87. Air flows in at 20°C and leaves at 25°C. If the radiator should transfer 25 kW, what is the mass flow rate of the glycerine and what is the volume flow rate of air in at 100 kPa?

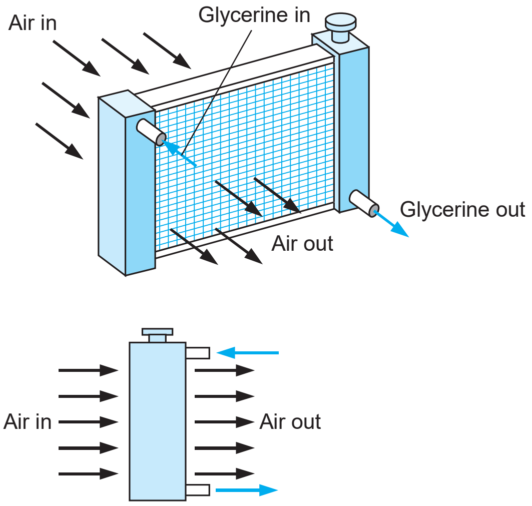


FIGURE P6.87

**6.88** A superheater brings 2.5 kg/s of saturated water vapor at 2 MPa to 450°C. The energy is provided by hot air at 1200 K flowing outside the steam tube in the opposite direction as the water, a setup known as a *counterflowing heat exchanger* (similar to Fig. P6.85). Find the smallest possible mass flow rate of the air to ensure that its exit temperature is 20°C larger than the incoming water temperature.

**6.89** A cooler in an air conditioner brings 0.5 kg/s of air at 35°C to 5°C, both at 101 kPa. It then mixes the output with a flow of 0.25 kg/s air at 20°C and 101 kPa, sending the combined flow into a duct. Find the total heat transfer in the cooler and the temperature in the duct flow.

**6.90** Steam at 500 kPa, 300°C is used to heat cold water at 15°C to 75°C for a domestic hot water supply. How much steam per kilogram of liquid water is needed if the steam should not condense?

**6.91** A two-fluid heat exchanger has 2 kg/s liquid ammonia at 20°C, 1003 kPa entering at state 3 and exiting at state 4. It is heated by a flow of 1 kg/s nitrogen at 1500 K, state 1, leaving at 600 K, state 2 similar to Fig. P6.85. Find the total rate of heat transfer inside the heat exchanger. Sketch the temperature versus distance for the ammonia and find state 4 ($T$, $v$) of the ammonia.

**6.92** A copper wire has been heat treated to 1000 K and is now pulled into a cooling chamber that has 1.5 kg/s air coming in at 20°C; the air leaves the other end at 60°C. If the wire moves 0.25 kg/s copper, how hot is the copper as it comes out?

## Mixing Processes

**6.93** Two air flows are combined to a single flow. One flow is 1 $m^3/s$ at 20°C and the other is 2 $m^3/s$ at 200°C, both at 100 kPa, as in Fig. P6.93. They mix without any heat transfer to produce an exit flow at 100 kPa. Neglect kinetic energies and find the exit temperature and volume flow rate.

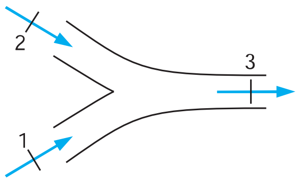


FIGURE P6.93

**6.94** A de-superheater has a flow of ammonia of 1.5 kg/s at 1000 kPa, 100°C that is mixed with another flow of ammonia at 25°C and quality 25% in an adiabatic mixing chanber. Find the flow rate of the second flow so that the outgoing ammonia is saturated vapor at 1000 kPa.

**6.95** An open feedwater heater in a power plant heats 4 kg/s water at 45°C, 100 kPa by mixing it with steam from the turbine at 100 kPa, 250°C, as in Fig. P6.95. Assume the exit flow is saturated liquid at the given pressure and find the mass flow rate from the turbine.

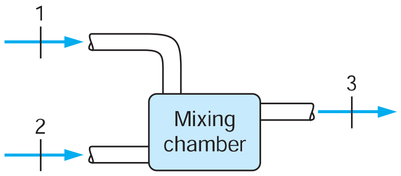


FIGURE P6.95

**6.96** A flow of water at 2000 kPa, 20°C is mixed with a flow of 2 kg/s water at 2000 kPa, 180°C. What should the flow rate of the first flow be to produce an exit state of 200 kPa and 100°C?

**6.97** A mixing chamber with heat transfer receives 2 kg/s of R-410a, at 1 MPa, 40°C in one line and 1 kg/s of R-410a at 15°C with a quality of 50% in a line with a valve. The outgoing flow is at 1 MPa, 60°C. Find the rate of heat transfer to the mixing chamber.

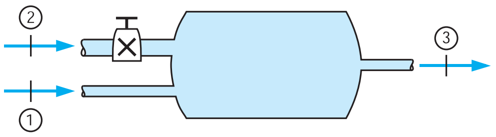


FIGURE P6.97

**6.98** An insulated mixing chamber receives 2 kg/s of R-134a at 1 MPa, 100°C in a line with low velocity. Another line with R-134a as saturated liquid at 60°C flows through a valve to the mixing chamber at 1 MPa after the valve, as shown in Fig. P6.97. The exit flow is saturated vapor at 1 MPa flowing at 20 m/s. Find the flow rate for the second line.

**6.99** To keep a jet engine cool, some intake air bypasses the combustion chamber. Assume that 2 kg/s of hot air at 2000 K and 500 kPa is mixed with 1.5 kg/s air at 500 K, 500 kPa without any external heat transfer, as in Fig. P6.99. Find the exit temperature using constant heat capacity from Table A.5.

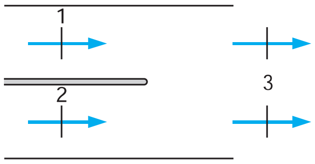


FIGURE P6.99

**6.100** Solve the previous problem using values from Table A.7.

**6.101** Two flows are mixed to form a single flow. Flow at state 1 is 1.5 kg/s of water at 400 kPa, 200°C, and flow at state 2 is at 500 kPa, 100°C. Which mass flow rate at state 2 will produce an exit $T_3 = 150°\text{C}$ if the exit pressure is kept at 300 kPa?

### Multiple Devices, Cycle Processes

**6.102** A flow of 5 kg/s water at 100 kPa, 20°C should be delivered as steam at 1000 kPa, 350°C to some application. Consider compressing it to 1000 kPa, 20°C and then heat it at a constant rate of 1000 kPa to 350°C. Determine which devices are needed and find the specific energy transfers in those devices.

**6.103** The following data are for a simple steam power plant as shown in Fig. P6.103. State 6 has $x_6 = 0.92$ and velocity of 200 m/s. The rate of steam flow is 25 kg/s, with 300 kW of power input to the pump. Piping diameters are 200 mm from the steam generator to the turbine and 75 mm from the condenser to the economizer and steam generator. Determine the velocity at state 5 and the power output of the turbine.

| State | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|
| $P$, kPa | 6200 | 6100 | 5900 | 5700 | 5500 | 10 | 9 |
| $T$, °C | | 45 | 175 | 500 | 490 | | 40 |
| $h$, kJ/kg | | 194 | 744 | 3426 | 3404 | | 168 |

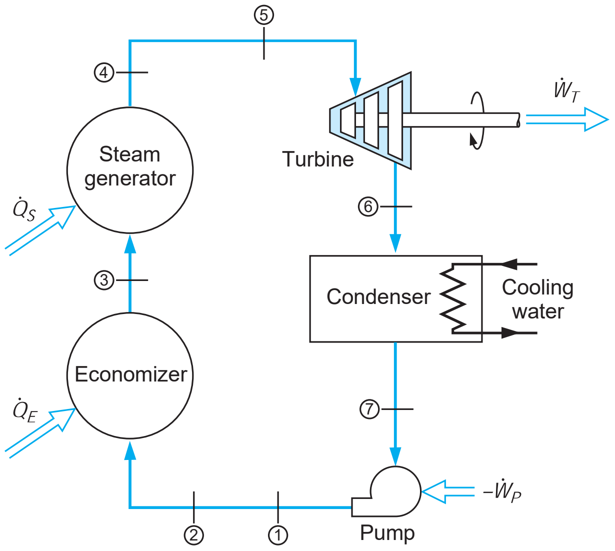


FIGURE P6.103

**6.104** For the steam power plant shown in Problem 6.103, assume that the cooling water comes from a lake at 15°C and is returned at 25°C. Determine the rate of heat transfer in the condenser and the mass flow rate of cooling water from the lake.

**6.105** For the steam power plant shown in Problem 6.103, determine the rate of heat transfer in the economizer, which is a low-temperature heat exchanger. Also find the rate of heat transfer needed in the steam generator.

**6.106** A somewhat simplified flow diagram for a nuclear power plant is given in Fig. P6.106. Mass flow rates and the various states in the cycle are shown in the accompanying table.

| Point | $\dot{m}$, kg/s | $P$, kPa | $T$, °C | $h$, kJ/kg |
|---|---|---|---|---|
| 1 | 75.6 | 7240 | sat vap | |
| 2 | 75.6 | 6900 | | 2765 |
| 3 | 62.874 | 345 | | 2517 |
| 4 | | 310 | | |
| 5 | | 7 | | 2279 |
| 6 | 75.6 | 7 | 33 | 138 |
| 7 | | 415 | | 140 |
| 8 | 2.772 | 35 | | 2459 |
| 9 | 4.662 | 310 | | 558 |
| 10 | | 35 | 34 | 142 |
| 11 | 75.6 | 380 | 68 | 285 |
| 12 | 8.064 | 345 | | 2517 |
| 13 | 75.6 | 330 | | |
| 14 | | | | 349 |
| 15 | 4.662 | 965 | 139 | 584 |
| 16 | 75.6 | 7930 | | 565 |
| 17 | 4.662 | 965 | | 2593 |
| 18 | 75.6 | 7580 | | 688 |
| 19 | 1386 | 7240 | 277 | 1220 |
| 20 | 1386 | 7410 | | 1221 |
| 21 | 1386 | 7310 | | |

The cycle includes a number of heaters in which heat is transferred from steam, taken out of the turbine at some intermediate pressure, to liquid water pumped from the condenser on its way to the steam drum. The heat exchanger in the reactor supplies 157 MW, and it may be assumed that there is no heat transfer in the turbines.

a. Assuming the moisture separator has no heat transfer between the two turbine sections, determine the enthalpy and quality ($h_4$, $x_4$).

b. Determine the power output of the low-pressure turbine.

c. Determine the power output of the high-pressure turbine.

d. Find the ratio of the total power output of the two turbines to the total power delivered by the reactor.

**6.107** Consider the power plant described in the previous problem.

a. Determine the quality of the steam leaving the reactor.

b. What is the power to the pump that feeds water to the reactor?

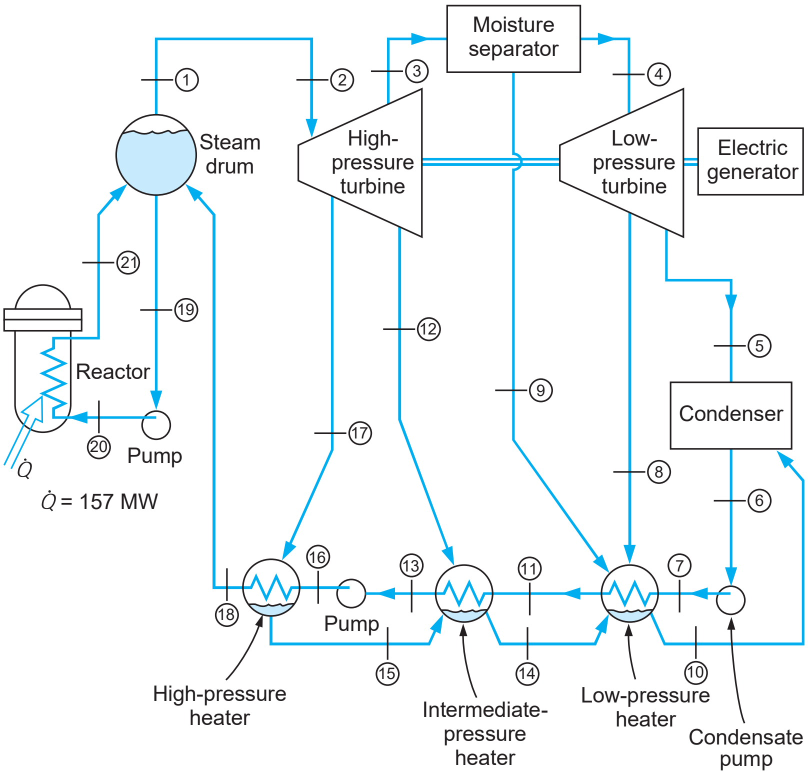


FIGURE P6.106

**6.108** An R-410a heat pump cycle shown in Fig. P6.108 has an R-410a flow rate of 0.05 kg/s with 5 kW into the compressor. The following data are given:

| **State** | **1** | **2** | **3** | **4** | **5** | **6** |
|---|---|---|---|---|---|---|
| *P*, kPa | 3100 | 3050 | 3000 | 420 | 400 | 390 |
| *T*, °C | 120 | 110 | 45 | | −10 | −5 |
| *h*, kJ/kg | 377 | 367 | 134 | — | 280 | 284 |

Calculate the heat transfer from the compressor, the heat transfer from the R-410a in the condenser, and the heat transfer to the R-410a in the evaporator.

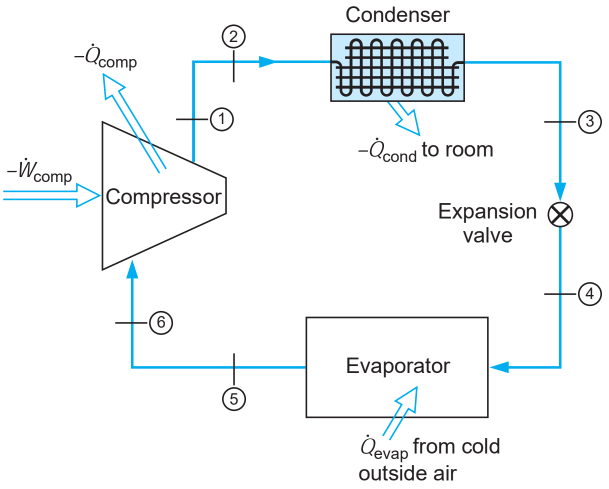


FIGURE P6.108

**6.109** A modern jet engine has a temperature after combustion of about 1500 K at 3200 kPa as it enters the turbine section (see state 3, Fig. P6.109). The compressor inlet is at 80 kPa, 260 K (state 1) and the outlet (state 2) is at 3300 kPa, 780 K; the turbine outlet (state 4) into the nozzle is at 400 kPa, 900 K and the nozzle exit (state 5) is at 80 kPa, 640 K. Neglect any heat transfer and neglect kinetic energy except out of the nozzle. Find the compressor and turbine specific work terms and the nozzle exit velocity.

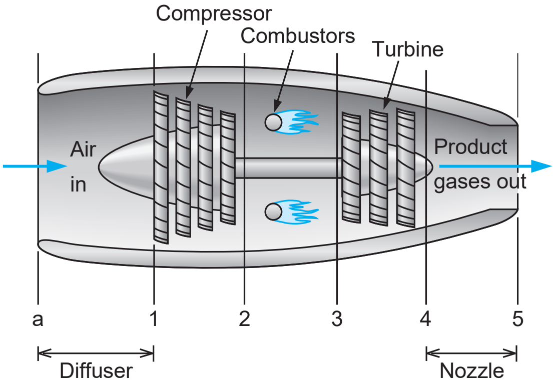


FIGURE P6.109

**6.110** A proposal is made to use a geothermal supply of hot water to operate a steam turbine, as shown in Fig. P6.110. The high-pressure water at 1.5 MPa, 180°C is throttled into a flash evaporator chamber, which forms liquid and vapor at a lower pressure of 400 kPa. The liquid is discarded, while the saturated vapor feeds the turbine and exits at 10 kPa with a 90% quality. If the turbine should produce 1 MW, find the required mass flow rate of hot geothermal water in kilograms per hour.

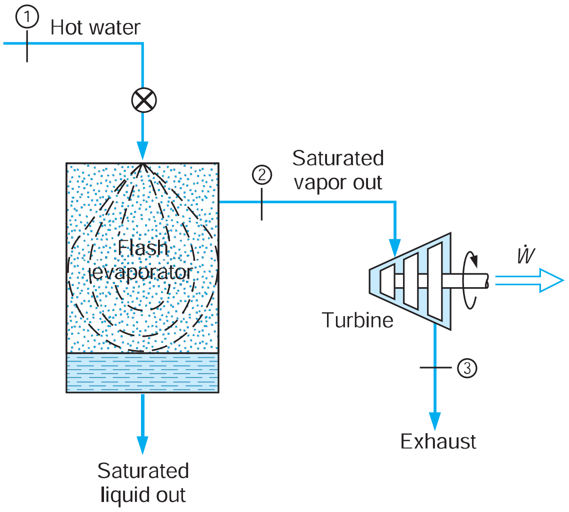


FIGURE P6.110

### Transient Processes

**6.111** An initially empty cylinder is filled with air from 20°C, 100 kPa until it is full. Assuming no heat transfer, is the final temperature above, equal to, or below 20°C? Does the final $T$ depend on the size of the cylinder?

**6.112** An evacuated 150-L tank is connected to a line flowing air at room temperature, 25°C, and 8 MPa pressure. The valve is opened, allowing air to flow into the tank until the pressure inside is 6 MPa. At this point the valve is closed. This filling process occurs rapidly and is essentially adiabatic. The tank is then placed in storage, where it eventually returns to room temperature. What is the final pressure?

**6.113** A 2.5-L tank initially is empty, and we want to fill it with 10 g of ammonia. The ammonia comes from a line with saturated vapor at 25°C. To achieve the desired amount, we cool the tank while we fill it slowly, keeping the tank and its content at 30°C. Find the final pressure to reach before closing the valve and the heat transfer.

**6.114** A tank contains 1 $m^3$ air at 100 kPa, 300 K. A pipe of flowing air at 1000 kPa, 300 K is connected to the tank and is filled slowly to 1000 kPa. Find the heat transfer needed to reach a final temperature of 300 K.

**6.115** An initially empty canister of volume 0.2 $m^3$ is filled with carbon dioxide from a line at 800 kPa, 400 K. Assume the process runs until it stops by itself and it is adiabatic. Use constant heat capacity to find the final temperature in the canister.

**6.116** Repeat the previous problem but use the ideal gas Tables A8 to solve it.

**6.117** An initially empty bottle is filled with water from a line at 0.8 MPa and 350°C. Assume that there is no heat transfer and that the bottle is closed when the pressure reaches the line pressure. If the final mass is 0.75 kg, find the final temperature and the volume of the bottle.

**6.118** A 1-$m^3$ tank contains ammonia at 150 kPa and 25°C. The tank is attached to a line flowing ammonia at 1200 kPa, 60°C. The valve is opened, and mass flows in until the tank is half full of liquid (by volume) at 25°C. Calculate the heat transferred from the tank during this process.

**6.119** A 25-L tank, shown in Fig. P6.119, that is initially evacuated is connected by a valve to an air supply line flowing air at 20°C, 800 kPa. The valve is opened, and air flows into the tank until the pressure reaches 600 kPa. Determine the final temperature and mass inside the tank, assuming the process is adiabatic. Develop an expression for the relation between the line temperature and the final temperature using constant specific heats.

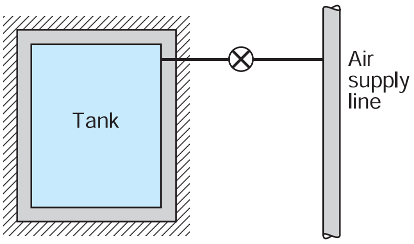


FIGURE P6.119

**6.120** A 200-L tank (see Fig. P6.120) initially contains water at 100 kPa and a quality of 1%. Heat is transferred to the water, thereby raising its pressure and temperature. At a pressure of 2 MPa, a safety valve opens and saturated vapor at 2 MPa flows out. The process continues, maintaining 2 MPa inside until the quality in the tank is 90%, then stops. Determine the total mass of water that flowed out and the total heat transfer.

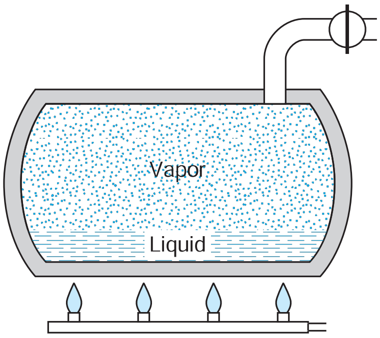


FIGURE P6.120

**6.121** Helium in a steel tank is at 250 kPa, 300 K with a volume of 0.1 $m^3$. It is used to fill a balloon. When the tank pressure drops to 150 kPa, the flow of helium stops by itself. If all the helium still is at 300 K, how big a balloon did I get? Assume the pressure in the balloon varies linearly with volume from 100 kPa ($V = 0$) to the final 150 kPa. How much heat transfer took place?

**6.122** An empty canister of volume 1 L is filled with R-134a from a line flowing saturated liquid R-134a at 0°C. The filling is done quickly, so it is adiabatic. How much mass of R-134a is there after filling? The canister is placed on a storage shelf, where it slowly heats up to room temperature of 20°C. What is the final pressure?

**6.123** A nitrogen line at 300 K, 0.5 MPa, shown in Fig. P6.123, is connected to a turbine that exhausts to a closed, initially empty tank of 50 $\text{m}^3$. The turbine operates to a tank pressure of 0.5 MPa, at which point the temperature is 250 K. Assuming the entire process is adiabatic, determine the turbine work.

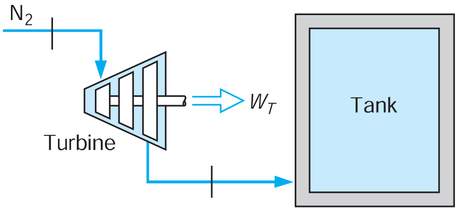


FIGURE P6.123

**6.124** A 750-L rigid tank, shown in Fig. P6.124, initially contains water at 250°C, which is 50% liquid and 50% vapor by volume. A valve at the bottom of the tank is opened, and liquid is slowly withdrawn. Heat transfer takes place such that the temperature remains constant. Find the amount of heat transfer required to reach the state where half of the initial mass is withdrawn.

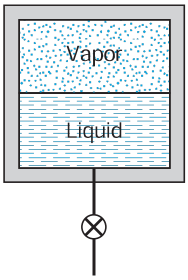


FIGURE P6.124

**6.125** Consider the previous problem, but let the line and valve be located in the top of the tank. Now saturated vapor is slowly withdrawn while heat transfer keeps the temperature inside constant. Find the heat transfer required to reach a state where half of the original mass is withdrawn.

**6.126** A 2-$\text{m}^3$ insulated vessel, shown in Fig. P6.126, contains saturated vapor steam at 4 MPa. A valve on the top of the tank is opened, and steam is allowed to escape. During the process any liquid formed collects at the bottom of the vessel, so only saturated vapor exits. Calculate the total mass that has escaped when the pressure inside reaches 1 MPa.

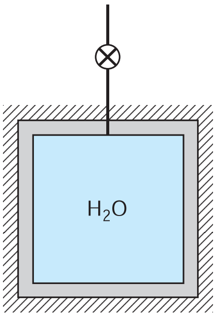


FIGURE P6.126

**6.127** A 2-m-tall cyclinder has a small hole in the bottom as in Fig. P6.127. It is filled with liquid water 1 m high, on top of which is a 1-m-high air column at atmospheric pressure of 100 kPa. As the liquid water near the hole has a higher $P$ than 100 kPa, it runs out. Assume a slow process with constant $T$. Will the flow ever stop? When?

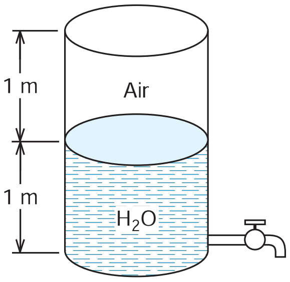


FIGURE P6.127

### Review Problems

**6.128** A pipe of radius $R$ has a fully developed laminar flow of air at $P_0$, $T_0$ with a velocity profile of $\mathbf{V} = \mathbf{V}_c\,[1 - (r/R)^2]$, where $\mathbf{V}_c$ is the velocity on the center-line and $r$ is the radius, as shown in Fig. P6.128. Find the total mass flow rate and the average velocity, both as functions of $\mathbf{V}_c$ and $R$.

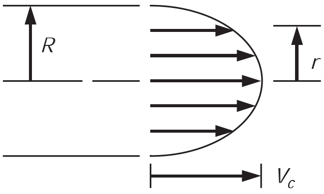


FIGURE P6.128

**6.129** Steam at 3 MPa, 400°C enters a turbine with a volume flow rate of 5 $m^3/s$. An extraction of 15% of the inlet mass flow rate exits at 600 kPa and 200°C. The rest exits the turbine at 20 kPa with a quality of 90% and a velocity of 20 m/s. Determine the volume flow rate of the extraction flow and the diameter of the final exit pipe.

**6.130** In a glass factory a 2-m-wide sheet of glass at 1500 K comes out of the final rollers, which fix the thickness at 5 mm with a speed of 0.5 m/s (see Fig. P6.130). Cooling air in the amount of 20 kg/s comes in at 17°C from a slot 2 m wide and flows parallel with the glass. Suppose this setup is very long, so that the glass and air come to nearly the same temperature (a coflowing heat exchanger); what is the exit temperature?

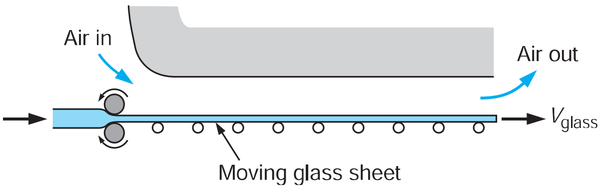


FIGURE P6.130

**6.131** Assume a setup similar to that of the previous problem, but with the air flowing in the opposite direction as the glass—it comes in where the glass goes out. How much air flow at 17°C is required to cool the glass to 450 K, assuming the air must be at least 120 K cooler than the glass at any location?

**6.132** A flow of 2 kg/s of water at 500 kPa, 20°C is heated in a constant-pressure process to 1700°C. Find the best estimate for the rate of heat transfer needed.

**6.133** A 500-L insulated tank contains air at 40°C, 2 MPa. A valve on the tank is opened, and air escapes until half the original mass is gone, at which point the valve is closed. What is the pressure inside at that point?

**6.134** Three air flows, all at 200 kPa, are connected to the same exit duct and mix without external heat transfer. Flow 1 has 1 kg/s at 400 K, flow 2 has 3 kg/s at 290 K, and flow 3 has 2 kg/s at 700 K. Neglect kinetic energies and find the volume flow rate in the exit flow.

**6.135** Consider the power plant described in Problem 6.106.

a. Determine the temperature of the water leaving the intermediate pressure heater, $T_{13}$, assuming no heat transfer to the surroundings.
b. Determine the pump work between states 13 and 16.

**6.136** Consider the power plant described in Problem 6.106.

a. Find the power removed in the condenser by the cooling water (not shown).
b. Find the power to the condensate pump.
c. Do the energy terms balance for the low-pressure heater or is there a heat transfer not shown?

**6.137** A 1-$m^3$, 40-kg rigid steel tank contains air at 500 kPa, and both tank and air are at 20°C. The tank is connected to a line flowing air at 2 MPa, 20°C. The valve is opened, allowing air to flow into the tank until the pressure reaches 1.5 MPa, and is then closed. Assume the air and tank are always at the same temperature and the final temperature is 35°C. Find the final air mass and the heat transfer.

**6.138** A steam engine based on a turbine is shown in Fig. P6.138. The boiler tank has a volume of 100 L and initially contains saturated liquid with a very small amount of vapor at 100 kPa. Heat is now added by the burner. The pressure regulator, which keeps the pressure constant, does not open before the boiler pressure reaches 700 kPa. The saturated vapor enters the turbine at 700 kPa and is discharged to the atmosphere as saturated vapor at 100 kPa. The burner is turned off when no more liquid is present in the boiler. Find the total turbine work and the total heat transfer to the boiler for this process.

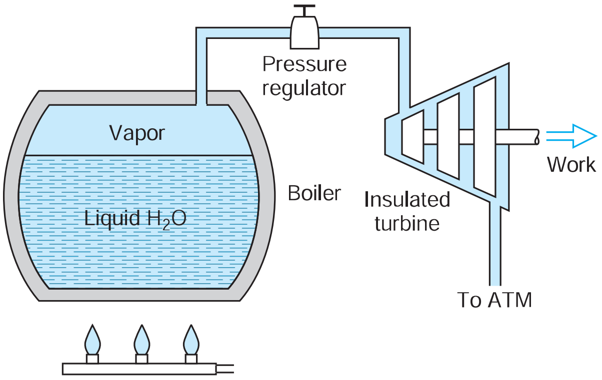


FIGURE P6.138

**6.139** An insulated spring-loaded piston/cyclinder device, shown in Fig. P6.139, is connected to an air line flowing air at 600 kPa and 700 K by a valve. Initially, the cylinder is empty and the spring force is zero. The valve is then opened until the cylinder pressure reaches 300 kPa. Noting that $u_2 = u_{\text{line}} + C_v(T_2 - T_{\text{line}})$ and $h_{\text{line}} - u_{\text{line}} = RT_{\text{line}}$, find an expression for $T_2$ as a function of $P_2$, $P_0$, and $T_{\text{line}}$. With $P_0 = 100$ kPa, find $T_2$.

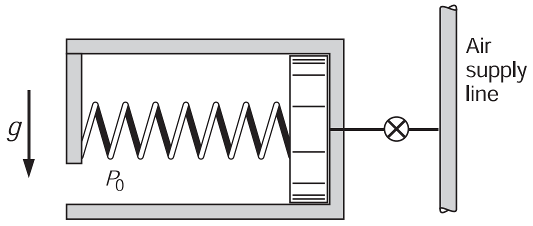


FIGURE P6.139

**6.140** A mass-loaded piston/cylinder shown in Fig. P6.140, containing air, is at 300 kPa, 17°C with a volume of 0.25 $m^3$, while at the stops $V = 1$ $m^3$. An air line, 500 kPa, 600 K, is connected by a valve that is then opened until a final inside pressure of 400 kPa is reached, at which point $T = 350$ K. Find the air mass that enters, the work, and the heat transfer.

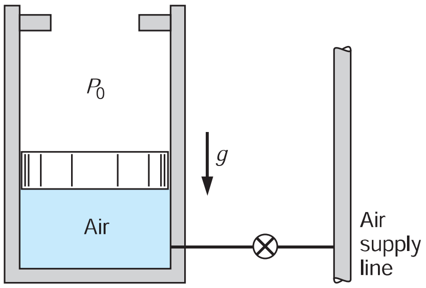


FIGURE P6.140

**6.141** A 2-$m^3$ storage tank contains 95% liquid and 5% vapor by volume of liquified natural gas (LNG) at 160 K, as shown in Fig. P6.141. It may be assumed that LNG has the same properties as pure methane. Heat is transferred to the tank and saturated vapor at 160 K flows into the steady flow heater, which it leaves at 300 K. The process continues until all the liquid in the storage tank is gone. Calculate the total amount of heat transfer to the tank and the total amount of heat transferred to the heater.

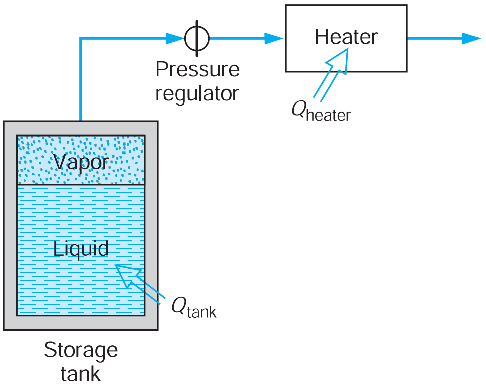


FIGURE P6.141

## Heat Transfer Problems

**6.142** Liquid water at 80°C flows with 0.2 kg/s inside a square duct 2 cm on a side, insulated with a 1-cm-thick layer of foam, $k = 0.1$ W/m K. If the outside foam surface is at 25°C, how much has the water temperature dropped for a 10-m length of duct? Neglect the duct material and any corner effects ($A = 4\ sL$).

**6.143** Saturated liquid carbon dioxide at 2500 kPa flows at 2 kg/s inside a 10-cm-outer-diameter steel pipe, and outside of the pipe is a flow of air at 22°C with a convection coefficient of $h = 150$ W/$m^2$ K. Neglect any $\Delta T$ in the steel and any inside convection $h$ and find the length of pipe needed to bring the carbon dioxide to saturated vapor.

**6.144** A counterflowing heat exchanger conserves energy by heating cold outside fresh air at 10°C with the outgoing combustion gas (air) at 100°C, as in Fig. P6.144. Assume both flows are 1 kg/s and the temperature difference between the flows at any point is 50°C. What is the incoming fresh air temperature after the heat exchanger operates? What is the equivalent (single) convective heat transfer coefficient between the flows if the interface area is 2 $m^2$?