The First Law of Thermodynamics

4. The First Law of Thermodynamics

4.1. INTRODUCTION

The first law of thermodynamics is commonly called the conservation of energy. In elementary physics courses, the study of the conservation of energy emphasizes changes in kinetic and potential energy and their relationship to work. A more general form of conservation of energy includes the effects of heat transfer and internal energy changes. This more general form is usually called the *first law of thermodynamics*. Other forms of energy may also be included, such as electrostatic, magnetic, strain, and surface energy. We will present the first law for a system and then for a control volume.

4.2. THE FIRST LAW OF THERMODYNAMICS APPLIED TO A CYCLE

Having discussed the concepts of work and heat, we are now ready to present the first law of thermodynamics. Recall that a law is not derived or proved from basic principles but is simply a statement that we write based on our observations of many experiments. If an experiment shows a law to be violated, either the law must be revised or additional conditions must be placed on the applicability of the law. Historically, the *first law of thermodynamics* was stated for a cycle: the net heat transfer is equal to the net work done for a system undergoing a cycle. This is expressed in equation form by

$$\Sigma W = \Sigma Q$$

(*4.1*)

or

$$\oint \delta W = \oint \delta Q$$

(*4.2*)

where the symbol $\oint$ implies an integration around a complete cycle.

The first law can be illustrated by considering the following experiment. Let a weight be attached to a pulley/paddle-wheel setup, such as that shown in Fig. 4-1*a*. Let the weight fall a certain distance thereby doing work on the system, contained in the insulated tank shown, equal to the weight multiplied by the distance dropped. The temperature of the system (the fluid in the tank) will rise an amount ΔT.

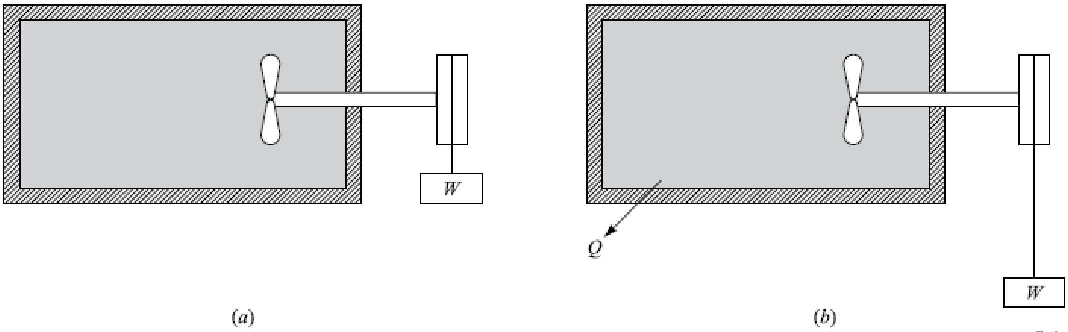

Figure 4-1. The first law applied to a cycle.

Now, the system is returned to its initial state (the completion of the cycle) by transferring heat to the surroundings, as implied by the Q in Fig. 4-1*b*. This reduces the temperature of the system to its initial temperature. The first law states that this heat transfer will be exactly equal to the work which was done by the falling weight.

EXAMPLE 4.1

A spring is stretched a distance of 0.8 m and attached to a paddle wheel (Fig. 4-2). The paddle wheel then rotates until the spring is unstretched. Calculate the heat transfer necessary to return the system to its initial state.

Solution: The work done by the spring on the system is given by

$$W_{1-2} = \int_0^{0.8} F\,dx = \int_0^{0.8} 100x\,dx = (100)\left[\frac{(0.8)^2}{2}\right] = 32\,\text{N}\cdot\text{m}$$

Since the heat transfer returns the system to its initial state, a cycle results. The first law then states that $Q_{2-1} = W_{1-2} = 32$ J.

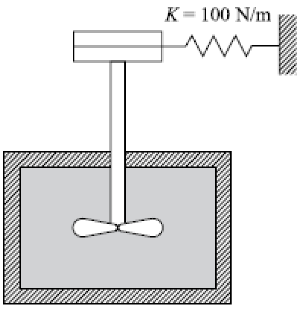

Figure 4-2.

4.3. THE FIRST LAW APPLIED TO A PROCESS

The first law of thermodynamics is often applied to a process as the system changes from one state to another. Realizing that a cycle results when a system undergoes several processes and returns to the initial state, we could consider a cycle composed of the two processes represented by A and B in Fig. 4-3. Applying the first law to this cycle, (*4.2*) takes the form

$$\int_1^2 \delta Q_A + \int_2^1 \delta Q_B = \int_1^2 \delta W_A + \int_2^1 \delta W_B$$

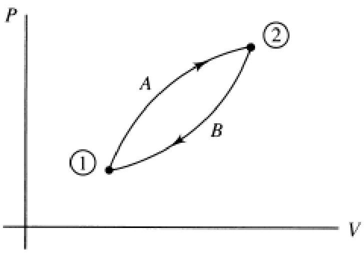

Figure 4-3. A cycle composed of two processes.

We interchange the limits on the process from 1 to 2 along B and write this as

$$\int_1^2 \delta Q_A - \int_1^2 \delta Q_B = \int_1^2 \delta W_A - \int_1^2 \delta W_B$$

or equivalently

$$\int_1^2 (\delta Q - \delta W)_A = \int_1^2 (\delta Q - \delta W)_B$$

That is, the change in the quantity $Q - W$ from state 1 to state 2 is the same along path A as along path B; since this change is independent between states 1 and 2, we let

$$\delta Q - \delta W = dE$$

(*4.3*)

where dE is an exact differential. The quantity E is an extensive property of the system and can be shown experimentally to represent the energy of the system at a particular state. Equation (4.3) can be integrated to yield

$$Q_{1-2} - W_{1-2} = E_2 - E_1$$

(4.4)

where Q_{1-2} is the heat transferred to the system during the process from state 1 to state 2, W_{1-2} is the work done by the system on the surroundings during the process, and E_2 and E_1 are the values of the property E. More often than not the subscripts will be dropped on Q and W when working problems.

The property E represents all of the energy: kinetic energy KE, potential energy PE, and internal energy U which includes chemical energy and the energy associated with the atom. Any other form of energy is also included in the total energy E. Its associated intensive property is designated e.

The first law of thermodynamics then takes the form

$$\begin{aligned} Q_{1-2} - W_{1-2} &= KE_2 - KE_1 + PE_2 - PE_1 + U_2 - U_1 \\ &= \frac{m}{2}(V_2^2 - V_1^2) + mg(z_2 - z_1) + U_2 - U_1 \end{aligned}$$

(4.5)

If we apply the first law to an isolated system, one for which $Q_{1-2} = W_{1-2} = 0$, the first law becomes the conservation of energy; that is,

$$E_2 = E_1$$

(4.6)

The internal energy U is an extensive property. Its associated intensive property is the specific internal energy u; that is, $u = U/m$. For simple systems in equilibrium, only two properties are necessary to establish the state of a pure substance, such as air or steam. Since internal energy is a property, it depends only on, say, pressure and temperature; or, for saturated steam, it depends on quality and temperature (or pressure). Its value for a particular quality would be

$$u = u_f + xu_{fg}$$

(4.7)

We can now apply the first law to systems involving working fluids with tabulated property values. Before we apply the first law to systems involving substances such as ideal gases or solids, it is convenient to introduce several additional properties that will simplify that task.

EXAMPLE 4.2

A 5-hp fan is used in a large room to provide for air circulation. Assuming a well-insulated, sealed room determine the internal energy increase after 1 h of operation.

Solution: By assumption, $Q = 0$. With $\Delta PE = KE = 0$ the first law becomes $-W = \Delta U$. The work input is

$$W = (-5\ \text{hp})(1\ \text{h})(746\ \text{W/hp})(3600\ \text{s/h}) = -1.343 \times 10^7\ \text{J}$$

The negative sign results because the work is input to the system. Finally, the internal energy increase is

$$\Delta U = -(-1.343 \times 10^7) = 1.343 \times 10^7\ \text{J}$$

EXAMPLE 4.3

A rigid volume contains 6 ft^3 of steam originally at a pressure of 400 psia and a temperature of 900 °F. Estimate the final temperature if 800 Btu of heat is added.

Solution: The first law of thermodynamics, with $\Delta KE = \Delta PE = 0$, is $Q - W = \Delta U$. For a rigid container the work is zero. Thus,

$$Q = \Delta U = m(u_2 - u_1)$$

From the steam tables we find $u_1 = 1324$ Btu/lbm and $v_1 = 1.978\ \text{ft}^3$/lbm. The mass is then

$$m = \frac{V}{v} = \frac{6}{1.978} = 3.033 \text{ lbm}$$

The energy transferred to the volume by heat is given. Thus,

$$800 = 3.033(u_2 - 1324) \qquad \therefore u_2 = 1588 \text{ Btu/lbm}$$

From Table C-3E we must find the temperature for which $v_2 = 1.978$ ft^3/lbm and $u_2 = 1588$ Btu/lbm. This is not a simple task since we do not know the pressure. At 500 psia if v = 1.978 ft^3/lbm, then $u = 1459$ Btu/lbm and $T = 1221$ °F. At 600 psia v = 1.978 ft^3/lbm, then $u = 1603$ Btu/lbm and $T = 1546$ °F. Now we linearly interpolate to find the temperature at $u_2 = 1588$ Btu/lbm:

$$T_2 = 1546 - \left(\frac{1603 - 1588}{1603 - 1459}\right)(1546 - 1221) = 1512\,°\text{F}$$

EXAMPLE 4.4 A frictionless piston is used to provide a constant pressure of 400 kPa in a cylinder containing steam originally at 200 °C with a volume of 2 m^3. Calculate the final temperature if 3500 kJ of heat is added.

Solution: The first law of thermodynamics, using $\Delta PE = \Delta KE = 0$, is $Q - W = \Delta U$. The work done during the motion of the piston is

$$W = \int P\, dV = P(V_2 - V_1) = 400(V_2 - V_1)$$

The mass before and after remains unchanged. Using the steam tables, this is expressed as

$$m = \frac{V_1}{v_1} = \frac{2}{0.5342} = 3.744 \text{ kg}$$

The volume V_2 is written as $V_2 = mv_2 = 3.744\ v_2$. The first law is then, finding u_1 from the steam tables,

$$3500 - (400)(3.744v_2 - 2) = (u_2 - 2647) \times (3.744)$$

This requires a trial-and-error process. One plan for obtaining a solution is to guess a value for v_2 and calculate u_2 from the equation above. If this value checks with the u_2 from the steam tables at the same temperature, then the guess is the correct one. For example, guess $v_2 = 1.0$m^3/kg. Then the equation gives $u_2 = 3395$ kJ/kg. From the steam tables, with $P = 0.4$ MPa, the u_2 value allows us to interpolate $T_2 = 654$°C and the v_2 gives $T_2 = 600$°C. Therefore, the guess must be revised. Try $v_2 = 1.06$ m^3/kg. The equation gives $u_2 = 3372$ kJ/kg. The tables are interpolated to give $T_2 = 640$°C; for v_2, $T_2 = 647$°C. The actual v_2 is a little less than 1.06 m^3/kg, with the final temperature being approximately

$$T_2 = 644\,°\text{C}$$

4.4. ENTHALPY

In the solution of problems involving systems, certain products or sums of properties occur with regularity. One such combination of properties can be demonstrated by considering the addition of heat to the constant-pressure situation shown in Fig. 4-4. Heat is added slowly to the system (the gas in the cylinder), which is maintained at constant pressure by assuming a frictionless seal between the piston and the cylinder. If the kinetic energy changes and potential energy changes of the system are neglected and all other work modes are absent, the first law of thermodynamics requires that

$$Q - W = U_2 - U_1$$

(*4.8*)

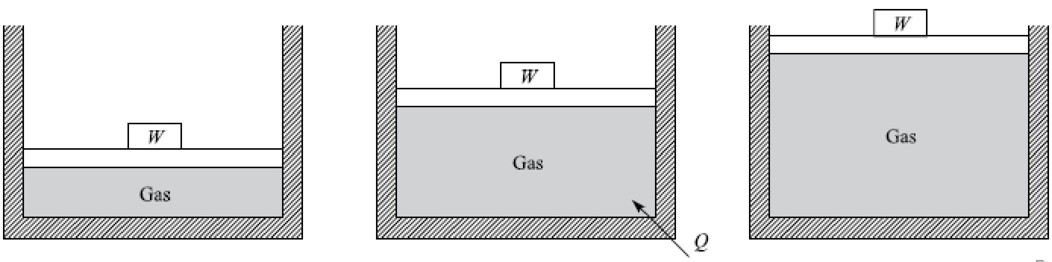

Figure 4-4. Constant-pressure heat addition.

The work done raising the weight for the constant-pressure process is given by

$$W = P(V_2 - V_1)$$

(*4.9*)

The first law can then be written as

$$Q = (U + PV)_2 - (U + PV)_1$$

(*4.10*)

The quantity in parentheses is a combination of properties and is thus a property itself. It is called the *enthalpy H* of the system; that is,

$$H = U + PV$$

(*4.11*)

The specific enthalpy h is found by dividing by the mass. It is

$$h = u + Pv$$

(*4.12*)

Enthalpy is a property of a system and is also found in the steam tables. The energy equation can now be written for a constant-pressure equilibrium process as

$$Q_{1-2} = H_2 - H_1$$

(*4.13*)

The enthalpy was defined using a constant-pressure system with the difference in enthalpies between two states being the heat transfer. For a variable-pressure process, the difference in enthalpy loses its physical significance when considering a system. But enthalpy is still of use in engineering problems; it remains a property as defined by (*4.11*). In a nonequilibrium constant-pressure process ΔH would not equal the heat transfer.

Because only *changes* in enthalpy or internal energy are important, we can arbitrarily choose the datum from which to measure h and u. We choose saturated liquid at 0 °C to be the datum point for water.

EXAMPLE 4.5

Using the concept of enthalpy solve the problem presented in Example 4.4.

Solution: The energy equation for a constant-pressure process is (with the subscript on the heat transfer omitted)

$$Q = H_2 - H_1 \qquad \text{or} \qquad 3500 = (h_2 - 2860)m$$

Using the steam tables as in Example 4.4, the mass is

$$m = \frac{V}{v} = \frac{2}{0.5342} = 3.744 \text{ kg}$$

Thus,

$$h_2 = \frac{3500}{3.744} + 2860 = 3795 \,\text{kJ/kg}$$

From the steam tables this interpolates to

$$T_2 = 600 + \left(\frac{92.6}{224}\right)(100) = 641\,^\circ\text{C}$$

Obviously, enthalpy was very useful in solving the constant-pressure problem. Trial and error was unnecessary, and the solution was rather straightforward. We illustrated that the quantity we made up, enthalpy, is not necessary, but it is quite handy. We will use it often in our calculations.

4.5. LATENT HEAT

The amount of energy that must be transferred in the form of heat to a substance held at constant pressure in order that a phase change occur is called the *latent heat*. It is the change in enthalpy of the substance at the saturated conditions of the two phases. The heat that is necessary to melt (or freeze) a unit mass of a substance at constant pressure is the *heat of fusion* and is equal to $h_{if} = h_f - h_i$, where h_i is the enthalpy of saturated solid and h_f is the enthalpy of saturated liquid. The *heat of vaporization* is the heat required to completely vaporize a unit mass of saturated liquid (or condense a unit mass of saturated vapor); it is equal to $h_{fg} = h_g - h_f$. When a solid changes phase directly to a gas, sublimation occurs; the *heat of sublimation* is equal to $h_{ig} = h_g - h_i$.

The heat of fusion and the heat of sublimation are relatively insensitive to pressure or temperature changes. For ice the heat of fusion is approximately 320 kJ/kg (140 Btu/lbm) and the heat of sublimation is about 2040 kJ/kg (880 Btu/lbm). The heat of vaporization of water is included as h_{fg} in Tables C-1 and C-2.

4.6. SPECIFIC HEATS

For a simple system only two independent variables are necessary to establish the state of the system. Consequently, we can consider the specific internal energy to be a function of temperature and specific volume; that is,

$$u = u(T, v)$$

(*4.14*)

Using the chain rule from calculus we express the differential in terms of the partial derivatives as

$$du = \left.\frac{\partial u}{\partial T}\right|_v dT + \left.\frac{\partial u}{\partial v}\right|_T dv$$

(*4.15*)

Since *u*, v, and *T* are all properties, the partial derivative is also a property and is called the *constant-volume specific heat* C_v; that is,

$$C_v = \left.\frac{\partial u}{\partial T}\right|_v$$

(*4.16*)

One of the classical experiments of thermodynamics, first performed by Joule in 1843, is illustrated in Fig. 4-5. Pressurize volume *A* with an ideal gas and evacuate volume *B*. After equilibrium is attained, open the valve. Even though the pressure and volume of the ideal gas have changed markedly, the temperature does not change. Because there is no change in temperature, there is no net heat transfer to the water. Observing that no work is done we conclude, from the first law, that the internal energy of an ideal gas does not depend on pressure or volume.

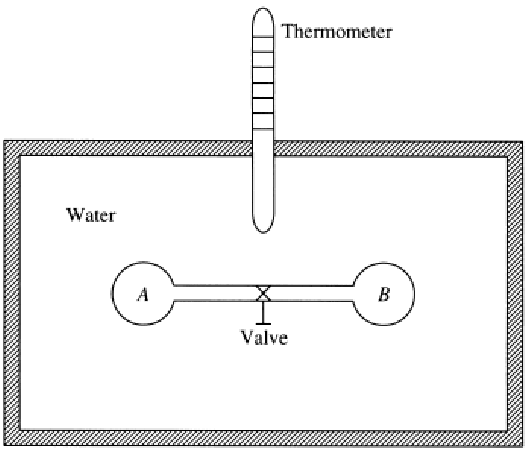

Figure 4-5. Joule's experiment.

For such a gas, which behaves as an ideal gas, we have

$$\left.\frac{\partial u}{\partial v}\right|_T = 0$$

(*4.17*)

Combining (*4.15*), (*4.16*), and (*4.17*),

$$du = C_v\, dT$$

(*4.18*)

This can be integrated to give

$$u_2 - u_1 = \int_{T_1}^{T_2} C_v\, dT$$

(*4.19*)

For a known $C_v(T)$ this can be integrated to find the change in internal energy over any temperature interval for an ideal gas.

Likewise, considering specific enthalpy to be dependent on the two variables T and P, we have

$$dh = \left.\frac{\partial h}{\partial T}\right|_P dT + \left.\frac{\partial h}{\partial P}\right|_T dP$$

(*4.20*)

The *constant-pressure specific heat* C_p is defined as

$$C_p = \left.\frac{\partial h}{\partial T}\right|_P$$

(*4.21*)

For an ideal gas we have, returning to the definition of enthalpy, (*4.12*),

$$h = u + Pv = u + RT$$

(*4.22*)

where we have used the ideal-gas equation of state. Since u is only a function of T, we see that h is also only a function of T for an ideal gas. Hence, for an ideal gas

$$\left.\frac{\partial h}{\partial P}\right|_T = 0$$

(*4.23*)

and we have, from (*4.20*),

$$dh = C_p\, dT$$

(*4.24*)

Over the temperature range T_1 to T_2 this is integrated to give

$$h_2 - h_1 = \int_{T_1}^{T_2} C_p\, dT$$

(*4.25*)

for an ideal gas.

It is often convenient to specify specific heats on a per-mole, rather than a per-unit-mass, basis; these *molar specific heats* are $\bar{C}_v$ and $\bar{C}_p$. Clearly, we have the relations

$$\bar{C}_v = MC_v \qquad \text{and} \qquad \bar{C}_p = MC_p$$

where m is the molar mass. Thus values of $\bar{C}_v$ and $\bar{C}_p$ may be simply calculated from the values of C_v and C_p listed in Table B-2. (The "overbar notation" for a molar quantity is used throughout this book.)

The equation for enthalpy can be used to relate, for an ideal gas, the specific heats and the gas constant. In differential form (*4.12*) takes the form

$$dh = du + d(Pv)$$

(*4.26*)

Introducing the specific heat relations and the ideal-gas equation, we have

$$C_p\, dT = C_v\, dT + R\, dT$$

(*4.27*)

which, after dividing by dT, gives

$$C_p = C_v + R$$

(*4.28*)

This relationship—or its molar equivalent $\bar{C}_p = \bar{C}_v + R_u$—allows C_v to be determined from tabulated values or expressions for C_p. Note that the difference between C_p and C_v for an ideal gas is always a constant, even though both are functions of temperature.

The *specific heat ratio k* is also a property of particular interest; it is defined as

$$k = \frac{C_p}{C_v}$$

(*4.29*)

This can be substituted into (*4.28*) to give

$$C_p = R\frac{k}{k-1}$$

(*4.30*)

or

$$C_v = \frac{R}{k-1}$$

(*4.31*)

Obviously, since R is a constant for an ideal gas, the specific heat ratio will depend only on temperature.

For gases, the specific heats slowly increase with increasing temperature. Since they do not vary significantly over fairly large temperature differences, it is often acceptable to treat C_v and C_p as constants. For such situations there results

$$u_2 - u_1 = C_v(T_2 - T_1)$$

(*4.32*)

$$h_2 - h_1 = C_p(T_2 - T_1)$$

(*4.33*)

For air we will use C_v = 0.717 kJ/kg·°C (0.171 Btu/lbm- °R) and C_p = 1.00 kJ/kg·°C (0.24 Btu/lbm- °R), unless otherwise stated. For more accurate calculations with air, or other gases, one should consult idealgas tables, such as those in Appendix E, which tabulate $h(T)$ and $u(T)$, or integrate using expressions for $C_p(T)$ found in Table B-5.

For liquids and solids the specific heat C_p is tabulated in Table B-4. Since it is quite difficult to maintain constant volume while the temperature is changing, C_v values are usually not tabulated for liquids and solids; the difference $C_p - C_v$ is usually quite small. For most liquids the specific heat is relatively insensitive to temperature change. For water we will use the nominal value of 4.18 kJ/kg·°C (1.00 Btu/lbm- °R). For ice the specific heat in kJ/kg·°C is approximately $C_p = 2.1 + 0.0069T$, where T is measured in °C; and in English units of Btu/lbm- °F it is $C_p = 0.47 + 0.001T$, where T is measured in °F. The variation of specific heat with pressure is usually quite slight except for special situations.

EXAMPLE 4.6

The specific heat of superheated steam at approximately 150 kPa can be determined by the equation

$$C_p = 2.07 + \frac{T - 400}{1480} \text{ kJ/kg}\cdot{}^\circ\text{C}$$

a. What is the enthalpy change between 300 °C and 700 °C for 3 kg of steam? Compare with the steam tables.

b. What is the average value of C_p between 300 °C and 700 °C based on the equation and based on the tabulated data?

Solution:

a. The enthalpy change is found to be

$$\Delta H = m \int_{T_1}^{T_2} C_p \, dT = 3 \int_{300}^{700} \left(2.07 + \frac{T - 400}{1480}\right) dT = 2565 \text{ kJ}$$

From the tables we find, using $P = 150$ kPa,

$$\Delta H = (3)(3928 - 3073) = 2565 \text{ kJ}$$

b. The average value $C_{p,\text{av}}$ is found by using the relation

$$mC_{p,\text{ av}} \, \Delta T = m \int_{T_1}^{T_2} C_p \, dT \quad \text{or}$$

$$(3)(400C_{p,\text{av}}) = 3 \int_{300}^{700} \left(2.07 + \frac{T - 400}{1480}\right) dT$$

The integral was evaluated in part (a); hence, we have

$$C_{p,\text{av}} = \frac{2565}{(3)(400)} = 2.14 \text{ kJ/kg}\cdot{}^\circ\text{C}$$

Using the values from the steam table, we have

$$C_{p,\text{av}} = \frac{\Delta h}{\Delta T} = (3928 - 3073)/400 = 2.14 \text{ kJ/kg}\cdot{}^\circ\text{C}$$

Because the steam tables give the same values as the linear equation of this example, we can safely assume that the $C_p(T)$ relationship for steam over this temperature range is closely approximated by a linear relation. This linear relation would change, however, for each pressure chosen; hence, the steam tables are essential.

EXAMPLE 4.7

Determine the value of C_p for steam at $T = 800$ °F and $P = 800$ psia.

Solution: To determine C_p we use a finite-difference approximation to (4.21). We use the entries at $T = 900$ °F and $T = 700$ °F, which gives a better approximation to the slope compared to using the values at 800 °F and 750 °F or at 900 °F and 800 °F. Table C-3E provides us with

$$C_p \cong \frac{\Delta h}{\Delta T} = \frac{1455.6 - 1338.0}{200} = 0.588 \text{ Btu/lbm-}^\circ\text{F}$$

Figure 4-6 shows why it is better to use values on either side of the position of interest. If values at 900 °F and 800 °F are used (a forward difference), C_p is too low. If values at 800 °F and 750 °C are used (a backward difference), C_p is too high. Thus, both a forward and a backward value (a central difference) should be used, resulting in a more accurate estimate of the slope.

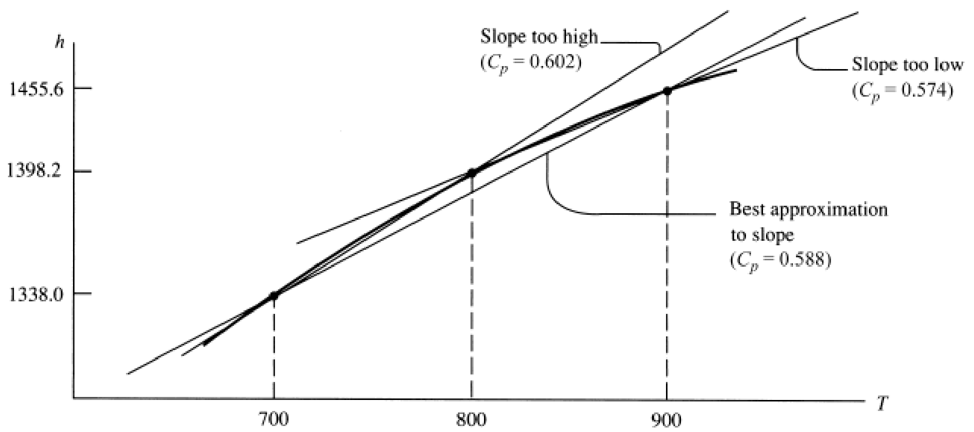

Figure 4-6

EXAMPLE 4.8

Determine the enthalpy change for 1 kg of nitrogen which is heated from 300 to 1200 K by (*a*) using the gas tables, (*b*) integrating $C_p(T)$, and (*c*) assuming constant specific heat. Use $M = 28$ kg/kmol.

Solution:

a. Using the gas table in Appendix E, find the enthalpy change to be

$$\Delta h = 36\,777 - 8723 = 28\,054 \text{ kJ/kmol} \qquad \text{or} \qquad 28\,054/28 = 1002 \text{ kJ/kg}$$

b. The expression for $C_p(T)$ is found in Table B-5. The enthalpy change is

$$\begin{aligned}\Delta h &= \int_{300}^{1200}\left[39.06 - 512.79\left(\frac{T}{100}\right)^{-1.5} + 1072.7\left(\frac{T}{100}\right)^{-2} - 820.4\left(\frac{T}{100}\right)^{-3}\right]dt \\ &= (39.06)(1200 - 300) - (512.79)\left(\frac{100}{-0.5}\right)(12^{-0.5} - 3^{-0.5}) \\ &\quad + (1072.7)\left(\frac{100}{-1}\right)(12^{-1} - 3^{-1}) - (820.4)\left(\frac{100}{-2}\right)(12^{-2} - 3^{-2}) \\ &= 28\,093 \text{ kJ/kmol} \quad \text{or } 1003 \text{ kJ/kg}\end{aligned}$$

c. Assuming constant specific heat (found in Table B-2) the enthalpy change is found to be

$$\Delta h = C_p \Delta T = (1.042)(1200 - 300) = 938 \text{ kJ/kg}$$

Note the value found by integrating is essentially the same as that found from the gas tables. However, the enthalpy change found by assuming constant specific heat is in error by over 6 percent. If T_2 were closer to 300 K, say 600 K, the error would be much smaller.

4.7. THE FIRST LAW APPLIED TO VARIOUS PROCESSES

4.7.1. The Constant-Temperature Process

For the isothermal process, tables may be consulted for substances for which tabulated values are available. Internal energy and enthalpy vary slightly with pressure for the isothermal process, and this variation must be accounted for in processes involving many substances. The energy equation is

$$Q - W = \Delta U$$

(*4.34*)

For a gas that approximates an ideal gas, the internal energy depends only on the temperature and thus $\Delta U = 0$ for an isothermal process; for such a process

$$Q = W$$

(*4.35*)

Using the ideal-gas equation $PV = mRT$, the work for a quasiequilibrium process can be found to be

$$W = \int_{V_1}^{V_2} P\, dV = mRT \int_{V_1}^{V_2} \frac{dV}{V} = mRT \ln\frac{V_2}{V_1} = mRT \ln\frac{P_1}{P_2}$$

(*4.36*)

4.7.2. The Constant-Volume Process

The work for a constant-volume quasiequilibrium process is zero, since dV is zero. For such a process the first law becomes

$$Q = \Delta U$$

(*4.37*)

If tabulated values are available for a substance, we may directly determine ΔU. For a gas, approximated by an ideal gas, we would have

$$Q = m \int_{T_1}^{T_2} C_v \, dT$$

(*4.38*)

or, for a process for which C_v is essentially constant,

$$Q = mC_v \, \Delta T$$

(*4.39*)

If nonequilibrium work, such as paddle-wheel work, is present, that work must be accounted for in the first law.

Equation (*4.39*) provides the motivation for the name "specific heat" for C_v. Historically, this equation was used to define C_v; thus, it was defined as the heat necessary to raise the temperature of one unit of substance one degree in a constant-volume process. Today scientists prefer the definition of C_v to be in terms of properties only, without reference to heat transfer, as in (*4.16*).

4.7.3. The Constant-Pressure Process

The first law, for a constant-pressure quasiequilibrium process, was shown in Sec. 4.4 to be

$$Q = \Delta H$$

(*4.40*)

Hence, the heat transfer for such a process can easily be found using tabulated values, if available.

For a gas that behaves as an ideal gas, we have

$$Q = m \int_{T_1}^{T_2} C_p \, dT$$

(*4.41*)

For a process involving an ideal gas for which C_p is constant there results

$$Q = mC_p \, \Delta T$$

(*4.42*)

For a nonequilibrium process the work must be accounted for directly in the first law and cannot be expressed as $P(V_2 - V_1)$. For such a process (*4.40*) would not be valid.

4.7.4. The Adiabatic Process

There are numerous examples of processes for which there is no, or negligibly small, heat transfer, e.g., the compression of air in an automobile engine or the exhaust of nitrogen from a nitrogen tank. The study of such processes is, however, often postponed until after the second law of thermodynamics is presented. This postponement is not necessary, and because of the importance of the adiabatic quasi-equilibrium process, it is presented here.

The differential form of the first law for the adiabatic process is

$$-\delta w = du$$

(*4.43*)

or, for a quasiequilibrium process, using $\rho w = P\ dv$, thereby eliminating nonequilibrium work modes,

$$du + P \, dv = 0$$

(*4.44*)

The sum of the differential quantities on the left represents a perfect differential which we shall designate as $d\,\psi$, ψ being a property of the system. This is similar to the motivation for defining the enthalpy h as a property. Since

$$d\psi = du + P\,dv$$

(*4.45*)

is a property of the system, it is defined for processes other than the adiabatic quasiequilibrium process.

Let us investigate this adiabatic quasiequilibrium process for an ideal gas with constant specific heats. For such a process, (*4.44*) takes the form

$$C_v\,dT + \frac{RT}{v}dv = 0$$

(*4.46*)

Rearranging, we have

$$\frac{C_v}{R}\frac{dT}{T} = -\frac{dv}{v}$$

(*4.47*)

This is integrated, assuming constant C_v, between states 1 and 2 to give

$$\frac{C_v}{R}\ln\frac{T_2}{T_1} = -\ln\frac{v_2}{v_1}$$

(*4.48*)

which can be put in the form

$$\frac{T_2}{T_1} = \left(\frac{v_1}{v_2}\right)^{R/C_v} = \left(\frac{v_1}{v_2}\right)^{k-1}$$

(*4.49*)

referring to (*4.31*). Using the ideal-gas law, this can be written as

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{(k-1)/k} \qquad \frac{P_2}{P_1} = \left(\frac{v_1}{v_2}\right)^{k}$$

(*4.50*)

Finally, the above three relations can be put in general forms, without reference to particular points. For the adiabatic quasiequilibrium process involving an ideal gas with constant C_p and C_v, we have

$$Tv^{k-1} = \text{const.} \qquad TP^{(1-k)/k} = \text{const.} \qquad Pv^k = \text{const.}$$

(*4.51*)

For a substance that does not behave as an ideal gas, we must utilize tables. For such a process we return to (*4.45*) and recognize that $d\,\psi = 0$, or ψ = const. We do not assign the property ψ a formal name, but, as we shall show in Chap. 7, the ψ function is constant whenever the quantity denoted by s, *the entropy*, is constant. Hence, when using the tables, an adiabatic quasiequilibrium process between states 1 and 2 requires $s_1 = s_2$.

4.7.5. The Polytropic Process

A careful inspection of the special quasiequilibrium processes presented in this chapter suggests that each process can be expressed as

$$PV^n = \text{const.}$$

(*4.52*)

The work is calculated

$$W = \int_{V_1}^{V_2} P\,dV = P_1 V_1^n \int_{V_1}^{V_2} V^{-n}\,dV$$
$$= \frac{P_1 V_1^n}{1-n}(V_2^{1-n} - V_1^{1-n}) = \frac{P_2 V_2 - P_1 V_1}{1-n}$$

(*4.53*)

except (*4.36*) is used if $n = 1$. The heat transfer follows from the first law.

Each quasiequilibrium process is associated with a particular value for n as follows:

$$\begin{aligned} \text{Isothermal:} &\quad n = 1 \\ \text{Constant-volume:} &\quad n = \infty \\ \text{Constant-pressure:} &\quad n = 0 \\ \text{Adiabatic:} &\quad n = k \end{aligned}$$

The processes are displayed on a (ln P) vs. (ln V) plot in Fig. 4-7. The slope of each straight line is the exponent on V in (*4.52*). If the slope is none of the values ∞, k, 1, or zero, then the process can be referred to as a *polytropic process*. For such a process any of the equations (*4.49*), (*4.50*), or (*4.51*) can be used with k simply replaced by n; this is convenient in processes in which there is some heat transfer but which do not maintain temperature, pressure, or volume constant.

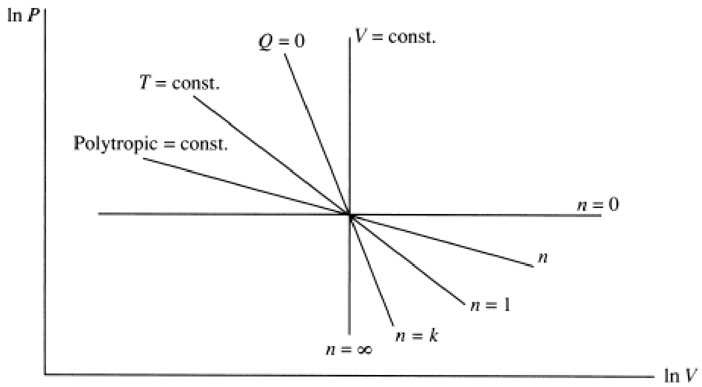

Figure 4-7. Polytropic exponents for various processes.

EXAMPLE 4.9

Determine the heat transfer necessary to increase the pressure of 70 percent quality steam from 200 to 800 kPa, maintaining the volume constant at 2 m^3. Assume a quasiequilibrium process.

Solution: For the constant-volume quasiequilibrium process the work is zero. The first law reduces to $Q = m(u_2 - u_1)$. The mass is found to be

$$m = \frac{V}{v} = \frac{2}{0.0011 + (0.7)(0.8857 - 0.0011)} = \frac{2}{0.6203} = 3.224 \text{ kg}$$

The internal energy at state 1 is

$$u_1 = 504.5 + (0.7)(2529.5 - 504.5) = 1922 \text{ kJ/kg}$$

The constant-volume process demands that $v_2 = v_1 = 0.6203$ m^3/kg. From the steam tables at 800 kPa we find, by extrapolation, that

$$u_2 = \left(\frac{0.6203 - 0.6181}{0.6181 - 0.5601}\right)(3661 - 3476) = 3668 \text{ kJ/kg}$$

Note that extrapolation was necessary since the temperature at state 2 exceeds the highest tabulated temperature of 800 °C. The heat transfer is then

$$Q = (3.224)(3668 - 1922) = 5629 \text{ kJ}$$

EXAMPLE 4.10

A piston-cylinder arrangement contains 0.02 m^3 of air at 50 °C and 400 kPa. Heat is added in the amount of 50 kJ and work is done by a paddle wheel until the temperature reaches 700 °C. If the pressure is held constant how much paddle-wheel work must be added to the air? Assume constant specific heats.

Solution: The process cannot be approximated by a quasiequilibrium process because of the paddle-wheel work. Thus, the heat transfer is not equal to the enthalpy change. The first law may be written as

$$Q - W_{\text{paddle}} = m(h_2 - h_1) = mC_p(T_2 - T_1)$$

To find *m* we use the ideal-gas equation. It gives us

$$m = \frac{PV}{RT} = \frac{(400\,000)(0.02)}{(287)(273+50)} = 0.0863 \text{ kg}$$

From the first law the paddle-wheel work is found to be

$$W_{\text{paddle}} = Q - mC_p(T_2 - T_1) = 50 - (0.0863)(1.00)(700 - 50) = -6.095 \text{ kJ}$$

Note: We could have used the first law as $Q - W_{\text{net}} = m(u_2 - u_1)$ and then let $W_{\text{paddle}} = W_{\text{net}} - P(V_2 - V_1)$. We would then need to calculate V_2.

EXAMPLE 4.11

Calculate the work necessary to compress air in an insulated cylinder from a volume of 6 ft^3 to a volume of 1.2 ft^3. The initial temperature and pressure are 50°F and 30 psia, respectively.

Solution: We will assume that the compression process is approximated by a quasiequilibrium process, which is acceptable for most compression processes, and that the process is adiabatic due to the presence of the insulation. The first law is then written as

$$-W = m(u_2 - u_1) = mC_v(T_2 - T_1)$$

The mass is found from the ideal-gas equation to be

$$m = \frac{PV}{RT} = \frac{[(30)(144)](6)}{(53.3)(460+50)} = 0.9535 \text{ lbm}$$

The final temperature T_2 is found for the adiabatic quasiequilibrium process from (*4.49*); it is

$$T_2 = T_1\left(\frac{V_1}{V_2}\right)^{k-1} = (510)\left(\frac{6.0}{1.2}\right)^{1.4-1} = 970.9^\circ\text{R}$$

Finally, $W = (-0.9535 \text{ lbm})(0.171 \text{ Btu/lbm-}^\circ\text{R})(970.9 - 510)\ ^\circ\text{R} = -75.1$ Btu.

4.8. GENERAL FORMULATION FOR CONTROL VOLUMES

In the application of the various laws we have thus far restricted ourselves to systems, with the result that no mass has crossed the system boundaries. This restriction is acceptable for many problems of interest and may, in fact, be imposed on the power plant schematic shown in Fig. 4-8. However, if the first law is applied to this system, only an incomplete analysis can be accomplished. For a more complete analysis we must relate W_{in}, Q_{in}, W_{out}, and Q_{out} to the pressure and temperature changes for the pump, boiler, turbine, and condenser, respectively. To do this we must consider each device of the power plant as a control volume into which and from which a fluid flows. For example, water flows into the pump at a low pressure and leaves the pump at a high pressure; the work input into the pump is obviously related to this pressure rise. We must formulate equations that allow us to make this necessary calculation. For most applications that we will consider it will be acceptable to assume both a *steady flow* (the flow variables do not change with time) and a *uniform flow* (the velocity, pressure, and density are constant over the cross-sectional area). Fluid mechanics treats the more general unsteady, nonuniform situations in much greater depth.

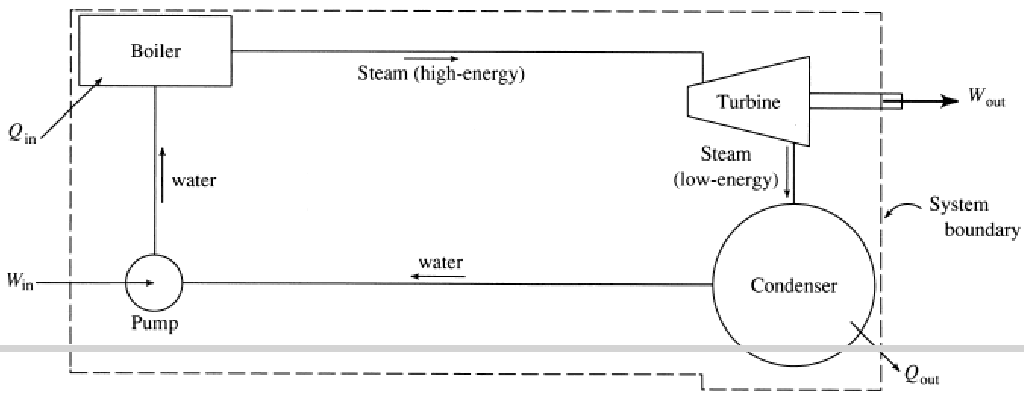

Figure 4-8. A schematic for a power plant.

4.8.1. The Continuity Equation

Consider a general control volume with an area A_1 where fluid enters and an area A_2 where fluid leaves, as shown in Fig. 4-9. It could have any shape and any number of entering and exiting areas, but we will derive the continuity equation using the geometry shown. *Conservation of mass* requires that

$$\begin{pmatrix}\text{Mass entering}\\ \text{control volume}\end{pmatrix} = \begin{pmatrix}\text{Mass leaving}\\ \text{control volume}\end{pmatrix} = \begin{pmatrix}\text{Change in mass}\\ \text{within control volume}\end{pmatrix}$$
$$m_1 \qquad = \qquad m_2 \qquad = \qquad \Delta m_{\text{c.v.}}$$

(*4.54*)

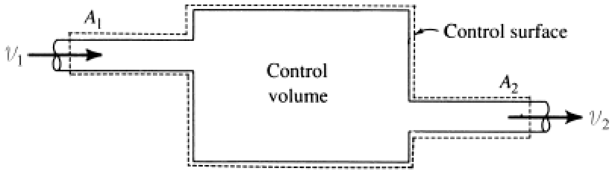

Figure 4-9. Mass entering and leaving a control volume.

The mass that crosses an area A over a time increment Δt can be expressed as $\rho AV\,\Delta t$, where $V\,\Delta t$ is the distance the mass particles travel and $AV\,\Delta t$ is the volume swept out by the mass particles. Equation (*4.54*) can thus be put in the form

$$\rho_1 A_1 V_1 \Delta t - \rho_2 A_2 V_2 \Delta t = \Delta m_{\text{c.v.}}$$

(*4.55*)

where the velocities V_1 and V_2 are perpendicular to the areas A_1 and A_2, respectively. We have assumed the velocity and density to be uniform over the two areas.

If we divide by Δt and let $\Delta t \to 0$, the derivative results and we have the *continuity equation*,

$$\rho_1 A_1 V_1 = \rho_2 A_2 V_2 = \frac{dm_{\text{c.v.}}}{dt}$$

(*4.56*)

For the steady-flow situation, in which the mass in the control volume remains constant, the continuity equation reduces to

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

(*4.57*)

which will find use in problems involving flow into and from various devices.

The quantity of mass crossing an area each second is termed the *mass flux* $\dot{m}$ and has units kg/s (lbm/sec). It is given by the expression

$$\dot{m} = \rho A V$$

(*4.58*)

The quantity $AV = \dot{V}$ is often referred to as the *flow rate* with units of m^3/s (ft^3/sec).

If the velocity and density are not uniform over the entering and exiting areas, the variation across the areas must be accounted for. This is done by recognizing that the mass flowing through a differential area element dA each second is given by $\rho V\,dA$, providing V is normal to dA. In this case (*4.58*) is replaced by $\dot{m} = \int_A \rho V\,dA$. Observe that for *incompressible* flow (ρ = constant), (*4.58*) holds whatever the velocity distribution, provided only that V be interpreted as the *average normal velocity* over the area A.

EXAMPLE 4.12

Water is flowing in a pipe that changes diameter from 20 to 40 mm. If the water in the 20-mm section has a velocity of 40 m/s, determine the velocity in the 40-mm section. Also calculate the mass flux.

Solution: The continuity equation (4.57) is used. There results, using $\rho_1 = \rho_2$,

$$A_1 V_1 = A_2 V_2 \qquad \left[\frac{\pi(0.02)^2}{4}\right](40) = \frac{\pi(0.04)^2}{4} V_2 \qquad \therefore V_2 = 10 \text{ m/s}$$

The mass flux is found to be

$$\dot{m} = \rho A_1 V_1 = (1000)\left(\frac{\pi(0.02)^2}{4}\right)(40) = 12.57 \text{ kg/s}$$

where $\rho = 1000 \text{ kg/m}^3$ is the standard value for water.

4.8.2. The Energy Equation

Consider again a general control volume as sketched in Fig. 4-10. The first law of thermodynamics for this control volume can be stated as

$$\begin{pmatrix}\text{Net energy}\\ \text{transferred to}\\ \text{the c.v.}\end{pmatrix} + \begin{pmatrix}\text{Energy}\\ \text{entering}\\ \text{the c.v.}\end{pmatrix} - \begin{pmatrix}\text{Energy}\\ \text{leaving}\\ \text{the c.v.}\end{pmatrix} = \begin{pmatrix}\text{Change of}\\ \text{energy in}\\ \text{the c.v.}\end{pmatrix}$$
$$Q - W \quad + \quad E_1 \quad - \quad E_2 \quad = \quad \Delta E_{\text{c.v.}}$$

(*4.59*)

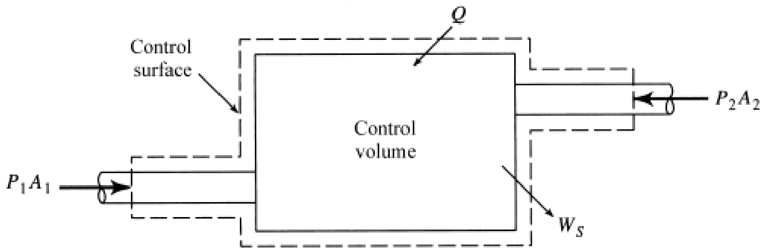

Figure 4-10. The control volume used for an energy balance.

The work W is composed of two parts: the work due to the pressure needed to move the fluid, sometimes called *flow work*, and the work that results from a rotating shaft, called *shaft work* W_S. This is expressed as

$$W = P_2 A_2 V_2 \Delta t - P_1 A_1 V_1 \Delta t + W_S$$

(*4.60*)

where PA is the pressure force and $V\,\Delta t$ is the distance it moves during the time increment Δt. The negative sign results because the work done on the system is negative when moving the fluid into the control volume.

The energy E is composed of kinetic energy, potential energy, and internal energy. Thus,

$$E = \frac{1}{2} m V^2 + mgz + mu$$

(*4.61*)

The first law can now be written as

$$Q - W_S - P_2 A_2 V_2\,\Delta t + P_1 A_1 V_1\,\Delta t + \rho_1 A_1 V_1 \left(\frac{V_1^2}{2} + gz_1 + u_1\right)\Delta t$$
$$- \rho_2 A_2 V_2 \left(\frac{V_2^2}{2} + gz_2 + u_2\right)\Delta t = \Delta E_{\text{c.v.}}$$

(*4.62*)

Divide through by Δt to obtain *the energy equation*:

$$\dot{Q} - \dot{W}_S = \dot{m}_2\left(\frac{V_2^2}{2} + gz_2 + u_2 + \frac{P_2}{\rho_2}\right) - \dot{m}_1\left(\frac{V_1^2}{2} + gz_1 + u_1 + \frac{P_1}{\rho_1}\right) + \frac{dE_{\text{c.v.}}}{dt}$$

(*4.63*)

where we have used

$$\dot{Q} = \frac{Q}{\Delta t} \qquad \dot{W}_S = \frac{W}{\Delta t} \qquad \dot{m} = \rho A V$$

(*4.64*)

For steady flow, a very common situation, the energy equation becomes

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

(*4.65*)

where the enthalpy of (4.12) has been introduced. This is the form most often used when a gas or a vapor is flowing.

Quite often the kinetic energy and potential energy changes are negligible. The first law then takes the simplified form

$$\dot{Q} - \dot{W}_S = \dot{m}(h_2 - h_1)$$

(*4.66*)

or

$$q - w_S = h_2 - h_1$$

(*4.67*)

where $q = \dot{Q}/\dot{m}$ and $w_S = \dot{W}_S/\dot{m}$. This simplified form of the energy equation has a surprisingly large number of applications.

For a control volume through which a liquid flows, it is most convenient to return to (4.63). For a steady flow with $\rho_2 = \rho_1 = \rho$, neglecting the heat transfer and changes in internal energy, the energy equation takes the form

$$-\dot{W}_S = \dot{m}\left[\frac{P_2 - P_1}{\rho} + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1)\right]$$

(*4.68*)

This is the form to use for a pump or a hydroturbine. If $\dot{Q}$ and Δu are not zero, simply include them.

4.9. APPLICATIONS OF THE ENERGY EQUATION

There are several points that must be considered in the analysis of most problems in which the energy equation is used. As a first step, it is very important to identify the control volume selected in the solution of a problem; dotted lines are used to outline the control surface. If at all possible, the control surface should be chosen so that the flow variables are uniform or known functions over the areas where the fluid enters or exits the control volume. For example, in Fig. 4-11 the area could be chosen as in part (*a*), but the velocity and the pressure are certainly not uniform over the area. In part (*b*), however, the control surface is chosen sufficiently far downstream from the abrupt area change that the exiting velocity and pressure can be approximated by uniform distributions.

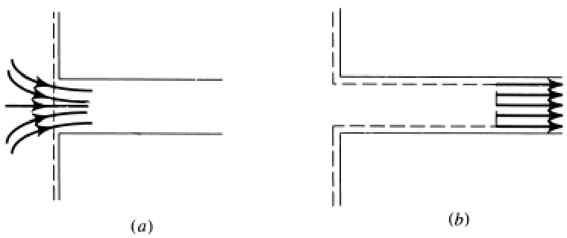

Figure 4-11. The control surface at an entrance.

It is also necessary to specify the process by which the flow variables change. Is it incompressible? isothermal? constant-pressure? adiabatic? A sketch of the process on a suitable diagram is often of use in the calculations. If the working substance behaves as an ideal gas, then the appropriate equations can be used; if not, tabulated values must be used, such as those provided for steam. For real gases that do not behave as ideal gases, specialized equations may be available for calculations; some of these equations will be presented in a later chapter.

Often heat transfer from a device or an internal energy change across a device, such as flow through a pump, is not desired. For such situations, the heat transfer and internal energy change may be lumped together as *losses*. In a pipeline losses occur because of friction; in a centrifugal pump, losses occur because of poor fluid motion around the rotating blades. For many devices the losses are included as an efficiency of the device. Examples will illustrate.

Kinetic energy or potential energy changes can often be neglected in comparison with other terms in the energy equation. Potential energy changes are usually included only in situations where liquid is involved and where the inlet and exit areas are separated by a large vertical distance. The following applications will illustrate many of the above points.

4.9.1. Throttling Devices

A throttling device involves a steady-flow adiabatic process that provides a sudden pressure drop with no significant potential energy or kinetic energy changes. The process occurs relatively rapidly, with the result that negligible heat transfer occurs. Two such devices are sketched in Fig. 4-12. If the energy equation is applied to such a device, with no work done and neglecting kinetic and potential energy changes, we have, for this adiabatic non-quasiequilibrium process [see (*4.67*)],

$$h_1 = h_2$$

(*4.69*)

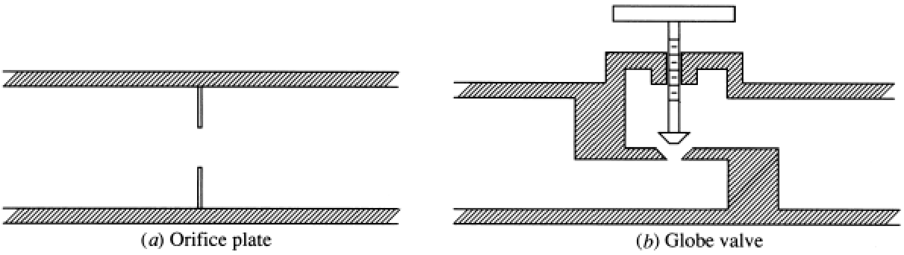

Figure 4-12. Throttling devices.

where section 1 is upstream and section 2 is downstream. Most valves are throttling devices, for which the energy equation takes the form of (*4.69*). They are also used in many refrigeration units in which the sudden drop in pressure causes a change in phase of the working substance. The throttling process is analogous to the sudden expansion of Fig. 3-5*b*.

EXAMPLE 4.13

Steam enters a throttling valve at 8000 kPa and 300 °C and leaves at a pressure of 1600 kPa. Determine the final temperature and specific volume of the steam.

Solution: The enthalpy of the steam as it enters is found from the superheat steam table to be $h_1 = 2785$ kJ/kg. This must equal the exiting enthalpy as demanded by (*4.69*). The exiting steam is in the quality region, since at 1600 kPa $h_g = 2794$ kJ/kg. Thus the final temperature is $T_2 = 201.4$ °C.

To find the specific volume we must know the quality. It is found from

$$h_2 = h_f + x_2 h_{fg} \qquad 2785 = 859 + 1935 x_2 \qquad x_2 = 0.995$$

The specific volume is then $v_2 = 0.0012 + (0.995)(0.1238 - 0.0012) = 0.1232$ m^3/kg.

4.9.2. Compressors, Pumps, and Turbines

A pump is a device which transfers energy to a liquid flowing through the pump with the result that the pressure is increased. Compressors and blowers also fall into this category but have the primary purpose of increasing the pressure in a gas. A turbine, on the other hand, is a device in which work is done by the fluid on a set of rotating blades; as a result there is a pressure drop from the inlet to the outlet of the turbine. In some situations there may be heat transferred from the device to the surroundings, but often the heat transfer can be assumed negligible. In addition the kinetic and potential energy changes are usually neglected. For such devices operating in a steady-state mode the energy equation takes the form [see (*4.66*)]

$$-\dot{W}_S = \dot{m}(h_2 - h_1) \qquad \text{or} \qquad -w_S = h_2 - h_1$$

(*4.70*)

where $\dot{W}_S$ is negative for a compressor and positive for a gas or steam turbine. In the event that heat transfer does occur, from perhaps a high-temperature working fluid, it must, of course, be included in the above equation.

For liquids, such as water, the energy equation (*4.68*), neglecting kinetic and potential energy changes, becomes

$$-w_S = \frac{P_2 - P_1}{\rho}$$

(*4.71*)

EXAMPLE 4.14

Steam enters a turbine at 4000 kPa and 500 °C and leaves as shown in Fig. 4-13. For an inlet velocity of 200 m/s calculate the turbine power output. (*a*) Neglect any heat transfer and kinetic energy change. (*b*) Show that the kinetic energy change is negligible.

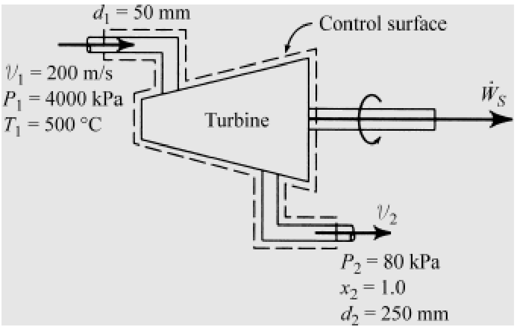

Figure 4-13.

Solution:

a. The energy equation in the form of (*4.70*) is $-\dot{W}_T = (h_2 - h_1)\dot{m}$. We find $\dot{m}$ as follows:

$$\dot{m} = \rho_1 A_1 V_1 = \frac{1}{v_1} A_1 V_1 = \frac{\pi(0.025)^2(200)}{0.08643} = 4.544 \text{ kg/s}$$

The enthalpies are found from Table C-3 to be

$$h_1 = 3445.2 \text{ kJ/kg} \qquad h_2 = 2665.7 \text{ kJ/kg}$$

The maximum power output is then $\dot{W}_T = -(2665.7 - 3445.2)(4.544) = 3542 \text{ kJ/s} \quad \text{or } 3.542 \text{ MW}$.

b. The exiting velocity is found to be

$$V_2 = \frac{A_1 V_1 \rho_1}{A_2 \rho_2} = \frac{\pi(0.025)^2(200/0.08643)}{\pi(0.125)^2/2.087} = 193 \text{ m/s}$$

The kinetic energy change is then

$$\Delta KE = \dot{m}\left(\frac{V_2^2 - V_1^2}{2}\right) = (4.544)\left(\frac{193^2 - 200^2}{2}\right) = -6250 \text{ J/s} \quad \text{or } -6.25 \text{ kJ/s}$$

This is less than 0.1 percent of the enthalpy change and is indeed negligible. Kinetic energy changes are usually omitted in the analysis of a turbine.

EXAMPLE 4.15

Determine the maximum pressure increase across the 10-hp pump shown in Fig. 4-14. The inlet of velocity of the water is 30 ft/sec.

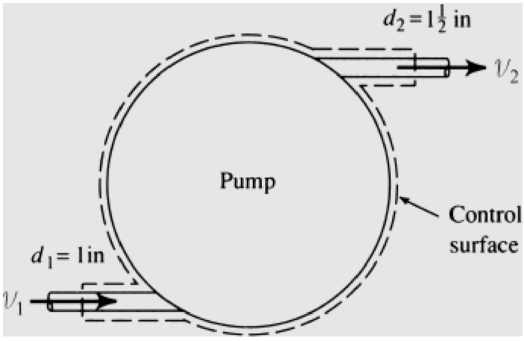

Figure 4-14.

Solution: The energy equation (*4.68*) is used. By neglecting the heat transfer and assuming no increase in internal energy, we establish the maximum pressure rise. Neglecting the potential energy change, the energy equation takes the form

$$-\dot{W}_S = \dot{m}\left(\frac{P_2 - P_1}{\rho} + \frac{V_2^2 - V_1^2}{2}\right)$$

The velocity V_1 is given, and V_2 is found from the continuity equation as follows:

$$\rho A_1 V_1 = \rho A_2 V_2 \qquad \left[\frac{\pi(1)^2}{4}\right](30) = \frac{\pi(1.5)^2}{4} V_2 \qquad \therefore V_2 = 13.33 \text{ ft/sec}$$

The mass flux, needed in the energy equation, is then, using $\rho = 62.4$ lbm/ft^3,

$$\dot{m} = \rho A_1 V_1 = (62.4)\left[\frac{\pi(1)^2}{(4 \times 144)}\right](30) = 10.21 \text{ lbm/sec}$$

Recognizing that the pump work is negative, the energy equation is

$$-(-10)(550) \text{ ft-lbf/sec} = (10.21 \text{ lbm/sec})\left[\frac{(P_2 - P_1) \text{ lbf/ft}^2}{62.4 \text{ lbm/ft}^3} + \frac{(13.33^2 - 30^2) \text{ ft}^2\text{/sec}^2}{(2)(32.2 \text{ lbm-ft/sec}^2\text{-lbf})}\right]$$

where the factor 32.2 lbm-ft/sec^2-lbf is needed to obtain the correct units on the kinetic energy term. This predicts a pressure rise of

$$P_2 - P_1 = (62.4)\left[\frac{5500}{10.21} - \frac{13.33^2 - 30^2}{(2)(32.2)}\right] = 34{,}310 \text{ lbf/ft}^2 \quad \text{or } 238.3 \text{ psi}$$

Note that in this example the kinetic energy terms are retained because of the difference in inlet and exit areas; if they were omitted, only a 2 percent error would result. In most applications the inlet and exit areas will be equal so that $V_2 = V_1$; but even with different areas, as in this example, kinetic energy changes are usually ignored in a pump or turbine and (*4.71*) is used.

4.9.3. Nozzles and Diffusers

A nozzle is a device that is used to increase the velocity of a flowing fluid. It does this by reducing the pressure. A diffuser is a device that increases the pressure in a flowing fluid by reducing the velocity. There is no work input into the devices and usually negligible heat transfer. With the additional assumptions of negligible internal energy and potential energy changes, the energy equation takes the form

$$0 = \frac{V_2^2}{2} - \frac{V_1^2}{2} + h_2 - h_1$$

(*4.72*)

Based on our intuition we expect a nozzle to have a decreasing area in the direction of flow and a diffuser to have an increasing area in the direction of flow. This is indeed the case for a subsonic flow in which $V < \sqrt{kRT}$. For a supersonic flow in which $V > \sqrt{kRT}$ the opposite is true: a nozzle has an increasing area and a diffuser has a decreasing area. This is shown in Fig. 4-15.

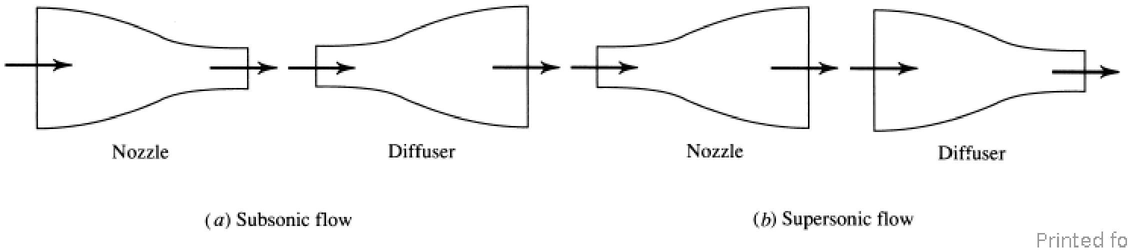

Figure 4-15. Nozzles and diffusers.

Three equations may be used for nozzle and diffuser flow; energy, continuity, and a process equation, such as for an adiabatic quasiequilibrium flow. Thus, we may have three unknowns at the exit, given the entering conditions. There may also be shock waves in supersonic flows or "choked" subsonic flows. These more complicated flows are included in a fluid mechanics course. Only the more simple situations will be included here.

EXAMPLE 4.16

Air flows through the supersonic nozzle shown in Fig. 4-16. The inlet conditions are 7 kPa and 420 °C. The nozzle exit diameter is adjusted such that the exiting velocity is 700 m/s. Calculate (*a*) the exit temperature, (*b*) the mass flux, and (*c*) the exit diameter. Assume an adiabatic quasiequilibrium flow.

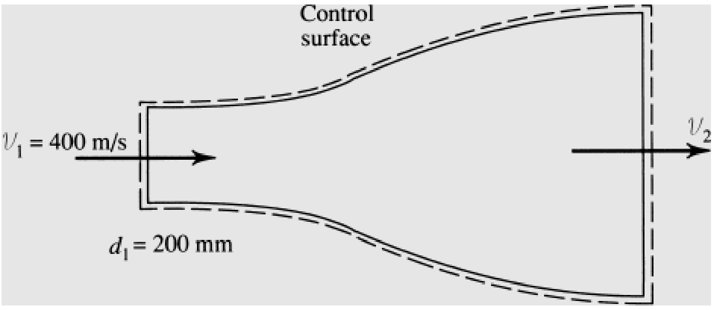

Figure 4-16.

Solution:

a. To find the exit temperature the energy equation (4.72) is used. It is, using $\Delta h = C_p\, \Delta T$,

$$\frac{V_1^2}{2} + C_p T_1 = \frac{V_2^2}{2} + C_p T_2$$

We then have, using C_p = 1000 J/kg·K,

$$T_2 = \frac{V_1^2 - V_2^2}{2C_p} + T_1 = \frac{400^2 - 700^2}{(2)(1000)} + 420 = 255\,°\mathrm{C}$$

b. To find the mass flux we must find the density at the entrance. From the inlet conditions we have

$$\rho_1 = \frac{P_1}{RT_1} = \frac{7000}{(287)(693)} = 0.03520\ \mathrm{kg/m^3}$$

The mass flux is then $\dot{m} = \rho_1 A_1 V_1 = (0.0352)(\pi)(0.1)^2(400) = 0.4423\ \mathrm{kg/s}.$

c. To find the exit diameter we would use the continuity equation $\rho_1 A_1 V_1 = \rho_2 A_2 V_2$. This requires the density at the exit. It is found by assuming adiabatic quasiequilibrium flow. Referring to (4.49), we have

$$\rho_2 = \rho_1 \left(\frac{T_2}{T_1}\right)^{1/(k-1)} = (0.0352)\left(\frac{528}{693}\right)^{1/(1.4-1)} = 0.01784\ \mathrm{kg/m^3}$$

Hence,

$$d_2^2 = \frac{\rho_1 d_1^2 V_1}{\rho_2 V_2} = \frac{(0.0352)(0.2^2)(400)}{(0.01784)(700)} = 0.0451 \qquad \therefore d_2 = 0.212\ \mathrm{m} \quad \text{or } 212\ \mathrm{mm}$$

4.9.4. Heat Exchangers

An important device that has many applications in engineering is the heat exchanger. Heat exchangers are used to transfer energy from a hot body to a colder body or to the surroundings by means of heat transfer. Energy is transferred from the hot gases after combustion in a power plant to the water in the pipes of the boiler and from the hot water that leaves an automobile engine to the atmosphere, and electrical generators are cooled by water flowing through internal flow passages.

Many heat exchangers utilize a flow passage into which a fluid enters and from which the fluid exits at a different temperature. The velocity does not normally change, the pressure drop through the passage is usually neglected, and the potential energy change is assumed zero. The energy equation then results in

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

(*4.73*)

since no work occurs in the heat exchanger.

Energy may be exchanged between two moving fluids, as shown schematically in Fig. 4-17. For a control volume including the combined unit, which is assumed to be insulated, the energy equation, as applied to the control volume of Fig. 4-17*a*, would be

$$0 = \dot{m}_A(h_{A2} - h_{A1}) + \dot{m}_B(h_{B2} - h_{B1})$$

(*4.74*)

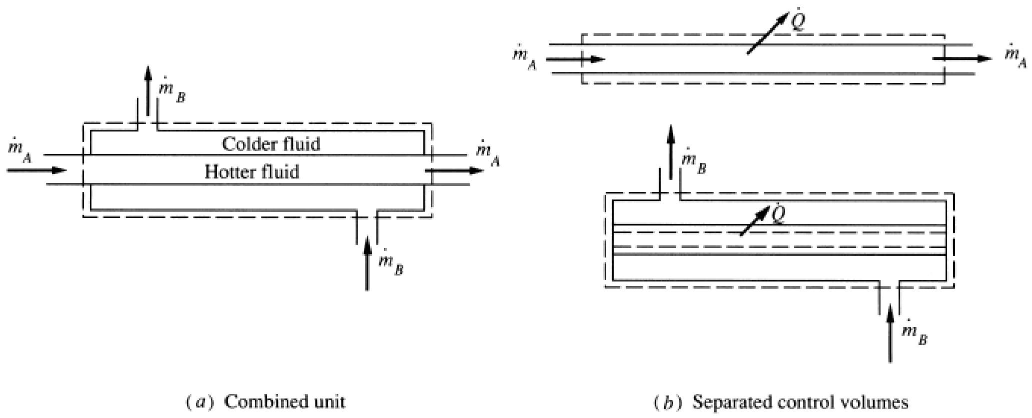

Figure 4-17. A heat exchanger.

The energy that leaves fluid *A* is transferred to fluid *B* by means of the heat transfer $\dot{Q}$. For the control volumes shown in Fig. 4-17*b* we have

$$\dot{Q} = \dot{m}_B(h_{B2} - h_{B1}) \qquad -\dot{Q} = \dot{m}_A(h_{A2} - h_{A1})$$

(*4.75*)

EXAMPLE 4.17

A liquid, flowing at 100 kg/s, enters a heat exchanger at 450 °C and exits at 350 °C. The specific heat of the liquid is 1.25 kJ/kg · °C. Water enters at 5000 kPa and 20 °C. Determine the minimum mass flux of the water so that the water does not completely vaporize. Neglect the pressure drop through the exchanger. Also, calculate the rate of heat transfer.

Solution: The energy equation (*4.74*) is used as $\dot{m}_s(h_{s1} - h_{s2}) = \dot{m}_w(h_{w2} - h_{w1})$, or

$$\dot{m}_s C_p(T_{s1} - T_{s2}) = \dot{m}_w(h_{w2} - h_{w1})$$

Using the given values, we have (use Table C-4 to find h_{w1})

$$(100)(1.25) \times (450 - 350) = \dot{m}_w(2792.8 - 88.7) \qquad \therefore \dot{m}_w = 4.623 \text{ kg/s}$$

where we have assumed a saturated vapor state for the exiting steam to obtain the maximum allowable exiting enthalpy. The heat transfer is found using the energy equation (*4.75*) applied to one of the separate control volumes.

$$\dot{Q} = \dot{m}_w(h_{w2} - h_{w1}) = (4.623)(2792.8 - 88.7) = 12\,500 \text{ kW} \qquad \text{or } 12.5 \text{ MW}$$

4.9.5. Power and Refrigeration Cycles

When energy in the form of heat is transferred to a working fluid, energy in the form of work may be extracted from the working fluid. The work may be converted to an electrical form of energy, such as is done in a power plant, or to a mechanical form, such as is done in an automobile. In general, such conversions of energy are accomplished by a power cycle. One such cycle is shown in Fig. 4-18. In the boiler (a heat exchanger) the energy contained in a fuel is transferred by heat to the water which enters, causing a high-pressure steam to exit and enter the turbine. A condenser (another heat exchanger) discharges heat, and a pump increases the pressure lost through the turbine.

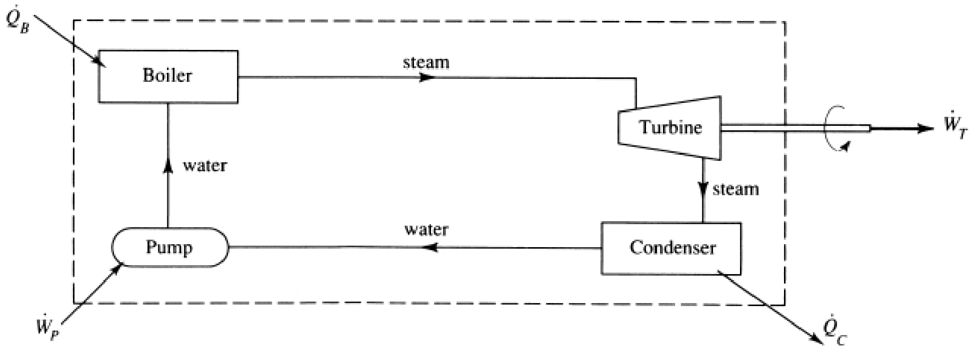

Figure 4-18. A simple power schematic.

The energy transferred to the working fluid in the boiler in the simple power cycle of Fig. 4-18 is the energy that is available for conversion to useful work; it is the energy that must be purchased. The *thermal efficiency* η is defined to be the ratio of the net work produced to the energy input. In the simple power cycle being discussed it is

$$\eta = \frac{\dot{W}_T - \dot{W}_P}{\dot{Q}_B}$$

(*4.76*)

When we consider the second law of thermodynamics, we will show that there is an upper limit to the thermal efficiency of a particular power cycle. Thermal efficiency is, however, a quantity that is determined solely by first-law energy considerations.

Other components can be combined in an arrangement like that shown in Fig. 4-19, resulting in a refrigeration cycle. Heat is transferred to the working fluid (the refrigerant) in the evaporator (a heat exchanger). The working fluid is then compressed by the compressor. Heat is transferred from the working fluid in the condenser, and then its pressure is suddenly reduced in the expansion valve. A refrigeration cycle may be used to add energy to a body (heat transfer $\dot{Q}_C$) or it may be used to extract energy from a body (heat transfer $\dot{Q}_E$).

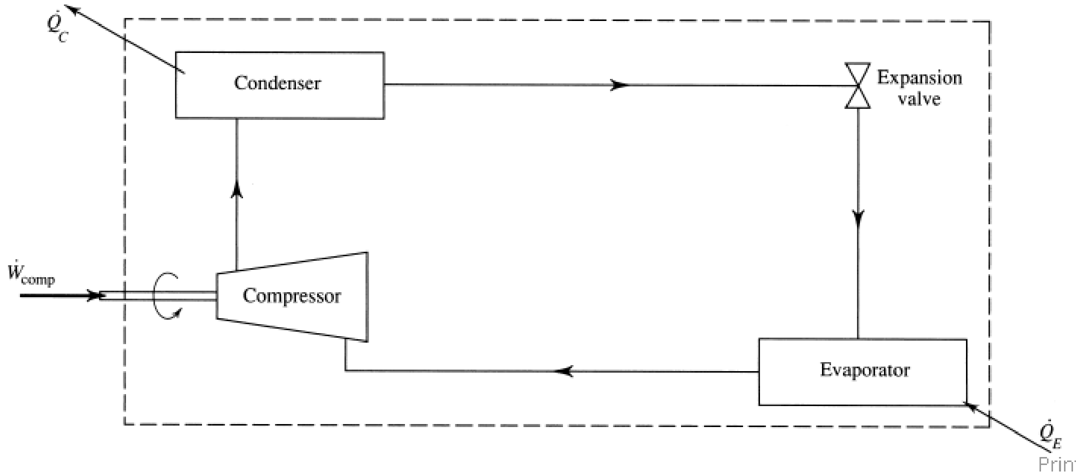

Figure 4-19. A simple refrigeration schematic.

It is not useful to calculate the thermal efficiency of a refrigeration cycle since the objective is not to do work but to accomplish heat transfer. If we are extracting energy from a body, our purpose is to cause maximum heat transfer with minimum work input. To measure this, we define a *coefficient of performance* (abbreviated COP) as

$$\text{COP} = \frac{\dot{Q}_E}{\dot{W}_{\text{comp}}} = \frac{\dot{Q}_E}{\dot{Q}_C - \dot{Q}_E}$$

(*4.77*)

If we are adding energy to a body, our purpose is, again, to do so with a minimum work input. In this case the coefficient of performance is defined as

$$\text{COP} = \frac{\dot{Q}_C}{\dot{W}_{\text{comp}}} = \frac{\dot{Q}_C}{\dot{Q}_C - \dot{Q}_E}$$

(*4.78*)

A device which can operate with this latter objective is called a *heat pump*; if it operates with the former objective only it is a *refrigerator*.

It should be apparent from the definitions that thermal efficiency can never be greater than unity but that the coefficient of performance can be greater than unity. Obviously, the objective of the engineer is to maximize either one in a particular design. The thermal efficiency of a power plant is around 35 percent; the thermal efficiency of an automobile engine is around 20 percent. The coefficient of performance for a refrigerator or a heat pump ranges from 2 to 6, with a heat pump having the greater values.

EXAMPLE 4.18

Steam leaves the boiler of a simple steam power cycle at 4000 kPa and 600 °C. It exits the turbine at 20 kPa as saturated steam. It then exits the condenser as saturated water. (See Fig. 4-20.) Determine the thermal efficiency if there is no loss in pressure through the condenser and the boiler.

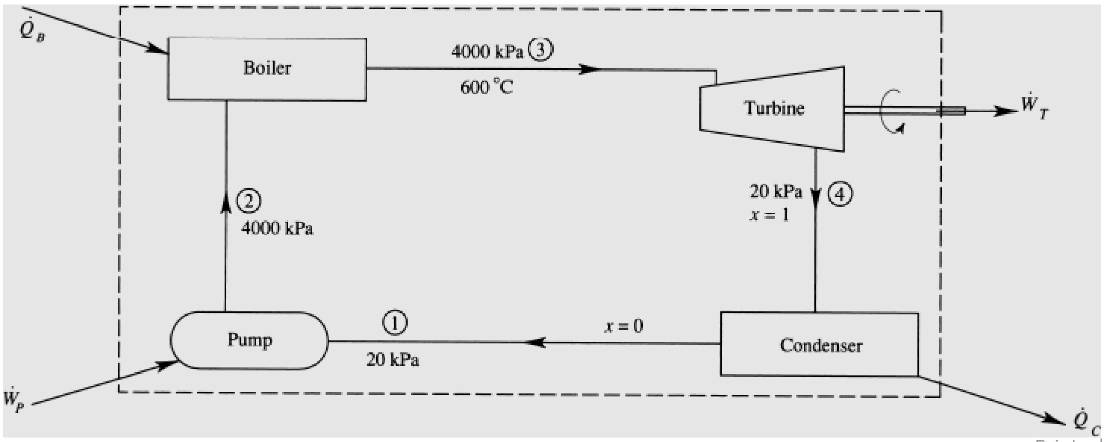

Figure 4-20.

Solution: To determine the thermal efficiency we must calculate the heat transferred to the water in the boiler, the work done by the turbine, and the work required by the pump. We will make the calculations for 1 kg of steam since the mass is unknown. The boiler heat transfer is, neglecting kinetic and potential energy changes, $q_B = h_3 - h_2$. To find h_2 we assume that the pump simply increases the pressure [see (*4.71*)]:

$$w_p = (P_2 - P_1)v = (4000 - 20)(0.001) = 3.98\ \text{kJ/kg}$$

The enthalpy h_2 is thus found to be, using (*4.70*),

$$h_2 = w_p + h_1 = 3.98 + 251.4 = 255.4\,\text{kJ/kg}$$

where h_1 is assumed to be that of saturated water at 20 kPa. From the steam tables we find $h_3 = 3674$ kJ/kg. There results

$$q_B = 3674 - 255.4 = 3420\,\text{kJ/kg}$$

The work output from the turbine is $w_T = h_3 - h_4 = 3674 - 2610 = 1064$ kJ/kg. Finally, the thermal efficiency is

$$\eta = \frac{w_T - w_P}{q_B} = \frac{1064 - 4}{3420} = 0.310 \quad \text{or } 31.0\%$$

Note that the pump work could have been neglected with no significant change in the results.

4.9.6. Transient Flow

If the steady-flow assumption of the preceding sections is not valid, then the time dependence of the various properties must be included. The filling of a rigid tank with a gas and the release of gas from a pressurized tank are examples that we will consider.

The energy equation is written as

$$\dot{Q} - \dot{W}_S = \frac{dE_{\text{c.v.}}}{dt} + \dot{m}_2\left(\frac{V_2^2}{2} + gz_2 + h_2\right) - \dot{m}_1\left(\frac{V_1^2}{2} + gz_1 + h_1\right)$$

(*4.79*)

We will consider the kinetic energy and potential energy terms to be negligible so that $E_{c.v.}$ will consist of internal energy only. The first problem we wish to study is the filling of a rigid tank, as sketched in Fig. 4-21. In the tank, there is only an entrance. With no shaft work present the energy equation reduces to

$$\dot{Q} = \frac{d}{dt}(um) - \dot{m}_1 h_1$$

(*4.80*)

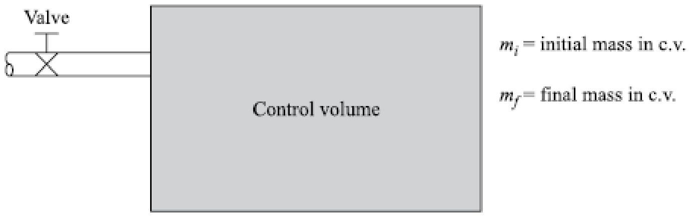

Figure 4-21. The filling of a rigid tank.

where m is the mass in the control volume. If we multiply this equation by dt and integrate from an initial time t_i, to some final time t_f, we have

$$Q = u_f m_f - u_i m_i - m_1 h_1$$

(*4.81*)

where

$$m_1 = \text{mass that enters}$$
$$m_f = \text{final mass in control volume}$$
$$m_i = \text{initial mass in control volume}$$

In addition, for the filling process the enthalpy h_1 is assumed constant over the time interval.

The continuity equation for the unsteady-flow situation may be necessary in the solution process. Since the final mass is equal to the initial mass plus the mass that entered, this is expressed as

$$m_f = m_i + m_1$$

(*4.82*)

Now consider the discharge of a pressurized tank. This problem is more complicated than the filling of a tank in that the properties at the exiting area are not constant over the time interval of interest; we must include the variation of the variables with time. We will assume an insulated tank, so that no heat transfer occurs, and again neglect kinetic energy and potential energy. The energy equation becomes, assuming no shaft work,

$$0 = \frac{d}{dt}(um) + \dot{m}_2(P_2 v_2 + u_2)$$

(*4.83*)

where m is the mass in the control volume. From the continuity equation,

$$\frac{dm}{dt} = -\dot{m}_2$$

(*4.84*)

If this is substituted into (*4.83*), we have

$$d(um) = (P_2 v_2 + u_2) dm$$

(*4.85*)

We will assume that the gas escapes through a small valve opening, as shown in Fig. 4-22. Just upstream of the valve is area A_2 with properties P_2, v_2, and u_2. The velocity at this exiting area is assumed to be quite small so that P_2, v_2, and u_2 are approximately the same as the respective quantities in the control volume. With this assumption (*4.85*) becomes

$$d(um) = (Pv + u)\,dm$$

(*4.86*)

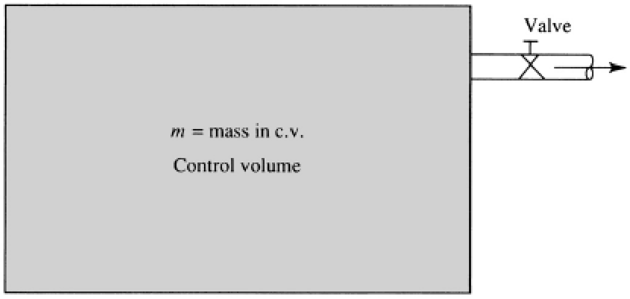

Figure 4-22. The discharge of a pressurized tank.

Letting $d(um) = udm + mdu$, there results

$$m\,du = Pv\,dm$$

(*4.87*)

Now we will restrict ourselves to a gas that behaves as an ideal gas. For such a gas $du = C_v\,dT$ and $Pv = RT$, and we obtain

$$mC_v\,dT = RT\,dm$$

(*4.88*)

This is put in the form

$$\frac{C_v}{R}\frac{dT}{T} = \frac{dm}{m}$$

(*4.89*)

which can be integrated from the initial state, signified by the subscript i, to the final state, signified by the subscript f. There results

$$\frac{C_v}{R}\ln\frac{T_f}{T_i} = \ln\frac{m_f}{m_i} \qquad \text{or} \qquad \frac{m_f}{m_i} = \left(\frac{T_f}{T_i}\right)^{1/(k-1)}$$

(*4.90*)

where we have used $C_v/R = 1/(k-1)$; see (*4.31*). In terms of the pressure ratio, (*4.50*) allows us to write

$$\frac{m_f}{m_i} = \left(\frac{P_f}{P_i}\right)^{1/k}$$

(*4.91*)

Remember that these equations are applicable if there is no heat transfer from the volume; the process is quasistatic in that the properties are assumed uniformly distributed throughout the control volume (this requires a relatively slow discharge velocity, say 100 m/s or less); and the gas behaves as an ideal gas.

EXAMPLE 4.19

A completely evacuated, insulated, rigid tank with a volume of 300 ft^3 is filled from a steam line transporting steam at 800 °F and 500 psia. Determine (*a*) the temperature of steam in the tank when its pressure is 500 psia and (*b*) the mass of steam that flowed into the tank.

Solution:

a. The energy equation used is (*4.81*). With $Q = 0$ and $m_i = 0$, we have $u_f m_f = m_i h_1$. The continuity equation (*4.82*) allows us to write $m_f = m_1$, which states that the final mass m_f in the tank is equal to the mass m_1 that entered the tank. Thus, there results $u_f = h_1$. From Table C3-E, h_1 is found, at 800 °F and 500 psia, to be 1412.1 Btu/lbm. Using $P_4 = 500$ psia as the final tank pressure, we can interpolate for the temperature, using $u_f =$ 1412.1 Btu/lbm, and find

$$T_f = \left(\frac{1412.1 - 1406.0}{1449.2 - 1406.0}\right)(100) + 1100 = 1114.1\,°\mathrm{F}$$

b. We recognize that $m_1 = m_f = V_{\mathrm{tank}}/v_f$. The specific volume of the steam in the tank at 500 psia and

$$v_f = \left(\frac{1114.1 - 1100}{100}\right)(1.9518 - 1.8271) + 1.8271 = 1.845\ \mathrm{ft}^3/\mathrm{lbm}$$

This gives $m_f = 300/1.845 = 162.6$ lbm.

EXAMPLE 4.20

An air tank with a volume of 20 m^3 is pressurized to 10 MPa. The tank eventually reaches room temperature of 25 °C. If the air is allowed to escape with no heat transfer until $P_f = 200$ kPa, determine the mass of air remaining in the tank and the final temperature of air in the tank.

Solution: The initial mass of air in the tank is found to be

$$m_i = \frac{P_i V}{RT_i} = \frac{10 \times 10^6 (20)}{(287)(298)} = 2338\ \mathrm{kg}$$

Equation (*4.91*) gives, using $k = 1.4$,

$$m_f = m_i \left(\frac{P_f}{P_i}\right)^{1/k} = (2338)\left(\frac{2 \times 10^5}{10 \times 10^6}\right)^{1/1.4} = 143.0\ \mathrm{kg}$$

To find the final temperature (*4.90*) is used:

$$T_f = T_i \left(\frac{m_f}{m_i}\right)^{k-1} = (298)(143/2338)^{0.4} = 97.46\ \mathrm{K} \quad \text{or} -175.5\,°\mathrm{C}$$

A person who accidently comes in contact with a flow of gas from a pressurized tank faces immediate freezing (which is treated just like a burn).

4.9.7. Solved Problems

4.1 A 1500-kg automobile traveling at 30 m/s is brought to rest by impacting a shock absorber composed of a piston with small holes that moves in a cylinder containing water. How much heat must be removed from the water to return it to its original temperature?

As the piston moves through the water, work is done due to the force of impact moving with the piston. The work that is done is equal to the kinetic energy change; that is,

$$W = \frac{1}{2} m V^2 = \left(\frac{1}{2}\right)(1500)(30)^2 = 675\,000\ \mathrm{J}$$

The first law for a cycle requires that this amount of heat must be transferred from the water to return it to its original temperature; hence, $Q = 675$ kJ.

4.2 A piston moves upward a distance of 5 cm while 200 J of heat is added (Fig. 4-23). Calculate the change in internal energy of the vapor if the spring is originally unstretched.

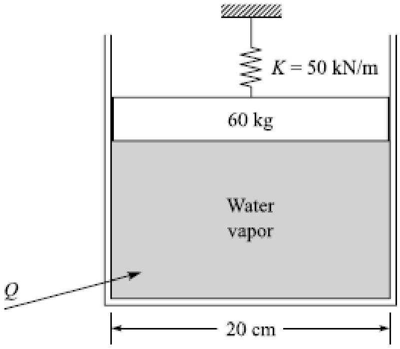

Figure 4-23.

The work needed to raise the weight and compress the spring is

$$W = (mg)(h) + \frac{1}{2}Kx^2 + (P_{atm})(A)(h)$$

$$= (60)(9.81)(0.05) + \left(\frac{1}{2}\right)(50\,000)(0.05)^2 + (100\,000)\left[\frac{\pi(0.2)^2}{4}\right](0.05) = 250 \text{ J}$$

The first law for a process without kinetic or potential energy changes is

$$Q - W = \Delta U$$

Thus, we have $\Delta U = 200 - 250 = -50$ J.

4.3 A system undergoes a cycle consisting of the three processes listed in the table. Compute the missing values. All quantities are in kJ.

Process	Q	W	ΔE
$1 \to 2$	a	100	100
$2 \to 3$	b	-50	c
$3 \to 1$	100	d	-200

Use the first law in the form $Q - W = \Delta E$: Applied to process $1 \to 2$, we have

$$a - 100 = 100 \qquad \therefore a = 200 \text{ kJ}$$

Applied to process $3 \to 1$, there results

$$100 - d = -200 \qquad \therefore d = 300 \text{ kJ}$$

The net work is then $\Sigma W = W_{1\text{-}2} + W_{2\text{-}3} + W_{3\text{-}1} = 100 - 50 + 300 = 350$ kJ. The first law for a cycle demands that

$$\Sigma Q = \Sigma W \qquad 200 + b + 100 = 350 \qquad \therefore b = 50 \text{ kJ}$$

Finally, applying the first law to process $2 \to 3$ provides

$$50 - (-50) = c \qquad \therefore c = 100 \text{ kJ}$$

Note that, for a cycle, $\Sigma\Delta E = 0$; this, in fact, could have been used to determine the value of c:

$$\Sigma\Delta E = 100 + c - 200 = 0 \qquad \therefore c = 100 \text{ kJ}$$

4.4 A 6-V insulated battery delivers a 5-A current over a period of 20 min. Calculate the heat transfer that must occur to return the battery to its initial temperature.

The work done by the battery is $W_{1\text{-}2} = VI\,\Delta t = (6)(5)[(20)(60)] = 36$ kJ. According to the first law, this must equal $-(U_2 - U_1)$ since $Q_{1\text{-}2} = 0$ (the battery is insulated). To return the battery to its initial state, the first law, for this second process in which no work is done, gives

$$Q_{2-1} - \cancel{W}^{0}_{2-1} = \Delta U = U_1 - U_2$$

Consequently, $Q_{2-1} = +36$ kJ, where the positive sign indicates that heat must be transferred to the battery.

4.5 A refrigerator is situated in an insulated room; it has a 2-hp motor that drives a compressor. Over a 30-minute period of time it provides 5300 kJ of cooling to the refrigerated space and 8000 kJ of heating from the coils on the back of the refrigerator. Calculate the increase in internal energy in the room.

In this problem we consider the insulated room as the system. The refrigerator is nothing more than a component in the system. The only transfer of energy across the boundary of the system is via the electrical wires of the refrigerator. For an insulated room ($Q = 0$) the first law provides

$$\cancel{Q}^0 - W = \Delta U$$

Hence, $\Delta U = -(-2 \text{ hp})(0.746 \text{ kW/hp})(1800 \text{ s}) = 2686$ kJ.

4.6 A2- ft^3 rigid volume contains water at 120 °F with a quality of 0.5. Calculate the final temperature if 8 Btu of heat is added.

The first law for a process demands that $Q - W = m\,\Delta u$. To find the mass, we must use the specific volume as follows:

$$v_1 = v_f + x(v_g - v_f) = 0.016 + (0.5)(203.0 - 0.016) = 101.5\,\text{ft}^3/\text{lbm}$$

$$\therefore m = \frac{V}{v} = \frac{2}{101.5} = 0.0197\ \text{lbm}$$

For a rigid volume the work is zero since the volume does not change. Hence, $Q = m\,\Delta u$. The value of the initial internal energy is

$$u_1 = u_f + xu_{fg} = 87.99 + (0.5)(961.9) = 568.9\ \text{Btu/lbm}$$

The final internal energy is then calculated from the first law:

$$8 = 0.0197(u_2 - 568.9) \qquad \therefore u_2 = 975\ \text{Btu/lbm}$$

This is less than u_g; consequently, state 2 is in the wet region with $v_2 = 101.5$ ft³/lbm. This requires a trial-and-error procedure to find state 2:

At $T = 140$ °F:

$$101.5 = 0.016 + x_2(122.9 - 0.016) \qquad \therefore x_2 = 0.826$$
$$975 = 108 + 948.2x_2 \qquad \therefore x_2 = 0.914$$

At $T = 150$ °F:

$$v_g = 96.99 \qquad \therefore \text{slightly superheat}$$
$$975 = 118 + 941.3x_2 \qquad \therefore x_2 = 0.912$$

Obviously, state 2 lies between 140 °F and 150 °F. Since the quality is insensitive to the internal energy, we find T_2 such that $v_g = 101.5$ ft³/lbm:

$$T_2 = 150 - \left(\frac{101.5 - 96.99}{122.88 - 96.99}\right)(10) = 148\,°\text{F}$$

A temperature slightly less than this provides us with $T_2 = 147$ °F.

4.7 A frictionless piston provides a constant pressure of 400 kPa in a cylinder containing R134a with an initial quality of 80 percent. Calculate the final temperature if 80 kJ/kg of heat is transferred to the cylinder.

The original enthalpy is found, using values from Table D-2, to be

$$h_1 = h_f + x_1 h_{fg} = 62.0 + (0.8)(190.32) = 214.3\ \text{kJ/kg}$$

For this constant-pressure process, the first law demands that

$$q = h_2 - h_1 \qquad 80 = h_2 - 214.3 \qquad \therefore h_2 = 294.3\ \text{kJ/kg}$$

Using $P_2 = 400$ kPa and $h_2 = 294.3$ kJ/kg, we interpolate in Table D-3 to find

$$T_2 = \left(\frac{294.3 - 291.8}{301.5 - 291.8}\right)(10) + 50 = 52.6\,°\text{C}$$

4.8 A piston-cylinder arrangement contains 2 kg of steam originally at 200 °C and 90 percent quality. The volume triples while the temperature is held constant. Calculate the heat that must be transferred and the final pressure.

The first law for this constant-temperature process is $Q - W = m(u_2 - u_1)$. The initial specific volume and specific internal energy are, respectively,

$$v_1 = 0.0012 + (0.9)(0.1274 - 0.0012) = 0.1148 \text{ m}^3/\text{kg}$$
$$u_1 = 850.6 + (0.9)(2595.3 - 850.6) = 2421 \text{ kJ/kg}$$

Using $T_2 = 200$ °C and $v_2 = (3)(0.1148) = 0.3444$ m^3/kg, we interpolate in Table C-3 and find the final pressure P_2 to be

$$P_2 = 0.8 - \left(\frac{0.3444 - 0.2608}{0.3520 - 0.2608}\right)(0.2) = 0.617 \text{ MPa}$$

We can also interpolate to find that the specific internal energy is

$$u_2 = 2638.9 - (2638.9 - 2630.6)\left(\frac{0.617 - 0.6}{0.8 - 0.6}\right) = 2638.2 \text{ kJ/kg}$$

To find the heat transfer we must know the work W. It is estimated using graph paper by plotting P vs. v and graphically integrating (counting squares). The work is twice this area since $m = 2$ kg. Doing this, we find

$$W = (2)(228) = 456 \text{ kJ}$$

Thus $Q = W + m(u_2 - u_1) = 456 + (2)(2638.2 - 2421) = 890$ kJ.

4.9 Estimate the constant-pressure specific heat and the constant-volume specific heat for R134a at 30 psia and 100 °F.

We write the derivatives in finite-difference form and, using values on either side of 100 °F for greatest accuracy, we find

$$C_p \cong \frac{\Delta h}{\Delta T} = \frac{126.39 - 117.63}{120 - 80} = 0.219 \text{ Btu/lbm-°F}$$

$$C_v \cong \frac{\Delta u}{\Delta T} = \frac{115.47 - 107.59}{120 - 80} = 0.197 \text{ Btu/lbm-°F}$$

4.10 Calculate the change in enthalpy of air which is heated from 300 K to 700 K if

(*a*) $C_p = 1.006$ kJ/kg·°C.

(*b*) $C_p = 0.946 + 0.213 \times 10^{-3}T - 0.031 \times 10^{-6}T^2$ kJ/kg·°C.

(*c*) The gas tables are used.

(*d*) Compare the calculations of (*a*) and (*b*) with (*c*).

a. Assuming the constant specific heat, we find that

$$\Delta h = C_p(T_2 - T_1) = (1.006)(700 - 300) = 402.4 \text{ kJ/kg}$$

b. If C_p depends on temperature, we must integrate as follows:

$$\Delta h = \int_{T_1}^{T_2} C_p\, dT = \int_{300}^{700} (0.946 + 0.213 \times 10^{-3}T - 0.031 \times 10^{-6}T^2)\, dT = 417.7 \text{ kJ/kg}$$

c. Using Table E-1, we find $\Delta h = h_2 - h_1 = 713.27 - 300.19 = 413.1$kJ/kg.

d. The assumption of constant specific heat results in an error of –2.59 percent; the expression for C_p produces an error of +1.11 percent. All three methods are acceptable for the present problem.

4.11 Sixteen ice cubes, each with a temperature of –10 °C and a volume of 8 milliliters, are added to 1 liter of water at 20 °C in an insulated container. What is the equilibrium temperature? Use $(C_p)_{\text{ice}} = 2.1$kJ/kg·°C.

Assume that all of the ice melts. The ice warms up to 0 °C, melts at 0 °C, and then warms up to the final temperature T_2. The water cools from 20 °C to the final temperature T_2. The mass of ice is calculated to be

$$m_i = \frac{V}{v_i} = \frac{(16)(8 \times 10^{-6})}{0.00109} = 0.1174 \text{ kg}$$

where v_i is found in Table C-5. If energy is conserved, we must have

Energy gained by ice = energy lost by water

$$m_i[(C_p)_i\Delta T + h_if + (C_p)_w\Delta T] = m_w(C_p)_w\Delta T$$
$$0.1174[(2.1)(10) + 320 + (4.81)(T_2 - 0)] = (1000 \times 10^{-3})(4.18)(20 - T_2)$$
$$T_2 = 9.33\text{°C}$$

4.12 A 5-kg block of copper at 300 °C is submerged in 20 liters of water at 0 °C contained in an insulated tank. Estimate the final equilibrium temperature.

Conservation of energy requires that the energy lost by the copper block is gained by the water. This is expressed as

$$m_c(C_p)_c(\Delta T)_c = m_w(C_p)_w(\Delta T)_w$$

Using average values of C_p from Table B-4, this becomes

$$(5)(0.39)(300 - T_2) = (0.02)(1000)(4.18)(T_2 - 0) \qquad \therefore T_2 = 6.84\,^\circ\text{C}$$

4.13 Two pounds of air is compressed from 20 psia to 200 psia while maintaining the temperature constant at 100 °F. Calculate the heat transfer needed to accomplish this process.

The first law, assuming air to be an ideal gas, requires that

$$Q = W + \cancel{\Delta U}^0 = mRT\ln\frac{P_1}{P_2} = (2\ \text{lbm})\left(53.3\frac{\text{ft-lbf}}{\text{lbm-}^\circ\text{R}}\right)(560\,^\circ\text{R})\left(\frac{1}{778}\frac{\text{Btu}}{\text{ft-lbf}}\right)\ln\frac{20}{200}$$

$$= -176.7\ \text{Btu}$$

4.14 Helium is contained in a 2-m^3 rigid volume at 50 °C and 200 kPa. Calculate the heat transfer needed to increase the pressure to 800 kPa.

The work is zero for this constant-volume process. Consequently, the first law gives

$$Q = m\Delta u = mC_v\,\Delta T = \frac{PV}{RT}C_v(T_2 - T_1)$$

The ideal-gas law, $PV = mRT$, allows us to write

$$\frac{P_1}{T_1} = \frac{P_2}{T_2} \qquad \frac{200}{323} = \frac{800}{T_2} \qquad \therefore T_2 = 1292\ \text{K}$$

The heat transfer is then, using values from Table B-2,

$$Q = \frac{(200)(2)}{(2.077)(323)}(3.116)(1292 - 323) = 1800\ \text{kJ}$$

4.15 The air in the cylinder of an air compressor is compressed from 100 kPa to 10 MPa. Estimate the final temperature and the work required if the air is initially at 100 °C.

Since the process occurs quite fast, we assume an adiabatic quasiequilibrium process. Then

$$T_2 = T_1\left(\frac{P_2}{P_1}\right)^{(k-1)/k} = (373)\left(\frac{10\,000}{100}\right)^{(1.4-1)/1.4} = 1390\ \text{K}$$

The work is found by using the first law with $Q = 0$:

$$w = -\Delta u = -C_v(T_2 - T_1) = -(0.717)(1390 - 373) = -729\ \text{kJ/kg}$$

The work per unit mass is calculated since the mass (or volume) was not specified.

4.16 Nitrogen at 100 °C and 600 kPa expands in such a way that it can be approximated by a polytropic process with $n = 1.2$ [see (*4.52*)]. Calculate the work and the heat transfer if the final pressure is 100 kPa.

The final temperature is found to be

$$T_2 = T_1\left(\frac{P_2}{P_1}\right)^{(n-1)/n} = (373)\left(\frac{100}{600}\right)^{(1.2-1)/1.2} = 276.7\ \text{K}$$

The specific volumes are

$$v_1 = \frac{RT_1}{P_1} = \frac{(0.297)(373)}{600} = 0.1846\ \text{m}^3/\text{kg} \qquad v_2 = \frac{RT_2}{P_2} = \frac{(0.297)(276.7)}{100} = 0.822\ \text{m}^3/\text{kg}$$

The work is then [or use (*4.53*)]

$$w = \int P dv = P_1 v_1^n \int v^{-n} dv = (600)(0.1846)^{1.2}\left(\frac{1}{-0.2}\right)(0.822^{-0.2} - 0.1846^{-0.2}) = 143\ \text{kJ/kg}$$

The first law provides us with the heat transfer:

$$q - w = \Delta u = C_v(T_2 - T_1) \qquad q - 143 = (0.745)(276.7 - 373) \qquad \therefore q = 71.3\text{kJ/kg}$$

4.17 How much work must be input by the paddle wheel in Fig. 4-24 to raise the piston 5 in? The initial temperature is 100 °F.

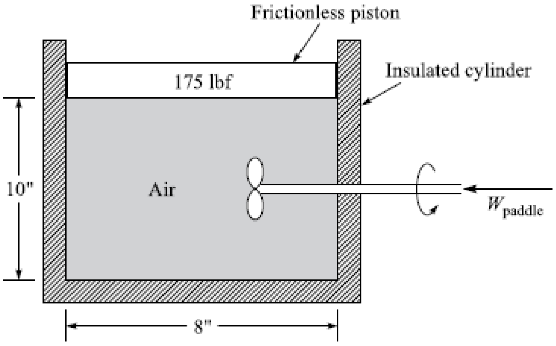

Figure 4-24.

The first law, with $Q = 0$, is

$$W = \Delta U \qquad \text{or} \qquad -P A \Delta h - W_{\text{paddle}} = m C_v (T_2 - T_1)$$

The pressure is found from a force balance on the piston:

$$P = 14.7 + \frac{175}{\pi (4)^2} = 18.18 \text{ psia}$$

The mass of the air is found from the ideal-gas law:

$$m = \frac{PV}{RT} = \frac{(18.18)(144)(\pi)(4)^2(10)/1728}{(53.3)(560)} = 0.0255 \text{ lbm}$$

The temperature T_2 is

$$T_2 = \frac{PV_2}{mR} = \frac{(18.18)(144)(\pi)(4)^2(15)/1728}{(0.0255)(53.3)} = 840\,^\circ\text{R}$$

Finally, the paddle-wheel work is found to be

$$W_{\text{paddle}} = -PA\Delta h - mC_v(T_2 - T_1) = -(18.18)(\pi)(4)^2(5/12) - (0.0255)(0.171)(778)(840 - 560)$$
$$= -1331 \text{ ft-lbf}$$

4.18 For the cycle in Fig. 4-25 find the work output and the net heat transfer if the 0.1 kg of air is contained in a piston-cylinder arrangement.

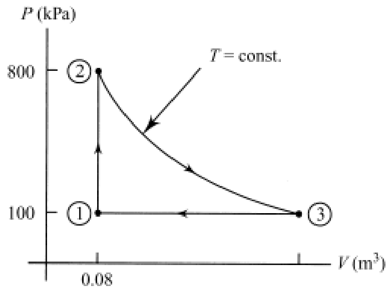

Figure 4-25.

The temperatures and V_3 are

$$T_1 = \frac{P_1 V_1}{mR} = \frac{(100)(0.08)}{(0.1)(0.287)} = 278.7 \text{ K} \qquad T_2 = T_3 = \frac{(800)(0.08)}{(0.1)(0.287)} = 2230 \text{ K}$$

$$V_3 = \frac{P_2 V_2}{P_3} = \frac{(800)(0.08)}{100} = 0.64 \text{ m}^3$$

Using the definition of work for each process, we find

$$W_{1-2} = 0 \qquad W_{2-3} = mRT \ln \frac{p_2}{p_3} = (0.1)(0.287)(2230) \ln \frac{800}{100} = 133.1 \text{ kJ}$$

$$W_{3-1} = P(V_1 - V_3) = (100)(0.08 - 0.64) = -56 \text{ kJ}$$

The work output is then $W_{\text{net}} = 0 + 133.1 - 56.0 = 77.1$ kJ. Since this is a complete cycle, the first law for a cycle provides us with

$$Q_{\text{net}} = W_{\text{net}} = 77.1 \text{ kJ}$$

4.19 Water enters a radiator through a 4-cm-diameter hose at 0.02 kg/s. It travels down through all the rectangular passageways on its way to the water pump. The passageways are each 10 × 1 mm and there are 800 of them in a cross section. How long does it take water to traverse from the top to the bottom of the 60-cm-high radiator?

The average velocity through the passageways is found from the continuity equation, using $\rho_{water} = 1000$ kg/m^3:

$$\dot{m} = \rho_1 V_1 A_1 = \rho_2 V_2 A_2 \qquad \therefore V_2 = \frac{\dot{m}}{\rho_2 A_2} = \frac{0.02}{(1000)[(800)(0.01)(0.001)]} = 0.0025 \text{ m/s}$$

The time to travel 60 cm at this constant velocity is

$$t = \frac{L}{V} = \frac{0.60}{0.0025} = 240 \text{ s or } 4 \text{ min}$$

4.20 A 10-m^3 tank is being filled with steam at 800 kPa and 400 °C. It enters the tank through a 10-cm-diameter pipe. Determine the rate at which the density in the tank is varying when the velocity of the steam in the pipe is 20 m/s.

The continuity equation with one inlet and no outlets is [see (4.56)]:

$$\rho_1 A_1 V_1 = \frac{dm_{c.v.}}{dt}$$

Since $m_{c.v.} = \rho V$, where V is the volume of the tank, this becomes

$$V\frac{d\rho}{dt} = \frac{1}{v_1} A_1 V_1 \qquad 10\frac{d\rho}{dt} = \left(\frac{1}{0.3843}\right)(\pi)(0.05)^2(20) \qquad \frac{d\rho}{dt} = 0.04087 \text{ kg/m}^3\cdot\text{s}$$

4.21 Water enters a 4-ft-wide, 1/2-in-high channel with a mass flux of 15 lbm/sec. It leaves with a parabolic distribution $V(y) = V_{max}(1 - y^2/h^2)$, where h is half the channel height. Calculate V_{max} and V_{avg}, the average velocity over any cross section of the channel. Assume that the water completely fills the channel.

The mass flux is given by $\dot{m} = \rho A V_{avg}$; hence,

$$V_{avg} = \frac{\dot{m}}{\rho A} = \frac{15}{(62.4)[(4)(1/24)]} = 1.442 \text{ ft/sec}$$

At the exit the velocity profile is parabolic. The mass flux, a constant, then provides us with

$$\dot{m} = \int_A \rho V dA$$

$$15 = \rho \int_{-h}^{h} V_{max}\left(1 - \frac{y^2}{h^2}\right) 4dy = (62.4)(4V_{max})\left[y - \frac{y^3}{3h^2}\right]_{-h}^{h} = (62.4)(4V_{max})\left[\frac{(4)(1/48)}{3}\right]$$

$$\therefore V_{max} = 2.163 \text{ft/sec}$$

4.22 R134a enters a valve at 800 kPa and 30 °C. The pressure downstream of the valve is measured to be 60 kPa. Calculate the internal energy downstream.

The energy equation across the valve, recognizing that heat transfer and work are zero, is $h_1 = h_2$. The enthalpy before the valve is that of compressed liquid. The enthalpy of a compressed liquid is essentially equal to that of a saturated liquid at the same temperature. Hence, at 30 °C in Table D-1, $h_1 = 91.49$ kJ/kg. Using Table D-2 at 60 kPa we find

$$h_2 = 91.49 = h_f + x_2 h_{fg} = 3.46 + 221.27 x_2 \qquad \therefore x_2 = 0.398$$

The internal energy is then

$$u_2 = u_f + x_2(u_g - u_f) = 3.14 + 0.398[(206.12 - 3.14)] = 83.9 \text{ kJ/kg}$$

4.23 The pressure of 200 kg/s of water is to be increased by 4 MPa. The water enters through a 20-cm-diameter pipe and exits through a 12-cm-diameter pipe. Calculate the minimum horsepower required to operate the pump.

The energy equation (4.68) provides us with

$$-\dot{W}_p = \dot{m}\left(\frac{\Delta P}{\rho} + \frac{V_2^2 - V_1^2}{2}\right)$$

The inlet and exit velocities are calculated as follows:

$$V_1 = \frac{\dot{m}}{\rho A_1} = \frac{200}{(1000)(\pi)(0.1)^2} = 6.366\ \mathrm{m/s} \qquad V_2 = \frac{\dot{m}}{\rho A_2} = \frac{200}{(1000)(\pi)(0.06)^2} = 17.68\ \mathrm{m/s}$$

The energy equation then gives

$$\dot{W}_P = -200\left[\frac{4\,000\,000}{1000} + \frac{(17.68)^2 - (6.366)^2}{2}\right] = -827\,200\ \mathrm{W} \quad \text{or } 1109\ \mathrm{hp}$$

Note: The above power calculation provides a minimum since we have neglected any internal energy increase. Also, the kinetic energy change represents only a 3 percent effect on $\dot{W}_P$ and could be neglected.

4.24 A hydroturbine operates on a stream in which 100 kg/s of water flows. Estimate the maximum power output if the turbine is in a dam with a distance of 40 m from the surface of the reservoir to the surface of the backwater.

The energy equation (4.68), neglecting kinetic energy changes, takes the form $-\dot{W}_T = \dot{m}g(z_2 - z_1)$, where we have assumed the pressure to be atmospheric on the water's surface above and below the dam. The maximum power output is then

$$\dot{W}_T = -(100)(9.81)(-40) = 39\,240\ \mathrm{W} \quad \text{or } 39.24\ \mathrm{kW}$$

4.25 A turbine accepts superheated steam at 800 psia and 1200 °F and rejects it as saturated vapor at 2 psia (Fig. 4-26). Predict the horsepower output if the mass flux is 1000 lbm/min. Also, calculate the velocity at the exit.

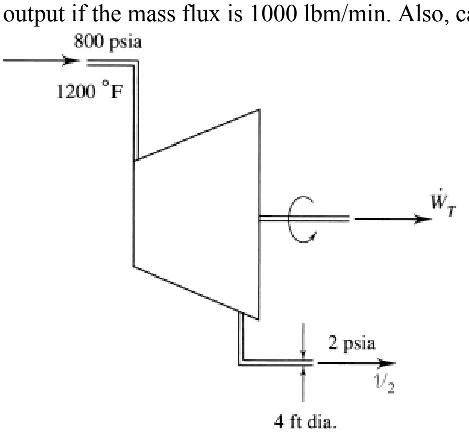

Figure 4-26.

Assuming zero heat transfer, the energy equation (4.66) provides us with

$$-\dot{W}_T = \dot{m}(h_2 - h_1) = \left(\frac{1000}{60}\right)(1116.1 - 1623.8) = -8462\ \mathrm{Btu/sec} \quad \text{or } 11\,970\ \mathrm{hp}$$

where Tables C-3E and C-2E have provided the enthalpies. By (4.58),

$$V_2 = \frac{v\dot{m}}{A} = \frac{(173.75)(1000/60)}{\pi(2)^2} = 230\ \mathrm{ft/sec}$$

4.26 Air enters a compressor at atmospheric conditions of 20 °C and 80 kPa and exits at 800 kPa and 200 °C. Calculate the rate of heat transfer if the power input is 400 kW. The air exits at 20 m/s through an exit diameter of 10 cm.

The energy equation, neglecting kinetic and potential energy changes, is $\dot{Q} - \dot{W}_S = \dot{m}C_p(T_2 - T_1)$; the mass flux is calculated to be

$$\dot{m} = \rho A V = \frac{P}{RT}AV = \frac{800}{(0.287)(473)}(\pi)(0.05)^2(20) = 0.9257\ \mathrm{kg/s}$$

Hence $\dot{Q} = (0.9257)(1.00)(200 - 20) + (-400) = -233.4\ \mathrm{kW}$. Note that the power input is negative, and a negative heat transfer implies that the compressor is losing heat.

4.27 Air travels through the 4 × 2 m test section of a wind tunnel at 20 m/s. The gage pressure in the test section is measured to be –20 kPa and the temperature 20 °C. After the test section, a diffuser leads to a 6-m-diameter exit pipe. Estimate the velocity and temperature in the exit pipe.

The energy equation (4.72) for air takes the form

$$V_2^2 = V_1^2 + 2C_p(T_1 - T_2) = 20^2 + (2)(1.00)(293 - T_2)$$

The continuity equation, $\rho_1 A_1 V_1 = \rho_2 A_2 V_2$, yields

$$\frac{P_1}{RT_1} A_1 V_1 = \rho_2 A_2 V_2 \qquad \therefore \rho_2 V_2 = \left[\frac{80}{(0.287)(293)}\right]\left[\frac{8}{\pi(3)^2}\right](20) = 5.384 \text{ kg/m}^2\cdot\text{s}$$

The best approximation to the actual process is the adiabatic quasiequilibrium process. Using (4.49), letting $\rho = 1/v$, we have

$$\frac{T_2}{T_1} = \left(\frac{\rho_2}{\rho_1}\right)^{k-1} \qquad \text{or} \qquad \frac{T_2}{\rho_2^{0.4}} = \frac{293}{[80/(0.287)(293)]^{0.4}} = 298.9$$

The above three equations include the three unknowns T_2, V_2, and ρ_2. Substitute for T_2 and V_2 back into the energy equation and find

$$\frac{5.384^2}{\rho_2^2} = 20^2 + (2)(1.00)[293 - (298.9)(\rho_2^{0.4})]$$

This can be solved by trial and error to yield $\rho_2 = 3.475$ kg/m^3. The velocity and temperature are then

$$V_2 = \frac{5.384}{\rho_2} = \frac{5.384}{3.475} = 1.55 \text{ m/s} \qquad T_2 = (298.9)(\rho_2^{0.4}) = (298.9)(3.475)^{0.4} = 492 \quad \text{or } 219\,°\text{C}$$

4.28 Steam with a mass flux of 600 lbm/min exits a turbine as saturated steam at 2 psia and passes through a condenser (a heat exchanger). What mass flux of cooling water is needed if the steam is to exit the condenser as saturated liquid and the cooling water is allowed a 15 °F temperature rise?

The energy equations (4.75) are applicable to this situation. The heat transfer rate for the steam is, assuming no pressure drop through the condenser,

$$\dot{Q}_s = \dot{m}_s(h_{s2} - h_{s1}) = (600)(94.02 - 1116.1) = -613{,}200 \text{ Btu/min}$$

This energy is gained by the water. Hence,

$$\dot{Q}_w = \dot{m}_w(h_{w2} - h_{w1}) = \dot{m}_w C_p(T_{w2} - T_{w1}) \qquad 613{,}200 = \dot{m}_w(1.00)(15) \qquad \dot{m}_w = 40{,}880 \text{ lbm/min}$$

4.29 A simple steam power plant operates on 20 kg/s of steam, as shown in Fig. 4-27. Neglecting losses in the various components, calculate (*a*) the boiler heat transfer rate, (*b*) the turbine power output, (*c*) the condenser heat transfer rate, (*d*) the pump power requirement, (*e*) the velocity in the boiler exit pipe, and (*f*) the thermal efficiency of the cycle.

(*a*) $\dot{Q}_B = \dot{m}(h_3 - h_2) = (20)(3625.3 - 167.5) = 69.15$ MW, where we have taken the enthalpy h_2 to be h_f at 40 °C.

(*b*) $\dot{W}_T = \dot{m}(h_4 - h_3) = -(20)(2584.6 - 3625.3) = 20.81$ MW.

(*c*) $\dot{Q}_C = \dot{m}(h_1 - h_4) = (20)(167.57 - 2584.7) = -48.34$ MW.

(*d*) $\dot{W}_P = \dot{m}(P_2 - P_1)/\rho = (20)(10\,000 - 10/1000) = 0.2$ MW.

(*e*) $V = \dot{m}v/A = (20)(0.03837)/\pi(0.15)^2 = 10.9$ m/s.

(*f*) $\eta = (\dot{W}_T - \dot{W}_P)/\dot{Q}_B = (20.81 - 0.2)/69.15 = 0.298$ or 29.8%.

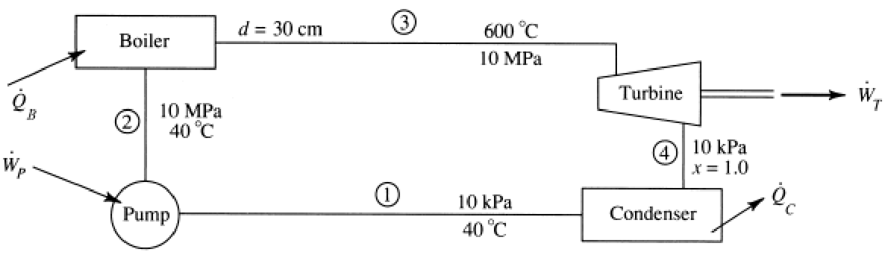

Figure 4-27.

4.30 An insulated 4-m^3 evacuated tank is connected to a 4-MPa 600 °C steam line. A valve is opened and the steam fills the tank. Estimate the final temperature of the steam in the tank and the final mass of the steam in the tank.

From (4.81), with $Q = 0$ and $m_i = 0$, there results $u_f = h_1$, since the final mass m_f is equal to the mass m_1 that enters. We know that across a valve the enthalpy is constant; hence,

$$h_1 = h_{\text{line}} = 3674.4 \text{ kJ/kg}$$

The final pressure in the tank is 4 MPa, achieved when the steam ceases to flow into the tank. Using $P_f = 4\text{MPa}$ and $u_f = 3674.4$ kJ/kg, we find the temperature in Table C-3 to be

$$T_f = \left(\frac{3674.4 - 3650.1}{3650.1 - 3555.5}\right)(500) + 800 = 812.8\ °\text{C}$$

The specific volume at 4 MPa and 812.8 °C is

$$v_f = \left(\frac{812.8 - 800}{50}\right)(0.1229 - 0.1169) + 0.1229 = 0.1244 \text{ ft}^3/\text{lbm}$$

The mass of steam in the tank is then

$$m_f = \frac{V_f}{v_f} = \frac{4}{0.1244} = 32.15 \text{ kg}$$

4.9.8. Supplementary Problems

4.31 An unknown mass is attached by a pulley to a paddle wheel which is inserted in a volume of water. The mass is then dropped a distance of 3 m. If 100 J of heat must be transferred from the water in order to return the water to its initial state, determine the mass in kilograms.

4.32 While 300 J of heat is added to the air in the cylinder of Fig. 4-28, the piston raises a distance of 0.2 m. Determine the change in internal energy.

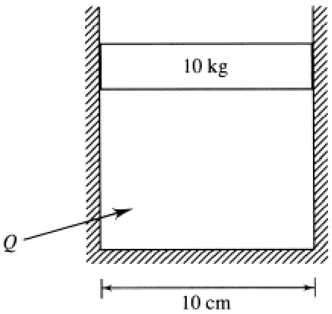

Figure 4-28.

4.33 A constant force of 600 lbf is required to move the piston shown in Fig. 4-29. If 2 Btu of heat is transferred from the cylinder when the piston moves the entire length, what is the change in internal energy?

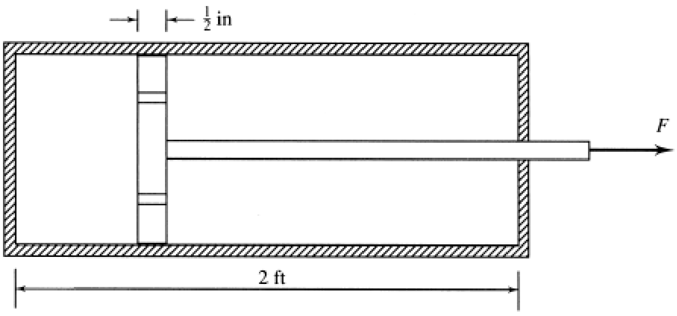

Figure 4-29.

4.34 Each of the letters (*a*) through (*e*) in the accompanying table represents a process. Supply the missing values, in kJ.

	Q	W	ΔE	E_2	E_1
(*a*)	20	5			7
(*b*)		– 3	6		8
(*c*)	40			30	15
(*d*)	– 10		20	10	
(*e*)		10		– 8	6

4.35 A system undergoes a cycle consisting of four processes. Some of the values of the energy transfers and energy changes are given in the table. Fill in all the missing values. All units are kJ.

Process	Q	W	ΔU
$1 \rightarrow 2$	-200	(a)	0
$2 \rightarrow 3$	800	(b)	(c)
$3 \rightarrow 4$	(d)	600	400
$4 \rightarrow 1$	0	(e)	-1200

4.36 A 12-V battery is charged by supplying 3 A over a period of 6 h. If a heat loss of 400 kJ occurs from the battery during the charging period, what is the change in energy stored within the battery?

4.37 A 12-V battery delivers a current of 10 A over a 30-min time period. The stored energy decreases by 300 kJ. Determine the heat lost during the time period.

4.38 A 110-V heater draws 15 A while heating a particular air space. During a 2-h period the internal energy in the space increases by 8000 Btu. Calculate the amount of heat lost in Btu.

4.39 How much heat must be added to a 0.3-m^3 rigid volume containing water at 200 °C in order that the final temperature be raised to 800 °C? The initial pressure is 1 MPa.

4.40 A 0.2-m^3 rigid volume contains steam at 600 kPa and a quality of 0.8. If 1000 kJ of heat is added, determine the final temperature.

4.41 A piston-cylinder arrangement provides a constant pressure of 120 psia on steam which has an initial quality of 0.95 and an initial volume of 100 in^3. Determine the heat transfer necessary to raise the temperature to 1000 °F. Work this problem without using enthalpy.

4.42 Steam is contained in a 4-liter volume at a pressure of 1.5 MPa and a temperature of 200 °C. If the pressure is held constant by expanding the volume while 40 kJ of heat is added, find the final temperature. Work this problem without using enthalpy.

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Schaum's Thermodynamics Supplementary Problem 4-42: Compression Expansion Work Using the Steam Tables

This video illustrates the use of the steam tables combined with finding compression/expansion (pdV) work in which an iterative approach is required.
Thom Adams, Ph.D., Professor, Mechanical Engineering, Rose-Hulman Institute of Technology
2013

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4.43 Work Prob. 4.41 using enthalpy.

4.44 Work Prob. 4.42 using enthalpy.

4.45 Calculate the heat transfer necessary to raise the temperature of 2 kg of steam, at a constant pressure of 100 kPa (*a*) from 50 °C to 400 °C and (*b*) from 400 °C to 750 °C.

4.46 Steam is contained in a 1.2-m^3 volume at a pressure of 3 MPa and a quality of 0.8. The pressure is held constant. What is the final temperature if (*a*) 3 MJ and (*b*) 30 MJ of heat is added? Sketch the process on a T-v diagram.

4.47 Estimate the constant-pressure specific heat for steam at 400 °C if the pressure is (*a*) 10 kPa, (*b*) 100 kPa, and (*c*) 30 000 kPa.

4.48 Determine approximate values for the constant-volume specific heat for steam at 800 °F if the pressure is (*a*) 1 psia, (*b*) 14.7 psia, and (*c*) 3000 psia.

4.49 Calculate the change in enthalpy of 2 kg of air which is heated from 400 K to 600 K if (*a*) $C_p = 1.006$ kJ/kg·K, (*b*) $C_p = 0.946 + 0.213 \times 10^{-3}T - 0.031 \times 10^{-6}T^2$ kJ/kg·K, and (*c*) the gas tables are used.

4.50 Compare the enthalpy change of 2 kg of water for a temperature change from 10 °C to 60 °C with that of 2 kg of ice for a temperature change from –60 °C to –10 °C.

4.51 Two MJ of heat is added to 2.3 kg of ice held at a constant pressure of 200 kPa, at (*a*) –60 °C and (*b*)0 °C. What is the final temperature? Sketch the process on a T-v diagram.

4.52 What is the heat transfer required to raise the temperature of 10 lbm of water from 0 °F (ice) to 600 °F (vapor) at a constant pressure of 30 psia? Sketch the process on a T-v diagram.

4.53 Five ice cubes (4 × 2 × 2 cm) at –20 °Care added to an insulated glass of cola at 20 °C. Estimate the final temperature (if above 0 °C) or the percentage of ice melted (if at 0 °C) if the cola volume is (*a*) 2 liters and (*b*) 0.25 liters. Use $\rho_{ice} = 917$ kg/m^3.

4.54 A 40-lbm block of copper at 200 °F is dropped in an insulated tank containing 3 ft^3 of water at 60 °F. Calculate the final equilibrium temperature.

4.55 A 50-kg block of copper at 0 °C and a 100-kg block of iron at 200 °C are brought into contact in an insulated space. Predict the final equilibrium temperature.

4.56 Determine the enthalpy change and the internal energy change for 4 kg of air if the temperature changes from 100 °C to 400 °C. Assume constant specific heats.

4.57 For each of the following quasiequilibrium processes supply the missing information. The working fluid is 0.4 kg of air in a cylinder.

	Process	Q (kJ)	W (kJ)	ΔU (kJ)	ΔH (kJ)	T_2 (°C)	T_1 (°C)	P_2 (kPa)	P_1 (kPa)	V_2 (m^3)	V_1 (m^3)
(*a*)	$T = C$	60				100		50			
(*b*)	$V = C$				80	300		200			
(*c*)	$P = C$	100					200		500		
(*d*)	$Q = 0$						250			0.1	0.48

4.58 For each of the quasiequilibrium processes presented in the table in Prob. 4.57, supply the missing information if the working fluid is 0.4 kg of steam. [Note: for process (*a*) it is necessary to integrate graphically.]

4.59 One thousand Btu of heat is added to 2 lbm of steam maintained at 60 psia. Calculate the final temperature if the initial temperature of the steam is (*a*) 600 °F and (*b*) 815 °F.

4.60 Fifty kJ of heat is transferred to air maintained at 400 kPa with an initial volume of 0.2 m^3. Determine the final temperature if the initial temperature is (*a*) 0 °C and (*b*) 200 °C.

4.61 The initial temperature and pressure of 8000 cm^3 of air are 100 °C and 800 kPa, respectively. Determine the necessary heat transfer if the volume does not change and the final pressure is (*a*) 200 kPa and (*b*) 3000 kPa.

4.62 Calculate the heat transfer necessary to raise the temperature of air, initially at 10 °C and 100 kPa, to a temperature of 27 °C if the air is contained in an initial volume with dimensions 3 × 5 × 2.4 m. The pressure is held constant.

4.63 Heat is added to a fixed 0.15-m^3 volume of steam initially at a pressure of 400 kPa and a quality of 0.5. Determine the final pressure and temperature if (*a*) 800 kJ and (*b*) 200 kJ of heat is added. Sketch the process on a *P*-v diagram.

4.64 Two hundred Btu of heat is added to a rigid air tank which has a volume of 3 ft^3. Find the final temperature if initially (*a*) $P = 60$ psia and $T = 30$ °F and (*b*) $P = 600$ psia and $T = 820$ °F. Use the air tables.

4.65 A system consisting of 5 kg of air is initially at 300 kPa and 20 °C. Determine the heat transfer necessary to (*a*) increase the volume by a factor of two at constant pressure, (*b*) increase the pressure by a factor of two at constant volume, (*c*) increase the pressure by a factor of two at constant temperature, and (*d*) increase the absolute temperature by a factor of 2 at constant pressure.

4.66 Heat is added to a container holding 0.5 m^3 of steam initially at a pressure of 400 kPa and a quality of 80 percent (Fig. 4-30). If the pressure is held constant, find the heat transfer necessary if the final temperature is (*a*) 500 °C and (*b*) 675 °C. Also determine the work done. Sketch the process on a *T*-v diagram.

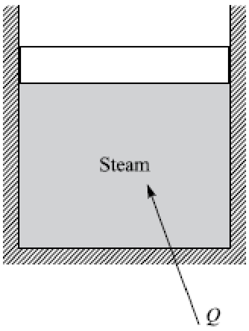

Figure 4-30.

4.67 A rigid 1.5-m^3 tank at a pressure of 200 kPa contains 5 liters of liquid and the remainder steam. Calculate the heat transfer necessary to (*a*) completely vaporize the water, (*b*) raise the temperature to 400 °C, and (*c*) raise the pressure to 800 kPa.

4.68 Ten Btu of heat is added to a rigid container holding 4 lbm of air in a volume of 100 ft^3. Determine ΔH.

4.69 Eight thousand cm^3 of air in a piston-cylinder arrangement is compressed isothermally at 30 °C from a pressure of 200 kPa to a pressure of 800 kPa. Find the heat transfer.

4.70 Two kilograms of air is compressed in an insulated cylinder from 400 kPa to 15 000 kPa. Determine the final temperature and the work necessary if the initial temperature is (*a*) 200 °C and (*b*) 350 °C.

4.71 Air is compressed in an insulated cylinder from the position shown in Fig. 4-31 so that the pressure increases to 5000 kPa from atmospheric pressure of 100 kPa. What is the required work if the mass of the air is 0.2 kg?

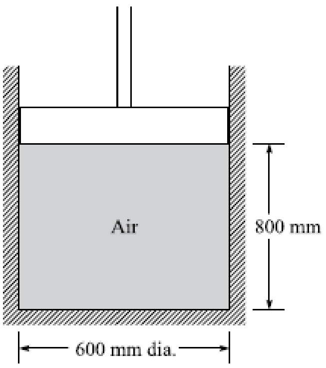

Figure 4-31.

4.72 The average person emits approximately 400 Btu of heat per hour. There are 1000 people in an unventilated room 10 × 75 × 150 ft. Approximate the increase in temperature after 15 min, assuming (*a*) constant pressure and (*b*) constant volume. (*c*) Which assumption is the more realistic?

4.73 Two hundred kJ of work is transferred to the air by means of a paddle wheel inserted into an insulated volume (Fig. 4-32). If the initial pressure and temperature are 200 kPa and 100 °C, respectively, determine the final temperature and pressure.

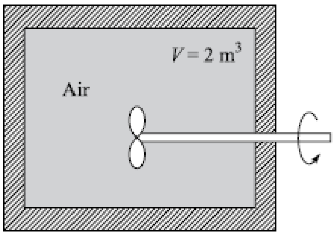

Figure 4-32.

4.74 A 2-kg rock falls from 10 m and lands in a 10-liter container of water. Neglecting friction during the fall, calculate the maximum temperature increase in the water.

4.75 A torque of 10 N·m is required to turn a paddle wheel at the rate of 100 rad/s. During a 45-s time period a volume of air, in which the paddle wheel rotates, is increased from 0.1 to 0.4 m^3. The pressure is maintained constant at 400 kPa. Determine the heat transfer necessary if the initial temperature is (*a*)0 °Cand (*b*)300 °C.

4.76 For the cycle shown in Fig. 4-33 find the work output and the net heat transfer, if 0.8 lbm of air is contained in a cylinder with T_1 = 800 °F, assuming the process from 3 to 1 is (*a*) an isothermal process and (*b*) an adiabatic process.

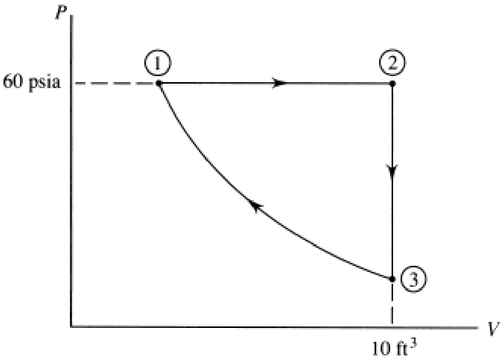

Figure 4-33.

4.77 For the cycle shown in Fig. 4-34 find the net heat transfer and work output if steam is contained in a cylinder.

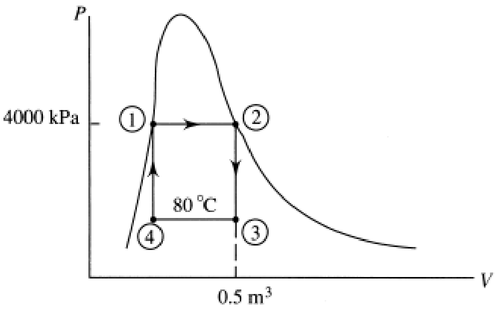

Figure 4-34.

4.78 If 0.03 kg of air undergoes the cycle shown in Fig. 4-35, a piston-cylinder arrangement, calculate the work output.

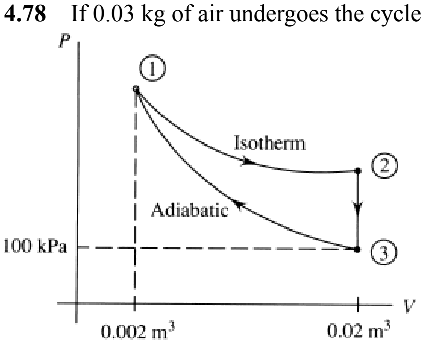

Figure 4-35.

4.79 Air is flowing at an average speed of 100 m/s through a 10-cm-diameter pipe. If the pipe undergoes an enlargement to 20 cm in diameter, determine the average speed in the enlarged pipe.

4.80 Air enters a vacuum cleaner through a 2-in-diameter pipe at a speed of 150 ft/sec. It passes through a rotating impeller (Fig. 4-36), of thickness 0.5 in., through which the air exits. Determine the average velocity exiting normal to the impeller.

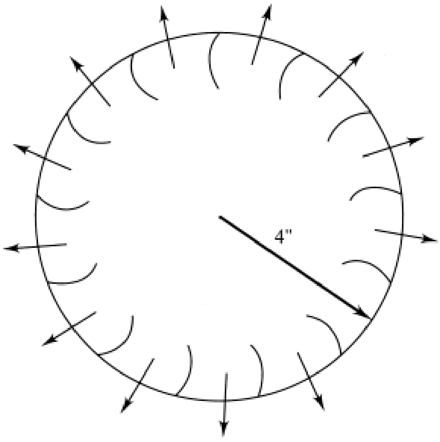

Figure 4-36.

4.81 Air enters a device at 4 MPa and 300 °C with a velocity of 150 m/s. The inlet area is 10 cm^2 and the outlet area is 50 cm^2. Determine the mass flux and the outlet velocity if the air exits at 0.4 MPa and 100 °C.

4.82 Air enters the device shown in Fig. 4-37 at 2 MPa and 350 °C with a velocity of 125 m/s. At one outlet area the conditions are 150 kPa and 150 °C with a velocity of 40 m/s. Determine the mass flux and the velocity at the second outlet for conditions of 0.45 MPa and 200 °C.

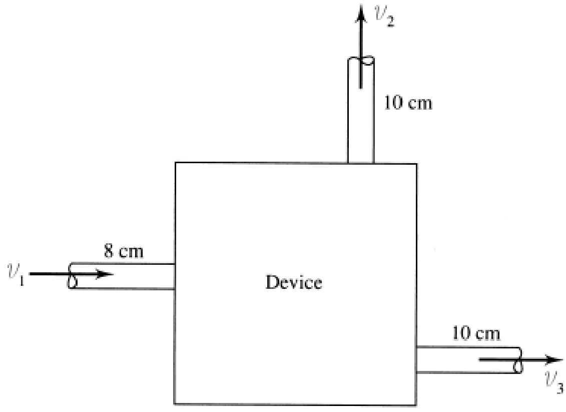

Figure 4-37.

4.83 Steam at 400 kPa and 250 °C is being transferred through a 50-cm-diameter pipe at a speed of 30 m/s. It splits into two pipes with equal diameters of 25 cm. Calculate the mass flux and the velocity in each of the smaller pipes if the pressure and temperature are 200 kPa and 200 °C, respectively.

4.84 Steam enters a device through a 2-in^2 area at 500 psia and 600 °F. It exits through a 10-in^2 area at 20 psia and 400 °F with a velocity of 800 ft/sec. What are the mass flux and the entering velocity?

4.85 Steam enters a 10-m^3 tank at 2 MPa and 600 °C through an 8-cm-diameter pipe with a velocity of 20 m/s. It leaves at 1 MPa and 400 °C through a 12-cm-diameter pipe with a velocity of 10 m/s. Calculate the rate at which the density in the tank is changing.

4.86 Water flows into a 1.2-cm-diameter pipe with a uniform velocity of 0.8 m/s. At some distance down the pipe a parabolic velocity profile is established. Determine the maximum velocity in the pipe and the mass flux. The parabolic profile can be expressed as $V(r) = V_{max}(1 - r^2/R^2)$, where R is the radius of the pipe.

4.87 Water enters the contraction shown in Fig. 4-38 with a parabolic profile $V(r) = 2(1 - r^2)$ m/s, where r is measured in centimeters. The exiting profile after the contraction is essentially uniform. Determine the mass flux and the exit velocity.

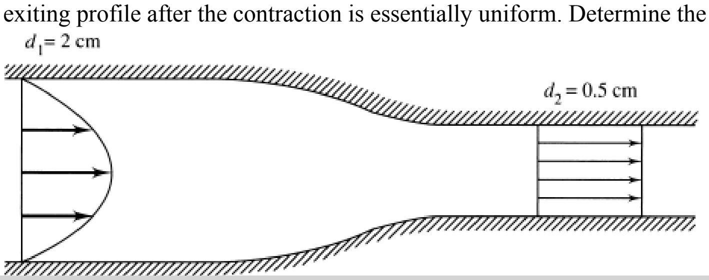

Figure 4-38.

4.88 Air enters a 4-in. constant-diameter pipe at 100 ft/sec with a pressure of 60 psia and a temperature of 100 °F. Heat is added to the air, causing it to pass a downstream area at 70 psia, 300 °F. Calculate the downstream velocity and the heat transfer rate.

4.89 Water at 9000 kPa and 300 °C flows through a partially open valve. The pressure immediately after the valve is measured to be 600 kPa. Calculate the specific internal energy of the water leaving the valve. Neglect kinetic energy changes. (*Note:* The enthalpy of slightly compressed liquid is essentially equal to the enthalpy of saturated liquid at the same temperature.)

4.90 Steam at 9000 kPa and 600 °C passes through a throttling process so that the pressure is suddenly reduced to 400 kPa. (*a*) What is the expected temperature after the throttle? (*b*) What area ratio is necessary for the kinetic energy change to be zero?

4.91 Water at 70 °F flows through the partially open valve shown in Fig. 4-39. The area before and after the valve is the same. Determine the specific internal energy downstream of the valve.

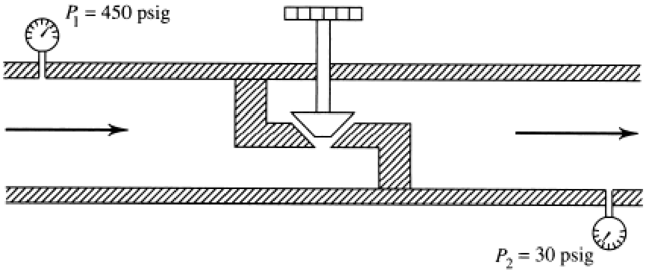

Figure 4-39.

4.92 The inlet conditions on an air compressor are 50 kPa and 20 °C. To compress the air to 400 kPa, 5 kW of energy is needed. Neglecting heat transfer and kinetic and potential energy changes, estimate the mass flux.

4.93 The air compressor shown in Fig. 4-40 draws air from the atmosphere and discharges it at 500 kPa. Determine the minimum power required to drive the insulated compressor. Assume atmospheric conditions of 25 °C and 80 kPa.

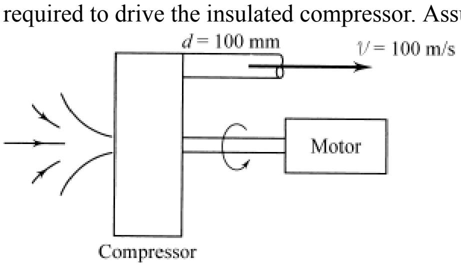

Figure 4-40.

4.94 The power required to compress 0.01 kg/s of steam from a saturated vapor state at 50 °C to a pressure of 800 kPa at 200 °C is 6 kW. Find the rate of heat transfer from the compressor.

4.95 Two thousand lbm/hr of saturated water at 2 psia is compressed by a pump to a pressure of 2000 psia. Neglecting heat transfer and kinetic energy change, estimate the power required by the pump.

4.96 The pump in Fig. 4-41 increases the pressure in the water from 200 to 4000 kPa. What is the minimum horsepower motor required to drive the pump for a flow rate of 0.1 m^3/s?

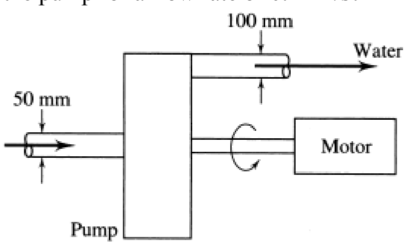

Figure 4-41.

4.97 A turbine at a hydroelectric plant accepts 20 m^3/s of water at a gage pressure of 300 kPa and discharges it to the atmosphere. Determine the maximum power output.

4.98 Water flows in a creek at 1.5 m/s. It has cross-sectional dimensions of 0.6 × 1.2 m upstream of a proposed dam which would be capable of developing a head of 2 m above the outlet of a turbine. Determine the maximum power output of the turbine.

4.99 Superheated steam at 800 psia and 1000 °F enters a turbine at a power plant at the rate of 30 lb/sec. Saturated steam exits at 5 psia. If the power output is 10 MW, determine the heat transfer rate.

4.100 Superheated steam enters an insulated turbine (Fig. 4-42) at 4000 kPa and 500 °C and leaves at 20 kPa. If the mass flux is 6 kg/s, determine the maximum power output and the exiting velocity. Assume an adiabatic quasiequilibrium process so that $s_2 = s_1$.

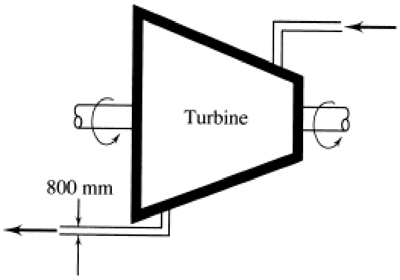

Figure 4-42.

4.101 Air enters a turbine at 600 kPa and 100 °C through a 100-mm-diameter pipe at a speed of 100 m/s. The air exits at 140 kPa and 20 °C through a 400-mm-diameter pipe. Calculate the power output, neglecting heat transfer.

4.102 A turbine delivers 500 kW of power by extracting energy from air at 450 kPa and 100 °C flowing in a 120-mm-diameter pipe at 150 m/s. For an exit pressure of 120 kPa and a temperature of 20 °C determine the heat transfer rate.

4.103 Water flows through a nozzle that converges from 4 in. to 0.8 in. in diameter. For a mass flux of 30 lbm/sec calculate the upstream pressure if the downstream pressure is 14.7 psia.

4.104 Air enters a nozzle like that shown in Fig. 4-43 at a temperature of 195 °C and a velocity of 100 m/s. If the air exits to the atmosphere where the pressure is 85 kPa, find (*a*) the exit temperature, (*b*) the exit velocity, and (*c*) the exit diameter. Assume an adiabatic quasiequilibrium process.

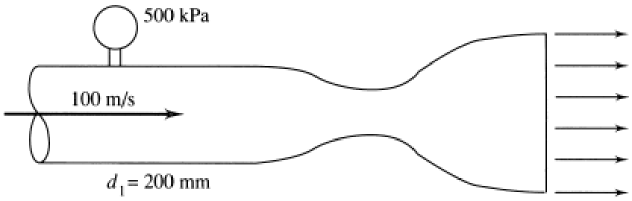

Figure 4-43.

4.105 Nitrogen enters a diffuser at 200 m/s with a pressure of 80 kPa and a temperature of –20 °C. It leaves with a velocity of 15 m/s at an atmospheric pressure of 95 kPa. If the inlet diameter is 100 mm, calculate (*a*) the mass flux and (*b*) the exit temperature.

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Schaum's Thermodynamics Supplementary Problem 4-105: Ideal Gas Flow through a Diffuser

This video illustrates the application of conservation of energy for nitrogen flowing through a diffuser.
Thom Adams, Ph.D., Professor, Mechanical Engineering, Rose-Hulman Institute of Technology
2013

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4.106 Steam enters a diffuser as a saturated vapor at 220 °F with a velocity of 600 ft/sec. It leaves with a velocity of 50 ft/sec at 20 psia. What is the exit temperature?

4.107 Water is used in a heat exchanger (Fig. 4-44) to cool 5 kg/s of air from 400 °C to 200 °C. Calculate (*a*) the minimum mass flux of the water and (*b*) the quantity of heat transferred to the water each second.

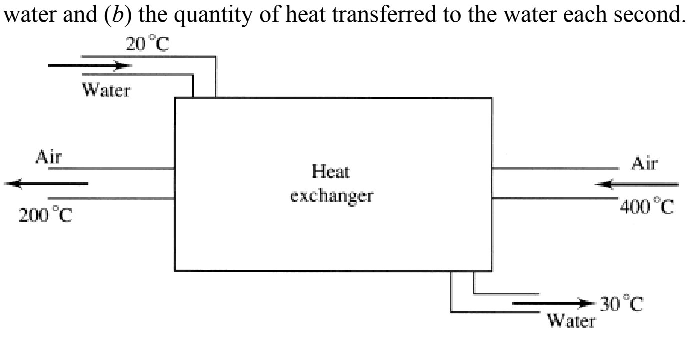

Figure 4-44.

4.108 A simple steam power plant, shown schematically in Fig. 4-45, operates on 8 kg/s of steam. Losses in the connecting pipes and through the various components are to be neglected. Calculate (*a*) the power output of the turbine, (*b*) the power needed to operate the pump, (*c*) the velocity in the pump exit pipe, (*d*) the heat transfer rate necessary in the boiler, (*e*) the heat transfer rate realized in the condenser, (*f*) the mass flux of cooling water required, and (*g*) the thermal efficiency of the cycle.

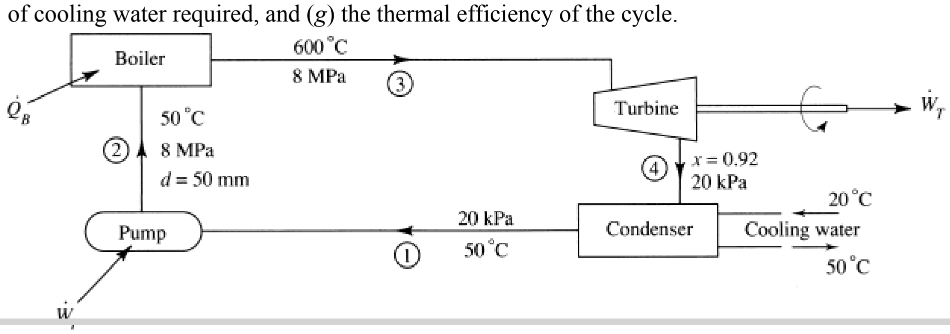

Figure 4-45.

4.109 A feed water heater is used to preheat water before it enters a boiler, as shown schematically in Fig. 4-46. A mass flux of 30 kg/s flows through the system and 7 kg/s is withdrawn from the turbine for the feed water heater. Neglecting losses through the various pipes and components determine (*a*) the feed water heater outlet temperature, (*b*) the boiler heat transfer rate, (*c*) the turbine power output, (*d*) the total pump power required, (*e*) the energy rejected by the condenser, (*f*) the cooling water mass flux, and (*g*) the thermal efficiency of the cycle.

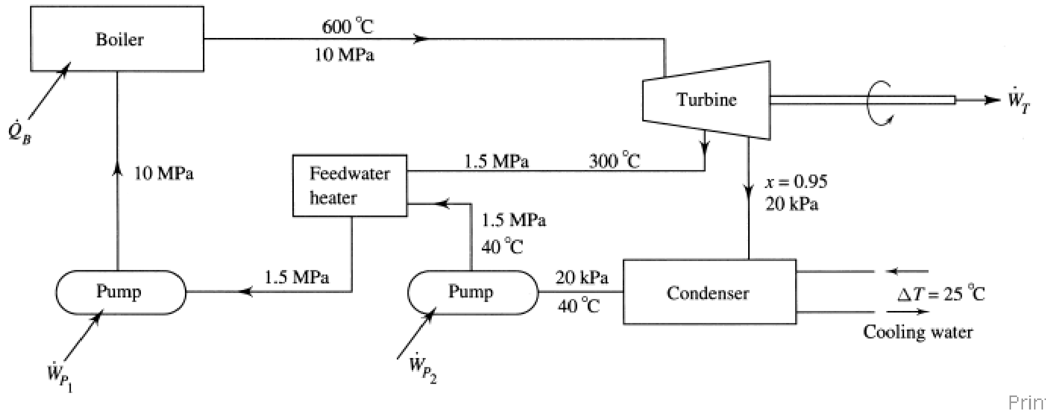

Figure 4-46.

4.110 A turbine is required to provide a total output of 100 hp. The mass flux of fuel is negligible compared with the mass flux of air. The exhaust gases can be assumed to behave as air. If the compressor and turbine (Fig. 4-47) are assumed adiabatic, calculate the following, neglecting all losses: (*a*) the mass flux of the air, (*b*) the horsepower required by the compressor, and (*c*) the power supplied by the fuel.

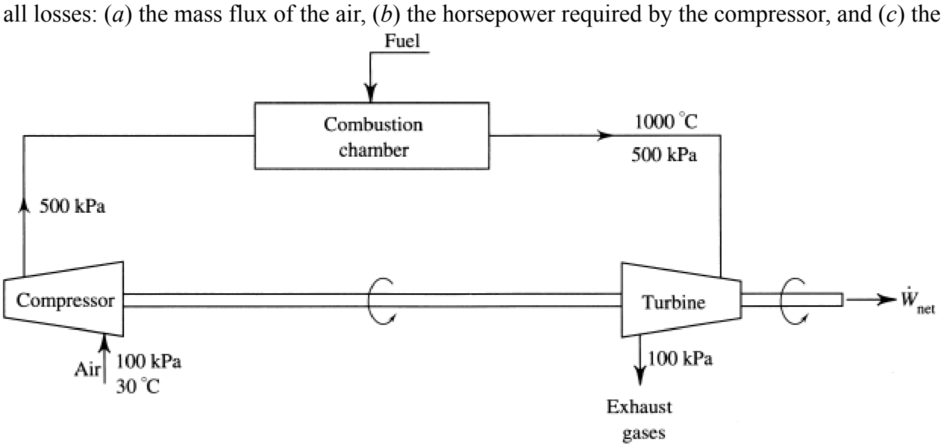

Figure 4-47.

4.111 A steam line containing superheated steam at 1000 psia and 1200 °F is connected to a 50-ft^3 evacuated insulated tank by a small line with a valve. The valve is closed when the pressure in the tank just reaches 800 psia. Calculate (*a*) the final temperature in the tank and (*b*) the mass of steam that entered the tank.

4.112 Air is contained in a 3-m^3 tank at 250 kPa and 25 °C. Heat is added to the tank as the air escapes, thereby maintaining the temperature constant at 25 °C. How much heat is required if the air escapes until the final pressure is atmospheric? Assume $P_{atm} = 80$ kPa.

4.113 An air line carries air at 800 kPa (Fig. 4-48). An insulated tank initially contains 20 °C air at atmospheric pressure of 90 kPa. The valve is opened and air flows into the tank. Determine the final temperature of the air in the tank and the mass of air that enters the tank if the valve is left open.

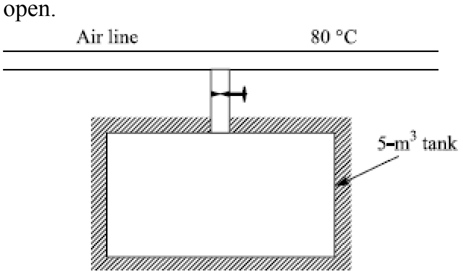

Figure 4-48.

4.114 An insulated tank is evacuated. Air from the atmosphere at 12 psia and 70 °F is allowed to flow into the 100-ft^3 tank. Calculate (*a*) the final temperature and (*b*) the final mass of air in the tank just after the flow ceases.

4.115 (*a*) An insulated tank contains pressurized air at 2000 kPa and 30 °C. The air is allowed to escape to the atmosphere ($P_{atm} = 95$ kPa, $T_{atm} = 30$ °C) until the flow ceases. Determine the final temperature in the tank. (*b*) Eventually, the air in the tank will reach atmospheric temperature. If a valve was closed after the initial flow ceased, calculate the pressure that is eventually reached in the tank.

4.116 An insulated tank with a volume of 4 m^3 is pressurized to 800 kPa at a temperature of 30 °C. An automatic valve allows the air to leave at a constant rate of 0.02 kg/s. (*a*) What is the temperature after 5 min? (*b*) What is the pressure after 5 min? (*c*) How long will it take for the temperature to drop to –20 °C?

4.117 A tank with a volume of 2 m^3 contains 90 percent liquid water and 10 percent water vapor by volume at 100 kPa. Heat is transferred to the tank at 10 kJ/min. A relief valve attached to the top of the tank allows vapor to discharge when the gage pressure reaches 600 kPa. The pressure is maintained at that value as more heat is transferred. (*a*) What is the temperature in the tank at the instant the relief valve opens? (*b*) How much mass is discharged when the tank contains 50 percent vapor by volume? (*c*) How long does it take for the tank to contain 75 percent vapor by volume?

4.9.9. Review Questions for the FE Examination

4.1FE Select a correct statement of the first law if kinetic and potential energy changes are negligible.

A. Heat transfer equals work for a process.

B. Net heat transfer equals net work for a cycle.

C. Net heat transfer minus net work equals internal energy change for a cycle.

D. Heat transfer minus work equals internal energy for a process.

4.2FE Select the incorrect statement of the first law if kinetic and potential energy changes are negligible.

A. Heat transfer equals internal energy change for a process.

B. Heat transfer and work have the same magnitude for a constant-volume quasiequilibrium process in which the internal energy remains constant.

C. The total energy input must equal the total work output for an engine operating on a cycle.

D. The internal energy change plus the work must equal zero for an adiabatic quasiequilibrium process.

4.3FE Ten kilograms of hydrogen is contained in a rigid, insulated tank at 20 °C. Estimate the final temperature if a 400-W resistance heater operates in the hydrogen for 40 minutes.

A. 116 °C

B. 84 °C

C. 29 °C

D. 27 °C

4.4FE Saturated water vapor at 400 kPa is heated in a rigid volume until T_2 = 400 °C. The heat transfer is nearest:

A. 407 kJ/kg

B. 508 kJ/kg

C. 604 kJ/kg

D. 702 kJ/kg

4.5FE Find the work needed to compress 2 kg of air in an insulated cylinder from 100 kPa to 600 kPa if T_1 = 20 °C.

A. –469 kJ

B. –390 kJ

C. –280 kJ

D. –220 kJ

4.6FE Find the temperature rise after 5 minutes in the volume of Fig. 4-49.

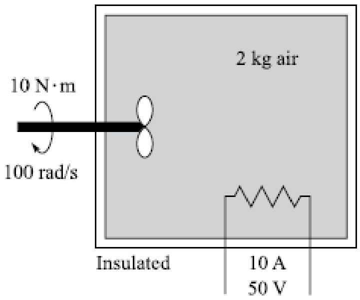

Figure 4-49.

A. 423 °C

B. 378 °C

C. 313 °C

D. 287 °C

4.7FE One kilogram of air is compressed at $T = 100$ °C until $V_1 = 2V_2$. How much heat is rejected?

A. 42 kJ

B. 53 kJ

C. 67 kJ

D. 74 kJ

4.8FE Energy is added to 5 kg of air with a paddle wheel until $\Delta T = 100$ °C. Find the paddle wheel work if the rigid volume is insulated.

A. 524 kJ

B. 482 kJ

C. 412 kJ

D. 358 kJ

4.9FE Initially $P_1 = 400$ kPa and $T_1 = 400$ °C, as shown in Fig. 4-50. What is T_2 when the frictionless piston hits the stops?

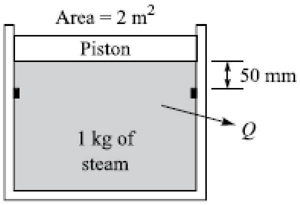

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Figure 4-50.

A. 315 °C

B. 316 °C

C. 317 °C

D. 318 °C

4.10FE What heat is released during the process of Question 4.9FE?

A. 190 kJ

B. 185 kJ

C. 180 kJ

D. 175 kJ

4.11FE After the piston of Fig. 4-50 hits the stops, how much additional heat is released before $P_3 = 100$ kPa?

A. 1580 kJ

B. 1260 kJ

C. 930 kJ

D. 730 kJ

4.12FE The pressure of 10 kg of air is increased isothermally at 60 °C from 100 kPa to 800 kPa. Estimate the rejected heat.

A. 1290 kJ

B. 1610 kJ

C. 1810 kJ

D. 1990 kJ

4.13FE Saturated water is heated at constant pressure of 400 kPa until $T_2 = 400$ °C. Estimate the heat removal.

A. 2070 kJ/kg

B. 2370 kJ/kg

C. 2670 kJ/kg

D. 2870 kJ/kg

4.14FE One kilogram of steam in a cylinder requires 170 kJ of heat transfer while the pressure remains constant at 1 MPa. Estimate the temperature T_2 if $T_1 = 320$ °C.

A. 420 °C

B. 410 °C

C. 400 °C

D. 390 °C

4.15FE Estimate the work required for the process of Question 4.14FE.

A. 89 kJ

B. 85 kJ

C. 45 kJ

D. 39 kJ

4.16FE The pressure of steam at 400 °C and $u = 2949$ kJ·kg is nearest:

A. 2000 kPa

B. 1900 kPa

C. 1800 kPa

D. 1700 kPa

4.17FE The enthalpy of steam at $P = 500$ kPa and $v = 0.7$ m^3/kg is nearest:

A. 3480 kJ/kg

B. 3470 kJ/kg

C. 3460 kJ/kg

D. 3450 kJ/kg

4.18FE Estimate C_p for steam at 4 MPa and 350 °C.

A. 2.48 kJ/kg °C

B. 2.71 kJ/kg °C

C. 2.53 kJ/kg °C

D. 2.31 kJ/kg °C

4.19FE Methane is heated at constant pressure of 200 kPa from 0 °C to 300 °C. How much heat is needed?

A. 731 kJ/kg

B. 692 kJ/kg

C. 676 kJ/kg

D. 623 kJ/kg

4.20FE Estimate the equilibrium temperature if 20 kg of copper at 0 °C and 10 L of water at 30 °C are placed in an insulated container.

A. 27.2 °C

B. 25.4 °C

C. 22.4 °C

D. 20.3 °C

4.21FE Estimate the equilibrium temperature if 10 kg of ice at 0 °C is mixed with 60 kg of water at 20 °C in an insulated container.

A. 12 °C

B. 5.8 °C

C. 2.1 °C

D. 1.1 °C

4.22FE The table shows a three-process cycle; determine *c*.

Process	Q	W	ΔU
$1 \rightarrow 2$	100	a	0
$2 \rightarrow 3$	b	60	40
$3 \rightarrow 1$	40	c	d

A. 140

B. 100

C. 80

D. 40

4.23FE Find w_1 –2 for the process of Fig. 4-51.

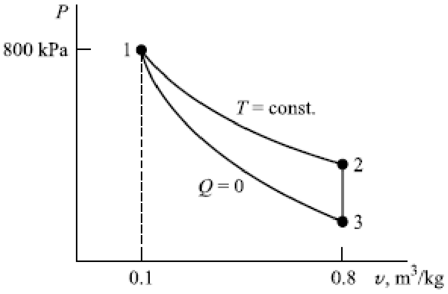

Figure 4-51.

A. 219 kJ/kg

B. 166 kJ/kg

C. 113 kJ/kg

D. 53 kJ/kg

4.24FE Find w_3 –1 for the process of Fig. 4-51.
A. –219 kJ/kg

B. –166 kJ/kg

C. –113 kJ/kg

D. –53 kJ/kg

4.25FE Find q_{cycle} for the processes of Fig. 4-51.
A. 219 kJ/kg

B. 166 kJ/kg

C. 113 kJ/kg

D. 53 kJ/kg

4.26FE Clothes are hung on a clothesline to dry on a freezing winter day. The clothes dry due to:
A. sublimation

B. evaporation

C. vaporization

D. melting

4.27FE Air is compressed adiabatically from 100 kPa and 20 °C to 800 kPa. T_2 is nearest:
A. 440 °C

B. 360 °C

C. 290 °C

D. 260 °C

4.28FE The work required to compress 2 kg of air in an insulated cylinder from 100 °C and 100 kPa to 600 kPa is nearest:
A. 460 kJ

B. 360 kJ

C. 280 kJ

D. 220 kJ

4.29FE One hundred people are in a 10 m × 20 m × 3 m meeting room when the air conditioning fails. Estimate the temperature increase if it is off for 15 min. Each person emits 400 kJ/hr of heat and the lights add 300 W of energy. Neglect all other forms of energy input.

A. 15 °C

B. 18 °C

C. 21 °C

D. 25 °C

4.30FE Air undergoes a three-process cycle with a P = const. process, a T = const. process, and a V = const. process. Select the correct statement for a piston-cylinder arrangement.

A. $W = 0$ for the P = const. process

B. $Q = 0$ for the V = const. process

C. $Q = 0$ for the T = const. process

D. $W = 0$ for the V = const. process

4.31FE The term $\dot{m}\Delta h$ in a control volume equation $\dot{Q} - \dot{W}_s = \dot{m}\Delta h$:

A. Accounts for the rate of change in energy of the control volume.

B. Represents the rate of change of energy between the inlet and outlet.

C. Is often neglected in control-volume applications.

D. Includes the work rate due to the pressure forces.

4.32FE Select an assumption that is made when deriving the continuity equation $\rho_1 A_1 V_1 = \rho_2 A_2 V_2$.

A. Incompressible flow

B. Steady flow

C. Uniform flow

D. Isothermal flow

4.33FE A nozzle accelerates air from 20 m/s to 200 m/s. What temperature change is expected?

A. 40 °C

B. 30 °C

C. 20 °C

D. 10 °C

4.34FE Steam enters a valve at 10 MPa and 550 °C and exits at 0.8 MPa. The exiting temperature is nearest:

A. 590 °C

B. 535 °C

C. 520 °C

D. 510 °C

4.35FE Air enters an insulated compressor at 100 kPa and 20 °C and exits at 800 kPa. The exiting temperature is nearest:

A. 530 °C

B. 462 °C

C. 323 °C

D. 258 °C

4.36FE If $\dot{m} = 2$ kg/s for the compressor of Question 4.35FE and $d_1 = 20$ cm, calculate V_1.
A. 62 m/s

B. 53 m/s

C. 41 m/s

D. 33 m/s

4.37FE 10 kg/s of saturated steam at 10 kPa is to be completely condensed using 400 kg/s of cooling water. Estimate the temperature change of the cooling water.
A. 32 °C

B. 24 °C

C. 18 °C

D. 14 °C

4.38FE 100 kg/min of air enters a relatively short, constant-diameter tube at 25 °C and leaves at 20 °C. Estimate the heat loss.
A. 750 kJ/min

B. 670 kJ/min

C. 500 kJ/min

D. 360 kJ/min

4.39FE The minimum power needed by a water pump that increases the pressure of 4 kg/s from 100 kPa to 6 MPa is:
A. 250 kW

B. 95 kW

C. 24 kW

D. 6 kW

4.40FE A key concept in analyzing the filling of an evacuated tank is:
A. The mass flow rate into the tank remains constant.

B. The enthalpy across a valve remains constant.

C. The internal energy in the tank remains constant.

D. The temperature in the tank remains constant.

4.41FE A given volume of material, initially at 100 °C, cools to 60 °C in 40 seconds. Assuming no phase change and only convective cooling to air at 20 °C, how long would it take the same material to cool to 60 °C if the heat transfer coefficient were doubled?
A. 3 s

B. 4 s

C. 20 s

D. 80 s

4.9.10. Answers to Supplementary Problems

4.31 3.398 kg

4.32 123.3 J

4.33 0.49 Btu

4.34 (*a*) 15, 22 (*b*) 3, 14 (*c*) 25, 15 (*d*) –30, –10 (*e*) –4, –14

4.35 (*a*) –200 (*b*) 0 (*c*) 800 (*d*) 1000 (*e*) 1200

4.36 378 kJ

4.37 84 kJ

4.38 3260 Btu

4.39 1505 kJ

4.40 686 °C

4.41 6.277 Btu

4.42 785 °C

4.43 6.274 Btu

4.44 787 °C

4.45 (*a*) 6140 kJ (*b*) 1531 kJ

4.46 (*a*) 233.9 °C (*b*) 645 °C

4.47 (*a*) 2.06 kJ/kg·°C (*b*) 2.07 kJ/kg·°C (*c*) 13.4 kJ/kg·°C

4.48 (*a*) 0.386 Btu/lbm- °F (*b*) 0.388 Btu/lbm- °F (*c*) 1.96 Btu/lbm- °F

4.49 (*a*) 402 kJ (*b*) 418 kJ (*c*) 412 kJ

4.50 418 kJ vs. 186 kJ

4.51 (*a*) 104 °C (*b*) 120.2 °C

4.52 14,900 Btu

4.53 (*a*) 16.2 °C (*b*) 76.4%

4.54 62.7 °F

4.55 139.5 °C

4.56 1200 kJ, 860 kJ

4.57 (*a*) 60, 0, 0, 100, 203, 0.856, 0.211; (*b*) 57.4, 0, 57.4, 100, 130, 0.329, 0.329; (*c*) 28.4, 71.6, 100, 450, 500, 0.166, 0.109; (*d*) 0, –131, 131, 182, 706, 1124, 125

4.58 (*a*) 49.4, 10.2, 11.8, 100, 100, 1.37, 0.671; (*b*) 80, 0, 80, 170, 170, 0.526, 0.526; (*c*) 23.5, 76.5, 100, 320, 500, 0.226, 0.177; (*d*) 0, –190, 190, 245, 550, 1500, 200

4.59 (*a*) 1551 °F (*b*) 1741 °F

4.60 (*a*) 49.0 °C (*b*) 249 °C

4.61 (*a*) –12.0 kJ (*b*) 44.0 kJ

4.62 753 kJ

4.63 (*a*) 1137 kPa, 314 °C (*b*) 533 kPa, 154 °C

4.64 (*a*) 1135 °F (*b*) 1195 °F

4.65 (*a*) 1465 kJ (*b*) 1050 kJ (*c*) –291 kJ (*d*) 1465 kJ

4.66 (*a*) 1584 kJ (*b*) 2104 kJ

4.67 (*a*) 9.85 MJ (*b*) 12.26 MJ (*c*) 9.53 MJ

4.68 14.04 Btu

4.69 –2.22 kJ

4.70 (*a*) –1230 kJ (*b*) –1620 kJ

4.71 –116 kJ

4.72 (*a*) 49.4 °F (*b*) 69.4 °F (*c*) constant pressure

4.73 174.7 °C, 240.1 kPa

4.74 4.69 °C

4.75 (*a*) 373 kJ (*b*) 373 kJ

4.76 (*a*) 7150 ft-lbf, 9.19 Btu (*b*) 9480 ft-lbf, 12.2 Btu

4.77 1926 kJ, 1926 kJ

4.78 4.01 kJ

4.79 25 m/s

4.80 37.5 ft/sec

4.81 3.65 kg/s, 195.3 m/s

4.82 6.64 kg/s, 255 m/s

4.83 4.95 kg/s, 109 m/s

4.84 2.18 lbm/sec, 182.2 ft/sec

4.85 0.01348 $kg/m^3 \cdot s$

4.86 1.6 m/s, 0.0905 kg/s

4.87 0.314 kg/s, 16 m/s

4.88 116.3 ft/sec, 121.2 Btu/sec

4.89 1282 kJ/kg

4.90 (*a*) 569 °C (*b*) 22.3

4.91 39.34 Btu/lbm

4.92 0.021 kg/s

4.93 571 kW

4.94 3.53 kW

4.95 4.72 hp

4.96 346 hp

4.97 6 MW

4.98 21.19 kW

4.99 –1954Btu/sec

4.100 6.65 MW, 80.8 m/s

4.101 373 kW

4.102 –70.5 kW

4.103 142.1 psia

4.104 (*a*) –3.3 °C (*b*) 638 m/s (*c*) 158 mm

4.105 (*a*) 1.672 kg/s (*b*) –0.91 °C

4.106 238 °F

4.107 (*a*) 23.9 kg/s (*b*) 1 MJ

4.108 (*a*) 9.78 MW (*b*) 63.8 kW (*c*) 4.07 m/s (*d*) 27.4 MW (*e*) 17.69 MW (*f*) 141 kg/s (*g*) 35.5%

4.109 (*a*) 197 °C (*b*) 83.4 MW (*c*) 30.2 MW (*d*) 289 kW (*e*) 53.5 MW (*f*) 512 kg/s (*g*) 35.9%

4.110 (*a*) 0.1590 kg/s (*b*) 37.7 hp (*c*) 126.1 kW

4.111 (*a*) 1587 °F (*b*) 33.1 lbm

4.112 503 kJ

4.113 184 °C, 25.1 kg

4.114 (*a*) 284 °F (*b*) 4.36 lbm

4.115 (*a*) –146 °C (*b*) 227 kPa

4.116 (*a*) 9.2 °C (*b*) 624 kPa (*c*) 11.13 min

4.117 (*a*) 158.9 °C (*b*) 815 kg (*c*) 11.25 h

4.9.11. Answers to Review Questions for the FE Examination

4.1FE (B) 4.2FE (A) 4.3FE (C) 4.4FE (A) 4.5FE (C) 4.6FE (C) 4.7FE (D) 4.8FE (D) 4.9FE (A) 4.10FE (D) 4.11FE (A) 4.12FE (D) 4.13FE (C) 4.14FE (C) 4.15FE (D) 4.16FE (D) 4.17FE (C) 4.18FE (C) 4.19FE (C) 4.20FE (B) 4.21FE (B) 4.22FE (C) 4.23FE (B) 4.24FE (C) 4.25FE (D) 4.26FE (A) 4.27FE (D) 4.28FE (B) 4.29FE (A) 4.30FE (D) 4.31FE (D) 4.32FE (B) 4.33FE (C) 4.34FE (D) 4.35FE (D) 4.36FE (B) 4.37FE (D) 4.38FE (C) 4.39FE (C) 4.40FE (B) 4.41FE (C)