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NAJAF TECHNICAL COLLEGE

Thermodynamics

الديناميكا الحرارية

اعداد الدكتور
علي شاکر باقر الجابري

Thermodynamics الديناميكا الحرارية

CHAPTER FOUR The First Law of Thermodynamics

4.1 The First Law Applied to a Cycle

4.2 The First Law Applied to a Process

4.3 Enthalpy

4.4 Latent Heat

4.5 Specific Heats

4.6 The First Law Applied to Control Volumes

4.7 Applications of the Energy Equation

Quiz No. 1

Quiz No. 2

Conservation of energy is expressed for a cycle, and changes of total energy are then written for a control mass. Kinetic and potential energy can be changed through the work of a force acting on the control mass, and they are part of the total energy.

The internal energy and the enthalpy are introduced as substance properties with the specific heats (heat capacity) as derivatives of these with temperature. Property variations for limited cases are presented for incompressible states of a substance such as liquids and solids, and for a highly compressible state as an ideal gas. The specific heat for solids and liquids changes little with temperature, whereas the specific heat for a gas can change substantially with temperature.

The energy equation is also shown in a rate form to cover transient processes.

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

- Recognize the components of total energy stored in a control mass
- Write the energy equation for a single uniform control mass
- Find the properties u and h for a given state in the Appendix B tables
- Locate a state in the tables with an entry such as (P, h)
- Find changes in u and h for liquid or solid states using Tables A.3 and A.4 or F.2 and F.3
- Find changes in u and h for ideal-gas states using Table A.5 or F.4
- Find changes in u and h for ideal-gas states using Tables A.7 and A.8 or F.5 and F.6
- Recognize that forms for C_p in Table A.6 are approximations to what is shown in Fig. 5.11 and the more accurate tabulations in Tables A.7, A.8, F.5, and F.6
- Formulate the conservation of mass and energy for a control mass that goes through a process involving work and heat transfers and different states
- Formulate the conservation of mass and energy for a more complex control mass where there are different masses with different states
- Use the energy equation in a rate form
- Know the difference between the general laws as the conservation of mass (continuity equation), conservation of energy (first law) and the specific laws that describes a device behavior or process

4.1 The First Law Applied to a Cycle

We are now ready to present the first law of thermodynamics. A law is not derived or proved from basic principles but is simply a statement that we write based on our observations. Historically, the *first law of thermodynamics*, simply called the *first law*, 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

$$\sum W = \sum Q$$

or, using the symbol \oint per equation here. to represent integration around a complete cycle,

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

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. 4.1a. Let the weight fall a certain distance thereby doing work on the system, contained in the tank shown, equal to the weight multiplied by the distance dropped. The temperature of the system (the substance in the tank) will immediately rise an amount ΔT . 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. 4.1b. 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 that was done by the falling weight.

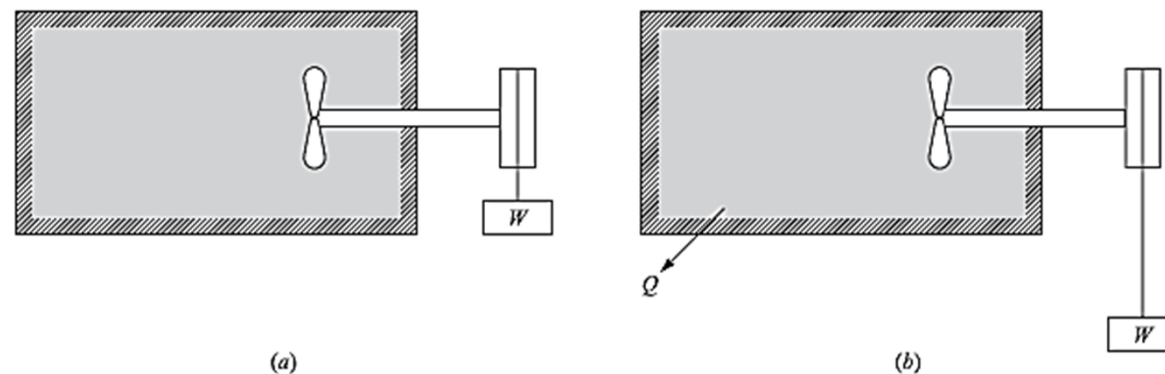


Figure 4.1 The first law applied to a cycle.

EXAMPLE 4.1

A linear spring, with spring constant $K = 100 \text{ kN/m}$, is stretched a distance of 0.8 m and attached to a paddle wheel. 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 linear spring on the system is given by

$$W_{1-2} = \int_0^{0.8} F dx = \int_0^{0.8} 100x dx = 100 \times \frac{0.8^2}{2} = 32 \text{ N} \cdot \text{m}$$

Since the heat transfer returns the system to its initial state, a cycle results. The first law then states that

$$Q_{1-2} = W_{1-2} = 32 \text{ J}$$

4.2 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 two or more processes and returns to the initial state, we could consider a cycle composed of the two processes represented by A and B in Fig. 4.2. Applying the first law to this cycle

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

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

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

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 of the path between states 1 and 2 we let

$$dQ - dW = dE$$

where dE is an exact differential.

The quantity E is an extensive property of the system and represents the *energy* of the system at a particular state. The last equation can be integrated to yield

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

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.

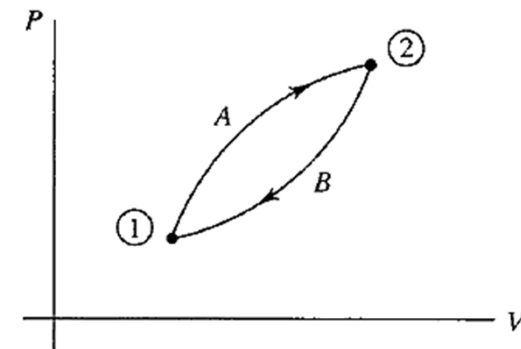


Figure 4.2 A cycle composed of two processes.

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 molecules and atoms. 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

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

If we apply the first law to an isolated system, one which is not in contact with its surroundings so that $Q_{1-2} = W_{1-2} = 0$, the first law becomes the conservation of energy; that is,

$$E_2 = E_1$$

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 steam in the quality region, it depends on quality and temperature (or pressure). For steam, its value for a particular quality would be

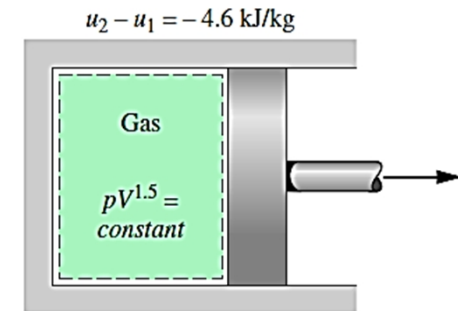
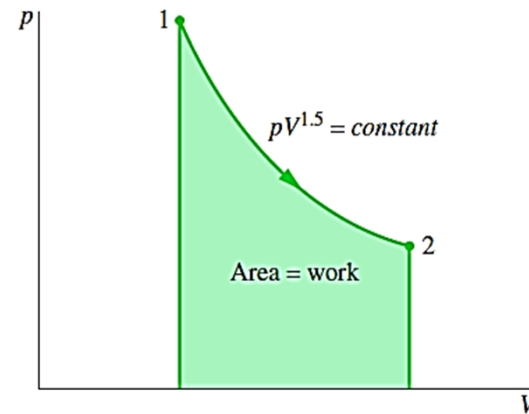
$$u = u_f + x(u_g - u_f)$$

EXAMPLE 4.2: Cooling a Gas in a Piston–Cylinder

Four kilograms of a certain gas is contained within a piston–cylinder assembly. The gas undergoes a process for which the pressure–volume relationship is

$$pV^{1.5} = \text{constant}$$

The initial pressure is 3 bar, the initial volume is 0.1 m^3 , and the final volume is 0.2 m^3 . The change in specific internal energy of the gas in the process is $u_2 - u_1 = -4.6 \text{ kJ/kg}$. There are no significant changes in kinetic or potential energy. Determine the net heat transfer for the process, in kJ.



Analysis: An energy balance for the closed system takes the form

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

where the kinetic and potential energy terms drop out by assumption 3. Then, writing ΔU in terms of specific internal energies, the energy balance becomes

$$m(u_2 - u_1) = Q - W$$

where m is the system mass. Solving for Q

$$Q = m(u_2 - u_1) + W$$

The value of the work for this process is determined in the solution to part (a) of Example 2.1: $W = +17.6 \text{ kJ}$. The change in internal energy is obtained using given data as

$$m(u_2 - u_1) = 4 \text{ kg} \left(-4.6 \frac{\text{kJ}}{\text{kg}} \right) = -18.4 \text{ kJ}$$

Substituting values

$$Q = -18.4 + 17.6 = -0.8 \text{ kJ}$$

EXAMPLE 4.3 Considering Alternative Systems

Air is contained in a vertical piston–cylinder assembly fitted with an electrical resistor. The atmosphere exerts a pressure of 1 bar on the top of the piston, which has a mass of 45 kg and a face area of $.09 \text{ m}^2$. Electric current passes through the resistor, and the volume of the air slowly increases by $.045 \text{ m}^3$ while its pressure remains constant. The mass of the air is $.27 \text{ kg}$, and its specific internal energy increases by 42 kJ/kg . The air and piston are at rest initially and finally. The piston–cylinder material is a ceramic composite and thus a good insulator. Friction between the piston and cylinder wall can be ignored, and the local acceleration of gravity is $g = 9.81 \text{ m/s}^2$. Determine the heat transfer from the resistor to the air, in kJ, for a system consisting of (a) the air alone, (b) the air and the piston.

Analysis: (a) Taking the air as the system, the energy balance

$$(\Delta KE^0 + \Delta PE^0 + \Delta U)_{\text{air}} = Q - W$$

$$Q = W + \Delta U_{\text{air}}$$

$$W = \int_{V_1}^{V_2} p \, dV = p(V_2 - V_1)$$

To determine the pressure p , we use a force balance on the slowly moving, frictionless piston. The upward force exerted by the air on the *bottom* of the piston equals the weight of the piston plus the downward force of the atmosphere acting on the *top* of the piston. In symbols

$$pA_{\text{piston}} = m_{\text{piston}}g + p_{\text{atm}}A_{\text{piston}}$$

$$p = \frac{m_{\text{piston}}g}{A_{\text{piston}}} + p_{\text{atm}}$$

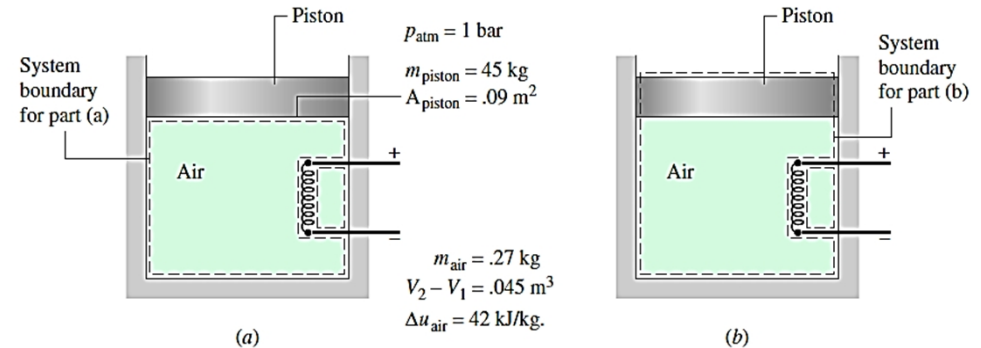
$$p = \frac{(45 \text{ kg})(9.81 \text{ m/s}^2)}{.09 \text{ m}^2} \left| \frac{1 \text{ bar}}{10^5 \text{ N/m}^2} \right| + 1 \text{ bar} = 1.049 \text{ bar}$$

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

$$= (1.049 \text{ bar})(.045 \text{ m}^3) \left| \frac{10^5 \text{ N/m}^2}{1 \text{ bar}} \right| \left| \frac{1 \text{ kJ}}{10^3 \text{ N} \cdot \text{m}} \right| = 4.72 \text{ kJ}$$

$$Q = W + m_{\text{air}}(\Delta u_{\text{air}})$$

$$= 4.72 \text{ kJ} + 11.07 \text{ kJ} = 15.8 \text{ kJ}$$



(b) Consider next a system consisting of the air and the piston.

$$(\Delta KE^0 + \Delta PE^0 + \Delta U)_{\text{air}} + (\Delta KE^0 + \Delta PE + \Delta U^0)_{\text{piston}} = Q - W$$

$$Q = W + (\Delta PE)_{\text{piston}} + (\Delta U)_{\text{air}}$$

$$W = \int_{V_1}^{V_2} p \, dV = p_{\text{atm}}(V_2 - V_1) = (1 \text{ bar})(.045 \text{ m}^3) \left| \frac{10^5 \text{ N/m}^2}{1 \text{ bar}} \right| \left| \frac{1 \text{ kJ}}{10^3 \text{ N} \cdot \text{m}} \right| = 4.5 \text{ kJ}$$

$$\Delta z = \frac{V_2 - V_1}{A_{\text{piston}}} = \frac{.045 \text{ m}^3}{.09 \text{ m}^2} = .5 \text{ m}$$

$$(\Delta PE)_{\text{piston}} = m_{\text{piston}}g\Delta z$$

$$= (45 \text{ kg})(9.81 \text{ m/s}^2)(.5 \text{ m}) = .22 \text{ kJ}$$

$$Q = W + (\Delta PE)_{\text{piston}} + m_{\text{air}}\Delta u_{\text{air}}$$

$$= 4.5 \text{ kJ} + .22 \text{ kJ} + 11.07 \text{ kJ} = 15.8 \text{ kJ}$$

EXAMPLE 4.4 Gearbox at Steady State

During steady-state operation, a gearbox receives 60 kW through the input shaft and delivers power through the output shaft. For the gearbox as the system, the rate of energy transfer by convection is $\dot{Q} = -hA(T_b - T_f)$

where $h = 0.171 \text{ kW/m}^2 \cdot \text{K}$ is the heat transfer coefficient, $A = 1.0 \text{ m}^2$ is the outer surface area of the gearbox, $T_b = 300 \text{ K}$ (27°C) is the temperature at the outer surface, and $T_f = 293 \text{ K}$ (20°C) is the temperature of the surrounding air away from the immediate vicinity of the gearbox. For the gearbox, evaluate the heat transfer rate and the power delivered through the output shaft, each in kW.

Analysis: Using the given expression for \dot{Q} together with known data, the rate of energy transfer by heat is

$$\begin{aligned}\dot{Q} &= -hA(T_b - T_f) \\ &= -\left(0.171 \frac{\text{kW}}{\text{m}^2 \cdot \text{K}}\right)(1.0 \text{ m}^2)(300 - 293) \text{ K} \\ &= -1.2 \text{ kW}\end{aligned}$$

$$\frac{dE}{dt} = \dot{Q} - \dot{W} \quad \text{or} \quad \dot{W} = \dot{Q}$$

The symbol \dot{W} represents the *net* power from the system.

The net power is the sum of \dot{W}_1 and the output power \dot{W}_2

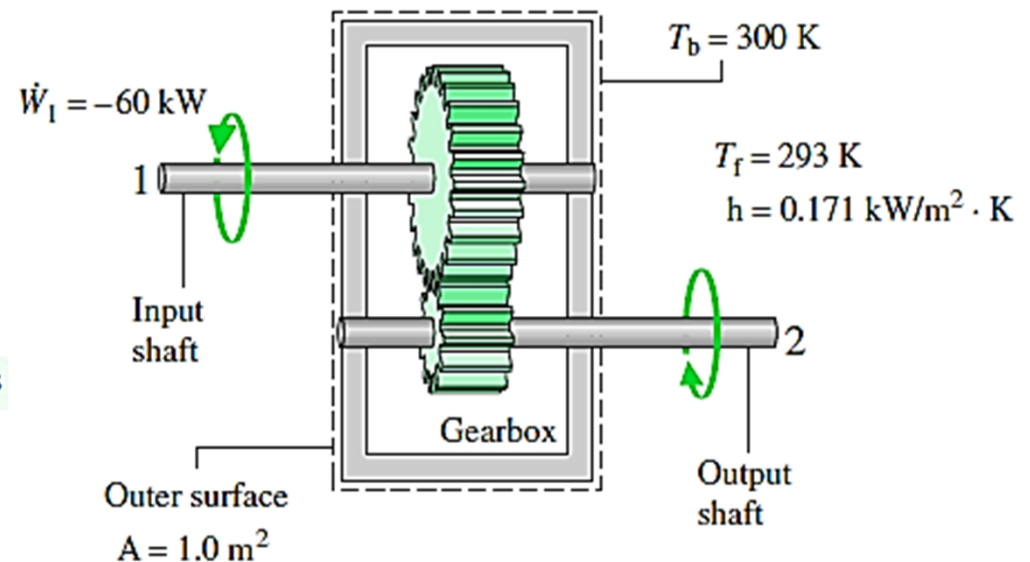
$$\dot{W} = \dot{W}_1 + \dot{W}_2$$

$$\dot{W}_1 + \dot{W}_2 = \dot{Q}$$

Solving for \dot{W}_2 , inserting $\dot{Q} = -1.2 \text{ kW}$, and $\dot{W}_1 = -60 \text{ kW}$, where the minus sign is required because the input shaft brings energy *into* the system, we have

$$\begin{aligned}\dot{W}_2 &= \dot{Q} - \dot{W}_1 \\ &= (-1.2 \text{ kW}) - (-60 \text{ kW}) \\ &= +58.8 \text{ kW}\end{aligned}$$

The positive sign for \dot{W}_2 indicates that energy is transferred from the system through the output shaft, as expected.



Example 4.5

A rigid vessel of $.1\text{m}^3$ volume contains refrigerant-12, 5% liquid and 95% vapor by volume at 24°C . the vessel is heated until the refrigerant exit as saturated vapor. Find (a) the initial pressure in the vessel (b) the mass of Refrigerant-12, (c) the final pressure and temperature, and (d) heat transfer occurs during the process:

Solution: Given $V=0.1\text{m}^3$ 10% liquid 90% vapor $T_1=24^\circ\text{C}$ second state is sat. vapor.

$$V_f = 0.05V = 0.05 \times 0.1 = 0.005\text{m}^3, \quad V_g = 0.95V = 0.95 \times 0.1 = 0.095\text{m}^3$$

and from the sat. R-12 table we find that the following properties at 24°C

$$P_{\text{sat}} = 634.05\text{kPa}, \quad v_f = 0.0007607\text{m}^3/\text{kg}, \quad v_g = 0.02759\text{m}^3/\text{kg},$$

$$u_f = 58.25\text{kJ/kg}, \quad u_g = 179.85\text{kJ/kg}$$

(a) The initial pressure: because the initial state is saturated mixture at 24°C , then $P_1 = P_{\text{sat at } 24^\circ\text{C}} = 634.05\text{ kPa}$

(b) The mass of R-12 in the vessel

$$m_f = \frac{V_f}{v_f} = \frac{0.005}{0.0007607} = 6.573\text{kg}, \quad m_g = \frac{V_g}{v_g} = \frac{0.095}{0.02759} = 3.443\text{kg}$$

$$m = m_f + m_g = 6.573 + 3.443 = 10.016\text{kg}$$

(c) The final pressure and temperature of the R-12 in the vessel: the

final state is saturated vapor with $v_2 = \frac{V}{m} = \frac{0.1}{10.016} = .01\text{m}^3/\text{kg}$

and at the second state $v_g = v_2 = 0.01\text{m}^3/\text{kg}$

from the pressure table we find the following data and using extrapolation we can find the data at the $v_g=0.01\text{m}^3/\text{kg}$

P kPa	T °C	$v_f \text{m}^3/\text{kg}$	$v_g \text{m}^3/\text{kg}$	$u_f \text{kJ/kg}$	$u_g \text{kJ/kg}$
1400	56.09	0.0008448	0.01222	90.28	191.11
1600	62.19	0.0008660	0.01054	96.80	192.95
1664.4	64.15	0.0008728	0.01	98.90	193.54

So $P_2=1664.4\text{kPa}$, $T_2=64.15^\circ\text{C}$

(d) The heat transfer: because there is no change in volume so $W=0$

$$Q = m(u_2 - u_1)$$

$$u_1 = u_f + x(u_g - u_f) = 58.25 + 0.344(179.85 - 58.25) = 100.08 \text{ kJ/kg}$$

$$u_2 = u_g \text{ at second state} = 193.54 \text{ kJ/kg}$$

$$Q = 10.016 \times (193.54 - 100.08) = 2940.9 \text{ kJ}$$

4.3 Enthalpy

In the solution of problems involving systems, certain products or sums of properties occur with regularity. One such combination of properties we define to be *enthalpy* H :

$$H = U + PV$$

This property will come in handy, especially in a constant-pressure process, but also in other situations, as we shall see in examples and applications in future chapters.

The specific enthalpy h is found by dividing by the mass: $h = H/m$.

$$h = u + Pv$$

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

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

In a nonequilibrium constant-pressure process ΔH would not equal the heat transfer.

It is only the change in enthalpy or internal energy that is important; hence, 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; there $h = 0$ and $u = 0$.

Example 4.6

A piston cylinder device contains water at 300kPa, and 250°C with a volume of 0.4m³. If the weight of the piston is required a pressure of 300kPa to rise it. The heat is transfer until the water become saturated mixture with quality of 80%. (a) prove that the heat transfer in a constant pressure process equal to the change in enthalpy.(b) the work done (c) heat transfer during the process.

Solution: Given $P_1 = 300kPa$, $V_1 = 0.4m^3$, $T_1 = 250^\circ C$ constant pressure

process. $x_2 = 0.8$

(a) for constant pressure process $W = P(V_2 - V_1) = PV_2 - PV_1$

The energy equation for closed system $Q = W + \Delta U$

$$Q = PV_2 - PV_1 + U_2 - U_1 = (P_2V_2 + U_2) - (P_1V_1 + U_1)$$

$$Q = H_2 - H_1 = \Delta H$$

(b) For $P_1 = 300kPa$, $T_1 = 250^\circ C$, from superheated water table

$$v_1 = 0.7964m^3/kg, u_1 = 2728.7kJ/kg, h_1 = 2967.6kJ/kg$$

at state 2 $P_2 = 300kPa$, $x_2 = 0.8$

$$v_2 = v_f + x(v_g - v_f) = 0.001073 + 0.8(0.6058 - 0.001073) = 0.4849m^3/kg$$

$$u_2 = u_f + xu_{fg} = 561.15 + 0.8 \times 1982.4 = 2147.07kJ/kg$$

$$h_2 = h_f + xh_{fg} = 561.47 + 0.8 \times 2163.8 = 2292.51kJ/kg$$

$$m = \frac{V_1}{v_1} = \frac{0.4}{0.7964} = 0.5023m^3/kg$$

$$W = mP(v_2 - v_1) = 0.5023 \times 300 \times (0.4849 - 0.7964) = -46.94kJ$$

(c) The heat transfer: it can be calculated by two ways,

$$(i) Q = W + m\Delta u = -46.94 + 0.5023 \times (2147.07 - 2728.7) = -339.1kJ$$

$$(ii) Q = m\Delta h = 0.5023 \times (2292.5 - 2967.6) = -339.1kJ$$

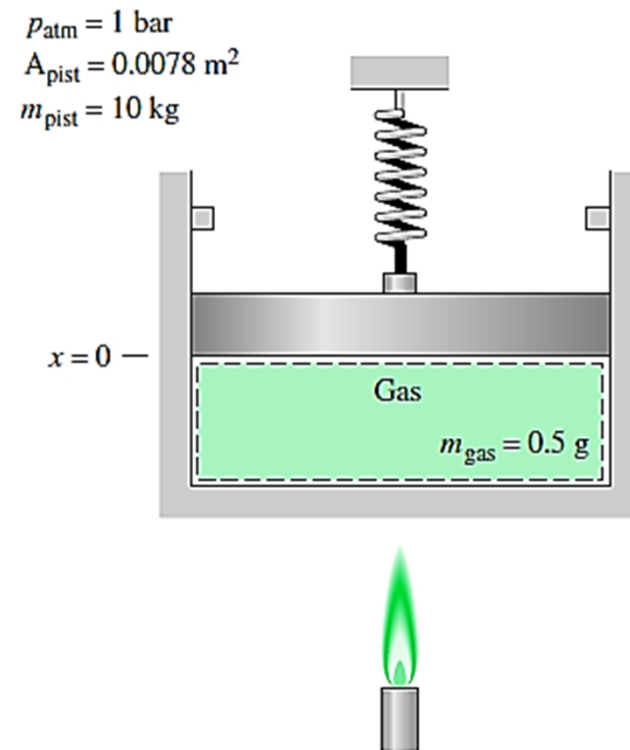
HOME WORK 1

A gas contained within a piston–cylinder assembly is shown in Figure below. Initially, the piston face is at $x = 0$, and the spring exerts no force on the piston. As a result of heat transfer, the gas expands, raising the piston until it hits the stops. At this point the piston face is located at $x = 0.06$ m, and the heat transfer ceases. The force exerted by the spring on the piston as the gas expands varies linearly with x according to $F_{\text{spring}} = kx$

where $k = 9,000$ N/m. Friction between the piston and the cylinder wall can be neglected. The acceleration of gravity is $g = 9.81$ m/s². Additional information is given on

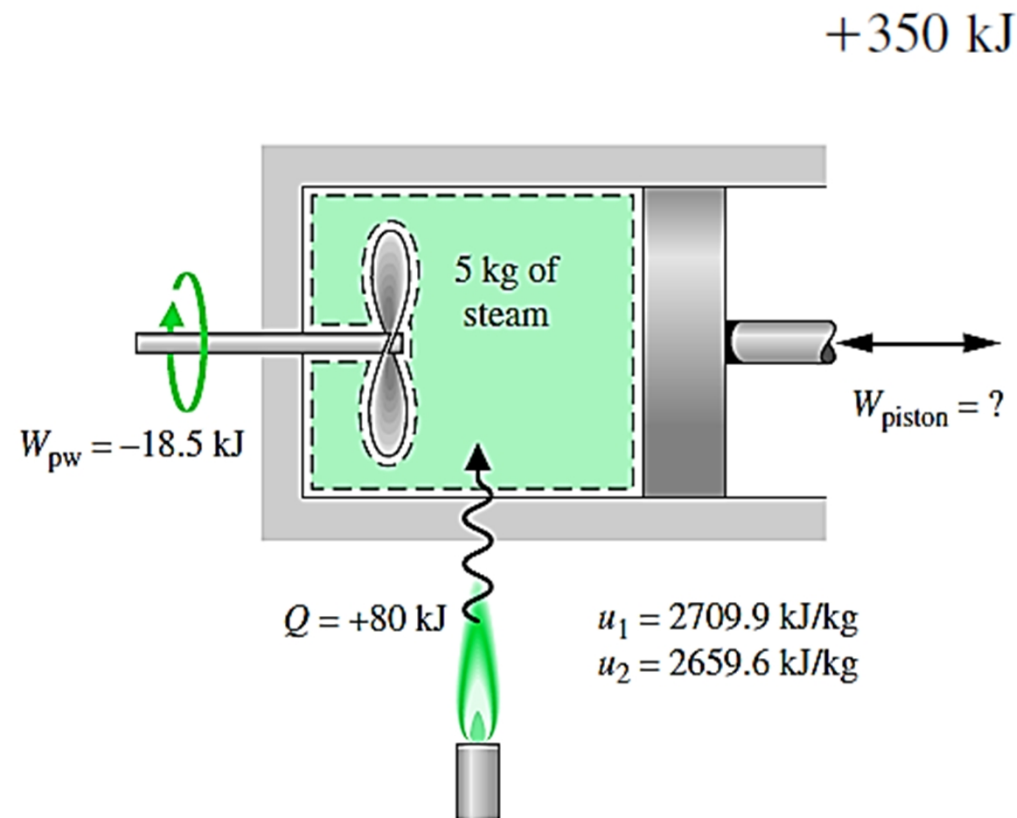
- (a) 112.6 Kpa
- (b) 68.89 J
- (c) 131.39 J

- (a) What is the initial pressure of the gas, in kPa?
- (b) Determine the work done by the gas on the piston, in J.
- (c) If the specific internal energies of the gas at the initial and final states are 210 and 335 kJ/kg, respectively, calculate the heat transfer, in J.



HOME WORK 2

As shown in Figure below, 5 kg of steam contained within a piston–cylinder assembly undergoes an expansion from state 1, where the specific internal energy is $u_1 = 2709.9$ kJ/kg, to state 2, where $u_2 = 2659.6$ kJ/kg. During the process, there is heat transfer *to* the steam with a magnitude of 80 kJ. Also, a paddle wheel transfers energy *to* the steam by work in the amount of 18.5 kJ. There is no significant change in the kinetic or potential energy of the steam. Determine the energy transfer by work from the steam to the piston during the process, in kJ.



4.4 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 occurs is called *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 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 (see Table C.5 for ice) 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; 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 330 kJ/kg and the heat of sublimation is about 2040 kJ/kg. The heat of vaporization of water is included as h_{fg} in Tables C.1 and C.2 and is very sensitive to pressure and temperature.

4.5 Specific Heats

Since only two independent variables are necessary to establish the state of a simple system, the specific internal energy can be expressed as a function of temperature and specific volume; that is,

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

Using the chain rule from calculus, the differential can be stated as

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

Joule's classical experiment showed that $u = u(T)$ for an ideal gas, so that $\partial u / \partial v|_T = 0$.

We define the *constant-volume specific heat* C_v as

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

$$du = C_v dT$$

This can be integrated to give

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

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

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

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

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

For an ideal gas we have

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

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, $\partial h / \partial P|_T = 0$

$$dh = C_p dT \quad \text{or} \quad h_2 - h_1 = \int_{T_1}^{T_2} C_p dT$$

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

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

where M is the molar mass. Thus, \bar{C}_v and \bar{C}_p may be simply derived from the values of M and C_v and C_p listed in Table B.2. (The common "overbar notation" for a molar quantity is used throughout thermodynamics.)

The equation for enthalpy can be used to relate, for an ideal gas, the specific heats and the gas constant.

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

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

$$C_p = C_v + R$$

This relationship, or its molar equivalent, 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

$$k = \frac{C_p}{C_v} \quad C_p = R \frac{k}{k-1} \quad \text{and} \quad C_v = R \frac{1}{k-1}$$

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

$$u_2 - u_1 = C_v(T_2 - T_1) \quad \text{and} \quad h_2 - h_1 = C_p(T_2 - T_1)$$

For air, we will use $C_v = 0.717 \text{ kJ/kg} \cdot \text{K}$ and $C_p = 1.00 \text{ kJ/kg} \cdot \text{K}$, unless otherwise stated.¹ For more accurate calculations with air, or other gases, one should consult ideal-gas tables, such as those in App. E, which tabulate $h(T)$ and $u(T)$, or integrate, using expressions for $C_p(T)$ found in text books. Once C_p is found, C_v can be calculated using $C_v = R - C_p$.

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 quite small. For most liquids the specific heat is relatively insensitive to temperature change. For water we will use the nominal value of $4.18 \text{ kJ/kg} \cdot \text{K}$. For ice, the specific heat in $\text{kJ/kg} \cdot \text{K}$ is approximately $C_p = 2.1 + 0.0069T$, where T is measured in $^{\circ}\text{C}$. The variation of specific heat with pressure is usually quite slight except for special situations.

Example 4.7

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 and 700°C for 3 kg of steam? Compare with the steam tables.
- (b) What is the average value of C_p between 300 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 $P = 150 \text{ kPa}$,

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

- (b) The average value $C_{p, \text{avg}}$ is found by using the relation

$$m C_{p, \text{avg}} \Delta T = m \int_{T_1}^{T_2} C_p dT \quad \text{or} \quad 3 C_{p, \text{avg}} \times 400 = 3 \int_{300}^{700} \left(2.07 + \frac{T - 400}{1480} \right) dT$$

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

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

Using the values from the steam table, we have

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

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, and (b) assuming constant specific heat. Use $M = 28 \text{ kg/kmol}$.

Solution

- (a) Using the gas table in App. E, find the enthalpy change to be

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

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

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

Example 4.7

Determine the specific heats at constant pressure and volume for saturated water vapor at 200°C

Solution: Given_ sat. water vapor $T=200^{\circ}\text{C}$

$$C_v = \frac{\Delta u}{\Delta T}, \quad C_p = \frac{\Delta h}{\Delta T}$$

we can take the temperature around 200°C at sat vapor state

$$T_1 = 195^{\circ}\text{C}, \quad u_g = 2592.8 \text{ kJ/kg}, \quad h_g = 2790 \text{ kJ/kg}$$

$$T_2 = 205^{\circ}\text{C}, \quad u_g = 2597.5 \text{ kJ/kg}, \quad h_g = 2796 \text{ kJ/kg}$$

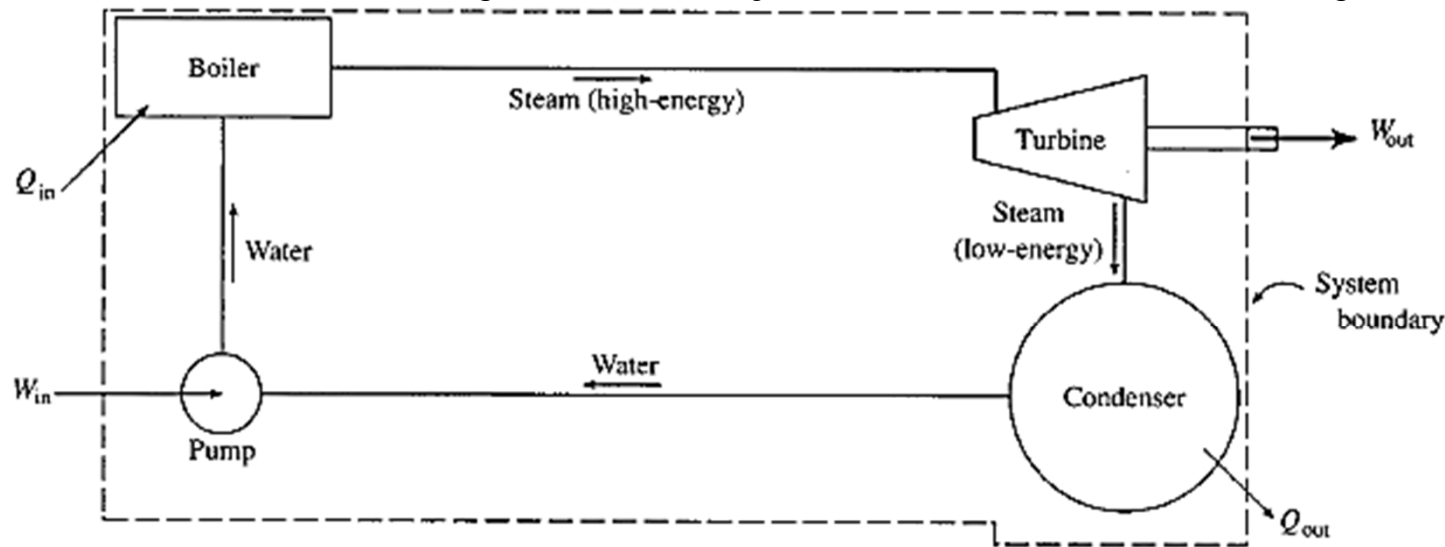
$$C_v = \frac{2597.5 - 2592.8}{205 - 195} = 0.47 \text{ kJ/kg.K}, \quad C_p = \frac{2796 - 2790}{205 - 195} = 0.6 \text{ kJ/kg.K}$$

4.6 The First Law Applied to Control Volumes

We have thus far restricted ourselves to systems; no mass crosses the boundary of a system. This restriction is acceptable for many problems of interest and may, in fact, be imposed on the power plant schematic shown in Figure below. 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 the necessary calculations. 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 detail.



A schematic for a power plant.

THE CONSERVATION OF MASS

Many devices have an inlet (usually a pipe) and an outlet (also typically a pipe).

Consider a device, a control volume, to be operating in a steady-flow mode with uniform profiles in the inlet and outlet pipes. During some time increment Δt , a small amount of mass Δm_1 leaves the inlet pipe and enters the device, and the same amount of mass Δm_2 leaves the device and enters the outlet pipe.

The amount of mass that enters the device is expressed as

$$\begin{aligned}\Delta m_1 &= \text{volume} \times \text{density} = \text{area} \times \text{length} \times \text{density} \\ &= \text{area} \times (\text{velocity} \times \text{time}) \times \text{density} \\ &= A_1 V_1 \Delta t \rho_1\end{aligned}$$

And, that which leaves the device is

$$\Delta m_2 = A_2 V_2 \Delta t \rho_2$$

Since $\Delta m_1 = \Delta m_2$ for this steady flow, we see that

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

The units on ρAV are kg/s and is referred to as the *mass flow rate* (or the *mass flux*) m . Above equation is the *continuity equation* and is often used in the solution of problems. For an incompressible flow ($\rho_1 = \rho_2$), we often introduce the *volume flow rate* Q_f defined by AV .

Example 4.8

Steam at 2000 kPa and 600°C flows through a 60-mm-diameter pipe into a device and exits through a 120-mm-diameter pipe at 600 kPa and 200°C. If the steam in the 60-mm section has a velocity of 20 m/s, determine the velocity in the 120-mm section. Also calculate the mass flow rate.

Solution

From the superheat Table C.3 we find

$$\rho_1 = \frac{1}{v_1} = \frac{1}{0.1996} = 5.01 \text{ kg/m}^3 \quad \rho_2 = \frac{1}{v_2} = \frac{1}{0.3520} = 2.84 \text{ kg/m}^3$$

The continuity equation (4.45) is used to write

$$\begin{aligned} \rho_1 A_1 V_1 &= \rho_2 A_2 V_2 & 5.01 \times \pi \times 0.03^2 \times 20 &= 2.84 \times \pi \times 0.06^2 \times V_2 \\ \therefore V_2 &= 8.82 \text{ m/s} \end{aligned}$$

The mass flow rate is

$$\dot{m} = \rho_1 A_1 V_1 = 5.01 \times \pi \times 0.03^2 \times 20 = 0.283 \text{ kg/s}$$

EXAMPLE 4.9 Feed water Heater at Steady State

A feedwater heater operating at steady state has two inlets and one exit. At inlet 1, water vapor enters at $p_1 = 7$ bar, $T_1 = 200^\circ\text{C}$ with a mass flow rate of 40 kg/s. At inlet 2, liquid water at $p_2 = 7$ bar, $T_2 = 40^\circ\text{C}$ enters through an area $A_2 = 25$ cm². Saturated liquid at 7 bar exits at 3 with a volumetric flow rate of 0.06 m³/s. Determine the mass flow rates at inlet 2 and at the exit, in kg/s, and the velocity at inlet 2, in m/s.

$$\frac{dm_{cv}}{dt} = \dot{m}_1 + \dot{m}_2 - \dot{m}_3$$

$$\dot{m}_2 = \dot{m}_3 - \dot{m}_1$$

The mass flow rate \dot{m}_1 is given. The mass flow rate at the exit can be evaluated from the given volumetric flow rate

$$\dot{m}_3 = \frac{(AV)_3}{v_3}$$

where v_3 is the specific volume at the exit. In writing this expression, one-dimensional flow is assumed. From Table A-3, $v_3 = 1.108 \times 10^{-3}$ m³/kg. Hence

$$\dot{m}_3 = \frac{0.06 \text{ m}^3/\text{s}}{(1.108 \times 10^{-3} \text{ m}^3/\text{kg})} = 54.15 \text{ kg/s}$$

The mass flow rate at inlet 2 is then

$$\dot{m}_2 = \dot{m}_3 - \dot{m}_1 = 54.15 - 40 = 14.15 \text{ kg/s}$$

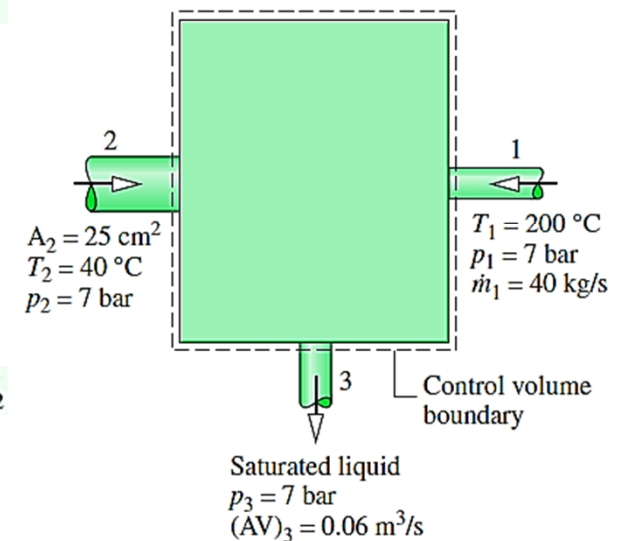
For one-dimensional flow at 2, $\dot{m}_2 = A_2 V_2 / v_2$, so

$$V_2 = \dot{m}_2 v_2 / A_2$$

State 2 is a compressed liquid. The specific volume at this state can be approximated by v_2

From Table A-2 at 40°C , $v_2 = 1.0078 \times 10^{-3}$ m³/kg. So

$$V_2 = \frac{(14.15 \text{ kg/s})(1.0078 \times 10^{-3} \text{ m}^3/\text{kg})}{25 \text{ cm}^2} \left| \frac{10^4 \text{ cm}^2}{1 \text{ m}^2} \right| = 5.7 \text{ m/s}$$



THE ENERGY EQUATION

Consider again a fixed control volume, a device, with one inlet and one outlet. At some time t the system occupies a small volume 1 (that enters the device from the inlet pipe over a time increment Δt) plus the device; then at $t + \Delta t$ the system occupies the device plus the small volume 2 that leaves the device. The first law for the steady state device (the energy in the device does not change with time) can be stated as

$$\begin{aligned} Q - W &= E_{\text{sys}}(t + \Delta t) - E_{\text{sys}}(t) \\ &= \Delta E_2(t + \Delta t) + E_{\text{device}}(t + \Delta t) - E_{\text{device}}(t) - \Delta E_1(t) \\ &= \rho_2 A_2 V_2 \Delta t \left(u_2 + \frac{1}{2} V_2^2 + g z_2 \right) - \rho_1 A_1 V_1 \Delta t \left(u_1 + \frac{1}{2} V_1^2 + g z_1 \right) \end{aligned}$$

where $\rho A V \Delta t$ is the mass in a small volume and Q and W are transferred to and from the system during the time increment Δt . Also, $E_{\text{device}}(t + \Delta t) = E_{\text{device}}(t)$ due to the steady-state operation. Note that the energy consists of internal energy, kinetic energy, and potential energy.

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

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

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. Substitute the expression for work W into previous equation and express the flow work term as $\rho A V (P/\rho) \Delta t$. The first law is then arranged as

$$Q - W_s = \rho_2 A_2 V_2 \left(\frac{V_2^2}{2} + g z_2 + u_2 + \frac{P_2}{\rho_2} \right) \Delta t - \rho_1 A_1 V_1 \left(\frac{V_1^2}{2} + g z_1 + u_1 + \frac{P_1}{\rho_1} \right) \Delta t$$

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

$$\dot{Q} - \dot{W}_s = \dot{m} \left(\frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1) + u_2 - u_1 + \frac{P_2}{\rho_2} - \frac{P_1}{\rho_1} \right)$$

where we have used $\dot{m} = \dot{m}_1 = \dot{m}_2$ for this steady flow, and

$$\dot{Q} = \frac{Q}{\Delta t} \quad \dot{W}_s = \frac{W_s}{\Delta t} \quad \dot{m} = \rho A V$$

For many devices of interest in thermodynamics, the potential energy and gravity effects do not influence its operation, so we write the energy equation as

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

since $h = u + Pv = u + P/\rho$. This energy equation is often used in the form

$$q - w_s = h_2 - h_1$$

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. A nozzle, or a diffuser, is a device in which the kinetic energy change cannot be neglected so previous equation could not be used for such devices.

4.7 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 the problems. 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 and exits the control volume. The control surface should be chosen sufficiently far downstream from an abrupt area change (an entrance or a sudden contraction) that the velocity and pressure can be approximated by uniform distributions.

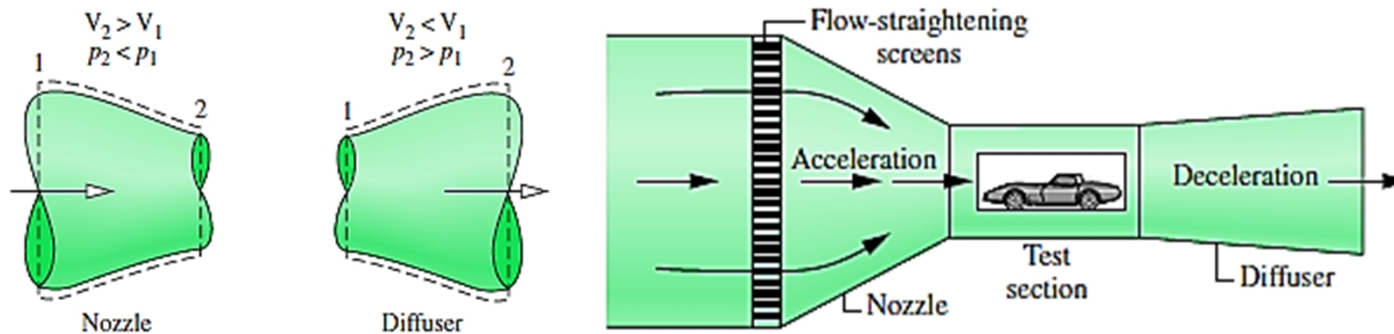
It is also necessary to specify the process by which the flow variables change. Is it incompressible? Isothermal? Constant-pressure? Adiabatic? A sketch of the process on a suitable diagram is often of use in the calculations. If the working substance behaves as an ideal gas, then the appropriate equations may 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, properties can be found in App. E.

Often heat transfer from a device or the internal energy change across a device, such as 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 pump, losses occur because of separated fluid flow around the rotating blades. For many devices the losses are included as an efficiency of the device.

Examples will illustrate.

A- NOZZLES AND DIFFUSERS

A *nozzle* is a flow passage of varying cross-sectional area in which the velocity of a gas or liquid increases in the direction of flow. In a *diffuser*, the gas or liquid decelerates in the direction of flow.



For nozzles and diffusers, the only work is *flow work* at locations where mass enters and exits the control volume, so the term \dot{W}_{cv} drops out of the energy rate equation for these devices. The change in potential energy from inlet to exit is negligible under most conditions. At steady state the mass and energy rate balances reduce, respectively, to

$$\frac{dm_{cv}}{dt} = \dot{m}_1 - \dot{m}_2$$

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

where 1 denotes the inlet and 2 the exit. By combining these into a single expression and dropping the potential energy change from inlet to exit

$$0 = \frac{\dot{Q}_{cv}}{\dot{m}} + (h_1 - h_2) + \left(\frac{V_1^2 - V_2^2}{2} \right)$$

where \dot{m} is the mass flow rate. The term \dot{Q}_{cv}/\dot{m} representing heat transfer with the surroundings per unit of mass flowing through the nozzle or diffuser is often small enough relative to the enthalpy and kinetic energy changes that it can be dropped, as in the next example.

EXAMPLE 4.10 Calculating Exit Area of a Steam Nozzle

Steam enters a converging–diverging nozzle operating at steady state with $p_1 = 40$ bar, $T_1 = 400^\circ\text{C}$, and a velocity of 10 m/s. The steam flows through the nozzle with negligible heat transfer and no significant change in potential energy. At the exit, $p_2 = 15$ bar, and the velocity is 665 m/s. The mass flow rate is 2 kg/s. Determine the exit area of the nozzle, in m^2 .

SOLUTION

The exit area can be determined from the mass flow rate \dot{m}

$$A_2 = \frac{\dot{m}v_2}{V_2}$$

To evaluate A_2 from this equation requires the specific volume v_2 at the exit, and this requires that the exit state be fixed. The state at the exit is fixed by the values of two independent intensive properties. One is the pressure p_2 , which is known. The other is the specific enthalpy h_2 , determined from the steady-state energy rate balance

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

$$0 = (h_1 - h_2) + \left(\frac{V_1^2 - V_2^2}{2}\right)$$

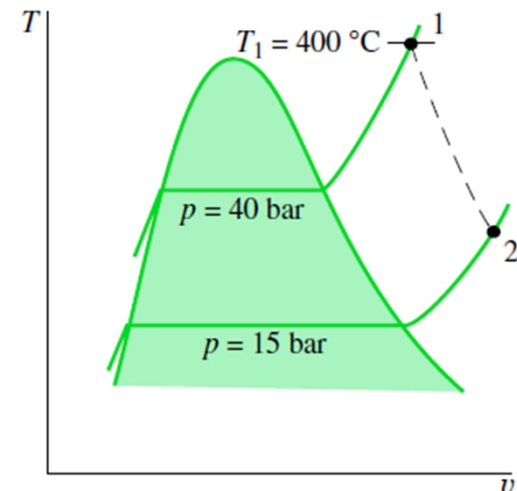
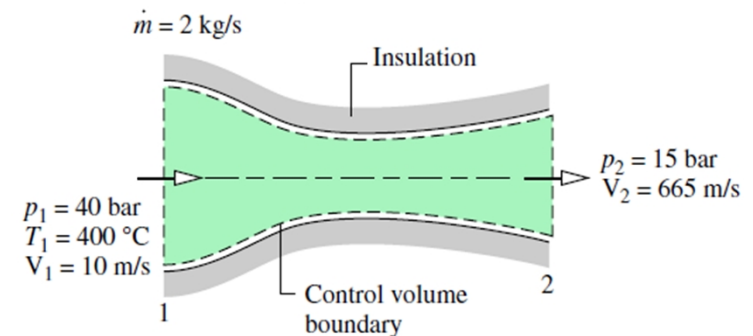
$$h_2 = h_1 + \left(\frac{V_1^2 - V_2^2}{2}\right)$$

From Table A-4, $h_1 = 3213.6$ kJ/kg. The velocities V_1 and V_2 are given. Inserting values and converting the units of the kinetic energy terms to kJ/kg results in

$$\begin{aligned} h_2 &= 3213.6 \text{ kJ/kg} + \left[\frac{(10)^2 - (665)^2}{2} \right] \left(\frac{\text{m}^2}{\text{s}^2} \right) \left| \frac{1 \text{ N}}{1 \text{ kg} \cdot \text{m/s}^2} \right| \left| \frac{1 \text{ kJ}}{10^3 \text{ N} \cdot \text{m}} \right| \\ &= 3213.6 - 221.1 = 2992.5 \text{ kJ/kg} \end{aligned}$$

Finally, referring to Table A-4 at $p_2 = 15$ bar with $h_2 = 2992.5$ kJ/kg, the specific volume at the exit is $v_2 = 0.1627$ m^3/kg . The exit area is then

$$A_2 = \frac{(2 \text{ kg/s})(0.1627 \text{ m}^3/\text{kg})}{665 \text{ m/s}} = 4.89 \times 10^{-4} \text{ m}^2$$



B- TURBINES

A *turbine* is a device in which work is developed as a result of a gas or liquid passing through a set of blades attached to a shaft free to rotate. A schematic of an axial-flow steam or gas turbine is shown in Fig. 4.1. Turbines are widely used in vapor power plants, gas turbine power plants, and aircraft engines. In these applications, superheated steam or a gas enters the turbine and expands to a lower exit pressure as work is developed. A hydraulic turbine installed in a dam is shown in Fig. 4.2. In this application, water falling through the propeller causes the shaft to rotate and work is developed.

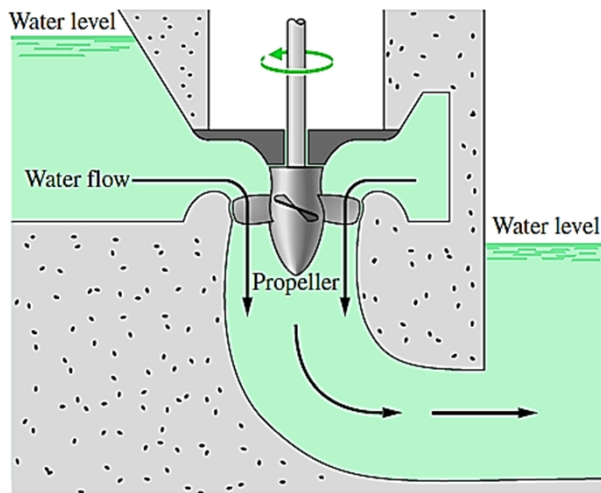


Figure 4.1 Schematic of an axial- flow turbine.

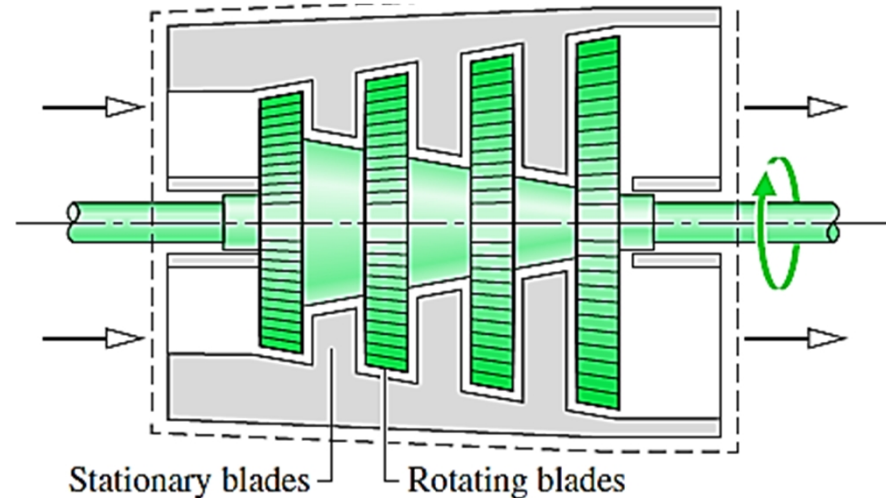


Figure 4.2 Hydraulic turbine installed in a dam.

For a turbine at steady state the mass and energy rate balances reduce to give Equation below

$$0 = \frac{\dot{Q}_{cv}}{\dot{m}} - \frac{\dot{W}_{cv}}{\dot{m}} + (h_1 - h_2) + \frac{(V_1^2 - V_2^2)}{2} + g(z_1 - z_2)$$

When gases are under consideration, the potential energy change is typically negligible. With a proper selection of the boundary of the control volume enclosing the turbine, the kinetic energy change is usually small enough to be neglected. The only heat transfer between the turbine and surroundings would be unavoidable heat transfer, and as illustrated in the next example this is often small relative to the work and enthalpy terms.

EXAMPLE 4.11 Calculating Heat Transfer from a Steam Turbine

Steam enters a turbine operating at steady state with a mass flow rate of 4600 kg/h. The turbine develops a power output of 1000 kW. At the inlet, the pressure is 60 bar, the temperature is 400°C, and the velocity is 10 m/s. At the exit, the pressure is 0.1 bar, the quality is 0.9 (90%), and the velocity is 50 m/s. Calculate the rate of heat transfer between the turbine and surroundings, in kW.

SOLUTION

To calculate the heat transfer rate, begin with the one-inlet, one-exit form of the energy rate balance for a control volume at steady state

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

where \dot{m} is the mass flow rate. Solving for \dot{Q}_{cv} and dropping the potential energy change from inlet to exit

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

First, the specific *enthalpy difference* is found. Using Table A-4, $h_1 = 3177.2$ kJ/kg. State 2 is a two-phase liquid–vapor mixture, so with data from Table A-3 and the given quality

$$\begin{aligned} h_2 &= h_{f2} + x_2(h_{g2} - h_{f2}) \\ &= 191.83 + (0.9)(2392.8) = 2345.4 \text{ kJ/kg} \end{aligned}$$

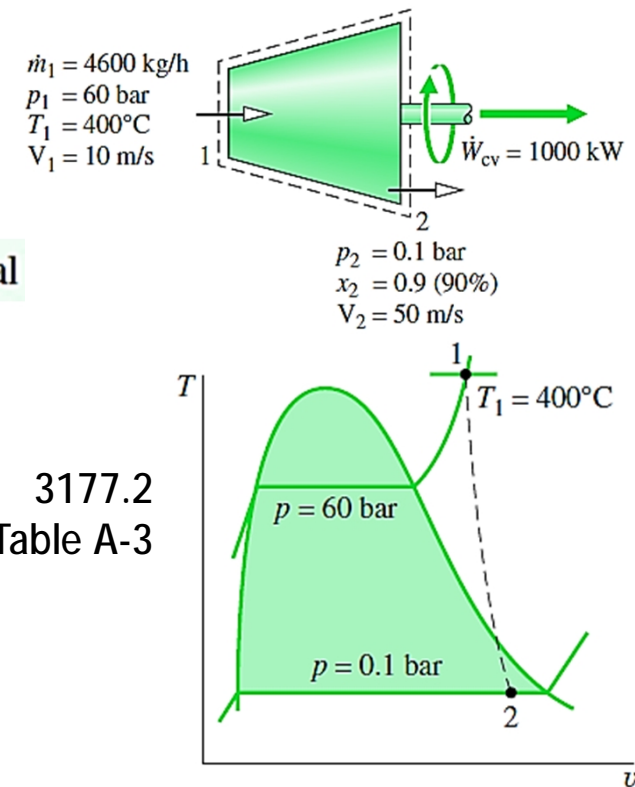
$$h_2 - h_1 = 2345.4 - 3177.2 = -831.8 \text{ kJ/kg}$$

Consider next the specific *kinetic energy difference*. Using the given values for the velocities

$$\left(\frac{V_2^2 - V_1^2}{2} \right) = \left[\frac{(50)^2 - (10)^2}{2} \right] \left(\frac{\text{m}^2}{\text{s}^2} \right) \left| \frac{1 \text{ N}}{1 \text{ kg} \cdot \text{m/s}^2} \right| \left| \frac{1 \text{ kJ}}{10^3 \text{ N} \cdot \text{m}} \right| = 1.2 \text{ kJ/kg}$$

Calculating \dot{Q}_{cv} from the above expression

$$\dot{Q}_{\text{cv}} = (1000 \text{ kW}) + \left(4600 \frac{\text{kg}}{\text{h}} \right) (-831.8 + 1.2) \left(\frac{\text{kJ}}{\text{kg}} \right) \left| \frac{1 \text{ h}}{3600 \text{ s}} \right| \left| \frac{1 \text{ kW}}{1 \text{ kJ/s}} \right| = -61.3 \text{ kW}$$



C- COMPRESSORS AND PUMPS

Compressors are devices in which work is done on a *gas* passing through them in order to raise the pressure. In *pumps*, the work input is used to change the state of a *liquid* passing through. A reciprocating compressor is shown in Fig. 4.3. Figure 4.4 gives schematic diagrams of three different rotating compressors: an axial-flow compressor, a centrifugal compressor, and a Roots type.

The mass and energy rate balances reduce for compressors and pumps at steady state, as for the case of turbines considered previously. For compressors, the changes in specific kinetic and potential energies from inlet to exit are often small relative to the work done per unit of mass passing through the device. Heat transfer with the surroundings is frequently a secondary effect in both compressors and pumps.

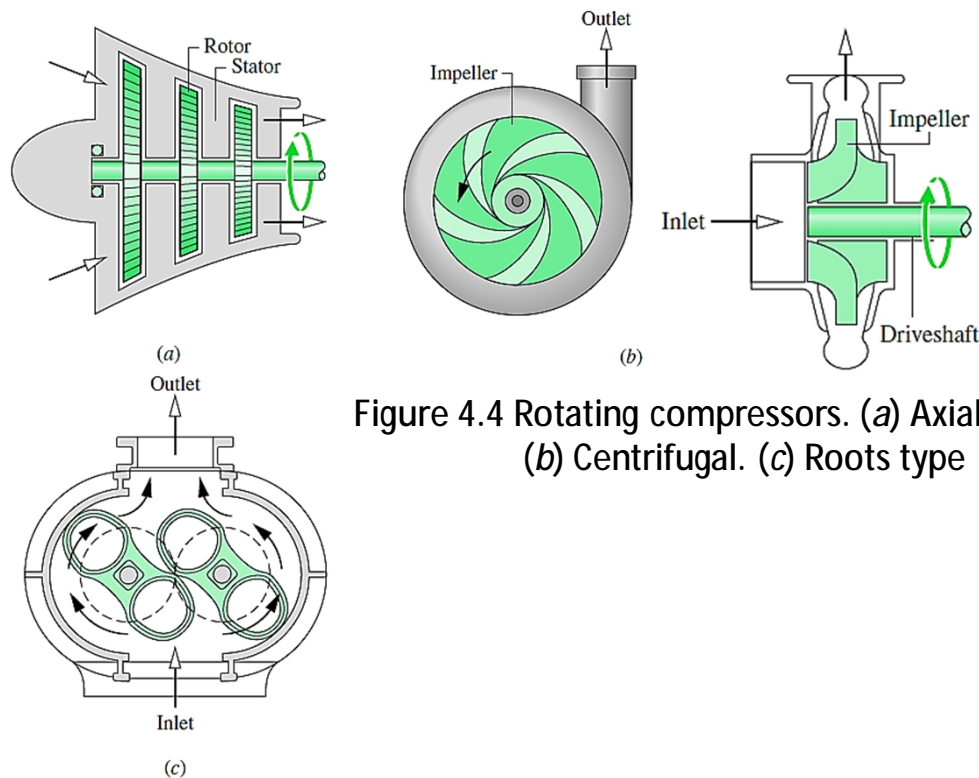


Figure 4.4 Rotating compressors. (a) Axial flow. (b) Centrifugal. (c) Roots type

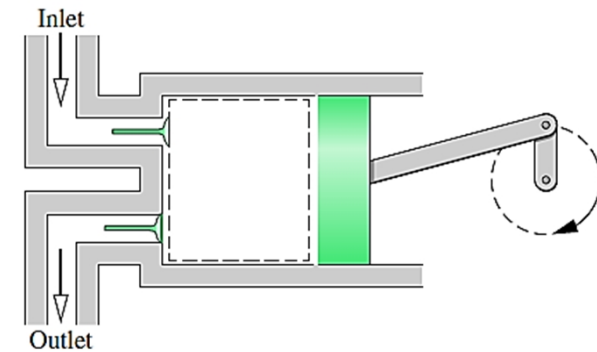


Figure 4.3 Reciprocating compressor

EXAMPLE 4.12 Calculating Compressor Power

Air enters a compressor operating at steady state at a pressure of 1 bar, a temperature of 290 K, and a velocity of 6 m/s through an inlet with an area of 0.1 m². At the exit, the pressure is 7 bar, the temperature is 450 K, and the velocity is 2 m/s. Heat transfer from the compressor to its surroundings occurs at a rate of 180 kJ/min. Employing the ideal gas model, calculate the power input to the compressor, in kW.

SOLUTION

To calculate the power input to the compressor, begin with the energy rate balance for the one-inlet, one-exit control volume at steady state:

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

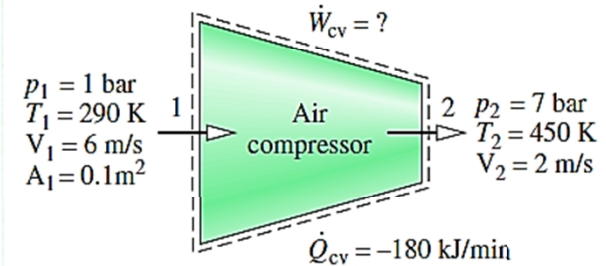
$$\dot{W}_{cv} = \dot{Q}_{cv} + \dot{m} \left[(h_1 - h_2) + \left(\frac{V_1^2 - V_2^2}{2} \right) \right]$$

The mass flow rate \dot{m} can be evaluated with given data at the inlet and the ideal gas equation of state.

$$\dot{m} = \frac{A_1 V_1}{v_1} = \frac{A_1 V_1 p_1}{(\bar{R}/M)T_1} = \frac{(0.1 \text{ m}^2)(6 \text{ m/s})(10^5 \text{ N/m}^2)}{\left(\frac{8314 \text{ N} \cdot \text{m}}{28.97 \text{ kg} \cdot \text{K}} \right)(290 \text{ K})} = 0.72 \text{ kg/s}$$

The specific enthalpies h_1 and h_2 can be found from Table A-22. At 290 K, $h_1 = 290.16 \text{ kJ/kg}$. At 450 K, $h_2 = 451.8 \text{ kJ/kg}$. Substituting values into the expression for \dot{W}_{cv}

$$\begin{aligned} \dot{W}_{cv} &= \left(-180 \frac{\text{kJ}}{\text{min}} \right) \left| \frac{1 \text{ min}}{60 \text{ s}} \right| + 0.72 \frac{\text{kg}}{\text{s}} \left[(290.16 - 451.8) \frac{\text{kJ}}{\text{kg}} \right. \\ &\quad \left. + \left(\frac{(6)^2 - (2)^2}{2} \right) \left(\frac{\text{m}^2}{\text{s}^2} \right) \left| \frac{1 \text{ N}}{1 \text{ kg} \cdot \text{m/s}^2} \right| \left| \frac{1 \text{ kJ}}{10^3 \text{ N} \cdot \text{m}} \right| \right] \\ &= -3 \frac{\text{kJ}}{\text{s}} + 0.72 \frac{\text{kg}}{\text{s}} (-161.64 + 0.02) \frac{\text{kJ}}{\text{kg}} \\ &= -119.4 \frac{\text{kJ}}{\text{s}} \left| \frac{1 \text{ kW}}{1 \text{ kJ/s}} \right| = -119.4 \text{ kW} \end{aligned}$$



D- HEAT EXCHANGERS

Devices that transfer energy between fluids at different temperatures by heat transfer modes are called *heat exchangers*. One common type of heat exchanger is a vessel in which hot and cold streams are mixed directly as shown in Fig. 4.5a. An open feed water heater is an example of this type of device. Another common type of heat exchanger is one in which a gas or liquid is *separated* from another gas or liquid by a wall through which energy is conducted. These heat exchangers, known as recuperators, take many different forms. Counter flow and parallel tube-within-a-tube configurations are shown in Figs. 4.5b and 4.5c, respectively. Other configurations include cross-flow, as in automobile radiators, and multiple-pass shell-and-tube condensers and evaporators. Figure 4.5d illustrates a cross-flow heat exchanger.

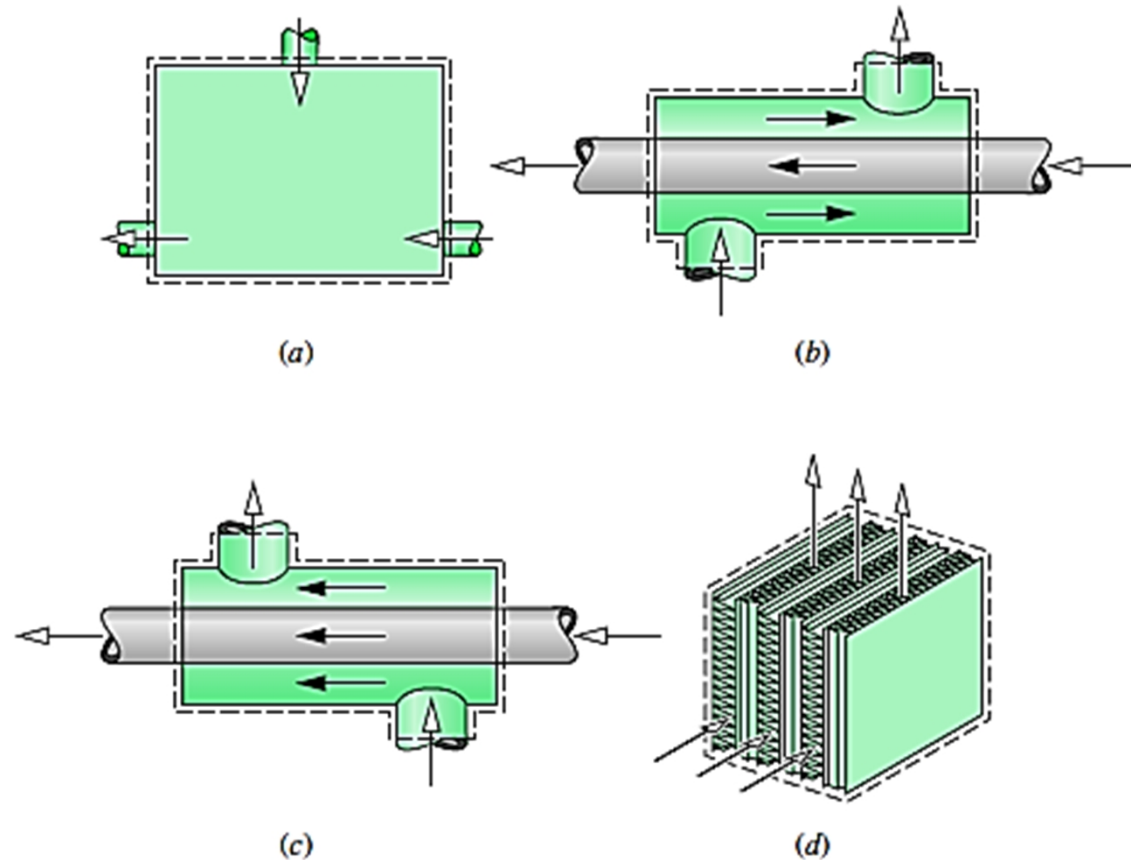


Figure 4.5 Common heat exchanger types.
(a) Direct contact heat exchanger. (b) Tube-within-a-tube counter flow heat exchanger.
(c) Tube-within-a-tube parallel flow heat exchanger. (d) Cross-flow heat exchanger.

EXAMPLE 4.13 Power Plant Condenser

Steam enters the condenser of a vapor power plant at 0.1 bar with a quality of 0.95 and condensate exits at 0.1 bar and 45°C. Cooling water enters the condenser in a separate stream as a liquid at 20°C and exits as a liquid at 35°C with no change in pressure. Heat transfer from the outside of the condenser and changes in the kinetic and potential energies of the flowing streams can be ignored. For steady-state operation, determine

- (a) the ratio of the mass flow rate of the cooling water to the mass flow rate of the condensing stream.
- (b) the rate of energy transfer from the condensing steam to the cooling water, in kJ per kg of steam passing through the condenser.

SOLUTION

The steam and the cooling water streams do not mix. Thus, the mass rate balances for each of the two streams reduce at steady state to give

$$\dot{m}_1 = \dot{m}_2 \quad \text{and} \quad \dot{m}_3 = \dot{m}_4$$

- (a) The ratio of the mass flow rate of the cooling water to the mass flow rate of the condensing steam \dot{m}_3/\dot{m}_1 , can be found from the steady-state form of the energy rate balance applied to the overall condenser as follows

$$0 = \dot{Q}_{cv} - \dot{W}_{cv} + \dot{m}_1 \left(h_1 + \frac{V_1^2}{2} + gz_1 \right) + \dot{m}_3 \left(h_3 + \frac{V_3^2}{2} + gz_3 \right) - \dot{m}_2 \left(h_2 + \frac{V_2^2}{2} + gz_2 \right) - \dot{m}_4 \left(h_4 + \frac{V_4^2}{2} + gz_4 \right)$$

The underlined terms drop out by assumptions 2 and 3. With these simplifications, together with the above mass flow rate relations, the energy rate balance becomes simply

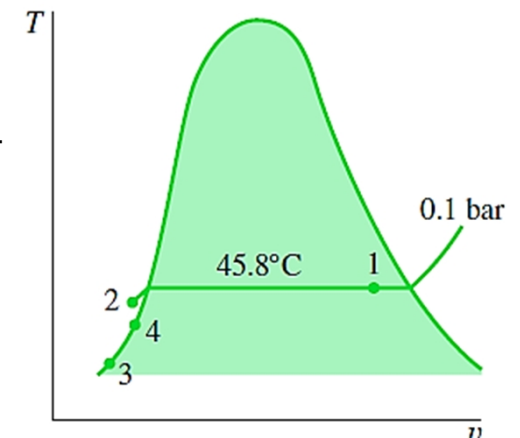
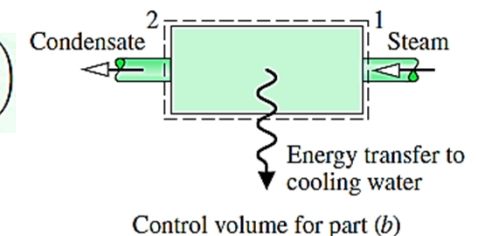
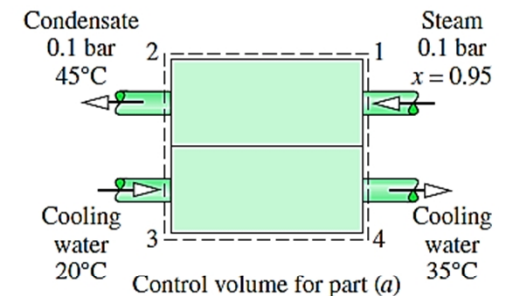
$$0 = \dot{m}_1(h_1 - h_2) + \dot{m}_3(h_3 - h_4) \quad \text{Solving, we get} \quad \frac{\dot{m}_3}{\dot{m}_1} = \frac{h_1 - h_2}{h_4 - h_3}$$

The specific enthalpy h_1 can be determined using the given quality and data from Table A-3. From Table A-3 at 0.1 bar, $h_f = 191.83$ kJ/kg and $h_g = 2584.7$ kJ/kg, so

$$h_1 = 191.83 + 0.95(2584.7 - 191.83) = 2465.1 \text{ kJ/kg}$$

Using assumption 4, the specific enthalpy at 2 is given by

$$h_2 \approx h_f(T_2) = 188.45 \text{ kJ/kg. Similarly, } h_3 \approx h_f(T_3) \text{ and } h_4 \approx h_f(T_4), \text{ giving } h_4 - h_3 = 62.7 \text{ kJ/kg. Thus}$$



$$\frac{\dot{m}_3}{\dot{m}_1} = \frac{2465.1 - 188.45}{62.7} = 36.3$$

For a control volume enclosing the steam side of the condenser only, the steady-state form of energy rate balance is

$$0 = \dot{Q}_{cv} - \dot{W}_{cv} + \dot{m}_1 \left(h_1 + \frac{V_1^2}{2} + gz_1 \right) - \dot{m}_2 \left(h_2 + \frac{V_2^2}{2} + gz_2 \right)$$

The underlined terms drop out by assumptions 2 and 3. Combining this equation with $\dot{m}_1 = \dot{m}_2$ the following expression for the rate of energy transfer between the condensing steam and the cooling water results:

$$\dot{Q}_{cv} = \dot{m}_1(h_2 - h_1)$$

Dividing by the mass flow rate of the steam, \dot{m}_1 , and inserting values

$$\frac{\dot{Q}_{cv}}{\dot{m}_1} = h_2 - h_1 = 188.45 - 2465.1 = -2276.7 \text{ kJ/kg}$$

where the minus sign signifies that energy is transferred *from* the condensing steam *to* the cooling water.

E- THROTTLING DEVICES

A significant reduction in pressure can be achieved simply by introducing a restriction into a line through which a gas or liquid flows. This is commonly done by means of a partially opened valve or a porous plug, as illustrated in Fig. 4.6. For a control volume enclosing such a device, the mass and energy rate balances reduce at steady state to

$$0 = \dot{m}_1 - \dot{m}_2$$

$$0 = \dot{Q}_{cv} - \dot{W}_{cv}^0 + \dot{m}_1 \left(h_1 + \frac{V_1^2}{2} + gz_1 \right) - \dot{m}_2 \left(h_2 + \frac{V_2^2}{2} + gz_2 \right)$$

There is usually no significant heat transfer with the surroundings and the change in potential energy from inlet to exit is negligible. With these idealizations, the mass and energy rate balances combine to give

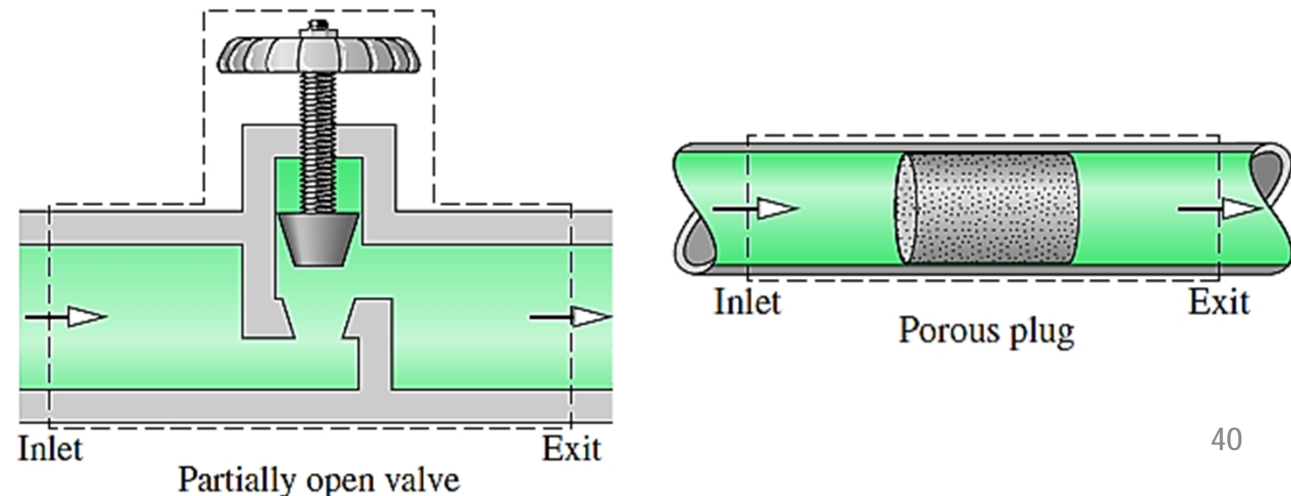
$$h_1 + \frac{V_1^2}{2} = h_2 + \frac{V_2^2}{2}$$

Although velocities may be relatively high in the vicinity of the restriction, measurements made upstream and downstream of the reduced flow area show in most cases that the change in the specific kinetic energy of the gas or liquid between these locations can be neglected.

With this further simplification, the last equation reduces to

$$h_1 = h_2$$

Figure 4.6 Examples of throttling devices.



EXAMPLE 4.14

Steam enters a throttling valve at 8000 kPa and 300°C and leaves at a pressure of 2000 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. The exiting steam is in the quality region, since at 2000 kPa $h_g = 2799.5$ kJ/kg.

Thus the final temperature is $T_2 = 212.4^\circ\text{C}$.

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

$$h_2 = h_f + xh_{fg} \quad 2785 = 909 + 1891x \quad \therefore x_2 = 0.992$$

The specific volume is then

$$\begin{aligned} v_2 &= v_f + x(v_g - v_f) \\ &= 0.0012 + 0.992 \times (0.0992 - 0.0012) \\ &= 0.0988 \text{ m}^3/\text{kg} \end{aligned}$$

EXAMPLE 4.15 Measuring Steam Quality

A supply line carries a two-phase liquid–vapor mixture of steam at 20 bars. A small fraction of the flow in the line is diverted through a throttling calorimeter and exhausted to the atmosphere at 1 bar. The temperature of the exhaust steam is measured as 120°C. Determine the quality of the steam in the supply line.

SOLUTION

For a throttling process, the energy and mass balances reduce to give $h_2 = h_1$. Thus, with state 2 fixed, the specific enthalpy in the supply line is known, and state 1 is fixed by the known values of p_1 and h_1 .

As shown on the accompanying p – v diagram, state 1 is in the two-phase liquid–vapor region and state 2 is in the superheated vapor region. Thus

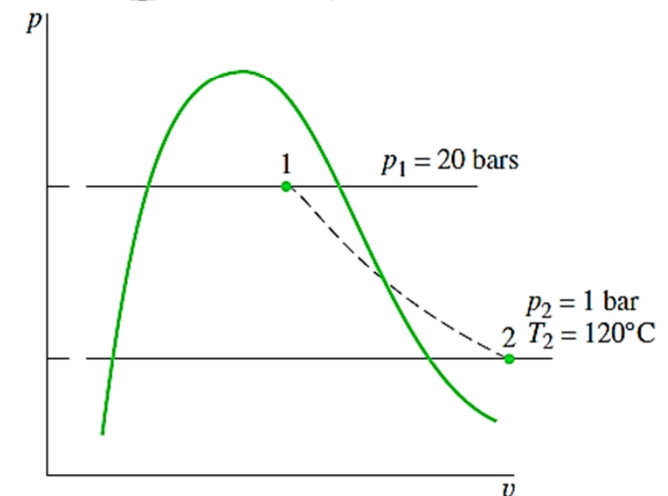
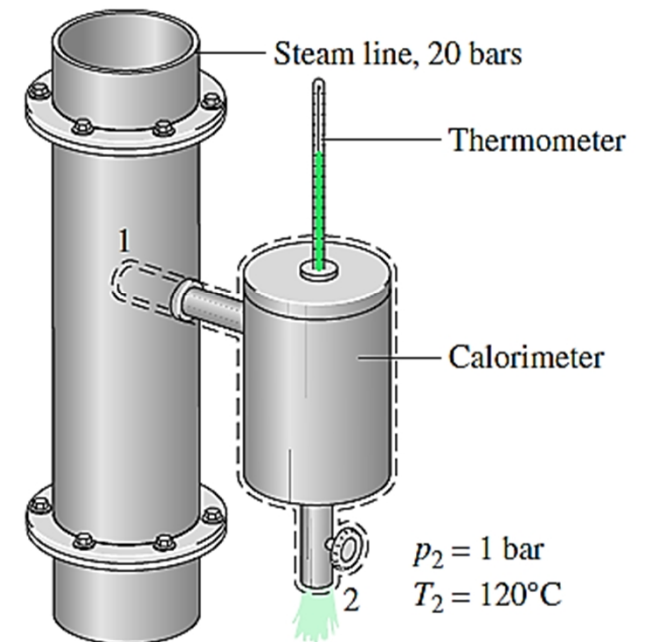
$$h_2 = h_1 = h_{f1} + x_1(h_{g1} - h_{f1})$$

Solving for x_1

$$x_1 = \frac{h_2 - h_{f1}}{h_{g1} - h_{f1}}$$

From Table A-3 at 20 bars, $h_{f1} = 908.79$ kJ/kg and $h_{g1} = 2799.5$ kJ/kg. At 1 bar and 120°C, $h_2 = 2766.6$ kJ/kg from Table A-4.

Inserting values into the above expression, the quality in the line is $x_1 = 0.956$ (95.6%).



Quiz No. 1

1. Select a correct statement of the first law if kinetic and potential energy changes are neglected.
 - (A) Heat transfer equals the work done for a process.
 - (B) Net heat transfer equals the 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.
2. Saturated water vapor at 400 kPa is heated in a rigid volume until $T_2 = 400^\circ\text{C}$. The heat transfer is nearest
 - (A) 406 kJ/kg
 - (B) 508 kJ/kg
 - (C) 604 kJ/kg
 - (D) 702 kJ/kg
3. How much heat must be added to a 0.3-m³ rigid volume containing water at 200°C in order that the final temperature is raised to 800°C? The initial pressure is 1 MPa.
 - (A) 1207 kJ
 - (B) 1308 kJ
 - (C) 1505 kJ
 - (D) 1702 kJ
4. A piston-cylinder arrangement provides a constant pressure of 800 kPa on steam which has an initial quality of 0.95 and an initial volume of 1200 cm³. Determine the heat transfer necessary to raise the temperature to 400°C.
 - (A) 97 kJ
 - (B) 108 kJ
 - (C) 121 kJ
 - (D) 127 kJ
5. One kilogram of steam in a cylinder accepts 170 kJ of heat transfer while the pressure remains constant at 1000 kPa. Estimate the temperature T_2 if $T_1 = 320^\circ\text{C}$.
 - (A) 420°C
 - (B) 410°C
 - (C) 400°C
 - (D) 390°C
6. Estimate the work required for the process of Prob. 5.
 - (A) 89 kJ
 - (B) 85 kJ
 - (C) 45 kJ
 - (D) 39 kJ
7. The pressure of steam at 400°C and $u = 2949$ kJ/kg is most nearly
 - (A) 2000 kPa
 - (B) 1900 kPa
 - (C) 1800 kPa
 - (D) 1700 kPa
8. Sixteen ice cubes, each with a temperature of -10°C and a volume of 8 mL, are added to 1 L of water at 20°C in an insulated container. What is the equilibrium temperature? Use $(C_p)_{\text{ice}} = 2.1$ kJ/kg·°C.
 - (A) 9°C
 - (B) 10°C
 - (C) 11°C
 - (D) 12°C
9. Two kilograms of air are compressed from 210 to 2000 kPa while maintaining the temperature constant at 30°C. The required heat transfer is nearest
 - (A) 392 kJ
 - (B) -392 kJ
 - (C) -438 kJ
 - (D) 438 kJ

10. Find the work needed to compress 2 kg of air in an insulated cylinder from 100 to 600 kPa if $T_1 = 20^\circ\text{C}$.
(A) -469 kJ
(B) -394 kJ
(C) -281 kJ
(D) -222 kJ
11. Energy is added to 5 kg of air with a paddle wheel until $\Delta T = 100^\circ\text{C}$. Find the paddle wheel work if the rigid container is insulated.
(A) -358 kJ
(B) -382 kJ
(C) -412 kJ
(D) -558 kJ
12. Methane is heated at constant pressure from 0 to 300°C . How much heat is needed if $P_1 = 200$ kPa?
(A) 731 kJ/kg
(B) 692 kJ/kg
(C) 676 kJ/kg
(D) 623 kJ/kg
13. The air in the cylinder of an air compressor is compressed from 100 kPa to 10 MPa. Estimate the work required if the air is initially at 100°C .
(A) -250 kJ/kg
(B) -395 kJ/kg
(C) -543 kJ/kg
(D) -729 kJ/kg
14. 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. Estimate the final temperature if 800 kJ of heat is added.
(A) 200°C
(B) 250°C
(C) 300°C
(D) 380°C
15. Select an assumption that is made when deriving the continuity equation $\dot{m}_1 = \dot{m}_2$.
(A) Constant density
(B) Steady flow
(C) Uniform flow
(D) Constant velocity
16. Steam enters a valve at 10 MPa and 550°C and exits at 0.8 MPa. What exiting temperature is expected?
(A) 505°C
(B) 510°C
(C) 520°C
(D) 530°C
17. A nozzle accelerates air from 20 to 200 m/s. What temperature change is expected?
(A) 10°C
(B) 20°C
(C) 30°C
(D) 40°C
18. The minimum power needed by a water pump that increases the pressure of 4 kg/s from 100 kPa to 6 MPa is nearest
(A) 250 kW
(B) 95 kW
(C) 24 kW
(D) 6 kW
19. 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 flow rate and the outlet velocity if the air exits at 0.4 MPa and 100°C .
(A) 195 m/s
(B) 185 m/s
(C) 175 m/s
(D) 165 m/s

20. A pump is to increase the pressure of 200 kg/s of water 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.

(A) 70 kW
(B) 85 kW
(C) 94 kW
(D) 107 kW

21. A turbine at a hydroelectric plant accepts 20 m³/s of water at a gage pressure of 300 kPa and discharges it to the atmosphere. Determine the maximum power output.

(A) 30 MW
(B) 25 MW
(C) 14 MW
(D) 6 MW

22. An air compressor draws air from the atmosphere and discharges it at 500 kPa through a 100-mm-diameter outlet at 100 m/s. Determine the minimum power required to drive the insulated compressor. Assume atmospheric conditions of 25°C and 80 kPa.

(A) 560 kW
(B) 450 kW
(C) 324 kW
(D) 238 kW

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

(A) -127 kJ/s
(B) -187 kJ/s
(C) -233 kJ/s
(D) -343 kJ/s

24. 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, the exit temperature is nearest:

(A) 0°C
(B) 10°C
(C) 20°C
(D) 30°C

Quiz No. 2

1. Select the incorrect statement of the first law (neglect kinetic and potential energy changes).

(A) The heat transfer equals the internal energy change for an adiabatic process.
(B) The heat transfer and the 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.

2. A system undergoes a cycle consisting of the three processes listed in the table. Compute the missing values (*a, b, c, d*). All quantities are in kJ.

Process	<i>Q</i>	<i>W</i>	ΔE
1 → 2	<i>a</i>	100	100
2 → 3	<i>b</i>	-50	<i>c</i>
3 → 1	100	<i>d</i>	-200

(A) (200, 50, 100, 300)
(B) (0, 50, 100, 300)
(C) (200, -50, 100, 300)
(D) (0, 50, -100, 300)

3. A 0.2-m³ rigid volume contains steam at 600 kPa and a quality of 0.8. If 1000 kJ of heat are added, the final temperature is nearest

(A) 720°C
(B) 710°C
(C) 690°C
(D) 670°C

4. A 2-m³ rigid volume contains water at 80°C with a quality of 0.5. Calculate the final temperature if 800 kJ of heat are added.
(A) 120°C
(B) 100°C
(C) 90°C
(D) 80°C
5. Steam is contained in a 4-L volume at a pressure of 1.5 MPa and a temperature of 400°C. If the pressure is held constant by expanding the volume while 20 kJ of heat is added, the final temperature is nearest
(A) 875°C
(B) 825°C
(C) 805°C
(D) 725°C
6. Saturated water is heated at constant pressure of 400 kPa until $T_2 = 400^\circ\text{C}$. How much heat must be added?
(A) 2070 kJ/kg
(B) 2370 kJ/kg
(C) 2670 kJ/kg
(D) 2870 kJ/kg
7. 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
8. 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
9. One kilogram of air is compressed at a constant temperature of 100°C until the volume is halved. How much heat is rejected?
(A) 42 kJ
(B) 53 kJ
(C) 67 kJ
(D) 74 kJ
10. Energy is added to 5 kg of air with a paddle wheel until $\Delta T = 100^\circ\text{C}$. Find the paddle wheel work if the rigid container is insulated.
(A) 524 kJ
(B) 482 kJ
(C) 412 kJ
(D) 358 kJ
11. Helium is contained in a 2-m³ rigid volume at 50°C and 200 kPa. Calculate the heat transfer needed to increase the pressure to 800 kPa.
(A) 1800 kJ
(B) 1700 kJ
(C) 1600 kJ
(D) 1500 kJ
12. Air is compressed adiabatically from 100 kPa and 20°C to 800 kPa. The temperature T_2 is nearest
(A) 440°C
(B) 360°C
(C) 290°C
(D) 260°C

13. 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 200 kPa .
- (A) -12 kJ
 (B) -32 kJ
 (C) -52 kJ
 (D) -72 kJ
14. Nitrogen at 100°C and 600 kPa expands in such a way that it can be approximated by a polytropic process with $n = 1.2$. Calculate the heat transfer if the final pressure is 100 kPa .
- (A) 76.5 kJ/kg
 (B) 66.5 kJ/kg
 (C) 56.5 kJ/kg
 (D) 46.5 kJ/kg
15. The term $\dot{m}\Delta h$ in the control volume equation $\dot{Q} - \dot{W}_s = \dot{m}\Delta h$
- (A) accounts for the rate of change in energy in 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.
16. Air enters an insulated compressor at 100 kPa and 20°C and exits at 800 kPa . Estimate the exiting temperature.
- (A) 530°C
 (B) 462°C
 (C) 323°C
 (D) 258°C
17. If $\dot{m}_1 = 2 \text{ kg/s}$ for the compressor of Prob. 16 and $d_1 = 20 \text{ cm}$, V_1 is nearest
- (A) 62 m/s
 (B) 53 m/s
 (C) 41 m/s
 (D) 33 m/s
18. Ten kilograms of saturated steam at 10 kPa are to be completely condensed using 400 kg/s of cooling water. ΔT of the cooling water is nearest
- (A) 14°C
 (B) 18°C
 (C) 24°C
 (D) 32°C
19. Steam at 9000 kPa and 600°C passes through a throttling process so that the pressure is suddenly reduced to 400 kPa . What is the expected temperature after the throttle?
- (A) 570°C
 (B) 540°C
 (C) 510°C
 (D) 480°C
20. 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 flow rate.
- (A) 0.094 kg/s
 (B) 0.053 kg/s
 (C) 0.021 kg/s
 (D) 0.016 kg/s
21. Superheated steam enters an insulated turbine at 4000 kPa and 500°C and leaves at 20 kPa with $x_2 = 0.9$. If the mass flow rate is 6 kg/s , the power output is nearest
- (A) 5.22 MW
 (B) 6.43 MW
 (C) 7.77 MW
 (D) 8.42 MW
22. Air enters a turbine at 600 kPa and 100°C and exits at 140 kPa and -20°C . Calculate the power output, neglecting heat transfer.
- (A) 140 kJ/kg
 (B) 120 kJ/kg
 (C) 100 kJ/kg
 (D) 80 kJ/kg

23. Air enters a nozzle with $P_1 = 585 \text{ kPa}$, $T_1 = 195^\circ\text{C}$, and $V_1 = 100 \text{ m/s}$. If the air exits to the atmosphere where the pressure is 85 kPa , find exiting velocity, assuming an adiabatic process.
- (A) 523 m/s
 - (B) 694 m/s
 - (C) 835 m/s
 - (D) 932 m/s
24. Water is used in a heat exchanger to cool 5 kg/s of air from 400 to 200°C . Calculate the minimum mass flow rate of the water if $\Delta T_{\text{water}} = 10^\circ\text{C}$.
- (A) 24 kg/s
 - (B) 32 kg/s
 - (C) 41 kg/s
 - (D) 53 kg/s