

The First Law of Thermodynamics

5

Having completed our review of basic definitions and concepts, we are ready to discuss the first law of thermodynamics. This law is often called the *conservation of energy law* and, as we will see later, this is essentially true. Our procedure will be to state this law for a system (control mass) undergoing a cycle and then for a change of state of a system.

After the energy equation is formulated, we will use it to relate the change of state inside a control volume to the amount of energy that is transferred in a process as work or heat transfer. When a car engine has transferred some work to the car, the car's speed is increased, so we can relate the kinetic energy increase to the work; or, if a stove provides a certain amount of heat transfer to a pot with water, we can relate the water temperature increase to the heat transfer. More complicated processes can also occur, such as the expansion of very hot gases in a piston cylinder, as in a car engine, in which work is given out and at the same time heat is transferred to the colder walls. In other applications we can also see a change in state without any work or heat transfer, such as a falling object that changes kinetic energy at the same time it is changing elevation. The energy equation then relates the two forms of energy of the object.

5.1 THE FIRST LAW OF THERMODYNAMICS FOR A CONTROL MASS UNDERGOING A CYCLE

The first law of thermodynamics states that during any cycle a system (control mass) undergoes, the cyclic integral of the heat is proportional to the cyclic integral of the work.

To illustrate this law, consider as a control mass the gas in the container shown in Fig. 5.1. Let this system go through a cycle that is made up of two processes. In the first process, work is done on the system by the paddle that turns as the weight is lowered. Let the system then return to its initial state by transferring heat from the system until the cycle has been completed.

Historically, work was measured in mechanical units of force times distance, such as foot pounds force or joules, and heat was measured in thermal units, such as the British thermal unit or the calorie. Measurements of work and heat were made during a cycle for a wide variety of systems and for various amounts of work and heat. When the amounts of work and heat were compared, it was found that they were always proportional. Such

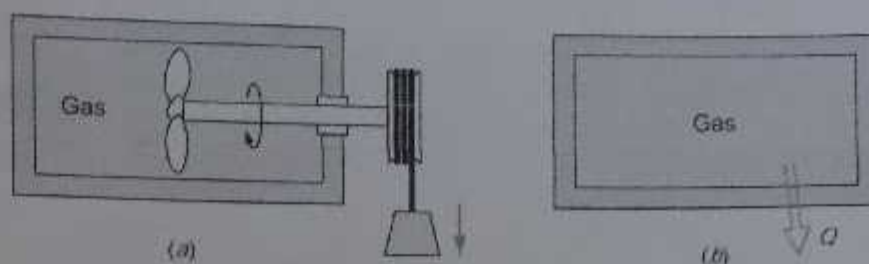


FIGURE 5.1 Example of a control mass undergoing a cycle.

observations led to the formulation of the first law of thermodynamics, which in equation form is written

$$J \oint \delta Q = \oint \delta W \quad (5.1)$$

The symbol $\oint \delta Q$, which is called the *cyclic integral of the heat transfer*, represents the net heat transfer during the cycle, and $\oint \delta W$, the *cyclic integral of the work*, represents the net work during the cycle. Here, J is a proportionality factor that depends on the units used for work and heat.

The basis of every law of nature is experimental evidence, and this is true also of the first law of thermodynamics. Many different experiments have been conducted on the first law, and every one thus far has verified it either directly or indirectly. The first law has never been disproved.

As was discussed in Chapter 4, the units for work and heat or for any other form of energy either are the same or are directly proportional. In SI units, the joule is used as the unit for both work and heat and for any other energy unit. In English units, the basic unit for work is the foot pound force, and the basic unit for heat is the British thermal unit (Btu). James P. Joule (1818–1889) did the first accurate work in the 1840s on measurement of the proportionality factor J , which relates these units. Today, the Btu is defined in terms of the basic SI metric units,

$$1 \text{ Btu} = 778.17 \text{ ft lbf}$$

This unit is termed the *International British thermal unit*. For much engineering work, the accuracy of other data does not warrant more accuracy than the relation $1 \text{ Btu} = 778 \text{ ft lbf}$, which is the value used with English units in the problems in this book. Because these units are equivalent, it is not necessary to include the factor J explicitly in Eq. 5.1, but simply to recognize that for any system of units, each equation must have consistent units throughout. Therefore, we may write Eq. 5.1 as

$$\oint \delta Q = \oint \delta W \quad (5.2)$$

which can be considered the basic statement of the first law of thermodynamics.

5.2 THE FIRST LAW OF THERMODYNAMICS FOR A CHANGE IN STATE OF A CONTROL MASS

Equation 5.2 states the first law of thermodynamics for a control mass during a cycle. Many times, however, we are concerned with a process rather than a cycle. We now consider the first law of thermodynamics for a control mass that undergoes a change of state. We begin by introducing a new property, energy, which is given the symbol E . Consider a system



that undergoes a cycle in which it changes from state 1 to state 2 by process A and returns from state 2 to state 1 by process B . This cycle is shown in Fig. 5.2 on a pressure (or other intensive property)–volume (or other extensive property) diagram. From the first law of thermodynamics, Eq. 5.2, we have

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

Considering the two separate processes, we have

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

Now consider another cycle in which the control mass changes from state 1 to state 2 by process C and returns to state 1 by process B , as before. For this cycle we can write

$$\int_1^2 \delta Q_C + \int_2^1 \delta Q_B = \int_1^2 \delta W_C + \int_2^1 \delta W_B$$

Subtracting the second of these equations from the first, we obtain

$$\int_1^2 \delta Q_A - \int_1^2 \delta Q_C = \int_1^2 \delta W_A - \int_1^2 \delta W_C$$

or, by rearranging,

$$\int_1^2 (\delta Q - \delta W)_A = \int_1^2 (\delta Q - \delta W)_C \quad (5.3)$$

Since A and C represent arbitrary processes between states 1 and 2, the quantity $\delta Q - \delta W$ is the same for all processes between states 1 and 2. Therefore, $\delta Q - \delta W$ depends only on the initial and final states and not on the path followed between the two states. We conclude that this is a point function, and therefore it is the differential of a property of the mass. This property is the *energy* of the mass and is given the symbol E . Thus we can write

$$dE = \delta Q - \delta W \quad (5.4)$$

Because E is a property, its derivative is written dE . When Eq. 5.4 is integrated from an initial state 1 to a final state 2, we have

$$E_2 - E_1 = {}_1Q_2 - {}_1W_2 \quad (5.5)$$

where E_1 and E_2 are the initial and final values of the energy E of the control mass, ${}_1Q_2$ is the heat transferred to the control mass during the process from state 1 to state 2, and ${}_1W_2$ is the work done by the control mass during the process.

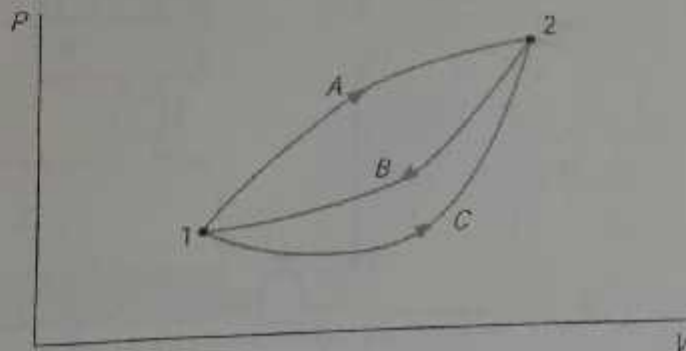


FIGURE 5.2
Demonstration of the
existence of
thermodynamic
property E .

Standard potential energy is

$$PE = mgH$$

so when this is equal to the kinetic energy KE we get

$$H = \frac{KE}{mg} = \frac{400 \text{ Btu} \times 778.17 \frac{\text{ft lbf}}{\text{Btu}} \times 32.174 \frac{\text{lbm ft}}{\text{lbf s}^2}}{2400 \text{ lbm} \times 32.174 \frac{\text{ft}}{\text{s}^2}}$$

$$= 129.7 \text{ ft}$$

Note the necessity of using the conversion constant $32.174 \frac{\text{lbm ft}}{\text{lbf s}^2}$ in both calculations.

Now, substituting the expressions for kinetic and potential energy into Eq. 5.6, we have

$$dE = dU + m\mathbf{V} d\mathbf{V} + mg dZ$$

Integrating for a change of state from state 1 to state 2 with constant g , we get

$$E_2 - E_1 = U_2 - U_1 + \frac{m\mathbf{V}_2^2}{2} - \frac{m\mathbf{V}_1^2}{2} + mgZ_2 - mgZ_1$$

Similarly, substituting these expressions for kinetic and potential energy into Eq. 5.7, we have

$$dE = dU + \frac{d(m\mathbf{V}^2)}{2} + d(mgZ) = \delta Q - \delta W \quad (5.10)$$

Assuming g is a constant, in the integrated form of this equation,

$$U_2 - U_1 + \frac{m(\mathbf{V}_2^2 - \mathbf{V}_1^2)}{2} + mg(Z_2 - Z_1) = {}_1Q_2 - {}_1W_2 \quad (5.11)$$

Three observations should be made regarding this equation. The first observation is that the property E , the energy of the control mass, was found to exist, and we were able to write the first law for a change of state using Eq. 5.5. However, rather than deal with this property E , we find it more convenient to consider the internal energy and the kinetic and potential energies of the mass. In general, this procedure will be followed in the rest of this book.

The second observation is that Eqs. 5.10 and 5.11 are in effect a statement of the conservation of energy. The net change of the energy of the control mass is always equal to the net transfer of energy across the boundary as heat and work. This is somewhat analogous to a joint checking account shared by a husband and wife. There are two ways in which deposits and withdrawals can be made—either by the husband or by the wife—and the balance will always reflect the net amount of the transaction. Similarly, there are two ways in which energy can cross the boundary of a control mass—either as heat or as work—and the energy of the mass will change by the exact amount of the net energy crossing the boundary. The concept of energy and the law of the conservation of energy are basic to thermodynamics.

5.3

INTERNAL ENERGY—A THERMODYNAMIC PROPERTY

Internal energy is an extensive property because it depends on the mass of the system. Kinetic and potential energies are also extensive properties.

The symbol U designates the internal energy of a given mass of a substance. Following the convention used with other extensive properties, the symbol u designates the internal energy per unit mass. We could speak of u as the specific internal energy, as we do with specific volume. However, because the context will usually make it clear whether u or U is referred to, we will use the term *internal energy* to refer to both internal energy per unit mass and the total internal energy.

In Chapter 3 we noted that in the absence of motion, gravity, surface effects, electricity, or other effects, the state of a pure substance is specified by two independent properties.

It is very significant that, with these restrictions, the internal energy may be one of the independent properties of a pure substance. This means, for example, that if we specify the pressure and internal energy (with reference to an arbitrary base) of superheated steam, the temperature is also specified.

Thus, in tables of thermodynamic properties such as the steam tables, the value of internal energy can be tabulated along with other thermodynamic properties. Tables 1 and 2 of the steam tables (Tables B.1.1 and B.1.2) list the internal energy for saturated states. Included are the internal energy of saturated liquid u_f , the internal energy of saturated vapor u_g , and the difference between the internal energy of saturated liquid and saturated vapor u_{fg} . The values are given in relation to an arbitrarily assumed reference state, which, for water in the steam tables, is taken as zero for saturated liquid at the triple-point temperature, 0.01°C . All values of internal energy in the steam tables are then calculated relative to this reference (note that the reference state cancels out when finding a difference in u between any two states). Values for internal energy are found in the steam tables in the same manner as for specific volume. In the liquid-vapor saturation region,

$$U = U_{\text{liq}} + U_{\text{vap}}$$

or

$$mU = m_{\text{liq}}u_f + m_{\text{vap}}u_g$$

Dividing by m and introducing the quality x gives

$$u = (1 - x)u_f + xu_g$$

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

As an example, the specific internal energy of saturated steam having a pressure of 0.6 MPa and a quality of 95% can be calculated as

$x = 0.95$

$$u = u_f + xu_{fg} = 669.9 + 0.95(1897.5) = 2472.5 \text{ kJ/kg}$$

Values for u in the superheated vapor region are tabulated in Table B.1.3, for compressed liquid in Table B.1.4, and for solid-vapor in Table B.1.5.

5.5 THE THERMODYNAMIC PROPERTY ENTHALPY

In analyzing specific types of processes, we frequently encounter certain combinations of thermodynamic properties, which are therefore also properties of the substance undergoing the change of state. To demonstrate one such situation, let us consider a control mass undergoing a quasi-equilibrium constant-pressure process, as shown in Fig. 5.7. Assume that there are no changes in kinetic or potential energy and that the only work done during the process is that associated with the boundary movement. Taking the gas as our control mass and applying the first law, Eq. 5.11, we have, in terms of Q ,

$${}_1Q_2 = U_2 - U_1 + {}_1W_2$$

The work done can be calculated from the relation

$${}_1W_2 = \int_1^2 P dV$$

Since the pressure is constant,

$${}_1W_2 = P \int_1^2 dV = P(V_2 - V_1)$$

Therefore,

$$\begin{aligned} {}_1Q_2 &= U_2 - U_1 + P_2 V_2 - P_1 V_1 \\ &= (U_2 + P_2 V_2) - (U_1 + P_1 V_1) \end{aligned}$$

We find that, in this very restricted case, the heat transfer during the process is given in terms of the change in the quantity $U + PV$ between the initial and final states. Because all these quantities are thermodynamic properties, that is, functions only of the state of the system, their combination must also have these same characteristics. Therefore, we find it convenient to define a new extensive property, the enthalpy,

$$H \equiv U + PV \quad (5.12)$$

or, per unit mass,

$$h \equiv u + Pv \quad (5.13)$$

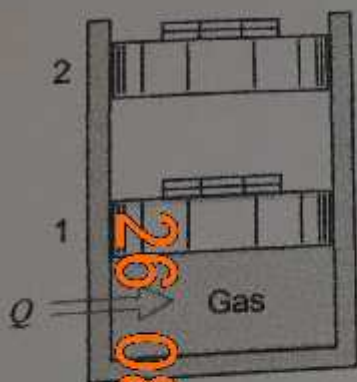


FIGURE 5.7 The constant-pressure quasi-equilibrium process.

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has the symbol h_f , saturated vapor h_g , and the increase in enthalpy during vaporization h_{fg} . For a saturation state, the enthalpy can be calculated by one of the following relations:

$$h = (1 - x)h_f + xh_g$$

$$h = h_f + xh_{fg}$$

The enthalpy of compressed liquid water may be found from Table B.1.4. For substances for which compressed-liquid tables are not available, the enthalpy is taken as that of saturated liquid at the same temperature.

3.2 pdV -WORK OR DISPLACEMENT WORK

Let the gas in the cylinder (Fig. 3.4) be a system having initially the pressure p_1 and volume V_1 . The system is in thermodynamic equilibrium, the state of which is described by the coordinates p_1 and V_1 . The piston is the only boundary which moves due to gas pressure. Let the piston move out to a new final position 2, which is also a thermodynamic equilibrium state specified by pressure p_2 and volume V_2 . At any intermediate point in the travel of the piston, let the pressure be p and the volume be V . This must also be an equilibrium state, since macroscopic properties p and V are significant only for equilibrium states. When the piston moves an infinitesimal distance dl , and if 'a' be the area of the piston, the force F acting on the piston $F = p \cdot a$ and the infinitesimal amount of work done by the gas on the piston

$$dW = F \cdot dl = padl = pdV \quad (3.1)$$

where $dV = a dl$ = infinitesimal displacement volume. The differential sign in δW with the line drawn at the top of it will be explained later.

When the piston moves out from position 1 to position 2 with the volume changing from V_1 to V_2 , the amount of work W done by the system will be

$$W_{1-2} = \int_{V_1}^{V_2} p dV$$

The magnitude of the work done is given by the area under the path 1-2, as shown in Fig. 3.5. Since p is at all times a thermodynamic coordinate, all the states passed through by the system as the volume changes from V_1 to V_2 must be equilibrium states, and the path 1-2 must be *quasi-static*. The piston moves infinitely slowly so that every state passed through is an equilibrium state. The integration $\int p dV$ can be performed only on a quasi-static path.

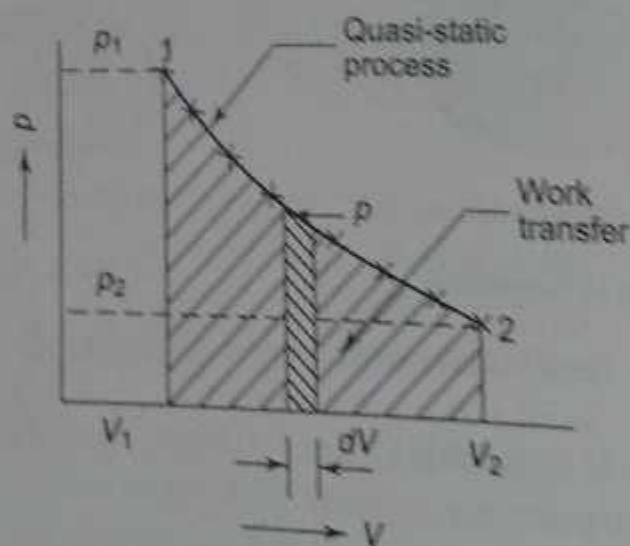


Fig. 3.5 Quasi-static pdV work

LO 3.2
Derive displacement work in a quasi-static process

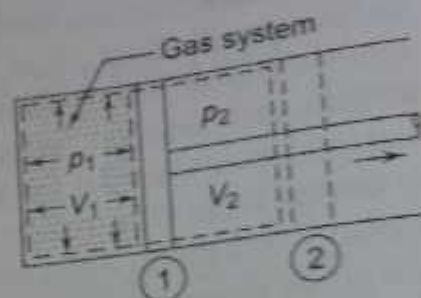


Fig. 3.4 pdV work

3.2.1 pdV -Work in Various Quasi-Static Processes

1. Constant pressure process (Fig. 3.6) (isobaric or isopiestic process)

$$W_{1-2} = \int_{V_1}^{V_2} p dV = p(V_2 - V_1) \quad (3.2)$$

2. Constant volume process (Fig. 3.7) (isochoric process)

$$W_{1-2} = \int p dV = 0 \quad (3.3)$$

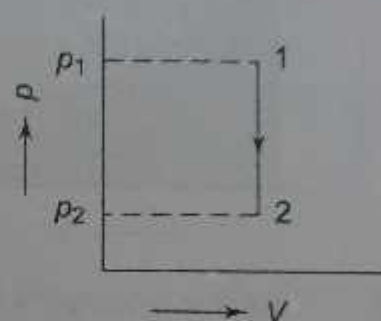
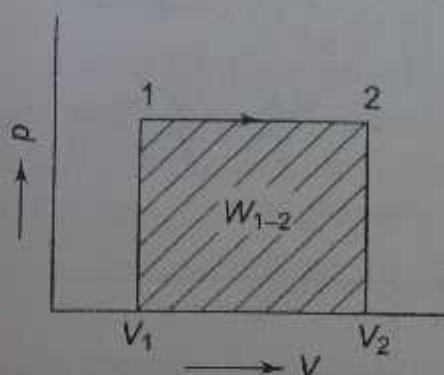


Fig. 3.6 Constant pressure process

Fig. 3.7 Constant volume process

3. Process in which $pV = C$ (Fig. 3.8) (isothermal process)

$$\begin{aligned} \therefore W_{1-2} &= \int_{V_1}^{V_2} p dV & pV &= p_1 V_1 = C \\ & & p &= \frac{(p_1 V_1)}{V} \\ W_{1-2} &= p_1 V_1 \int_{V_1}^{V_2} \frac{dV}{V} = p_1 V_1 \ln \frac{V_2}{V_1} \\ &= p_1 V_1 \ln \frac{p_1}{p_2} \end{aligned} \quad (3.4)$$

4. Process in which $pV^n = C$, where n is a constant (Fig. 3.9) (polytropic process).

$$\begin{aligned} pV^n &= p_1 V_1^n = p_2 V_2^n = C \\ \therefore p &= \frac{(p_1 V_1^n)}{V^n} \\ \therefore W_{1-2} &= \int_{V_1}^{V_2} p dV = \int_{V_1}^{V_2} \frac{p_1 V_1^n}{V^n} \cdot dV = (p_1 V_1^n) \left[\frac{V^{-n+1}}{-n+1} \right]_{V_1}^{V_2} \\ &= \frac{p_1 V_1^n}{1-n} (V_2^{1-n} - V_1^{1-n}) = \frac{p_2 V_2^n \times V_2^{1-n} - p_1 V_1^n \times V_1^{1-n}}{1-n} \\ &= \frac{p_1 V_1 - p_2 V_2}{n-1} = \frac{p_1 V_1}{n-1} \left[1 - \left(\frac{p_2}{p_1} \right)^{\frac{n-1}{n}} \right] \end{aligned} \quad (3.5)$$

Similarly, for process in which $pV^\gamma = c$, where $\gamma = c_p/c_v$,

$$W_{1-2} = \frac{P_1 V_1}{n-1} \left[1 - \left(\frac{P_2}{P_1} \right)^{\frac{\gamma-1}{\gamma}} \right] \quad (3.5a)$$

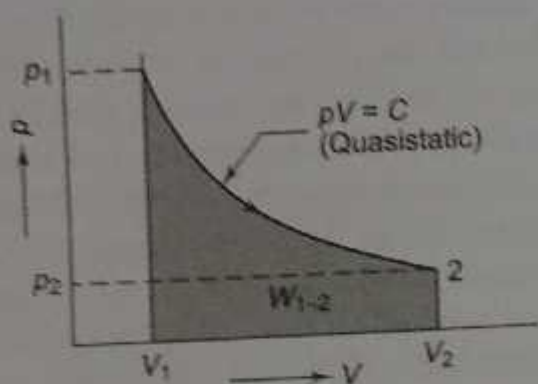


Fig. 3.8 Process in which $pV = \text{Constant}$

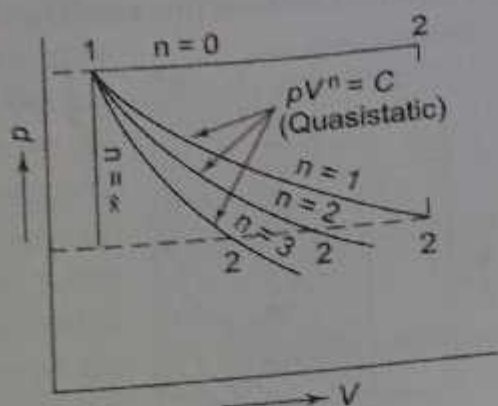


Fig. 3.9 Process in which $pV^n = \text{Constant}$

3.3 PATH FUNCTION AND POINT FUNCTION

With reference to Fig. 3.10, it is possible to take a system from state 1 to state 2 along many quasi-static paths, such as A, B or C. Since the area under each curve represents the work for each process, the amount of work involved in each case is not a function of the end states of the process, and it depends on the path the system follows in going from state 1 to state 2. For this reason, work is called a *path function*, and dW is an *inexact or imperfect differential*.

Thermodynamic properties are *point functions*, since for a given state, there is a definite value for each property. The change in a thermodynamic property of a system in a change of state is independent of the path the system follows during the change of state, and depends only on the initial and final states of the system. The differentials of point functions are *exact or perfect differentials*, and the integration is implied.

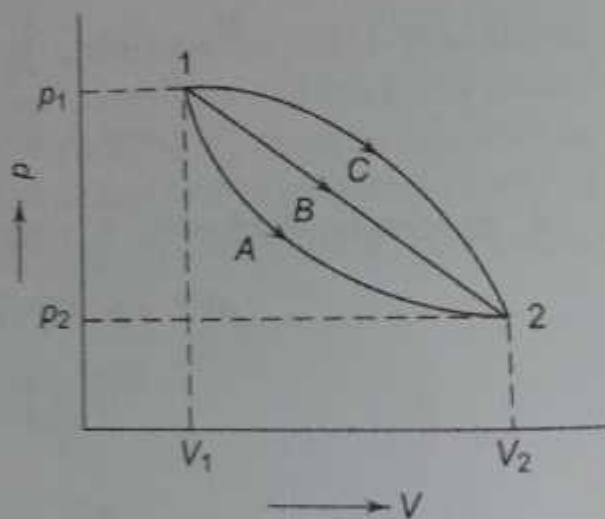


Fig. 3.10 Work—A path function

$$\int_{V_1}^{V_2} dV = V_2 - V_1$$

The change in volume thus depends only on the end states of the system irrespective of the path the system follows. realized
On the other hand, work done in a quasi-static process between two given states depends on the path followed.

LO 3.3

Explain the concept of path and point function

3.5 OTHER TYPES OF WORK TRANSFER

There are forms of work other than pdV or displacement work. The followings are the additional types of work transfer which may get involved in system-surroundings interactions.

1. Electrical work When a current flows through a resistor (Fig. 3.13), taken as a system, there is a work transfer into the system. This is because the current can drive a motor, the motor can drive a pulley and the pulley can raise a weight.

The current flow, I , in amperes, is given by

$$I = \frac{dC}{d\tau}$$

where C is the charge in coulombs and τ is time in seconds. Thus dC is the charge crossing a boundary during time $d\tau$. If E is the voltage potential, the work is

$$\begin{aligned} dW &= E \cdot dC \\ &= EI d\tau \end{aligned}$$

$$\therefore W = \int_1^2 EI d\tau \quad (3.12)$$

The electrical power will be

$$W = \lim_{d\tau \rightarrow 0} \frac{dW}{d\tau} = EI \quad (3.13)$$

This is the rate at which work is transferred.

2. Shaft work When a shaft, taken as the system (Fig. 3.14a), is rotated by a motor, there is work transfer into the system. This is because the shaft can rotate a pulley which can raise a weight. If T is the torque applied to the shaft and $d\theta$ is the angular displacement of the shaft, the shaft work is

$$W = \int_1^2 T d\theta \quad (3.14)$$

and the shaft power is

$$W = \int_1^2 T \frac{d\theta}{d\tau} = T\omega \quad (3.14b)$$

where ω is the angular velocity and T is considered a constant in this case.

LO 3.5
Identify and discuss work transfers other than displacement work

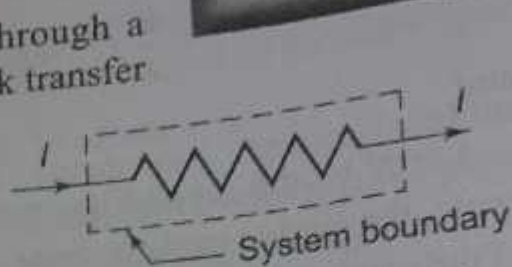


Fig. 3.13 Electrical work

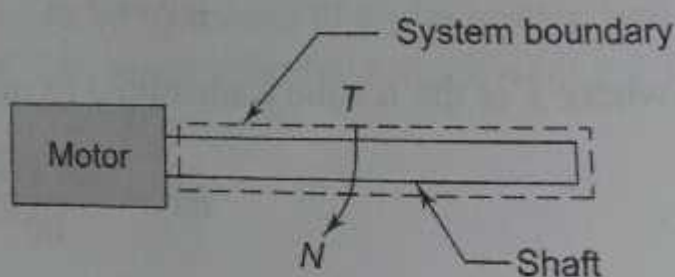


Fig. 3.14(a) Shaft work

Some common shaft work machines are shown in Fig. 3.14(b).

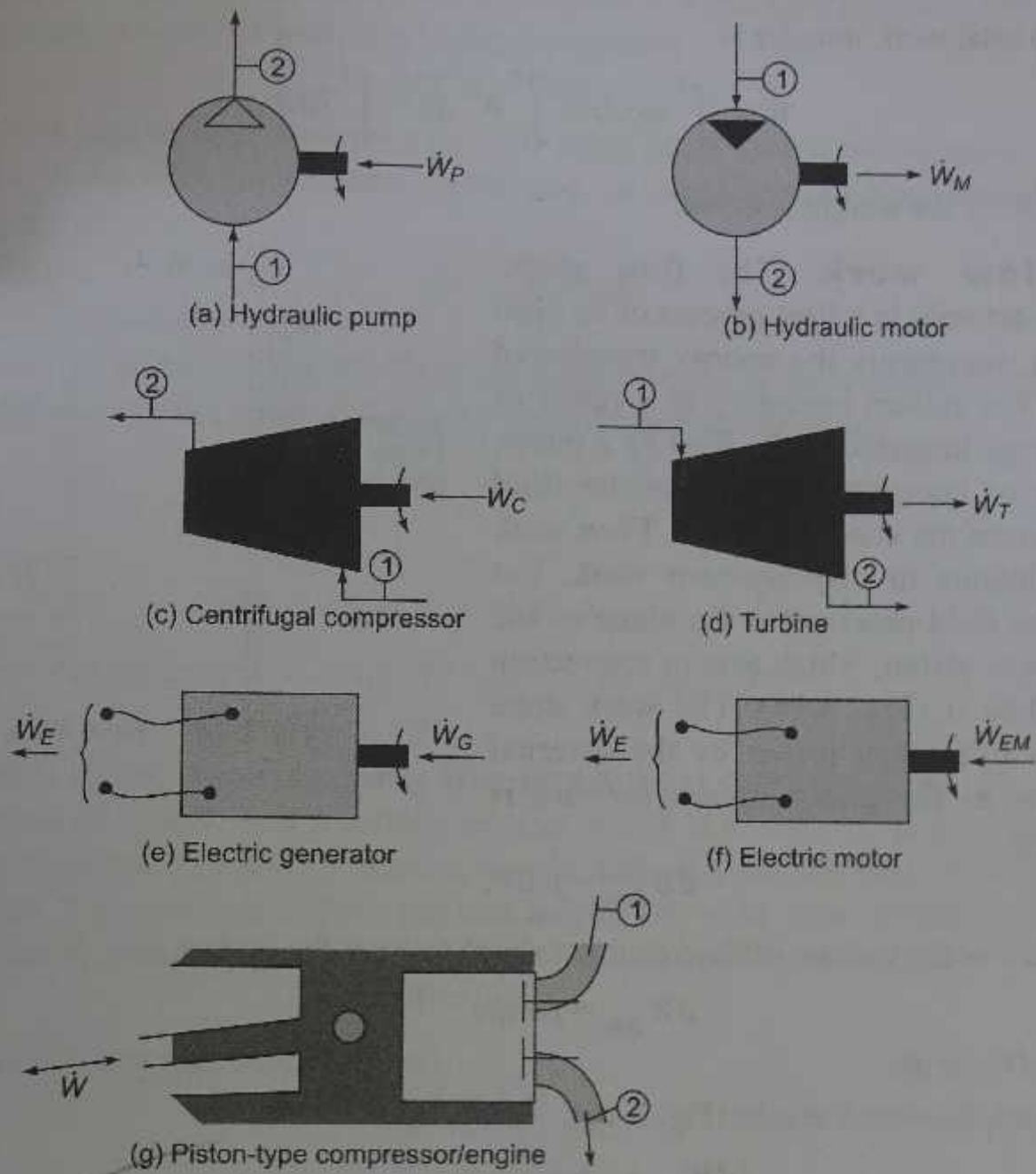


Fig. 3.14(b) Graphical symbols for common shaft work machines

3. Paddle-wheel work or stirring work As the weight is lowered, and the paddle wheel turns (Fig. 3.15), there is work transfer into the fluid system which gets stirred. Since the volume of the system remains constant, $\int pdV = 0$. If m is the mass of the weight lowered through a distance dz and T is the torque transmitted by the shaft in rotating through an angle $d\theta$, the differential work transfer to the fluid is given by

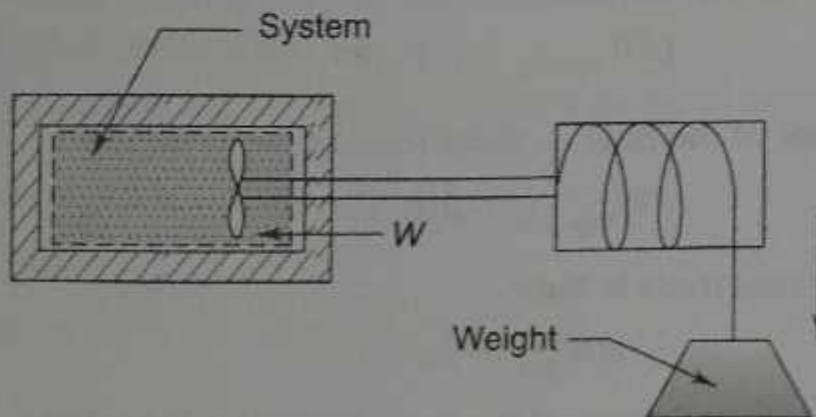


Fig. 3.15 Paddle-wheel work

$$dW = mgdz = Td\theta$$

(3.15)

and the total work transfer is

$$W = \int_1^2 mgdz = \int_1^2 W' dz = \int_1^2 Td\theta$$

where W' is the weight lowered.

4. Flow work The flow work, significant only in a flow process or an open system, represents the energy transferred across the system boundary as a result of the energy imparted to the fluid by a pump, blower or compressor to make the fluid flow across the control volume. Flow work is analogous to displacement work. Let p be the fluid pressure in the plane of the imaginary piston, which acts in a direction normal to it (Fig. 3.16). The work done on this imaginary piston by the external pressure as the piston moves forward is given by

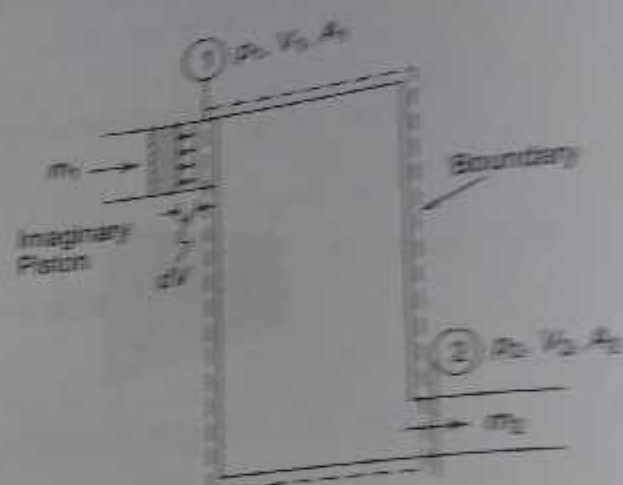


FIG. 3.16 Flow work

$$dW_{\text{flow}} = p dV,$$

(3.16)

where dV is the volume of fluid element about to enter the system.

$$\therefore dW_{\text{flow}} = p v dm$$

(3.17)

where $dV = v dm$

Therefore, flow work at inlet (Fig. 3.16),

$$(dW_{\text{flow}})_{\text{in}} = p_1 v_1 dm_1$$

(3.18)

Equation (3.18) can also be derived in a slightly different manner. If the normal pressure p_1 is exerted against the area A_1 , giving a total force ($p_1 A_1$) against the piston, in time $d\tau$, this force moves a distance $V_1 d\tau$, where V_1 is the velocity of flow (piston). The work in the time $d\tau$ is $p_1 A_1 V_1 d\tau$, or the work per unit time is $p_1 A_1 V_1$. Since the flow rate

$$w_1 = \frac{A_1 V_1}{v_1} = \frac{dm_1}{d\tau}$$

the work done in time $d\tau$ becomes

$$(dW_{\text{flow}})_{\text{in}} = p_1 v_1 dm_1$$

Similarly, flow work of the fluid element leaving the system is

$$(dW_{\text{flow}})_{\text{out}} = p_2 v_2 dm_2$$

(3.19)

The flow work per unit mass is thus

$$dW_{\text{flow}} = p v$$

It is the displacement work done at the moving system boundary.

(3.20)

5. Work done in stretching a wire Let us consider a wire as the system. If the length of the wire in which there is a tension F is changed from L to $L + dL$, the infinitesimal amount of work that is done is equal to

$$dW = - F dL$$

The minus sign is used because a positive value of dL means an expansion of the wire, for which work must be done on the wire, i.e. negative work. For a finite change of length,

$$W = - \int_1^2 F dL \quad (3.21)$$

If we limit the problem to within the elastic limit, where E is the modulus of elasticity, s is the stress, ϵ is the strain and A is the cross-sectional area, then

$$F = sA = E\epsilon A, \text{ since } \frac{s}{\epsilon} = E$$

$$d\epsilon = \frac{dL}{L}$$

$$dW = - F dL = - E\epsilon AL d\epsilon$$

$$\therefore W = - A\epsilon L \int_1^2 \epsilon d\epsilon = - \frac{AEL}{2} (\epsilon_2^2 - \epsilon_1^2) \quad (3.22)$$

6. Work done in changing the area of a surface film A film on the surface of a liquid has a surface tension, which is a property of the liquid and the surroundings. The surface tension acts to make the surface area of the liquid a minimum. It has the unit of force per unit length. The work done on a homogeneous liquid film in changing its surface area by an infinitesimal amount dA is

$$dW = - \sigma dA$$

where σ is the surface tension (N/m).

$$\therefore W = - \int_1^2 \sigma dA \quad (3.23)$$

7. Magnetisation of a paramagnetic solid The work done per unit volume on a magnetic material through which the magnetic and magnetisation fields are uniform is

$$dW = - HdI$$

and

$$W_{1-2} = - \int_{I_1}^{I_2} HdI \quad (3.24)$$

where H is the field strength, and I is the component of the magnetisation field in the direction of the field. The minus sign provides that an increase in magnetisation (positive dI) involves negative work.

The following equations summarise the different forms of work transfer:

Displacement work
(compressible fluid) $W = \int_1^2 p dV$

Electrical work $W = \int_1^2 E dC = \int_1^2 EI d\tau$

3.7 NET WORK DONE BY A SYSTEM

Often different forms of work transfer occur simultaneously during a process executed by a system. When all these work interactions have been evaluated, the total or net work done by the system would be equal to the algebraic sum of these as given below:

$$W_{\text{total}} = W_{\text{displacement}} + W_{\text{shear}} + W_{\text{electrical}} + W_{\text{stirring}} + \dots$$

3.8 HEAT TRANSFER

If a system has a non-adiabatic boundary, its temperature is not independent of the temperature of the surroundings, and for the system between the states 1 and 2, the work W depends on the path, and the differential dW is inexact.

The work depends on the terminal states 1 and 2 as well as the non-adiabatic path connecting them. For consistency with the principle of conservation of energy, some other type of energy transfer besides work must have taken place between the system and surroundings. This type of energy transfer must have occurred because of the temperature difference between the system and its surroundings, and it is identified as 'heat'. Thus, when an effect in a system occurs solely as a result of temperature difference between the system and some other system, the process in which the effect occurs shall be called a transfer of heat from the system at the higher temperature to the system at the lower temperature.

Heat is defined as the form of energy that is transferred across a boundary by virtue of a temperature difference. The temperature difference is the 'potential' or 'force' and heat transfer is the 'flux'.

LO 3.7

Define heat transfer and its sign convention

The transfer of heat between two bodies in direct contact is called *conduction*. Heat may be transferred between two bodies separated by empty space or gases by the mechanism of *radiation* through electromagnetic waves. A third method of heat transfer is *convection* which refers to the transfer of heat between a wall and a fluid system in motion.

The direction of heat transfer is taken from the high temperature system to the low temperature system. *Heat flow into a system is taken to be positive, and heat flow out of a system is taken as negative* (Fig. 3.18). The symbol Q is used for heat transfer, i.e. the quantity of heat transferred within a certain time.

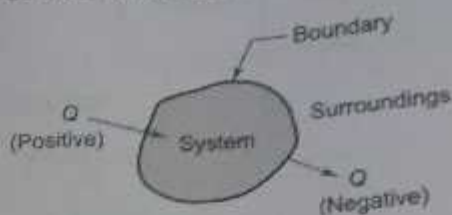


Fig. 3.18 Direction of heat transfer

Heat is a form of energy in transit (like work transfer). It is a boundary phenomenon, since it occurs only at the boundary of a system. Energy transfer by virtue of temperature difference only is called *heat transfer*. All other energy interactions may be termed as work transfer.

Heat is not that which inevitably causes a temperature rise. When heat is transferred to an ice-and-water mixture, the temperature does not rise until all the ice has melted. When a temperature rise in a system occurs, it may not be due to heat transfer, since a temperature rise may be caused by work transfer also. Heat, like work, is not a conserved quantity, and is not a property of a system.

A process in which no heat crosses the boundary of the system is called an *adiabatic process*.

Thus, an adiabatic process is one in which there is only work interaction between the system and its surroundings.

A wall which is impermeable to the flow of heat is an *adiabatic wall*, whereas a wall which permits the flow of heat is a *diathermic wall*.

The unit of heat is Joule in S.I. units.

The rate of heat transfer or work transfer is given in kW or W.

3.9 HEAT TRANSFER—A PATH FUNCTION

The heat flow Q in a process can be quantified in terms of the work W done in the same process between two given terminal states. Work W is different for different non-adiabatic processes between these two states and it is not conserved. However, from the principle of conservation of energy, the difference $(Q - W)$ is conserved for all paths between the same two states. The heat flow Q , like W , depends on the process and is path-dependent and not a property.

Heat transfer is a *path function*, that is, the amount of heat transferred when a system changes from state 1 to state 2 depends on the intermediate states through which the system passes, i.e. its path. Therefore, dQ is an inexact differential and we write

LO 3.8

Illustrate heat and work transfer as path functions

$$\int_1^2 dQ = Q_{1-2} \quad \text{or} \quad {}_1Q_2$$

The displacement work is given by

$$W_{1-2} = \int_1^2 dW = \int_1^2 p dV$$

It is valid for a quasi-static process, and the work transfer involved is represented by the area under the path on p - v diagram (Fig. 3.19a). Whenever there is a difference in pressure, there will be displacement work. The pressure difference is the cause and work transfer is the effect. The work transfer is equal to the integral of the product of the intensive property, p and the differential change in the extensive property, dV .

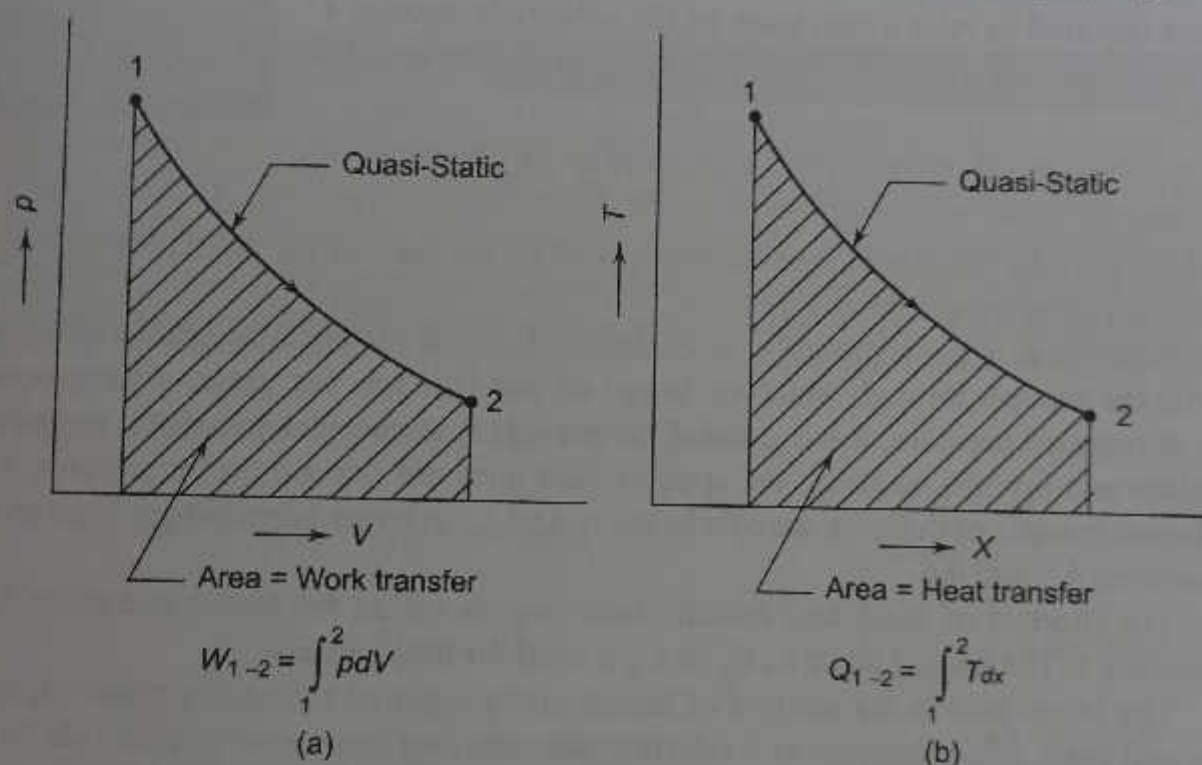


Fig. 3.19 Representation of work transfer and heat transfer in quasi-static processes on p - v and T - x coordinates

Likewise, whenever there is a difference in temperature, there will be heat flow. The temperature difference is the cause and heat transfer is the effect. Just like the displacement work, the heat transfer can also be written as the integral of the product of the intensive property T and the differential change of an extensive property, say X (Fig. 3.19b).

$$Q_{1-2} = \int_1^2 dQ = \int_1^2 T dX \quad (3.26)$$

It must also be valid for a quasi-static process only, and the heat transfer involved is represented by the area under the path 1-2 in T - X plot (Fig. 3.19b). Heat transfer is, therefore, a path function, i.e. the amount of heat transferred when a system changes from state 1 to state 2 depends on the path the system follows (Fig. 3.19b). Therefore dQ is an inexact differential. Now,

5.6 THE CONSTANT-VOLUME AND CONSTANT-PRESSURE SPECIFIC HEATS

- In this section we will consider a homogeneous phase of a substance of constant composition. This phase may be a solid, a liquid, or a gas, but no change of phase will occur. We will then define a variable termed the *specific heat*, the amount of heat required per unit mass to raise the temperature by one degree. Since it would be of interest to examine the relation between the specific heat and other thermodynamic variables, we note first that the heat transfer is given by Eq. 5.10. Neglecting changes in kinetic and potential energies, and assuming a simple compressible substance and a quasi-equilibrium process, for which the work in Eq. 5.10 is given by Eq. 4.2, we have

$$\delta Q = dU + \delta W = dU + P dV$$

We find that this expression can be evaluated for two separate special cases:

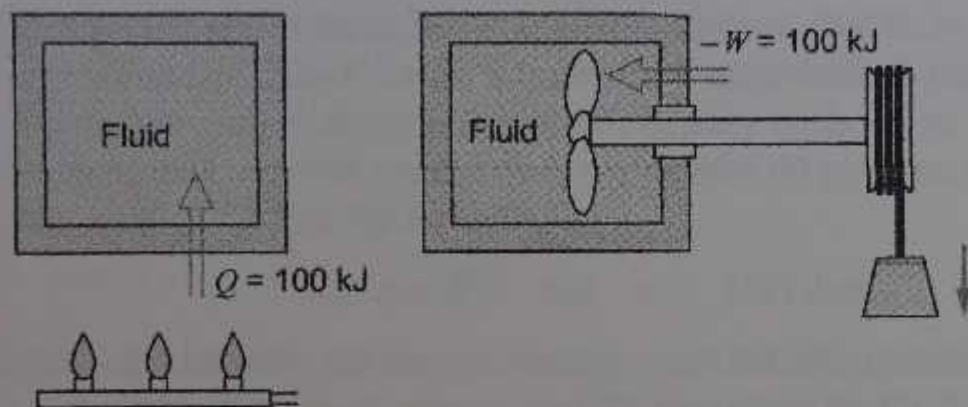
1. Constant volume, for which the work term ($P dV$) is zero, so that the specific heat (at constant volume) is

$$C_v = \frac{1}{m} \left(\frac{\delta Q}{\delta T} \right)_v = \frac{1}{m} \left(\frac{\partial U}{\partial T} \right)_v = \left(\frac{\partial u}{\partial T} \right)_v \quad (5.14)$$

2. Constant pressure, for which the work term can be integrated and the resulting PV terms at the initial and final states can be associated with the internal energy terms, as in Section 5.5, thereby leading to the conclusion that the heat transfer can be expressed in terms of the enthalpy change. The corresponding specific heat (at constant pressure) is

$$C_p = \frac{1}{m} \left(\frac{\delta Q}{\delta T} \right)_p = \frac{1}{m} \left(\frac{\partial H}{\partial T} \right)_p = \left(\frac{\partial h}{\partial T} \right)_p \quad (5.15)$$

Note that in each of these special cases, the resulting expression, Eq. 5.14 or 5.15, contains only thermodynamic properties, from which we conclude that the constant-volume and constant-pressure specific heats must themselves be thermodynamic properties. This means that, although we began this discussion by considering the amount of heat transfer required to cause a unit temperature change and then proceeded through a very specific development leading to Eq. 5.14 (or 5.15), the result ultimately expresses a relation among a set of thermodynamic properties and therefore constitutes a definition that is independent of the particular process leading to it (in the same sense that the definition of enthalpy in the previous section is independent of the process used to illustrate one situation in which the property is useful in a thermodynamic analysis). As an example, consider the two identical fluid masses shown in Fig. 5.9. In the first system 100 kJ of heat is transferred to it, and in the second system 100 kJ of work is done on it. Thus, the change of internal energy is the same for each, and therefore the final state and the final temperature are the same in each. In accordance with Eq. 5.14, therefore, exactly the same value for the average constant-volume specific heat would be found for this substance for the two processes, even though the two processes are very different as far as heat transfer is concerned.



Solids and Liquids

As a special case, consider either a solid or a liquid. Since both of these phases are nearly incompressible,

$$dh = du + d(Pv) \approx du + v dP \quad (5.16)$$

Also, for both of these phases, the specific volume is very small, such that in many cases

$$dh \approx du \approx C dT \quad (5.17)$$

where C is either the constant-volume or the constant-pressure specific heat, as the two would be nearly the same. In many processes involving a solid or a liquid, we might further assume that the specific heat in Eq. 5.17 is constant (unless the process occurs at low temperature or over a wide range of temperatures). Equation 5.17 can then be integrated to

$$h_2 - h_1 \approx u_2 - u_1 \approx C(T_2 - T_1) \quad (5.18)$$

Specific heats for various solids and liquids are listed in Tables A.3, A.4 and F.2, F.3.

In other processes for which it is not possible to assume constant specific heat, there may be a known relation for C as a function of temperature. Equation 5.17 could then also be integrated.

Temperature

Learning Objectives

After reading this chapter you should be able to

- LO 2.1 State Zeroth law of thermodynamics
- LO 2.2 Discuss the thermometric property of various thermometers and methods used for temperature measurement
- LO 2.3 Compare standard parameters of various thermometers
- LO 2.4 Describe ideal gas equation of state and gas thermometers
- LO 2.5 Explain how to use ideal gas concept to obtain ideal gas temperature scale
- LO 2.6 Relate Celsius temperature scale with ideal gas scale
- LO 2.7 Examine the thermometric property utilized in electrical resistance thermometer
- LO 2.8 Understand the principle of working of thermocouple
- LO 2.9 Discuss about international practical temperature scale and its need

2.1 ZEROTH LAW OF THERMODYNAMICS

The property which distinguishes thermodynamics from other sciences is temperature. One might say that temperature bears as important a relation to thermodynamics as force does to statics or velocity does to dynamics. Temperature is associated with the ability to distinguish hot from cold. When two bodies at different temperatures are brought into contact, after sometime they attain a common temperature and are then said to exist in thermal equilibrium.

When a body A is in thermal equilibrium with a body B, and also separately with a body C, then bodies B and C will be in thermal equilibrium with each other.

This is known as the *zeroth law of thermodynamics*. It is the basis of temperature measurement.

In order to obtain a quantitative measure of temperature, a reference body is used, and a certain physical characteristic of this body which changes with temperature is selected. The changes in the selected characteristic may be taken as an indication

LO 2.1

State Zeroth law of thermodynamics

of changes in temperature. The selected characteristic is called the *thermometric property*, and the reference body which is used in the determination of temperature is called the *thermometer*. A very common thermometer consists of a small amount of mercury in an evacuated capillary tube. In this case the extension of the mercury in the tube is used as the thermometric property.

There are five different kinds of thermometer, each with its own thermometric property, as shown in Table 2.1.

2.2 MEASUREMENT OF TEMPERATURE—THE REFERENCE POINTS

The temperature of a system is a property that determines whether or not a system is in thermal equilibrium with other systems. If a body is at, say, 70°C , it will be 70°C , whether measured by a mercury-in-glass thermometer, resistance thermometer or constant volume gas thermometer. If X is the thermometric property, let us arbitrarily choose for the temperature common to the thermometer and *to all systems in thermal equilibrium with it* the following *linear* function of X :

LO 2.2

Discuss the thermometric property of various thermometers and methods used for temperature measurement

Table 2.1 *Thermometers and thermometric properties*

<i>Thermometer</i>	<i>Thermometric property</i>	<i>Symbol</i>
1. Constant volume gas thermometer	Pressure	p
2. Constant pressure gas thermometer	Volume	V
3. Electrical resistance thermometer	Resistance	R
4. Thermocouple	Thermal e.m.f.	ϵ
5. Mercury-in-glass thermometer	Length	L

- (c) The Fahrenheit temperature scale and the Rankine scale differ only in respect to the zero point of the scale, and the Fahrenheit degree and the rankine are units of exactly the same size.
- (d) The Fahrenheit degree is smaller than the Celsius degree by the factor 1.8; they are related exactly as the rankine and the kelvin.

All these relationships are easily seen in Fig. 1-3.

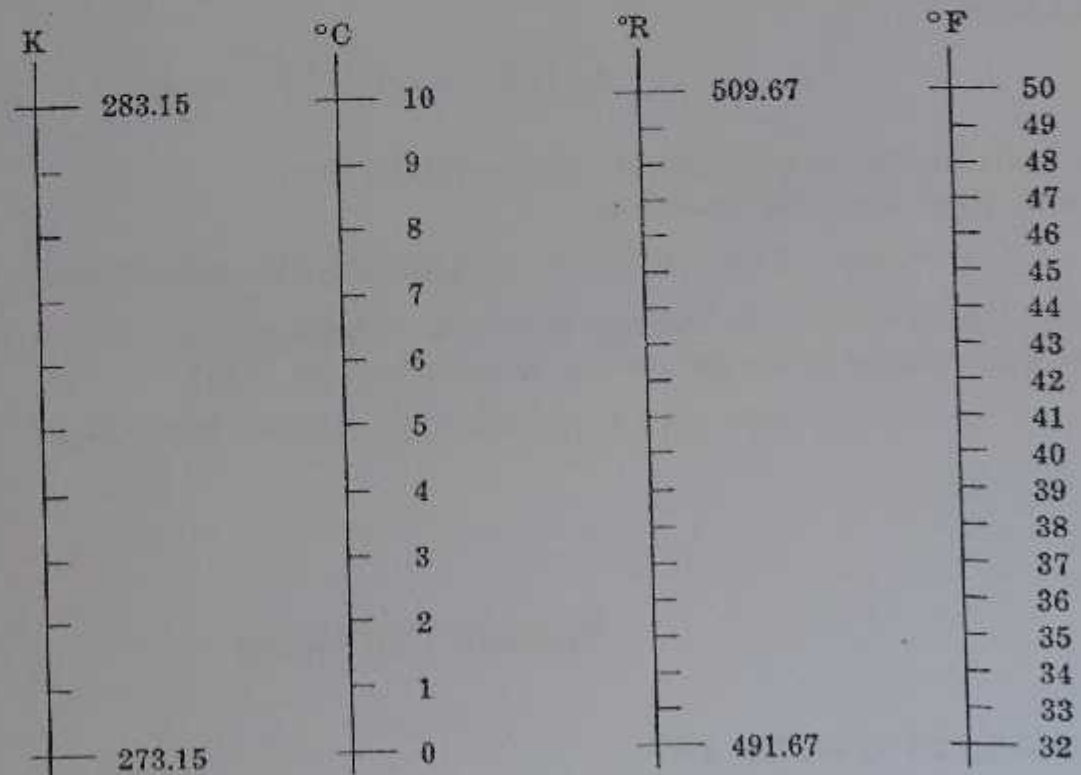


Fig. 1-3

$$^{\circ}\text{F} = \frac{9}{5} \text{C} + 32$$

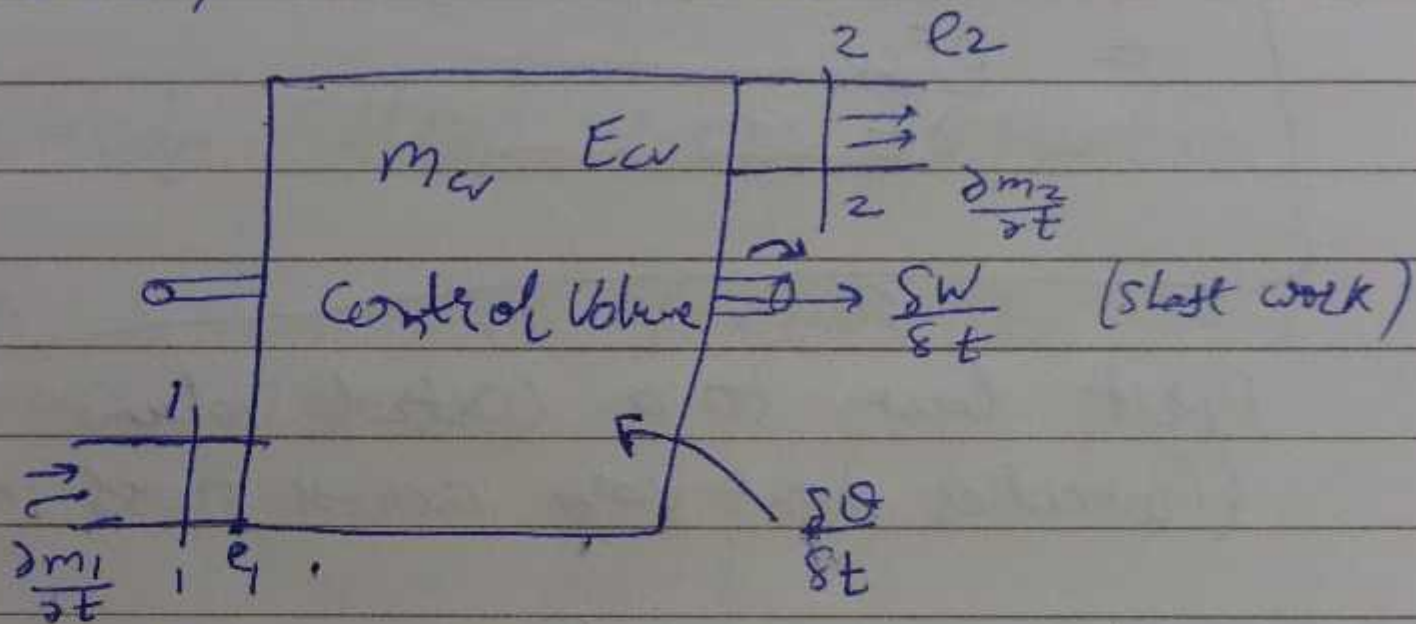
$$\text{F} = 1.8 \text{C} + 32$$

$$\text{R} = 1.8 \text{K}$$

$$\text{F} = \text{R} - 459.67$$

$$\text{F} = 1.8 \text{K} - 459.67$$

First law applied to open system / control volume



Conservation of mass

$$\frac{dm_1}{dt} - \frac{dm_2}{dt} = \frac{dm_{cv}}{dt}$$

Conservation of energy:

e (stored energy in a stream of fluid)

$$e = u + p v + \frac{V^2}{2} + g z$$

$$\frac{dm_1}{dt} e_1 \text{ (inlet energy)} \quad \frac{dm_2}{dt} e_2 \text{ (outlet energy)}$$

$$\frac{dm_1 e_1}{dt} + \frac{\delta Q}{\delta t} - \frac{dm_2 e_2}{dt} - \frac{\delta W}{\delta t} = \frac{\delta E_{cv}}{dt}$$

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$$\frac{dm_1}{dt} \left(u_1 + p_1 v_1 + \frac{V_1^2}{2} + g z_1 \right) + \frac{\delta Q}{\delta t} -$$

$$\frac{dm_2}{dt} \left(u_2 + p_2 v_2 + \frac{V_2^2}{2} + g z_2 \right) - \frac{\delta W}{\delta t}$$

$$= \frac{\partial E_{cv}}{\partial t}$$

First law to a Control Volume
(Properties don't vary across cross section)

at Steady State

$$\frac{\partial m_{cv}}{\partial t} = 0, \quad \frac{\partial E_{cv}}{\partial t} = 0$$

hence $\frac{\partial m_1}{\partial t} = \frac{\partial m_2}{\partial t} = \frac{\partial m}{\partial t}$ (Put above)

$$\frac{\partial m}{\partial t} \left(u_1 + p_1 v_1 + \frac{V_1^2}{2} + g z_1 \right) + \frac{\delta Q}{\delta t} - \frac{\partial m}{\partial t} \left(u_2 + p_2 v_2 + \frac{V_2^2}{2} + g z_2 \right) - \frac{\delta W}{\delta t} = 0$$

inlet

Date _____ outlet

$$\left(u_1 + p_1 \rho_1 + \frac{V_1^2}{2} + g z_1 \right) + \frac{\delta Q}{\delta m} - \left(u_2 + p_2 \rho_2 + \frac{V_2^2}{2} + g z_2 \right)$$

$$- \frac{\delta W}{\delta m} = 0$$

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

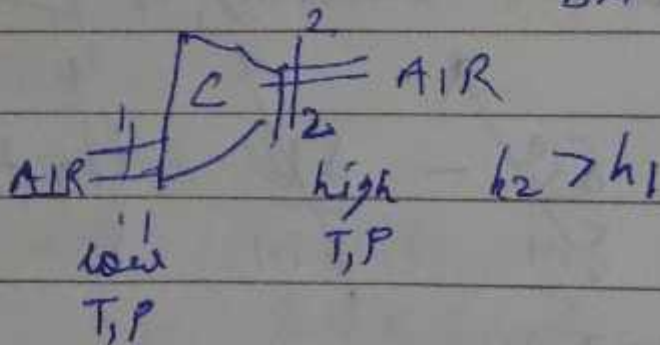
steady flow energy equation,

When K-E, P-E changes are small compared to h.

$$\frac{\delta Q}{\delta m} - \frac{\delta W}{\delta m} = h_2 - h_1$$

For work interacting device $\frac{\delta Q}{\delta m} = 0$

$$\frac{\delta W}{\delta m} = h_1 - h_2$$



Compressor, takes
work. as $\frac{\delta W}{\delta m} < 0$

4.3.1 Hydroturbine

In a hydroturbine water flows from a height and strikes the turbine blades to generate electricity (Figure 4.2). Through the process, the height at exit can be considered zero if the shaft height is considered as datum. Also, the specific volume is not going to change before and after impact. There can be no effective heat transfer either. As there is no change in temperature, the change in internal energy becomes zero. Water does work meaning the work is done by the system and hence, it is positive in the equation.

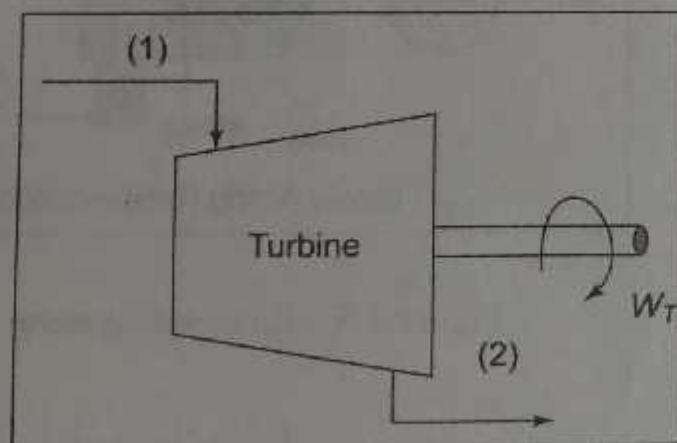


Figure 4.2 Hydroturbine system

Thus, in summary,

$$z_2 = 0; V_2 = V_1 = V; Q = 0; U_2 - U_1 = 0$$

Substituting in the general equation,

$$0 = m \left[(U_2 - U_1) + (p_2 V_2 - p_1 V_1) + \frac{1}{2} (v_2^2 - v_1^2) + (z_2 g - z_1 g) \right] + W$$

$$0 = m \left[(p_2 - p_1) V + \frac{1}{2} (v_2^2 - v_1^2) - z_1 g \right] + W$$

1. Derive the equation for a flow in hydroturbine from the Steady Flow Energy Equation (SFEE).
2. State the Steady Flow Energy Equation and explain how this equation can be applied for (i) Nozzle, (ii) Boiler, and (iii) Steam Turbine. (GTU, 2015)
3. Derive the equation for a flow in steam turbine from the Steady Flow Energy Equation (SFEE).
4. Derive the equation for a flow in centrifugal pump from the Steady Flow Energy Equation (SFEE).
5. Derive the equation for a flow in centrifugal compressor from the Steady Flow Energy Equation (SFEE). Hence, derive the equation for the reciprocating pump.
6. Derive the equation for a flow in steam boiler from the Steady Flow Energy Equation (SFEE).
7. Derive the equation for a flow in condenser from the Steady Flow Energy Equation (SFEE).
8. Derive the equation for a flow in an evaporator from the Steady Flow Energy Equation (SFEE).
9. Derive the equation for a flow in nozzle from the Steady Flow Energy Equation (SFEE).
10. Derive the equation for a flow encountering a blunt body such as the nose of an airplane from the Steady Flow Energy Equation (SFEE).

4.3.2 Steam Turbine

In a steam turbine, steam from a steam generator or boiler impacts on the turbine blades (Figure 4.3). Therefore, the heights can be considered the same. Then the general equation reduces to:

$$Q = m \left[(U_2 - U_1) + (p_2 V_2 - p_1 V_1) + \frac{1}{2} (\vartheta_2^2 - \vartheta_1^2) \right] + W$$

$$Q = m \left[(H_2 - H_1) + \frac{1}{2} (\vartheta_2^2 - \vartheta_1^2) \right] + W$$

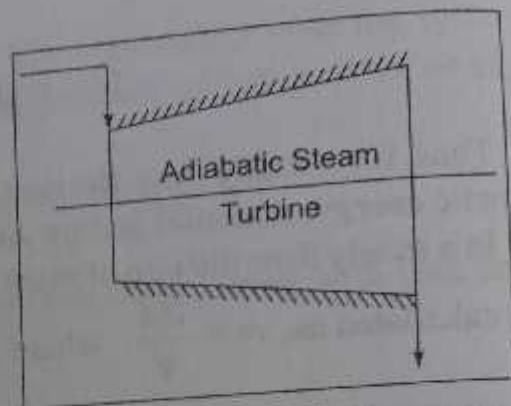


Figure 4.3 Steam turbine system

4.3.3 Centrifugal Pump

A centrifugal water pump is used to draw water from a lower level to pump to a higher level as required (Figure 4.4). Work is required to run the pump and this may be supplied from an external source such as an electric motor or a diesel engine. Here, there is no heat transfer. Therefore, $Q = 0$ and the internal energy, $\Delta U = 0$ as there is no change in temperature of water; Further, the inlet and exit volumes are the same $V_1 = V_2 = V$ (Figure 4.5). Applying these to the steady flow equation,

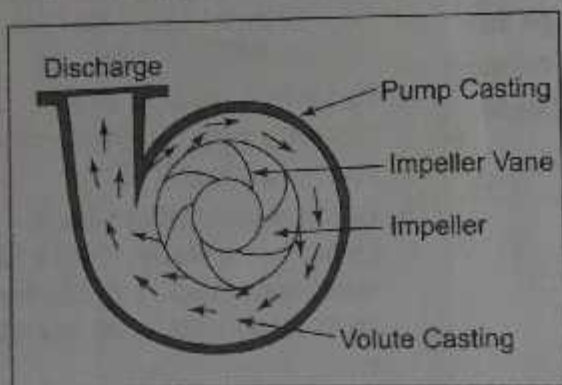


Figure 4.4 Centrifugal pump

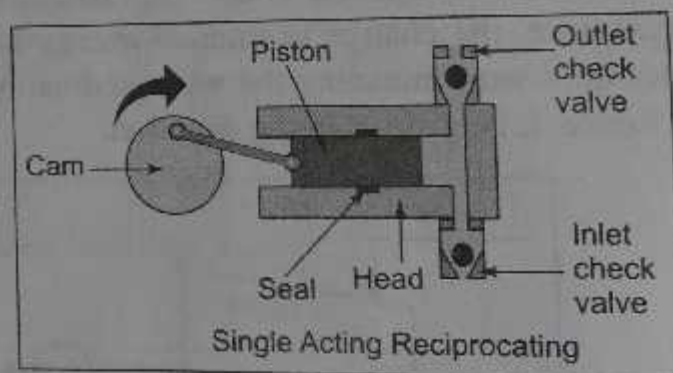


Figure 4.5 Reciprocating pump

$$Q = m \left[(U_2 - U_1) + (p_2 V_2 - p_1 V_1) + (z_2 g - z_1 g) + \frac{1}{2} (\vartheta_2^2 - \vartheta_1^2) \right] + W$$

$$m \left[(p_2 - p_1)V + (z_2 - z_1)g + \frac{1}{2} (\vartheta_2^2 - \vartheta_1^2) \right] + W = 0$$

Note: W would be negative as the work is done on the system.

4.3.4 Centrifugal Compressor

For an air compressor, the incoming and exit pressures are the same and generally the exit and entry are at the same height (Figure 4.6). The heat is taken out of the system while the work is done on the system (Figure 4.7). Therefore, both are negative. Substituting these the general equation turns out to be:

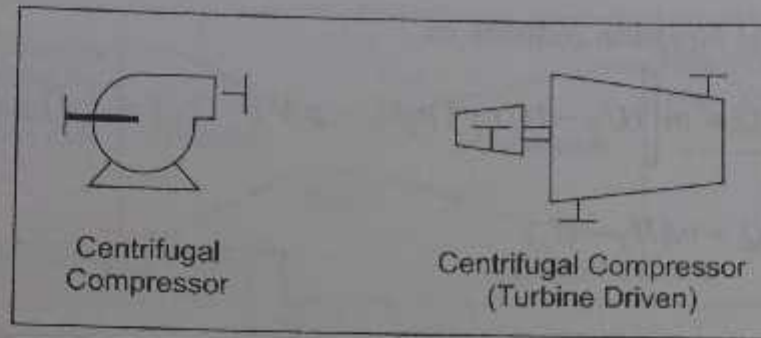


Figure 4.6 Centrifugal compressor

$$Q = m \left[(U_2 - U_1) + (p_2 V_2 - p_1 V_1) + (z_2 g - z_1 g) + \frac{1}{2} (\vartheta_2^2 - \vartheta_1^2) \right] + W$$

$$-Q = m \left[H_2 - H_1 + \frac{1}{2} (\vartheta_2^2 - \vartheta_1^2) \right] - W$$

For a reciprocating compressor, the velocities are also equal. Therefore, it reduces to:

$$-Q = m[H_2 - H_1] - W$$

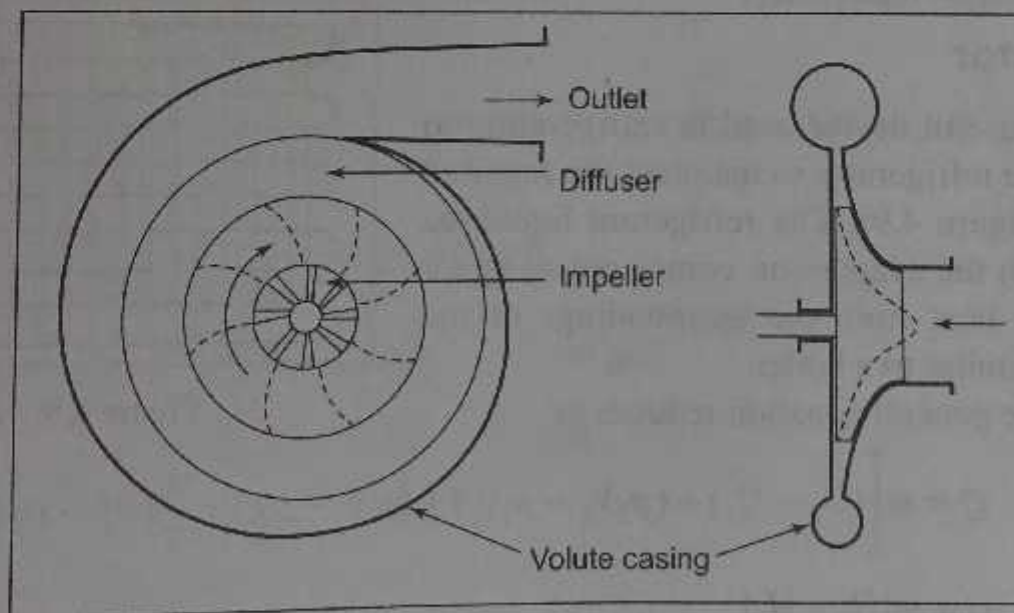


Figure 4.7 Schematic diagram of centrifugal compressor

4.3.5 Steam Boiler

For a steam boiler, it generates steam due to heat supplied by heat from below. Therefore, changes in the energy due to elevation and kinetic energy are zero. Also, no work is done on the system or by the system.

In such a case, the general equation reduces to:

$$Q = m \left[(U_2 - U_1) + (p_2V_2 - p_1V_1) + (z_2g - z_1g) + \frac{1}{2}(\vartheta_2^2 - \vartheta_1^2) \right] + W$$

$$-Q = m[H_2 - H_1]$$

4.3.6 Condenser

A condenser is used to condense steam or other vapors to their liquid form (Figure 4.8). Both the potential and kinetic energies appear small before enthalpies and hence can be neglected. There is no work done either.

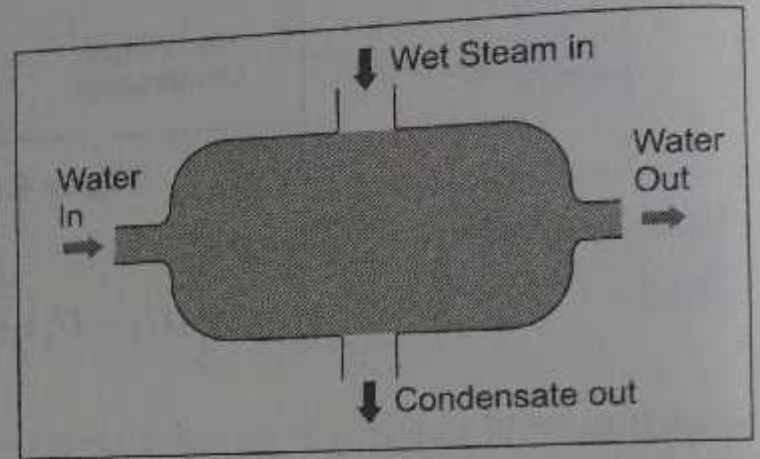


Figure 4.8 Water-cooled surface type condenser

In such a case, the general equation reduces to:

$$Q = m \left[(U_2 - U_1) + (p_2V_2 - p_1V_1) + (z_2g - z_1g) + \frac{1}{2}(\vartheta_2^2 - \vartheta_1^2) \right] + W$$

$$-Q = m[H_2 - H_1]$$

4.3.7 Evaporator

An evaporator is a useful device used in refrigeration to extract heat from the refrigerator to maintain the required low temperature (Figure 4.9). The refrigerant liquid, as it passes out through the evaporator, comes out as vapor absorbing its latent heat from the surroundings of the evaporator. This is similar to a boiler.

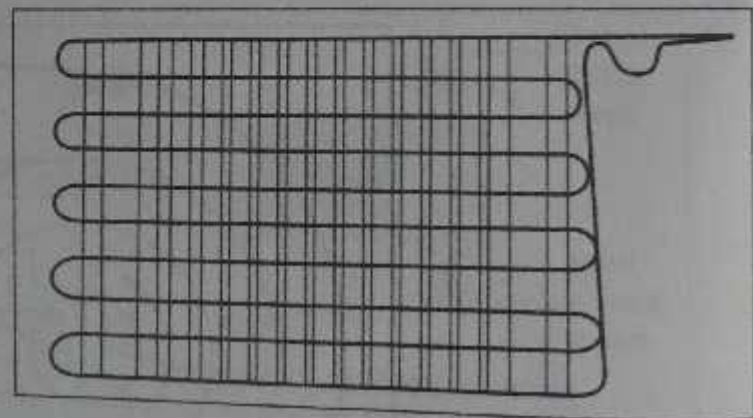


Figure 4.9 Evaporator

In such a case, the general equation reduces to:

$$Q = m \left[(U_2 - U_1) + (p_2V_2 - p_1V_1) + (z_2g - z_1g) + \frac{1}{2}(\vartheta_2^2 - \vartheta_1^2) \right] + W$$

$$Q = m[H_2 - H_1]$$

4.3.8 Nozzle

In case of a nozzle, the velocity increases due to change in kinetic energy at the cost of potential energy (Figure 4.10). This action also results in the decrease of enthalpy. A pressure drop is also observed. Thus, there is no heat transfer or work done and, therefore, the equation reduces to:

$$Q = m \left[(U_2 - U_1) + (p_2V_2 - p_1V_1) + (z_2g - z_1g) + \frac{1}{2}(\vartheta_2^2 - \vartheta_1^2) \right] + W$$

$$H_2 - H_1 + \frac{1}{2}(\vartheta_2^2 - \vartheta_1^2) = 0$$

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