1 Introduction

CHAPTER OUTLINE

OBJECTIVES

After studying this chapter, you will be able:

- To understand important thermodynamic properties
- To understand basics of thermodynamics
- To understand the laws of thermodynamics

1.1 Introduction

An element of mechanical engineering course is designed to understand concept and working of basic mechanical components and proves a prominent position of understanding concept of mechanical engineering. It basically consists of basics of thermodynamics, introduction to fundamental mechanical elements like belt, clutch, brakes, prime movers, concept of internal combustion engine, concept of refrigeration and engineering etc.

1.1.1 Sources of Energy

Basically sources of energy are classified in two ways:

(a) Conventional energy sources, like coal, crude, thermal power, hydro power, nuclear power etc.
(b) Non-conventional energy sources, which include solar energy, wind energy, tidal energy, geothermal energy and ocean wave energy, bio fuels etc.

1.1.2 Prime Movers

A prime mover is defined as a device which converts energy from natural sources to mechanical energy.

1.1.3 Types of Prime Movers

According to utilization of sources, prime movers are generally classified as follows:

(a) Thermal energy prime movers:
   - Steam engines
   - Steam turbines
   - Internal combustion engines
   - Gas turbine
   - Bio gas plant
   - Solar energy converter etc.
(b) Non-thermal energy prime movers
   - Electric motors
   - Hydraulic turbines
   - Wind mills etc.

1.2 Force, Mass and Weight

1.2.1 Mass (m)

Mass is amount of matter, which is independent of force acting on it and remains same at any location in universe.

The unit of mass is kilogram (Kg).

1.2.2 Force (F)

Force is a mass of unit acceleration. According to Newton's second law of motion, force is given by:

Force = Mass × Acceleration

= m × a

Unit of force is Newton or Kg-m/s^2.

1.2.3   *Weight (W)*

Weight is the force exerted due to gravity. It is given as:

Weight = mass × gravitational acceleration

Weight of the object varies in different places due to change in gravitational acceleration in universe, but mass remains constant.

1.3   *Pressure*

Pressure is defined as force per unit area. Thus, if a force F is applied to an area A, and if this force is uniformly distributed over the area, then the pressure P exerted is given by the equation

$$P = \frac{F}{A}$$ [1]

If F = force in newtons (N) and A = area in square metres (m^2) then the unit of pressure becomes the newton/metre^2 (N/m^2), which is the basic unit of pressure in the SI system of units. This unit of pressure is sometimes called the **pascal** (Pa).

Common multiples of this basic unit of pressure will be the kilonewton/metre^2 (1 kN/m^2 = 10^3 N/m^2) and the meganewton/metre^2 (1 MN/m^2 = 10^6 N/m^2). The **bar** may also be commonly used (1 bar = 10^5 N/m^2) as may also the **hectobar** (1 hbar = 10^{2}bar= 10^{7}N/m^2).

The bar is sometimes seen as being useful in that it is very nearly equal to one standard atmosphere.

1 standard atmosphere = 1.013 25 bar = 0.101 325 MN/m^2 [2]

If a force is applied to a solid then it will be transmitted through the solid in the direction of application of the force.

Fig. 1.1(a) shows a solid being pressed against a fixed wall by means of a force F. If the contact area is A then the pressure set up at the contact surface = F/A and it is normal to the contact surface.

On the other hand, Fig. 1.1(b) shows a piston of area A enclosing a fluid in a cylinder. If a force F is now applied to the piston then a pressure $P = F/A$ will be set up in the fluid. Unlike the solid, however, where this pressure would be transmitted in the line of action of the applied force, in the fluid, this pressure $P = F/A$ is set up in all directions in the cylinder. Any vessel then, in which there is a fluid under pressure, must be capable of withstanding the pressure in all directions. The fact that the pressure distribution in a fluid does occur in all directions is easily demonstrated by blowing up a balloon which swells up in all directions.
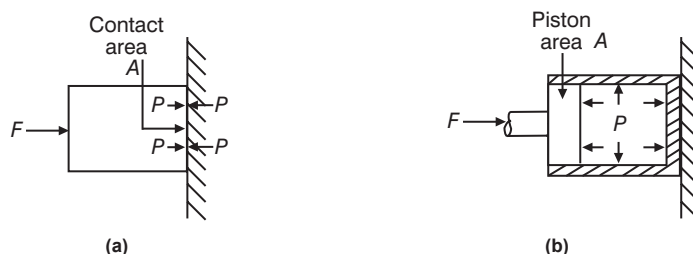
Fig. 1.1 Concept of pressure: (a) of a solid (b) using a piston

1.4 Volume

Volume is a property associated with cubic measure. The unit of volume is the cubic metre (m^3) together with its multiples and submultiples. Sometimes the litre (1) may be used. 1 litre = 1 cubic decimetre ($1 \text{ dm}^3 = (10^{-1} \text{ m})^3$).

If the volume of a substance increases then the substance is said to have been expanded. If the volume of a substance decreases then the substance is said to have been compressed. Specific volume is given the symbol *v*. The volume of any mass, other than unity, is given the symbol *V*.

1.5 Work

If a system exists in which a force at the boundary of the system is moved through a distance, then **work** is done by or on the system. As soon as the force ceases to be moved, it ceases to do any work. Work is therefore a **transient quantity;** it describes a process by which a force is moved through a distance. Work, being a transient quantity, is therefore not a property.

Work is given the symbol *W*. If it is required to indicate a rate at which work is being done then a dot is placed over the symbol *W*. Thus

$\dot{W}$ = work done/unit time

1.5.1 Work and P–V Diagram

Consider Fig. 1.2. In the lower half of the diagram is shown a cylinder in which a fluid at pressure *P* is trapped using a piston of area *A*. The fluid here is the system.

From this

Force on piston = pressure × area = *PA*   [1]

Let this force *PA* be just sufficient to overcome some external load.

Now let the piston move back a distance *L* along the cylinder while at the same time the pressure of the fluid remains constant. The force on the piston will have remained constant.

Work done = force × distance
$$= PA \times L \qquad\qquad [2]$$
This equation could be rearranged to read

Work done = $PA \times AL$
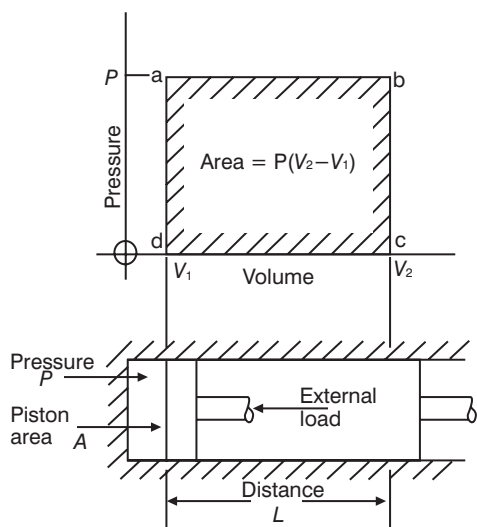
Fig. 1.2 Work and the *P–V* diagram

But

$\qquad$ AL = volume swept out by the piston, called the **swept** or **stroke** volume

$\qquad\qquad$ = $(V_2 - V_1)$

$\therefore$ $\quad$ Work done = $P(V_2 - V_1)$ $\hfill$ [3]

Above the diagram of the piston and cylinder is shown a graph of the operation plotted with the axes of pressure and volume. Such a graph is called a *P–V* diagram, sometimes said to be illustrated on a *P–V* plane. The graph appears as horizontal straight line *ab* whose height is at pressure *P* and whose length is from original volume V_1 to final volume V_2.

Now consider the area *abcd* under this graph.

$\qquad$ Area = $P(V_2 - V_1)$ $\hfill$ [4]

But this is the same as the right-hand side of equation [3].

Hence it follows that the area under a *P–V* diagram gives the work done. This can be shown to be true by an analysis of the units.

If the pressure is in newtons (N/m^2) and the volume is in cubic metres (m^3) then, by equation [3], the work done is given by the product of pressure and change in volume.

$\therefore$ $\quad$ Units of work done = $\dfrac{N}{m^2} \times m^3 = Nm$ $\hfill$ [5]

The unit, N m (newton-metre) is the unit of work, the joule.

$\qquad$ 1 N m = 1 J

Now the graph shown in Fig. 1.2 illustrates the particular case of constant pressure expansion.
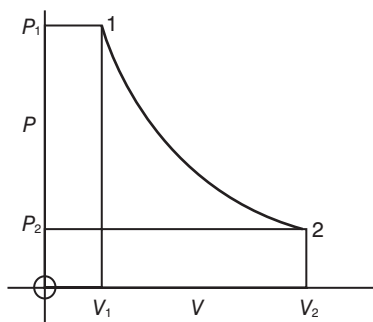
Fig. 1.3   Usual *P–V* diagram

Consider Fig. 1.3. Here is shown a *P–V* diagram of the type usually obtained when an expansion takes place in a thermal engine. It is now a curve with original pressure and volume P_1 and V_1 respectively. The final pressure and volume are P_2 and V_2, respectively. Both the pressure and the volume have changed in this case. What of the area under this graph and will it still give the work done?

Fig. 1.4 shows the same graph but this time it has been divided up into small rectangles. The area of each small rectangle represents work done as has been shown. The sum of all the areas of these small rectangles would therefore approximate very closely to the area under the graph and hence the work done. The greater the number of rectangles then the more nearly equal are the sum and the actual area, hence the actual work done. If the number of rectangles were made infinitely great, the sum would, in fact, equal the actual area, which would then give the actual work done. Now this is exactly what happens when the area is solved by the use of the integral calculus.
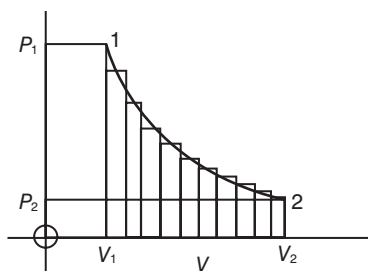
Fig. 1.4   Area division of *P–V* diagram

Consider Fig. 1.5. This is the same *P–V* diagram. Consider some point in the expansion, X say, where the pressure is *P* and the volume is *V*. Let there be an elemental expansion δV from this volume *V*.

Then

Work done during the elemental expansion $= P\delta V$ [6]

The total work done will be obtained by summing all the elemental strips of width δV from volume V_1 to volume V_2.
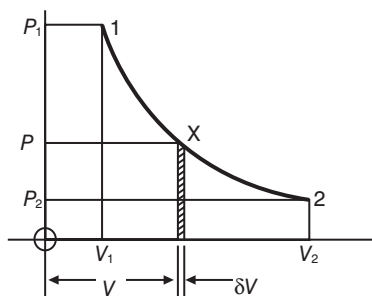
Fig. 1.5   Area calculation on *P−V* diagram

$$\therefore \quad \text{Total work done} = \sum_{V=V_1}^{V=V_2} P\delta V \qquad\qquad\qquad [7]$$

Now, if an infinite number of strips are taken, in which case δV becomes infinitely small (this is written as $\delta V \to 0$), then

$$\text{Work done} = \int_{V_1}^{V_2} P\mathrm{d}V \qquad\qquad\qquad [8]$$

It is important to note that the discussion has concentrated on expansion. In engines, however, many cases of compression are encountered. The compression is really the reverse of an expansion. What has been said about expansion, therefore, applies equally well to compression. The compression curve plotted on a *P−V* diagram has the same general shape as an expansion curve except that it is in a reverse direction. This means that the volume decreases while the pressure increases. The area under the curve, given by equation [6], gives the work done.

It should be noted the area for an expansion is positive, indicating that work is obtained from an expansion.

The area for a compression is negative, indicating that work must be done on the working fluid in order to compress it.

Example 1.1   *A fluid in a cylinder is at a pressure of 700 kN/m². It is expanded at constant pressure from a volume of 0.28 m³ to a volume of 1.68 m³. Determine the work done.*

SOLUTION

$$\text{Work done} = W = P(V_2 - V_2)$$
$$= 700 \times 10^3 \times (1.68 - 0.28)$$
$$= 7 \times 10^5 \times 1.4$$
$$= (9.8 \times 10^5)\,\text{N m}$$
$$= (9.8 \times 10^5)\,\text{J}$$
$$= 980\,\text{kJ}$$
$$= \mathbf{0.98\ MJ}$$

1.5.2 Work and Polytropic Process

Changes of state of working substances in thermodynamic systems are often brought about by the expansion or compression of the working substance.

Suppose that an experiment is conducted on a mass of working substance such that an expansion takes place changing the state from state 1 to state 2. Let the pressure change from P_1 to P_2 and the volume from V_1 to V_2. Assume that arrangements are made to record the pressure and volume as the experiment proceeds. From the results obtained, if values of pressure and volume are plotted on a $P-V$ graph, they produce a smooth curve as shown in Fig. 1.6.
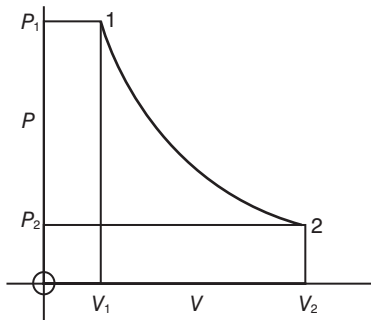
Fig. 1.6 General $P-V$ curve

Simply by inspection of the curve, it is not directly possible to tell whether there is a law connecting pressure and volume for the expansion carried out. However, suppose now that log P is plotted against log V. The graph obtained is as shown in Fig. 1.7. This is much better for the graph appears as a straight line and is of the form

$$\log P = -n \log V + \log C \tag{1}$$

where $-n =$ slope of the line
  $\log C =$ intercept on the log P axis

Now equation [1] can be rewritten

$$\log P + n \log V = \log C$$

or taking antilogs

$$PV^n = C, \text{ a constant} \tag{2}$$
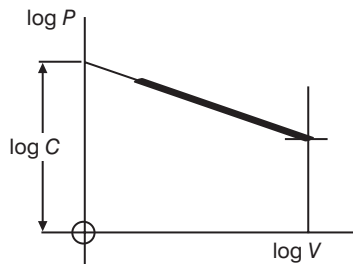
Fig. 1.7 Plot of log P against log V

Further experiments on different substances taking different quantities of substance also including the case of compression as well as expansion will yield a similar result. Equation [2] may therefore be considered as the law for the general case of expansion or compression of a substance. This general case of expansion or compression of a substance according to the law $PV^n = C$ is called a **polytropic expansion** or **compression** or a **polytrope.** It should be noted the value of the constant C will change with each change of condition, so also will the value of n, which is called the **index** of the expansion or compression, or the **polytropic exponent.**

Since all conditions of state during the expansion or compression lie on the curve $PV^n = C$, it follows that

$$P_1 V_1^n = P_2 V_2^n = P_3 V_3^n = P_4 V_4^n = \cdots, \text{etc.} \tag{3}$$

where 1**,** 2, 3, 4, etc., represent different conditions of state taken during the expansion or compression.

To give an idea of the value of the index n, it will generally lie within the range 1 to 1.7. For most cases, however, it will probably lie more closely within the range 1.2 to 1.5.

Further, note that if $n = 0$ the equation becomes

$$PV^0 = C, \text{ a constant} \tag{4}$$

and since $V^0 = 1$ then equation [4] becomes

$$P = C, \text{ a constant} \tag{5}$$

which indicates a constant pressure process.

Also, the equation $PV^n = C$ can be rearranged to read

$$P^{1/n}V = C, \text{ a constant} \tag{6}$$

This is obtained by taking the nth root of both sides. Now if $n = \infty$ then $p^{1/n} = p^{1/\infty} = p^0 = 1$, in which case, equation [6] becomes

$$V = C, \text{ a constant} \tag{7}$$

which indicates a constant volume process.

Example 1.2   *0.112 m^3 of gas has a pressure of 138 kN/m^2. It is compressed to 690 kN/m^2 according to the law $PV^{1.4} = C$. Determine the new volume of the gas.*

SOLUTION
Since the gas is compressed according to the law $PV^{1.4} = C$, then

$$P_1 V_1^{1.4} = P_2 V_2^{1.4}$$

$$\therefore \quad \frac{P_1}{P_2} = \left(\frac{V_2}{V_1}\right)^{1.4} \text{ or } \frac{V_2}{V_1} = \left(\frac{P_1}{P_2}\right)^{1/1.4}$$

from which

$$V_2 = V_1 \left(\frac{P_1}{P_2}\right)^{1/1.4} = V_1 \sqrt[1.4]{\frac{P_1}{P_2}}$$

$$= 0.112 \times \sqrt[1.4]{\frac{138}{690}} = 0.112 \sqrt[1.4]{\frac{1}{5}}$$

$$= \frac{0.112}{\sqrt[1.4]{5}} = \frac{0.112}{3.157}$$

$$= \mathbf{0.035\,5\,m}$$

If a substance is to be compressed from a lower pressure to a higher pressure then work will be required in order to carry out the compression. When the substance is at the new high pressure, it has the potential to expand and, in expanding, do some work. It is important to determine the magnitude of this quantity of work. It has already been shown that work done is given by the area under a $P-V$ diagram of an expansion or compression; now the problem is to determine the area under a curve of the form $PV^n = C$. Consider Fig. 1.8; it shows a $P-V$ graph of an expansion according to the law $PV^n = C$ from state P_1, V_1 to new state P_2, V_2.
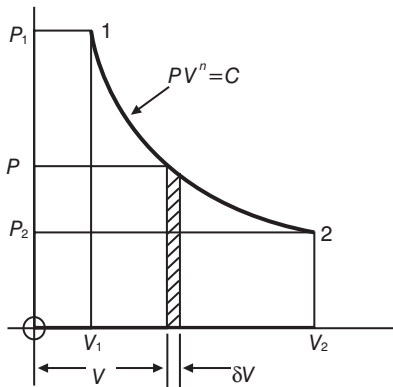
Fig. 1.8   Graph for $PVn = C$

Consider a point on the curve at which the pressure is P and the volume is V. Let the gas expand from this point by very small volume δV according to the law $PV^n = C$. The work done during this very small expansion is very nearly equal to $P\delta V$. In the limit, as $\delta V \to 0$, the area, and hence the work done $= PdV$. For the whole expansion from 1 and 2

$$\text{Work done} = \int_{V_1}^{V_2} PdV \tag{1}$$

Now $PV^n = C,$ or
$$P = C\,V^{-n} \tag{2}$$

Substituting equation [2] in equation [1]

$$\text{Work done} = C\int_{V_1}^{V_2} PdV \tag{3}$$

Integrating

$$\text{Work done} = \frac{C}{-n+1}\Big[V^{-n+1}\Big]_{V_1}^{V_2}$$

$$= \frac{C}{-n+1}\Big[V_2^{-n+1} - V_1^{-n+1}\Big]$$

$$= \frac{C}{-n+1}\Big[V_2^{-n}V_2 - V_1^{-n}V_1\Big]$$

$$= \frac{P_2V_2 - P_1V_1}{-n+1} \quad \text{(from equation [2])}$$

Multiplying top and bottom by −1

$$\text{Work done} = \frac{P_1V_1 - P_2V_2}{n-1} \qquad\qquad [4]$$

Equation [4] will apply equally well to an expansion or a compression.

By reading P_1, V_1 as the original conditions and P_2, V_2 as the final conditions it will be found that for an expansion, the work done is positive, meaning that work is done by the substance.

For a compression, however, again reading P_1, V_1 as the original conditions and P_2, V_2 as the final conditions, it will be found that the work done is negative, meaning that the work must be done on the substance.

Example 1.3   *0.014 m^3 gas at a pressure of 2070 kN/m^2 expands to a pressure of 207 kN/m^2 according to the law* $PV^{1.35} = C$. *Determine the work done by the gas during the expansion.*

SOLUTION

The work done during a polytropic expansion is given by

$$\text{Work done} = \frac{P_1V_1 - P_2V_2}{n-1}$$

In this problem V_2 is, as yet, unknown and must therefore be calculated.

Now $P_1V_1^n = P_2V_2^n$

$$\therefore \quad V_2 = V_1\left(\frac{P_1}{P_2}\right)^{1/n}$$

or

$$V_2 = 0.014 \times \left(\frac{2070}{207}\right)^{1/1.35} = 0.014 \times \sqrt[1.35]{10} = 0.014 \times 5.05$$

$$= \mathbf{0.077 m^3}$$

$$\therefore \quad \text{Work done} = \frac{(2070 \times 10^3 \times 0.014) - (207 \times 10^3 \times 0.0}{1.35 - 1}$$

$$= \frac{10^3}{0.35}(29 - 15.95) = \frac{10^3}{0.35} \times 13.05$$

$$= (37.3 \times 10^3) \text{N m}$$

$$= (37.3 \times 10^3) \text{J} \ (1 \text{ N m} = 1 \text{ J})$$

$$= \textbf{37.3 kJ}$$

1.5.3 Work and Hyperbolic Process

The hyperbolic process is a particular case of the polytropic process, $PV^n - C$, for $n = 1$.

Thus, the law for the hyperbolic process is

$$PV = C \tag{1}$$

This law, if plotted on a $P-V$ diagram will appear as a rectangular hyperbola, hence its name.

For a hyperbolic change from state 1 to state 2, from equation [1]

$$P_1 V_1 = P_2 V_2 \tag{2}$$

An expression for the work done during a polytropic process has already been determined. This has been shown to be

$$\text{Work done} = \frac{P_1 V_1 - P_2 V_2}{n - 1} \tag{3}$$

In the case of a hyperbolic process $P_1 V_1 = P_2 V_2$; substituting this in equation [3] together with the fact that $n = 1$ gives

$$\text{Work done} = \frac{P_1 V_1 - P_2 V_2}{n - 1} = \frac{0}{0}$$

This is indeterminate.

Now if the law $PV = C$ is plotted on a $P-V$ graph there is a definite area beneath the curve. So it appears that a start from first principles is necessary to determine this area.

Consider Fig. 1.9. By similar analysis to that given for the polytropic expansion

$$\text{Work done} = \int_{V_1}^{V_2} P \mathrm{d}V$$

In this case, however $PV = C$, hence $P = C/V$ and substituting this in equation [4] gives

$$\text{Work done} = C \int_{V_1}^{V_2} \frac{dV}{V} = C \left[\ln V \right]_{V_1}^{V_2}$$

$$= C[\ln V_2 - \ln V_1]$$

$$= C \ln \frac{V_2}{V_1} = PV \ln \frac{V_2}{V_1} \tag{5}$$

since $PV = C$. Here 1n represents $\log_e$.
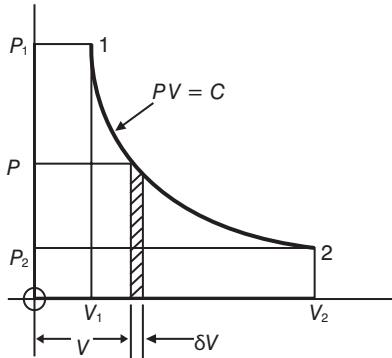
Fig. 1.9 Graph for *PV* = *C*

Now V_2/V_1 is the expression ratio, often designated by the letter *r*, so

Work done $= PV \ln r$ [6]

Example 1.4 *A gas is compressed hyperbolically from a pressure and volume of 100 kN/m² and 0.056 m³, respectively, to a volume of 0.007 m³. Determine the final pressure and the work done on the gas.*

Sᴏʟᴜᴛɪᴏɴ

Since the gas is compressed hyperbolically

$$P_1 V_1 = P_2 V_2 \text{ or } P_2 = P_1 \frac{V_1}{V_2} = 100 \times \frac{0.056}{0.007} = 100 \times 8$$

$$= \mathbf{800\ kN/m^2}$$

$$\text{Work done} = PV \ \text{In } r = PV \ln \frac{V_2}{V_1}$$

$$= 100 \times 10^3 \times 0.056 \ \ln \frac{0.007}{0.056}$$

$$= -100 \times 10^3 \times 0.056 \ \ln \frac{0.056}{0.007}$$

$$= -5.6 \times 10^3 \ \ln 8$$

$$= -5.6 \times 10^3 \times 2.079$$

$$= -(11.64 \times 10^3) \ \text{N m} \quad (10^3 \text{N m} = 1 \text{ kJ})$$

$$= -\mathbf{11.64\ kJ}$$

The work done on the gas is 11.64 kJ.

1.6 Temperature with Units

Temperature describes the degree of hotness or coldness of a body.

The subject of temperature investigation is called **thermometry.**

Many attempts have been made in the past to lay down a scale of temperature. The work has culminated in the generally accepted use of two temperature scales, **Fahrenheit** and **Celsius.** The Fahrenheit scale is named after its German inventor, Daniel Gabriel Fahrenheit (1686–1736) of Danzig (now Gdansk,

Poland). The Celsius scale (often referred to as the centigrade scale) is named after Anders Celsius (1701–1744), a Swedish astronomer born at Uppsala.

The Celsius scale is the temperature scale which is most commonly used worldwide. The Fahrenheit scale is generally becoming progressively phased out. The customary temperature scale adopted for use with the SI system of units is the Celsius scale. For customary use, the lower fixed point is the temperature of the melting of pure ice, commonly referred to as the freezing point. This point is designated 0 °C. The upper fixed point is the temperature at which pure water boils and this is designated 100 °C. In the past, this customary temperature scale has been referred to as the centigrade scale. The use of the word *centigrade* is now discouraged, the accepted reference now being that of the Celsius scale. Of interest, the freezing and boiling points of pure water are designated 32 °F and 212 °F, respectively, on the Fahrenheit scale.

It will be shown later, when dealing with the properties of solids, liquids and vapours, that the temperature at which a liquid freezes or boils depends upon the pressure exerted at the surface of the liquid. This temperature increases as the pressure increases in the case of boiling and slightly decreases with increase of pressure in the case of freezing. To standardise the freezing and boiling temperature on a thermometric scale, one must therefore standardise the pressure at which the freezing or boiling occurs. This pressure is taken as 760 mm of mercury which is called the **standard atmospheric pressure** or the **standard atmosphere,** being a mean representative pressure of the atmosphere.

Fig. 1.10 shows the way the customary Celsius scale is divided up. The lower fixed point is 0 °C and the upper fixed point is 100 °C; there are 100 Celsius degrees between them. These 100 Celcius degrees are together called the **fundamental interval.**
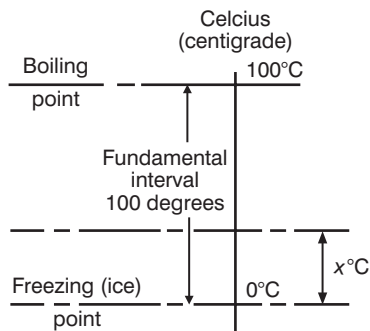
Fig. 1.10 Celsius scale of temperature

In the above discussion it will be noted that the choice of the fixed points was of an arbitrary nature. The freezing and boiling points of water were chosen for convenience. Other points on the **International Temperature Scale** are then chosen and referred to the originally conceived scale. The original choice of fixed points was arbitrary, so the Celsius scale is sometimes called the **normal,** the **empirical,** the **customary** or the **practical** temperature scale.

Since the Celsius scale is only a part of the more extensive **thermodynamic,** or **absolute** temperature scale, it is sometimes called a **truncated thermodynamic** scale. Subsequent work will show that there is the possibility of an absolute zero of temperature which will then suggest an **absolute temperature scale.**

An absolute zero of temperature would be the lowest temperature possible and therefore this would be a more reasonable temperature to adopt as the zero for a temperature scale. The absolute thermodynamic

temperature scale is called the **Kelvin** scale. It was devised by Lord Kelvin, a British scientist, in about 1851.

The Kelvin unit of temperature is called the **kelvin** and is given the symbol K. A temperature, T, on the Kelvin scale is written T K, not T °K. The kelvin has the same magnitude as the Celsius degree for all practical purposes.

The absolute zero of temperature appears impossible to reach in practice. However, its identity is defined by giving to the triple point of water a value of 273.16 kelvin (273.16 K). The triple point is defined in Chapter 4. With the absolute zero so defined, the zero of the Celsius thermodynamic scale is defined as 0 °C = 273.15 K.

Thus

$$t = T - 273.15 \tag{1}$$

where t = temperature on the Celsius thermodynamic scale = t °C
        T = temperature on the Kelvin thermodynamic scale = T K

From equation [1]

$$T = t + 273.15 \text{ (can use 273 for most calculations)} \tag{2}$$

By choosing the zero of the Celsius thermodynamic scale as 0 °C = 273.15 K, this approximates very closely to the customary Celsius scale and thus 0 °C on the customary Celsius scale is very nearly equal to 0 °C on the Celsius thermodynamic scale. Also, 100 °C on the customary Celsius scale is very nearly equal to 100 °C on the Celsius thermodynamic scale.

1.7   Heat

The discussion on internal energy suggested how bodies were once believed to contain heat. This is now not considered as being the case; the internal store of energy is now called internal energy, which is a property.

However, it was further suggested that, during an energy transfer process which results from the temperature difference between one body and another, the energy so transferred is called **heat.** The heat, having been transferred, will then disperse into other forms of energy, such as internal energy or work, the disposal being a function of the system employed.

Note that heat is a transient quantity; it describes the energy transfer process through a system boundary resulting from temperature different. If there is no temperature difference, there is no heat transfer.

And since the term *heat* is used to describe a transfer process, heat energy ceases to exist when the process finishes. Thus heat is not a property.

Heat energy is given the symbol Q. To indicate a rate of heat transfer, a dot is placed over the symbol, thus

$\dot{Q}$ = heat transfer/unit time

1.7.1   Specific Heat Capacity

For unit mass of a particular substance at a temperature t, let there be a change of temperature δt brought about by a transfer of heat δQ.

The specific heat capacity, *c*, of the substance at temperature *t* is defined by the ratio $\delta Q/\delta t$. Thus

$$c = \frac{\delta Q}{\delta t}$$ [1]

In the limit, as $\delta t \rightarrow 0$, then

$$c = \frac{\mathrm{d}Q}{\mathrm{d}t}$$ [2]

Specific heat capacity is generally found to vary with temperature. For example, the specific heat capacity of water falls slightly from a temperature of 0 °C to a minimum of about 35 °C and then begins to rise again.

Specific heat capacity can also vary with pressure and volume. This is particularly true of compressible fluids such as gases (see Chapter 3).

It is common practice to use an average value of specific heat capacity within a given temperature range.

This average value is then used as being constant within the temperature range, so equation [2] can be rewritten

$$c = \frac{Q}{\Delta t}$$ [3]

where Q = heat transfer/unit mass, J/kg
  Δt = change in temperature, K

Note that from equation [3] the basic unit for specific heat capacity is **joules/kilogram kelvin** or **J/kg K;** multiples such as kilojoules/kilogram kelvin (kJ/kg K) may also be used.

A particular application of specific heat capacity arises from the use of water as a measuring device in calorimetry. Temperature measurements during a calorimetric experiment are made while the pressure of the water remains constant.

A process in which the pressure remains constant is said to be **isobaric.** The specific heat capacity in this case is therefore said to be the **isobaric specific heat capacity** and is written c_p.

Table 1.1 gives a few examples of average specific heat capacities of some solids and liquids.

Table 1.1   Average specific heat capacities

Solid	Specific heat capacity (J/kg K)	Solid	Specific heat capacity (J/kg K)	Liquid	Specific heat capacity (J/kg K)
Aluminium	915	Lead	130	Benzene	1700
Brass	375	Nickel	460	Ether	2300
Cast iron	500	Steel	450	Ethanol	2500
Cppper	390	Tin	230	Paraffin	2130
Crown glass	670	Zinc	390	Mercury	140

Example 1.5   *5 kg of steel, specific heat capacity 450 J/kg K, is heated from 15 °C to 100 °C. Determine the heat transfer.*

Sᴏʟᴜᴛɪᴏɴ

From equation [1]

Heat required $= mc(t_2 - t_1)$
$$= 5 \times 450 \times (100 - 15)$$
$$= 5 \times 450 \times 85$$
$$= 191\ 250 \text{ J}$$
$$= \textbf{191.25 kJ}$$

Example 1.6   *A copper vessel of mass 2 kg contains 6 kg of water. If the initial temperature of the vessel plus water is 20 °C and the final temperature is 90 °C, how much heat is transferred to accomplish this change, assuming there is no heat loss? Take the specific heat capacity of water to be 4.19 kJ/kg K.*

Sᴏʟᴜᴛɪᴏɴ

From the table of average specific heat capacities

Specific heat capacity of copper $= 390$ J/kg K
Heat required by copper vessel $= 2 \times 390 \times (90 - 20)$
$$= 2 \times 390 \times 70$$
$$= 54\ 600 \text{ J}$$
$$= \textbf{54.6 kJ}$$

Heat required by water $= 6 \times 4.19 \times (90 - 20)$
$$= 6 \times 4.19 \times 70$$
$$= \textbf{1759.8 kJ}$$

Heat to vessel + water $= 54.64 + 1759.8$
$$= \textbf{1814.4 kJ}$$

Example 1.7   *An iron casting of mass 10 kg has an original temperature of 200 °C. If the casting loses heat to the value 715.5 kJ, determine the final temperature.*

Sᴏʟᴜᴛɪᴏɴ

From the table of average specific heat capacities

Specific heat capacity of cast iron $= 500$ J/kg K
Heat transferred from casting $= mc(t_2 - t_1)$ [1]

Heat transferred $= -715.5$ kJ
$$= -715\ 500 \text{ J}$$

Note the negative sign, indicating a heat loss.

From equation [1]

$$-715\,509 = 10 \times 500 \times (t_2 - 200)$$

$$\therefore \quad t_2 = 200 - \frac{715\,500}{10 \times 500} = 200 - 143.1$$

$$= \mathbf{56.9\ °C}$$

Example 1.8   *A liquid of mass 4 kg has its temperature increased from 15 °C to 100 °C. Heat transfer into the liquid to the value 714 kJ is required to accomplish the increase in temperature. Determine the specific heat capacity of the liquid.*

SOLUTION

Heat transfer required $= Q = mc(t_2 - t_1)$

$$\therefore \quad c = \frac{Q}{m(t_2 - t_1)} \quad \text{and} \quad Q = 714\ \text{kJ} = 714\,000\ \text{J}$$

$$= \frac{714\,000}{4(100 - 15)} = \frac{714\,000}{4 \times 85}$$

$$= \frac{714\,000}{340}$$

$$= 2100\ \text{J/Kg K}$$

$$= \mathbf{2.1\,kJ/Kg\ K}$$

1.7.2   *Relationship Between Heat and Work*

Fig. 1.11 shows two containers each containing a mass of water m and each having a thermometer inserted such that temperature measurement can be made. In each case, the mass of water is the system. And for this discussion, any other fluid of mass m could also be considered as the system.

In (a) it is arranged that an external heater can transfer heat energy Q through the system boundary into the water. In (b) it is arranged that a paddle-wheel is immersed in water such that external paddle or stirring work W is done when the wheel is rotated. In each case it is assumed that there is no energy loss from the system.
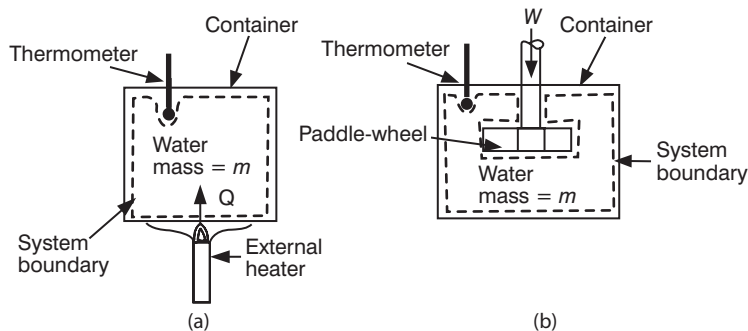

Fig. 1.11   Temperature rise by (a) supplying heat (b) doing work

Consider the arrangement in (a). It is common experience to heat water in some containing vessel by means of some external heating device. Let the initial temperature as recorded on the thermometer be t_1, and after heating, in which heat energy Q is transferred into the water, let the final temperature be t_2.

Consider, now, the arrangement in (b). The container once again contains a mass of water m but in this case a paddle-wheel is introduced into the water. It is common experience that friction makes things warm. The simple experience of rubbing one's hands together in a brisk manner will show this. In the case under consideration it is possible to rotate the paddle-wheel against the frictional resistance of the water. Assume that the initial temperature of the water is t_1, and, after doing an amount of work W on the paddle-wheel, the final temperature is t_2.

Now a similar effect has been produced in both cases (a) and (b) in that a mass of water m starting at a temperature t_1 has experienced a rise in temperature $(t_2 - t_1)$.

Case (a) used a heat transfer to produce an effect; case (b) used a work transfer to produce the same effect.

The conclusion must be that there is a relationship between heat and work.

If the unit of energy is the same for both work and heat, since the same effect was produced in each case, the relationship is of the form

$$W = Q \qquad\qquad\qquad\qquad\qquad\qquad [1]$$

The unit of energy in the SI system of units is the joule (J).

$1\text{J} = 1 \text{ N m}$

which has the units $\ \text{kg} \ \dfrac{\text{m}}{\text{s}^2} \times \text{m} = \text{kg} \ \dfrac{\text{m}^2}{\text{s}^2}$

From equation [1], since $W = Q$, then the unit of energy for both work and heat is the **joule,** named after James Prescott Joule (1819–1889), an English physicist.

In older systems of units, heat energy was defined using water as a reference substance. This is now abandoned and in its place is the energy unit, the joule. In some calorimetric devices, however, water is used as a means of measurement.

1.8   Enthalpy

It has been shown that internal energy, pressure and volume are properties. During subsequent discussion a particular combination of these properties will often appear. The combination is in the form $u + Pv$ and, because this combination has a particular significance in some processes, it is given a name. The name is **enthalpy** and is given **the** symbol h. Thus, $h = u + Pv$. Note that, since pressure, volume and temperature are properties, their combination is also a property, so enthalpy is a property. Specific enthalpy is designated h. The enthalpy of any mass other than unity is designated H.

1.9   Thermodynamic Engine and Efficiency

The thermodynamic engine is a device in which energy is supplied in the form of heat and some of this energy is transformed into work. It would be ideal if all the energy supplied was transformed into work. Unfortunately, no such complete transformation process exists.

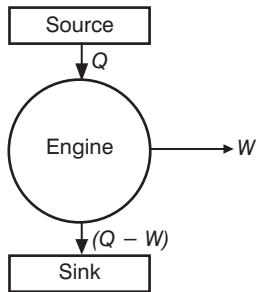The usual process in the engine can be followed by reference to Fig. 1.12.

Fig. 1.12 Thermodynamic engine

With all engines there must be a source of supply of heat and, with any quantity of heat Q supplied from the source to the engine, an amount W will successfully be converted into work. This will leave a quantity of heat $(Q - W)$ to be rejected by the engine into the sink.

The ratio

$$\frac{W}{Q} = \frac{\text{Work done}}{\text{Heat received}}$$
[1]

is called the **thermal efficiency** and determines what fraction of the heat input has actually been successfully converted into work output. It will be evident that the object in all engines is, or should be, to make the thermal efficiency as near to unity as possible.

All engines use a working substance as the means of carrying out the conversion of heat energy into work. The heat energy is usually obtained by burning a fuel or by thermonuclear reaction. This heat energy is suitably transferred into the working substance and, consequently, the pressure and temperature of the substance are usually raised above that of the surroundings. In this condition the substance is capable of doing work. For example, it could be enclosed by using a piston in a cylinder; if the piston were free to move, it would be pushed down the cylinder and work would be done as the substance expanded. The substance would lose some of its energy in doing this work. When the substance has performed as much work as is practically possible, it could be removed from the cylinder and rejected to the sink. By returning the piston to its original position and then introducing some more high-energy-containing substance, the process could be repeated. This is what happens in any piston engine. The intake and rejection processes of the working substance are intermittent in this case.

In the majority of turbine engines, however, the working substance passes through in a continuous flow.

There are two possibilities with regard to the introduction of the energy into the working substance which, in most cases, is either a vapour or a gas.

The first possibility is to transfer heat into the substance outside the engine and then to pass the high-energy-containing substance over into the engine. This is the usual process carried out when using steam as the working substance which is formed outside the engine in a boiler and is then passed to the engine. This is a case of a vapour being used as the working substance.

The second possibility is to introduce the energy directly into the working substance in the engine. This is the usual process carried out in petrol, oil and gas engines in which the fuel is introduced directly into, and burnt in, the engine cylinders. When this is the case, the engines are called **internal combustion engines,** IC engines. Each method naturally has its own complexity. More will be said in later chapters.

Now a further note about thermal efficiency. It has already been stated that the process in the engine is that of receiving heat, converting some of it into work and then rejecting the remainder. So it appears that, neglecting losses, the difference between the heat received and the heat rejected is equal to the work done, or

$$\text{Heat received} - \text{Heat rejected} = \text{Work done} \qquad\qquad [2]$$

Now

$$\text{Thermal } \eta = \frac{\text{Work done}}{\text{Heat received}} \quad \text{(see equation [1])} \qquad\qquad [3]$$

(η, Greek letter eta, is the symbol usually used for efficiency.)
Using equation [2] in [3]

$$\text{Thermal } \eta = \frac{\text{Heat received} - \text{Heat rejected}}{\text{Heat received}} \qquad\qquad [4]$$

$$= 1 - \frac{\text{Heat rejected}}{\text{Heat received}} \qquad\qquad [5]$$

From equation [3]

$$\text{Work done} = \text{Heat received} \times \text{Thermal } \eta \qquad\qquad [6]$$

Also

$$\text{Heat received} = \frac{\text{Work done}}{\text{Thermal } \eta} \qquad\qquad [7]$$

Now from equation [4]

$$\text{Thermal } \eta = \frac{\text{Heat received} - \text{Heat rejected}}{\text{Heat received}}$$

$$\therefore \quad \text{Heat received} \times \text{Thermal } \eta = \text{Heat received} - \text{Heat rejected}$$

From which

$$\text{Heat rejected} = \text{Heat received} - (\text{Heat received} \times \text{Thermal } \eta)$$
$$= (1 - \text{Thermal } \eta) \times \text{Heat received} \qquad\qquad [8]$$

Strictly, equations [1] to [8] will only apply to a system in which heat and work only transfer across the system boundary, a heat engine in fact. For other systems, such as an IC engine, the thermal efficiency may be defined as

$$\text{Thermal } \eta = \frac{\text{Work done}}{\text{Energy received}} \qquad\qquad [9]$$

It is useful to note here that the amount of energy liberated by a fuel when burnt is defined by its **calorific value** (see Chapter 2).

The calorific value of a fuel is defined as the amount of energy liberated by burning unit mass or volume of the fuel. Thus, if by burning 1 kg of petrol, 43 MJ/kg are liberated then the calorific value of the petrol is 43 MJ/kg: Special calorimeters have been developed for the determination of the calorific value of fuels. They are described in Chapter 8.

Example 1.9   *A petrol engine uses 20.4 kg of petrol per hour of calorific value 43 MJ/kg. The thermal efficiency of the engine is 20 per cent. Determine the power output of the engine and the energy rejected/min.*

SOLUTION

$$20.4 \text{ kg petrol/h} = \frac{20.4}{3600}\text{kg/s}$$

$$\text{Energy liberated petrol} = \left(\frac{20.4}{3600} \times 43 \times 10^6 \right) \text{J/s}$$

Of this, only 20 per cent is successfully transformed into power output.

$$\therefore \quad \text{Power output} = \left(\frac{20.4}{3600} \times 43 \times 10^6 \times 0.2 \right) \text{J/s}$$

$$= \left(\frac{20.4 \times 43 \times 0.2}{3.6} \times 10^3 \right) \text{W}$$

$$= \left(\frac{20.4 \times 43 \times 0.2}{3.6} \right) \text{kW}$$

$$= \mathbf{48.7 \text{ kW}}$$

Energy rejected = (1 − thermal *η)* × Energy received   (see equation [8])

$$= (1 - 0.2)\left(\frac{20.4}{60} \times 43 \times 10^6 \right) \text{J/min}$$

$$= \left(0.8 \times \frac{20.4}{60} \times 43 \times 10^6 \right) \text{J/min}$$

$$= \left(0.8 \times \frac{20.4}{60} \times 43 \right)$$

$$= \mathbf{11.7 \text{ MJ}/\text{min}}$$

It may be thought that a thermal efficiency of 20 per cent seems extremely low. It is unfortunately the case that engine thermal efficiencies are very low; more on this later when dealing with engines and plant.

Example 1.10   *A steam plant uses 3.045 tonne of coal per hour. The steam is fed to a turbine whose output is 4.1 MW. The calorific value of the coal is 28 MJ/kg. Determine the thermal efficiency of the plant.*

SOLUTION

$$3.045 \text{ tonne/h} = 3.045 \times 10^6 \text{ megagram/h}$$

$$= 3045 \text{ kg/h} = \frac{3045}{3600} = 0.846 \text{ kg/s}$$

Energy liberated by coal $= (0.846 \times 28 \times 10^6)$ J/s

Power output from turbine $= (4.1 \times 10^6)$ W

$$= (4.1 \times 10^6) \text{ J/s}$$

Thermal $\eta = \dfrac{\text{Power output}}{\text{Energy liberated by coal}}$

$$= \dfrac{4.1 \times 10^6}{0.846 \times 28 \times 10^6}$$

$$= \mathbf{0.173} \text{ or } \mathbf{17.3\%}$$

1.10   Mechanical Power

Power is defined as the rate of doing work, or

$$\text{Power} = \dfrac{\text{Work done}}{\text{Time taken}} \qquad [1]$$

If the unit of work is the joule (J) and the time taken is in seconds (s), equation [1] gives the unit of power as

$\dfrac{\text{J}}{\text{s}}$ or joule/second.

The rate of doing work of 1 joule/second is called the **watt** (W), thus

$$1 \text{ W} = 1 \text{ J/s} \qquad [2]$$

The watt is named after James Watt (1736−1819) of steam engine fame.

In section 1.11 it will be shown that the unit of electrical power is also the watt, thus giving a very convenient comparison between mechanical and electrical power.

Example 1.11   *At a speed of 50 km/h the resistance to motion of a car is 900 N. Neglecting losses, determine the power output of the engine of the car at this speed.*

SOLUTION

Speed $= 50 \text{ km/h} = \dfrac{50 \times 10^3}{3600} \text{ m/s}$

Power $=$ Work done/s $=$ Resistance to motion (N) $\times$ speed (m/s)

$$= \left(\dfrac{900 \times 50 \times 10^3}{3600} \right) \text{ N m/s}$$

$$= (12.5 \times 10^3) \text{ N m/s} = (12.5 \times 10^3) \text{ J/s}$$

$$= (12.5 \times 10^3) \text{ W}$$

$$= \mathbf{12.5 \, kW}$$

The power output of the engine is 12.5 kW.

1.11   Electrical Power

The use of electricity is now so widespread that it is essential to have a knowledge of electrical power. The fact that electrical energy can be converted into mechanical energy can be readily observed in the electric motor. Again, electrical energy can be converted into thermal energy using the common electric heater.

Since electrical energy can readily be converted into work, electrical energy input to an electrical circuit is sometimes referred to as electric work transfer.

The effort which drives electricity through an electric circuit is called the **potential difference,** symbol *V.* This effort is usually supplied by a generator or a battery. The unit of potential difference is called the **volt** (V). An instrument called a voltmeter is made to measure potential difference. To measure the potential difference of a generator or battery a voltmeter is connected across the terminals of the generator or battery.

The quantity of electricity being driven round a circuit is called the **current,** symbol *I*. The unit of current is the **ampere** or **amp** (A). An instrument called the ammeter is made to measure electric current. In order to measure the current, the ammeter is connected in the circuit such that the current must flow through it.

Fig. 1.13 illustrates the connections of the voltmeter and ammeter into an electric circuit. Note that the voltmeter is connected across the circuit, thus measuring the potential difference. If any electrical device is connected across a circuit in this manner it is said to be connected in parallel.
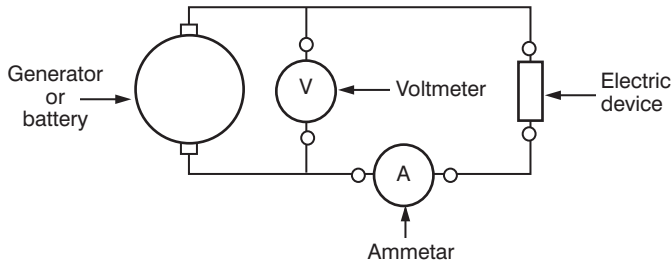
Fig. 1.13   Simple electric circuit

The ammeter, on the other hand, is connected actually in the circuit such that the current must flow through it and hence the ammeter will measure the current. If any device is connected actually in an electric circuit, such as the ammeter, it is said to be connected in series.

In some generators, and in all batteries, the current delivered to any circuit is always in the same direction. The connections to either the generator or battery are made by means of terminals. Current flowing in one direction is said to be **direct current,** abbreviated d.c. One of the terminals of either the generator or battery is said to be positive, marked +, and the other is said to be negative, marked −. Direct current is always considered as flowing from the positive to the negative terminal. The generator of direct current electricity is referred to as a d.c. generator.

Other generators generate electricity in which the current is continuously changing its direction. Such current is called **alternating current,** abbreviated a.c. In this case, neither terminal can be designated as positive or negative; both are continuously changing in polarity. The type of meters to measure potential difference and current are different in design in this case but they measure potential difference in volts and current in amps, as before. The generator to develop alternating current electricity is

referred to as an **alternator.** Most electric power developed in power stations is a.c, and in the United Kingdom the standard number of current direction changes is 50 per second. Each change from positive to negative and back is called a cycle. Thus, in the above case, the current is said to have 50 cycles per second, which is called the current **frequency.** Now a frequency of 1 cycle per second is called **1 hertz** (Hz). Hence a frequency of 50 cycles per second = 50 c/s = 50 Hz.

The unit of power in an electric circuit is called the **watt,** and this is the rate of working in an electrical circuit whose potential difference is 1 volt with a current flow of 1 amp.

Thus for any circuit

$$VI = W \tag{1}$$

where V = potential difference in volts

I = current in amps

W = power in watts

The unit of electric power, the watt, has the same magnitude as that of the unit of mechanical power (1 W = 1 J/s). This is arranged by the choice of the units of potential difference and current.

Example 1.12   *An engine drives an electric generator and 8 per cent of its power is lost in the transmission to the generator. The generator has an efficiency of 95 per cent and its electrical output is at 230 volts. It delivers a current of 60 amps. Determine the power output of the engine.*

SOLUTION

$$\text{Power delivered by generator} = VI \text{ watts}$$
$$= (230 \times 60)$$
$$= 13\ 800 \text{ W}$$
$$= \textbf{13.8 kW}$$

But the generator is only 95 per cent efficient.

$$\therefore \quad \text{Power input from engine} = \frac{13.8}{0.95} = \textbf{14.53 kW}$$

Also, 8 per cent of the engine power is lost in transmission. Hence, 14.55 kW represents 92 per cent of the available engine output.

$$\therefore \quad \text{Power output from engine} = \frac{14.53}{0.92} = \textbf{15.79 kW}$$

Example 1.13   *A 4-kilowatt heater operates at 230 volts. Determine the current taken in amps.*

SOLUTION

$VI = W$ where W is in watts

$$\therefore \quad I = \frac{W}{V} = \frac{4 \times 1000}{230} = \textbf{17.4 amps}$$

Example 1.14   *A power station output is 500 megawatts. During a test it is found that this represents 28 per cent of the energy put into the plant by burning coal in the boilers. The coal used liberates 29.5 MJ/kg. Determine the mass of coal burnt by the power station in 1 hour.*

Solution

$$500 \text{ MW} = (500 \times 10^6) \text{ W}$$

This represents 28 per cent of the energy available from the coal.

$$\therefore \quad \text{Energy from coal} = \frac{\left(500 \times 10^6\right)}{0.28} \text{ W}$$

$$= \frac{\left(500 \times 10^6\right)}{0.28} \text{ J/s}$$

$$= \frac{\left(500 \times 10^6 \times 3600\right)}{0.28} \text{ J/h}$$

The coal liberates 29.5 MJ/kg = (29.5×10^6) J/kg

$$\therefore \quad \text{Mass of coal used/h} = \frac{500 \times 10^6 \times 3600}{0.28 \times 29.5 \times 10^6}$$

$$= \frac{5 \times 10^2 \times 3.6 \times 10^3}{0.28 \times 29.5}$$

$$= (2.18 \times 10^5) \text{ kg}$$

$$= 218\ 000 \text{ kg}$$

$$= \textbf{218 t (tonne)}$$

(1 t = 1 tonne = 1 megagram = 10^3 kg)

1.12   *Energy*

Energy is defined as that capacity a body or substance possesses which can result in the performance of work. Here, work is defined, as in mechanics, as the result of moving a force through a distance. The presence of energy can only be observed by its effects and these can appear in many different forms. An example where some of the forms in which energy can appear is in the motor car.

The petrol put into the petrol tank must contain a potential chemical form of energy because, by burning it in the engine and through various mechanisms, it propels the motor car along the road. Thus work, by definition, is being done because a force is being moved through a distance.

As a result of burning the petrol in the engine, the general temperatures of the working substances in the engine, and the engine itself, will be increased and this increase in temperature must initially have been responsible for propelling the motor car.

Due to the increase in temperature of the working substances then, since the motor car is moved and work is done, the working substance at the increased temperature must have contained a form of energy resultant from this increased temperature. This energy content resultant from the consideration of the temperature of a substance is called **internal energy**.

Some of this internal energy in the working substances of the engine will transfer to the cooling system of the engine because the cooling water becomes hot. A transfer of energy in this way, because of temperature differences, is called **heat transfer** (see section 1.7).

The motor car engine will probably have an electric generator, or alternator, which is rotated by the engine and is used to charge the battery. The battery, by its construction and chemical nature, stores energy which can appear at the battery terminals as electricity. The electricity from the battery can be used to rotate the engine starter which, in turn, rotates and starts the engine. By rotating the engine to start it, the electric motor must be doing work; thus electricity must have the capacity for doing work, hence it is a form of energy.

To stop the motor car the brakes are applied. After the motor car has stopped, the brake drums are hot, so the internal energy of the brake drum materials must have been increased. This internal energy increase resulted from the stopping of the motor car, so there must have been a type of energy which the motor car possessed while it was in motion. This energy of motion is called **kinetic energy.**

It will be seen that energy can appear in many forms, and through the action of various devices, it can be converted from one form into another.

All the possible forms of energy have not been discussed here.

More will be said about energy, and its various forms, later in the text.

1.12.1   Types of Energy

Various energy forms can exist in thermodynamic systems. In some systems they may all be present. In other systems only some may be present. The various forms of energy appearing in thermodynamic systems are listed below. The basic unit of energy, in all forms, is the joule (J). Multiples such as the kilojoule (kJ) or the megajoule (MJ) are often used.

1.12.2   System

All physical things in nature have some form of boundary whose shape in general identifies it as a particular object. Inside its boundary there are various features which have particular characteristics and functions. This internal arrangement is called a **system.** Outside the boundary of the object are the surroundings, and the reaction between the system and surroundings in general controls the behaviour pattern of the object. A human being and a tree are systems. Heat engines and allied arrangements, which are the concern here, are other systems. It is not necessary that at any one time a complete object need be under investigation. Only part may be under study and this part may then be considered as the system. In other words, a system can be defined as a particular region which is under study. It is identified by its boundary around which are the surroundings.

The boundary need not be fixed. For example, a mass of gas (the system) may expand, so the boundary in this case will modify and interactions will occur with the surroundings at the boundary. If the

mass of a system remains constant, the system is a **closed system.** If, on the other hand, the mass of a system changes, or is continuously changing, the system is an **open system.** For example, an air compressor is an open system since air is continuously streaming into and out of the machine, in other words, air mass is crossing its boundary. This is called a **two-flow open** system.

Another example is air leaving a compressed air tank. This would be a **one-flow open system** since air is only leaving the tank and none is entering. In any system, energies such as work and heat could be arranged to cross the boundary. Closed and open systems are illustrated in Fig. 1.14.
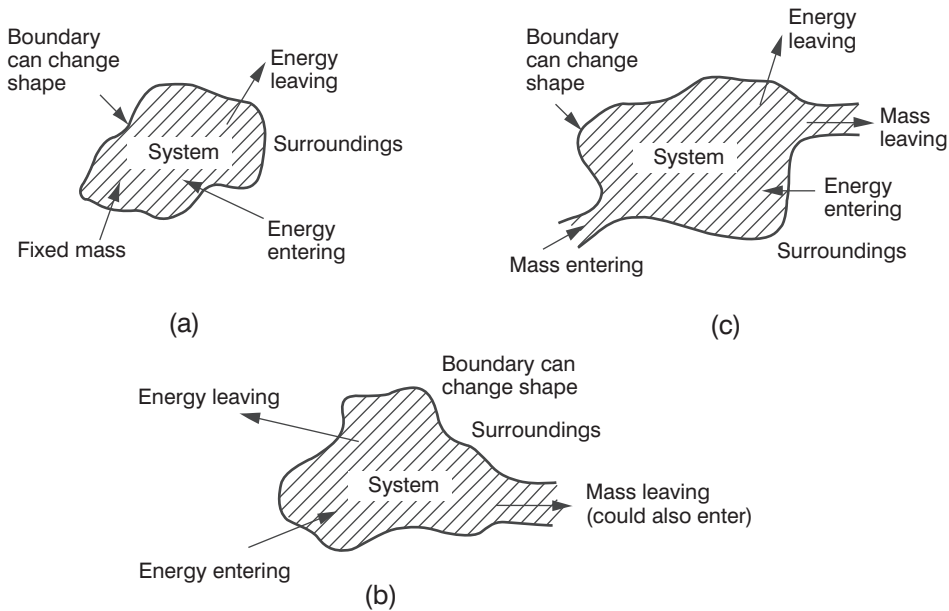
Fig. 1.14.   Systems: (a) closed; (b) open, one-flow; (c) open, two-flow

1.12.3   Total Energy in Closed System

The idea of the closed system was discussed in section 1.12.1. Consider the possible forms of energy which can be associated with such a system. The substance enclosed by the system will possess internal energy *U,* resulting from the motion of its atoms or molecules.

Furthermore, if the substance within the system is some type of fluid or gas, it may experience some degree of turbulence. Any part of the substance, considered separately, could therefore be experiencing its own changes in gravitational potential energy (PE) when referred to some datum level and also changes in kinetic energy (KE).

There could also be some other random energies such as electrical, magnetic and surface tension, but these forms of random energy will be neglected here as being insignificantly small.

In a closed system, the sum of all the energies possessed by the contained substance is called the **total energy** (*E*).

$$E = U + \bullet \text{ PE} + \bullet \text{ KE} \tag{1}$$

where $\sum$PE and $\sum$KE are the summation of the separate local gravitational potential and kinetic energies. Consider now a process carried out on a closed system. Let

E_1 = initial total energy of the contained substance
E_2 = final total energy of the contained substance
Q = heat transferred to or from the substance in the system
W = work transferred to or from the substance in the system

Then by the principle of conservation of energy

| Initial energy of the system | + | Energy entering the system | = | Final energy of the system | + | Energy leaving the system |

or in this case

$$E_1 + Q = E_2 + W \tag{2}$$

from which

$$Q = (E_2 - E_1) + W \tag{3}$$

also

$$Q - W = E_2 - E_1 \tag{4}$$

Note that in equation [2] it has been assumed that heat has been transferred into the system, so Q is positive. Had the heat transfer been out of the system, Q would have been negative.

Similarly, the work transfer has been assumed to be from the system, so W is positive. Had work been transferred into the system, W would have been negative.

Note also, from equation [4], that Q and W are the energy forms which are responsible for the change of E in a closed system. Equation [4] is as statement of the first law of thermodynamics (see section 1.15).

Example 1.15   *In a process carried out on a closed system, the heat transferred into the system was 2500 kJ and the work transferred from the system was 1400 kJ. Determine the change in total energy, and state whether it is an increase or a decrease.*

SOLUTION
From equation [4]

$$E_2 - E_1 = Q - W$$
$$= 2500 - 1400$$
$$= \mathbf{1100J}$$

This is positive, so there is an increase in total energy.

Example 1.16 *In a process carried out on a closed system, the work transferred into the system was 4200 kJ and the increase in the total energy of the system was 3500 kJ. Determine the heat transferred and state the direction of transfer.*

SOLUTION
From equation [3]

$$Q = (E_2 - E_1) + W$$
$$= 3500 + (-4200) \quad (-4200 \text{ because work is transferred into the system})$$
$$= 3500 - 4200$$
$$= -\mathbf{700\ kJ}$$

This is negative, so heat is transferred from the system.

1.12.4   Total Energy in Open System

This section examines the two-flow open system, in which an equal mass of fluid per unit time is both entering and leaving the system, called continuity of mass flow.

Consider the two-flow open system illustrated in Fig. 1.15, The forms of energy which will be associated with the moving fluid mass entering the system will be

$$\text{Internal energy} = U_1$$
$$\text{Displacement or flow energy} = P_1\,V_1 \quad \text{(see section 1.12.1)}$$
$$\text{Kinetic energy} = KE_1$$
$$\text{Gravitational potential energy} = PE_1$$

The forms of energy which will be associated with the fluid mass leaving the system will be

$$\text{Internal energy} = U_2$$
$$\text{Displacement or flow energy} = P_2\,V_2$$
$$\text{Kinetic energy} = KE_2$$
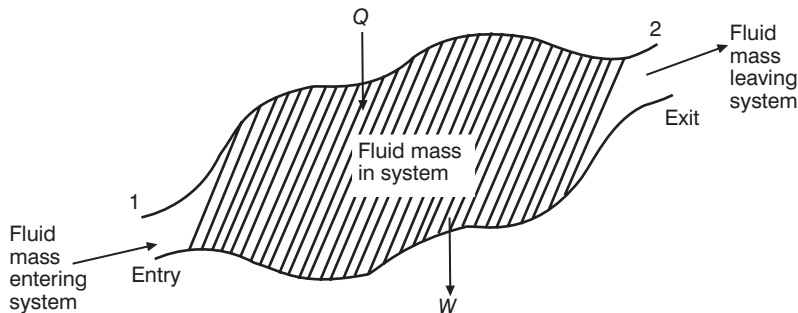$$\text{Gravitational potential energy} = PE_2$$

Fig. 1.15   Open system

As the fluid mass enters the system, let the total energy of the fluid mass actually in the system be E_{S1}.

After passing through the system, as the fluid mass leaves the system, let the total energy of the fluid mass remaining in the system be E_{S2}.

In its passage through the system let the fluid mass transfer heat be Q and the transfer work be W. For the two-flow open system

Energy of the fluid mass entering the system $= U_1 + P_1 V_1 + KE_1 + PE_1$

Energy of the fluid mass leaving the system $= U_2 + P_2V_2 + KE_2 + PE_2$

By the principle of conservation of energy

$$\begin{matrix} \text{Initial energy of} \\ \text{the system} \end{matrix} + \begin{matrix} \text{Energy entering} \\ \text{the system} \end{matrix} = \begin{matrix} \text{Final energy of} \\ \text{the system} \end{matrix} + \begin{matrix} \text{Energy leaving} \\ \text{the system} \end{matrix}$$

or

$$E_{S1} + U_1 + P_1V_1 + KE_1 + PE_1 + Q = E_{S2} + U_2 + P_2V_2 + KE_2 + PE_2 + W \qquad [1]$$

From section 1.8

$$U + PV = H = \text{Enthalpy} \qquad [2]$$

So equation [1] can be written

$$E_{S1} + H_1 + KE_1 + PE_1 + Q = E_{S2} + H_2 + KE_2 + PE_2 + W \qquad [3]$$

From equation [3]

$$Q - W = (E_{S2} - E_{S1}) + (H_2 - H_1) + (KE_2 - KE_1) + (PE_2 - PE_1) \qquad [4]$$

1.13 Entropy

During many processes it is necessary to investigate the degree to which heat is transferred during the process. The heat transferred during a process can affect any work transfer which may occur during the process and also the end state after the process. Furthermore, it has been shown that the theoretical amount of heat transferred, determined by calculation, is transferred reversibly.

Suppose a graph could be developed such that the area underneath a process plotted on the graph gave the amount of heat transferred reversibly during the progress of the process. Such a graph might perform a useful function. The idea is analogous to the area of the pressure-volume graph, which gives the work done during a reversible process.

The problem now is to decide upon the axes of the graph. Let one axis be absolute temperature T and the other some new function s as shown in Fig. 1.16(a). Absolute temperature is chosen as one axis because it has a very close relationship with the energy level of a substance, notably internal energy and enthalpy.

Also, when a substance is at the absolute zero of temperature, it is assumed that its internal energy content is also zero. And remember that heat is defined as energy transfer which will occur as the result of a temperature difference.
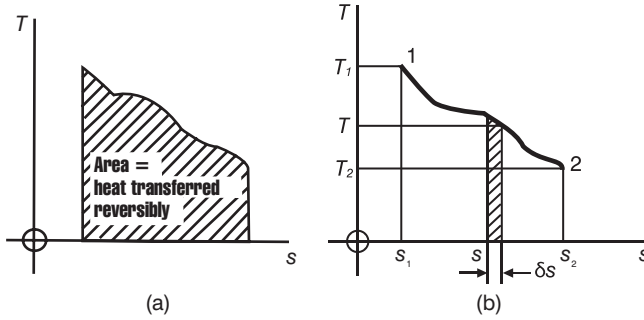
Fig 1.16   Entropy: (a) absolute temperature plotted against another function so that area = heat transferred reversibly; (b) a small change in this new function during a process

Now consider Fig. 1.16(b) which shows a process plotted on the graph where a change has occurred from state 1 to state 2. Consider some point on this graph where the coordinates are T and s. Let the state change from this point such that there is a small change in s, δs, then

Heat transferred reversibly = Area swept out by this small change
$$= T\delta s \text{ (very nearly)}$$

From this, heat transferred reversibly from 1 to 2 is equal to

$$\text{Total area under graph from 1 to 2} = \sum_{s=s_1}^{s=s_2} T\delta s$$

In the limit as $\delta s \to 0$, heat transferred reversibly from 1 to 2 is

$$\int_{s_1}^{s_2} T\mathrm{d}s = Q_{\text{rev}}$$

Differentiating equation [1]

$$\mathrm{d}Q_{\text{rev}} = T\mathrm{d}s \tag{1}$$

or

$$\mathrm{d}s = \frac{\mathrm{d}Q_{\text{rev}}}{T} \tag{2}$$

This equation gives the relationship which must exist between s, T and Q_{rev} in order that the area of the graph shall be heat transferred reversibly.

Now it has already been shown that it is possible to calculate the amount of heat transferred reversibly during a non-flow process. Thus, by using equation [2], changes in s can be determined. It is this function s which is called **entropy.**

Inspection of equation [2] will show that if heat is received, which makes Q_{rev} positive, then the entropy of the receiving substance has increased.

Conversely, if heat is rejected, which makes Q_{rev} negative, then the entropy of the rejecting substance is decreased.

Thus, positive and negative changes of entropy show whether heat has been received or rejected during the process considered.

Now consider an isolated system in which an amount of heat energy Q is transferred from a hot source at temperature T_1 into a cooler sink at temperature T_2.

The loss of entropy from the hot source is Q/T_1 whereas the gain of entropy to the cooler sink is Q/T_2.

The amount of heat transferred is the same for both the source and the sink but, since $T_1 > T_2$, it follows that the gain of entropy to the cooler sink is greater than the loss of entropy from the hot source. This is because

$$\frac{Q}{T_2} > \frac{Q}{T_1} \qquad\qquad [3]$$

Now, by the second law of thermodynamics, heat transfer will only occur down a temperature gradient as a natural occurrence. This makes the natural transfer of heat an irreversible process.

Thus a process occurring in an isolated system such that there is an increase in entropy appears to be irreversible.

This leads to the statement of the **principle of increase of entropy:**

An isolated system can only change to states of equal or greater entropy.

Expressed mathematically

$$\Delta s \geq 0 \qquad\qquad [4]$$

where Δs = change of entropy

The higher the temperature of a system above its surroundings, the greater becomes the availability of the energy obtained by heat transfer.

Since entropy is a function of temperature (see equation [2]), it follows that entropy is associated with the usefulness of energy.

The method of calculation of changes of entropy will now be investigated. The expressions for change of entropy are developed assuming the processes to be reversible. It must be remembered, however, that a change is dependent only upon the end states; it does not matter how the change occurred. Thus the expressions for change of entropy can also be used for irreversible processes.

Note, from equation [2], if unit mass of substance is considered, the unit of specific entropy becomes J/kg K or, very often, kJ/kg K.

1.14   Zeroth Law of Thermodynamics

This law is concerned with thermal equilibrium. It states.

If two bodies are separately in thermal equilibrium with a third body then they must be in thermal equilibrium with each other.

Thus, in Fig. 1.17, if bodies B and C are in thermal equilibrium with body A then bodies B and C must be in thermal equilibrium with each other.
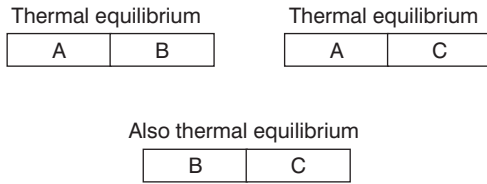
Thermal equilibrium

A	B

Thermal equilibrium

A	C

Also thermal equilibrium

B	C

Fig. 1.17   Thermal equilibrium

Thermal equilibrium means there is no change of state and hence the zeroth law implies that the bodies A, B and C will all be at the same temperature and, furthermore, that all bodies, if in thermal equilibrium, will be at the same temperature.

As an example, this situation arises when taking a temperature using a mercury-in-glass thermometer. When the thermometer is steady, it is assumed that the mercury, the glass container and the body whose temperature is being measured, are all at the same temperature, so they are in thermal equilibrium.

The concept of this law was generally developed after the enunciation of the first, second and third laws of thermodynamics (see sections 1.15, 1.16 and 1.17). However, the law is concerned with thermal equilibrium, a type of base, as it were. The other laws have concern for possible work and energy transfers, plus the further possibility of temperature difference, so they are involved with change. It is thus considered that the law involved with thermal equilibrium should logically precede the other laws, so it is called the zeroth law (law number zero).

1.15   First Law of Thermodynamics

Section 1.7.2 established a relationship between heat and work of the form

$$W = Q \tag{1}$$

where W = work transfer
Q = heat transfer

The fact that there is a relationship between heat and work, as in equation [1], is a statement of the **first law of thermodynamics.**

Equation [1] is not meant to imply that if a certain amount of work is done on a system, it is all converted into heat or, conversely, if a certain amount of heat is supplied to a system, it is all converted into work.

Equation [1] simply means that, if some work is converted into heat or some heat is converted into work, the relationship between the heat and the work so converted will be of the form $W = Q$.

It is possible to convert work completely into heat by friction, for example. The reverse process of converting heat completely into work is impossible.

A further extension of equation [1] appears in work with thermodynamic cycles. To complete a cycle, a working substance is taken through a sequence of events and is returned to its original state. If the working substance is returned to its original state, its final properties are identical with its original properties before the cycle.

If work is transferred during the cycle then, since there is no final change in the properties of the working substance, the energy to provide the work must have been transferred as heat and must exactly equal the work. During some processes in a cycle, work will be done by the substance; during other processes, work is done on the substance. Similarly, during some processes, heat is transferred out of the substance; during others, it is transferred into the working substance.

Thus, for a cycle, since there is no net property change

Net heat transfer − Net work transfer = 0 [2]

or

Net heat transfer = Net work transfer [3]

or

$$\sum Q = \sum W \qquad [4]$$

or

$$\oint Q = \oint W \qquad [5]$$

The symbol $\oint$ means the summation round the cycle.

Equations [2], [3], [4] and [5] are further statements of the first law of thermodynamics. The first law implies that, in a cycle, there must be heat transfer for there to be work transfer.

For example, an engine which could provide work transfer without heat transfer would violate the first law because it would create energy. This is contrary to the principle of conservation of energy. No violation of the first law has been shown.

An engine which could provide work transfer without heat transfer would run forever; in other words, it would have perpetual motion! Such an engine would have what is sometimes called **perpetual motion of the first kind.**

Consider now a closed system which does not execute a cycle. If a process is carried out on a substance in a closed system such that there is both heat and work transfer, it is not necessarily the case that the algebraic sum of these energy transfers is zero. If this is the case, then

$$\sum Q \neq \sum W \qquad [6]$$

Now, the principle of conservation of energy states that

Energy in = Energy out [7]

Thus, if the heat and work transfers are not equal, any energy difference must have been added to the substance or have been lost from the substance.

This again introduces the concept of internal energy, energy residing within the substance (see sections 1.12.1). With the inclusion of internal energy, equation [1] becomes

$$Q = \Delta U + W \qquad [8]$$

where Q = heat transfer
ΔU = change of internal energy
W = work transfer

Equation [8] is the non-flow energy equation (see section 1.15.1); it is another statement of the first law of thermodynamics.

Section 1.15.2 developed the steady-flow energy equation for an open system (see equations [6], [7] and [8] of section 1.15.2).

The steady-flow energy equation was shown to be of the form

$$u_1 + P_1 v_1 + \frac{C_1^2}{2} + gZ_1 + Q = u_2 + P_2 v_2 + \frac{C_2^2}{2} + gZ_2 + W \tag{9}$$

where u = specific internal energy

$P_1 v_1$ = specific flow work

C = velocity (gives specific kinetic energy)

Z = height above given datum level (gives specific gravitational potential energy)

Q = heat transfer

W = work transfer

The steady-flow energy equation is a further statement of the first law of thermodynamics.

1.15.1   Non-flow Energy Equation

Section 1.12.3 discussed energies associated with the closed system.

The sum of all the energies possessed by the contained substance was called the total energy (E), where

$E = U + \sum \text{PE} + \sum \text{KE}$

If the contained substance is considered to be at rest, there is no turbulence; in this case the random potential and kinetic energies will be zero.

Thus, for a substance at rest, the contained energy will be only the internal energy U. In this case, equation [2] of section 1.12.3 becomes

$$U_1 + Q = U_2 + W \tag{1}$$

from which

$$Q = (U_2 - U_1) + W = \Delta U + W \tag{2}$$

Also

$$Q - W = U_2 - U_1 = \Delta U \tag{3}$$

where

$\Delta U = U_2 - U_1$

Because the system is closed, there is no flow of substance into or out of the system.

Therefore the process in a closed system is called a **non-flow process,** and equation [3] is referred to as the **non-flow energy equation** (NFEE). A typical non-flow process is the expansion or compression of a substance in a cylinder.

Equations [1], [2] and [3] are further statements of the first law of thermodynamics (see section 1.15).

Example 1.17   *During the working stroke of an engine the heat transferred out of the system was 150 kJjkg of working substance. The internal energy also decreased by 400 kJ/kg of working substance. Determine the work done and stale whether it is work done on or by the engine.*

SOLUTION
From equation [3], the non-flow energy equation

$$Q - \Delta u + W \quad (\Delta u \text{ because energies/kg are given})$$

From this

$$W = Q - \Delta u$$
$$= -150 - (-400) \quad (-400 \text{ because there is a decrease in internal energy})$$
$$= -150 + 400$$
$$= \mathbf{250 \ kJ/kg}$$

This is positive, so is work done by the engine per kilogram of working substance.

1.15.2   Steady-flow Energy Equation

In a steady-flow system it is considered that the mass flow rate of fluid or substance throughout the system is constant. It is further considered that the total energy of the fluid mass in the system remains constant.
 If this is the case then

$$E_{S1} = E_{S2} \tag{1}$$

hence

$$E_{S2} - E_{S1} = 0 \tag{2}$$

Using this, equation [4] in section 1.12.4 becomes

$$Q - W = (H_2 - H_1) + (KE_2 - KE_1) + (PE_2 - PE_1) \tag{3}$$

 This is known as the **steady-flow energy equation** (SFEE).
 To put more detail into the steady-flow energy equation, consider equation [1] of section 1.12.4 and assume that $E_{S1} = E_{S2}$ as before, then

$$U_1 + P_1 V_1 + KE_1 + PE_1 + Q = U_2 + P_2 V_2 + KE_2 + PE_2 + W \tag{4}$$

 This equation is for any mass flow rate. It is often convenient, however, to consider the flow of unit mass through a system, in which case specific quantities are used and equation [4] becomes

$$u_1, + P_1 v_1 + KE_1 + PE_1 + Q = u_2 + P_2 v_2 + KE_2 + PE_2 + W \tag{5}$$

 Fig. 1.18 illustrates a steady-flow open system into which a fluid flows with pressure P_1, specific volume v_1, specific internal energy u_1 and velocity C_1. The entry is at height Z_1 above a datum level.
 In its passage through the system, specific heat energy Q and specific work W are transferred into or out of the system. The fluid leaves the system with pressure P_2, specific volume v_2, specific internal energy u_2 and velocity C_2. The exit is at height Z_2 above the datum level.
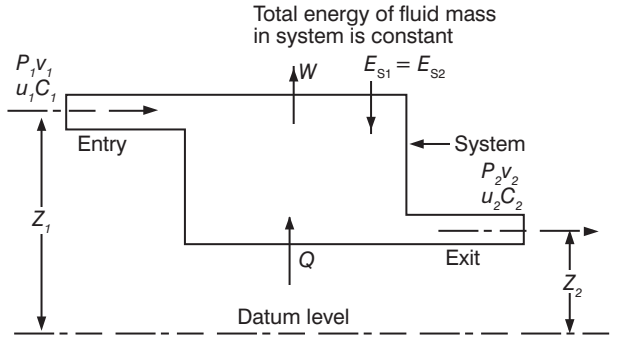
Fig. 1.18 Steady-flow open system

Using equation [5] the steady-flow energy equation for the system becomes

$$u_1 + P_1v_1 + \frac{C_1^2}{2} + gZ_1 + Q = u_2 + P_2v_2 + \frac{C_2^2}{2} + gZ_2 + W \qquad [6]$$

In thermodynamic systems, any changes in gravitational potential energy are mostly small compared with other energy forms. The *gZ* terms are therefore neglected.

Equation [6] then becomes

$$u_1 + P_1v_1 + \frac{C_1^2}{2} + Q = u_2 + P_2v_2 + \frac{C_2^2}{2} + W \qquad [7]$$

Also, since $u_1 + P_1v_1 = h$ = specific enthalpy (see section 1.8), equation becomes

$$h_1 + \frac{C_1^2}{2} + Q = h_2 + \frac{C_2^2}{2} + W \qquad [8]$$

Note that the various forms of the steady-flow energy equation, such as equations [6], [7] and [8], are further statements of the first law of thermodynamics (see section 1.15).

1.15.3 Continuity of Mass Flow

During the discussion on the steady-flow open system in section 1.15.2, reference was made to the continuity of mass flow.

For a fluid substance flowing through a steady-flow open system, the mass flow rate through any section in the system must be constant.

At any section in the system, let

$\dot{m}$ = mass flow, kg/s
v = specific volume, m³/kg
A = cross-sectional area, m²
C = velocity, m/s

Consider the volume of fluid substance passing the section per second $= \dot{V} \, \text{m}^3 /\text{s}$. Now

$$\dot{V} = \dot{m}v \qquad\qquad [1]$$

also

$$\dot{V} = AC \qquad\qquad [2]$$

From this

$$\dot{V} = \dot{m}v = AC \qquad\qquad [3]$$

so

$$\dot{m} = \frac{AC}{v} \qquad\qquad [4]$$

This mass flow rate must be constant at all sections of the system for steady-flow. (Note that to indicate a rate of flow a dot is placed over the appropriate symbol. Thus, $\dot{m}$ indicates mass flow rate and $\dot{V}$ indicates volume flow rate.)

Example 1.18   *In a steady-flow open system a fluid substance flows at the rate of 4 kg/s. It enters the system at a pressure of 600 kN/m², a velocity of 220 m/s, internal energy 2200 kJ/kg and specific volume 0.42 m³/kg. It leaves the system at a pressure of 150 kN/in², a velocity of 145 m/s, internal energy 1650 kJ/kg and specific volume 1.5 m³/kg. During its passage through the system, the substance has a loss by heat transfer of 40 kJ/ kg to the surroundings.*

Determine the power of the system, stating whether it is from or to the system. Neglect any change of gravitational potential energy.

SOLUTION

The steady-flow energy equation for the system is

$$u_1 + P_1 v_1 + \frac{C_1^{\,2}}{2} + Q = u_2 + P_2 v_2 + \frac{C_2^{\,2}}{2} + W$$

From this

$$W = \left(u_1 - u_2\right) + \left(P_1 v_1 - P_2 v_2\right) + \left(\frac{C_1^{\,2} - C_2^{\,2}}{2}\right) + Q$$

Working in kilojoules (kJ)

$$\text{Specific work} = W = \left(2200 - 1650\right) + \left(600 \times 0.42 - 150 \times 1.5\right) + \left(\frac{220^2 - 145^2}{2 \times 10^3}\right) - 40$$

(Q is -40 kJ/kg because the heat transfer is a loss from the system.)

$$\therefore \quad W = 550 + (252 - 225) + \frac{(48\,400 - 21\,025)}{2 \times 10^3} - 40$$

$$= 550 + 27 + \frac{27\,375}{2 \times 10^3} - 40$$

$$= 550 + 27 + 13.69 - 40$$

$$= \mathbf{550.69 \ kJ/Kg}$$

This is positive, so power is output from the system.

For a fluid substance flow rate of 4 kg/s

$$\text{Power output from the system} = 550.69 \times 4$$
$$= 2202.75 \text{ kJ/s}$$
$$= \mathbf{2202.75 \text{ kW}} \quad (1 \text{ kJ/s} = 1 \text{ kW})$$

Example 1.19. *Lead is extruded slowly through a horizontal die. The pressure difference across the die is 154.45 MN/m2. Assuming there is no cooling through the die, determine the temperature rise of the lead. Assume the lead is incompressible and to have a density of 11 360 kg/m³ and a specific heat capacity of 130 J/kg K.*

SOLUTION

Consider the steady-flow energy equation applied to the given extrusion process.

Since the die is horizontal then there will be no change in gravitational potential energy from inlet to outlet. Hence the potential energy terms can be neglected.

The velocity is also low, in which case any change in kinetic energy will be small enough to be sensibly neglected.

There is no cooling and no external work is done, so they too can be neglected.

From this the energy equation now becomes

$$P_1 V_1 + U_1 = P_2 V_2 + U_2$$

so

$$U_2 - U_1 = P_1 V_1 - P_2 V_2 \qquad [1]$$

Capital letters are used to indicate that a mass other than unity is being considered.

If a substance experiences a temperature rise, the energy associated with this temperature rise is given by

$$\text{mass} \times \text{specific heat capacity} \times \text{temperature rise} = mct \qquad [2]$$

The lead in this case is assumed to be incompressible, so no energy transfer will be associated with work of expansion or compression.

Hence, the energy transfer associated with temperature rise in this case will appear as a change of internal energy only

$$\therefore \quad mct = U_2 - U_1 \qquad [3]$$

Also, since it is assumed that the lead is incompressible

$$V_1 = V_2 = V, \text{ say} \qquad [4]$$

Substituting equations [3] and [4] in equation [1]

$$mct = V(P_1 - P_2)$$

from which

$$t = \frac{V(P_1 - P_2)}{mc} \qquad [5]$$

and considering 1 m^3 of lead

$$t = \frac{1 \times \left(154.45 \times 10^6\right)}{11\,360 \times 130}$$

$$= 104.6 \text{ K}$$

$$= \textbf{104.6 °C}$$

The temperature rise of the lead is 104.6 °C.

Example 1.20   *Air passes through a gas turbine system at the rate of 4.5 kg/s. It enters the turbine system with a velocity of 90 m/s and a specific volume of 0.85 m^3/kg. It leaves the turbine system with a specific volume of 1.45 m^3/kg. The exit area of the turbine system is 0.038 m^2. In its passage through the turbine system, the specific enthalpy of the air is reduced by 200 kJ/kg and there is a heat transfer loss of 40 kJ/kg. Determine*

(a) the inlet area of the turbine in m^2
(b) the exit velocity of the air in m/s
(c) the power developed by the turbine system in kilowatts

(a)
At inlet

$$\dot{m} = \frac{A_1 C_1}{v_1} \quad \text{(see section 1.15.3 equation [4])}$$

$$\therefore \quad A_1 = \frac{\dot{m} v_1}{C_1}$$

$$= \frac{4.45 \times 0.85}{90}$$

$$= \textbf{0.042 m}^2$$

The inlet area is 0.042 m^2.

(b)
At exit

$$\dot{m} = \frac{A_2 C_2}{v_2}$$

$$\therefore \quad C_2 = \frac{\dot{m} v_2}{A_2}$$

$$= \frac{4.5 \times 1.45}{0.038}$$

$$= \textbf{171.71 m/s}$$

The exit velocity is 171.71 m/s.

(c)

The steady-flow energy equation for this system is

$$h_1 + \frac{C_1^2}{2} + Q = h_2 + \frac{C_2^2}{2} + W \quad \text{(see section 1.15.2 equation [8])}$$

from which

$$W = (h_1 - h_2) + \frac{C_1^2 - C_2^2}{2 \times 10^3} \quad \text{(energy in kJ/kg)}$$

$$= 200 + \frac{(90 - 171.71^2)}{2 \times 10^3} - 40 \quad \text{(loss by heat transfer)}$$

$$= 200 + \frac{(8100 - 29\,484.3)}{2 \times 10^3} - 40$$

$$= 200 - \frac{(21\,384.3)}{2 \times 10^3} - 40$$

$$= 149.3 \text{ kJ/kg}$$

$$\therefore \quad \text{Power developed} = 149.3 \times 4.5$$
$$= 671.85 \text{ kJ/s}$$
$$= \mathbf{671.85 \text{ kW}} \quad \text{(1 kJ/s = 1 kW)}$$

1.16   *Second Law of Thermodynamics*

The second law of thermodynamics is a directional law in that it states that heat transfer will occur of its own accord down a temperature gradient as a natural phenomenon.

Heat transfer can be made to transfer up a gradient but not without the aid of external energy.

Natural heat transfer down a temperature gradient degrades energy to a less valuable level. A limit occurs when temperatures become equal, thus there is thermal equilibrium.

From the first law of thermodynamics, for a cycle, and hence for engines because engines must work in cycles in order to continue in operation

Net work transfer = Net heat transfer $\hfill$ [1]

or

$\Sigma W = \Sigma Q$ $\quad$ (see section 1.15) $\hfill$ [2]

But experience always shows that

Net work transfer < Net heat transfer $\hfill$ [3]

or

$\Sigma W < \Sigma Q$ $\hfill$ [4]

Since the work transfer is less than the heat transfer

$\Sigma Q - \Sigma W > 0$ $\hfill$ [5]

and has some positive value.

This means that some heat transfer must be rejected and is lost. Therefore there must always be some inefficiency.

Note that, from the second law of thermodynamics, unless there is a temperature difference, there is no heat transfer. Equations [1], [2], [3], [4] and [5] require that there is heat transfer in order that there shall be work transfer. Thus it is implied that there can be no work transfer unless there is a temperature difference.

The concept of the second law of thermodynamics were put together in the past in various forms, notably as follows.

Sadi Carnot (1796-1832)

Whenever a temperature difference exists, motive power can be produced.

Strictly, Carnot's proposition was not given as a statement of the second law of thermodynamics.

Carnot's concept of heat was in error in that, at that time, heat was thought to have the properties of a fluid which flowed into or out of a body. It was suggested that as the result of this fluid flow, a body became hotter if it flowed in and colder if it flowed out. Heat was not considered as an energy transfer process occurring naturally as the result of temperature difference, now the accepted definition (see sections 1.6). However, the suggestion that temperature difference is the prerequisite of the ability to produce motive power is correct.

The statement by Sadi Carnot is a positive statement in that it declares when it is possible to produce motive power. The statements which follow are negative because they declare impossibilities.

Rudolf Clausius (1822-1888)

It is impossible for a self-acting machine, unaided by any external agency, to convey heat from a body at a low temperature to one at a higher temperature.

The implication of the Clausius statement is that, unless external energy is made available, heat transfer up a gradient of temperature is impossible.

The fact that heat transfer can be made to occur up a temperature gradient is made manifest in the refrigerator. However, the refrigerator is not self-acting. It requires external energy in order that it can operate.

Lord Kelvin (1824-1907)

We cannot transfer heat into work merely by cooling a body already below the temperature of the coldest surrounding objects.

Lord Kelvin (William Thomson) implies that when a body reaches the temperature of the coldest surrounding objects no further heat transfer is possible, hence no further work transfer is possible.

Max Planck (1858-1947)

It is impossible to construct a system which will operate in a cycle, extract heat from a reservoir, and do an equivalent amount of work on the surroundings.

According to Planck, the complete conversion of heat transfer into work transfer is an impossibility. The inference is that there must always be some heat transfer rejection, which is a loss from the system.

Kelvin-Planck

> It is impossible for a heat engine to produce net work in a complete cycle if it exchanges heat only with bodies at a single fixed temperature.

The Kelvin-Planck combination implies that it is not possible to produce work transfer if a heat engine system is connected only to a single heat energy source or reservoir which is at a single fixed temperature. Note that if such a heat engine system were possible it would have perpetual motion! This arrangement is said to have **perpetual motion of the second kind.** No such arrangement exists (see section 1.15 for perpetual motion of the first kind).

In summary, the implications of the second law of thermodynamics are as follows:

- Heat transfer will only occur, and will always naturally occur, when a temperature difference exists, and always naturally down the temperature gradient.
- If, due to temperature difference, there is heat transfer availability, then work transfer is always possible. However, there is always some heat transfer loss.
- Temperature can be elevated but not without the expenditure of external energy. Elevation of temperature cannot occur unaided.
- There is no possibility of work transfer if only a single heat energy source or reservoir at a fixed temperature is available.
- No contradiction of the second law of thermodynamics has been demonstrated.
- If work transfer is supplied to a system, it can all be transformed in heat energy.

Examples of work being transformed into heat energy are seen in the cases of friction and the generation of electricity. But heat energy transfer cannot all be transformed into work transfer. There will always be some loss. Thus work transfer appears to have a higher transfer value than heat transfer. It is important to attenuate this last statement because it is usual that work transfer is only made available by the expenditure of heat transfer.

From the second law of thermodynamics it follows that, in order to run all the engines and devices in use at the present time and to maintain and develop modern industrial society, a supply of suitable fuels is absolutely essential. It is by burning and consuming these fuels that the various working substances (e.g. air and steam) have their temperatures raised above the temperature of their surroundings, thus enabling them to release energy by heat transfer in a natural manner according to the second law of thermodynamics.

By virtue of the second law of thermodynamics it is essential that all fuels should be used as efficiently as possible in order that fuel stocks may be preserved for as long as possible. It must always be remembered that, once energy has been degraded by heat transfer down a temperature gradient, further energy is only made available at the expense of further fuel.

1.17   The Third Law of Thermodynamics

This law is concerned with the level of availability of energy. Section 1.12 discussed the concept of internal energy. This section suggests that the internal energy of a substance results from the random motion of its atoms and molecules. Furthermore, this motion is also associated with temperature, and from this develops the idea of an absolute zero of temperature when all random motion ceases.

For a substance, if the random translational, rotational and vibrational types of motion of its constituent atoms and molecules are reduced to zero, the substance is considered to become perfectly crystalline and the energies associated with these forms of motion will be reduced to zero. Thus, the energy within the substance is reduced to the **ground state.** This neglects the energy within the basic atomic structure of the substance, associated with electrons, neutrons and other particles.

These considerations led to the development of the third law of thermodynamics:

At the absolute zero of temperature the entropy of a perfect crystal of a substance is zero.

Summary

Sources of Energy

Basically sources of energy are classified in two ways:

(a) Conventional energy sources, like coal, crude, thermal power, hydro power, nuclear power etc.

(b) Non-conventional energy sources, which include solar energy, wind energy, tidal energy, geothermal energy and ocean wave energy, bio fuels etc.

Prime Movers

A prime mover is defined as a device which converts energy from natural sources to mechanical energy.

Pressure

Pressure is defined as force per unit area. Thus, if a force F is applied to an area A, and if this force is uniformly distributed over the area, then the pressure P exerted is given by the equation $P = F/A$.

Volume

Volume is a property associated with cubic measure. The unit of volume is the cubic metre (m³) together with its multiples and submultiples.

Work

If a system exists in which a force at the boundary of the system is moved through a distance, then work is done by or on the system.

Work and Polytropic Process

$PV^n = C$, a constant

$$\text{Work done} = \frac{P_1V_1 - P_2V_2}{n-1}$$

Work and Hyperbolic Process

$PV = C$

$$P_1V_1 = P_2V_2 \ \text{ or } \ P_2 = P_1\frac{V_1}{V_1}$$

Temperature

Temperature describes the degree of hotness or coldness of a body.

Heat

An energy transfer process which results from the temperature difference between one body and another, the energy so transferred is called heat.

Specific Heat Capacity

The specific heat capacity, c, of the substance at temperature t is defined by the ratio $\delta Q/\delta t$.

Heat required $= mc(t_2 - t_1)$

Enthalpy

Enthalpy is a property of internal energy, pressure and volume. Specific enthalpy is designated as $h = u + Pv$

Thermodynamic Efficiency

$$\text{Thermal } \eta = \frac{\text{Heat received} - \text{Heat rejected}}{\text{Heat received}}$$

Calorific Value

The calorific value of a fuel is defined as the amount of energy liberated by burning unit mass or volume of the fuel.

Power

Power is defined as the rate of doing work, or Power = Work done/Time taken

Energy

Energy is defined as that capacity a body or substance possesses which can result in the performance of work. Here, work is defined, as in mechanics, as the result of moving a force through a distance.

System

All physical things in nature have some form of boundary whose shape in general identifies it as a par=ticular object. Inside its boundary there are various features which have particular characteristics and functions. This internal arrangement is called a system.

Total Energy

The sum of all the energies possessed by the contained substance is called the total energy (E).

$E = U + \Sigma PE + \Sigma KE$

where ΣPE and ΣKE are the summation of the separate local gravitational potential and kinetic energies.

The principle of conservation of energy

| Initial Energy of the System | + | Energy entering the System | = | Final energy of the System | + | Energy leaving the System |

Entropy

Entropy is transformation.

Mathematically,

$$ds = \frac{dQ_{rev}}{T}$$

Zeroth Law of Thermodynamics

If two bodies are separately in thermal equilibrium with a third body then they must be in thermal equilibrium with each other.

First Law of Thermodynamics

$W = Q$

where W = work transfer

               Q = heat transfer

The fact that there is a relationship between heat and work, as in equation [1], is a statement of the first law of thermodynamics.

Second Law of Thermodynamics

According to Kelvin–Plank, it is impossible for a heat engine to produce net work in a complete cycle if it exchanges heat only with bodies at a single fixed temperature.

Continuity of Mass Flow

For a fluid substance flowing through a steady-flow open system, the mass flow rate through any section in the system must be constant.

$$m = \frac{AC}{v}$$

Third Law of Thermodynamics

At the absolute zero of temperature the entropy of a perfect crystal of a substance is zero.

Questions

1. The temperature of 4.5 kg of water is raised from 15 °C to 100 °C at constant atmospheric pressure. Determine the heat transfer required. Take the specific heat capacity of water to be 4.18 kJ/kg K.

[1598.9 kJ]

2. A gas turbine plant delivers an output of 150 MW. The gas consumption is 55 000 m^3/h. The calorific value of the gas used is 38.3 MJ/m^3. Determine the thermal efficiency of the plant.

[25.6%]

3. A car has a mass of 1600 kg. It has an engine which develop 35 kW when travelling at a speed of 70 km/h. Neglecting losses, determine the resistance to motion in N/kg.

[1.25 N/kg]

4. A power station has an output of 800 MW and the thermal efficiency is 28 per cent. Determine the coal consumed in tonne per hour if the calorific value of the coal is 31 MJ/kg.

[331.8 tonne/h]

5. A diesel engine uses 54.5 kg of fuel oil per hour of calorific value 45 MJ/kg. The thermal efficiency of the engine is 25 per cent. Determine the power output of the engine in kilowatts.

[170.3 kW]

6. An engine rejects 1260 MJ/h when running at a thermal efficiency of 22 per cent. The calorific value of the fuel used is 42 MJ/kg. Determine the power output of the engine in kilowatts and the mass of fuel used per hour.

[98.7 kW; 38.46 kg/h]

7. 14.5 litres of gas at a pressure of 1720 kN/m^2 is contained in a cylinder. It is expanded at constant pressure until its volume becomes 130.5 litres. Determine the work done by the gas.

[199.5 kJ]

8. A quantity of steam, the original pressure and volume being 140 kN/m^2 and 150 litres respectively, is compressed to a volume of 30 litres, the law of compression being $PV^{1.2} = C$. Determine the final pressure and the work done.

[966 kN/m^2; −39.9 kJ]

9. A quantity of gas has an initial pressure of 2.72 MN/m^2 and a volume of 5.6 dm^3 (1). It is expanded according to the law $PV^{1.35} = C$ down to a pressure of 340 kN/m^2. Determine the final volume and the work done.

[26.15 dm^3; 18.2 kJ]

10. In a non-flow process there is a heat transfer loss of 1055 kJ and an internal energy increase of 210 kJ. Determine the work transfer and state whether the process is an expansion or a compression.

[−1265 kJ, a compression]

11. In a non-flow process carried out on 5.4 kg of fluid substance, there is a specific internal energy decrease of 50 kj/kg and a work transfer from the substance of 85 kJ/kg. Determine the heat transfer.

[189 kJ, again]

12. Air enters a gas turbine system with a velocity of 105 m/s and has a specific volume of 0.8 m^3/kg. The inlet area of the gas turbine system is 0.05 m^2. At exit the air has a velocity of 135 m/s and has a specific volume of 1.5 m^3/kg. In its passage through the turbine system, the specific enthalpy of the air is reduced by 145 kJ/kg and the air also has a heat transfer loss of 27 kJ/kg. Determine
    (a) the mass flow rate of the air through the turbine system in kg/s
    (b) the exit area of the turbine system in m^2
    (c) the power developed by the turbine system in kW

[(a) 6.56 kg/s; (b) 0.073 m^2; (c) 750.46 kW]

13. Air is compressed by a rotary compressor in a steady-flow process at a rate of 1.5 kg/s. At entry, the air has a specific volume of 0.9 m^3/kg and has a velocity of 80 m/s. At exit, the air has a specific volume of 0.4 m^3/kg and has a velocity of 45 m/s. In its passage through the compressor, the specific enthalpy of the air is increased by 110 kJ/kg and it experiences a heat transfer loss of 20 kJ/kg. Determine
    (a) the inlet and exit areas of the compressor in m^2
    (b) the power required to drive the compressor in kW

[(a) 0.0169 m^2, 0.013 3 m^2; (b) −191.72 kW]

Previous Years' GTU Examination Questions

1. State the first law of thermodynamics. State its limitations.

[Dec '08]

2. What are the various forms of energy? List the non-conventional sources of energy.

[Dec '08]

3. What are the sources of energy?

4. Write only the statement of (i) Zeroth Law (ii) First and Second Law of Thermodynamics.

[Mar '09]

5. What are prime movers? How are they classified?

[Jun '09]

6. Define prime movers. Classify the prime movers.

[Sep '09]

7. Define Zeroth Law of Thermodynamics and First Law of Thermodynamics.

[Sep '09]

8. Define force and mass.

[Sep '09]

9. State and explain First Law of Thermodynamics.

[Jan '10]

10. What do you mean by non-conventional energy sources? How does it differ from conventional sources?

[Jan '10]

11. Define the following terms:
    (i) Prime mover
    (ii) Specific heat
    (iii) Internal energy

[Jun '10]

12. Give the statements of Zeroth Law, First Law and Second Law of Thermodynamics.

[Jun '10]

13. State and explain Zeroth Law of Thermodynamics.

[Jun '10]