

## 1.1 Thermodynamics – its meaning and relevance

The word *thermodynamics* derives from two Greek ideas: *thermē* meaning hot or heat, and *dynamikos* originally meaning power or powerful and now the study of matter in motion.

Thus, thermodynamics is the study of heat related to matter in motion. Much of the study of engineering (or applied) thermodynamics is concerned with work producing or utilising machines such as engines, turbines and compressors together with the working substances used in such machines. Their development has given us the ability to create our modern industrial society.

It is important to understand that without thermodynamic engines – petrol engines, gas turbines, steam turbines, etc. – modern industrial society could not survive. But this raises many ethical questions, questions which need to be addressed. For example, there is the exploitation of natural finite global resources, e.g. oil and coal; there is the massive atmospheric pollution which occurs; there is always considerable political debate and conflict concerning energy resources and reserves.

It will be seen, therefore, that as humankind insists, at present, on the continuance of industrial societies, a study of engineering thermodynamics remains essential.

There are certain topics which are common and fundamental to many sections of the study of engineering thermodynamics. It is the purpose of this general introduction to investigate these common fundamentals. In the chapters which follow, it will be seen how they apply and are related to other sections of the study.

## 1.2 Working substance

All thermodynamic systems require some working substance in order that the various operations required of each system can be carried out. The working substances are, in general, fluids which are capable of deformation in that they can readily be expanded

and its molecular structure does not vary. For example, steam and water mixture of steam and water can be considered as pure substances. Each has the same molecular or chemical structure through its mass. Air in its gaseous and liquid form is a pure substance. However, during the liquefaction process of air, which is a mixture of gases, mainly oxygen and nitrogen, the oxygen and nitrogen liquefy at different temperatures. Until all the air becomes liquid, the relative concentrations of oxygen and nitrogen (and other gases) in the liquid that has formed will therefore be different from those of the original air. The relative concentrations will also differ between the condensing vapour and the original air. Thus the air in these circumstances ceases to be a pure substance.

The importance of the concept of a pure substance in this work is that the condition, or state, of a pure substance can be completely defined by any two independent properties of the substance. For example, if the pressure and volume of a fixed mass of oxygen is known, then its temperature and such other properties as will be discussed later are also completely known.

#### *1.4 Macroscopic and microscopic analysis*

If the properties of a particular mass of a substance, such as its pressure, volume and temperature, are analysed, then the analysis is said to be **macroscopic**. This is the method of analysis usually used by the engineer and is the type of analysis used therefore in the study of heat engines and engineering thermodynamics. If, however, an analysis is made in which the behaviour of the individual atoms and molecules of a substance are under investigation, then the analysis is said to be **microscopic**. Some studies in nuclear physics would be of a microscopic nature, such as the atomic structure of a fissionable material like uranium.

#### *1.5 Properties and state*

In the macroscopic analysis of a substance any characteristic of the substance which can be observed or measured is called a **property** of the substance. Examples of properties are pressure, volume and temperature. This type of property which is dependent upon the physical and chemical structure of the substance is called an **internal** or **thermodynamic** property. Other types of thermodynamic properties will be discussed later.

If a value can be assigned to a property then it is said to be a **point function** because its value can be plotted on a graph. Properties which are independent of mass, such as temperature and pressure, are said to be **intensive** properties. Properties which are dependent upon mass, such as volume and energy in its various forms, are called **extensive** properties.

of the substance. If a property, or properties, are changed, then the substance has passed through from one state to another, being dependent only upon the end states. In fact, a property can be identified if it is observed to be a function of state only.

Since, at a particular state, a substance will have certain properties which are functions of that state, then there will be certain relationships which exist between them. These property relationships will be investigated in the text.

A property which includes a function of time, used to define a rate at which some interaction can occur, such as the transfer of mass, momentum or energy, is referred to as a **transport property**. Examples of transport properties are thermal conductivity and viscosity.

### 1.6 Specific quantity

In the discussion of properties it was suggested that those properties which were associated with the mass of a substance are called extensive properties. For convenience, at times, it is useful to discuss the properties of unit mass of a substance. To indicate that this is the case, the word *specific* is used to prefix the property.

Thus, the specific volume of a substance, at some particular state, is the volume occupied by unit mass of the substance at that particular state. Other specific quantities will be discussed in the text.

Heat { Sensation of warmth is called heat }

### 1.7 Temperature

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 Gdańsk, 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.

From equation (1)

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

By choosing the zero of the Celsius thermodynamic scale as  $0^\circ\text{C} = 273.15\text{ K}$ , this approximates very closely to the customary Celsius scale and thus  $0^\circ\text{C}$  on the customary Celsius scale is very nearly equal to  $0^\circ\text{C}$  on the Celsius thermodynamic scale. Also,  $100^\circ\text{C}$  on the customary Celsius scale is very nearly equal to  $100^\circ\text{C}$  on the Celsius thermodynamic scale.

## 1.8 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

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

If  $F =$  force in newtons (N) and  $A =$  area in square metres ( $\text{m}^2$ ) then the unit of pressure becomes the newton/metre<sup>2</sup> ( $\text{N}/\text{m}^2$ ), 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<sup>2</sup> ( $1\text{ kN}/\text{m}^2 = 10^3\text{ N}/\text{m}^2$ ) and the meganewton/metre<sup>2</sup> ( $1\text{ MN}/\text{m}^2 = 10^6\text{ N}/\text{m}^2$ ). The **bar** may also be commonly used ( $1\text{ bar} = 10^5\text{ N}/\text{m}^2$ ) as may also the **hectobar** ( $1\text{ hbar} = 10^2\text{ bar} = 10^7\text{ N}/\text{m}^2$ ).

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

$$1\text{ standard atmosphere} = 1.01325\text{ bar} = 0.101325\text{ MN}/\text{m}^2 \quad [2]$$

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

Figure 1.2(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. 1.2(b) shows a piston of area  $A$  enclosing a fluid in a

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.

Figure 1.1 shows the way the customary Celsius scale is divided up. The lower fixed point is  $0^{\circ}\text{C}$  and the upper fixed point is  $100^{\circ}\text{C}$ ; there are 100 Celsius degrees between them. These 100 Celsius degrees are together called the **fundamental interval**.

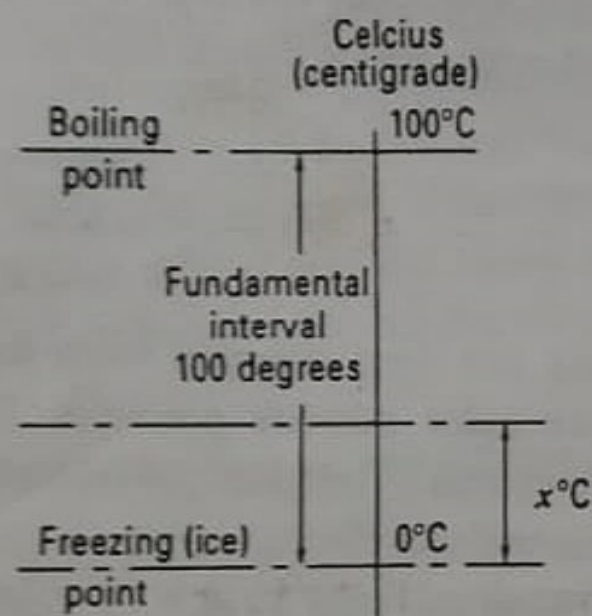


Fig. 1.1 Celsius scale of temperature

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**

... named in honour of Lord Kelvin, a British scientist, in about 1851.



Fig. 1.2 Concept of pressure: (a) of a solid (b) using a piston

### 1.9 Volume

Volume is a property associated with cubic measure. The unit of volume is the cubic metre ( $\text{m}^3$ ) together with its multiples and submultiples. Sometimes the litre (l) 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  $V$ .

### 1.10 Phase

When a substance is of the same nature throughout its mass, it is said to be in a **phase**. Matter can exist in three phases; solid, liquid and vapour (or gas). If the matter exists in only one of these forms then it is in a **single phase**. If two phases exist together then the substance is in the form of a **two-phase mixture**. Examples of this are when a solid is being melted into a liquid or when a liquid is being transformed into a vapour. In a single phase the substance is said to be **homogeneous**. If it is two-phase it is said to be **heterogeneous**. A heterogeneous mixture of three phases can exist. This is covered by the section on the triple point during the discussion on steam (see section 4.4).

### 1.11 Two-property rule

Now that the concept of properties, state and phase have been indicated, it is possible to write down the two-property rule.

If two independent properties of a pure substance are defined, then all other properties, or the state of the substance, are also defined. If the state of the substance is known then the phase or mixture of phases of the substance are also known.

The idea of the two-property rule was suggested in section 1.3.

### 1.12 Process

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.

### 1.18 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 (see Chapter 2). 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

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

### 1.19 Work and the pressure-volume diagram

Consider Fig. 1.3. 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

$$\text{Force on piston} = \text{pressure} \times \text{area} = PA \quad [1]$$

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

Each repeated sequence of events is called a cycle.

#### 1.14 *The constant temperature process*

This is a process carried out such that the temperature remains constant throughout the process. It is often referred to as an **isothermal** process. Particular cases of the constant temperature process will be dealt with in the text.

#### 1.15 *The constant pressure process*

This is a process carried out such that the pressure remains constant throughout the process. It is often referred to as an **isobaric** or **isopiestic** process. Particular cases of the constant pressure process will be dealt with in the text.

#### 1.16 *The constant volume process*

This is a process carried out such that the volume remains constant throughout the process. It is often referred to as an **isometric** or **isochoric** process. Particular cases of the constant volume process will be dealt with in the text.

#### 1.17 *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.



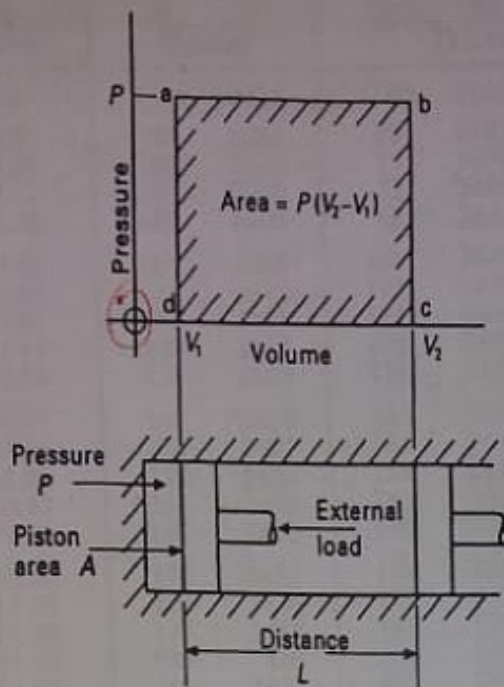


Fig. 1.3 Work and the  $P$ - $V$  diagram

But

$$AL = \text{volume swept out by the piston, called the swept or stroke volume} \\ = (V_2 - V_1)$$

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

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.

$$\text{Area} = P(V_2 - V_1) \quad [4]$$

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

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

The unit,  $\text{N m}$  (newton-metre) is the unit of work, the joule.

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

Now the graph shown in Fig. 1.3 illustrates the particular case of constant pressure expansion.

## 1.1 Heat, work, and the system

In order to deal with the subject of applied thermodynamics rigorously it is necessary to define the concepts used.

*Heat* is a form of energy which is transferred from one body to another body at a lower temperature, by virtue of the temperature difference between the bodies.

For example, when a body A at a certain temperature, say  $20^{\circ}\text{C}$ , is brought into contact with a body B at a higher temperature, say  $21^{\circ}\text{C}$ , then there will be a transfer of heat from B to A until the temperatures of A and B are equal (Fig. 1.2). When the temperature of A is the same as the temperature of B no heat transfer takes place between the bodies, and they are said to be in *thermal equilibrium*. Heat is apparent during the process only and is therefore transitory energy. Since heat energy flows from B to A there is a reduction in the intrinsic energy possessed by B and an increase in the intrinsic energy possessed by A. This intrinsic energy of a body, which is a function of temperature at least, must not be confused with heat. Heat can never be contained in a body possessed by a body.

A *system* may be defined as a collection of matter within prescribed and identifiable boundaries (Fig. 1.3). The boundaries are not necessarily inflexible; for instance the fluid in the cylinder of a reciprocating engine during



Surroundings

Insulation

Not isolated

Contact

Surroundings

System

Definition

expansion stroke may be defined as a system whose boundaries move with the walls and the piston crown. As the piston moves so do the boundaries move (Fig. 1.4). This type of system is known as a *closed system*.

An *open system* is one in which there is a transfer of mass across the boundaries; for instance, the fluid in a turbine at any instant may be defined as an open system whose boundaries are as shown in Fig. 1.5.

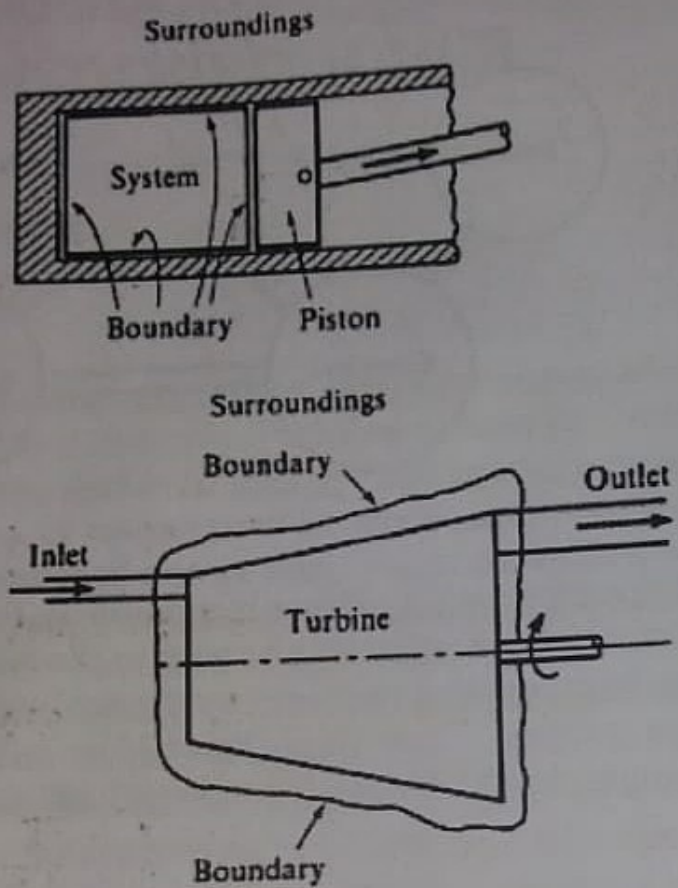
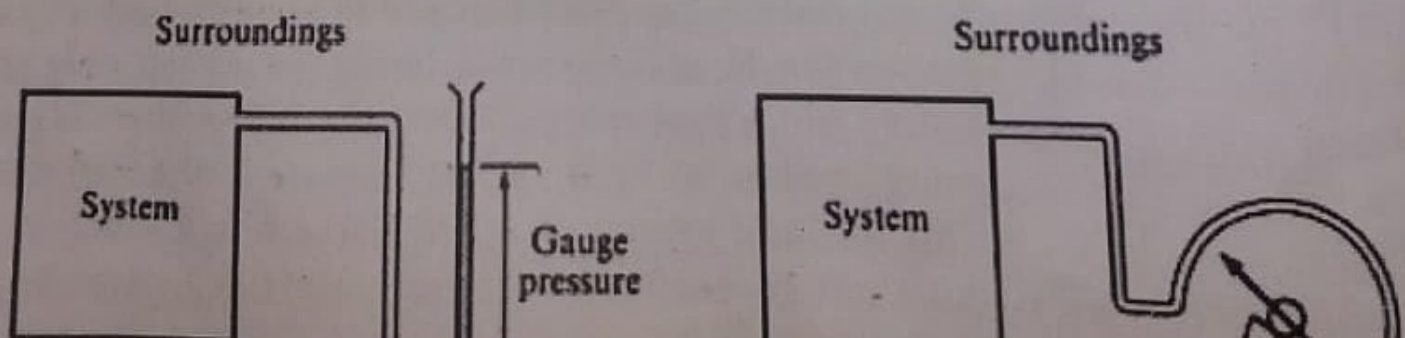


Fig. 1.7 Vacuum pressure and barometric pressure

The *pressure* of a system is the force exerted by the system on unit area of its boundaries. Units of pressure are, for example, pascal, Pa (where  $1 \text{ Pa} = 1 \text{ N/m}^2$ ), or bar; the symbol  $p$  will be used for pressure. Pressure as defined here is called *absolute pressure*. A gauge for measuring pressure (e.g. as shown in Fig. 1.6(a) and 1.6(b)), records the pressure above atmospheric. This is called *gauge pressure*, i.e. absolute pressure equals gauge pressure plus atmospheric pressure.

The gauge shown in Fig. 1.6(b) is called a Bourdon gauge. The absolute pressure of the system in a closed elliptical section tube forces the tube out of

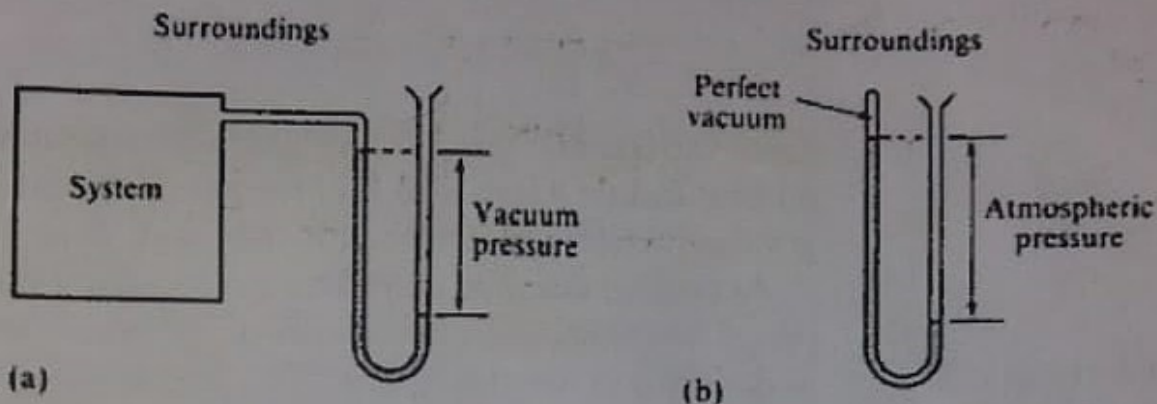


position against the pressure of the atmosphere. The tube's displacement is recorded by a pointer on a circular scale, which can be calibrated directly in bars.

When the pressure of a system is below atmospheric, it is called *vacuum pressure* (Fig. 1.7(a)).

When one side of a U-tube is completely evacuated and then sealed, the gauge will act as a *barometer* and the atmospheric pressure can be measured (Fig. 1.7(b)).

Vacuum  
and barometric



The gauges shown in Figs 1.6(a) and 1.7(a) measure gauge pressure in mm of a liquid of known relative density, and are called manometers.

For example, when water is the liquid, then

$$1 \text{ mm of water} = \frac{1}{10^3} \times 9806.65 \text{ N/m}^2 = 9.81 \text{ N/m}^2 = 9.81 \text{ Pa}$$

where  $1 \text{ m}^3$  of water weighs 9810 N, say.

Mercury (Hg) is very often used in gauges. Taking the relative density of mercury as 13.6, then

$$1 \text{ mm Hg} = \frac{1}{10^3} \times 13.6 \times 9810 \text{ N/m}^2 = 133.4 \text{ N/m}^2 = 133.4 \text{ Pa}$$

For a simple introduction to manometers and pressure measurement, see ref. 1.2.

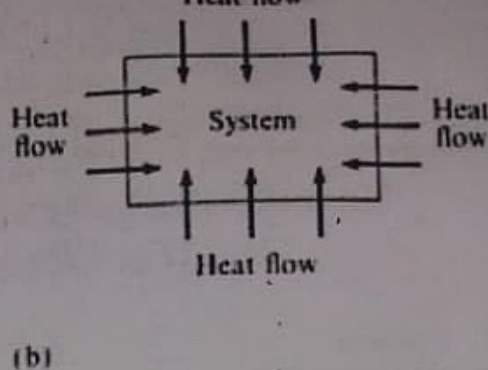
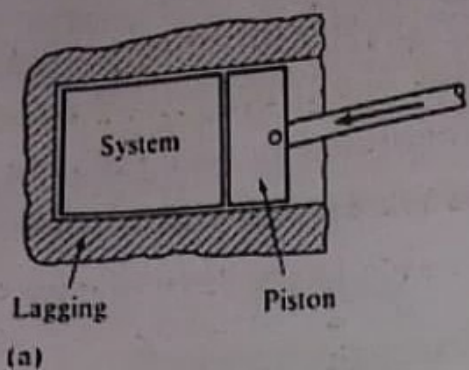
The *specific volume* of a system is the volume occupied by unit mass of the system. The symbol used is  $v$  and the units are, for example,  $\text{m}^3/\text{kg}$ . The symbol  $V$  will be used for volume. (Note that the specific volume is the reciprocal of density.)

*Work* is defined as the product of a force and the distance moved in the direction of the force. When a boundary of a closed system moves in the direction of the force acting on it, then the surroundings do work on the system. When the boundary is moved outwards the work is done by the system on its surroundings. The units of work are, for example, N m. If work is done on unit mass of a fluid, then the work done per kilogram of fluid has units of N m/kg.

Work is observed to be energy in transition. It is never contained in a body or possessed by a body.

Heat and work are both transitory energies and must not be confused with the intrinsic energy possessed by a system. For example, when a gas contained

Fig. 1.8 Intrinsic energy increase by work or heat input



hence the intrinsic energy of the gas increases. Since the cylinder is well lagged, no heat can flow into or out of the gas. The increase in intrinsic energy of the gas has therefore been caused by the work done by the piston on the gas.

As another example, consider a gas contained in a rigid container and heated (Fig. 1.8(b)). Since the boundaries of the system are rigidly fixed then no work is done on or by the system. The pressure and temperature of the gas are observed to increase, and hence the intrinsic energy of the gas will increase. The increase in intrinsic energy has been caused by the heat flow to the system.

In the example of Fig. 1.8(a) the work done on the system is energy which is apparent only during the actual process of compression. There is an intrinsic energy of the system initially and an intrinsic energy finally, but the work done appears only in transition from the initial to the final condition. Similarly, in the example of Fig. 1.8(b), the heat supplied appears only in transition from one state of the gas to another.

Another way in which work may be transferred to a system is illustrated in Fig. 1.9. The paddle wheel imparts a change of momentum to the fluid and a work input is required to turn the shaft. The kinetic energy attained by the fluid is dissipated by internal fluid friction, and friction between the fluid and the container. When the container is well lagged, all the work input goes to increasing the intrinsic energy of the system.

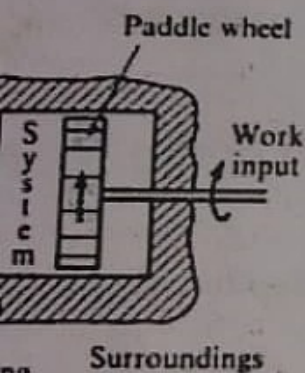


Fig. 1.9 Paddle wheel input

## Convention

The sign convention used in this book assumes that all external inputs to a system are positive. That is

Heat supplied to a system,  $Q$ , is positive.

Work input to a system,  $W$ , is positive.

When a system boundary is drawn to define the system then it follows that heat supplied,  $Q$ , and work input,  $W$ , will always be shown by arrows pointing into the system. In algebraic equations it will be quite clear when numbers are substituted whether the value of  $Q$  and/or  $W$  is positive or negative; a negative value for  $Q$  will indicate that heat is rejected from the system; a negative value for  $W$  will indicate that work is done by the system on its surroundings.

In many cases it would cause unnecessary confusion by referring throughout to negative quantities; for example, it is clear that for a device designed to

input to the system is always negative. Although the above sign convention will be used for all algebraic equations it will be made clear in the wording that the system is producing a work output. For example

$$\text{Work done by the system} = -W$$

Similarly, for the case of a system designed specifically to cool a fluid, such as a condenser for example, it is clear that the heat supplied to the system is always negative. Hence we can write

$$\text{Heat rejected by the system} = -Q$$

## 1.2 Units

Throughout this book SI units will be used. The International System of Units (Système International d'Unités, abbreviation SI) was adopted by the General Conference of Weights and Measures in 1960 and subsequently endorsed by the International Organization for Standardization. It is a *coherent* system. In a coherent system all derived unit quantities are formed by the product or quotient of other unit quantities. In SI units six physical quantities are arbitrarily assigned unit value and hence all other physical quantities are derived from these. The six quantities chosen and their units are as follows: length (metre, m); mass (kilogram, kg); time (second, s); electric current (ampere, A); thermodynamic temperature (degree kelvin, K); luminous intensity (candela, cd).

Thus, for example, velocity = length/time has units of m/s; acceleration = velocity/time has units of m/s<sup>2</sup>; volume = length × length × length has units of m<sup>3</sup>; specific volume = volume/mass has units of m<sup>3</sup>/kg.

### Force, energy, and power

Newton's second law may be written as force  $\propto$  mass  $\times$  acceleration for a body of constant mass, i.e.

$$F = kma \tag{1.1}$$

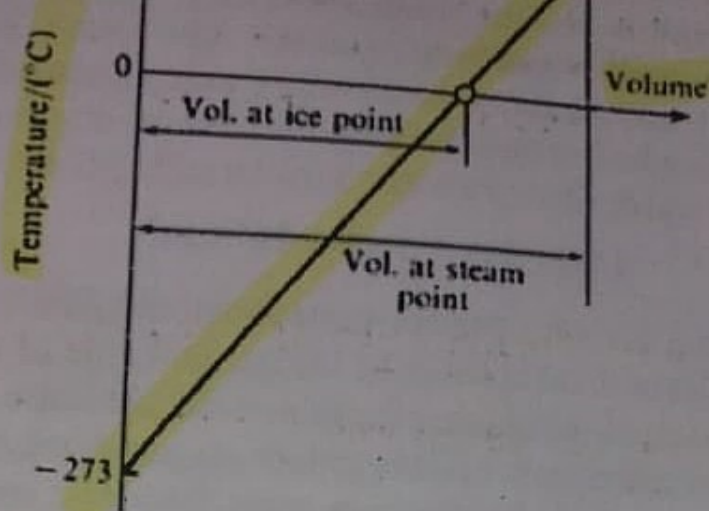
where  $m$  is the mass of a body accelerated with an acceleration  $a$ , by a force  $F$ ;  $k$  is a constant.

In a coherent system of units such as SI,  $k = 1$ , hence

$$F = ma$$

The SI unit of force is therefore kg m/s<sup>2</sup>. This composite unit is called the *newton*, N, i.e. 1 N is the force required to give a mass of 1 kg an acceleration of 1 m/s<sup>2</sup>.

It follows that the SI unit of work (= force  $\times$  distance) is the newton metre, N m. As stated earlier heat and work are both forms of energy, and hence both



obtained by adding 273 to all temperatures on the Celsius scale; this scale is called the *Kelvin* scale. The unit of temperature is the degree kelvin and is given the symbol K, but since the Celsius scale which is used in practice has a different zero the temperature in degrees Celsius is given the symbol C (e.g.  $20^{\circ}\text{C} = 293\text{ K}$  approximately; also,  $30^{\circ}\text{C} - 20^{\circ}\text{C} = 10\text{ K}$ ). In this text capital *T* is used for absolute temperature and small *t* for other temperatures.

In Chapter 5 an absolute scale of temperature will be introduced as a direct consequence of the Second Law of Thermodynamics. It is found that the gas thermometer absolute scales approach the ideal scale as a limit. Also, with regard to the practical absolute temperature scale, there is an internationally agreed working scale which gives temperatures in terms of more practicable and more accurate instruments than the gas thermometer (see ref. 1.3).

## Multiples and sub-multiples

Multiples and sub-multiples of the basic units are formed by means of prefixes, and the ones most commonly used are shown in the following table:

<i>Multiplying factor</i>	<i>Prefix</i>	<i>Symbol</i>
One million million	tera	T
One thousand million	giga	G
One million, $10^6$	mega	M
One thousand, $10^3$	kilo	k
One thousandth, $10^{-3}$	milli	m
One millionth, $10^{-6}$	micro	$\mu$
One thousand millionth	nano	n
One million millionth	pico	p

For most purposes the multiplying factors shown in the above table are sufficient

or  $1 \text{ J} = 1 \text{ N m}$   
The use of additional names for composite units is extended further by introducing the *watt*,  $W$ , as the unit of power,  
i.e.  $1 \text{ watt}, W = 1 \text{ J/s} = 1 \text{ N m/s}$

## Pressure

The unit of pressure (force per unit area) is  $\text{N/m}^2$  and this unit is sometimes called the *pascal*,  $\text{Pa}$ . For most cases occurring in thermodynamics the pressure expressed in pascals would be a very small number; a new unit is defined as follows:

$$1 \text{ bar} = 10^5 \text{ N/m}^2 = 10^5 \text{ Pa}$$

The advantage of using a unit such as the bar is that it is approximately equal to atmospheric pressure. In fact the standard atmospheric pressure is exactly 1.013 25 bar.

As indicated in section 1.1, it is often convenient to express a pressure as a head of a liquid. We have:

$$\text{Standard atmospheric pressure} = 1.013 25 \text{ bar} = 0.76 \text{ m Hg}$$

## Temperature

The variation of an easily measurable property of a substance with temperature can be used to provide a temperature-measuring instrument. For example, the length of a column of mercury will vary with temperature due to the expansion and contraction of the mercury. The instrument can be calibrated by marking the length of the column when it is brought into thermal equilibrium with the vapour of boiling water at atmospheric pressure and again when it is in thermal equilibrium with ice at atmospheric pressure. On the Celsius (or Centigrade) scale 100 divisions are made between the two fixed points and the zero is taken at the ice point.

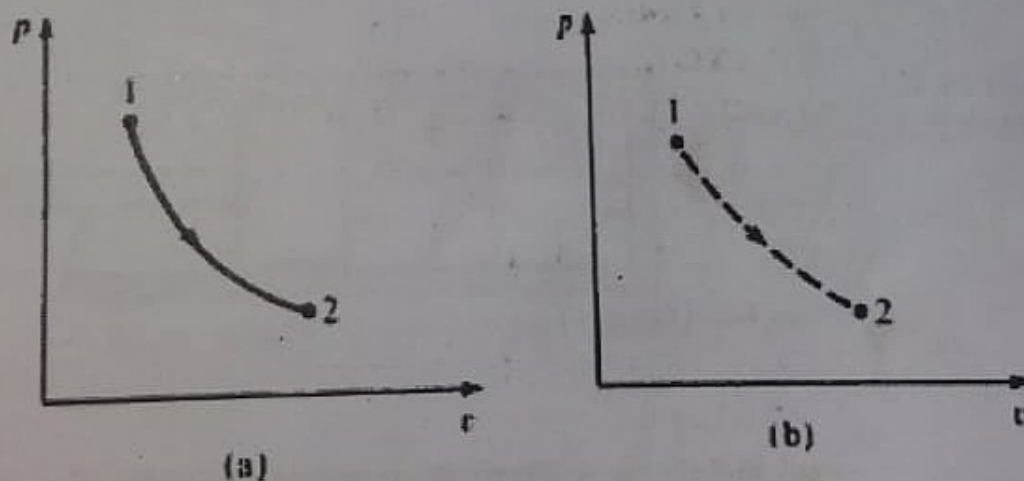
The change in volume at constant pressure, or the change in pressure at constant volume, of a fixed mass of gas which is not easily liquefied (e.g. oxygen, nitrogen, helium, etc.) can be used as a measure of temperature. Such an instrument is called a *gas thermometer*. It is found for all gases used in such thermometers that if the graph of temperature against volume in the constant pressure gas thermometer is extrapolated beyond the ice point to the point at which the volume of the gas would become zero, then the temperature at this point is  $-273^\circ\text{C}$  approximately (Fig. 1.10). Similarly if the graph of temperature against pressure in the constant



against  $v$  (Fig. 1.11(b) and 1.11(c)). At any other instant the piston may be moved in the cylinder such that the pressure and specific volume are changed to  $p_2$  and  $v_2$ . State 2 can then be marked on the diagrams. Diagrams of properties are used continually in applied thermodynamics to plot state changes. The most important are the pressure-volume and temperature-entropy diagrams, but enthalpy-entropy and pressure-enthalpy diagrams are also used frequently.

## 1.4 Reversibility

In section 1.3 it was shown that the state of a fluid can be represented by a point located on a diagram using two properties as coordinates. When a system changes state in such a way that at any instant during the process the state point can be located on the diagram, then the process is said to be *reversible*. The fluid undergoing the process passes through a continuous series of equilibrium states. A reversible process between two states can therefore be drawn as a line on any diagram of properties (Fig. 1.12(a)). In practice, the fluid undergoing a process cannot be kept in equilibrium in its intermediate states and a continuous path cannot be traced on a diagram of properties. Such real processes are called *irreversible processes*. An irreversible process is usually represented by a dotted line joining the end states to indicate that the intermediate states are indeterminate (Fig. 1.12(b)).



A more rigorous definition of reversibility is as follows:

*When a fluid undergoes a reversible process, both the fluid and its surroundings can always be restored to their original state.*

The criteria of reversibility are as follows:

- (a) The process must be frictionless. The fluid itself must have no internal friction and there must be no mechanical friction (e.g. between cylinder and piston). The difference in pressure between the fluid and its surroundings during the

cubic millimetre,  $\text{mm}^3$ , and the cubic metre,  $\text{m}^3$ , is much too great (a factor of  $10^9$ ), and the most commonly used intermediate unit is the cubic decimetre,  $\text{dm}^3$ , which is equal to one-thousandth of a cubic metre (i.e.  $1 \text{ dm}^3 = 10^{-3} \text{ m}^3$ ). The cubic decimetre can also be called the *litre*, *l*,

i.e.  $1 \text{ litre}, l = 1 \text{ dm}^3 = 10^{-3} \text{ m}^3$

(Note, for very precise measurements,  $1 \text{ litre} = 1.000\,028 \text{ dm}^3$ .)

Certain exceptions to the general rule of multiplying factors are inevitable. The most obvious example is in the case of the unit of time. Instead of the centisecond, kilosecond, or megasecond, for instance, the minute, hour, day, etc. are used. Similarly, a mass flow rate may be expressed in kilograms per hour,  $\text{kg/h}$ , if this gives a more convenient number than when expressed in kilograms per second,  $\text{kg/s}$ . Also the speed of road vehicles is expressed in kilometres per hour,  $\text{km/h}$ , since this is more convenient than the normal unit of velocity which is metres per second,  $\text{m/s}$ .

### 1.3 The state of the working fluid

In all problems in applied thermodynamics we are concerned with energy transfers to or from a system. In practice the matter contained within the boundaries of the system can be liquid, vapour, or gas, and is known as the *working fluid*. At any instant the *state* of the working fluid may be defined by certain characteristics called its *properties*. Many properties have no significance in thermodynamics (e.g. electrical resistance), and will not be considered. The thermodynamic properties introduced in this book are pressure, temperature, specific volume, specific internal energy, specific enthalpy, and specific entropy. It has been found that, for any pure working fluid, only two independent properties are necessary to define completely the state of the fluid. Since any two independent properties suffice to define the state of a system, it is possible to represent the state of a system by a point situated on a diagram of properties. For example, a cylinder containing a certain fluid at pressure  $p_1$  and specific volume  $v_1$  is at state 1, defined by point 1 on a diagram of  $p$  against  $v$  (Fig. 1.11(a)). Since the state is defined, then the temperature of the fluid,  $T$ , is



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and the hypothesis that it can be  
used by scientists in the early part of the

Whitcomb

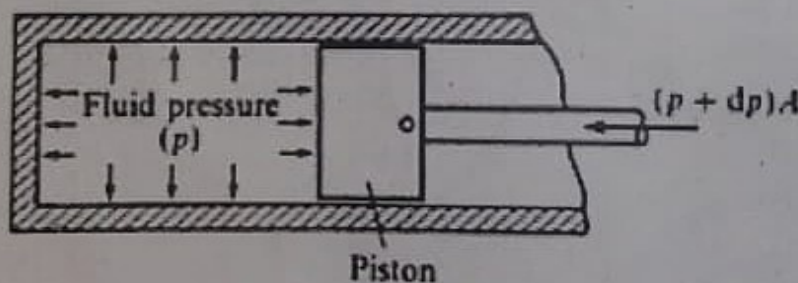
the process rejected to or from the fluid must be transferred infinitely slowly.

It is obvious from the above criteria that no process in practice is truly reversible. However, in many practical processes a very close approximation to an *internal reversibility* may be obtained. In an internally reversible process, although the surroundings can never be restored to their original state, the fluid itself is at all times in an equilibrium state and the path of the process can be exactly retraced to the initial state. In general, processes in cylinders with a reciprocating piston are assumed to be internally reversible as a reasonable approximation, but processes in rotary machinery (e.g. turbines) are known to be irreversible due to the high degree of turbulence and scrubbing of the fluid.

## 1.5 Reversible work

Consider an ideal frictionless fluid contained in a cylinder behind a piston. Assume that the pressure and temperature of the fluid are uniform and that there is no friction between the piston and the cylinder walls. Let the cross-sectional area of the piston be  $A$ , let the pressure of the fluid be  $p$ , let the pressure of the surroundings be  $(p + dp)$  (Fig. 1.13). The force exerted by the piston on the fluid is  $pA$ . Let the piston move under the action of the force exerted a distance  $dl$  to the left. Then work done on the fluid by the piston is given by force times the distance moved,

i.e. Work done,  $dW = -(pA) \times dl = -p dV$



where  $dV$  is a small increase in volume. The negative sign is necessary because the volume is decreasing.

Or for a mass,  $m$ ,

$$dW = -mp dv$$

where  $v$  is the specific volume. This is only true when criteria (a) and (b) hold as stated in section 1.4.

When a fluid undergoes a reversible process a series of state points can be joined up to form a line on a diagram of properties. The work done on the fluid during any reversible process,  $W$ , is therefore given by the area under the line of the process.

energy of the system is the same at the beginning and end of the cycle. During the various processes that make up the cycle work is done on or by the fluid and heat is supplied or rejected; the network input can be defined as  $\sum W$ , and the net heat supplied as  $\sum Q$ , where the symbol  $\sum$  represents the sum for a complete cycle.

Since the intrinsic energy of the system is unchanged the First Law of Thermodynamics states that:

*When a system undergoes a thermodynamic cycle then the net heat supplied to the system from its surroundings plus the net work input to the system from its surroundings must equal zero.*

That is

$$\sum Q + \sum W = 0 \quad (1.3)$$

1.3

In a certain steam plant the turbine develops 1000 kW. The heat supplied to the steam in the boiler is 2800 kJ/kg, the heat rejected by the steam to the cooling water in the condenser is 2100 kJ/kg and the feed-pump work required to pump the condensate back into the boiler is 5 kW. Calculate the steam flow rate.

tion

The cycle is shown diagrammatically in Fig. 1.21. A boundary is shown which encompasses the entire plant. Strictly, this boundary should be thought of as encompassing the working fluid only. For unit mass flow rate

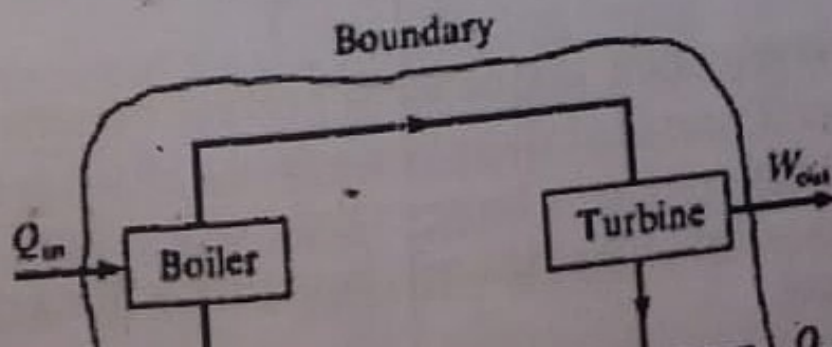
$$\sum dQ = 2800 - 2100 = 700 \text{ kJ/kg}$$

Let the steam flow be  $m$  kg/s. Therefore

$$\sum dQ = 700m \text{ kW}$$

and 
$$\sum dW = 5 - 1000 = -995 \text{ kW}$$

plant



$$dQ + dW = du$$

(1.5)

Example 1.4

In the compression stroke of an internal-combustion engine the heat rejected to the cooling water is 45 kJ/kg and the work input is 90 kJ/kg. Calculate the change in specific internal energy of the working fluid stating whether it is a gain or a loss.

Solution

$$Q = -45 \text{ kJ/kg}$$

(-ve sign since heat is rejected).

$$W = 90 \text{ kJ/kg}$$

Using equation (1.4)

$$Q + W = u_2 - u_1$$

$$-45 + 90 = u_2 - u_1$$

therefore

$$u_2 - u_1 = 45 \text{ kJ/kg}$$

i.e. Gain in internal energy = 45 kJ/kg

---

Example 1.5

In the cylinder of an air motor the compressed air has a specific internal energy of 420 kJ/kg at the beginning of the expansion and a specific internal energy of 200 kJ/kg after expansion. Calculate the heat flow to or from the cylinder when the work done by the air during the expansion is 100 kJ/kg.

Solution

From equation (1.4)

$$Q + W = u_2 - u_1$$

i.e.  $Q - 100 = 200 - 420$

therefore

$$Q = -120 \text{ kJ/kg}$$

i.e. Heat rejected by the air = +120 kJ/kg

---

It is important to note that equations (1.3), (1.4), and (1.5) are true whether or not the process is reversible. These are energy equations.

For reversible non-flow processes we have, from equation (1.2)

$$W = -m \int_1^2 p \, dv$$

i.e.  $700 \dot{m} - 995 = 0$

therefore

$$\dot{m} = 995/700 = 1.421 \text{ kg/s}$$

i.e. Steam mass flow rate required = 1.421 kg/s

---

## 1.7 The non-flow equation

In section 1.6 it is stated that when a system possessing a certain intrinsic energy is made to undergo a cycle by heat and work transfer, then the net heat supplied plus the net work input is zero.

This is true for a complete cycle when the final intrinsic energy of the system is equal to its initial value. Consider now a process in which the intrinsic energy of the system is finally greater than the initial intrinsic energy. The sum of the net heat supplied and the net work input has increased the intrinsic energy of the system, i.e.

$$\text{Gain in intrinsic energy} = \text{Net heat supplied} + \text{net work input}$$

When the net effect is to transfer energy from the system, then there will be a loss in the intrinsic energy of the system.

When a fluid is not in motion then its intrinsic energy per unit mass is known as the *specific internal energy* of the fluid and is given the symbol  $u$ . The specific internal energy of a fluid depends on its pressure and temperature, and is itself a property. The simple proof that specific internal energy is a property is given in ref. 1.4. The internal energy of mass,  $m$ , of a fluid is written as  $U$ , i.e.  $mu = U$ . The units of internal energy,  $U$ , are usually written as kJ.

Since internal energy is a property, then gain in internal energy in changing from state 1 to state 2 can be written  $U_2 - U_1$ .

Also, gain in internal energy = net heat supplied + net work input,

i.e. 
$$U_2 - U_1 = \sum_1^2 dQ + \sum_1^2 dW$$

This equation is true for a process or series of processes between state 1 and state 2 provided there is no flow of fluid into or out of the system. In any one non-flow process there will be either heat supplied or heat rejected, but not both; similarly there will be either work input or work output, but not both. Hence,

$$U_2 - U_1 = Q + W \text{ for a non-flow process}$$

Energy required at exit to push unit mass flow rate of fluid across the boundary  
 $= p_2 v_2$

Consider now the energy entering and leaving the system. The energy entering the system consists of the energy of the flowing fluid at inlet

$$\dot{m} \left( u_1 + \frac{C_1^2}{2} + Z_1 g \right)$$

the energy term  $\dot{m} p_1 v_1$ , the heat supplied  $\dot{Q}$ , and the rate of work input,  $\dot{W}$ . The energy leaving the system consists of the energy of the flowing fluid at the outlet section

$$\dot{m} \left( u_2 + \frac{C_2^2}{2} + Z_2 g \right)$$

and the energy term  $\dot{m} p_2 v_2$ . Since there is steady flow of fluid into and out of the system, and there are steady flows of heat and work, then the energy entering must exactly equal the energy leaving.

$$\dot{m} \left( u_1 + \frac{C_1^2}{2} + Z_1 g + p_1 v_1 \right) + \dot{Q} + \dot{W} = \dot{m} \left( u_2 + \frac{C_2^2}{2} + Z_2 g + p_2 v_2 \right) \quad (1.8)$$

In nearly all problems in applied thermodynamics, changes in height are negligible and the potential energy terms can be omitted from the equation. The terms in  $u$  and  $pv$  occur on both sides of the equation and always will do so in a flow process, since a fluid always possesses a certain internal energy, and the term  $pv$  always occurs at inlet and outlet as seen in the above proof. The sum of specific internal energy and the  $pv$  term is given the symbol  $h$ , and is called *specific enthalpy*,

i.e. **Specific enthalpy,  $h = u + pv$**  (1.9)

The specific enthalpy of a fluid is a property of the fluid, since it consists of the sum of a property and the product of two properties. Since specific enthalpy is a property like specific internal energy, pressure, specific volume, and temperature, it can be introduced into any problem whether the process is a flow process or a non-flow process. The enthalpy of mass,  $m$ , of a fluid can be written as  $H$  (i.e.  $mh = H$ ). The units of  $h$  are the same as those of internal energy.

Substituting equation (1.9) in equation (1.8)

$$\dot{m} \left( u_1 + \frac{C_1^2}{2} + p_1 v_1 \right) + \dot{Q} + \dot{W} = \dot{m} \left( u_2 + \frac{C_2^2}{2} + p_2 v_2 \right) \quad (1.10)$$



Hence for any reversible non-flow process for unit mass, substituting equation (1.5)

$$dQ = du + p dv$$

or substituting in equation (1.4)

$$Q = (u_2 - u_1) + \int_1^2 p dv$$

Equations (1.6) and (1.7) can only be used for ideal reversible non-flow processes.

## 1.8 The steady-flow equation

In section 1.7, the specific internal energy of a fluid was said to be the intrinsic energy of the fluid due to its thermodynamic properties. When unit mass of fluid with specific internal energy,  $u$ , is moving with velocity  $C$  and is a height  $Z$  above a datum level, then it possesses a total energy of  $u + (C^2/2) + Zg$  where  $C^2/2$  is the kinetic energy of unit mass of the fluid and  $Zg$  is the potential energy of unit mass of the fluid.

In most practical problems the rate at which the fluid flows through a machine or piece of apparatus is constant. This type of flow is called *steady flow*.

Consider a fluid flowing in steady flow with a mass flow rate,  $\dot{m}$ , through a piece of apparatus (Fig. 1.22). This constitutes an open system as defined in section 1.2. The boundary is shown cutting the inlet pipe at section 1 and the outlet pipe at section 2. This boundary is sometimes called a *control surface* and the system encompassed, a *control volume*.

Fig. 1.22 Steady-flow open system

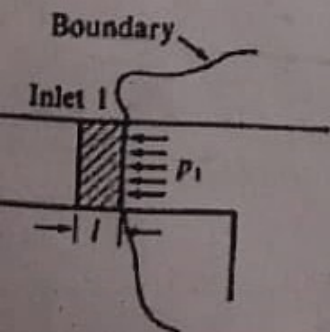
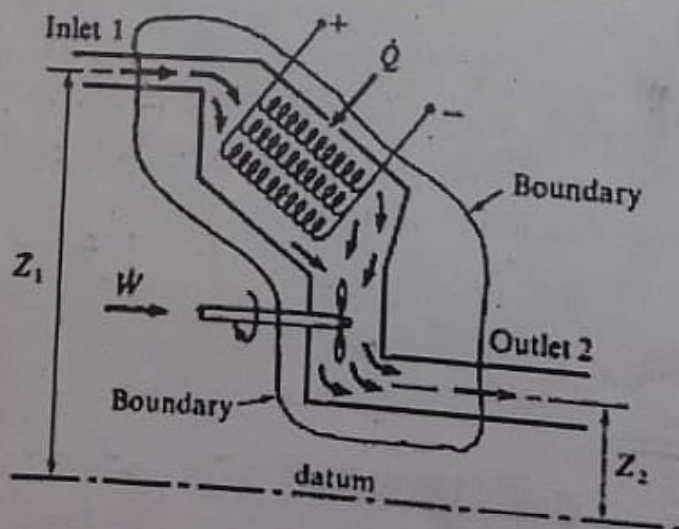


Fig. 1.23 Section at inlet to the system

Let it be assumed that a steady rate of flow of heat  $\dot{Q}$  units is supplied, and that  $\dot{W}$  is the rate of work input on the fluid as it passes through the apparatus. Now in order to introduce the fluid across the boundary an expenditure of energy is required; similarly in order to push the fluid across the boundary at exit, an expenditure of energy is required. The inlet section is shown enlarged in Fig. 1.23. Consider an element of fluid, length  $l$ , and let the cross-sectional area of the inlet pipe be  $A_1$ . Then we have

Energy required to push element across boundary

$$= (p_1 A_1) \times l = p_1 \times (\text{volume})$$

therefore

$$Q = -119.3 \text{ kW}$$

i.e. Heat rejected = +119.3 kW

To find the inlet area, use equation (1.11), i.e.

$$\dot{m} = \frac{CA}{v} \quad \text{or} \quad A = \frac{\dot{m}v}{C}$$

therefore

$$\text{Inlet area, } A_1 = \frac{17 \times 0.5}{60} = 0.142 \text{ m}^2$$

Example 1.7

Air flows steadily at the rate of 0.4 kg/s through an air compressor, entering at 6 m/s with a pressure of 1 bar and a specific volume of 0.85 m<sup>3</sup>/kg, and leaving at 4.5 m/s with a pressure of 6.9 bar and a specific volume of 0.16 m<sup>3</sup>/kg. The specific internal energy of the air leaving is 88 kJ/kg greater than that of the air entering. Cooling water in a jacket surrounding the cylinder absorbs heat from the air at the rate of 59 kW. Calculate the power required to drive the compressor and the inlet and outlet pipe cross-sectional areas.

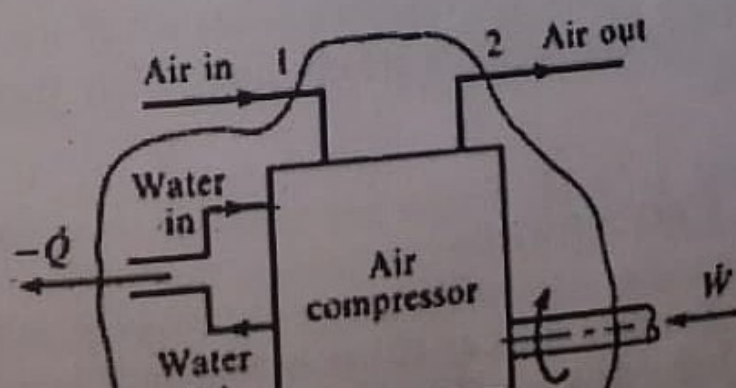
Solution

In this problem it is more convenient to write the flow equation as in equation 1.8, omitting the Z terms,

$$\text{i.e.} \quad \dot{m} \left( u_1 + \frac{C_1^2}{2} + p_1 v_1 \right) + \dot{Q} + \dot{W} = \dot{m} \left( u_2 + \frac{C_2^2}{2} + p_2 v_2 \right)$$

A diagrammatic representation of the compressor is shown in Fig. 1.25. Note that the heat rejected across the boundary is equivalent to the heat removed by the cooling water from the compressor. For unit mass flow rate:

$$\frac{C_1^2}{2} = \frac{6 \times 6}{2} \text{ J/kg} = 18 \text{ J/kg} = 0.018 \text{ kJ/kg}$$



where  $v$  is the specific volume at the section and  $\rho$  the density at the section. This equation is known as the *continuity of mass equation*.

With reference to Fig. 1.22

$$\dot{m} = \frac{C_1 A_1}{v_1} = \frac{C_2 A_2}{v_2}$$

**Example 1.6**

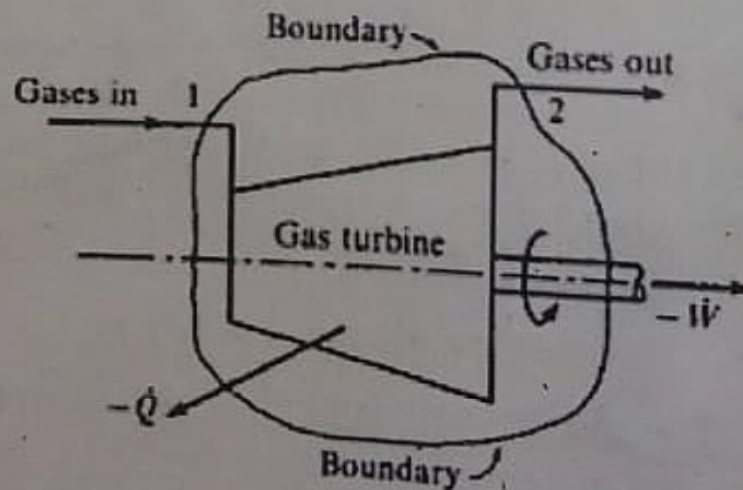
In the turbine of a gas turbine unit the gases flow through the turbine at a mass flow rate of 17 kg/s and the power developed by the turbine is 14 000 kW. The specific enthalpies of the gases at inlet and outlet are 1200 kJ/kg and 360 kJ/kg respectively, and the velocities of the gases at inlet and outlet are 60 m/s and 150 m/s respectively. Calculate the rate at which heat is rejected from the turbine. Find also the area of the inlet pipe given that the specific volume of the gases at inlet is 0.5 m<sup>3</sup>/kg.

**Solution**

A diagrammatic representation of the turbine is shown in Fig. 1.24. For the control volume shown in Fig. 1.24, the energy equation (1.10), neglecting changes in height

$$\dot{m} \left( h_1 + \frac{C_1^2}{2} \right) + \dot{Q} + \dot{W} = \dot{m} \left( h_2 + \frac{C_2^2}{2} \right)$$

gas turbine  
1.6



For unit mass flow rate:

$$\begin{aligned} \text{Kinetic energy at inlet} &= \frac{C_1^2}{2} = \frac{60^2}{2} \text{ m}^2/\text{s}^2 = \frac{60^2 \text{ kg m}^2}{2 \text{ s}^2 \text{ kg}} \\ &= 1800 \text{ N m/kg} = 1.8 \text{ kJ/kg} \end{aligned}$$