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THE EFFICIENT USE OF STEAM

General Editor: P. M. Goodall

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**THE
EFFICIENT USE
OF STEAM**

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Preface

Sir Oliver Lyle's *The Efficient Use of Steam* has always been one of my favourite textbooks; its freshness of approach singled it out as something special when it was first published. However, it is over thirty years since it first came out, and because of the continuing development of steam engineering and its allied subjects, it was thought that the time had come for a complete revision of the book.

The original intention was to do just that — to take out old material and to introduce new subjects, and modern methods. Like Chaucer's Monk, we wanted 'to let go by the things of yesterday, and take the modern world's more spacious way'. It became clear however that for copyright reasons this could not be done, and the book would have to be rewritten.

There has been no attempt to imitate the original style — it was inimitable; one exception has been made in Chapter 20 where a typical piece of Sir Oliver's analytical style has been introduced.

The original title has been kept; it was a good title and has served the book well during thirty years, but this new book does cover a little more of the subject. It might well be subtitled 'The Steam Engineer's Manual', because we have tried to provide all the necessary information an industrial steam engineer, or designer, would want about the 'steam-water stuff'. In general the book has been produced for engineers operating in the middle range of industrial power, with an upper limit of about 100 MW. An exception has been made in the material supplied by the Central Electricity Generating Board on installations of 500 MW upwards, because their approach to the efficient use of steam and their monitoring of station performance must surely have lessons for all.

I shall not give an account of my indebtedness to the many people who have helped, because I have thanked each of them individually, but I must make one exception, in the case of my typist. Mrs Mandy Smith has managed to decipher the more lurid details of thermodynamics, written in a bad hand, with an astonishing precision. My debt to her is very great.

It should be clear that any mistakes in the book are my responsibility. If such mistakes occur, I must enter the same plea as that used 200 years ago by Dr Johnson. A lady had taken him to task for a flagrantly wrong definition in his dictionary. When she asked him how he could make such a mistake he replied, 'Ignorance, Madam, pure ignorance'.

Philip M. Goodall
Chideock, December 1979

Steam pressures

The usual problems have arisen as to whether to use the gauge or absolute pressure of steam. It has been decided to make it as simple as possible by using absolute pressure *unless otherwise stated*. Clearly in those cases where general considerations of pressure are being discussed, and no calculations are involved, it is unimportant whether absolute or gauge pressures are being mentioned, but in all other cases, unless bar gauge is specially mentioned, pressures are all in bar abs.

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1

The properties of water and steam

- 1.1 The chemical and physical properties
- 1.2 Terms and concepts
- 1.3 The thermodynamic properties of water and steam
- 1.4 Steam tables and charts

1.1 The chemical and physical properties

In 1712 Newcomen completed the construction of the first practical steam engine, which was a reciprocating (beam) engine used extensively for mine drainage and later adapted for locomotive propulsion. Steam (i.e. water vapour) has therefore been used as a working fluid since the earliest days of the industrial revolution, and it is difficult to appreciate its impact on and importance for the development of that revolution. Today, its use is common throughout industry not only for mechanical power production, but also for many and varied heating and process applications. The advantages of using steam as the working fluid are partly that it can be easily distributed and controlled and also that it can serve as the same working fluid for combined power generation and/or heating and/or process work duties. In addition, water and steam possess the following unusual merits:

1. Water is by far the most common liquid on the earth and is therefore plentiful and cheap. It is also chemically stable and non-hazardous to health.
2. Water is evaporated into steam at temperatures well below the metallurgical limit of boiler steels.
3. Water and steam both act as good heat sponges and the evaporation of water into steam also involves a high heat absorption. Hence, plant sizes and costs are not impracticably large.

In order for these chemical and physical properties of water and steam to be understood, it is necessary to describe the molecular and atomic structure of matter in a general way and then to discuss the particular structure of the water and steam substance.

All chemical substances consist of vast numbers of very small discrete particles called *molecules*. For example, one kilogram of ice, water or steam consists of about 3×10^{25} molecules, each about 2×10^{-10} m in diameter. Molecules are composed of even smaller particles called atoms, but the molecule is the smallest particle of a substance to possess all the chemical properties of that substance, that is, the qualities which enable us to

distinguish between water, salt, iron and so on. The molecules are in constant motion and are separated from one another in the bulk substance by empty space. Any substance can exist in three possible physical states or *phases* — solid, liquid or vapour — depending upon the degree of freedom of movement of its molecules.

In the solid phase, the movement of individual molecules is restricted to a vibration about a mean bonded position, and the molecules are very closely packed in a lattice-type structure. The distance separating adjacent molecules is less than the diameter of a molecule. If the solid is heated the molecules vibrate more energetically and at some stage the vibration will be sufficiently energetic for the molecules to break away from their bonded structures, and the solid then melts into a liquid. This phase change requires the absorption of heat to break the lattice bonding and hence the substance does not become hotter during the melting process. The amount of heat required to melt unit mass of the substance is called the *latent heat of melting*, and this value differs from one substance to another depending upon the strength of the lattice bonding that is broken. The reverse process is freezing, and it occurs with the release of the same amount of latent heat to the surroundings.

In the liquid state, the molecules are free to move about, but only within the restricted volume occupied by the bulk substance. This volume is of no fixed shape, but assumes the shape of the containing (solid) vessel. The liquid molecules are still very close to one another (less than one molecular diameter apart) and chance collisions occur frequently. If the liquid is heated, its molecules move faster and collisions become more frequent and energetic. The collisions result in some molecules having above-average speeds for short periods of time, whilst others have below-average speeds. Molecules with above-average speeds and near the liquid surface may overcome the attractive forces of the surrounding liquid molecules, and they will therefore escape from the bulk liquid and will form the vapour envelope above the liquid surface. If more heat is supplied, the average speed of the molecules will eventually equal the escape speed and then the liquid evaporates into a vapour, or in other words boiling occurs. As in melting, this requires the absorption of heat in order to break the mutual attractions of the closely packed liquid molecules, and therefore the substance does not become hotter during the evaporation process. The amount of heat required to evaporate a unit mass of the substance at its boiling temperature is called the *latent heat of evaporation*. The reverse process is *condensation* and occurs with the release of the same amount of latent heat to the surroundings.

The molecules in the vapour state have no mutual attraction and move in random directions with high velocities of up to several thousand kilometres per second. Under atmospheric conditions they are separated from one another by about ten molecular diameters, and the molecules occupy the whole space that is available, the only restriction being the walls of a containing vessel. If the vessel has a movable wall (for example the piston of a reciprocating engine), and this wall is moved so as to increase the available volume, then the vapour will expand to fill the increased volume. The movements of the individual molecules are dictated by the results of chance collisions with one another and with the walls of the containing vessel. If the vapour is heated it will eventually reach a state such that it cannot be forced by compression to change back into a liquid. At and above this temperature the vapour is then called a gas.

This description of the molecular structure of matter applies to the ice, water and steam substance. However, this substance possesses certain additional and unusual properties and we shall now discuss these. First, let us consider why water is the most common liquid on earth and why therefore it is plentiful and cheap. Each molecule of ice, water and steam consists of two atoms of the element hydrogen (of chemical symbol H) bonded together with one atom of oxygen (of chemical symbol O). The resulting chemical compound therefore has the formula H_2O and is thought to be the most common chemical compound in the universe. Out of every 10 000 atoms in the universe, about 9200 are hydrogen, 790 are helium, 5 are oxygen, 2 are neon, 2 are nitrogen and 1 is carbon. All the other elements make up an insignificant contribution. Since helium does not combine with any other elements, it follows that the most common compound-forming elements are hydrogen and oxygen, and the atomic structures of these elements dictate the chemical bonding of the two atoms of hydrogen with one of oxygen. Naturally, H_2O is not common everywhere in the universe. It does not exist in stars (because of break-up of molecules at very high temperatures) and on small planets (because gravitational forces are too weak to trap the molecules). However, the earth's planetary position, size and mean temperature are such as to contain and hold a more representative sample of H_2O , and it is therefore plentiful and hence cheap on the Earth.

The other special properties of H_2O are due to the unusual type of bonding (called the *hydrogen bond*) of the hydrogen and oxygen atoms. This results in H_2O molecules' having extra-strong mutual attractions, and consequently possessing the following unusual properties:

1. Much higher melting and boiling temperatures than would be expected for such a chemical substance. Without the extra-strong bonds, H_2O would be a gas at atmospheric temperatures and life as we know it would not exist on the earth.
2. Water, in all its three phases, absorbs more heat for each one-degree rise in temperature than would be the case if the extra-strong bonding did not exist. Thus, ice, water and steam are all good heat sponges. This results, for example, in only slight variations in ocean temperatures between summer and winter.
3. Water has unusually high latent heats of melting and evaporation owing to the necessity of breaking the extra-strong molecular bonds. Hence, evaporating water into steam is an effective heat sponge process.
4. Water has a maximum density at 4°C (and not at 0°C) and is an extremely good solvent. Again, if water did not have these properties, life as we know it would not exist on the earth.

The chemical and physical properties of the H_2O substance having been described, the rest of this chapter is concerned with its thermodynamic properties. To this end, we shall use a number of terms and concepts, and these are defined and discussed in the next section.

1.2 Terms and concepts

Mass

The *mass*, m , of a substance is a measure of the amount of matter (atoms and molecules) comprising the substance. Thus, 10 kg of steam consists of ten times as many H_2O molecules as 1 kg of steam.

Furthermore, 1 kg of steam contains exactly the same number of molecules as 1 kg of water or 1 kg of ice.

Density and specific volume

The *density*, ρ , of a substance is the mass (m) per unit volume (V) of the substance. The *specific volume*, v , is the volume per unit mass and is therefore the inverse of density. Its units are m^3/kg or dm^3/kg where $10^3 \text{ dm}^3/\text{kg} = 1 \text{ m}^3/\text{kg}$. Hence

$$\rho = \frac{m}{V} = \frac{1}{v} \quad (1.1)$$

From our discussions on the molecular structure of liquids and vapours we would expect the density of steam to be much smaller than that of water because the steam molecules are more widely separated from one another, and at typical atmospheric conditions the densities of water and steam are

respectively 1000 kg/m^3 and 0.6 kg/m^3 . One kg of steam at atmospheric conditions therefore occupies a volume about 1700 times that of 1 kg of water. This enormous volume difference is appreciated if a kettle of water is left to boil; the resulting steam soon fills the entire room.

Temperature

The *temperature*, t or T , of a substance is a measure of the degree of hotness or coldness of the substance. From our discussion on the molecular structure of matter, the temperature of a substance is seen to be related to the intensity of molecular and atomic motion; the more energetic the motion of the molecules and atoms, the more energetic are the collisions, the hotter is the substance and the higher its temperature.

In SI units, temperature is measured in $^\circ\text{C}$ or K units. The *Celsius* (or *centigrade*) $^\circ\text{C}$ scale is the one most commonly used by the engineer as it has a convenient (but false) zero corresponding to the freezing temperature of water. The *absolute* (or *Kelvin*) K scale is a similar scale with the same increments, but with a true zero corresponding to the minimum possible temperature of a substance when all molecular and atomic motion has ceased. It is impossible for a substance to consist of molecules and atoms having negative motion, and therefore it is impossible for a substance to be at a negative absolute temperature. The absolute temperature at which water freezes to ice is 273 K, and hence the two scales of temperature are interchangeable according to the relation

$$T (\text{K}) = t (^\circ\text{C}) + 273^\circ \quad (1.2)$$

For example, at atmospheric pressure water boils into steam at 100°C or 373 K. As both scales have the same increments, a temperature difference of 1°C is the same as 1 K.

Temperature measurement

The mercury-in-glass thermometer is the common instrument for measuring water or steam temperatures. When the instrument is subjected to a change in temperature, the mercury expands or contracts far more than the glass container. The resulting differential volume change is recorded as a change in position of the mercury column up or down a suitably graduated scale.

Another type of commonly used thermometer is the thermocouple. This consists of two insulated wires of different metals, which are joined together at both ends. When the two junctions are at different temperatures there is an electrical potential difference between the junctions that is proportional to the temperature difference. The cold junction is built into the meter, and there is

4 The properties of water and steam

normally a compensating device for variations in meter temperature. The hot junction is subjected to the water or steam temperature which is to be measured. The meter measures the resulting potential difference and indicates it as a reading on a temperature scale.

Force

Newton's first law of motion tells us that a body must be subjected to a force if it is to undergo acceleration or deceleration. Newton's second law relates the force F (in newtons, N) necessary to cause a mass m (kg) to accelerate by an amount a (m/s^2) of

$$F = ma \quad (1.3)$$

Thus, 1 N is the force which must be applied to a mass of 1 kg in order to accelerate it by 1 m/s^2 .

Weight

The *weight* (wt) of a substance is the force of the earth's gravitational pull on that substance. Since all substances falling freely anywhere in the vicinity of the earth are pulled towards the earth with an acceleration g of 9.81 m/s^2 , application of Newton's second law gives

$$\text{wt} = mg$$

Thus, 1 kg of any substance on the earth has a weight of 9.81 N.

Pressure

The *pressure*, p , of a vapour acting on the interior walls of its containing vessel is the force acting on a unit area of the walls caused by the multiple impacts of the vapour molecules against the wall. Heating the vapour will result in its molecules becoming more energetic, and their impacts with the wall molecules more frequent and intense. Therefore, heating will result in an increase in both the temperature and pressure of the vapour if the vessel's volume does not change.

A pressure of 1 N/m^2 is very small because 1 N is not a large force and yet 1 m^2 is quite a big area. Hence, a more common pressure unit for the practical engineer is the *bar*, defined as $1 \text{ bar} = 10^5 \text{ N/m}^2$. The bar is a convenient unit as it is closely equal to the pressure of the atmosphere.

Atmospheric pressure

The earth is surrounded by an atmosphere consisting mainly of about 79% (by volume) nitrogen gas and 21% (by volume) oxygen gas. The atmosphere extends outwards and the further out from the earth's surface, the less dense it becomes. It has no abrupt ending, but at about 800 km the air is so

rarefied that the contribution above this altitude can be neglected.

All the molecules of the atmosphere are held in the earth's vicinity by gravitational pull. The earth's surface is pressurized by the weight of the air above, and is therefore subjected to atmospheric pressure. Its magnitude of approximately 1 bar is an appreciable pressure, but we do not notice it because we live within this environment. Atmospheric pressure varies slightly from one day to the next owing to changes in weather affecting the temperature and density of the air near the earth's surface. One *standard atmosphere* is atmospheric pressure at sea-level on a day when the temperature is 15°C . Its value is 1.013 bar.

Types of pressure

Figure 1.1 illustrates four ways of indicating pressure, defined as:

1. The *absolute pressure* (in bar abs) of a vapour is its pressure measured from the datum of a perfect vacuum, i.e. from a datum of zero bar abs. It is impossible for a vapour to have a negative absolute pressure.
2. The *gauge pressure* (in bar g) of a vapour is its pressure above that of the prevailing atmosphere. Thus, gauge pressure equals absolute pressure minus atmospheric pressure.
3. The *vacuum* or *negative gauge pressure* of a vapour is the pressure of the vapour below that of the atmosphere. This term is therefore used only if the vapour has a pressure below that of the atmosphere. A vacuum of zero bar corresponds to atmospheric pressure and a vacuum of 1 bar corresponds to close to a perfect vacuum.
4. A *differential pressure* is simply the pressure difference between any two pressures.

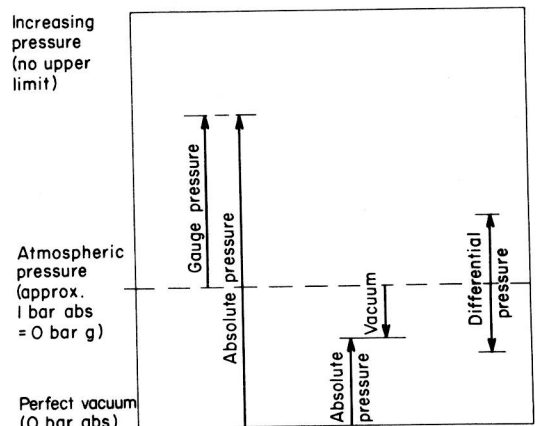


Figure 1.1 Four types of pressure: absolute, gauge, vacuum and differential

Atmospheric pressure measurement — the mercury barometer

The mercury barometer consists of a tube held vertically with its open bottom-end submerged in a mercury bath and with its sealed top-end evacuated. Atmospheric pressure acts on the surface of the mercury bath and forces the mercury to a definite height within the tube. Measurement of the height h of the mercury column enables the atmospheric pressure to be calculated, because

$$\begin{aligned} \text{Atmospheric pressure} &= \text{hydrostatic pressure at the base of the mercury column} \\ \frac{\text{mercury weight}}{\text{base area } A \text{ of column}} &= \frac{(\text{mercury mass}) (g)}{A} \\ &= \frac{(\text{mercury density } \rho)(\text{volume})(g)}{A} \\ &= \frac{(\rho)(A \times h)(g)}{A} = \rho gh \end{aligned} \quad (1.4)$$

For example, if the height h of the mercury column on a particular day is measured as 750 mm, since ρ for mercury is $13.6 \times 10^3 \text{ kg/m}^3$ and $g = 9.81 \text{ m/s}^2$, the atmospheric pressure on that day is calculated as

$$\begin{aligned} \text{Atmospheric pressure} &= \rho gh = (13.6 \times 10^3) \times \\ (9.81)(0.75) \text{ N/m}^2 &= 10^5 \text{ N/m}^2 = 1 \text{ bar} \end{aligned} \quad (1.5)$$

Steam-pressure measurement using dial Bourdon gauges

The dial pressure gauge is the instrument commonly used for measuring steam pressures above atmospheric, and the dial vacuum gauge is used for pressures below atmospheric. Both measure pressure relative to the prevailing

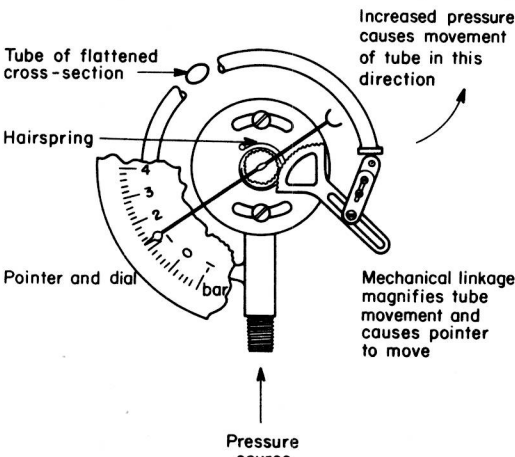


Figure 1.2 The construction of the dial pressure and vacuum Bourdon gauge

atmospheric pressure, and they can be combined into one instrument for measuring pressures both above and below atmospheric. Figure 1.2 illustrates the construction of these gauges. Atmospheric pressure acts around the outside of a curved, flattened tube and tends to keep the tube flat and curved. The inside of the tube is subjected to the pressure which is to be measured, and if this pressure is greater than atmospheric the tube tends to straighten, and the resulting curvature change causes a pointer to move round a precalibrated scale. If the internal pressure is below atmospheric, the tube becomes more curved and again this is translated into a corresponding movement of the pointer. The gauges are calibrated and their calibration should be periodically checked using dead-weight testers.

Steam pressure measurement using manometers

Steam pressures in the vicinity of atmospheric pressure can be measured accurately using the U-tube manometer, i.e. a glass tube in the shape of the letter U which is partly filled with some fluid, usually mercury. One end of the tube is open to the atmosphere and the other end is connected to a tapping from the steam supply.

Measurement of the differential height of the columns in the two U-tube limbs enables the steam gauge or vacuum to be calculated using the previous hydrostatic pressure equation. For example, if the differential height is 1 m of mercury, then

$$\begin{aligned} \text{Steam gauge pressure} &= \rho gh \\ &= (13.6 \times 10^3) (9.81)(1) \text{ N/m}^2 = 1.33 \text{ bar g} \end{aligned} \quad (1.5)$$

Hence, if the barometer reads 750 mm, the atmospheric pressure is 1 bar, and the steam absolute pressure is 2.33 bar abs.

Work

Work is a form of energy transfer. For example, work must be supplied to push a car along a road. The work is supplied to move a force F (counteracting the frictional resistance between tyre and road, and air resistance) through the distance x the car moves. The greater the resistance forces which must be overcome or the greater the distance the car is moved, then the greater must be the work supplied. Hence, work $W = \text{force } F \times \text{displacement } x$.

In SI units, one joule (J) is the work required to overcome the resistive force of 1 N over a distance of 1 m. For most engineering calculations, the joule is a small unit and therefore work is usually quoted in kilojoules (kJ), where $1 \text{ kJ} = 1000 \text{ J}$.

Work must also be supplied to rotate a shaft.

This energy is used to overcome the resistive forces (of bearing friction, coupling load if present, etc.) and to overcome them whilst the shaft rotates through an angular distance. Hence, if r is the shaft radius and θ is the angular displacement (in radians), then

$$\begin{aligned} \text{Work } W &= \text{force } F \times \text{displacement } r\theta \\ &= (F \times r)(\theta) \\ &= T \times \theta \end{aligned} \quad (1.6)$$

where T is the torque on the shaft in N m.

Power

Power is defined as the rate of doing work. Consider a young man and an old man both walking along a road. When they reach the end both will have expended the same amount of work. This will have been used in overcoming the resistive forces (of shoe-to-road friction, etc.) and overcoming these forces over the same distance. However, because the young man reaches the end of the road first, his rate of work is greater and hence the power expended is greater, but over a shorter period of time.

Since power is the rate of doing work it is given the symbol \dot{W} just as \dot{m} is the rate of mass flow and \dot{V} is the rate of volume flow. Hence for linear displacement

$$\begin{aligned} \dot{W} &= \frac{\text{force } F \times \text{displacement } x}{\text{time } t} = \\ &\text{force } F \times \text{linear velocity} \end{aligned} \quad (1.7)$$

and for rotational displacement

$$\dot{W} = \frac{\text{torque } T \times \text{angular displacement } \theta}{\text{time } t} = T \times \omega \quad (1.8)$$

where ω = angular velocity in rad/s, = $2\pi N/60$ where N is in rev/min. In both cases the units of \dot{W} are J/s, defined as a *watt* (W). Again, a more practical unit is the kilowatt (kW), where 1000 W = 1 kW.

Heat

Heat, Q, is another type of energy transfer. If two bodies at different temperatures are placed in contact with one another, heat will be transferred from the hotter to the colder until they are both at the same temperature. The units of heat are the same as those of work since both are types of energy. Hence, heat is usually measured in kJ. The rate of heat transfer \dot{Q} is not given a special name, unlike the rate of work transfer (power). Heat transfer can occur in three possible ways: by

conduction, convection or radiation. These are discussed in Chapter 12.

Specific heat

The *specific heat, C*, of a substance is a measure of its capacity to absorb heat. It is the amount of heat that must be supplied to a unit mass of the substance in order to cause a unit increase in temperature of the substance, and its units are therefore kJ/kg °C or kJ/kg K. Its value for a particular substance varies both with its temperature and pressure. The high values for both water and steam, as discussed earlier in this chapter, are listed below for atmospheric pressure and temperature:

water	4.19 kJ/kg °C
steam	1.86 kJ/kg °C
air	1.01 kJ/kg °C
mercury	0.14 kJ/kg °C

Energy components of a fluid and enthalpy

We have previously indicated that a fluid does not contain or possess work or heat energy. Rather, it may accept work and/or heat from its surroundings, or reject work and/or heat to its surroundings. Let us now consider what energy components a fluid possesses when it is at a certain condition or state.

The total energy E of a fluid is the sum of the following components:

1. Potential energy (PE), or its energy of position within a gravitational field. Increasing the elevation of the fluid increases its potential energy.
2. Kinetic energy (KE), or its energy of motion. Increasing the velocity of the fluid increases its kinetic energy.
3. Enthalpy H , or its energy due to both the pressure and the temperature of the fluid. The energy due to the pressure is called the *pressure energy* (PrE) and is associated with pressurizing the fluid up to its prevailing pressure and therefore with forcing its molecules into closer proximity to one another. The energy due to the temperature of the fluid is called the *internal energy, U*, and is associated with the kinetic energies of its molecules. Hence

$$H = \text{PrE} + U \quad (1.9)$$

The enthalpy of a fluid therefore increases if its pressure and/or its temperature increases. The specific enthalpy h of a fluid is the enthalpy for unit mass of the fluid, and specific internal energy u is the internal energy for unit mass of fluid.

4. Various other energy components, usually

not of interest to us because their values do not alter during normal thermodynamic processes, for example the chemical energy of the bonding energy of the fluid's atoms into its molecules; atomic energy of the bonding energy of the sub-atomic particles into its atoms; and electrical energy of the movement of charged atoms and charged sub-atomic particles.

All these four components are various forms of energy and therefore each is measured in J or kJ. The specific enthalpy of a fluid is measured in kJ/kg.

Entropy

The entropy S and specific entropy s (i.e. its value for unit mass) of a fluid are difficult concepts to understand. The formal definition of entropy is as follows. If, during a perfectly reversible (i.e. frictionless) process, a small quantity of heat Q is supplied to a fluid, small enough not to change the absolute temperature T of the fluid, then the resultant entropy increase of the fluid is Q/T . The word 'reversible' is important; it implies that if the process is reversed by removing the heat Q no change can be detected in the system or its surroundings. If a large quantity of heat is involved, the temperature of the system will increase and we have to imagine that the process is broken down into a number of small processes. The total change of entropy is then found by adding up all the terms Q/T . Thus, if S_1 is the initial entropy of the fluid and S_2 is its entropy after such a change,

$$S_2 - S_1 = \Sigma \frac{Q}{T} \quad \text{or} \quad s_2 - s_1 = \Sigma \frac{Q}{mT} \quad (1.10)$$

where Σ means 'the sum of all the terms of' and m is the mass of the fluid.

From the above definition, a perfectly reversible process in which $Q = 0$ is a constant-entropy process.

This definition requires clarification. The entropy of a fluid quantifies the degree of orderly or disorderly motion of its molecules when the fluid is at a particular temperature and pressure. Increasing the degree of order of the motions, for example by condensing steam into water, results in a decrease in the entropy of the fluid. Supplying heat to a fluid increases its entropy because its molecules become more agitated, collisions become more frequent and the molecular motions become more chaotic. Although entropy is a property of a fluid, like its pressure and temperature, it cannot be measured directly; there is no instrument capable of measuring the degree of orderly or disorderly motion of molecules.

Instead, it has to be calculated from the other property values of pressure and temperature. From the above definition its units are kJ/K and the units of specific entropy are kJ/kg K.

1.3 The thermodynamic properties of water and steam

Thermodynamic properties

There are six properties of a fluid which are called *thermodynamic properties*. These are specific volume v , temperature t , pressure p , specific internal energy u , specific enthalpy h , and specific entropy s . We have defined and discussed each of these in the previous section. Graphical plots of any one of these against any other for the water and steam substance are of particular interest to the steam engineer because they describe the behaviour of water and steam. Some of the plots reveal the behaviour more clearly than the others and we shall describe these in this section.

The temperature–time and temperature–pressure plots

Suppose we conduct an experiment in which a quantity of ice at -50°C is heated at a pressure of 1 bar. The ice is enclosed in a vertical cylinder fitted with a piston capable of moving vertically up and down and the piston weight is such as to maintain the pressure constant. The supply of heat initially causes the temperature of the ice to increase. At 0°C the ice melts into water and during the melting the temperature remains constant at 0°C . Supplying more heat causes the water temperature to increase from 0°C up to 100°C and then the second phase change occurs in which the water evaporates to form steam. Again, the temperature remains constant until this phase change is completed. Supplying further heat to the steam at 100°C causes the steam temperature to increase.

We can repeat this experiment for different piston weights and hence for different constant pressures. *Figure 1.3* shows the resulting temperature–time curves for five such experiments corresponding to pressures of 0.005, 1, 15.5, 85.9 and 250 bar. The slopes of the near-vertical lines of these curves and the lengths of the horizontal portions are dependent upon the rate of heat supply and are not of importance in this discussion. Rather, we are interested in the number and comparative positions of the horizontal steps. All five curves have steps at 0°C , but only the middle three have second steps and these occur at different temperature levels. Let us relate the shapes of the curves to the changes that occur within the cylinder as heat is supplied. At