4 Properties of Steam

CHAPTER OUTLINE

OBJECTIVES

After studying this chapter, you will be able:

- To understand the concept of steams, their types and parameters etc.
- To understand important thermodynamic properties of gases
- To understand the measurement of dryness fraction of steam and different calorimeters

4.1 Introduction

Before investigating the formation and properties of steam it will be useful to discuss the various forms which matter can take and the relationship between them. Matter can take the forms, solid, liquid, vapour or gas, and many substances can exist in any one of these forms.

Consider, for example, a metal. In its natural state, metal is solid. If it is heated, at some temperature the metal will melt and become a liquid. Further transfer of heat, to the now liquid metal, will ultimately transform the liquid into a vapour and finally a gas. If the temperature is now reduced, the gaseous metal will pass back through all the stages it passed through until it finally becomes a solid once again.

Each change from one form to another is called a change of **phase,** and each change of phase is accomplished by the addition or extraction of heat. The temperature at which the changes of phase take place will vary according to the substance being used.

A further point to be considered is that a change of phase is accompanied by a change of volume.

Generally, the change of volume which accompanies a change from solid to liquid is not very great. On the other hand, the change of volume during the change from liquid to vapour or gas can be very large. The ability of a fluid readily to expand or contract is the requisite feature for successful operation of a thermodynamic engine. Thus both vapours and gases can be used in thermodynamic engines, but the technique for vapours is somewhat different from the technique for gases.

A vapour results from a change of phase of a liquid due to a transfer of heat. The bulk of the liquid is generally very much smaller than the bulk of the vapour formed. It follows, therefore, that any liquid which can be easily obtained and handled can be used as the generator of the vaporous working substance for use in an engine.

Water is such a liquid. It is in abundant supply, can be easily handled and readily turned into its vaporous phase called steam. Consequently, the change of phase from water into steam deserves closer investigation. But before doing this, it is useful to note that any other liquid undergoing a change of phase into a vapour will follow the

same general features as the water-steam transformation. The difference lies in the pressures, temperatures and energy quantities at which the various phenomena occur.

A system in which a liquid is being transformed into a vapour is a **two-phase system.** The mixture of liquid and vapour is a **two-phase mixture.**

4.2 Steam

In the following discussion it will be assumed that the water and ultimately the steam are in some suitable container which can accommodate any changes of state. The container is called a **boiler,** and the way in which it accommodates the changes will be discussed in Chapter 6. Steam is almost invariably formed at constant pressure, so that it is a good place to begin.

If a mass of water is heated then, like all other substances, its temperature increases. There is also a small increase in volume. For a time, these are the only changes which take place. After a while, small bubbles appear, clinging to the side of the containing vessel. They are soon released then float to the surface and disappear. These bubbles are the dissolved gases being driven off; as well as being able to dissolve some solids, water can also dissolve some of the atmospheric gases. Further heating produces further temperature rise but, apart from this, there is no other apparent external change. Soon, however, signs of internal activity appear.

Small steam bubbles are formed on and near the heating surface; they rise a little through the water and collapse. Their density is lower than the surrounding water, so they rise through it. The surrounding water is cooler so it extracts some energy from the steam bubble, which immediately collapses. This collapse of steam bubbles is the reason for the singing of a kettle. The temperature continues to rise with the transfer of heat and the bubble activity increases correspondingly. Finally, the water mass is at such a temperature that the steam bubbles are able to rise completely through the water, escaping from its surface. The water mass is now in an extremely turbulent state; it is **boiling.** A rather more technical term used for boiling is to say that the water is in a state of **ebullition.**

But what of the temperature now? As soon as boiling commenced the temperature ceased to rise, remaining at what is commonly called the **boiling point.** This is important because, while boiling continues, the temperature will remain constant, independent of the quantity of heat transferred to the water. In fact, so long as there is water present, it is apparently impossible to increase the temperature beyond the boiling point. A name is given to this boiling point; it is called **saturation temperature.**

4.2.1 Types of Steam

The boiling water is now in great turbulence as a result of the steam bubbles formed, forcing their way up through the water to break through the surface. The turbulence can be increased or decreased by increasing or decreasing heat energy supply. As the steam breaks away from the water surface it will carry with it small droplets of water. The larger droplets will tend to gravitate back to the water surface, but the smaller droplets will continue on their way with the steam. Steam with these small droplets of water in suspension is called **wet steam.** Steam formed from a water mass will always be wet to a greater or lesser extent; wetness generally depends on the turbulence occurring in the water. It is impossible to obtain dry steam while water is present.

Continuing the heating process will produce more and more wet steam until eventually the whole of the water mass disappears. The temperature, by the way, has remained constant at saturation temperature. The water droplets in suspension make the wet steam visible. Steam itself is a transparent vapour, but the inclusion of water droplets in suspension gives it the white cloudy appearance. What really is being seen is the cumulative effect of the water droplets reflecting light.

Further transfer of heat to the wet steam will convert the suspended water droplets into steam and finally a state will be reached when all the water has been turned into steam. The steam is then called **dry saturated steam.** It has now lost its visible characteristic; it has become completely transparent; this condition marks the end of the constant temperature intermediate phase.

Still further transfer of heat to the now dry saturated steam produces a temperature rise and the steam now becomes **superheated steam.** This is the last phase in the transformation of water into steam. It thus appears there are three distinct stages in the production of steam from water.

4.2.2 Steam Formation

Stage 1

Stage 1 is the warming phase in which the temperature of the water increases up to saturation temperature. The energy required to produce this temperature rise is called the **liquid enthalpy.**

Stage 2

Stage 2 takes place at constant temperature; it is when the water is transformed into steam. Stage 2 begins with all water at saturation temperature and ends with all dry saturated steam at saturation temperature. Between these two extremes, the steam formed will always be wet steam. The energy required to produce the total change from all water into all steam is called the **enthalpy of evaporation.** It is sometimes colloquially known as **latent heat** because no temperature rise is produced in this stage.

Stage 3

Stage 3 begins when all dry saturated steam has been formed at saturation temperature. Further transfer of heat produces superheated steam which is accompanied by a rise in temperature. The amount of energy added in the superheat phase is called the **superheat enthalpy.**

Note that temperature increase (or it could be decrease) only takes place during the transfer of heat when a substance is in a single phase. In this case there has to be all water or all dry steam before the temperature changes.

The phenomenon of temperature change happens with all substances but it only occurs in a single phase, be it solid, liquid or vapour. If a two-phase mixture exists (solid-liquid or liquid-vapour), the temperature remains constant until a complete change from one phase to another has been completed.

A word here about the three phases of matter – solid, liquid and vapour (or gas) -as they are related to atomic or molecular activity. In the solid phase the atoms or molecules of a substance oscillate about a mean position. As the temperature increases, the degree of oscillation increases until the atoms or molecules are able to overcome interatomic or intermolecular attractions. When this occurs, the substance becomes fluid and the atoms or molecules are now able to move freely but not independent of the main mass. The substance is now a liquid. The temperature remains constant while the change from solid to liquid occurs; energy increase is necessary to accelerate the atoms or molecules to the velocity required to produce freedom of movement. When the substance is all liquid, energy increase produces an increase in temperature once again and the atoms or molecules move about faster and faster. If the atoms or molecules of a liquid move about faster and faster as the temperature increases, the liquid must become turbulent. Eventually, some atoms or molecules must reach escape velocity; they are able to escape from the liquid mass at its free surface because their velocity is sufficient to overcome all internal interatomic or intermolecular attractions. This is the phenomenon of boiling; once again the temperature remains constant white all atoms or molecules absorb enough energy to attain escape velocity. Eventually, all atoms or molecules attain this velocity and the whole mass is now a vapour. From here on, further energy increases will increase the atomic or molecular velocities, causing the temperature to rise.

4.2.3 Saturation Temperature and Pressure

The previous discussion centred round the fact that steam is usually produced at constant pressure. This pressure can be higher or lower, as the case may be. Boiling will occur at saturation temperature, and it is found that saturation temperature depends upon the pressure exerted at the surface of the water. In other words, it depends upon the pressure at which the steam is being formed. If atmospheric pressure is increased, the boiling point (or saturation temperature) increases. Conversely, if the pressure decreases then so does the saturation temperature.

Fig. 4.1 shows the type of curve obtained when saturation temperature is plotted against absolute pressure. It is called the liquid-vapour equilibrium line.

It will be noted that the rate of increase of saturation temperature is not as great at the higher pressures as at the lower pressures.

4.2.4 The Triple Point

Fig. 4.1 represents changes in saturation temperature with pressure for steam. Fig. 4.2 enlarges this plot for the region of low temperatures and low pressures. The line dividing the liquid and vapour phases is the liquid-vapour equilibrium line; the line dividing the solid and liquid phases is the solid-liquid equilibrium line. The two lines join at point 3, the **triple point.**

The solid-liquid equilibrium is shown as horizontal, indicating there is little change in the solid-liquid (melting) point as a result of change in pressure. Actually, increase in pressure very slightly depresses the freezing point of water up to about 200 MN/m^2. The liquid-vapour equilibrium line shows the increase in saturation temperature with pressure increase as already discussed.

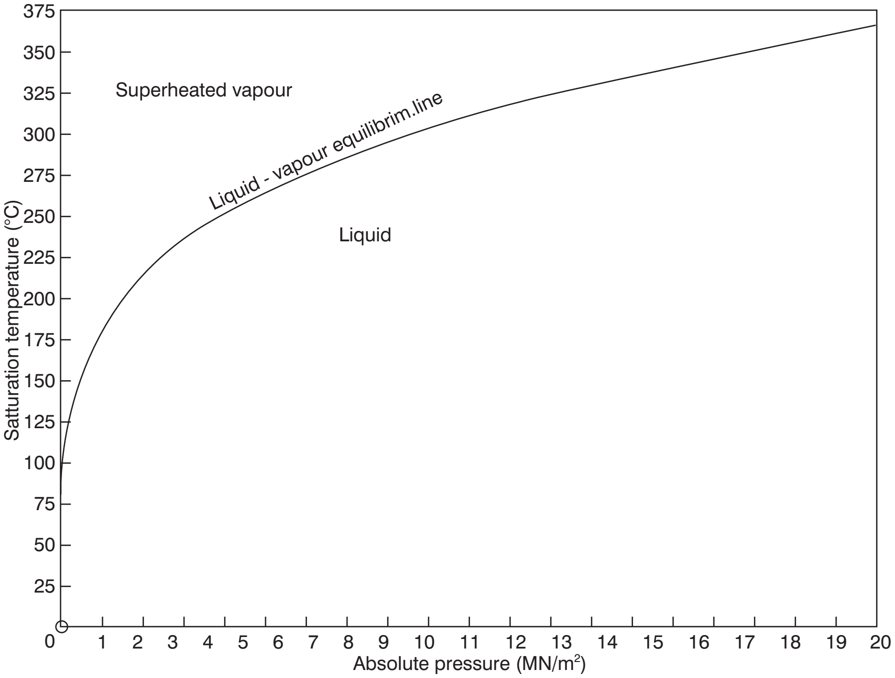

Fig. 4.1 Liquid – vapour equilibrium line

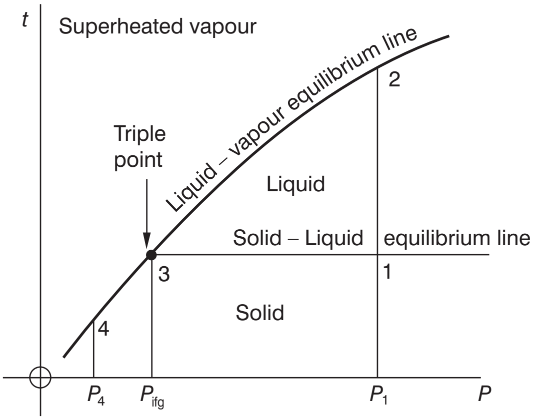

Fig. 4.2 Triple point

Referring to Fig. 4.2, at a pressure P_1 and at temperatures below point 1, the substance is solid (ice). At point 1 a change from solid into liquid takes place (melting point) and the solid is in equilibrium with the liquid. At temperatures above point 1 and below point 2 the substance is all liquid (water). At point 2 a change from liquid into vapour takes place (boiling point) and the liquid is in equilibrium with the vapour. Above point 2 the substance is all vapour (superheated steam, see section 4.2.1).

At the triple point pressure P_{ifg}, and at temperatures below point 3, the substance is all solid. At point 3, the triple point, solid, liquid and vapour can exist in equilibrium, hence the name. Above point 3 the substance is all vapour.

At pressure P_4 ($<P_{\text{ifg}}$), and at temperatures below point.4, the substance is all solid. At point 4 a direct change from solid into vapour takes place and the solid is in equilibrium with the vapour. This direct change from solid into vapour is called **sublimation.** At temperatures above point 4 the substance is all vapour.

4.2.5 Dryness Fraction of Steam

The vapour produced at saturation temperature in the transformation stage will contain liquid droplets in suspension for as long as there is liquid present. Vapour so produced is called **wet vapour.** It should be noted that vapour, as such, is dry. If the vapour is made wet by liquid droplets in suspension, it is important to know the degree of wetness.

Any mass of wet vapour will consist of some dry saturated vapour and some liquid droplets in suspension.

The ratio

$$\frac{\text{Mass of dry saturated vapour}}{\text{Mass of wet vapour containing the dry saturated vapour}}$$

is called the **dryness fraction,** symbol *x*.

Consider 1 kg of wet vapour of dryness fraction x. The 1 kg will be made up of x kg of dry saturated vapour at saturation temperature t_f together with $(1 - x)$ kg of liquid droplets in suspension, also at saturation temperature t_f. Evidently, then, only x kg have received the enthalpy of evaporation.

$$\therefore \text{ Specific enthalpy of evaporation of wet vapour} = xh_{fg} \qquad [1]$$

and

$$\text{Specific enthalpy of wet vapour} = h = h_f + xh_{fg} \qquad [2]$$

4.2.6 Steam Tables

In 1956 the Fifth International Conference on Properties of Steam recommended that the liquid at the triple point (water) should be made the datum state for steam tables.

At this datum, it was proposed that specific internal energy and specific entropy should be considered as zero. The triple point for water is at a pressure P_{ife}. = 0.611 2 kN/m^2 and a temperature f_{ifg} = 0.01°C (273.16 K).

It should be noted that enthalpy values as given in tables are not absolute values. They are simply change values from the reference state. Above the reference state values of enthalpy will be positive. Below the reference state values of enthalpy, if given, will be negative. A similar situation arises with temperature measurement. Above the zero of the conventional temperature scale, recordings will be positive but below this zero, recordings will be negative.

Similar sets of tables are prepared for vapours other than steam. Each vapour has its own reference state.

4.3 Enthalpy and Steam

4.3.1 Introduction

Consider unit mass of a substance and let heat energy Q be transferred at constant pressure P, thus changing the state of the substance from specific internal energy u_1 and specific volume v_1 to specific internal energy u_2 and specific volume v_2. By the non-flow energy equation

$$Q = \Delta u + W \qquad [1]$$

For this case

$$Q = (u_2 - u_1) + p(v_2 - v_1) \qquad [2]$$

$$= (u_2 + Pv_2) - (u_1 + Pv_1) \qquad [3]$$

or

$$Q = h_2 - h_1 = \text{change of specific enthalpy} \qquad [4]$$

since

$$h = u + Pv = \text{specific enthalpy} \qquad [5]$$

In section 4.2.2 it was mentioned that steam is almost invariably formed at constant pressure, so it follows that heat energy transferred during the formation of steam (or some other vapour), at constant pressure, appears as a change of enthalpy in the steam.

4.3.2 Enthalpy Tables

Enthalpy values during the formation of steam and other vapours at constant pressure are commonly set out in tabular form. In the case of steam, preparation of tables began in about the middle of the nineteenth century, but most of the work has been carried out since 1900. Notable early names in this connection are Callendar, and Keenan and Keyes. There are now many others. Values shown in tables are the result of experimental investigation.

Most tables are made out for the formation of unit mass (1 kg) of steam or vapour. Enthalpy tables may be very extensive, but abridged tables in common use give an appropriate selection of values.

4.3.3 Liquid Enthalpy

The first phase in the production of steam is the warming of water to saturation temperature, t_f. The energy added to the water in this phase is called **liquid enthalpy.** For unit mass of steam, specific liquid enthalpy is written h_f. The accurate value of h_f at any given saturation temperature corresponding to a particular pressure is given in steam tables.

The units of h_f are usually given as kJ/kg. In the absence of tables, an approximate value for h_f is given by

$$h_f = 4.186\,8 t_f \text{ kJ/kg where } t_f \text{ is in °C.}$$

This equation is only approximately correct at lower pressures and temperatures.

For example, at 1 standard atmosphere = 0.101 35 MN/m^2, $t_f = 100$°C

$$\therefore \quad h_f \approx 4.186\,8 \times 100 = \mathbf{418.68\ kJ/kg}$$

From the tables, the accurate value is

$$h_f = \mathbf{417.5\ kJ/kg}$$

The calculated value is not very far out in this case.

As another example, at 1 MN/m^2, $t_f = 179.9$°C

$$\therefore \quad h_f \approx 4.186\,8 \times 179.9 = \mathbf{753.2\ kJ/kg}$$

From tables, the accurate value is

$$h_f = \mathbf{762.2\ kJ/kg}$$

There is some error in this case and the error becomes even greater at higher pressures and temperatures. It is always preferable to refer to tables for accurate values.

4.3.4 Enthalpy of Evaporation

The specific enthalpy of evaporation is written h_{fg}. As with specific liquid enthalpy, it can be looked up in tables. The evaporation of a liquid into vapour takes place at constant saturation temperature, as already stated. Thus h_{fg} is added at constant saturation temperature t_f.

Starting with unit mass of liquid at temperature t_f, the addition of h_{fg} will transform the liquid into dry saturated vapour, also at temperature t_f. The units of h_{ff} are commonly kJ/kg. Enthalpy of evaporation used to be called latent heat; this term has now largely been dropped.

4.3.5 Enthalpy of Dry Saturated Vapour

The specific enthalpy of dry saturated vapour is written h_g. In order that a vapour shall become dry saturated, firstly the liquid enthalpy must be introduced and to this must be added the enthalpy of evaporation. Thus

$$h_g = h_f + h_{fg}$$

h_g is commonly given in kJ/kg.

Example 4.1 *Determine the specific liquid enthalpy, specific enthalpy of evaporation and specific enthalpy of dry saturated steam at 0.5 MN/m².*

SOLUTION

Look up the values in steam tables.

Pressure (MN/m²)	Saturation temperature t_f (°C)	Specific enthalpy (kJ/kg)		
		h_f	h_{fg}	h_g
0.50	151.8	640.1	2 107.4	*2747.5*

Thus

Specific liquid enthalpy = **640.1 kJ/kg**
Specific enthalpy of evaporation = **2107.4 kJ/kg**
Specific enthalpy of dry saturated steam = **2747.5 kJ/kg**

Note that

$$\begin{aligned} h_g &= h_f + h_{fg} \\ &= 640.1 + 2107.4 = \mathbf{2747.5\ kJ/kg} \end{aligned}$$

Note also that saturation temperature = **151.8°**C.

Example 4.2 *Determine the saturation temperature, specific liquid enthalpy, specific enthalpy of evaporation and specific enthalpy of dry saturated steam at a pressure of 2.04 MN/m².*

SOLUTION

If 2.04 MN/m² is looked up in abridged steam tables it will be found that a line is not given for this pressure. There is a line for 2.0 MN/m² and another for 2.1 MN/m². When this occurs, interpolated values for 2.04 MN/m² must be extracted. It is accurate enough to assume that values between those actually given behave in a linear manner. Proportional values are thus extracted between the given values. For the case given, the two lines, 2.1 MN/m² and 2.0 MN/m² are written down, top pressure first.

Pressure (MN/m^2)	Saturation temperature t_f (°C)	Specific enthalpy (kJ/kg)		
		h_f	h_{fg}	h_g
2.1	214.9	920.0	1878.2	2798.2
2.0	212.4	908.6	1888.6	2797.2
Difference + 0.1	+2.5	+11.4	+10.4	+1.0
Require +0.04 Adding 2.04	$\frac{0.04}{0.1}\times 2.5 = 1.0$	$\frac{0.04}{0.1}\times 11.4 = 4.56$	$\frac{0.04}{0.1}\times 104.4 = -4.16$	$\frac{0.04}{01}\times 1.0 = +0.4$
	213.4	913.16	1884.44	2 797.6

Hence, at 2.04 MN/m^2

Saturation temperature = **213.4**°C

Specific liquid enthalpy = **913.16 kJ/kg**

Specifi centhalpy of evaporation = **1884.44kJ/kg**

Specific enthalpy of dry staurated steam = **2797.6 kJ/kg**

4.3.6 Enthalpy of Super Heated Vapour

From dry saturated condition, a vapour receives superheat and its temperature rises above saturation temperature, t_f. It has now entered the superheat phase.

The difference between the superheat vapour temperature, t, and the saturation temperature, t_f, is called the **degree of superheat.** Thus

$$\text{Degree of superheat} = (t - t_f)\ \text{K} \qquad [1]$$

The enthalpy added during the superheat phase is the superheat enthalpy. The total enthalpy of superheated vapour will be the sum of the enthalpy of dry saturated vapour and the superheat enthalpy, or

$$h = h_g + \text{superheat enthalpy} \qquad [2]$$

An approximation of the value of the superheat enthalpy can be found as follows.

Let

C_p = specific heat capacity of superheated vapour at constant pressure

then

$$\text{Specific superheat enthalpy} = C_p\,(t - t_f) \qquad [3]$$

Hence, from equations [2] and [3]

$$h = h_g + C_p(t - t_f) \qquad [4]$$

An average value of C_p for superheated steam is 2.0934 kJ/kg K.

Accurate values of h are given in tables; equation [4] is used as an approximation only.

Example 4.3 *Determine the specific enthalpy of steam at 2 MN/m² and with a temperature of 250°C.*

SOLUTION

At 2 MN/m², from tables, t_f = **212.4°**C

The steam must therefore be superheated because its temperature is above t_f.

Degree of superheat = 250 – 212.4 **– 37.6 K**

The specific enthalpy can be looked up in steam tables under the heading **superheated states.**
From tables

Specific enthalpy of steam at 2 MN/m² with a temperature of 250°C = **2902 kJ/kg**

Alternatively

$$\begin{aligned} h &= h_f + C_p(t - t_f) \\ &= 2797.2 + (2.093\,4 \times 37.5) \\ &= 2797.2 + 78.7 \\ &= \mathbf{2875.9\ kJ/kg} \end{aligned}$$

Note that this gives an approximation only.

Example 4.4 *Determine the specific enthalpy of steam at a pressure of 2.5 MN/m² and with a temperature of 320°C.*

SOLUTION

Looking up steam tables shows that at 2.5 MN/m² the saturation temperature is 223.9°C. The steam is therefore superheated.

Degree of superheat = 320 – 223.9 = **96.1 K**

The specific enthalpy could be estimated using

$$\begin{aligned} h &= h_g + C_p(t - t_f) \\ &= 2800.9 + (2.093\,4 \times 96.1) \\ &= 2800.9 + 201.18 \\ &= \mathbf{3002.08\ kJ/kg} \end{aligned}$$

However, a more accurate value can be interpolated from tables giving specific enthalpy against temperature. Looking up these tables will show that nweither the pressure of 2.5 MN/m² nor the temperature of 320°C are given. Interpolation for both pressure and temperature is therefore required. A note is made of values of specific enthalpy on either side of the pressure and temperature.

	Pressure (MN/m^2)	2	4
		Specific enthalpy (kJ/kg)	
	Temperature (°C)		
	325	3 083	3 031
	300	3 025	2 962
Difference	+25	+58	+69
Require Adding	+20	$\frac{20}{25}\times 58 = +46.4$	$\frac{20}{25}\times 69 = +55.2$
	320	3071.4	3017.2

This gives values of specific enthalpy at the temperature of 320°C.

An interpolation is now required for the pressure.

	Pressure (MN/m^2)	Specific enthalpy (kJ/kg)
	4	3017.2
	2	3071.4
Difference	+2	–54.2
Require	+0.5	$\frac{0.5}{2}\times -54.2 = -13.6$
Adding	2.5	3057.8

Thus, the specific enthalpy of steam at a pressure of 2.5 MN/m^2 and with a temperature of 320°C = **3057.8 kJ/kg.**

Note that the estimated value of 3002.08 kJ/kg was not very accurate.

Example 4.5 *Determine the specific enthalpy of wet steam at a pressure of 70 kNjm^2 and having a dryness fraction of 0.85.*

SOLUTION

$$
\begin{aligned}
h &= h_f + x h_{fg} \\
&= 376.8 + (0.85 \times 2283.3) \quad \text{(values of } h_f \text{ and } h_{fg} \text{ from tables)} \\
&= 376.8 + 1945 \\
&= \mathbf{2321.8\ kJ/kg}
\end{aligned}
$$

4.3.7 Temperature–Enthalpy Diagram

Fig. 4.3 illustrates the type of curve obtained if temperature is plotted against enthalpy for the constant pressure formation of steam. Consider some moderately low-pressure, formation of steam. At 273.16 K (0.01°C) the enthalpy of water is considered as being zero. Starting at this point on the temperature axis and plotting the liquid phase will produce a curve such as AB. At B the specific liquid enthalpy h_f has been introduced for the pressure under consideration, and saturation temperature t_f has been reached. From here on, specific enthalpy of evaporation h_{fg} is introduced from B to C at constant temperature t_f.

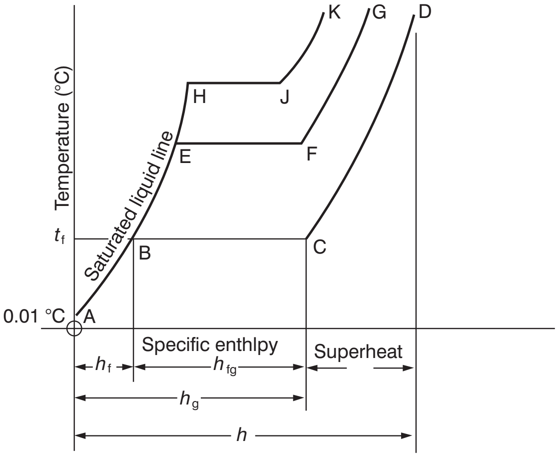

Fig. 4.3 T–s diagram for a vapour

The superheat phase then follows from C in which superheat is added and the temperature rises, producing a curve such as CD. Note that the three stages of formation are very clearly shown on this graph. If the formation pressure is increased, it produces curves like AEFG and AHJK. The line ABEH is called the **saturated liquid line.**

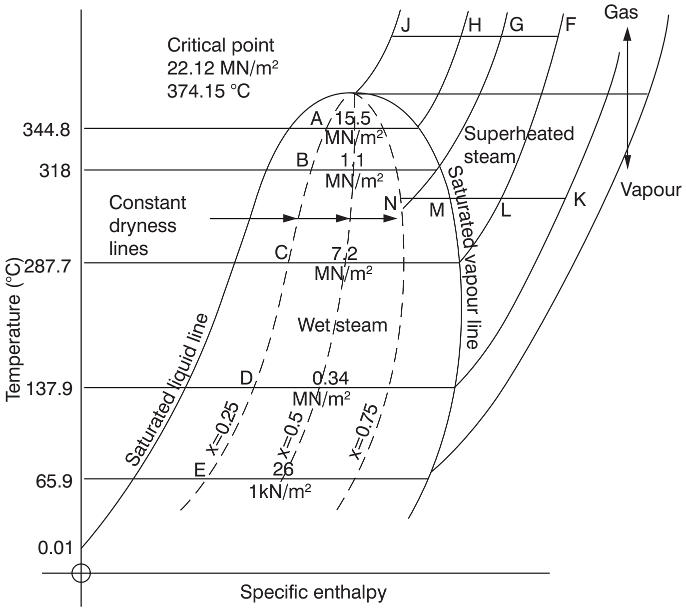

Fig. 4.4 Complete T–h digram for a vapour

Dry saturated steam points C, F and J appear to lie on a smooth curve. If a wide range of pressures are considered and the results plotted at suitable pressure intervals, the complete temperature-enthalpy diagram is obtained (Fig. 4.4).

In this diagram it will be noted that the dry saturated steam points have been joined by a smooth curve, called the **saturated vapour line**. This line and the saturated liquid line enclose an area in which the steam is wet. To the right of the saturated vapour line the steam is superheated. Inside the wet steam area can be drawn lines of constant dryness (shown dotted). These lines are obtained by joining such points as A, B, C, D and E, where the dryness is the same.

It is very important to realise that the liquid line and the saturated vapour line may be continued upward until eventually they meet. The point at which the two lines join is called the **critical point.** This point is found to occur at a pressure of 22.12 MN/m^2 and a temperature of 374.15°C. As the pressure increases toward the **critical pressure**, the required enthalpy at evaporation is reduced until it finally becomes zero at the critical point.

This implies that, at the critical point, the water changes directly into dry saturated steam. The critical point is really the division between behaviour as a vapour and behaviour as a gas. When a gas is compressed it does not liquefy in the normal course of events. This can be explained with reference to the temperature-enthalpy diagram and the critical point. The diagram shows that liquid, in this case water, can only exist at temperatures below the critical point.

Consider the case of a compression above the critical point and, for simplicity, let

the compression be at constant temperature. Such a compression would appear as FGHJ, for example, moving from right to left. Inspection shows that, no matter how much compression takes place, no liquefaction occurs or can occur. On the other hand, if compression at constant temperature takes place below the critical point, it will appear as KLMN, for example. This shows that compression passes out of the superheat region into the wet region, thus liquefaction is taking place.

As long as the temperature is above the critical temperature, no change of phase occurs during compression or expansion; the behaviour is similar to that of a gas. In fact, at temperatures higher than the critical temperature, the vapour becomes a gas.

It should again be noted here that, although the above discussion has concentrated on the production of a temperature-enthalpy diagram for steam, similar diagrams can be developed for other vapours. The temperature-enthalpy diagram and others which will follow are called **phase diagrams.**

4.4 Specific Volume

4.4.1 Specific Volume of Steam

As with all other substances, the volume of water and of steam increases as the temperature increases. In the lower pressure ranges the volume of water is very small compared with the volume of steam it produces. The main change of volume occurs in the evaporation stage. But as the pressure and temperature approach the critical point, the change in volume decreases until, at the critical point, there is no change of volume from the water phase to the dry steam phase. However, the vast majority, or applications for steam use a pressure below the critical pressure, so the three stages of formation have to be considered.

4.4.2 Specific Volume of Dry Saturated Steam

The specific volume of dry saturated steam is tabulated against its corresponding saturation temperature and pressure in steam tables and is designated as vg. Volume is given in m^3/kg.

4.4.3 Specific Volume of Wet Steam

Consider 1 kg of wet steam at dryness fraction x. This steam will be made up of x kg of dry saturated steam and $(1 - x)$ kg of water in suspension.

$$\therefore \text{ Volume of wet steam} = v = xv_g + (1 - x)\, v_f$$

At the lower pressures the volume v_f is very small compared with the volume v_g, and $(1 - x)$ is generally small compared with x.

Hence the term $(1 - x)\, v_f$ can be sensibly neglected, so

$$\text{Volume of wet steam} = v = xv_g$$

Note that from this

$$x = \frac{v}{v_g}$$

This equation can sometimes be used to determine the dryness fraction.

4.4.4 Specific Volume of Superheated Steam

Steam tables quote the specific volume of superheated steam, either with pressure against actual steam temperature or with pressure against degree of superheat, volume is given in m³/kg.

4.4.5 Specific Volume of Water

Steam tables quote the specific volume of water. At saturation temperature, for a given pressure, the specific volume of water is tabulated as v_f m³/kg. Alternatively, specific volume may be tabulated at a particular temperature against various pressures.

4.5 Density of Steam

If the specific volume of any quality steam is v, then

$$\text{Density} = \rho = \frac{1}{v}\,\text{kg/m}^3 \qquad [1]$$

Thus the density of superheated steam in Example 4.9 is given by

$$\text{Density} = \frac{1}{0.1321} = \mathbf{7.57\ kg/m^3}$$

If the density is known, then

$$\text{Specific volume} = v = \frac{1}{\rho}\,\text{m}^3/\text{kg} \qquad [2]$$

Example 4.6 *Determine the specific volume of water at saturation temperature for a pressure of 4.0 MN/m*^{2}

SOLUTION

Look up the values in steam tables.

Pressure (MN/m^2)	Saturation temperature (°C)	Specific volume v_f(m^3/kg)
4.0	250.3	0.001 252

Example 4.7 *Determine the specific volume of water at a temperature of 175°C and a pressure of 4.0 MN/m*^{2}.

SOLUTION

Look up the values in steam tables.

Pressure (MN/m^2)	2	4	6
		Specific volume (m^3/kg	
Temperature (˚C)			
150	0.001 089	0.001 088	0.001 087
175	0.001 120	0.001 119	0.001 116
200	0.001 156	0.001 153	0.001 152

So the specific volume of water at a temperature of 175°C and a pressure of 4.0 MN/m^2 is 0.001 119 m^3/kg.

Example 4.8 *Determine the specific volume of wet steam of dryness fraction 0.9 at a pressure of 1.25 MN/m*^{2}.

SOLUTION

From tables, at 1.25 MN/m^2, $v_g = 0.156\,9$ m^3/kg

$$\therefore\ v = xv_g = 0.9 \times 0.156\,9 = \mathbf{0.141\,2\ m^3/kg}$$

Example 4.9 *Determine the specific volume of steam at a pressure of 2 MN/m*^{2} *and with a temperature of 325°C.*

SOLUTION

Sesam tables give pressures and temperatures near to the required state.

Pressure (MN/m^2)	1	2	4
		Specific volume (m^3/kg)	
Temperature (°C)			
300	0.257 7	0.125 5	0.058 8
325	0.270 3	0.132 1	0.062 8
350	0.282 5	0.138 5	0.066 4

This shows that the specific volume of steam at a pressure of 2 MN/m^2 and with a temperature of 325°C = **0.132 1 m^3/kg.**

Saturation temperature at 2 MN/m^2 = 212.4°C. The actual steam temperature is 325°C so the steam is superheated. The degree of superheat is 325 – 212,4 = 112.6 K. Some superheat steam tables give the degree of superheat instead of the actual steam temperature.

Example 4.10 *Steam 0.95 dry at a pressure of 0.7 MN/m^2 is supplied to a heater through a pipe of 25 mm internal diameter; the velocity in the pipe is 12 m/s. Water enters the heater at 19°C, the steam is blow into it and the mixture of water and condensate leaves the heater at 90°C. Calculate*

(a) the mass of steam entering the heater in kg/h

(b) the mass of water entering the heater in kg/h

Extract from tables

Pressure (MN/m^2)	Sat. temp. t_f (°C)	Spec. enthalpy (kJ/kg)			Spec. vol. v_g (m^3/kg)
		h_f	h_{fg}	h_g	
0.7	165	697.1	2 064.9	2 762.0	0.273

(a)

Specific volume of steam 0.95 dry and at pressure 0.7 MN/m^2 is

$$xv_g = 0.95 \times 0.273 = \mathbf{0.259\ m^3/kg}$$

$$\text{Volume of steam passing/s } = \left[\frac{\pi}{4}\times\left(25\times10^{-3}\right)^2\times12\right]\text{m}^3$$

$$\text{Volume of steam passing/}h\ = \left[\frac{\pi}{4}\times\left(25\times10^{-3}\right)^2\times3600\right]\text{m}^3$$

$$\therefore\quad \text{Mass of steam entering/}h = \frac{\pi\times25^2\times10^{-6}\times12\times3600}{4\times0.259}$$

$$= \mathbf{81.9kg}$$

(b)

Specific enthalpy of steam entering heater is

$$\begin{aligned} h_f + xh_{fg} &= 697.1 + (0.95 \times 2064.9) \\ &= 697.1 + 1961.7 \\ &= \mathbf{2658.8\ kJ/kg} \end{aligned}$$

Enthalpy gained by water = Enthalpy lost by steam

Let m = mass of water per hour

From steam tables

at 90 ºC, hf = 3**76.8 kJ/kg**

at 19 ºC, hf = **79.8kJ/kg**

Hence

$$m(376.8 - 79.8) = 81.9\,(2658.8 - 376.8)$$

$$= \frac{81.9 \times (2658.8 - 376.8)}{(376.8 - 79.8)}$$

$$= \frac{81.9 \times 2282}{297}$$

$$= \mathbf{629.28\,kg/h}$$

4.6 The Pressure–Volume Diagram for a Vapour

Fig. 4.5 shows another phase diagram for a vapour; this time the axes are pressure and specific volume. It plots a whole series of isotherms (lines of constant temperature). At a temperature less than the critical temperature ($T < T_c$) an isotherm will appear as ABCD. Note that points such as B will generate the saturated liquid line, whereas points such as C will generate the saturated vapour line. These two lines will again join at the top at the critical point F. The area enclosed by the two lines will be the wet vapour area (liquid-vapour mixture area). The critical temperature isotherm ($T = T_c$) is shown dotted as line EFG. Between the critical temperature isotherm and the saturated vapour line the vapour is superheated. At temperatures above critical ($T > T_c$), the isotherms gradually lose their discontinuity and eventually become smooth curves such as HJ. The behaviour then becomes that of a gas.

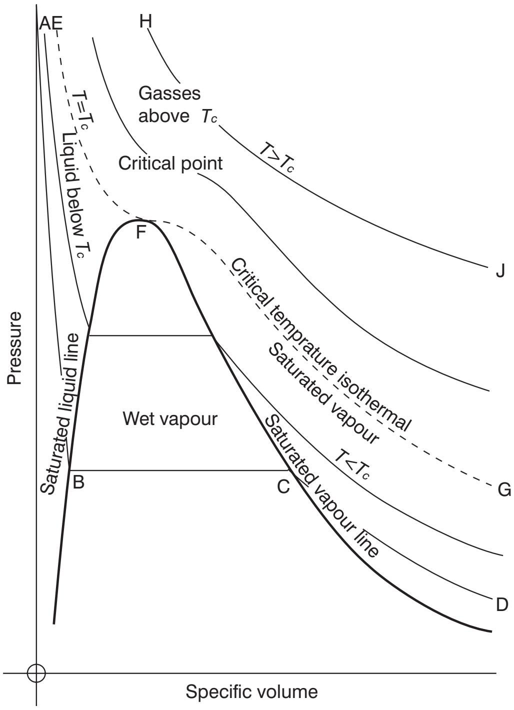

Fig. 4.5 *P–V* phase digram

4.7 Internal Energy and Steam Vapours

Heat energy transferred during the formation of vapour constant pressure appears as a change of enthalpy in the vapour. And it has been shown that tables of properties, such as enthalpy and specific volume, are prepared for a variety of vapours, including steam. Now

$$h = u + Pv \quad \text{(see section 4.3.1)} \qquad [1]$$

$$\therefore \quad u = h - p_v \qquad [2]$$

where u = specific internal energy, J/kg
h = specific enthalpy, J/kg
P = absolute pressure, N/m^2
v = specific volume, m^3/kg

Thus, by using tables of properties and by suitable substitution into equation [2], the specific internal energy of a vapour at a particular state can be determined. Note that some tables actually tabulate specific internal energy.

Example 4.11 *1.5 kg of steam originally at a pressure of 1 MN/m^2 and temperature 225°C is expanded until the pressure becomes 0.28 MN/m^2. The dryness fraction of the steam is then 0.9. Determine the change of internal energy which occurs.*

SOLUTION

At 1 MN/m^2 and 225°C, from tables

$$h_1 = \mathbf{2886\ kJ/kg}$$
$$v_1 = \mathbf{0.2198\ m^3/kg}$$

$$\therefore\ u_1 = h_1 - P_1v_1 = 2886 - 1\times\frac{10^6}{10^3}\times 0.2198$$
$$= 2886 - 219.8$$
$$= \mathbf{2566.2\ kJ}$$

At 0.28 MN/m^2 and Dryness fraction 0.9

$$h_2 = h_{f2} + xh_{fg2}$$
$$= 551.4 + (0.9 \times 2170.1)$$
$$= 551.4 + 1953.09$$
$$= \mathbf{2504.49\ kJ/kg}$$
$$v_2 = xv_{g2} = 0.9 \times 0.646$$
$$= \mathbf{0.581\ 4\ m^3/kg}$$

$$\therefore\ u_2 = h_2 - P_2v_2 = 2504 - \left(0.28\times\frac{10^6}{10^3}\times 0.5814\right)$$
$$= 2504.49 - 162.8$$
$$= \mathbf{2341.69\ kJ/kg}$$

Hence

$$u_2 - u_1, = 2341.69 - 2566.2$$
$$= \mathbf{-324.51\ kJ/kg}$$

This is a loss.

For 1.5 kg

Loss of internal energy = –324.51 × 1.5
= **–486.77 kJ**

4.8 Throttling

If a gas or steam (or any other vapour) is passed through a fine orifice, as shown in Fig 4.6, it is said to have been throttled. The gas or steam will pass from the high-pressure side to the low-pressure side, so throttling is a flow condition when applied to the steady-flow energy equation developed in section 1.15.2.

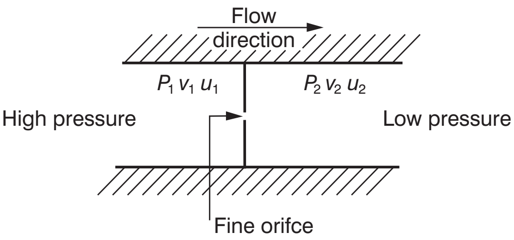

Fig. 4.6 Throttling

The steady-flow energy equation was shown to be

$$g^{Z_1} + u_1 + p_1v_1 + \frac{c^2_{\ 1}}{2} + Q = g^{Z}{}_2 + u_2 + p_2v_2 + \frac{c^2_{\ 2}}{2} + W \qquad [1]$$

Now in throttling there will be no change in potential energy, so the terms gZ can be neglected. Also there will be little or no change in kinetic energy, so the terms$C^2/2$ can be neglected. And, theoretically, there will be no heat transfer to or from the surroundings (the system is adiabatic, $Q = 0$); no external work is done. The terms Q and W can therefore be neglected.

Hence, the energy equation for the throttling process becomes

$$u_1 + P_1v_1 = u_2 + P_2v_2 \qquad [2]$$

or

$$h_1 = h_2 \qquad [3]$$

That is

Specific enthalpy before throttling = Specific enthalpy after throttling [4]

Also, more generally, for any mass of gas or steam

Enthalpy before throttling = Enthalpy after throttling [5]

4.9 The Effect of Throttling on a Vapour

The pressure on the downstream side of a throttle orifice is lower than on the upstream side, so the liquid enthalpy after throttling can be less than before throttling. But the total enthalpy is the same before and after throttling.

Let h_1 = specific enthalpy before throttling

h_2 = specific enthalpy after throttling

h_{f1} = liquid enthalpy before throttling

h_{f2} = liquid enthalpy after throttling

Now $h_1 = h_2$, so

if $h_{f2} < h_{f1}$ then $h_1 - h_{f1} < h_2 - h_{f2}$

The quantity h – hf is the enthalpy available to the enthalpy of evaporation. Hence the enthalpy of evaporation after throttle > the enthalpy of evaporation before throttle. From this, if $h_2 - h_{f2} > h_{fg}{}^2$ then the vapour after throttle becomes superheated.

Example 4.12 *Steam at 1.4 MN/m² and of dryness fraction 0.7 is throttled to 0.11 MN/m². Determine the dryness fraction of the steam after throttling.*

SOLUTION

For a throttle

$$h_1 = h_2$$

and in this case

$$h_{f1} + x_1 h_{fg1} = h_{f2} + x_2 h_{fg2}$$

$$830.1 + (0.7 \times 1957.7) = 428.8 + (x_2 \times 2250.8)$$

$$\therefore x_2 = \frac{\left[830.1 + \left(0.7 \times 1957.7\right)\right] - 428.8}{2250.8}$$

$$= \frac{\left(830.1 + 1370.4\right) - 428.8}{2250.8}$$

$$= \frac{1771.7}{2250.8}$$

$$= \mathbf{0.787}$$

Note that the steam becomes drier in this case.

Throttling does not always dry the steam; this is illustrated in Fig. 4.7. Dry saturated steam at about 4.0 MN/m^2 is throttled and immediately moves into the wet region until, at about 3.0 MN/m^2, it reaches its maximum wetness. This is because at about 3.0 MN/m^2 the enthalpy of dry saturated steam is at a maximum. After 3.0 MN/m^2, continuing the throttle, the steam becomes drier and, at about 2.4 MN/m^2, it again becomes dry saturated. Throttling to pressures lower than 2.4 MN/m^2 produces superheated steam in this case.

This ability to produce superheated steam, given appropriate initial pressure and dryness, is exploited in the throttling calorimeter.

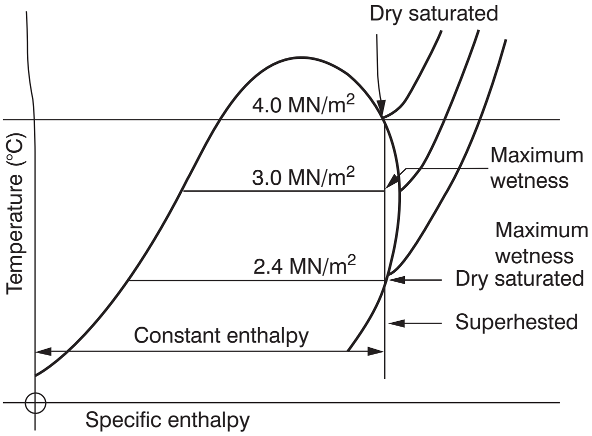

Fig. 4.7 Throtting and steam quality

Example 4.13 *Steam at a pressure of 2 MN/m^2, a temperature of 300°C and flowing at a rate of 2 kg/s is throttled to a pressure of 800 kN/m^2. It is then mixed with steam at a pressure of 800 N/m^2 and 0.9 dry which flows at a rate of 5 kg/s. Determine*

(*a*) *the condition of the resulting steam mixture*

(*b*) *the internal diameter of the pipe to convey the steam at 2 MN/m^2 if the velocity of the steam is limited to 15 m/s*

(a)

Specific enthalpy of steam at a pressure of 2 MN/m^2 and a temperature of 300°C = **3025 kJ/kg.**

At a pressure of 2 MN/m^2 the saturation temperature, t_f = **212.4°C**. So at 300°C the steam is superheated.

For the throttling process

$$\begin{aligned}\text{Specific enthalpy before throttling} &= \text{Specific enthalpy after throttling}\\ &= \mathbf{3025\ kJ/kg}\end{aligned}$$

$$\begin{aligned}\therefore\ \text{Total enthalpy of 2 kg of this steam} &= 2 \times 3025\\ &= \mathbf{6050\ kJ}\end{aligned}$$

Specific enthalpy of steam at a pressure of 800 kN/m^2 and with a dryness fraction of 0.9 is

$$720.9 + (0.9 \times 2046.5) = 720.9 + 1841.85$$
$$= \mathbf{2562.75\ kJ/kg}$$

∴ Total enthalpy of 5 kg of this steam = 5 × 2562. = **12 813.75 kJ**

Total mass of mixture = 2 + 5 = **7 kg/s**

Total enthalpy of steam mixture = 6050 + 12 813.75

= **18 863.75 kJ/s**

Specific enthalpy of steam mixture = 18 863.75/7

= **2694.82 kJ/kg**

At a pressure of 800 MN/m^2, hg = **2761.5 kJ/kg** so the steam mixture is wet.

Now, for wet steam

$h = h_f + xh_{fg}$ (see section 4.2.5)

from this

$$x = \frac{h - h_f}{h_{f_g}}$$

$$= \frac{2694.82 - 720.9}{2046.5}$$

$$= \frac{1973.92}{2046.5}$$

$$= \mathbf{0.964}$$

The condition of the resulting mixture is 0.964 dry.

(b)

Now

$$m = \frac{AC}{v} \quad \text{(see section 1.15.3)}$$

where A = area of cross-section, m^2

C = velocity, m/s

m = mass flow, kg/s

$$\therefore \quad A = \frac{mv}{C} = \frac{2 \times 0.1255}{15}$$

$$= \mathbf{0.0167\ m^2}$$

$$\therefore \quad \frac{\pi d^2}{4} = 0.0167 \times 10^6 \quad \text{where } d = \text{diameter in mm}$$

From this

$$d^2 = \frac{0.0167 \times 10^6 \times 4}{\pi} = 0.02126 \times 10^2\,\text{mm}^2$$

$$d = \sqrt{(0.02126 \times 106)} = \mathbf{145.8\ mm}$$

4.10 Measurement of Dryness Fraction

4.10.1 Separating Calorimeter

The separating calorimeter (Fig. 4.8) is really a mechanical device, not a thermodynamic device. It has already been indicated that wet steam consists of dry saturated steam and suspended water droplets. The density of water is higher than the density of dry saturated steam. If a mass of wet steam is rotated, the water in suspension will move outwards, by centrifugal action, and will separate from the dry steam. This is the principle of the separating calorimeter.

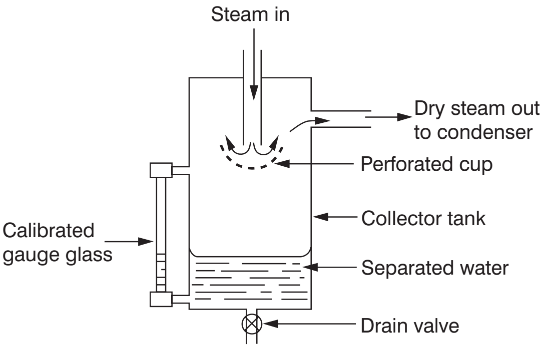

Fig. 4.8 Separating calorimeter

Fig. 4.8 shows a collector tank that is fed with the steam under test. The entry steam pipe feeds into the top of a perforated cup suspended in the collector tank. A calibrated gauge glass fits into the side of the collector tank. A dry steam exit is provided from the side of the tank at the top and a drain valve is provided at the bottom.

In operation, the steam passes into the calorimeter and is rapidly forced to change its direction when it hits the perforated cup. This introduces vortex motion into the steam and the water separates out by centrifugal action. Some drains through the perforated cup, some falls as large droplets and some precipitates on the walls of the tank and will drain down. All will collect at the bottom of the tank, where the level will be recorded by the gauge glass. The dry steam will pass out of the apparatus into a small condenser for collection as condensate. The perforated cup shown in Fig. 4.8 is just one of many devices used to create a vortex in the steam.

Several precautions should be taken when using the separating calorimeter. It must be adequately warmed up before starting any measurement, otherwise condensation will occur on the interior of the apparatus, which will introduce an error into the results. As far as is possible, care must be taken to ensure that the steam does not come into contact with the water which has already been separated, otherwise a certain amount of condensation will occur and this too will affect the results.

The calorimeter should have adequate thermal insulation to prevent condensation due to heat loss. Theoretically the system should be adiabatic ($Q = 0$).

It is found in practice that not all the water is separated out; some passes out with the assumed dry steam. Consequently, this apparatus can only give a close approximation of the dryness fraction of the steam.

From the results obtained, let

M = mass of dry steam condensed
m = mass of suspended water separated in calorimeter in same time

then

$$\text{Dryness fraction } = x = \frac{\text{Mass of dry steam}}{\text{Mass of wet steam contaning dry steam}}$$

$$= \frac{M}{M+m}$$

Example 4.14 *Estimate the dryness fraction of the steam entering a separating calorimeter if the separated water collected is 0.2 kg and the mass of condensate in the same time is 1.8 kg.*

SOLUTION

$$x = \frac{M}{M+m} = \frac{1.8}{1.8+0.2} = \frac{1.8}{2} = 0.9$$

It can be noted here that a device called a separator is often fitted in series into a wet steam main to help improve the steam quality (i.e. to make the steam dryer). It works in a similar way to the separating calorimeter.

One such separator takes the full steam flow and induces a rapid U-turn change of direction to the wet steam. This rapid change of direction precipitates some of the suspended water from the steam. The precipitated water can then be removed through a steam trap after it has drained to the bottom of the separator.

4.10.2 Throttling Calorimeter

Fig. 4.9 shows the throttling calorimeter. Steam is drawn from the main through a sampling tube placed across the steam main. The tube is perforated by many small holes and its end is sealed. Steam is forced through the small holes to obtain a representative sample across the main. The sampling tube could be placed in any direction across the main. But the steam to be analysed is wet, so the suspended water tends to gravitate to the bottom of a horizontal steam main. A vertical sampling tube will therefore pick off steam from the driest at the top to the wettest at the bottom. Hence the average sample, which then proceeds to the throttling calorimeter, will be more truly representative than for any other orientation of the sampling tube. If the steam main is vertical, the dryness will be near enough constant across the main, so the sampling tube can be placed in any direction.

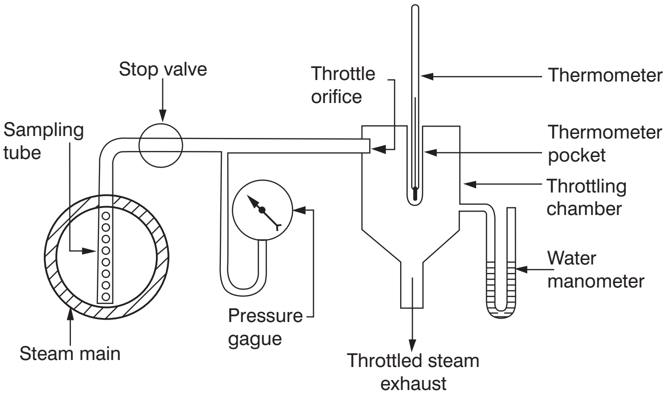

Fig. 4.9 Throttling calorimeter

From the sampling tube the steam under test proceeds, via a stop valve and a pressure gauge, to the throttle orifice of the calorimeter. The stop valve is provided in under that the calorimeter can be isolated from the main when not in use. After throttling, the steam passes into the throttle chamber of the calorimeter where its pressure can be determined using a water manometer and its temperature determined using a thermometer. The steam then passes away to exhaust, either to atmosphere or to a small condenser, where it can be collected as condensate and its mass determined after condensation. The mass of the condensate need not be determined when using the calorimeter alone. It will be noted that the manometer is a water manometer because the pressure after throttling is usually similar to atmospheric pressure. Mercury would be much too dense for this application; it would not be sensitive enough to record the small pressure change that occurs.

To operate the throttling calorimeter the stop valve is fully opened, ensuring that the steam does not experience a partial throttle as it passes through the valve. Steam is then allowed to pass through the apparatus for a while in order that pressure and temperature conditions become steady. As a general check on whether the steam is being throttled to superheat condition, remember that the pressure after throttle will not be greatly different from atmospheric pressure. Saturation temperature in this case will be round about 100°C. If the temperature after throttle is somewhat above 100°C, it can be taken that the steam is being superheated.

After conditions have become steady, the gauge pressure before throttling is read from the pressure gauge. The temperature and gauge pressure after throttle are recorded from the thermometer and manometer, respectively. The barometric pressure is also recorded. Let

$$\text{Gauge pressure before throttle} = P\ kN/\text{m}^2$$
$$\text{Barometric height} = h \text{ mm Hg}$$

then

$$\text{Absolute pressure before throttle} = P_1 = (P + 0.133\,4h)\ \text{kN/m}^2$$

Let h_{f1} = specific liquid enthalpy before throttle, kJ/kg
$h_{\text{fg}1}$ = specific enthalpy of evaporation before throttle, kJ/kg
x_1 = unknown dryness fraction before throttle

then

Specific enthalpy before throttle = $(h_{f1} + x_1 h_{fg1})$ kJ/kg

For the condition after throttle, let

Manometer height = h_m mm H_2O

Then

$$\text{Absolute pressure after throttle} = p_2 = 0.1334\left(h \pm \frac{h_m}{13.6}\right) \text{kN/m}^2$$

Let the Celsius temperature after throttle be t_2. Then, from steam tables, at pressure P_2 and temperature t_2

Specific enthalpy after throttle = h_2 kJ/kg

For a throttle

Specific enthalpy before throttle = Specific enthalpy after throttle

$$\therefore\; h_{f1} + x_1 h_{fg1} = h_2$$

Hence

$$x = \frac{h_2 - h_{f1}}{h_{fg1}}$$

It is important to realise that, after throttling, the steam must be superheated. If it is not, then an unknown dryness fraction will exist after throttling as well as the dryness fraction to be determined before throttling. So unless the steam become superheated after throttling, the calorimeter is of no value. This means that the throttling calorimeter cannot be used to determine the dryness fraction of moderately wet steam. The limit of its use is when the steam after throttle is just dry saturated, so that

$$x_1 = \frac{h_2 - h_{f1}}{h_{fg1}}$$

where h_{g2} = specific enthalpy of dry saturated steam at pressure P_2 after the throttle, kJ/kg

Dryness fractions below this value will produce wet steam after throttle, so no calculation can be made. Strictly, for successful operation, there must be some degree of superheat after throttling, because when the steam is dry saturated it is at saturation temperature. Any quality of wet steam is also at saturation temperature, so if the temperature after throttle were found to be saturation temperature, it would be impossible to tell whether the steam had been dry saturated or wet. However, the theoretical dryness limit is as determined by the above equation.

Example 4.15 *The dryness fraction of steam at a pressure of 2.2 MN/m^2 is measured using a throttling calorimeter. After throttling, the pressure in the calorimeter is 0.13 MN/m^2 and the temperature is 112°C. Determine the dryness fraction of the steam at 2.2 MN/m^2.*

Extract from steam tables

Saturated steam

Pressure (MN/m^2)	Sat. temp. t_f (°C)	Spec. enthalpy (kJ/kg)		
		h_f	h_{fg}	h_g
2.2	217.2	931	1 870	2 801

Saturated steam

Pressure (MN/m2)	Sat. temp. (°C)	Spec. enthalpy (kJ/kg)	
		*h*g	at 150°C
0.1	99.6	2 675	2 777
0.5	111.4	2 693	2 773

Solution

For a throttling process

Specific enthalpy before throttling = Specific enthalpy after throttling

After throttling, the steam is at a pressure of 0.13 MN/m^2 and a temperature of 112°C. To determine the specific enthalpy of this steam, linear interpolation is required from the superheat steam tables.

	Pressure (MN/m^2)	Sat. temp. t_f (°C)	Spec. enthalpy (kJ/kg)	
			hg	at 150°C
	0.15	111.4	2 693	2 773
	0.1	99.6	2 675	2777
Difference	+0.05	+ 11.8	+ 18	–4
Require	+0.03	$+11.8\times\frac{0.03}{0.05}=7.08$	$+18\times\frac{0.03}{0.05}=+10.08$	$-4\times\frac{0.03}{0.05}=-2.4$
Adding	0.13	106.68	2 685.8	2 774.6

The last line of the table uses linear interpolation to determine the specific enthalpy of the steam at 0.13 MN/m^2 and 112°C. The steam is superheated because the saturation temperature at the pressure of 0.13 MN/m^2 has been determined as being at 106.68°C.

Thus, specific enthalpy at the pressure of 0.13 MN/m^2 and with a temperature of 112°C is

$$h_2 = 2685.2 + (2774.6 - 2685.8)\frac{(112 - 106.68)}{(150 - 106.68)}$$

$$= 2685.2 + 88.8 \times \frac{5.32}{43.32}$$

$$= 2685.2 + 10.9$$

$$\mathbf{= 2696.1\ kJ/kg}$$

Now, for wet steam, before the throttle

$h_1 = h_{f1} + x_1 h_{fg1}$ where x_1 = required dryness fraction

$= 931 + (x_1 \times 1870)$

For the throttling process

$$h_1 = h_2$$

$$\therefore \quad 931 + (x_1 \times 1870) = 2696.1$$

$$x_1 = \frac{2696.1 - 431}{1870}$$

$$= \frac{1765.1}{1870}$$

$$= \mathbf{0.944}$$

Example 4.16 *What is the minimum dryness fraction which, can theoretically be determined using a throttling calorimeter if the steam to be tested is at a pressure of 1.8 MN/m²? The pressure after throttling is 0.11 MN/m².*

Solution

The theoretical dryness fraction occurs when the steam is just dry saturated after throttling (see section 4.11). At 0.11 MN/m² and just dry saturated the specific enthalpy = **2680 kJ/kg**.

At 1.8 MN/m²

Specific enthalpy = 885 + (x × 1912) kJ/kg

where x = minimum dryness fraction

Now for the throttling process

Specific enthalpy before throttling = Specific enthalpy after throttling

Hence

$$885 + (x \times 1912) = 2680$$

from which

$$x = \frac{2680 - 885}{1912}$$

$$= \mathbf{0.939}$$

4.11 Non-flow Processes and Steam

Steam involved in a non-flow process can be expanded or compressed. It can also be associated with heat and work transfer during the process.

It follows, therefore, that the non-flow energy equation

$$Q = \Delta u + W$$

will apply to steam.

In the following cases, let

P_1 = original pressure
v_1 = original specific volume
u_1 = original specific internal energy
h_1 = original specific enthalpy

P_2 = final pressure
v_2 = final specific volume
u_2 = final specific internal energy
h_2 = final specific enthalpy

4.11.1 Constant Volume Process (Isochoric)

The volume remains constant in this case, so

$$v_1 = v_2 = v \qquad [1]$$

And there is no change of volume, so there can be no external work done. Hence, $W = 0$ and the non-flow energy equation becomes

$$Q = \Delta u \qquad [2]$$

From this

$$\begin{aligned} Q &= u_2 - u_1 \\ &= (h_2 - P_2 v_2) - (h_1 - P_1 v_1) \\ &= (h_2 - h_1) - (P_2 v_2 - P_1 v_1) \\ &= (h_2 - h_1) - v(P_2 - P_1) \quad \text{(from equation [1])} \qquad [3] \end{aligned}$$

Q in this case is the transfer of heat per unit mass.

Example 4.17 *A closed vessel of 0.8 m³ capacity contains dry saturated steam at 360 kN/m². The vessel cooled until the pressure is reduced to 200 kN/m². Calculate.*

(a) *the mass of steam in the vessel*
(b) *the final dryness of the steam*
(c) *the amount of heat transferred during the cooling process*

(a)

At 360 kN/m², v_g = **0.510 m³/kg**

$$\therefore \text{ Mass of steam in vessel} = \frac{0.8}{0.51} = \mathbf{1.569\ kg}$$

(b)

At 200 kN/m², v_g = **0.885 m³/kg**

The volume remains constant, so

Specific volume after cooling = Specific volume before cooling

$\therefore x \times 0.885 = 0.510$

$$x = \frac{0.510}{0.885} = \mathbf{0.576}$$

The final dryness fraction of the steam is 0.576.

(c)
For a non-flow process, $Q = \Delta u + W$, and for a constant volume change $W = 0$

$$\therefore\ Q = \Delta u$$

Hence, the heat transferred is equal to the change of internal energy. Now $u = h - Pv$, so at 360 kN/m^2, dry saturated

$$\begin{aligned} u_1 &= 2732.9 - (360 \times 0.510) \\ &= 2732.9 - 183.6 \\ &= \mathbf{2549.3\ kJ/kg} \end{aligned}$$

At 200 kN/m^2, dryness 0.576

$$\begin{aligned} h_2 &= 504.7 + (0.576 \times 2201.6) \\ &= 504.7 + 1268.1 \\ &= \mathbf{1772.8\ kJ/kg} \\ \therefore\ u_2 &= 1772.8 - (200 \times 0.510) \\ &= 1772.8 - 102 \\ &= \mathbf{1670.8\ kJ/kg} \end{aligned}$$

$$\begin{aligned} \therefore \text{Change in specific internal energy} &= u_2 - u_1 \\ &= 1670.8 - 2549.3 \\ &= \mathbf{-878.5\ kJ/kg} \quad \text{(a loss)} \end{aligned}$$

But there are 1.569 kg of steam in the vessel, so the amount of heat transferred during the cooling process is

$$-878.5 \times 1.569 = \mathbf{-1378.4\ kJ} \quad \text{(a loss)}$$

4.11.2 Constant Pressure Process (Isobaric)

This process follows the normal processes already discussed in the formation of steam at constant pressure. The heat received or rejected is therefore equal to the change in enthalpy.

The non-flow energy equation therefore becomes

$$Q = \Delta u + W$$

or

$$h_2 - h_1 = (u_2 - u_1) + P(v_2 - v_1)$$

These are energy conditions per unit mass.

Example 4.18 *Steam at 4 MN/m^2 and dryness fraction 0.95 receives heat at constant pressure until its temperature becomes 350°C. Determine the heat received by the steam per kilogram.*

SOLUTION
At 4 MN/m^2 and 0.95 dry

$$\begin{aligned} h_1 &= 1087.4 + (0.95 \text{ x } 1712.9) \\ &= 1087.4 + 1627.3 \\ &= \mathbf{2714.7\ kJ/kg} \end{aligned}$$

At 4 MN/m^2 and temperature 350°C

$$h_2 = \mathbf{3095\ k\ J/kg}$$

The steam in this case is superheated because saturation temperature at 4 MN/m^2 = **250.3**°C

$$\therefore \text{ Heat received} = h_2 - h_1$$
$$= 3095 - 2714.7$$
$$= \mathbf{380.3\ kJ/kg}$$

4.11.3 The Hyperbolic Process PV = C

In the hyperbolic process (Fig. 4.10) steam is assumed to be expanded or compressed according to the law $PV = C$. This is the law of the rectangular hyperbola, hence **hyperbolic process.** It was introduced in section 1.5.2.

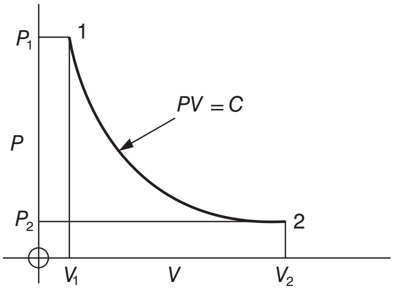

Fig. 4.10 Hyberbolic process, *PV = C*

$$P_1V_1 = P_2V_2 \qquad [1]$$

Also

$$\text{Work done} = W = PV \text{ In } \frac{v_2}{v_1} \text{ for any mass} \qquad [2]$$

$$= Pv \text{ In } \frac{v_2}{v_1} \text{ for unit mass} \qquad [3]$$

The non-flow energy equation becomes

$$Q = \Delta u + W$$

Or

$$Q = \left(u_2 - u_1\right) + Pv \text{ In} \frac{v_2}{v_1}$$

$$Q = \left(h_2 - P_2v_2\right) - \left(h_2 - P_1v_1\right) + Pv \text{ In} \frac{v_2}{v_1}$$

$$= \left(h_2 - h_2\right) + Pv \text{ In} \frac{v_2}{v_1} \qquad [4]$$

because $P_1V_1 = P_2V_2$ from equation [1].

These are energy conditions for unit mass. But Fig. 4.10 has been illustrated using any mass because the volumes are written as V_1 and V_2.

The actual mass can be determined by the ratio V_1/v_1 or V_2/v_2 because v_1 and v_2 are specific volumes. Note that $v_2/v_1 = V_2/V_1$. Note also that Fig. 4.10 shows an expansion; for a compression, 1 and 2 are interchanged.

Example 4.19 *A quantity of dry saturated steam occupies 0.395 I m³ at 1.5 MN/m². Determine the condition of the steam*

(a) after isothermal compression to half its initial volume

(b) after hyperbolic ($PV = C$) compression to half its initial volume

In case (a) determine the heat rejected during the compression.

Extract from steam tables

Pressure (MN/m²)	Sat. temp. t_f (°C)	Spec, enthalpy (kJ/kg)			Spec. vol. v_g (m³/kg)
		h_f	h_{fg}	h_g	
1.5	198.3	844.7	1 945.2	2 789.9	0.131 7
3.0	233.8	1 008.4	1 793.9	2 802.3	0.066 6

(a)

v_g at 1.5 MN/m2 = 0.1317 m³/kg

$$\therefore \text{Quantity of steam present} = \frac{0.39511}{0.3137} = \mathbf{3\ kg}$$

The steam is operating in the evaporation region because the temperature remains constant.

$$\therefore \frac{v_g}{2} = \frac{0.1317}{2} = \mathbf{0.0659\ m^3/kg}$$

The final specific volume is 0.065 9 m3/kg, hence final condition is at 1.5 MN/m2 with a dryness fraction of

$$\frac{0.0659}{0.1317} = \mathbf{0.5}$$

$$\begin{aligned}\text{Specific enthalpy} &= 844.7 + (0.5 \times 1945,2)\\ &= 844.7 + 972.6\\ &= \mathbf{1817.3\ kJ/kg}\end{aligned}$$

For 3 kg

$$\text{Enthalpy} = 3 \times 1817.3 = \mathbf{5451.9\ kJ}$$

The loss of heat during this process will be the loss of enthalpy of evaporation, changing from dry saturated steam to wet steam of dryness fraction 0.5 at constant temperature.

$$\therefore \text{Heat loss} = 0.5h_{fg} = 0.5 \times 1945.2 = 972.6\ \text{kJ/kg}$$

For 3 kg

$$\text{Heat loss} = 972.6 \times 3 = \mathbf{2917.8\ kJ}$$

(b)

If the compression is according to the law $PV = C$, then $P_1 V_1 - P_2 V_2$

$$\therefore P_2 = P_1 \frac{V_1}{V_2} = 1.5 \times 2$$

$$= \mathbf{3.0\ MN/m^2}$$

Specific volume after compression = **0.065 9 m^3/kg**

At 3.**0** MN/m^2

v_g = **0.066 6 m^3/kg**

So the dryness fraction after compression is

$$\frac{0.0659}{0.0666} = \mathbf{0.989}$$

Specific enthalpy = 1008.4 + (0.989 × 1793.9)

= 1008.4+ 1774.2

= **2782.6 kJ/kg**

For **3** kg

Enthalpy = 3 × 2782.6

= **8347.8 kJ**

4.11.4 The Polytropic Process $PV^n = C$

In the polytropic process (Fig. 4.11) the steam is assumed to be expanded or compressed according to the law $PV^n = C$. It was introduced in sections 1.5.2.

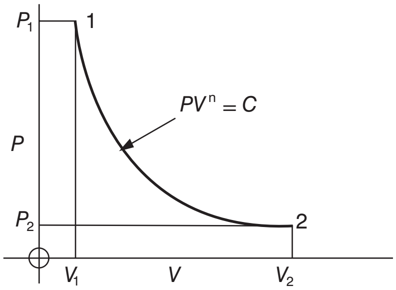

Fig. 4.11 Polytropic process, $PV^n = C$

Since $PV^n = C$, then [1]

$$P_1 V_1{}^n = P_2 V^n{}_2$$

Also

$$\text{Work done} = W = \frac{P_1V_1 - P_2V_2}{n-1} \text{ for any mass} \qquad [2]$$

$$= \frac{p_1v_1 - p_2v_2}{n-1} \text{ for unit mass} \qquad [3]$$

The non-flow energy equation becomes

$$Q = \Delta u + W$$

or

$$Q = \left(u_2 - u_1\right) + \left(\frac{P_1v_1 - P_2v_2}{n-1}\right)$$

$$= (h_2 - P_2v_2) - (h_2 - P_2v_2) + \left(\frac{h_2 - P_2v_2}{n-1}\right)$$

$$= \left(h_2 - h_1\right) - \left(P_2v_2 - P_1v_1\right) + \left(\frac{P_1v_1 - P_2v_2}{n-1}\right)$$

$$= \left(h_2 - h_1\right) + \left(1 + \frac{1}{n-1}\right)\left(P_1v_1 - P_2v_2\right)$$

$$= \left(h_2 - h_1\right) + \left(\frac{n-1+1}{n-1}\right)\left(P_1v_1 - P_2v_2\right)$$

$$Q = \left(h_2 - h_1\right) + \frac{n}{n-1}\left(P_1v_1 - P_2v_2\right)$$

These are energy conditions for unit mass. The actual mass can be determined by volume ratios V_1/v_1 or V_2/v_2 because v_1 and v_2 are specific volumes. Note that Fig. 4.11 shows an expansion; for a compression, 1 and 2 are interchanged.

Example 4.20 *A quantity of steam at a pressure of 2.1 MN/m² and 0.9 dry occupies a volume of 0.427 m³. It is expanded according to the law $PV^{1.25}$ = constant to a pressure of 0.7 MN/m².*

Determine

(a) the mass of steam present

(b) the work transfer

(c) the change of internal energy

(d) the heat exchange between the steam and surroundings, stating the direction of transfer

Extract from steam tables

Pressure (MN/m^2)	Sat. temp. t_f (°C)	Spec. enthalpy (kJ/kg)			Spec. vol. v_g (m^3/kg)
		h_f	h_{fg}	hg	
0.7	165	697.1	2 064.9	2 762.0	0.273
2.1	214.9	920.0	1 878.2	2 798.2	0.094 9

(a)

Specific volume of steam at 2.1 MN/m^2 and 0.9 dry is

$$V_1 = x_1 V_{g1} = 0.9 \times 0.094\,9 = \mathbf{0.085\,4\ m^3/kg}$$

$$\text{Mass of steam present} = \frac{0.427}{0.0854} = \mathbf{5\ kg}$$

(b)

For the expansion, $P_1 v_1^{1.25} = P_2 v_2^{1.25}$

$$\therefore v_2 = v_1\left(\frac{P_1}{P_2}\right)^{1/1.25} = 0.0854 \times \left(\frac{2.1}{0.7}\right)^{1/1.25}$$

$$= 0.0854 \times 3^{1/1.25}$$

$$= 0.0854 \times 2.41$$

$$= \mathbf{0.205\,8\ m^3/kg}$$

The steam is wet after expansion; its dryness fraction is

$$x_2 = \frac{v_2}{v_{g2}} = \frac{0.2058}{0.273} = 0.754$$

$$\text{Work transfer} = \frac{P_1 v_1 - P_1 v_1}{n-1}$$

$$= \frac{10^3 \times (2.1 \times 0.0854 - 0.7 \times 0.2058)}{1.25 - 1}$$

$$= \frac{10^3 \times (0.1793 - 0.1441)}{0.25}$$

$$= 10^3 \times \frac{0.0352}{0.25} = 10^3 \times 0.1408$$

$$= \mathbf{140.8\ kj/kg}$$

$\therefore$ Work transfer for 5 kg = 140.8 × 5

=**704 k J**

(c)

$u_1 = h_1 - p_1 v_1$

$$h_1 = h_{f1} + x_1 h_{fg1} = 920.0 + (0.9 \times 1878.2)$$
$$= 920.0 + 1690.4$$
$$= \mathbf{2610.4\ kJ/kg}$$

$$\therefore \quad u_1 = 2610.4 - \frac{10^6}{10^3} \times 2.1 \times 0.0854$$
$$= 2610.4 - 179.3$$
$$= 2431.1\ \text{kj/kg}$$

$u_2 = h_2 - P_2 v_2$

$$h_2 = h_{f2} + x_2 h_{fg2} = 697.1 + (0.754 \times 2064.9)$$
$$= 697.1 + 1556.9$$
$$= 2254.0\text{kj/kg}$$

$$\therefore \quad u_2 = 2254.0 - \frac{10^6}{10^3} \times 0.7 \times 0.2058$$
$$= 2254.0 - 144.1$$
$$= 2109.9\ \text{kj/kg}$$

$\therefore$ Change in internal energy $= u_2 - u_1$

$$= 2109.9 - 2431.1$$
$$= -321.2\ \text{kj/kg} \quad \text{(a loss)}$$

For 5 kg of steam

Loss of internal energy = – 321.2 × 5 = **– 1606 kJ**

(d)

$$Q = \Delta U + W$$
$$= -\ 1606\ +\ 704$$

= –**902 kJ** (a loss to the surroundings)

4.11.5 The Adiabatic Process

The adiabatic process was defined as a process carried out such that there is no heat transfer during the process, i.e. Q = 0.

It is possible to conceive of steam being expanded or compressed adiabatically. Such a process with steam will be a particular case of the law $PV^n = C$. The value of n will be the value which will satisfy the condition $Q = 0$.

Hence, for an adiabatic expansion or compression with steam from state 1 to state 2

$$P_1 V_1^n = P_2 V_2^n \qquad [1]$$

Also

$$\text{Work done } = \frac{P_1 v_1 - P_2 v_2}{n-1} \text{ for any mass} \qquad [2]$$

$$= \frac{P_1 v_1 - P_2 v_2}{n-1} \text{ for unit mass} \qquad [3]$$

The non-flow energy equation becomes

$$Q \Delta u + W$$

and for an adiabatic process $Q = 0$

$$\therefore \quad 0 = \Delta u + W$$

or

$$W = -\Delta u \qquad [4]$$

This means that:

- Work transfer during an adiabatic expansion is done at the expense of the internal energy of the substance, in this case, steam.
- Work transfer during an adiabatic compression increases the store of internal energy of the substance.

From equation [4]

$$W = \; - \Delta u$$

or

$$\left(\frac{P_1 v_1 - P_2 v_2}{n-1} \right) = \left(u_1 - u_2 \right)$$

or

$$\left(\frac{P_1 v_1 - P_2 v_2}{n-1} \right) = \left(h_1 - P_1 v_2 \right) - \left(h_2 - P_2 v_2 \right) \qquad [5]$$

The approximate values of n for the adiabatic compression or expansion of steam are

$n = 1.13$ for wet steam
$n = 1.3$ for superheated steam

Energy conditions given above are for unit mass.

Example 4.21

(a) Determine the volume occupied by 1 kg of steam at a pressure of 0.85 MN/m^2 and having a dryness fraction of 0.97.

(b) This volume is expanded adiabatically to a pressure of 0.17 MN/m^2; the law of expansion is $PV^{1.13} = \text{constant}$. Determine

(i) the final dryness fraction of the steam

(ii) the change of internal energy of the steam during the expansion

Extract from steam tables

Pressure (MN/m^2)	Spec. vol. v_g (m^3/kg)
0.17	1.031
0.85	0.226 8

(A)

$v_1 = x_1 v_{g1} = 0.97 \times 0.226\,8 = \mathbf{0.22\ m^2/kg}$

(B)

(i) $$P_1 v_1^{1.13} = P_2 v_2^{1.13}$$

$$\therefore v_2 = v_1 \left(\frac{P_1}{P_2}\right)^{1/1.13}$$

$$= 0.22 \times \left(\frac{0.85}{0.17}\right)^{1/1.13}$$

$$= 0.22 \times 5^{1/1.1}$$

$$= 0.22 \times 4.15$$

$$= \mathbf{0.913\ m^3/kg}$$

At 0.17 MN/m^2, v_{g2} – **1.031 m^3/kg**

The steam is wet; its final dryness fraction is

$$x_2 = \frac{v_2}{v_{g2}} = \frac{0.913}{1.031} = \mathbf{0.886}$$

(ii) For an adiabatic expansion, $\Delta u = -W$

$$\therefore \quad u_2 - u_1 = \frac{-\left(P_1 v_1 - P_2 v_2\right)}{n-1}$$

$$= -\frac{10^6}{10^3} \times \frac{\left(0.85 \times 0.22 - 0.17 \times 0.913\right)}{1.13 - 1}$$

$$= -10^3 \times \frac{\left(0.187 - 0.155\right)}{0.13} = 10^3 \times \frac{0.032}{0.13}$$

$$= -10^3 \times 0.246$$

$= \mathbf{-246\ kJ/kg}$ *(a loss of internal energy)*

4.11.6 The Isothermal Process

Section 4.2.2 described the evaporation stage during the formation of a vapour from a liquid. Throughout the evaporation stage the temperature remains constant at saturation temperature, t_f. Since the isothermal process is defined as a process carried out at constant temperature, the evaporation of liquid to vapour is an isothermal process. It is also carried out at constant pressure, so the energy involved is the enthalpy of evaporation. See sections 4.3.4 and 4.2.5 plus Example 4.19.

Summary

Steam

Steams are of wet, saturated and superheated types.

Dryness Fraction of Steam

The ratio

$$\frac{\text{Mass of dry saturated vapour}}{\text{Mass of wet vapour containing the dry saturated vapour}}$$

is called the **dryness fracion**, symbol x.

Dryness fraction can be measured by separating and throttling calorimeter or by combine of both of these.

Enthalpy and Steam

$$h_g = h_f + h_{fg}$$

$$h = h_g + c_p(t - t_f)$$

Here hf = Liquid Enthalpy
hfg = Enthalpy of Evaporation
hg = Enthalpy of Dry Saturated Vapour
h = Enthalpy of Superheated Steam
(t – tt) = Degree of Superheat

For specific pressure and temperature; values of the said enthalpies can be obtained from steam tables.

Specific Volume of Steam

The specific volume of dry saturated steam is tabulated against its corresponding saturation temperature and pressure in steam tables and is designated as vg. Volume is given in m^3/k[illegible]

$$\text{Volume of wet steam} = v = xv_g$$

Steam tables quote the specific volume of superheated steam, either with pressure against actual steam temperature or with pressure against degree of superheat, volume is given in m^3/kg.

Steam tables quote the specific volume of water. At saturation temperature, for a given pressure, the specific volume of water is tabulated as vf m^3/kg.

Density of Steam

$$\text{Density} = \frac{1}{v}\ \text{kg/m}^3$$

Throttling

If a gas or steam (or any other vapour) is passed through a fine orifice, it is said to have been throttled.

Enthalpy before throttling = Enthalpy after throttling

Non-flow Processes and Steam

$$Q = \Delta u + W$$

1. Constant Volume Process (Isochoric); W = 0

$$Q = u_2 - u_1 = (h_2 - h_1) - v(P_2 - P_1)$$

2. Constant Pressure Process (Isobaric)

$$Q = \Delta u + W$$

Or

$$h_2 - h_1 = (u_2 - u_1) - P(v_2 - v_1)$$

3. The Hyperbolic Process PV = C

$$Q = \Delta u + W$$

$$= (h_2 - h_1) + Pv\ \text{In}\frac{v_2}{v_1}$$

4. The Polytropic Process PV$^{n}_{n}$ = C

$$Q = (h_2 - h_1) + \frac{n}{n-1}(P_1v_1 - P_2v_2)$$

5. The Adiabatic Process

Q = 0 and;

$$\left(\frac{P_1v_1 - P_2v_2}{n-1}\right) = (h_2 - P_1v_2) - (h_2 - P_2v_2)$$

6. The Isothermal Process

Isothermal process is defined as a process carried out at constant temperature, the evaporation of liquid to vapour is an isothermal process. It is also carried out at constant pressure, so the energy involved is the enthalpy of evaporatio

Questions

1. Determine the enthalpy, volume and density of 1.0 kg of steam at a pressure of 5 MN/m^2 and with a dryness fraction of 0.94.

[2695.82 kJ/kg; 0.037 m^3/kg; 27.03 kg/m^3]

2. Determine the enthalpy, volume and density of 4.5 kg of steam at a pressure of 2 MN/m^2 and with a temperature of 300°C.

[13 612.5 kJ; 0.562 5 m^3; 7.97 kg/m^3]

3. Determine the specific enthalpy and the specific volume of steam at a pressure of 18 bar and with a temperature of 320°C.

[3075.16 kJ/kg; 0.149 m^3/kg]

4. Steam at a pressure of 28 kN/m^2 is passed into a condenser and leaves as condensate at a temperature of 59°C. Cooling water circulates through the condenser at the rate of 500 kg/min. It enters at 15°C and leaves at 30°C. If the steam flow rate is 14 kg/ min, determine the dryness fraction of the steam as it enters the condenser.

[0.942]

5. Steam at a pressure of 1.25 MN/m^2 and with a dryness fraction of 0.96 flows through a steam main of 150 mm internal diameter with a velocity of 26 m/s. The steam is throttled to a pressure of 0.12 MN/m^2. After throttling, 5 kg of the steam is blown into a tank containing 98 kg of water, the original temperature of which is 16°C. Take the specific heat capacity of superheated steam at constant pressure as 2.09 kJ/ kg K. and, neglecting heat losses, determine
   - (a) the mass flow of steam through the steam main in kg/s
   - (b) the temperature of the steam after throttling
   - (c) the temperature of the water in the tank after receiving the 5 kg of blown steam

Extract from steam tables

Pressure (MN/m^2)	Sat. temp. t_f (°c)	Spec. enthalpy (kJ/kg)			Spec. vol v_g (m^3/kg)
		h_f	h_{fg}	h_g	
0.12	104.8	439.4	2 244.1	2 683.4	1.428
1.25	189.8	806.7	1 977.4	2 784.1	0.156 9

[(a) 3.04 kg/s; (b) 115.1°C; (c) 48.54°C)

6. A quantity of steam at a pressure of 3 MN/m^2 has a dryness fraction of 0.72. The steam occupies a volume of 0.4 m^3. Heat is transferred into the steam while the pressure remains constant at 3 MN/m^2 until the steam becomes dry saturated. The steam is then cooled at constant volume until the pressure becomes 1.8 MN/m^2. Determine
   - (a) the heat transferred during the constant pressure process
   - (b) the percentage of the heat transfer which appears as work transfer
   - (c) the heat transferred during the constant volume process

Extract from steam tables

Pressure (MN/m^2)	Sat. temp. t_f (°C)	Spec. enthalpy (kJ/kg)			Spec. vol v_g
		h_f	h_{fg}	h_g	(m^3/kg)

1.8	207.3	884.6	1 910.3	2 794.8	0.110 3
3.0	233.8	1 008.4	1 793.9	2 802.3	0.066 6

[(a) 4189.1 kJ; (b) 11.14%; (c) –5704.6 kJ]

7. Water enters a heater at a temperature of 18°C. Steam at a pressure of 1.2 bar and 0.95 dry is mixed with, and condensed in, the water. The mixture of water and condensate leaves the heater as hot water. The mass of steam is 8 per cent of the combined hot water leaving the heater. Neglecting heat transfer loss, determine the temperature of the hot water output. Take the specific heat capacity of water at constant pressure as 4.19 kJ/kg K.

Extract from steam tables

Pressure (bar)	Sat. temp. t_f (°C)	Spec. enthalpy (kJ/kg)		
		h_f	h_{fg}	h_g
0.12	104.8	439.4	2 244.1	2 683.4

[65.7°C]

8. A quantity of steam at a pressure of 2 MN/m^2 has a volume of 0.75 m^3 and an enthalpy content of 21.5 MJ. Determine (a) the dryness fraction of the steam and (b) the mass of the steam. If some of this steam is throttled to a pressure of 1.2 MN/m^2, determine (c) the quality of the steam after throttling.

Extract from steam tables

Pressure (MN/m^2)	Sat. temp. t_f (°c)	Spec. enthalpy (kJ/kg)			Spec. vol v_g (m^3/kg)
		h_f	h_{fg}	h_g	
1.2	188.0	798.4	1 984.3	2 787.7	0.163 2
2.0	212.4	908.6	1 888.6	2 797.2	0.099 5

(a) 0.943; (b) 8 kg; (c) 0.953]

9. Steam at a pressure of 2 MN/m^2 and with a temperature of 250°C is expanded to a pressure of 0.4 MN/m^2; the law of expansion is $PV^{1.2} = C$. After expansion the steam is cooled at constant volume to a pressure of 0.2 MN/m^2. Determine

   (a) the condition of the steam after expansion according to the law $PV^{1.2} = C$
   (b) the heat transferred per kilogram of steam during the expansion
   (c) the condition of the steam after the constant volume cooling
   (d) the heat transferred during the constant volume cooling

[(a) 0.921; (b) –91 kJ/kg;(c) 0.481; (d) –921 kJ/kg]

10. Superheated steam at a pressure of 4 MN/m^2 and with a temperature of 375°C enters a desuperheater at the rate of 5 tonne/h. Water at a temperature of 75°C is sprayed into the superheated steam as it passes through the desuperheater to produce a combined mixture of output steam at a pressure of 4 MN/m^2 and with a dryness of 0.96. Determine

   (a) the mass of the output steam in tonne/h
   (b) the internal diameter of the steam pipe required to carry the output steam if the steam velocity is 20 m/s

[(a) 5.878 tonne/h; (b) 70.5 mm]

11. 2.5 kg of steam at a pressure of 100 kN/m^2 and with a dryness fraction of 0.96 is compressed hyperbolically to a pressure of 8.0 bar. Determine
    (a) the final condition of the steam
    (b) the heat transferred during the compression

[(a) 0.845; (b) –1182.5 kJ]

12. A throttling calorimeter is used to determine the quality of steam which is at a pressure of 2.2 MN/m^2. The pressure and temperature after throttling are 0.12 MN/m^2 and 109.6°C, respectively. Determine
    (a) the dryness fraction of the steam at 2.2 MN/m^2
    (b) the least dryness fraction which can be theoretically determined under the given pressure conditions

    Take the specific capacity of superheated steam as 2.1 kJ/kg K.

Extract from steam tables

Pressure (MN/m^2)	Sat. temp. t_f (°c)	Spec. enthalpy (kJ/kg)		
		h_f	h_{fg}	h_g
0.12	104.8	439.4	2 244.1	2 683.4
2.2	217.2	931.0	1 868.1	2 799.1

[(a) 0.943; (b) 0.938]

13. Steam at a pressure of 1.5 bar and with a dryness fraction of 0.9 is compressed adiabatically to a pressure of 7 bar. The law of compression is $PV^{1.13} = C$. Determine
    (a) the final condition of the steam
    (b) the final density of the steam
    (c) the change of specific internal energy of the steam

Extract from steam tables

Pressure (bar)	Spec. vol. v_g (m^3/kg)
1.5	1.159
7	0.272 8

[(a) 0.98; (b) 3.75 kg/m^3; (c) +234.6 kJ/kg]

14. A refrigerant is at a pressure of 0.745 MN/m^2 and has a temperature of 45°C. It is cooled at constant pressure until it becomes liquid at saturation temperature. It is then throttled down to a pressure of 0.219 MN/m^2. Determine
    (a) the heat transfer during the constant pressure cooling process per kilogram of refrigerant
    (b) the quality of the refrigerant after throttling

Extract from steam tables

Pressure (MN/m ^{2})	Sat. temp. t_f (°C)	Spec. enthalpy (kJ/kg)		
		h_f	h_{fg}	superheated by 20 K
0.219	–10	26.9	183.2	195.7
0.745	30	64.6	199.6	214.3

[(a) –146.03; (b) 0.241]

15. Steam at a pressure of 3 MN/m^2 and with a temperature of 250°C is mixed with wet steam at a pressure of 3 MN/m^2 and with a dryness fraction of 0.92 in the ratio of 1:2.5 by mass. Determine
    (a) the quality of the steam mixture
    (b) the density of the steam mixture

[(a) 0.952; (b) 15.77 kg/m^3]

16. Steam flows through a turbine at a rate of 3 kg/s. The steam enters the turbine at a pressure of 4 MN/m^2 and with a temperature of 350°C. The pressure at exhaust from **the** turbine is 60 kN/m^2 and the dryness fraction is 0.92. Neglecting any change in kinetic energy of the steam and any heat transfer loss, determine
    (a) the theoretical power output from the turbine
    (b) the steam exit area at the turbine exhaust if the steam velocity at exit is 32 m/s

[(a) 1875 kW; (b) 0.235 m^2]

Previous Years' GTU Examination Questions

1. A sample of wet steam at a pressure of 25 bar absolute has dryness fraction 0.80. Determine its enthalpy and internal energy.

[Dec '08]

2. Combined separating and throttling calorimeter is used to find out dryness fraction of steam. Following readings were taken:

Main pressure = 12 bar ab.

Mass of water collected in separating calorimeter = 2 kg

Mass of steam condensed in throttling calorimeter = 20 kg

Temperature of steam after throttling = 110°C

Pressure of steam after throttling = 1 bar ab.

Assume Cp of steam = 2.1 kJ/kg K

Calculate dryness fraction of steam.

[Dec '08]

3. Define

(i) Enthalpy

(ii) Specific Volume of Steam.

(iii) Dryness Fraction of Steam

(iv) Internal Energy

[Mar '09]

4. Drawing a diagram explain construction and working of combined calorimeter.

[Mar '09]

5. Determine the mass of 0.15m^3 of wet steam at a pressure of 4 bar and dryness fraction 0.8. Also calculate the heat of 1 m^3 of steam.

[Mar '09]

6. Prove that dryness fraction + wetness fraction = 1.

[Jun '09]

7. Determine condition of steam at a 12 bar if 2580 kJ/kg heat is required to produce it from water at 0°C.

   [Sep ’09]

8. The following information is available from test of a combined separating and throttling calorimeter:

   (i) Pressure of steam in a steam main = 9.0 bar
   (ii) Pressure after throttling = 1.0 bar
   (iii) Temperature after throttling =115°C
   (iv) Mass of steam condensed after throttling = 1.8 kg
   (v) Mass of water collected in the separator = 0.2 kg

   Calculate the dryness fraction of the steam in the main.

   [Sep ’09]

9. What is dryness fraction? Explain throttling calorimeter.

   [Jan ’10]

10. Determine dryness fraction of steam supplied to a separating and throttling calorimeter.

    Water separated in separating calorimeter = 0.45 kg
    Steam discharge from throttling calorimeter = 7 kg
    Steam pressure in main pipe = 1.2 MPa
    Barometer reading = 760 mm of Hg
    Manometer reading = 180 mm of Hg
    Temperature of steam after throttling = 140°C
    Take Cps = 2.1 kJ/kg K.

    [Jan ’10]

11. Define the following terms:

    (i) Dryness fraction of steam
    (ii) Degree of superheat

    [Jun ’10]

12. Determine the enthalpy and internal energy of 1 kg of steam at a pressure 10 bar(abs.),

    (i) When the dryness fraction of the steam is 0.85
    (ii) When the steam is dry and saturated
    (iii) When the steam is superheated to300ºC

    Neglect the volume of water and take the specific heat of superheated steam as 2.1 kJ/kg K.

    [Jun ’10]