# 3
# PROPERTIES OF STEAM

## 3.1 Introduction

Steam is a vapour. It is used as the working substance in the operation of steam engines and steam turbines. As stated in chapter 2, a vapour is a partially evaporated liquid carrying in it particles of liquid and it can be liquefied by minor changes in temperature or pressure. Steam as a vapour would not obey the laws of perfect gases unless it is in a highly dried condition. Steam in such a dried state is known as ***superheated steam*** and it is assumed to behave like a perfect gas when highly superheated.

Although steam is considered as a perfect gas on account of it being a mixture of dry steam (gas) and moisture (water), it possesses properties like those of gases : namely, pressure, volume, temperature, internal energy, enthalpy and entropy. But the pressure, volume and temperature of steam as a vapour are not connected by any simple relationship such as is expressed by the characteristic equation for a perfect gas.

Properties of steam were first investigated experimentally by Regnault and subsequently investigated by Prof. Callender by carrying out extensive thermodynamic experiments by means of electrical calorimeters. Tables giving the properties of steam in each condition were compiled from study of the equations derived experimentally. These properties are also represented on charts. The quantities tabulated in steam tables are :

- Pressure,
- Temperature,
- Specific Volume,
- Enthalpy, and
- Entropy.

Pressure, temperature and volume can be given their actual absolute values; whereas, enthalpy and entropy are purely relative quantities. They are measured relatively from convenient datum condition and calculated per 1 kg of steam. For steam, datum point is arbitrarily fixed as the condition of the water at 0°C. Thus, the enthalpy, the internal energy and the entropy of water at 0°C are assumed to be zero. All their values measured above this temperature are considered positive and those measured below are taken as negative.

The general conservation of energy equation is applicable to steam in the same manner as it is applicable to gases. The properties of steam and the changes in the properties can be determined by using standard steam tables or steam charts.

## 3.2 Formation of Steam at Constant Pressure

Consider a cylinder fitted with frictionless piston which may be loaded to any desired pressure $p$ bar as shown in fig. 3-1(a). Now, assume for convenience that there is one kilogram of water initially at temperature 0°C in the cylinder under the piston and the piston exerts a constant pressure $p$ bar. Let the area of the piston be one square metre and the volume of one kilogram of water be $v_w$ $m^3$, the length of the cylinder occupied by water will be $v_w$ m. Now, let heat be supplied to the water in the cylinder. The temperature of water will rise when sensible enthalpy be supplied. The rise in temperature will continue until the boiling point is reached, where it will remain constant. The temperature at which water boils depends upon the pressure on it. For any given pressure, there is one *definite* boiling point. The boiling point is called the saturation temperature ($t_s$) or the temperature of steam formation. Water boils at 99·63°C when the pressure on it is 1 bar, and at 184·09°C when the pressure on it is 11 bar (these values are taken from steam tables).

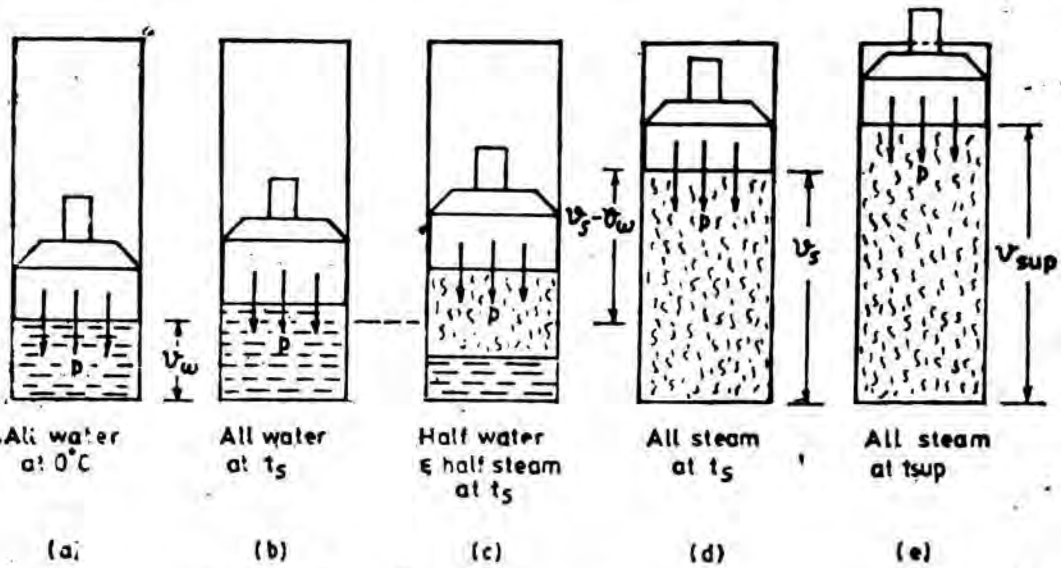


Fig. 3-1. Formation of steam at constant pressure.

The water will expand slightly during the rise of temperature. The increase in volume of water causes the piston to move up slightly as shown in the fig. 3-1(b), thus, work is done in moving the piston against this pressure $p$. This work, however, is only a small portion of the heat added to water during the rise in temperature and may be neglected in general. Figure 3-1(a) represents the condition before the first stage commences and fig. 3-1(b) represents the condition at the end of the first stage. It will be noted that the piston is at slightly higher level at the end of operation.

The next stage, as shown in fig. 3-1(c), is the actual production of steam. If the heating of this one kilogram of water is continued after the boiling point is reached, it will be noticed that there is no further increase in temperature, as the pressure is maintained constant but steam begins to form and piston commences to ascend (rise) in the cylinder, rising higher and higher as more and more steam is formed. The heat absorbed is now utilised in converting water into steam and is known as *evaporation enthalpy* or *latent heat*. As long as there is some water left unevaporated in the cylinder, the steam formed will not be pure (dry) steam, but will have some water mixed with it. In fig. 3-1(c), part of water is evaporated and the cylinder has in it, mixture of water and steam (about half steam and half water). A mixture of steam and water is called ***wet steam***.

If the heating of this *wet steam* is further continued and as soon as last particle of water in suspension in wet steam disappears (evapcrates), the steam produced is known as ***dry saturated steam***.

Figure 3-1(d) shows that the process of formation of steam is completed. The water is entirely evaporated and the volume of steam below the piston is $v_s$ m$^3$ ($v_s$ is the volume of one kilogram of dry saturated steam at a given pressure $p$). The piston will rise to accommodate this increased volume, and will occupy length $v_s$ m of the cylinder. The work done on the piston during the change of volume of the steam from $v_w$ to $v_s$

$$= \frac{10^5\, p\,(v_s - v_w)}{10^3} \text{ kJ} \quad \text{where } p \text{ is the pressure in bar.} \qquad ..\ (3.1a)$$

If $p$ is in kPa, then the above expression is written as

$$\text{Work done} = p(v_s - v_w) \text{ kJ} \qquad ..\ (3.1b)$$

Finally, if further heat is added to one kilogram of dry steam in the cylinder at the constant pressure, the temperature of steam will rise and there will be further increase in volume of steam as shown in fig. 3-1(e). The steam produced is known as ***superheated steam.***

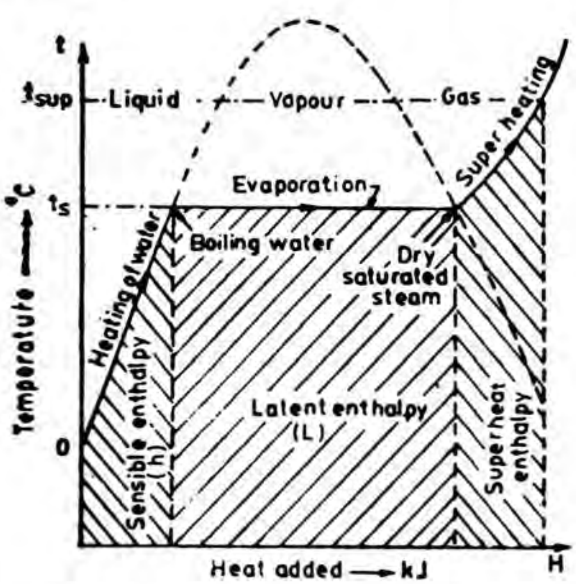


Fig. 3-2. Formation of steam at constant pressure.

Figure 3-2 shows graphically that what happens when heat is added to one kilogram of water initially at 0°C. The heat added is plotted along the horizontal axis in kJ units while the corresponding temperatures are plotted along the vertical axis in centigrade units.

During the first stage of heating, the temperature of water will begin to rise until the water boils at a temperature known as **saturation temperature** which depends upon the pressure in the cylinder. After the boiling temperature is reached, steam begins to be formed during which time the temperature remains constant. Until the point is reached at which all water is converted into steam, the contents of mixture will be steam and water known as ***wet steam.*** When all the water including those particles of water held in suspension will be evaporated, the steam is said to be dry and is known as ***dry saturated steam.*** As heating continues further, the temperature of steam begins to rise again and steam is now known as ***superheated steam*** and behaves more or less as a perfect gas.

**3.2.1 Enthalpy :** For reasons too long to explain here, the term heat content is not recommended for use in thermodynamics. The terms formerly known as "heat of water" (sensible heat), "heat of evaporation" (latent heat) and "total heat of steam" are now known as the "enthalpy of (saturated) water", "enthalpy of evaporation" and "enthalpy of saturated steam" respectively. Similarly, the term total heat of superheated steam is now known as "enthalpy of superheated steam". Enthalpy of evaporation is the difference between enthalpy of dry saturated steam and enthalpy of (saturated) water, i.e,

Enthalpy of evaporation = Enthalpy of dry saturated steam – Enthalpy of boiling water

**3.2.2 Enthalpy of Water :** The amount of heat absorbed by one kilogram of water in being heated from the freezing point (0°C) to the boiling point $t_s$, is known as the *enthalpy of the saturated water (sensible heat of water)* and is denoted by the symbol

$h$. It is customary to reckon the enthalpy of water from 0°C at which temperature the enthalpy of water is said to be zero. To raise the temperature of one kilogram of water from 0°C to 100°C requires 4·187 × 100 = 418·7 kJ; hence this number is the enthalpy of one kg of water at 100°C. If the temperature of water to begin with is say 20°C instead of 0°C, then number of heat units required to raise 1 kg of water at 20°C to water at 100°C is equal to 4·187 (100 − 20) = 334·96 kJ, where 4·187 kJ/kg K is the specific heat water.

If the specific heat of water were 4·187 kJ/kg K at all temperatures, then the enthalpy of water would be 4·187 ($t_s$ − 0) kJ/kg. For engineering purpose, it is of sufficient accuracy to assume the value of specific heat of water ($k$) to be 4·187 kJ/kg K at low pressures in which case,

Enthalpy of (saturated) water, $h$ at any temperature $t_s$ above 0°C is

$$h = 4 \cdot 187 \times (t_s - 0) \text{ kJ/kg} \quad \text{.. (3.2)}$$

The error in results calculated by this formula becomes larger as the temperature rises. The value of enthalpy of saturated water, $h$ given in column 4 of the steam tables (given at the end of this book) should be used in preference to the results calculated from the above formula.

**3.2.3 Enthalpy of Evaporation** : The enthalpy of evaporation (or latent heat) is defined as the amount of heat required to convert one kilogram of water at a given temperature $t_s$ and pressure $p$ into steam at the same temperature and pressure. The value of enthalpy of evaporation varies with the pressure. It is usually expressed by the symbol $L$ and its value at 1 bar is 2,258 kJ per kg. The value of enthalpy of evaporation, $L$ of 1 kg of dry saturated steam can be directly obtained from the steam tables.

The value of enthalpy of evaporation of dry saturated steam is given in column 5 of the steam tables.

**3.2.4 Enthalpy of Dry Saturated Steam** : It is the sum of enthalpy of saturated water and enthalpy of evaporation and is defined as the quantity of heat required to raise the temperature of one kilogram of water from freezing point to the temperature of evaporation $t_s$ (corresponding to given pressure $p$) and then convert it into dry saturated steam at that temperature and pressure. It is denoted by the symbol $H_s$. The *enthalpy* of one kg of dry saturated steam, $H_s$ = enthalpy of (saturated) water + enthalpy of evaporation,

$$\text{i.e.,} \quad H_s = h + L \text{ kJ/kg} \quad \text{... (3.3)}$$

The value of enthalpy (total heat), $H_s$ of 1 kg of dry saturated steam can be directly obtained from the steam tables corresponding to given value of pressure or temperature. The value of enthalpy of dry saturated steam is given in column 6 of the steam tables.

Enthalpy of evaporation is the enthalpy difference between dry saturated steam and saturated water.

**3.2.5 Wet Steam** : The steam in the steam space of a boiler generally contains water mixed with it in the form of a mist (fine water particles). Such a steam is termed as *wet steam*. The quality of steam as regards its dryness is termed as ***dryness fraction.*** Dryness fraction is usually expressed by the symbol $x$ or $q$. Dryness fraction is often spoken as the *quality of wet steam.*

If $m_s$ = mass of dry steam contained in the steam considered, and

$m$ = mass of water in suspension in the steam considered.

Then, dryness fraction, $x = \frac{m_s}{m_s + m}$ ... (3.4)

Thus, if drynes fraction of wet steam, $x = 0{\cdot}8$, then one kg of wet steam contains 0·2 kg of moisture (water) in suspension and 0·8 kg of dry steam.

When the steam produced is not dry steam, but a mixture of steam and water as is often the case, the enthalpy of one kilogram of mixture of water and steam (wet steam) is less than enthalpy of the same quantity of pure or dry steam. To generate steam of dryness fraction 0·8, takes only 0·8 of the enthalpy of evaporation necessary for the formation of dry steam at the same temperature. Hence, enthalpy of evaporation of one kg of wet steam is the value of the enthalpy of evaporation given in steam tables for dry steam, at the required pressure, multiplied by its dryness fraction $x$.

i.e. Enthalpy of evaporation of 1 kg of wet steam = $xL$ kJ/kg ... (3.5)

Enthalpy of wet steam is the amount of heat required to raise the temperature of one kilogramof water from freezing point (0°C) to the boiling point $t_s$ (corresponding to given pressure, $p$) and then to convert the boiling water into wet steam,

i.e. Enthalpy of one kg of wet steam = enthalpy of saturated water + enthalpy of evaporation,

i.e. $H_{wet} = h + xL$ kJ/kg ... (3.6)

**3.2.6 Superheated Steam :** If the steam remains in intimate contact with water during its formation, interchange of molecules between the water and steam will result. This interchange of molecules will continue as long as there is any water in the cylinder of fig. 3-1(d). This will not allow the steam to become dry.

If the water is entirely evaporated and further heat is then supplied, the first effect on the steam is to make it dry if it is not already dry. The temperature of steam will then begin to increase with a corresponding Increase in volume. Steam in this condition, heated out of contact with water, is said to be superheated. Superheating is assumed to take place at constant pressure. The amount of superheating is measured by the rise in temperature of the steam above its saturation temperature ($t_s$). Greater the amount of superheating, the more will the steam acquire the properties of a perfect gas.

In practice, steam is superheated after it has left the boiler by passing it through a nest of tubes known as *superheater.* The superheater is heated externally by the furnace gases of the boiler. The additional heat supplied to steam during the process of superheating is known as the heat of superheat.

Heat absorbed per kg of dry steam during superheating = $k_p(t_{sup} - t_s)$ kJ/kg ...(3.7)

where $t_{sup}$ = temperature of superheated steam,

$t_s$ = saturation temperature at the given pressure, and

$k_p$ = mean specific heat of superheated steam at constant pressure.

The temperature rise ($t_{sup} - t_s$) is termed as *dgree of superheat.* It means the number of degrees of temperature by which steam at a given pressure is raised above the saturation temperature corresponding to that pressure. The condition of superheated steam is given either by its degree of superheat or by its temperature. The value of specific heat of superheated steam ($k_p$) varies with the pressure and degree of superheating. It increases with the increase of pressure and decreases with the increase of degree of superheating. The value of specific heat at constant pressure of superheated steam ($k_p$) varies from 2 to 2·5 kJ/kg K.

The enthalpy (or total heat) of one kg of superheated steam may be defined as the number of heat units required to convert one kg of water at freezing temperature (0°C) into superheated steam at a given pressure and temperature, assuing that the heat is added at constant pressure, which is the case in practice. The enthalpy of 1 kg of superheated steam is, therefore, the sum of enthalpy of water, the enthalpy of evaporation, and the heat of superheat. It is denoted by symbol $H_{sup}$. Hence, enthalpy of one kg of superheated steam,

$$H_{sup} = h + L + k_p(t_{sup} - t_s) = H_s + k_p(t_{sup} - t_s) \text{ kJ/kg} \quad \text{... (3.8)}$$

**3.2.7 Specific Volume of Steam :** The volume of one kilogram of dry saturated steam at all pressures is given in column 3 of the steam tables. The value in cubic metre per kg of dry saturated steam ($m^3$/kg) is known as the *specific volume of dry saturated steam* and its symbol is $v_s$.

Density of dry steam is the mass of one cubic metre of steam (kg/$m^3$) and is the reciprocal of specific volume and, therefore, is equivalent to $1/v_s$ kg per cubic metre.

If the steam is *wet*, having a dryness fraction of $x$, one kg of wet steam will consist of $x$ kg of dry (pure) steam and $(1 - x)$ kg of water held in suspension.

Specific volume of wet steam, having a dryness fraction of $x$

= volume of dry steam + volume of water particles

$= xv_s + (1 - x)v_w$

where, $v_s$ and $v_w$ denote the specific volume of steam and water respectively.

As the volume of water at low pressure is very small compared with the steam, the term $(1 - x)v_w$ will become still smaller and can be neglected.

Hence, the specific volume of wet steam, neglecting volume of water particles

$= xv_s$ $m^3$/kg, and density of wet steam $= 1/xv_s$ kg/$m^3$.

For some problems of thermodynamics, it is sufficiently accurate that, at a given pressure, the volume of superheated steam is proportional to its absolute temperature. This assumption is made on the ground that superheated steam behaves like a perfect gas. The approximate specific volume of *superheated steam* may be calculated from the expression,

$$v_{sup} = v_s \times \frac{T_{sup}}{T_s} \quad m^3/\text{kg} \quad \text{... (3.9)}$$

where $T_{sup}$ is the absolute temperature of superheated steam, $T_s$ is the absolute saturation temperature of steam and $v_s$ is the specific volume of dry saturated steam.

## 3.3 Steam Tables

Reference is now made to the steam tables which give the properties of 1 kg of dry saturated steam. The information given in steam tables (given at the end of this book) has been obtained by performing experiments on dry saturated steam at various pressures and temperatures. In the steam tables, the initial temperature of water is taken as 0°C.

Absolute pressures given in column 1 of the steam tables are in bar. Before the steam tables can be used, it is necessary to convert boiler gauge pressure (shown by the steam pressure gauge fitted on the boiler) to absolute pressure. This is obtained by adding atmospheric (barometric) pressure to boiler gauge pressure. See solved problem no.5. The information contained in steam tables is as under :

| | |
|---|---|
| Absolute pressure of steam | .. $p$ bar |
| Saturation temperature of steam (temperature of formation of steam) | .. $t_s$°C |
| Specific volume of dry saturated steam | .. $v_s$ m$^3$/kg |
| Enthalpy of saturated water (reckoned above 0°C) | .. $h$ kJ/kg |
| Enthalpy of evaporation of dry steam | .. $L$ kJ/kg |
| Enthalpy of dry saturated steam (reckoned above 0°C) | .. $H_s$ kJ/kg |
| Entropy of saturated water | .. $\Phi_w$ kJ/kg K |
| Entropy of dry saturated steam | .. $\Phi_s$ kJ/kg K |

It is important to note that the data given in steam tables is for *dry saturated steam only* and therefore, the effect of dryness fraction ($x$) must be taken into account in the manner already explained. The enthalpy of wet steam and superheated steam can be calculated by using eqns. (3.6) and (3.8).

*The properties of 1 kg of dry saturated steam at various absolute pressures are given in steam tables, at the end of this book.*

Note : In this text, the pressures stated in bar, kPa and MPa will indicate absolute pressures. Gauge pressure will be indicated as gauge pressure or pressure gauge reading.

**Problem-1** : *Determine the dryness fraction of steam if 0·8 of water is in suspension with 45 kg of dry steam.*

Mass of wet steam

$$= \left\{\begin{matrix}\text{mass of dry steam in} \\ \text{certain mass of wet steam}\end{matrix}\right\} + \left\{\begin{matrix}\text{mass of water in suspension} \\ \text{in the same mass of wet steam}\end{matrix}\right\}$$

$= 45 + 0{\cdot}8 = 45{\cdot}8$ kg.

Thus, in 45·8 kg of wet steam, the dry steam is 45 kg.

The dryness fraction of wet steam is the ratio of the mass of actual dry steam to the mass of wet steam containing it.

$\therefore$ Dryness fraction, $x = 45/45{\cdot}8 = \mathbf{0{\cdot}982}$

i.e. Steam is **98·2 per cent dry or 1·8** per cent wet.

**Problem-2** : *How much heat is needed to convert 1 kg of feed water at 20°C into dry saturated steam at 10 bar (1 MPa) ? Take specific heat of water as 4·187 kJ/kg K.*

From steam tables, at 10 bar, enthalpy of saturated water, $h$ = 762·81 kJ/kg and enthalpy of evaporation, $L$ = 2,015·3 kJ/kg.

Enthalpy of dry saturated steam at 10 bar (above 0°C), $H_s = h + L$

$= 762{\cdot}81 + 2{,}015{\cdot}3 = 2{,}778{\cdot}11$ kJ/kg.

Enthalpy of 1 kg of feed water at 20°C above 0°C $= k(t_1 - 0)$

$= 4{\cdot}187\ (20 - 0) = 83{\cdot}74$ kJ/kg.

$\therefore$ Heat supplied to convert 1 kg of feed water at 20°C into dry saturated steam at 10 bar = enthalpy of dry saturated steam − enthalpy of feed water

$= 2{,}778{\cdot}11 - 83{\cdot}74 = \mathbf{2{,}694{\cdot}37}$ **kJ/kg.**

**Problem-3** : *How much heat is needed to convert 5 kg of water at 40°C into 90 per cent dry (or 10 per cent wet) steam at 5 bar (500 kPa) ? Take specific heat of water as 4·187 kJ/kg K.*

From steam tables, at 5 bar, $h$ = 640·23 kJ/kg and $L$ = 2,108·5 kJ/kg.

Enthalpy of 1 kg of wet steam at 5 bar and 0·9 dry above 0°C,

$$H_{wet} = h + xL = 640{\cdot}23 + 0{\cdot}9 \times 2{,}108{\cdot}5 = 2{,}537{\cdot}88 \text{ kJ/kg.}$$

Enthalpy of 1 kg of feed water at 40°C above 0°C

$$= k(t_1 - 0) = 4{\cdot}187\ (40 - 0) = 167{\cdot}48 \text{ kJ/kg.}$$

∴ Heat needed to convert 1 kg of feed water at 40°C into wet steam at 5 bar and 0·9 dry = Enthalpy of wet steam – Enthalpy of feed water

$$= 2{,}537{\cdot}88 - 167{\cdot}48 = 2{,}370{\cdot}4 \text{ kJ/kg.}$$

∴ Heat supplied to convert 5 kg of water at 40°C into steam at 5 bar and 0·9 dry

= 5 × 2,370·4 = **11,852 kJ.**

**Problem-4** : *How much heat is needed to convert 4 kg of water at 20°C into steam at 8 bar (800 kPa) and 200°C. Take $k_p$ of superheated steam as 2·1 kJ/kg K and specific heat of water as 4·187 kJ/kg K.*

From steam tables, at 8 bar, $t_s$ = 170·43°C, $h$ = 721·11 kJ/kg and $L$ = 2,048 kJ/kg. Since the temperature (200°C) of given steam is more than saturation temperature, $t_s$ (170·43°C), the steam is superheated.

Degree of Superheat = $t_{sup} - t_s$ = 200 – 170·43 = 29·57°C.

Enthalpy of 1 kg of superheated steam (above 0°C),

$$H_{sup} = h + L + k_p\ (t_{sup} - t_s) = 721{\cdot}11 + 2{,}048 + 2{\cdot}1\ (200 - 170{\cdot}43)$$

$$= 2{,}831{\cdot}21 \text{ kJ/kg}$$

Enthalpy of 1 kg of water above 0°C = $k\ (t_1 - 0)$ = 4·187 (20 – 0) = 83·74 kJ/kg.

Heat needed to convert 1 kg of water at 20°C into superheated steam at 8 bar and 200°C = Enthalpy of superheated steam – Enthalpy of water

= 2,831·21 – 83·74 = 2,747·47 kJ/kg

∴ Heat needed to convert 4 kg of water into steam = 4 × 2,747·47 = **10,990 kJ.**

**Problem-5** : *A boiler is supplied with feed water at a temperature of 44°C and converted into steam at a gauge pressure of 4·493 bar and a temperature of 188°C. If 900 kg of steam is generated by the boiler in one hour, find the quantity of heat supplied per minute to feed water to produce steam assuming barometric pressure of 750 mm of Hg and $k_p$ of superheated steam as 2·1 kJ/kg K.*

Now, 760 mm of Hg = 1·01325 bar.

$$\therefore \text{ 750 mm of Hg} = \frac{1{\cdot}01325 \times 750}{760} = 1{\cdot}007 \text{ bar (barometric pressure)}$$

Absolute pressure of steam = Boiler gauge pressure + Barometric pressure

$$= 4{\cdot}493 + 1{\cdot}007 = 5{\cdot}5 \text{ bar.}$$

Referring to steam tables, at 5·5 bar $h$ = 655·93 kJ/kg, $L$ = 2,097 kJ/kg and $t_s$ = 155·48°C. Since the temperature of given steam (188°C) is more than the saturation temperature (155·48°C), the steam produced is superheated.

Enthalpy of 1 kg of feed water at 44°C above 0°C = $k\ (t_1 - 0)$

$$= 4{\cdot}187\ (44 - 0) = 184{\cdot}23 \text{ kJ/kg.}$$

$\therefore$ Enthalpy of (saturated) water $= h - k(t_1 - 0) = 655{\cdot}93 - 184{\cdot}23 = 471{\cdot}7$ kJ/kg.

Heat supplied/kg $= [h - k\ (t_1 - 0) + L + k_p(t_{sup} - t_s)]$

$= 471{\cdot}7 + 2{,}097 + 2{\cdot}1\ (188 - 155{\cdot}48) = 2{,}636{\cdot}99$ kJ/kg

$\therefore$ Heat supplied per min. $= \dfrac{900}{60} \times 2{,}636{\cdot}99 = 39{,}554{\cdot}85$ **kJ/min.**

**Problem-6 :** *Find the volume of one kilogram of steam at a pressure of 15 bar (1·5 MPa) in each of the following cases :*

*(i) when steam is dry saturated,*

*(ii) when steam is wet having dryness fraction of 0·9, and*

*(iii) when steam is superheated, the degree of superheat being 40°C.*

At 15 bar, $v_s = 0{\cdot}13177$ m³/kg and $t_s = 198{\cdot}32$°C (from steam tables).

*(i) When steam is dry saturated :*

Specific volume ($v_s$) of dry saturated steam at 15 bar is **0·13177 m³/kg.**

*(ii) When steam is wet, dryness fraction 0·9 :*

Specific volume of wet steam of dryness fraction $x$, neglecting the volume of water $= xv_s$ m³/kg.

$\therefore$ Volume of wet steam at a pressure of 15 bar and 0·9 dry $= xv_s$

$= 0{\cdot}9 \times 0{\cdot}13177 =$ **0·1186 m³/kg**

*(iii) When steam is superheated by 40°C :*

Absolute temperature of saturated steam, $T_s = 198{\cdot}32 + 273 = 471{\cdot}32$ K

Absolute temperature of superheated steam, $T_{sup} = 198{\cdot}32 + 40 + 273 = 511{\cdot}32$ K

The specific volume of superheated steam is given by eqn. (3·9),

$$v_{sup} = v_s \times \frac{T_{sup}}{T_s} = 0{\cdot}13177 \times \frac{511{\cdot}32}{471{\cdot}32} = 0{\cdot}1426 \text{ m}^3\text{/kg.}$$

**Problem-7 :** *A closed vessel contains 1·2 m³ of dry saturated steam at 14 bar (1·4 MPa). What is the temperature and mass of this steam ?*

From steam tables, saturation temperature corresponding to 14 bar = **195·7°C.**

Specific volume ($v_s$) at 14 bar = 0·14084 m³/kg (from steam tables).

$$\therefore \text{ Mass of steam} = \frac{\text{Volume of steam}}{\text{Specific volume of steam } (v_s)} = \frac{1{\cdot}2}{0{\cdot}14084} = \mathbf{8{\cdot}52 \text{ kg.}}$$

**Problem-8 :** *Determine the condition of steam in each of the following cases :*

*(i) at a pressure of 10 bar and temperature 200°C,*

*(ii) at a pressure of 8 bar and volume 0·22 m³/kg, and*

*(iii) at a pressure of 12 bar, if 2,688 kJ/kg are required to produce it from water at 0°C.*

(i) Saturation temperature ($t_s$) corresponding to pressure of 10 bar from steam tables is 179·91°C. Since the temperature of given steam is 200°C, the steam is superheated. Its degree of superheat, $t_{sup} - t_s = 200 - 179{\cdot}91 =$ **20·09°C.**

(ii) Specific volume of dry saturated steam ($v_s$) at 8 bar is 0·2404 $m^3/kg$. Since the volume of given steam (0·22 $m^3$) is less than the specific volume of dry saturated steam, it is obvious that the steam with a volume of 0·22 $m^3/kg$ is wet.

$\therefore$ Dryness fraction, $x = 0{\cdot}22/0{\cdot}2404 = 0{\cdot}915$ i.e. **91·5% dry.**

(iii) Enthalpy of dry saturated steam ($H$) at 12 bar from steam tables is 2,784·8 kJ/kg. Since the enthalpy of given steam(2,688 kJ/kg) is less than the enthalpy of dry saturated steam, we conclude that the given **steam is wet.**

At 12 bar, $h = 798{\cdot}65$ kJ/kg, $L = 1{,}986{\cdot}2$ kJ/kg (from steam tables).

Using eqn. (3·6) for determining quality of steam, $H_{wet} = h + xL$

i.e. $2{,}688 = 798{\cdot}65 + x\ 1{,}986{\cdot}2$

$\therefore$ Dryness fraction of steam, $x = \dfrac{2{,}688 - 798{\cdot}65}{1{,}986{\cdot}2} = 0{\cdot}9513$ i.e. **95·13% dry**

**Problem-9** : *A boiler is supplying steam at a pressure of 9 bar and 90 percent dry. Find : (i) the mass of 5 $m^3$ of this steam, and (ii) the enthalpy per $m^3$ of this steam above 0°C.*

(i) From steam tables, at 9 bar,

$h = 742{\cdot}83$ kJ/kg, $L = 2{,}031{\cdot}1$ kJ/kg, and $v_s = 0{\cdot}215$ $m^3/kg$.

Mass of one $m^3$ of wet steam $= \dfrac{1}{xv_s} = \dfrac{1}{0{\cdot}9 \times 0{\cdot}215} = 5{\cdot}168$ kg

$\therefore$ Mass of 5 $m^3$ of wet steam $= 5 \times 5{\cdot}168 =$ **25·84 kg**

(ii) Enthalpy of 1 kg of wet steam at a pressure of 9 bar and dryness fraction 0·9,

$H_{wet} = h + xL = 742{\cdot}83 + 0{\cdot}9 \times 2{,}031{\cdot}1 = 2{,}570{\cdot}83$ kJ/kg

$\therefore$ Enthalpy of one $m^3$ of wet steam = mass of steam $\times$ $(h + xL)$

$= 5{\cdot}168 \times 2{,}570{\cdot}83 =$ **13,286 kJ.**

**Problem-10** : *Determine from steam tables the following :*

*(i) Enthalpy and volume of 1 kg of steam at 12·1 bar and dryness fraction 0·9, and*

*(ii) Enthalpy and volume of 1 kg of steam at 12·1 bar and 225°C.*

*Take the specific heat at constant pressure for superheated steam as 2·1 kJ/kg K.*

By using steam tables and *interpolating* to find the values for a pressure of 12·1 bar, a table is constructed as shown below :

| $p$ bar | $t_s$ °C | $h$ kJ/kg | $L$ kJ/kg | $H$ kJ/kg | $v_s$ $m^3/kg$ | |
|---|---|---|---|---|---|---|
| 12·0 | 187·99 | 798·65 | 1986·2 | 2784·8 | 0·16333 | from steam tables |
| 12·2 | 188·74 | 801·98 | 1983·4 | 2785·4 | 0·16077 | from steam tables |
| 0·2 | 0·75 | 3·33 | 2·8 | 0·6 | 0·00256 | for 0·2 bar |
| 0·1 | 0·38 | 1·67 | 1·4 | 0·3 | 0·00128 | for 0·1 bar |
| 12·1 | 188·37 | 800·32 | 1984·8 | 2785·1 | 0·16205 | by interpolating |

(i) Enthalpy of 1 kg of steam at 12·1 bar and 0·9 dry,

$H_{wet} = h + xL = 800{\cdot}32 + 0{\cdot}9 \times 1{,}984{\cdot}8 =$ **2,463·52 kJ/kg.**

Volume of 1 kg of steam at 12·1 bar and 0·9 dry

$= x \times v_s = 0{\cdot}9 \times 0{\cdot}16205 = \mathbf{0{\cdot}14585\ m^3/kg}$

(ii) Enthalpy of 1 kg of steam at 12·1 bar and 225°C,

$$H_{sup} = H + k_p(t_{sup} - t_s) = 2{,}785{\cdot}1 + 2{\cdot}1(225 - 188{\cdot}37) = \mathbf{2{,}862{\cdot}02\ kJ/kg}$$

Using eqn. (3·9), volume of 1 kg of superheated steam at 12·1 bar and 225°C,

$$v_{sup} = v_s \times \frac{T_{sup}}{T_s} = 0{\cdot}16205 \times \frac{498}{461{\cdot}37} = \mathbf{0{\cdot}1751\ m^3/kg.}$$

**Problem-11** : *One kg of steam initially at 8 bar (800 kPa) and 0·7 dry, receives 410 kJ heat at constant pressure. Determine the enthalpy, condition, and density of steam at the end of constant pressure heat supply.*

From steam tables, at 8 bar, $h$ = 721·11 kJ/kg, $L$ = 2,048 kJ/kg, $v_s$ = 0·2404 m$^3$/kg.

Enthalpy initially, $H_1 = h_1 + x_1L_1$ = 721·11 + 0·7 × 2,048 = 2,154·71 kJ/kg

Enthalpy at the end of constant pressure process, $H_2$ = 2,154·71 + 410 = **2,564·71 kJ/kg**

Let the final condition of steam be $x_2$. Then, $H_2 = h_2 + x_2L_2$

From which, $x_2 = \dfrac{H_2 - h_2}{L_2} = \dfrac{2{,}564{\cdot}71 - 721{\cdot}11}{2{,}048} = \mathbf{0{\cdot}9\ dry}$ (final condition of steam)

Density of steam $= \dfrac{1}{x_2v_s} = \dfrac{1}{0{\cdot}9 \times 0{\cdot}2404} = \mathbf{4{\cdot}62\ kg/m^3}$.

**Problem-12** : *Two boilers A and B, are delivering steam in equal proportion to a common mains steam pipe, both at a pressure of 14 bar. Boiler A has a superheater and boiler B is without a superheater. The temperature of steam supplied by the boiler A is 300°C. The temperature of the resulting mixture of steam in the steam mains is 235°C. Assuming $k_p$ for the superheated steam as 2·1 kJ/kg K, estimate the quality of steam supplied by the boiler without the superheater, i.e., boiler B.*

From steam tables, at 14 bar, $L$ = 1,959·7 kJ/kg and $t_s$ = 195·07°C.

The wet steam from boiler *B* gains heat from the superheated steam produced by boiler *A*. As a result of which it (wet steam) becomes superheated. During the process of its mixing with superheated steam, first its moisture content is evaporated and then it is superheated. Let the dryness fraction of wet steam generated by boiler *B* be *x*.

Then, moisture in 1 kg of wet steam = $(1 - x)$ kg. Heat required to evaporate this moisture and to make it dry = $(1 - x)L$ kJ/kg.

Heat required to superheat this dry steam = $k_p(t_{sup2} - t_s)$ kJ/kg.

∴ Heat gained by the wet steam of boiler $B = (1 - x)L + k_p(t_{sup2} - t_s)$ kJ/kg.

Heat lost by the superheated steam of boiler $A = k_p(t_{sup1} - t_{sup2})$

Heat gained by wet steam of boiler *B* = Heat lost by superheated steam of boiler *A*

i.e. $(1 - x)\ L + k_p(t_{sup2} - t_s) = k_p(t_{sup1} - t_{sup2})$

i.e. $(1 - x)\ 1{,}959{\cdot}7 + 2{\cdot}1(235 - 195{\cdot}07) = 2{\cdot}1(300 - 235)$

$\therefore x = \dfrac{1{,}907{\cdot}05}{1{,}959{\cdot}7} = 0{\cdot}9732$ i.e. **97·32 % dry** (quality of steam supplied by boiler *B*)

**Problem-13** : *A boiler generates 1,400 kg of steam per hour at a pressure of 18 bar (1·8 MPa) and 0·95 dry. The steam after leaving the boiler stop valve, passes through a superheater where its temperature is raised to 305°C. If the feed water supplied to the* *boiler is at 40°C, calculate : (a) the heat supplied to feed water per hour to produce wet steam, and (b) the percentage of the heat absorbed in the boiler and in the superheater. Take $k_p$ of superheated steam as 2·3 kJ/kg K and specific heat of water as 4·187 kJ/kg K.*

From steam tables, at 18 bar, $H$ = 884·79 kJ/kg, $L$ = 1,912·4 kJ/kg and $t_s$ = 207·15°C.

(a) Heat supplied to feed water to produce wet steam in the boiler per hour

$= W_s\ [h - k(t_1 - 0) + xL]$

$= 1{,}400\ [884{\cdot}97 - (4{\cdot}187 \times 40) + 0{\cdot}95 \times 1{,}912{\cdot}4]$ = **35,47,700 kJ/hr.**

(b) The heat absorbed by superheater is utilized to remove the moisture content of wet steam and then to superheat the dry saturated steam from 207·15°C to 305°C.

Heat absorbed by the superheater per hour $= W_s\ [(1 - x)L + k_p(t_{sup} - t_s)]$

$= 1{,}400\ [(1 - 0{\cdot}95)\ 1{,}912{\cdot}4 + 2{\cdot}3\ (305 - 207{\cdot}15)]$ = **4,48,950 kJ/hg.**

Total heat absorbed per hour = 35,47,700 + 4,48,950 = 39,96,650 kJ/kg

Percentage of heat absorbed in boiler $= \dfrac{35{,}47{,}700}{39{,}96{,}650} \times 100$ = **88·76 %**

Percentage of heat absorbed in superheater $= \dfrac{4{,}48{,}950}{39{,}96{,}650} \times 100$ = **11·24 %**

**Problem-14 :** *Wet steam of mass 2·5 kg and occupying a volume of 0·49 m³ at 7·5 bar has a total heat (enthalpy) increase of 1,500 kJ when superheated at constant pressure. Determine :*

*(i) Initial quality of steam,*

*(ii) Final quality (degree of superheat) of steam, and*

*(iii) Increase in volume of steam after superheating.*

*Assume $k_p$ for the superheated steam to be 2·1 kJ/kg K.*

(i) From steam tables, at 7·5 bar,

$h$ = 709·47 kJ/kg, $t_s$ = 167·78°C, $L$ = 2,057 kJ/kg, $v_s$ = 0·2556 m³/kg.

Total volume of 2·5 kg of dry saturated steam = 2·5 × 0·2556 = 0·639 m³

As the volume of 2·5 kg of steam in data is given as 0·49 m³ at 7·5 bar (which is less than 0·639 m³), the steam is wet.

∴ Initial dryness fraction (quality) of steam = 0·49/0·639 = 0·767 i.e. **76·7 % dry.**

(ii) 1,500 kJ of heat supplied (added) at constant pressure is utilized in evaporating the moisture content of wet steam and then superheating it. Let $t_{sup}$ be the temperature of superheated steam. Then,

$W_s\ [(1 - x)L + k_p(t_{sup} - t_s)]$ = Heat supplied to superheat 2·5 kg of wet steam

i.e. $2{\cdot}5\ [(1 - 0{\cdot}767)\ 2{,}057 + 2{\cdot}1\ (t_{sup} - 167{\cdot}78)] = 1{,}500$

Solving the equation, $t_{sup}$ = 225·2°C.

∴ Degree of superheat $= t_{sup} - t_s$ = 225·2 − 167·78 = 57·42°C i.e. steam is superheated by **57·42°C.**

(iii) Now, $T_s$ = 167·78 + 273 = 440·78 K; and $T_{sup}$ = 225·2 + 273 = 498·2 K

Let $v_{sup}$ = Specific volume of superheated steam,

(specific volume of superheated steam is proportional to its absolute temperature)

Then, volume of superheated steam is given by eqn. (3·9),

$$\therefore \ v_{sup} = v_s \times \frac{T_{sup}}{T_s} = 0{\cdot}2556 \times \frac{498{\cdot}2}{440{\cdot}78} = 0{\cdot}2891 \ \text{m}^3/\text{kg}$$

$\therefore$ Total volume of 2·5 kg of superheated steam = 2·5 ×0·2891

= 0·7228 m$^3$ (final volume)

$\therefore$ Increase in volume of steam after superheating = 0·7228 − 0·49 = **0·2328 m$^3$**.

**Problem-15 :** *Steam enters a steam engine at a pressure of 12 bar with 67°C of superheat and is exhausted at 0·15 bar and 0·94 dry. Calculate the drop in enthalpy from admission to exhaust, and volume of 1 kg of steam at admission and exhaust conditions. Take $k_p$ of superheated steam as 2·1 kJ/kg K.*

From steam tables, at 12 bar,

$h$ = 798·65 kJ/kg, $L$ = 1,986·2 kJ/kg, $t_s$ = 187·99°C and $v_s$ = 0·16333 m$^3$/kg.

From steam tables, at 0·15 bar,

$h$ = 225·94 kJ/kg, $L$ = 2,373·1 kJ/kg and $v_s$ = 10·022 m$^3$/kg.

Enthalpy of superheated steam at 12 bar (*at admission*),

$H_{sup} = h + L + k_p \times$ degree of superheat

= 798·65 + 1,986·2 + 2·1 (67) = 2,925·55 kJ/kg

Enthalpy of wet steam at 0·15 bar (*at exhaust*),

$H_{wet} = h + xL$ = 225·94 + 0·94 × 2,373·1 = 2,456·65 kJ/kg.

Hence, enthalpy difference (or drop) from admission to exhaust (during expansion)

= $H_{sup} - H_{wet}$ = 2,925·55 − 2,456·65 = **468·9 kJ/kg**

At 12 bar, $t_s$ = 187·99°C, and $T_s$ = 187·99 + 273 = 460·99 K,

$t_{sup}$ = 187·99 + 67 = 254·99°C, and

$T_{sup}$ = 254·99 + 273 = 527·99 K.

Since, specific volume of steam is assumed to be proportional to its absolute temperature for approximate calculations. Using eqn. (3·9),

$$v_{sup} = v_s \times \frac{T_{sup}}{T_s} = 0{\cdot}16333 \times \frac{527{\cdot}99}{460{\cdot}99} = \mathbf{0{\cdot}1871 \ m^3/kg} \ (\textit{at admission})$$

Volume of wet steam (neglecting the volume of water) at 0·15 bar

= $xv_s$ = 0·94 × 10·022 = **9·421 m$^3$/kg** (*at exhaust*).

**Problem-16 :** *A vessel having a capacity of 1 m$^3$ contains steam at 10 bar and 0·92 dry. The steam is blown off from the vessel by opening the valve until the pressure drops to 5 bar. The valve is then closed and the vessel is cooled until the pressure is 4 bar. Assuming that the enthalpy per kg of steam in the vessel remains constant during the blowing off period, determine :*

*(a) the mass of steam blown off, (b) the dryness fraction of the steam in the vessel after cooling, and (c) the heat lost by the steam per kg during cooling.*

From steam tables :

| $p$ bar | $v_s$ $m^3/kg$ | $h$ kJ/kg | $L$ kJ/kg |
|---|---|---|---|
| 10 | 0·19444 | 762·81 | 2,015·3 |
| 5 | 0·3749 | 640·23 | 2,108·5 |
| 4 | 0·4625 | 604·74 | 2,133·8 |

(a) *Before blowing-off,* $p_1 = 10$ bar, $v = 1\ m^3$, $x_1 = 0{\cdot}92$ and $v_{s1} = 0{\cdot}19444\ m^3.kg$.

Initial mass of steam in the vessel *before blowing-off,*

$$m_1 = \frac{1}{x_1 v_{s1}} = \frac{1}{0{\cdot}92 \times 0{\cdot}19444} = 5{\cdot}642 \text{ kg}$$

*After blowing of,* $p_2 = 5$ bar, $v = 1\ m^3$ and $v_{s2} = 0{\cdot}3749\ m^3/kg$.

As given in the data,

Enthalpy before blowing off (at 10 bar) = Enthalpy after blowing off (at 5 bar)

i.e. $h_1 + x_1 L_1 = h_2 + x_2 L_2$

i.e. $762{\cdot}81 + 0{\cdot}92 \times 2{,}015{\cdot}3 = 640{\cdot}23 + x_2 \times 2{,}108{\cdot}5 \quad \therefore\ x_2 = 0{\cdot}9373$

Final mass of steam in the vessel *after blowing-off,*

$$m_2 = \frac{1}{x_2 v_{s2}} = \frac{1}{0{\cdot}9373 \times 0{\cdot}3749} = 2{\cdot}846 \text{ kg}$$

$\therefore$ Mass of steam blown off $= m_1 - m_2 = 5{\cdot}642 - 2{\cdot}846 =$ **2·796 kg.**

(b) *After cooling,* $p_3 = 4$ bar, $v_{s3} = 0{\cdot}4625\ m^3/kg$, and $m_3 = 2{\cdot}846$ kg.

Dryness fraction of steam in the vessel after cooling,

$$x_3 = \frac{1}{v_{s3} \times m_3} = \frac{1}{0{\cdot}4625 \times 2{\cdot}846} = 0{\cdot}76 \text{ or } \mathbf{76\%\ dry}$$

(c) Enthalpy *before* cooling, $H_2 = h_2 + x_2 L_2$

$= 640{\cdot}23 + 0{\cdot}9373 \times 2{,}108{\cdot}5 = 2{,}615{\cdot}23$ kJ/kg

Now, Enthalpy *after* cooling, $H_3 = h_3 + x_3 L_3$

$= 604{\cdot}74 + 0{\cdot}76 \times 2{,}133{\cdot}8 = 2{,}226{\cdot}43$ kJ/kg

Enthalpy difference or heat lost per kg of steam during cooling,

$H_2 - H_3 = 2{,}615{\cdot}23 - 2{,}226{\cdot}43 =$ **388·8 kJ/kg**

**Problem-17 :** *Steam at a pressure of 6 bar (600 kPa) is passed into a tank containing water where it is condensed. Before the steam is introduced in the tank, the mass and temperature of water in the tank is 74 kg and 15°C respectively. The water equivalent of tank is one kg. Calculate the dryness fraction of steam as it enters the tank if 2·5 kg of steam is condensed in the tank and the resulting temperature of the mixture is 35°C. Assume no losses and specific heat of water as 4·187 kJ/kg K.*

From steam tables, at 6 bar, $h = 670{\cdot}56$ kJ/kg, and $L = 2{,}086{\cdot}3$ kJ/kg.

Mass of steam condensed, $M_s = 2{\cdot}5$; total mass of water, $M_w = 1 + 74 = 75$ kg.

Assuming that all heat lost by steam is gained by water

i.e. Heat lost by steam = Heat gained by water i.e. $M_s\ [h + xL - k \times t_2] = M_w \times k \times (t_2 - t_1)$

(where, $t_2$ = temp. of mixture, and $t_1$ = initial temp. of water)

$$\text{i.e. } h + xL - k \times t_2 = \frac{M_w}{M_s} \times k \times (t_2 - t_1)$$

$$\text{i.e. } 670{\cdot}56 + 2{,}086{\cdot}3\ x - 4{\cdot}187 \times 35 = \frac{75}{2{\cdot}5} \times 4{\cdot}187 \times (35 - 15)$$

$\therefore$ $x$ = **0·95 (dryness fraction of steam)**

**Problem-18 :** *Exhaust steam at a pressure of 0·5 bar and 0·8 dry enters a surface condenser. the water resulting from the condensation leaves the condenser at a temperature of 56°C. Assuming that all the heat lost by steam is taken up by the condensing water, find the heat removed from the steam per kg and also the mass of condensing water required per kg of steam, if the temperature rise of condensing water is 28°C. Take specific heat of water as 4·187 kJ/kg K.*

From steam tables, at 0·5 bar, $h$ = 340·49 kJ/kg and $L$ = 2,305·4 kJ/kg.

Enthalpy of exhaust steam per kg as it enters the condenser

= $h + xL$ = 340·49 + 0·8 × 2,305·4 = 2,184·81 kJ/kg

Enthalpy of water formed by condensation of steam per kg

= 4·187×(56 − 0) = 234·47 kJ/kg.

$\therefore$ Heat removed by cooling or condensing water from 1 kg of exhaust steam in condenser or heat lost by 1 kg of exhaust steam = 2,184·81 − 234·47 = **1,950·34 kJ/kg**

Each kg of condensing water removes (from data) 28 × 4·187 = 117·24 kJ

$\therefore$ Mass of condensing water required per kg of exhaust steam,

$$m_w = \frac{1{,}950{\cdot}34}{117{\cdot}24} = \mathbf{16{\cdot}63\ kg}$$

*Alternatively,* assuming that all the heat lost by exhaust steam is gained by condensing water,

Heat lost by 1 kg of exhaust steam = Heat gained by $m_w$ kg of condensing water

i.e. $1\ [(h + xL) - 56 \times 4{\cdot}187] = m_w \times 28 \times 4{\cdot}187$

i.e. $1\ [340{\cdot}49 + (0{\cdot}8 \times 2{,}305{\cdot}4) - 234{\cdot}47] = m_w \times 117{\cdot}24$

$$\therefore\ m_w = \frac{1{,}950{\cdot}34}{117{\cdot}24} = 16{\cdot}63 \text{ kg of water/kg of exhaust steam.}$$

### 3.4 External Work Done during Evaporation

The enthalpy of evaporation (latent heat) absorbed by the steam during evaporation is utilized in two ways :

Firstly, in overcoming internal molecular resistance of water in changing its condition from water to steam and secondly, in overcoming the external resistance of the piston to its increasing volume during evaporation.

The first of these effects of enthalpy of evaporation (latent heat) is called *internal work,* because changes have been brought within the body itself, and the second is called *external work* because work has been done on the bodies external to itself. The first represents the energy stored in the steam and is known as *internal latent heat* and the second represents the energy which has passed out of the steam having been utilized in doing work on the piston and is known as *external work of evaporation.* The value of enthalpy of evaporation (latent heat) = internal latent heat + external latent heat, can be directly obtained from the steam tables. In evaporating water to steam the volume increases from $v_w$ to $v_s$ (fig. 3-1) under a constant pressure $p$; external work is thus done and the energy for performing this work is obtained during the absorption of enthalpy of evaporation. This work is known as external work of evaporation.

External work done per kg of dry saturated steam

$$= \frac{10^5 \times p \times (v_s - v_w)}{10^3} \quad \text{kJ/kg} \qquad \text{...(3.10)}$$

where, $p$ = absolute pressure of steam in bar, $v_s$ = volume of 1 kg of dry saturated steam in $m^3$ at presure $p$, and $v_w$ = volume of 1 kg of water in $m^3$.

It is sufficiently accurate to neglect the term $v_w$ in eqn. (3.10) as at low pressure, the volume of 1 kg of water is very small compared with the volume of the steam it forms.

The eqn. (3.10) may be written as

$$\text{Work of evaporation of dry saturated steam} = \frac{10^5 p v_s}{10^3} \quad \text{kJ/kg} \qquad \text{... (3.11)}$$

If the steam is wet having a dryness fraction of $x$, the final volume of wet steam is $xv$, then

$$\text{External work done per kg of wet steam} = \frac{10^5 p\,(xv_s)}{10^3} \quad \text{kJ/kg} \qquad \text{... (3.12)}$$

$$\text{External work done per kg of superheated steam} = \frac{10^5 p v_{sup}}{10^3} \quad \text{kJ/kg}$$

The above expressions for external work of evaporation give the portion of latent heat which has been transformed into mechanical work or represent the heat energy which has passed out of the steam. The remainder of the heat energy supplied remains as internal energy or energy stored in the steam and is known as *internal latent heat.* It is found by subtracting the external work of evaporation from the full latent heat.

$$\text{i.e. Internal latent heat} = L - \frac{10^5 p v_s}{10^3} \quad \text{kJ/kg (for dry saturated steam)} \qquad \text{... (3.13)}$$

For wet steam having dryness fraction $x$,

$$\text{Internal latent heat} = xL - \frac{10^5 p\,(xv_s)}{10^3} \quad \text{kJ/kg} \qquad \text{...(3.14)}$$

where $p$ = absolute pressure in bar, $v_s$ = volume of 1 kg of dry saturated steam in $m^3$ at pressure $p$, $x$ = dryness fraction of steam, and $L$ = enthalpy of evaporation in kJ/kg.

### 3.5 Internal Engery of steam

The internal energy of steam is the actual heat energy above the freezing point of water stored in the steam, and is the sum of internal latent enthalpy and sensible enthalpy reckoned from 0°C. It has already been shown that the latent enthalpy of steam consists of the internal latent enthalpy plus the external work of evaporation; hence the total enthalpy of steam consists of the sensible enthalpy, plus the internal latent enthalpy and the external work of evaporation. But the external work of evaporation is utilized in doing external work and represents the heat energy which has passed out of the steam. Hence, the internal energy of steam denoted by symbol $u$ consists of two terms only, namely, the internal latent enthalpy and the sensible enthalpy.

Thus, internal energy is found by substracting external work of evaporation from the enthalpy of steam.

If the steam is dry saturated, Enthalpy, $H_s = h + L$ kJ/kg, and

$$\text{Internal energy, } u = H_s - \frac{10^5 p v_s}{10^3} \text{ kJ/kg} \quad \text{... (3.15)}$$

If the steam is wet having dryness fraction $x$, Enthalpy, $H_{wet} = h + xL$ kJ/kg, and

$$\text{Internal energy, } u = H_{wet} - \frac{10^5 p\,(x v_s)}{10^3} \text{ kJ/kg} \quad \text{... (3.16)}$$

If the steam is superheated to temperature $t_{sup}$ and volume $v_{sup}$ m$^3$ per kg,

Enthalpy of superheated steam, $H_{sup} = H_s + k_p\,(t_{sup} - t_s)$ kJ/kg, and

$$\left.\begin{aligned} \text{Internal energy, } u &= H_{sup} - \frac{10^5 p v_{sup}}{10^3} \text{ kJ/kg} \\ &= H_{sup} - \frac{10^5 p \left( v_s \dfrac{t_{sup} + 273}{t_s + 273} \right)}{10^3} \text{ kJ/kg} \end{aligned}\right] \quad \text{... (3.17)}$$

**Problem-19** : *Find the external work done during evaporation, internal latent enthalpy and internal energy per kg of steam at a pressure of 15 bar (1,500 kPa) when the steam is (i) 0·9 dry, and (ii) dry saturated.*

(i) For wet steam (0·9 dry):

From steam tables, at 15 bar,

$h = 844{\cdot}89$ kJ/kg; $L = 1{,}947{\cdot}3$ kJ/kg; $H_s = 2{,}792{\cdot}2$ kJ/kg; $v_s = 0{\cdot}13177$ m$^3$/kg.

Specific volume of wet steam neglecting the volume of water,

$= x v_s = 0{\cdot}9 \times 0{\cdot}13177$ m$^3$/kg

External work done during evaporation per kg of steam

$$= \frac{10^5\,p\,(x\,v_s)}{1{,}000} = \frac{10^5 \times 15(0{\cdot}9 \times 0{\cdot}13177)}{1{,}000} = \mathbf{177{\cdot}89 \text{ kJ/kg.}}$$

Internal latent enthalpy

= enthalpy of evaporation – heat absorbed in doing work of formation of steam

$$= xL - \frac{10^5\,p\,(x\,v_s)}{1{,}000} = (0{\cdot}9 \times 1{,}947{\cdot}3) - 177{\cdot}89 = \mathbf{1{,}574{\cdot}68 \text{ kJ/kg.}}$$

Enthalpy of wet steam, $H_{wet} = h + xL = 844{\cdot}89 + 0{\cdot}9 \times 1{,}947{\cdot}3 = 2{,}597{\cdot}46$ kJ/kg.

Using eqn. (3·16), internal energy, $u$

= Enthalpy of 1 kg of wet steam–External work of evaporation

$$\therefore \; u = H_{wet} - \frac{10^5 p(x\,v_s)}{1{,}000} = 2{,}597{\cdot}46 - 177{\cdot}89 = \mathbf{2{,}419{\cdot}57 \text{ kJ/kg}}$$

(ii) For dry saturated steam :

External work done during evaporation per kg of dry saturated steam

$$= \frac{10^5\, p \times v_s}{1{,}000} = \frac{10^5 \times 15 \times 0{\cdot}13177}{1{,}000} = \mathbf{197{\cdot}66 \text{ kJ/kg}}$$

Internal latent enthalpy $= L - \dfrac{10^5\, p \times v_s}{1{,}000} = 1{,}947{\cdot}3 - 197{\cdot}66 = \mathbf{1{,}749{\cdot}64 \text{ kJ/kg}}$

Internal energy, $u = H_s - \dfrac{10^5\, p \times v_s}{1{,}000} = 2{,}792{\cdot}2 - 197{\cdot}66 = \mathbf{2{,}594{\cdot}54 \text{ kJ/kg}}$.

**Problem-20 :** *0·025 $m^3$ of steam at 3·5 bar and dryness fraction 0·8 is converted into dry saturated steam at 11 bar. By how much are the enthalpy and internal energy changed ?*

From steam tables :

| $p$ bar | $h$ kJ/kg | $L$ kJ/kg | $H$ kJ/kg | $v_s$ $m^3$/kg |
|---|---|---|---|---|
| 3·5 | 584·33 | 2,148·1 | — | 0·5243 |
| 11 | — | — | 2,781·7 | 0·17753 |

Volume of one kg of wet steam (at 3·5 bar and 0·8 dry) $= xv_s$

$= 0{\cdot}8 \times 0{\cdot}5243 = 0{\cdot}41944$ m$^3$/kg,

$\therefore$ Mass of 0·025 m$^3$ of steam (at 3·5 bar and 0·8 dry) = 0·025/0·41944 = 0·0597 kg

Enthalpy of one kg of *wet* steam (at 3·5 bar and 0·8 dry), $H_{wet} = h + xL$

$= 584{\cdot}33 + 0{\cdot}8 \times 2{,}148{\cdot}1 = 2{,}302{\cdot}81$ kJ/kg.

$\therefore$ Enthalpy of 0·0597 kg of *wet* steam (at 3·5 bar and 0·8 dry), $H_{wet}$

$= 0{\cdot}0597 \times 2{,}302{\cdot}81 = 137{\cdot}48$ kJ

Enthalpy of 0·0597 kg of dry saturated steam (at 11 bar), $H_s$

$= 0{\cdot}0597 \times 2{,}781{\cdot}7 = 166{\cdot}07$ kJ

$\therefore$ Change in Enthalpy = 166·07 − 137·48 = **28·59 kJ**

Using eqn. (3·16), initial internal energy of 0·025 m$^3$ of steam at 3·5 bar and 0·8 dry,

$$u_1 = H_{wet} - \frac{10^5\, pv}{10^3} = 137{\cdot}48 - \frac{10^5 \times 3{\cdot}5 \times 0{\cdot}025}{10^3} = 128{\cdot}73 \text{ kJ}$$

Using eqn. (3·15), final internal energy of *dry saturated* steam at 11 bar,

$$u_2 = H_s - \frac{10^5\, pv}{10^3} = 166{\cdot}07 - \frac{10^5 \times 11 \times (0{\cdot}0579 \times 0{\cdot}17753)}{10^3} = 154{\cdot}41 \text{ kJ}$$

$\therefore$ Change in internal energy, $u_2 - u_1 = 154{\cdot}41 - 128{\cdot}73 =$ **25·68 kJ**

**Problem-21 :** *The internal energy of 1 kg of steam at a pressure of 14 bar (1·4 MPa) is 2,420 kJ. Calculate the dryness fraction of this steam. Find the increase in internal energy if this steam is superheated at constant pressure to a temperature of 295°C. Take $k_p$ of superheated steam as 2·3 kJ/kg K.*

From steam tables, at 14 bar,

$h$ = 830·3 kJ/kg, $L$ = 1,959·7 kJ/kg, $v_s$ = 0·14084 $m^3$/kg and $t_s$ = 195·07°C.

Internal energy of 1 kg of *wet* steam,

$$u_1 = H_{wet} - \text{External work done during evaporation}$$

$$= (h + xL) - \frac{10^5\, p(xv_s)}{1{,}000}$$

$$\text{i.e. } 2{,}420 = (830{\cdot}3 + 1{,}959{\cdot}7\, x) - \frac{10^5 \times 14\ (x \times 0{\cdot}14084)}{1{,}000}$$

$$\text{i.e. } 2{,}420 = (830{\cdot}3 + 1{,}959{\cdot}7x) - 197{\cdot}18\, x$$

$$\therefore\ x = \frac{2{,}420 - 830{\cdot}3}{1{,}959{\cdot}7 - 197{\cdot}18} = 0{\cdot}9 \text{ (dryness fraction)}$$

Using eqn. (3·17), Internal engery of 1 kg of superheated steam,

$$u_2 = \{h + L + k_p\,(t_{sup} - t_s\} - \left\{\frac{10^5\, p\left(v_s \times \dfrac{t_{sup} + 273}{t_s + 273}\right)}{1{,}000}\right\}$$

$$= \{830{\cdot}3 + 1{,}959{\cdot}7 + 2{\cdot}3\,(295 - 195{\cdot}07)\} - \left\{\frac{10^5 \times 14 \times \left(0{\cdot}14084 \times \dfrac{295 + 273}{195{\cdot}07 + 273}\right)}{1{,}000}\right\}$$

$$= 3{,}020 - 239{\cdot}2 = 2{,}780{\cdot}8 \text{ kJ/kg}$$

Increase in internal energy, $u_2 - u_1$ = 2,780·8 − 2,420 = **360·8 kJ/kg**

**Problem-22 :** *What fraction of enthalpy of 1 kg of steam at 10 bar and 0·9 dry represents the internal energy ? What is the change in internal energy when the pressure and temperature of this steam is raised to 13 bar and 250°C ? Take $k_p$ of superheated steam as 2·1 kJ/kg K.*

*For wet steam at 10 bar and 0·9 dry :*

From steam tables, at 10 bar,

$h$ = 762·81 kJ/kg, $L$ = 2,015·3 kJ/kg and $v_s$ = 0·19444 $m^3$/kg.

Enthalpy of 1 kg of wet steam (at 10 bar and 0·9 dry), $H_{wet} = h + xL$

$$= 762{\cdot}81 + 0{\cdot}9 \times 2{,}015{\cdot}3 = 2{,}576{\cdot}58 \text{ kJ/kg}$$

$$\text{External work done during evaporation} = \frac{10^5 \times p(xv_s)}{10^3}$$

$$= \frac{10^5 \times 10(0{\cdot}9 \times 0{\cdot}19444)}{10^3} = 175 \text{ kJ/kg}$$

Internal energy, $u_1$ = Enthalpy − External work done during evaporation

$$= 2{,}576{\cdot}58 - 175 = 2{,}401{\cdot}58 \text{ kJ/kg}$$

$$\therefore \text{ Required fraction of enthalpy} = \frac{2{,}401{\cdot}58}{2{,}576{\cdot}58} = 0{\cdot}9324$$

*For superheated steam at 13 bar and 250°C :*

At 13 bar (from steam tables), $v_s$ = 0·15125 $m^3$/kg, $H_s$ = 2,787·6 kJ/kg,

$t_s$ = 191·64°C or $T_s$ = 191·64 + 273 = 464·64 K;

$t_{sup}$ = 250°C, or $T_{sup}$ = 250 + 273 = 523 K.

Enthalpy of 1 kg of superheated steam (at 13 bar and at 250°C),

$$H_{sup} = H_s + k_p\,(t_{sup} - t_s) = 2{,}787{\cdot}6 + 2{\cdot}1\,(250 - 191{\cdot}64) = 2{,}910{\cdot}16 \text{ kJ/kg}$$

Using eqn. (3·9), volume of 1 kg of superheated steam,

$$v_{sup} = v_s \times \frac{T_{sup}}{T_s} = 0{\cdot}15125 \times \frac{523}{464{\cdot}64} = 0{\cdot}1702 \text{ m}^3\text{/kg}$$

External work done during evaporation,

$$= \frac{10^5 \times p \times v_{sup}}{10^3} = \frac{10^5 \times 13 \times 0{\cdot}1702}{10^3} = 221{\cdot}26 \text{ kJ/kg}$$

Internal energy, $u_2$ = Enthalpy – External work done during evaporation

= 2,910·16 – 221·26 = 2,688·9 kJ/kg

∴ Change in internal energy = $u_2 - u_1$ = 2,688·9 – 2,401·58 = **287·32 kJ/kg.**

**Problem-23 :** *A certain quantity of steam in a closed vessel of fixed volume of 0·14 m*$^3$ *exerts a pressure of 10 bar at 250°C. If the vessel is cooled so that the pressure falls to 3·6 bar, determine : (a) the final quality of steam, (b) the final temperature, (c) the change in internal energy, and (d) the heat transferred during the process. Take* $k_p$ *for superheated steam as 2·1 kJ/kg K.*

(a) From steam tables, at 10 bar,

$t_s$ = 179·91°C, $v_s$ = 0·19444 m$^3$/kg, $H_s$ = 2,778·1 kJ/kg

Given steam is superheated with $t_{sup}$ = 250°C, or $T_{sup}$ = 250 + 273 K

Initial enthalpy of superheated steam,

$$H_1 = H_{sup} = H_s + k_p\,(t_{sup} - t_s) = 2{,}778{\cdot}1 + 2{\cdot}1\,(250 - 179{\cdot}91)$$
$$= 2{,}925{\cdot}29 \text{ kJ/kg}$$

$$v_1 = v_{sup} = v_s \times \frac{T_{sup}}{T_s} = 0{\cdot}19444 \times \frac{250 + 273}{179{\cdot}91 + 273} = 0{\cdot}2246 \text{ m}^3\text{/kg}$$

$$m_s = \text{mass of steam} = \frac{\text{Volume of steam}}{\text{Sp. volume of steam}} = \frac{0{\cdot}14}{0{\cdot}2246} = 0{\cdot}6233 \text{ kg.}$$

Initial internal energy, $u_1 = m_s\left(H_1 - \dfrac{10^5\, p_1 v_1}{10^3}\right)$

$$= 0{\cdot}6233\,\left(2{,}925{\cdot}29 - \frac{10^5 \times 10 \times 0{\cdot}2246}{10^3}\right)$$

$$= 0{\cdot}6233\,(2{,}925{\cdot}29 - 224{\cdot}6) = 1{,}683{\cdot}34 \text{ kJ}$$

At 3·6 bar, $t_s$ = 139·87°C, $v_s$ = 0·5106 m$^3$/kg. $h$ = 588·59 kJ/kg, $L$ = 2145·1 kJ/kg.

If steam is dry saturated at 3·6 bar, its volume

= $m_s$ × specific volume of dry saturated steam = 0·6233 × 0·5106 = 0·3183 m$^3$

But the volume of steam is equal to the volume of vessel, i.e. 0·14 m$^3$.

Therefore, steam is wet with dryness fraction, $x_2 = \frac{0.14}{0.3183} = 0.44$

Thus, finally steam is wet having dryness fraction of 0·44.

(b) As steam is wet at 3·6 bar, its temperature is equal to saturation temperature corresponding to this pressure, i.e. 139·87°C (from steam tables).

(c) Enthalpy at final state, $H_2 = h_2 + x_2L_2 = 588.59 + 0.44 \times 2{,}145.1 = 1{,}502.43$ kJ/kg and $v_1 = v_2 = 0.2246$ m³/kg.

Final internal energy, $u_2 = m_s \left(H_2 - \frac{10^5\, p_2 v_2}{10^3}\right)$

$$= 0.6233 \left(1{,}502.43 - \frac{10^5 \times 3.6 \times 0.2246}{10^3}\right) = 885.82 \text{ kJ}$$

Change in internal energy $= u_2 - u_1 = 885.82 - 1{,}683.34 =$ **−797·52 kJ.**

(d) As this is a constant volume process, the work done is zero and hence, heat transferred is equal to change in internal energy, i.e., **−797·52 kJ.**

### 3.6 Summary of Formulae

Following are the important formulae derived in this chapter :

Enthalpy of 1 kg of wet steam, $H_{wet} = h + xL$ kJ

Enthalpy of 1 kg of dry saturated steam, $H_s = h + L$ kJ

Enthalpy of 1 kg of superheated steam, $H_{sup} = H_s + k_p\,(t_{sup} - t_s)$ kJ

Volume of 1 kg of dry saturated steam $= v_s$ m³

Volume of 1 kg of wet steam $= xv_s$ m³

Volume of 1 kg of superheated steam, $v_{sup} = v_s \times \frac{T_{sup}}{T_s}$ m³ eqn. ( 3·9)

External work done per kg of dry saturated steam $= \frac{10^5\, pv_s}{10^3}$ kJ eqn. (3·11)

External work done per kg of wet steam $= \frac{10^5\, p\,(xv_s)}{10^3}$ kJ eqn. (3·12)

External work done per kg of superheated steam $= \frac{10^5\, pv_{sup}}{10^3}$ kJ

Internal latent enthalpy per kg of dry saturated steam $= L - \frac{10^5\, pv_s}{10^3}$ kJ eqn. (3·13)

Internal latent enthalpy per kg of wet steam $= xL - \frac{10^5\, p\,(xv_s)}{10^3}$ kJ eqn. (3·14)

Internal energy of 1 kg of dry saturated steam $= H_s - \frac{10^5\, pv_s}{10^3}$ kJ eqn. (3·15)

Internal energy of 1 kg of wet steam $= H_{wet} - \frac{10^5\, p\,(xv_s)}{10^3}$ kJ eqn. (3·16)

Internal energy of 1 kg of superheated steam $= H_{sup} - \frac{10^5\, pv_{sup}}{10^3}$ kJ eqn. (3·17)

## Tutorial - 3

1. What are phases of a substance ? Explain the importance of vapour as a working medium in thermal engineering.

2. Explain the following terms :

(i) Saturated steam, (ii) Dry saturated steam, (iii) Wet steam, (iv) superheated steam, (v) Dryness fraction of steam, (vi) Specific volume of steam, and (vii) Saturated water.

3. Explain the term dryness fraction of stteam.

Determine the dryness fraction of steam if 0·6 kilogram of water is in suspension with 24 kilograms of dry steam.

[0·976]

4.(a) Explain the following terms as referred to steam :

(i) Enthalpy of water. (ii) Enthalpy of evaporation, (iii) Superheat, (iv) Specific volume, and (v) Enthalpy of dry saturated steam.

(b) Determine from steam tables the enthalpy of one kg of steam above 0°C :

(i) at a pressure of 10 bar and 0·9 dry, and

(ii) at a pressure of 15 bar and with 140°C of superheat.

Take specific heat at constant pressure of superheated steam as 2·1 kJ/kg K.

[(i) 2,576·58 kJ; (ii) 3,086·2 kJ]

5. (a) Differentiate between saturated steam and dry saturated steam.

(b) Estimate the amount of heat needed to convert 5 kg of water at 50°C into steam at a pressure of 9 bar and with 110°C of superheat. Take specific heat at constant pressure for superheated steam as 2·1 kJ/kg K and specific heat of water as 4·187 kJ/kg K.

[13,978 kJ]

6. (a) How much heat is needed to convert one kg of feed water at 20°C into dry saturated steam at a pressure of 9 bar ? Take specific heat of water as 4·187 kJ/kg K.

(b) How much heat is needed to convert 5 kg of water at 45°C into steam at pressure of 4 bar and 80 per cent dry. Take specific heat of water as 4·187 kJ/kg K.

[(a) 2,690·19 kJ; (b) 10,616·8 kJ]

7. What information can be found in steam tables ? What is the effect of increase in pressure on saturation temperature, enthalpy of saturated water, enthalpy of evaporation and enthalpy of dry saturated steam.

8. (a) What is meant by critical point ? What are critical parameters of $H_2O$ ?

(b) Find the heat required to produce 0·9 kg of steam at 7 bar and 240°C from water at 28°C. Take $k_p$ of superheated steam as 2·26 kJ/kg K and specific heat of water as 4·187 kJ/kg K.

[(b) 2,534·27 kJ]

9. Temperature of feed water entering a boiler is 50°C and the pressure of steam in the boiler is 13 bar. How much heat will be required to produce one kilogram of steam if the steam produced is (a) 0·97 dry, (b) dry saturated, and (c) superheated with 40°C of superheat ? Take the specific heat at constant pressure for superheated steam as 2·1 kJ/kgK and specific heat of water as 4·187 kJ/kg K.

[(a) 2,519·1 kJ; (b) 2,578·28 kJ; (c) 2,662·25 kJ]

10. Distinguish clearly between the various qualities of steam.

Find the heat required to convert one kilogram of steam at 8 bar and 80 per cent dry into steam at 8 bar and 200°C. Assume $k_p$ for superheated steam as 2·1 kJ/kg K.

[471·74 kJ]

11. A boiler is supplied with feed water at 65°C and produces steam at 17 bar and 260°C. If 75% of the heat of the coal of calorific value of 29,300 kJ/kg is utilised in producing steam, calculate the mass of coal consumed in producing 5,000 kg of steam per hour. Take specific heat at constant pressure for superheated steam as 2·1 kJ/kg K.

[600·8 kg]

12. find the volume of one kilogram of steam at a pressure of 10 bar in each of the following cases : (i) when the steam is dry saturated, (ii) when the steam is wet, having a dryness fraction of 0·8 (neglecting the volume of water), and (iii) when the steam is superheated and temperature of steam is 240°C. Take specific heat at constant pressure for superheated steam as 2·1 kJ/kg K.

[(i) 0·19444 $m^3$/kg; (ii) 0·15555 $m^3$/kg; (iii) 0·2202 $m^3$/kg]

13. Calculate the specific volume of superheated steam at 11 bar and 250°C, treating the superheated steam as a perfect gas. Take $k_p$ for superheated steam = 2·1 kJ/kg K.

[0·2031 $m^3$/kg]

14. Find the volume of one kg of steam at a pressure of 9·8 bar (980 kPa) in each of the following cases :

(i) when the steam is dry saturated,

(ii) when the steam is wet, having a dryness fraction of 0·8, and

(iii) when the steam is superheated and the temperature of steam is 240°C.

Take specific heat at constant pressure of superheated steam as 2·1 kJ/kg K.

[(i) 0·1982 $m^3$/kg; (ii) 0·15856 $m^3$/kg; (iii) 0·22496 $m^3$/kg]

15. Use the steam tables to find the following :

(a) Enthalpy and volume per kg of steam of dryness fraction 0·85 at a pressure of 8·5 bar.

(b) Enthalpy and volume per kg of steam at 16 bar and at 230°C. Take specific heat at constant pressure for superheated steam as 2·1 kJ/kg K.

(c) Dryness fraction of steam at 4·5 bar having enthalpy of 2,580 kJ/kg.

(d) Density of 1 kg of steam at 7 bar, having a dryness fraction of 0·9.

(e) Enthalpy of one cubic metre of steam at 9 bar and 0·9 dry.

[(a) 2,465·71 kJ/kg, 0·193 $m^3$/kg; (b) 2,854 kJ/kg, 0·1312 $m^3$/kg; (c) 0·923; (d) 4·071 kg/$m^3$; (e) 13,280 kJ]

16. Determine the condition of steam in each of the following cases :

(a) at a pressure of 10 bar, if 2,640 kJ/kg are required to produce it from water at 0°C.

(b) at a pressure of 8 bar and temperature 200°C, and

(c) at a pressure of 12 bar and volume 0·144 $m^3$/kg.

[(a) wet, dryness fraction 0·9313; (b) superheated by 29·57°C; (c) wet, dryness fraction 0·8816]

17. (a) What is meant by saturation temperature ? Differentiate between saturated water and dry saturated steam.

(b) Determine the condition of steam in each of the following cases :

(i) At a pressure of 10 bar (1 MPa) and temperature 200°C,

(ii) At a pressure of 8 bar and volume 0·22 $m^3$/kg, and

(iii) At a pressure of 12 bar, if 2,688 kJ/kg are required to produce it from water at 0°C.

[(i) steam is superheated by 20·09°C; (ii) wet, 91·5% dry; (iii) wet, 95·15% dry]

18. Use the steam tables and find the following :

(i) Dryness fraction of steam at a pressure of 5 bar (500 kPa) having enthalpy of 2,500 kJ/kg.

(ii) Density of 1 kg of steam at a pressure of 6 bar, having a dryness fraction of 0·8.

(iii) Enthalpy and volume per kg of steam at a temperature of 250°C and at a pressure of 15 bar. Take $k_p$ of superheated steam as 2·1 kJ/kg K.

(iv) Enthalpy and volume per kg of steam at a pressure of 9 bar and 0·9 dry.

[(i) 0·882 dry; (ii) 3·96 kg/$m^3$; (iii) 2,900·72 kJ/kg, 0·14626 $m^3$/kg; (iv) 2,573·81 kJ/kg, 0·1935 $m^3$/kg]

19. (a) A closed vessel contains 0·9 $m^3$ of dry saturated steam at a pressure of 7·5 bar. How many kg of steam does the vessel contain ?

(b) A closed vessel contains 1·5 $m^3$ of dry saturated steam at 12 bar. What is the temperature and mass of this steam ?

[(a) 3·521 kg; (b) 187·99°C, 9·184 kg]

20. (a) A boiler supplies steam at a pressure of 11 bar and 0·8 dry. Find the mass of 0·5$m^3$ of this steam and its enthalpy per cubic metre above 0°C.

(b) A closed drum of 0·15 $m^3$ capacity contains 1·25 kg of wet steam at a pressure of 10 bar. Find the quality of steam.

[(a) 3·52 kg, 16,770 kJ; (b) 0·617 dry]

21. Two boilers discharge equal amount of steam into the main steam pipe. The steam from one is at a pressure of 14 bar and temperature of 290°C and from the other at the same pressure and 92% dry. What is the resulting condition of the steam after mixing ? Take $k_p$ of superheated steam as 2·1 kJ/kg K.

[superheated by 10·13°C]

22. A tank containing 180 kg of water of 16°C is to be heated to 66°C by blowing dry saturated steam at 2 bar into the tank. Find the mass of steam that should enter the tank to heat the water to the required temperature. Assume no losses. Take specific heat of water as 4·187 kJ/kg K.

[13·92 kg]

23. Dry saturated steam enters a surface condenser at a pressure of 1·1 bar and the condensate leaves at 85°C. The cooling water enters at 15°C and leaves at 60°C. Find the amount of cooling water required to cndense 1 kg of steam. Assume that all the heat lost by steam is taken up by the cooling water. Take specific heat of water as 4·187 kJ/kg K.

[12·31 kg]

24. Exhaust steam at a pressure of 0·5 bar (50 kPa) and 0·8 dry enters a surface condenser. The water resulting from the condensation leaves the condenser at a temperature of 56°C. Assuming that all heat lost by steam is taken up by condensing water, find the mass of condensing water required per kg of steam, if the temperature rise of condensing water is 28°C. Take specific heat of water as 4·187 kJ/kg K.

[16·63 kg]

25. Steam is exhausted from a steam engine into a condenser at the rate of 5 kg/min. The pressure inside the condenser is 0·15 bar. The steam from the condenser leaves as water at 40°C. Cooling water is circulated through the condenser tubes at the rate of 115 kg/min. with a rise in temperature from inlet to outlet of 20°C. Calculate the dryness fraction of the steam entering the condenser. Take specific heat of water as 4·187 kJ/kg K.

[0·7954 dry]

26. (a) Explain the following terms as applied to steam :

(i) Internal latent heat, (ii) External work of evaporation, and (iii) Internal energy.

(b) Find the external work of evaporation, internal latent heat and internal energy of one kg of steam at a pressure of 12 bar (1·2 MPa) :

(i) when the steam is dry saturated, and (ii) when the steam is 0·8 dry.

[(i) 196 kJ/ig, 1,790·2 kJ/kg, 2,588 kJ/kg; (ii) 156·8 kJ/kg, 1,432·16 kJ/kg, 2,230·81 kJ/kg]

27. Calculate the internal energy of 1 kg of steam at a pressure of 8 bar (800 kPa) : (a) when the steam is dry saturated, (b) when the steam is 0·8 dry, and (c) when the steam is superheated and temperature of steam is 270°C. Take specific heat of superheated steam at constant pressure as 2·2 kJ/kg K.

[(a) 2,576·79 kJ/kg; (b) 2,205·65 kJ/kg; (c) 2,752·56 kJ/kg]

28. Distinguish clearly between enthalpy and internal energy of steam.

1 kg of steam at 10 bar occupies a volume of 0·18 $m^3$. Determine the condition of steam, and the enthalpy and internal energy of steam.

[0·9258 dry; 2,627·81 kJ; 2,447·81 kJ]

29. Use the steam tables to calculate the following :

(a) The internal energy of 1 kg of steam of dryness fraction 0·85, at a pressure of 6 bar.

(b) The internal energy of 1 kg of steam at 10 bar and temperature 200°C. Take $k_p$ of superheated steam as 2·1 kJ/kg K.

(c) Internal energy of 0·125 $m^3$ of steam at 12 bar and dryness fraction 0·75.

[(a) 2,282·94 kJ; (b) 2,617·09 kJ; (c) 2,184·13 kJ]

30. The internal energy of 1 kg of steam at 10 bar is 2,400 kJ. Calculate the dryness fraction of this steam. Also find the increase in internal energy when the above steam is superheated at constant pressure to a temperature of 250°C. Take $k_p$ of superheated steam as 2·1 kJ/kg K.

[0·899 dry, 300·92 kJ/kg]

31. (a) Find the external work of evaporation and internal energy of 1 kg of steam at a temperature of 200°C and at a pressure of 10 bar (1 MPa). Take $k_p$ of superheated steam as 2·1 kJ/kg K.

(b) What fraction of enthalpy of 1 kg of steam at a temperature of 200°C and at a pressure of 10 bar represents the internal energy ?

[(a) 203 kJ/kg, 2,617·3 kJ/kg; (b) 0·929]

32. A certain quantity of steam in a closed vessel of fixed volume of 0·3 $m^3$ exerts a pressure of 15 bar at 280°C. If the vessel is cooled so that the pressure falls to 10 bar, determine : (a) the final temperature , (b) the final quality of steam, (c) the change in internal energy, and (d) the heat transferred during the process. Take $k_p$ for superheated steam = 2·1 kJ/kg K.

[(a) 179·91°C; (b) 0·7953 dry; (c) − 1,010 kJ; (d) − 1,010 kJ]