Thermodynamics of Steam

Learning Outcome

When you complete this module you will be able to:

Describe the principles of the thermodynamics of steam and the associated terms.

Learning Objectives

Here is what you will be able to do when you complete each objective:

1. Describe the terminology used for the thermodynamic properties of steam.
2. Find and use data in the first 10 columns of the steam tables to calculate the heat required to generate steam.
3. Calculate boiler efficiency, using steam table data.

CHANGE OF STATE

When heat is applied to a body or substance, then the internal energy of the body or substance will increase and an increase in temperature or a change of state will occur.

Sensible Heat

When heat is supplied or taken away and causes an immediate change in temperature without changing the state, then the heat is known as sensible heat.

Latent Heat

When heat is supplied or taken away and causes a change in state without a change in temperature, then the heat is known as latent heat.

1. Latent Heat of Fusion

The latent heat of fusion is the heat required to change a unit mass of solid to a unit mass of liquid at the same temperature. For example, at atmospheric conditions the latent heat of fusion of ice is 335 kJ/kg; that is, it requires 335 kJ of heat to change every kg of ice at 0°C, into water at 0°C.

2. Latent Heat of Evaporation

The latent heat of evaporation is the heat required to change a unit mass of liquid to a unit mass of vapour or gas, at the same temperature and pressure. For example, at atmospheric conditions the latent heat of evaporation of water is 2257 kJ/kg, that is, it requires 2257 kJ of heat to change every kg of water at 100°C, into steam at 100°C.

NOTE: Latent heats of fusion and evaporation, are found by experiment. The latent heat of evaporation varies with pressure: it decreases in value as the pressure rises.

Example 1:

How much heat is required to convert 10 kg of ice at 0°C to steam at 100°C?

Solution:

Heat required to melt ice

= mass in kg x heat of fusion

= 10 kg x 335 kJ/kg

= **3350 kJ**

Heat required to raise temperature of water from 0°C to boiling point

= mass in kg x specific heat x temperature difference

= 10 kg x 4.2 kJ/kg°C x (100°C - 0°C)

= 42 kJ/°C x 100°C

= **4200 kJ**

Heat required to convert water at 100°C into steam at 100°C

= mass in kg x latent heat of evaporation

= 10 kg x 2257 kJ/kg

= **22 570 kJ**

The total heat required to convert the 10 kg of ice to steam

= 3350 + 4200 + 22 570

= **30 120 kJ** (Ans.)

Thus, to convert the ice to water at its boiling point, it took 3350 + 4200 = 7550 kJ or 25% of the total 30 120 kJ of heat supplied. To convert the boiling water to steam, it took 22 570 kJ or 75% of the total 30 120 kJ of heat supplied.

In other words, it takes much less heat to change the ice to water and to raise water to its boiling point, than it does to boil all the hot water into steam. **Steam contains a lot more heat compared to hot boiling water.**

Saturation Temperature

The temperature at which the change from water to steam takes place is called the boiling point or saturation temperature and this temperature will depend on the pressure on the surface of the water.

Absolute Pressure	Boiling Point or Saturation Temperature
101.3 kPa	100°C
200 kPa	120.23°C
300 kPa	133.55°C
400 kPa	143.63°C

Table 1
Saturation Temperatures

It can be seen that calculations concerning steam are complex due to variations in temperature and pressure. All values of the properties of steam have been determined accurately and are listed in steam tables which are available and easy to use.

Similar tables are also available for most liquids and gases such as refrigerants and industrial gases.

Saturated Steam

As mentioned before, the change of state from water to steam takes place at the saturation temperature (or boiling point) corresponding to the pressure acting on the water surface. Water at the saturation temperature corresponding to a particular pressure is called saturated water, it being saturated with sensible heat. The steam produced is called saturated steam. If this steam does not contain any particles of water in suspension, then it is called dry saturated steam. If, however, the steam has particles of water suspended in it, then it is called wet steam.

Thus, saturated steam is just at the temperature of the change of state from liquid to vapour and if any heat is removed from it, it will immediately begin to condense.

Superheated Steam

Saturated steam may be perfectly dry, that is, containing no water particles in suspension as it leaves the boiler. But as it begins to lose heat and fall in temperature, there will be a certain amount of condensation loss in the steam line. To avoid or minimize these losses, the saturated steam can be heated to a higher temperature than that corresponding to its pressure by passing it through rows of tubes placed in the combustion chamber of the boiler before entering the main steam header. These tubes make up a device known as a superheater. This heating of the steam to a higher temperature than its saturation temperature is called superheating, and the steam produced is called superheated steam.

This steam will not condense until the temperature has dropped to the saturation temperature. This means the superheated steam can be transmitted long distances to turbines or equipment without encountering excessive condensation losses.

In buildings using steam for heating, it is almost always saturated steam that is used. Superheated steam is used mainly for steam turbines or very high temperature processes.

Gage and Absolute Pressure

Boiler steam gages and most other pressure gages around a plant show gage pressure (pressure above atmospheric). However, under certain circumstances, steam heating systems and refrigerating systems operate under vacuum (sub-atmospheric pressure) part of the time and above atmospheric pressure at other times. These systems use pressure gages called compound gages that will measure pressures above as well as below atmospheric pressure. They indicate sub-atmospheric pressures in centimetres of mercury vacuum below atmospheric pressure, and above-atmospheric pressures in kilopascals gage pressure above atmospheric pressure.

STEAM TABLES

Certain properties of steam such as the volume per kilogram, the sensible and latent heat per kg, and the saturation temperature corresponding to certain absolute pressures, are known as the thermodynamic properties of steam. These values and many others must be known in order to solve problems involving the use of steam. All these properties of steam have been obtained by careful experiments and the values are tabulated in the steam tables.

Table I of the steam tables lists the properties of steam for various saturation pressures. Number the columns from left to right.

Columns 1, 2, 3, and 4

These columns list various pressures and their corresponding temperatures, plus the specific volumes of saturated liquids and vapours.

Column 1 lists the absolute pressure (p) in kPa.

It should be remembered that the absolute pressure is obtained by the following formula

$$\text{absolute pressure} = \text{gage pressure} + 101.3 \text{ kPa}$$

Column 2 lists the corresponding saturation temperature (t) in °C for each absolute pressure.

The student should observe by examining the values in columns 1 and 2 that the temperature of saturated steam increases as the pressure increases. That is, the boiling point of water increases as the pressure increases.

For example:

p	**t**
100 kPa	99.63°C
500 kPa	151.86°C
1500 kPa	198.32°C

Column 3 lists the specific volume (v_f) in cm^3 per gram of water at each saturation temperature and pressure (that is, the volume occupied by 1 gram of water at that pressure and temperature). Note that the specific volume of saturated water (water at its boiling point) increases with the pressure and temperature.

For example:

p	t	v_f
100 kPa	99.63°C	1.0432 cm^3
500 kPa	151.86°C	1.0926 cm^3
1500 kPa	198.32°C	1.1539 cm^3

Column 4 lists the specific volume (v_g) in cm^3 per gram of saturated steam for each pressure (that is, the volume occupied by 1 gram of steam at that pressure and temperature). Note that the specific volume of the saturated steam decreases with increasing pressure.

For example:

p	t	v_g
100 kPa	99.63°C	1694.0 cm^3
500 kPa	151.86°C	374.9 cm^3
1500 kPa	198.32°C	131.77 cm^3

It is interesting that one gram of saturated water at 100 kPa has a volume of 1.0432 cm^3 and that if this water is converted into saturated steam at the same pressure, the volume becomes 1694 cm^3. That is, the volume increases over **1600 times** when the change of state from water to steam occurs.

Columns 5, 6 and 7

These columns are concerned with internal energy. Internal energy is the sum of all of the energy in the atoms and molecules in a substance due to the fact that they are in constant motion. These three columns are not a direct concern to the student at this point in their studies.

Columns 8, 9 and 10

These columns of the steam tables indicate specific enthalpy. Enthalpy is a measure of internal energy plus the product of volume and pressure of a substance.

Column 8 lists the enthalpy (h_f) in kilojoules per kilogram of the saturated water for each pressure.

The term enthalpy here refers to the amount of heat added to the water to raise its temperature from 0°C to the saturation temperature. This heat is sensible heat since it raises the temperature of the water without changing its state.

Column 9 lists the enthalpy (h_{fg}) of evaporation in kilojoules per kilogram for each pressure.

In this case the enthalpy is the heat added to the water at saturation temperature to convert it to saturated steam at the same temperature. In other words, it is the latent heat of evaporation.

Column 10 lists the total enthalpy (h_g) in kilojoules per kilogram of the saturated steam for each pressure. Note saturated steam is steam that is fully saturated with latent heat and has no water particles present.

It should be noted that:

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

h_g is the heat necessary to produce saturated steam from water at 0°C and consists of the sensible heat plus the latent heat.

Columns 11, 12 and 13

These columns list values of entropy which are beyond the scope of this course.

USING THE STEAM TABLES

NOTE: All pressures given in this module are absolute unless stated otherwise.

Example 2:

From the steam tables find the following:

(a) the sensible heat of one gram of saturated water at 200 kPa.

(b) the latent heat of one gram of saturated steam at 200 kPa.

(c) the total enthalpy of one gram of saturated steam at 200 kPa.

Solution:

Using columns 8, 9, and 10:

(a) h_f = **504.7 kJ/kg** (Ans.)

(b) h_{fg} = **2201.9 kJ/kg** (Ans.)

(c) h_g = **2706.7 kJ/kg** (Ans.)

Example 3:

(a) Find the sensible heat required to raise 5 kg of feedwater from 0°C to the boiling point at 300 kPa.

(b) What is the boiling point at this pressure?

Solution:

(a) h_f at 300 kPa = 561.47 kJ/kg

h_f at 0°C = zero

Sensible heat = 561.47 kJ/kg

Therefore the sensible heat required to raise 5 kg of water to its boiling point at 300 kPa is

= 561.47 kJ/kg x 5 kg

= **2807.35 kJ** (Ans.)

(b) From the steam tables, the boiling point or saturation temperature (t) at 300 kPa is

= **133.55°C** (Ans.)

The student should realize that values of sensible heat given in the steam tables are measured from 0°C. That is, at 0°C the value of the enthalpy of water is zero.

Since feedwater is not usually supplied at this low temperature, it is necessary for the student to determine the enthalpy of feedwater at the supply temperatures.

Now turn to Table II of the steam tables which lists saturation temperatures. Again number the columns from left to right. The first column gives the temperature, and the enthalpy can be found in Columns 8, 9 and 10 as in the pressure table previously discussed.

Example 4:

How much heat will be required to convert 10 kg of water at 60°C into saturated steam at 200 kPa?

Solution:

Enthalpy of saturated steam at 200 kPa is found in Table 1 (pressure table).

h_g = 2706.7 kJ/kg

Enthalpy of water at 60°C is found in Table 2 (temperature table).

h_f = 251.13 kJ/kg

Therefore heat required for 1 kg

= $h_g - h_f$

= 2706.7 kJ/kg - 251.13 kJ/kg

= 2455.57 kJ/kg

Heat required for 10 kg

= 2455.57 kJ/kg x 10 kg

= **24 555.7 kJ** (Ans.)

The heat required to convert the 10 kg of water at 60°C to saturated steam at 200 kPa is 24 555.7 kJ.

Temperature Enthalpy Chart

The process of changing water into dry, saturated steam can be shown in a temperature enthalpy chart.

Example 5:

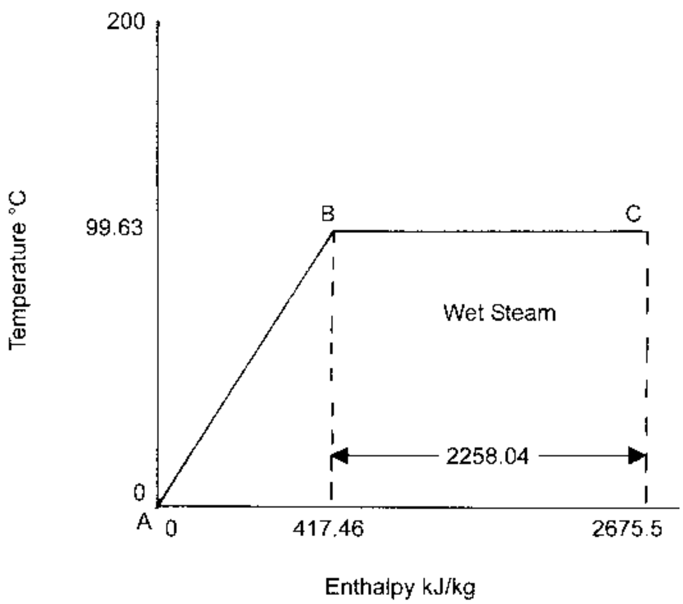
Using information from the steam tables, plot the values of heat required to produce dry saturated steam from feedwater at 0°C at a pressure of 100 kPa.

At 100 kPa

saturation temperature = 99.63°C

h_f = 417.46 kJ/kg
h_{fg} = 2258 kJ/kg
h_g = 2675.5 kJ/kg

Plotting these values gives a graph similar to the one shown in Fig. 1.



A to B = sensible heat
B to C = latent heat
B to C = wet steam zone

Figure 1
Temperature/Enthalpy Values

If all the various pressures were plotted in the same manner and the points joined we would get a temperature-enthalpy chart as in Fig. 2.

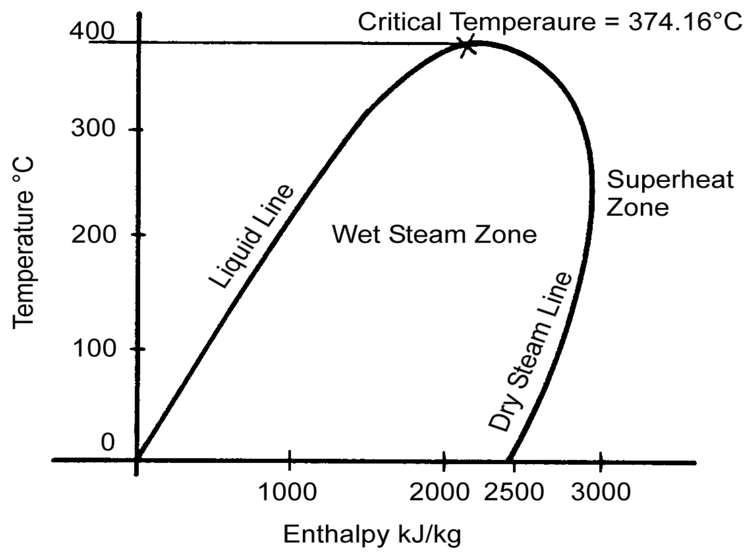


Figure 2
Temperature/Enthalpy Chart

Temperature-enthalpy charts have the advantage that the properties of steam at any pressure can be determined, whereas the steam tables are limited to the pressures listed.

Wet Steam

The values given for saturated steam in the steam tables are not always obtained in an actual steam boiler.

The steam produced may contain particles of saturated water (that is, water at the same temperature as the steam) due to the vigorous boiling action at the water surface. Obviously if steam has 10% wetness, then the dryness portion must be 90%. Thus, 90% of a gram (or kilogram) of water has been converted into saturated steam, but the remaining 10% of the gram (or kilogram) remains as saturated water entrained as droplets in the steam. That is, a gram or kilogram of saturated water has only received 90% of its latent heat since only that percentage has been converted to saturated steam.

Example 6:

If steam having a dryness fraction of 90% is produced from saturated water at 200 kPa, what amount of heat must be supplied per kilogram?

Solution:

Dryness fraction of 90% (or 0.9) means that only that portion has been converted to saturated steam. The remaining 10% is called the wetness fraction.

Let X	=	dryness fraction of steam
Latent heat required	=	X x 2201.9
	=	0.9 x 2201.9
	=	**1981.7 kJ/kg** (Ans.)

Thus 1981.7 kJ/kg of heat is required to convert saturated water at 200 kPa into wet steam with a dryness fraction of 90%.

Example 7:

How much heat must be supplied to water at 0°C to make wet steam at 200 kPa which is 90% dry? (give answer in kJ/kg)

Solution:

Since the water is raised from 0°C to saturation temperature, one kilogram of water receives its full sensible heat (h_f). But since only 90% of the saturated water is converted to saturated steam, the latent heat received is only 90% of h_{fg}.

Heat required	=	h_f + (90% of h_{fg})
	=	504.70 + (0.9 x 2201.9)
	=	504.70 + 1981.7
	=	**2486.4 kJ/kg** (Ans.)

Thus 2486.4 kJ/kg of heat is required to convert water at 0°C into wet steam at 200 kPa having a dryness fraction of 90%.

Boiler Efficiency

The efficiency of a steam boiler is the ratio of the heat energy required to make steam, to the heat energy supplied by the combustion of the fuel.

$$\text{Boiler efficiency} = \frac{\text{heat given to steam}}{\text{heating value of fuel}}$$

(or expressed as a percentage)

$$\text{Boiler efficiency} = \frac{m_s\,(h_1 - h_2)}{\text{heating value of fuel}} \times 100$$

where m_s = kg of steam produced per kg of fuel

h_1 = enthalpy of steam kJ/kg

h_2 = enthalpy of feedwater kJ/kg

Heating values of fuel = kJ/kg of fuel

Example 8:

A boiler generates 7 kg of dry saturated steam per kg of fuel oil burned, the heating value of the oil is 30 000 kJ/kg. The feedwater is supplied at 60°C and the boiler pressure is 200 kPa.

Calculate the boiler efficiency.

Solution:

h_2 = enthalpy of feedwater (h_f) = 251.13 kJ/kg

h_1 = enthalpy of dry saturated steam at 200 kPa (h_g)
= 2706.7 kJ/kg

$$\text{Boiler efficiency} = \frac{m_s\,(h_1 - h_2)}{\text{heating value of fuel}} \times 100$$

$$= \frac{7\,(2706.7 - 251.13)}{30\,000} \times 100$$

$$= 7 \times \frac{2455.57 \times 100}{30\ 000}$$

Boiler efficiency = **57.3%** (Ans.)

This means that 57.3% of the heat available in the fuel was effectively used in the production of steam. The remaining 42.7% of the heat is referred to as the **boiler losses**. These losses include such items as loss due to sensible heat in dry gaseous products of combustion, loss due to incomplete combustion, and loss due to moisture in fuel. The attainment of maximum efficiency in daily operation of boiler equipment is dependent upon keeping boiler losses to a minimum.

Notes: