Applied Thermodynamics for Marine Systems

Prof. P. K. Das

Department of Mechanical Engineering

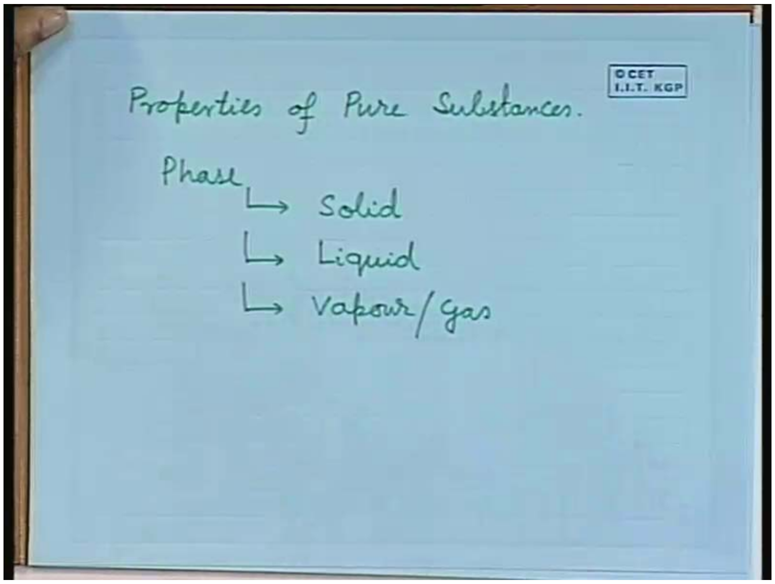
Indian Institute of Technology, Kharagpur

Lecture No. - 06

Property of Pure Substance, Steam Table

Good afternoon. Today, we will start a new topic that is, the properties of pure substances.

(Refer Slide Time: 01:03)



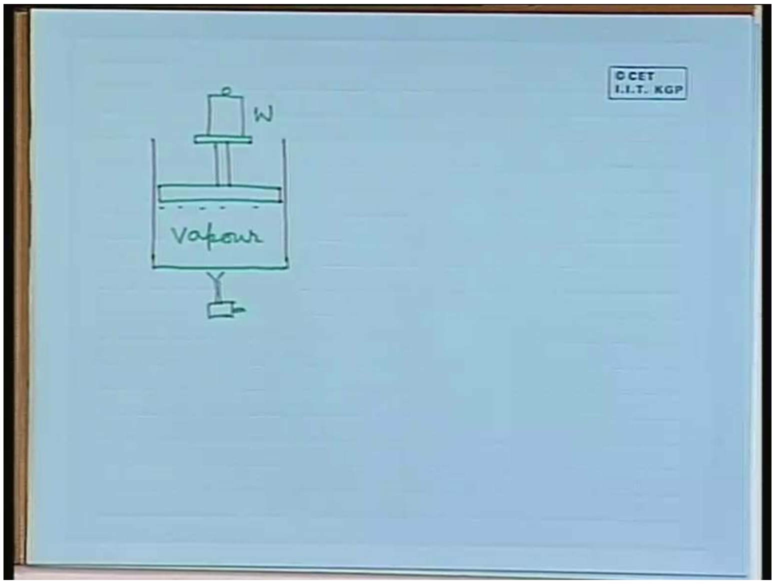
© CET
I.I.T. KGP

Properties of Pure Substances.

Phase
- ↳ Solid
- ↳ Liquid
- ↳ Vapour/gas

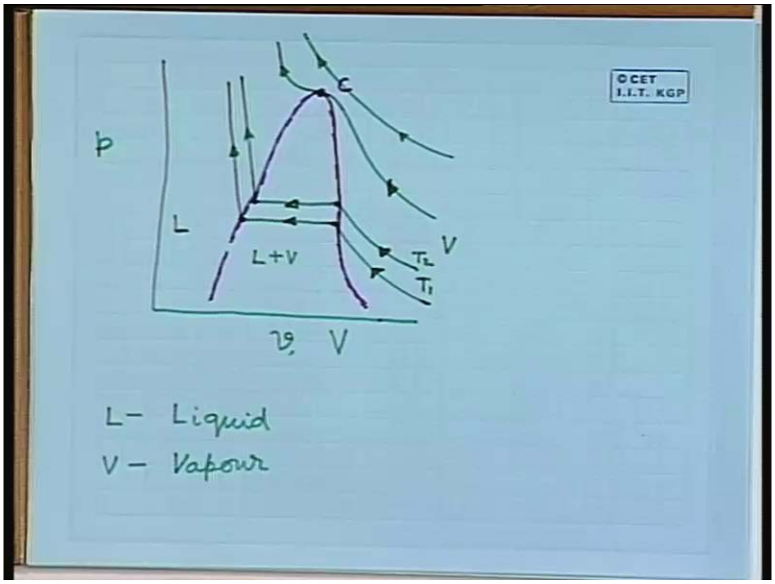
A pure substance can remain at a particular phase or can remain as a mixture of different phases. By phase, we mean the state of the substance; it can be solid, it can be a liquid phase and it can be either in vapour or in gas phase. There is a subtle different between vapour and gas phase which we will know when we discuss further. Out of this particularly when we will see the different engineering systems of our interest, we will find that the working medium could be either in the liquid phase or in the vapour phase or gas phase, or it could be a mixture of liquid and vapour phase. In engineering thermodynamics or the branch of engineering thermodynamics which we are studying, there we will be concerned with the determination of thermodynamic properties of liquids, vapours and gasses and the mixture of liquid and vapour. There could be some properties of a solid material which are also thermodynamic properties but we are not interested in that. Generally, a metallurgist or physicist will discuss those properties and that is not within the discussion of the present course. Let us take one example.

(Refer Slide Time: 03:08)



Let us say, we take a certain vapour in a piston cylinder arrangement and the piston is loaded by a constant load like W. Inside this piston cylinder arrangement some vapour is there and we are transferring heat to this vapour at a slow rate, so that at any instant the temperature of the vapour mass anywhere inside this piston cylinder arrangement is uniform and constant. But, it is changing with time. That means as we are giving or supplying more and more heat the temperature of the vapour mass as a whole is changing but it is not changing from point to point. If we do this experiment and then if we try to measure its different properties then what will we find? If we transfer heat and there is an expansion of this vapour mass, there will be a change in volume. But, we are applying a constant weight on the piston so the pressure remains constant. It is a constant pressure process. The volume changes and there could be change in temperature. If we note down the change of volume then, one can find out the change in volume with the application of heat. Similarly one can think of a process in which we are plotting the change of volume.

(Refer Slide Time: 05:21)



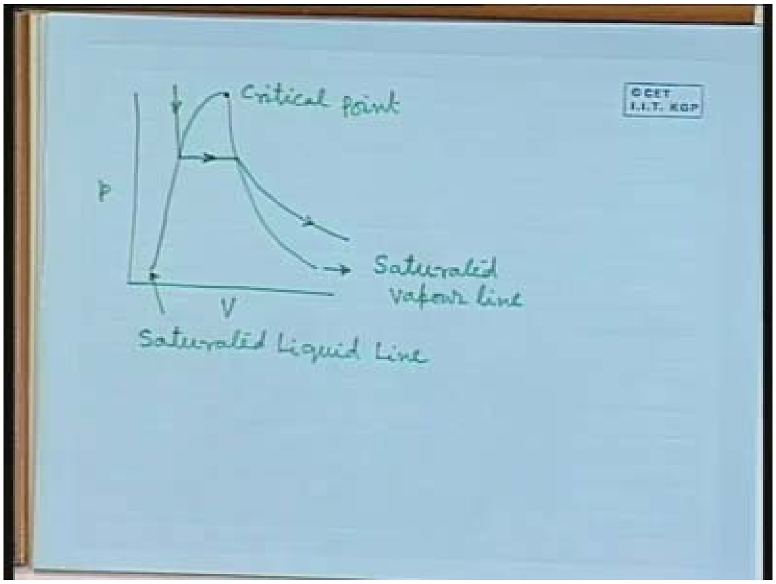
Either we can think of specific volume or we can think of total volume and this side we have got pressure. We can think of the change of pressure and volume while the temperature is kept constant; so the process will be something like this. Let us say, we are going for a cooling process. The process will be something like this. Here, what we have done is, we have kept the temperature constant. At this point let us say we are coming to the saturated state of the vapour. We have started at any arbitrary pressure, volume and temperature of a vapour. Then we are cooling it. That means, we are extracting heat from the vapour mass, keeping the temperature constant.

We are plotting the pressure and volume at different stages. At one stage we will reach the saturated vapour condition. After that, if we extract more heat what will we find? We find that temperature will remain constant and pressure will also remain constant till this saturated vapour completely gets converted into saturated liquid. At this point we are getting a saturated liquid. After this if we extract more heat then, we will find that there is a rise in pressure but during this process there is very less change in volume. Here we are having a liquid state and in the liquid state it is almost incompressible, so the change in volume will be small. Let us say this is at temperature T_1. We can repeat this process for another temperature. Let us repeat this process for another temperature and we will get something like this. We are getting basically three regions of the curve. In this region, we are getting super heated vapour, in this region this is the saturated vapour point, here we are getting vapour liquid mixture, this is the saturated liquid point and here we call it sub-cooled liquid. This is liquid, this is vapour and in between we have a zone where mixture of liquid and vapour exists. If we do this experiment for different temperatures, we will have different points for saturated vapour. Similarly, we will have different points for saturated liquid. If we combine all these points by some sort of a smooth curve, then you will get some sort of a dome like this.

Let us say, this is the line which passes through points of all the saturated vapour and this is the line which passes through all the points of saturated liquid. If they are extended they will join at a particular point which is known as critical point. Let me denote this point as C or critical point. If somebody does the same experiment or same type of curves are plotted then, through the critical point one will get a curve like this. Beyond critical point the nature of the curve will be something like this. Let me write down. This side we are having liquid which is denoted by L. Inside the dome we are having liquid plus vapour and this side we are having vapour. L denotes liquid and v denotes vapour. If we have the dome, on the left hand side of the dome and on the right hand side of the dome we have got single phase regions, while inside the dome we have got a two phase region or mixture of two phases.

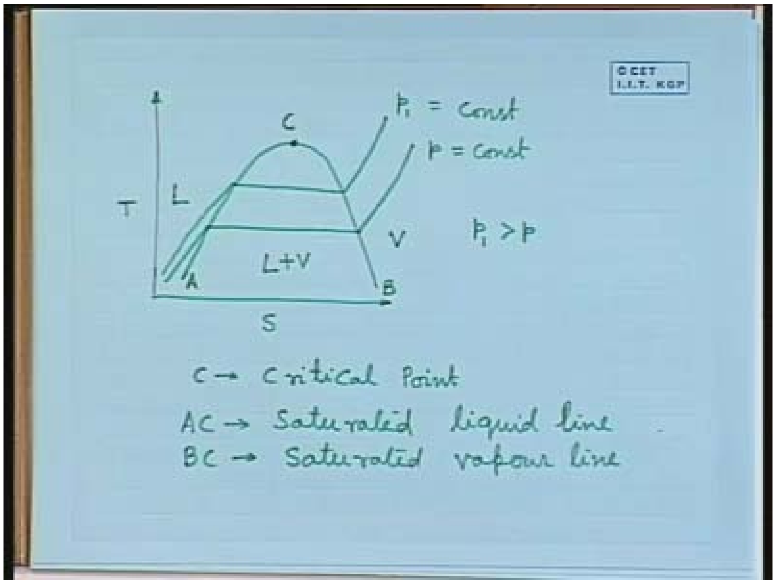
For a pure substance if it is in single phase, then if we have know two independent thermodynamic properties, then any third property can be determined. In this region or in the vapour region if we have know two independent thermodynamic properties, let us say, if we know pressure and temperature we can determine volume, we can determine enthalpy, we can determine entropy or any other properties for that matter. Similarly, in the liquid region, if, say pressure and temperature are known, other thermodynamic properties can be determined. In the two phase region we need any three independent properties for determining another thermodynamic property. We will see how to determine the thermodynamic properties and what the important thermodynamic properties are. Mainly our working substance will be either in the gaseous phase or vapour phase or it will be in the liquid phase or it will be a mixture of liquid and vapour. Common working medium with which our engineering cycles run are like steam; it can be a refrigerant. Basically, steam is used in number of engineering cycles and it is a medium which is extensively used for the production of power. We will study the properties of pure substance with reference to properties of steam.

(Refer Slide Time: 13:08)



For steam, the diagram which I have shown you is known as pV diagram. For steam this is the pV diagram. Here, these are constant temperature lines. This is a constant temperature heating line. Earlier I have shown a constant temperature cooling line. This point is known as the critical point. This line is known as saturated vapour line and this line is known as saturated liquid line.

(Refer Slide Time: 14:37)



C → Critical Point

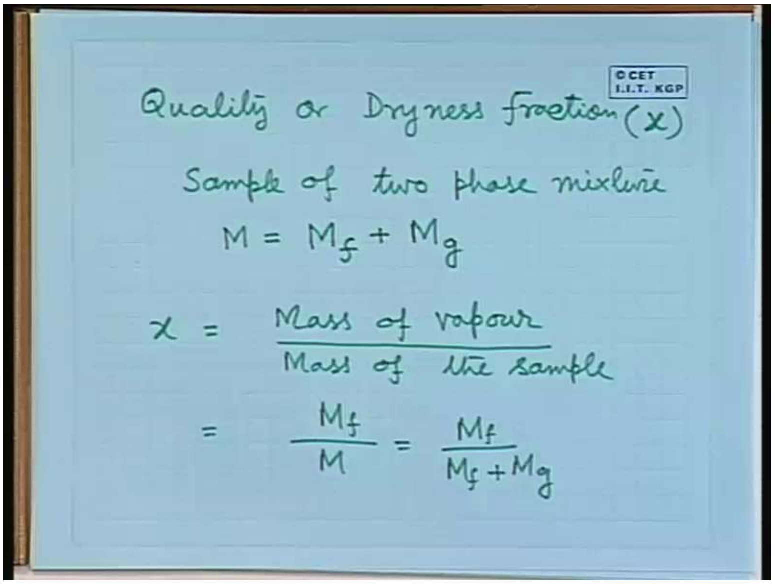
AC → Saturated liquid line

BC → Saturated vapour line

Similarly, one can have another thermodynamic plane for representing the pure substance. This is a TS plane or temperature entropy plane. In this temperature entropy plane we can have constant pressure lines like this. This is a constant pressure line, so we can call it p is equal to constant. Another line we can have; let us say, this P_1 is constant where P_1 is greater than P. Here also we are having the critical point here at the top of the dome. C is the critical point. Then, if I have these two lines A to C or line AC, this is the saturated liquid line and BC is saturated vapour line. Here, we can see a dome type structure within which there is both liquid plus vapour. On the left hand side of the dome we have the liquid and on the right hand side of the dome we have got vapour. At the critical point one cannot make any demarcation between the liquid phase and the vapour phase and at the top of the critical point we have got gaseous phase of the matter.

This holds good for both pV diagram and for the TS diagram. That means, at the critical point we do not have any demarcation between liquid phase and vapour phase and above the critical point or at the top of the critical point we have got gaseous phase. I have mentioned that for any pure substance if it is in single phase, we need two independent properties for determining the third property or for determining any other thermodynamic property. Inside this dome we have got a mixture. Though it is a pure substance here two different phases are existing together; liquid and vapour. Here, we need one additional information for determining the property values. That information is known as quality or dryness fraction.

(Refer Slide Time: 18:02)



Quality or Dryness fraction (x)

Sample of two phase mixture

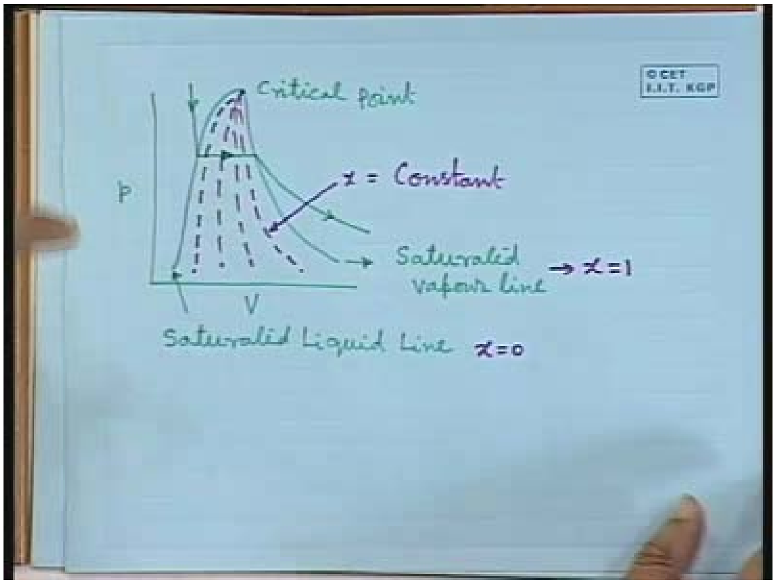
$$M = M_f + M_g$$

$$x = \frac{\text{Mass of vapour}}{\text{Mass of the sample}}$$

$$= \frac{M_f}{M} = \frac{M_f}{M_f + M_g}$$

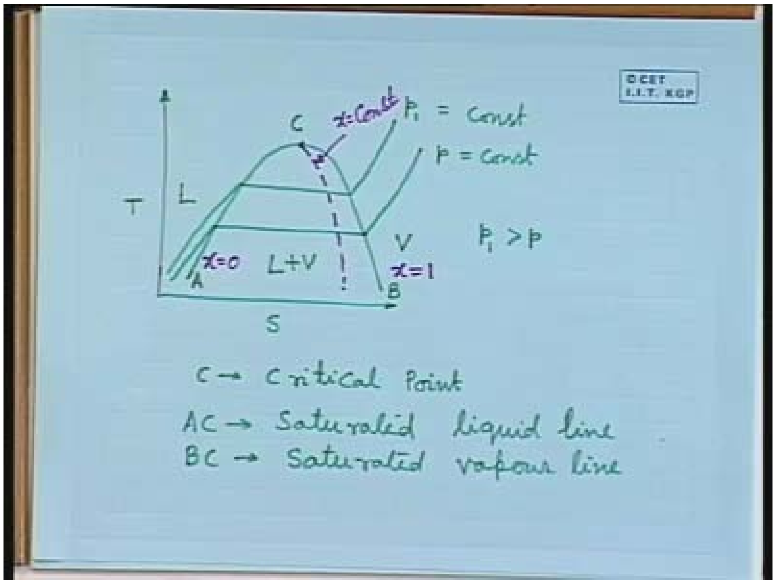
Let us say, we take a sample of a two phase mixture. The mass of the sample is M. As it is a mixture of two phases, it is made up partly with liquid and partly with vapour. Conventionally, liquid is expressed with a subscript f and vapour is denoted with a subscript g. M total will be M_f plus M_g. The quality or dryness fraction is denoted as x. So, x is mass of vapour divided by the mass of the sample. In this case it will be M_f by M or it will be M_f by M_f plus M_g. This quality or dryness fraction will be used as another property inside the two phase dome.

(Refer Slide Time: 20:20)



If we go back to our earlier diagram we can write at the saturated vapour line, x is equal to 1; saturated liquid line x is equal to zero and in between values of x that will lie between these two lines. In other words we will have different curves for different values of x inside the dome. These are constant x values or constant x lines; so we can write x is equal to constant.

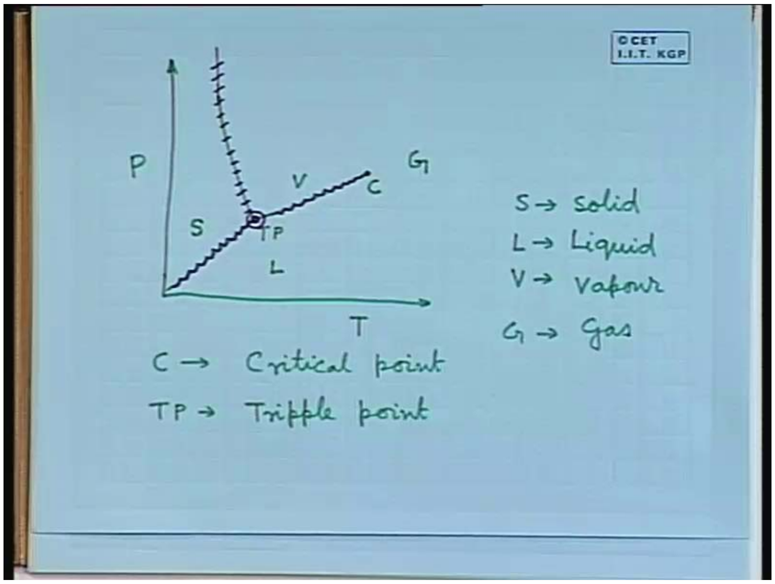
(Refer Slide Time: 21:10)



C → Critical Point
AC → Saturated liquid line
BC → Saturated vapour line

A similar thing is there in this TS diagram; x is equal to 1, here x is equal to zero and in between there are number of lines. Let us say, this is one typical line where x is equal to constant. As I have mentioned in the beginning, we are not much concerned with the property of solids. Let us see the total scenario on a PT diagram, pressure temperature diagram.

(Refer Slide Time: 22:00)



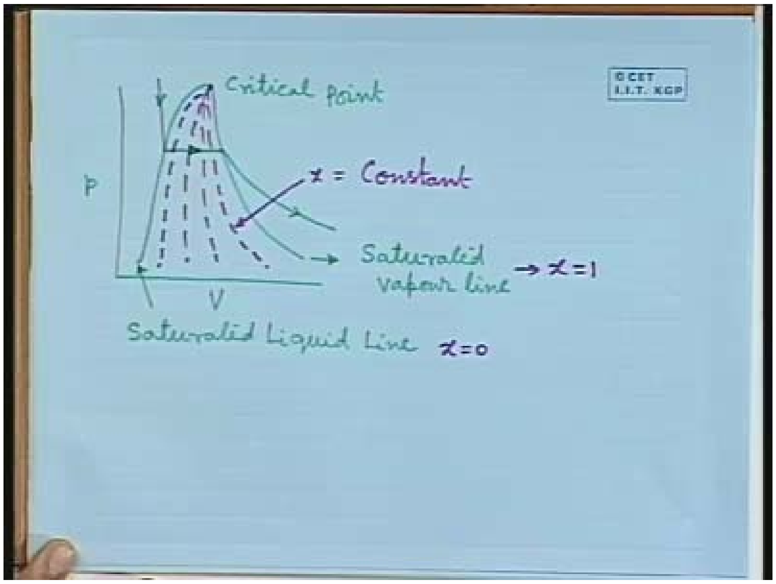
This is a PT plane for any thermodynamic substance. Here, the transformation of phases can be denoted by lines like this. This side we will have solid, this is liquid, this is vapour and this is gas; this is extended. If we give different names, this point is C and this is TP. S denotes solid, L denotes liquid, V denotes vapor and G denotes gas. C denotes critical point and TP denotes triple point. This is a very important diagram. It shows depending on the values of pressure and temperature, what will be the phase of a particular substance? Whether it will be in solid phase or it will be in liquid phase or it will be in vapour or gaseous phase?

This line indicates the transformation between solid and liquid; so this line indicates either melting process or solidification process. This line indicates the transformation between solid and vapour. So, this is indicative of sublimation and de-sublimation process and this line indicates transformation between liquid and vapour, so it is boiling and condensation. Here we can see the critical point beyond which or at which there is no physical demarcation between the liquid phase and the vapour phase. If we compare between this PV diagram and the PT diagram of a substance where all the three phases are shown, this is the saturated liquid line and this is the saturated vapour line. These two lines are coincident in this line where there is a transformation between vapour and liquid phase. In between there is a point which is known as triple point. This point is a very important one and at this pressure and temperature, all the three phases can coexist. These lines show the coexistence of two phases but this point shows the coexistence of three phases; all the three phases can coexist at triple point. This is for the general information, but for the branch of engineering thermodynamics in which we are interested, we are interested in this line only where transformation between vapour phase and liquid phase is taking place.

Let us recapitulate once again what we have learnt so far and then we will go for determination of different properties. What we have seen so far is that, a pure substance can remain in different phases like solid, liquid and gas or vapour. As far as engineering thermodynamics is concerned, we are interested in liquid phase and vapour phase and sometimes in gaseous phase. In a pure substance when there is transformation between liquid to vapour phase and vapour to liquid phase, we are interested in those processes and those processes can be expressed on different thermodynamic plane. Two thermodynamic planes I have shown. One is a pV plane and another is a TS plane. In all these planes we can see that there are three regions; one is a liquid region another is a mixture of vapour and liquid region and third one is the vapour region. The mixture of liquid and vapour region is bounded by two lines.

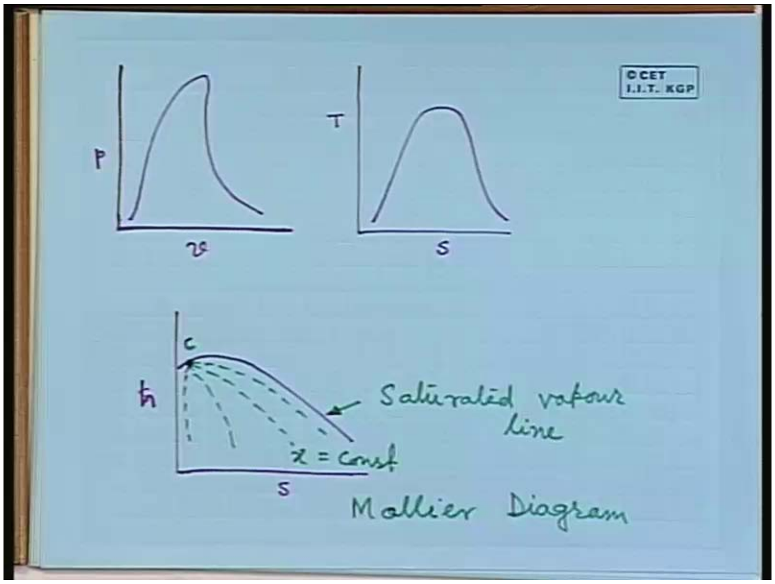
In any diagram like this one, on one side we have got saturated liquid line and on the other side we have got saturated vapour line.

(Refer Slide Time: 28:06)



This saturated liquid line and saturated vapour line intersect at one point which is known as critical point. At the critical point, there is no demarcation between liquid and vapour and above critical point we have got gaseous region. These are the important things. There is another important information which I have provided. Inside the two phase region, we need another property for determining any thermodynamic property of the mixture and that property which we take generally is dryness fraction or quality. By definition this is the ratio of the mass of vapour divided by the total mass.

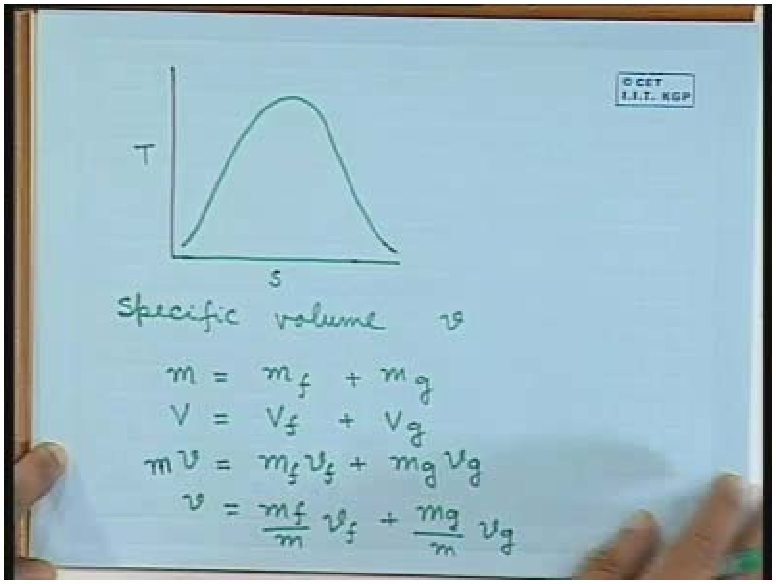
(Refer Slide Time: 29:06)



Let me draw the thermodynamic plane which we generally use for discussing the change between the liquid phase and vapour phase. One is a pv plane, as I have shown; this is the pv plane. Another is a TS plane. The third one is hs plane. The hs plane looks like this. In the hs plane also we have got the critical point. This is critical point c and you will have different values of x like this. This is x and it is equal to constant and this line is your saturated vapour line. This hs diagram, where enthalpy and entropy are taken as the coordinates, has got another name that is known as Mallier diagram or sometimes it is called Mallier chart. This diagram is very useful in solving problems because directly one can get the enthalpy values and changes in entropy in different processes, from this chart. As in different steady state steady flow processes, changes of enthalpy is a very important quantity and it has to be computed number of times. This Mallier chart is very handy in calculating problems and representing different thermodynamic cycles. Other planes are also possible; like in the refrigeration cycle we can use a different thermodynamic plane but those we will discuss later on. Mainly for steam properties or for the processes involving steam, to represent the process we will use either a pv diagram or a TS diagram or an hs diagram.

Which are the properties we are interested in? Let us say that we will be interested in the specific volume. So what is the specific volume?

(Refer Slide Time: 32:46)

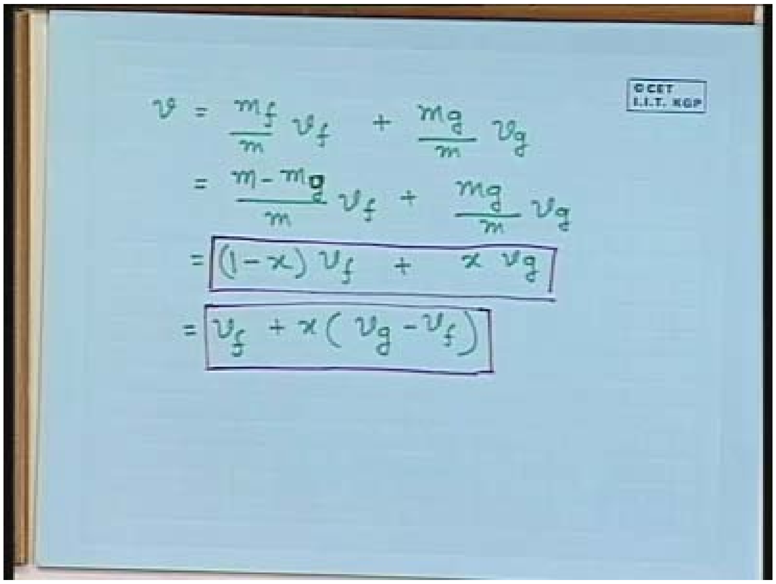


Specific volume v

$$m = m_f + m_g$$
$$V = V_f + V_g$$
$$mv = m_f v_f + m_g v_g$$
$$v = \frac{m_f}{m} v_f + \frac{m_g}{m} v_g$$

If we think of any thermodynamic plane, let us say we are interested in the TS plane and in this TS plane we want to represent a process. The end points of the process can be anywhere, either it can be in the liquid region or it can be in the two phase region or it can be in the vapour region. Accordingly, we have to determine the properties in those regions. Let us say, we are interested in one property which is the specific volume, v. If it is in the super heated vapour region then we can determine it knowing other two properties like pressure and temperature. Similarly, if it is in the liquid region we can determine it knowing two independent properties. Let us say, again we take pressure and temperature; these two properties are easily measurable properties. From there we can determine what the specific volume is. But inside the two phase dome what should we do? We can proceed like this. The mass balance if we make, m sample could be m liquid plus m vapour. V sample, total volume of the sample, that could be V liquid plus V vapour. Then one can write m into v. What is this quantity? This quantity is the specific volume multiplied by mass that means it will give the total volume. That could be written as m_f into v_f plus m_g into v_g and then we can divide both side by m; so it will be m_f by m into v_f plus m_g by m into v_g.

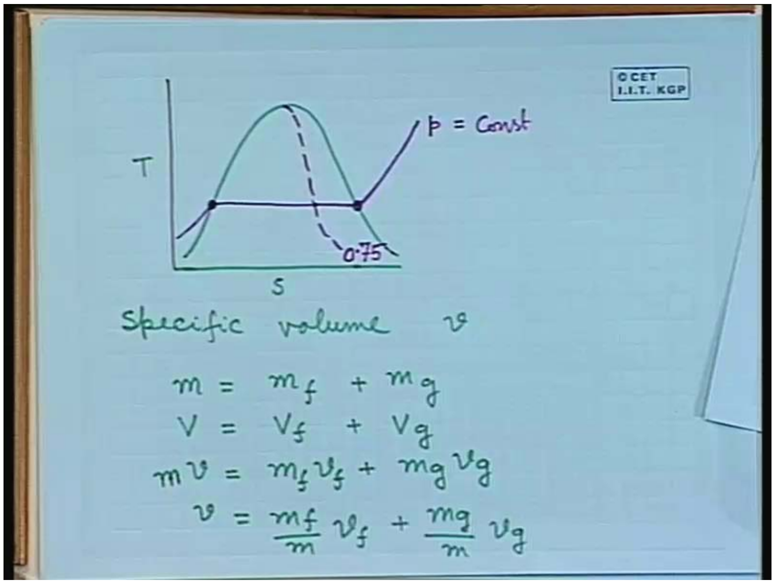
(Refer Slide Time: 35:41)



$$
\begin{aligned}
v &= \frac{m_f}{m} v_f + \frac{m_g}{m} v_g \\
&= \frac{m - m_g}{m} v_f + \frac{m_g}{m} v_g \\
&= \boxed{(1-x) v_f + x v_g} \\
&= \boxed{v_f + x(v_g - v_f)}
\end{aligned}
$$

Basically, we are getting the specific volume of the mixture is equal to m_f by m multiplied by v_f plus m_g by m multiplied by v_g. By definition, the first term in this particular quantity is the dryness fraction or x. Similarly here, what is m_f? m minus m_g that is your m_f divided by m into v_f plus m_g by m into v_g. This will be 1 minus x into v_f plus x into v_g. One can simplify it slightly. So, one can write v_f plus x into v_g minus v_f. Here, either of these two expressions can be used for denoting the specific volume of the mixture. Either the first expression or the second expression can be used for determining or denoting the specific volume of the mixture. What do we need for determining the specific volume of the mixture? We need the specific volume of the fluid and we need the specific volume of the gas or vapour and at the same time we need the mass fraction of any of this component or we need the quality or dryness fraction.

(Refer Slide Time: 38:20)

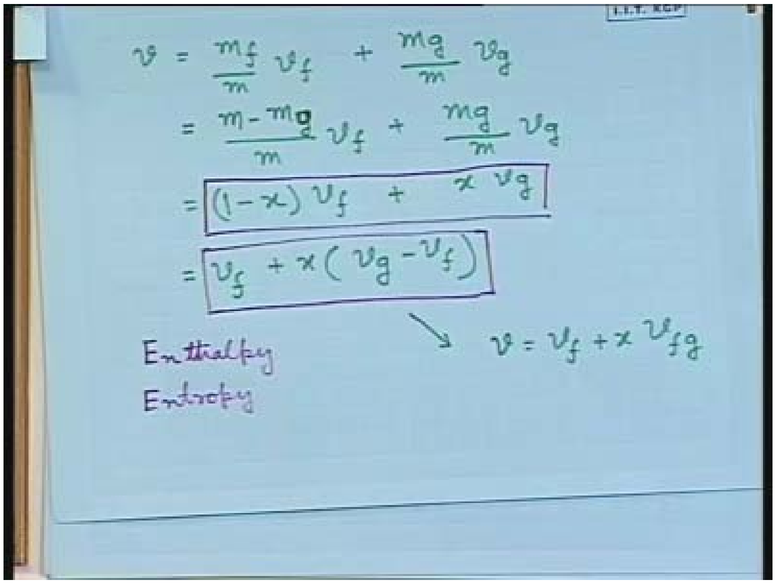


Specific volume v

$$m = m_f + m_g$$
$$V = V_f + V_g$$
$$mv = m_f v_f + m_g v_g$$
$$v = \frac{m_f}{m} v_f + \frac{m_g}{m} v_g$$

If we go back to this diagram, this is a constant pressure line and we are interested in this pressure. This is a constant dryness fraction line. Let us say, this dryness fraction is 0.75. We are interested in determining, at p bar and at dryness fraction is equal to 0.75, what is the specific volume of the mixture. What we have to determine? First, we have to know what v_f is. That v_f corresponds to this value of the saturated liquid. We have to know v_g. v_g corresponds to the specific volume of the saturated vapour at p bar and already it it specified that we have to determine it at x is equal to 0.75. We know the magnitude of this quantity v_f here. We know the value of v_g here; we know the value of x here. So, that can be plugged in this equation and ultimately we can find out the specific volume of the mixture. This holds good for any other property.

(Refer Slide Time: 40:32)



$$v = \frac{m_f}{m} v_f + \frac{m_g}{m} v_g$$

$$= \frac{m - m_g}{m} v_f + \frac{m_g}{m} v_g$$

$$= \boxed{(1-x) v_f + x v_g}$$

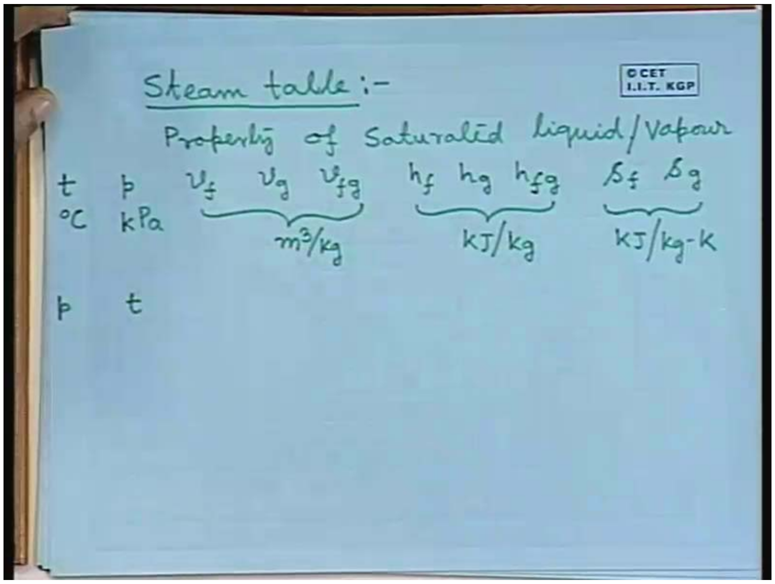
$$= \boxed{v_f + x(v_g - v_f)} \rightarrow v = v_f + x v_{fg}$$

Enthalpy

Entropy

If we want to determine enthalpy, we can use similar type of additive formula. If we are interested in determining entropy, we can use similar type of expressions. Sometimes, instead of using v_g minus v_f their difference is used and then this expression is like this v is equal to v_f plus x v_{fg}. That means, this is the difference between v_g and v_f. So this expression is also used in some of the occasions.

(Refer Slide Time: 41:49)



Steam table :-

Property of Saturated liquid/Vapour

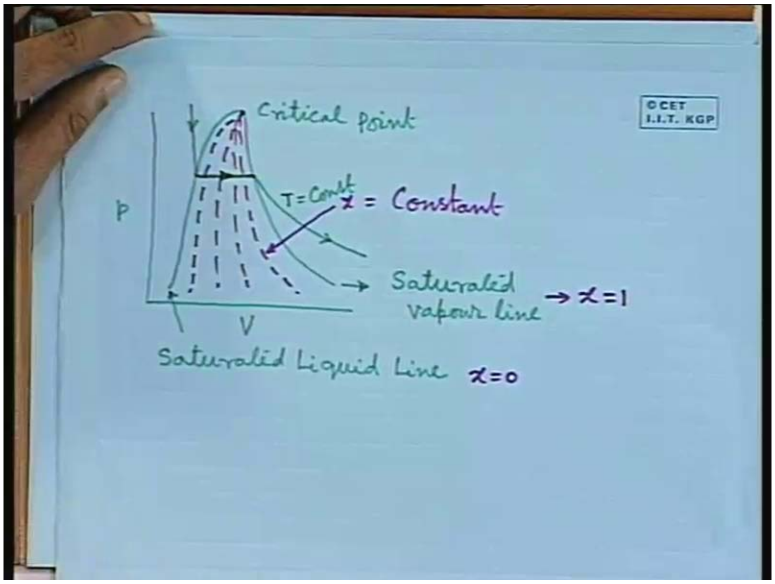
t	p	v_f	v_g	v_{fg}	h_f	h_g	h_{fg}	s_f	s_g
°C	kPa	m^3/kg			kJ/kg			kJ/kg-K	

p t

For determining the steam properties, we use steam table. This is a very useful tool for thermodynamic calculations where steam is the working substance or steam and water are the working substances. There are different steam tables available in the market; we can use them and the only thing is that, we need to know how to read this steam table. Mainly it has got different parts. In the first part of this steam table, we will see that property of saturated steam or saturated vapour and saturated liquid will be given. The property of saturated liquid will be given in the first part of the steam table; saturated liquid and vapour. Basically, we can say that property of saturated fluid will be given in the first part of the steam table. Which are the properties that will be given? Here properties like pressure, temperature, specific volume, enthalpy and entropy will be given. In the steam table either the properties can be tabulated based on pressure or it can be tabulated based on temperature. In most of these steam tables, both we will find. Tables based on pressure or pressure based table and table based on temperature or temperature based table, both we can find in most of the steam tables.

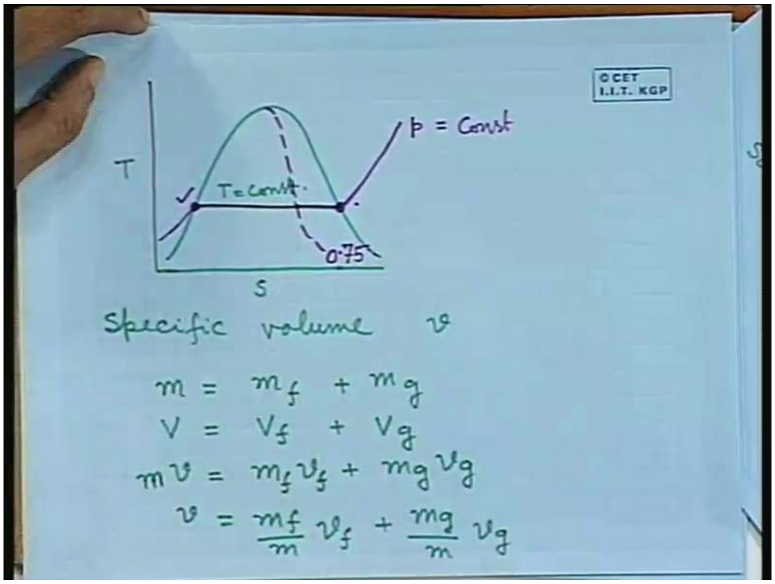
If there is a table which is temperature based, their property values will be given at regular intervals of temperature. Temperature in the steam table denotes the saturation temperature. We give the saturation temperature from any of these diagrams, either the pv diagram or the TS diagram. In this pv diagram I have shown a constant temperature curve.

(Refer Slide Time: 44:59)



Let us say, T is constant here for this green curve. If T is constant within this two phase zone, for this portion of the curve p is also a constant. If I specify the temperature and call it the saturation temperature, automatically the saturation pressure becomes fixed. Once I give the temperature value then the pressure value is also fixed because I am determining the property at the saturated state, either for the saturated vapour or for the saturated liquid. Similar thing in this curve also; this p is equal to constant.

(Refer Slide Time: 45:54)



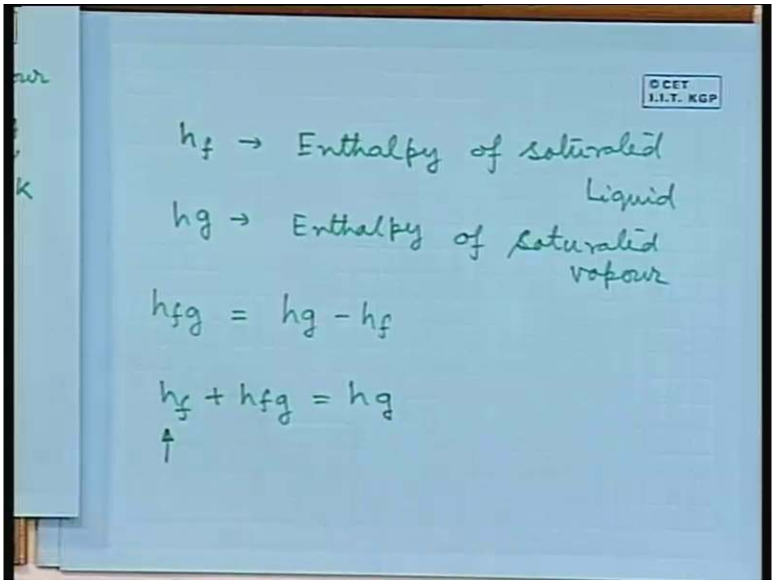
Specific volume v

$$m = m_f + m_g$$
$$V = V_f + V_g$$
$$mv = m_f v_f + m_g v_g$$
$$v = \frac{m_f}{m} v_f + \frac{m_g}{m} v_g$$

But we can see in the two phase zone also T is a constant. The same thing holds good. That means if I specify the pressure, the temperature remains a constant because we are determining properties at a saturated condition. A pressure based table or a temperature based table, let us think of a temperature based table. A temperature based table will be something like this. We will have temperature and then we will have pressure. Then we can have v_f, that is the specific volume of the liquid. We can have v_g, we can have v_{fg} also in some tables. Then we can have h_f, h_g, h_{fg}, s_f and s_g. This is temperature, this is pressure, this is specific volume for a saturated liquid, this is the specific volume for saturated vapour, this is the difference of specific volumes for saturated vapour and liquid, this is enthalpy of the liquid at saturated condition, this is enthalpy of the vapour at saturated condition and this is the difference between these two quantities. Then this is the entropy of the saturated liquid and this is the entropy of the saturated vapour.

The units which are used are SI units. So one can have degree Celsius here; for pressure we can have kilo Pascal. All these three quantities they can have a unit of meter cube per kg that is for specific volume. All these three quantities, three enthalpies, they can have a unit of kilo Joule per kg. This is a specific quantity per unit mass and these two entropies will have kilo Joule per kg Kelvin. These are the units which will be used in the steam table. Here, it is interesting to note in this context that we are getting or determining the quantity h_{fg}. This quantity h_{fg} has got a physical meaning. Also from the physics point of view, this is one quantity which is of interest. What is this quantity?

(Refer Slide Time: 49:39)



© CET I.I.T. KGP

$h_f \rightarrow$ Enthalpy of saturated Liquid

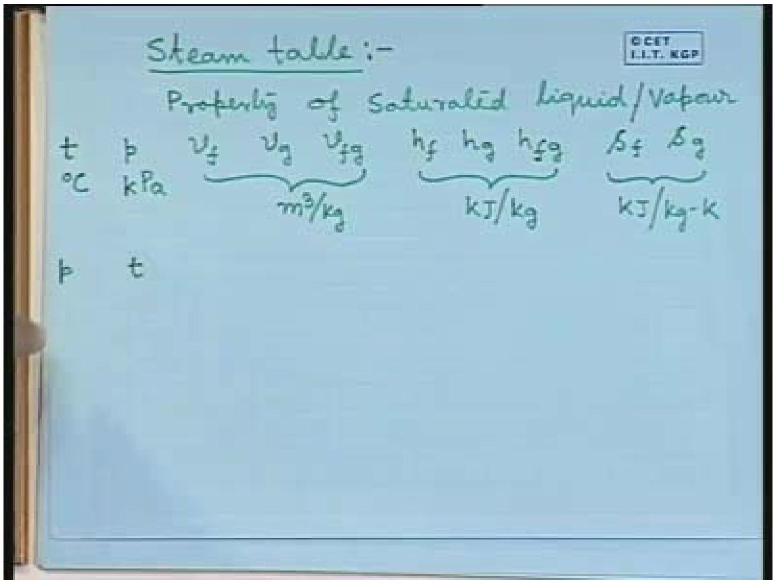
$hg \rightarrow$ Enthalpy of saturated vapour

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

$$\underset{\uparrow}{h_f} + h_{fg} = h_g$$

h_f is the enthalpy of saturated liquid and hg is the enthalpy of saturated vapour. h_{fg} is basically, h_g minus h_f. This is the difference between the enthalpy of the saturated vapour and the saturated liquid or in other words, we can write h_f plus h_{fg} that is equal to h_g. Here, this is the enthalpy of the saturated liquid. It needs some more enthalpy to get converted into saturated vapour at the same pressure and temperature. What is this quantity? This quantity is the latent heat of vaporization. Either it is the latent heat of vaporization or the latent heat of condensation, whichever process we may consider. So, h_{fg} has got a physical meaning; it is the latent heat of vaporization. These are the quantities which we can read directly from the steam table and this is the temperature based tabulation for the steam table.

(Refer Slide Time: 51:30)



Steam table :-

© CET I.I.T. KGP

Property of Saturated liquid/Vapour

$$t \quad p \quad \underbrace{v_f \quad v_g \quad v_{fg}}_{m^3/kg} \quad \underbrace{h_f \quad h_g \quad h_{fg}}_{kJ/kg} \quad \underbrace{s_f \quad s_g}_{kJ/kg\text{-}K}$$

°C kPa

p t

Similarly, one can have a pressure based tabulation of the steam table. In that case, what will happen? We will have p to start with and property values will be tabulated at regular intervals of p and then it will be followed by t; corresponding to this pressure, the saturation temperature will be tabulated here. What is the difference between these two tables? Here, we will see a regular interval of temperature but pressure intervals will not be regular. Whereas in the second case here we will have a regular interval of pressure and corresponding saturation temperatures will be tabulated in the next column but the temperature intervals may not be regular. In fact, it will not be a regular. So, that is the only difference between these two tabulations of the steam table. Next, I will take some examples and explain how the data are tabulated and what can we do with the help of this table? We will continue in our next class.