

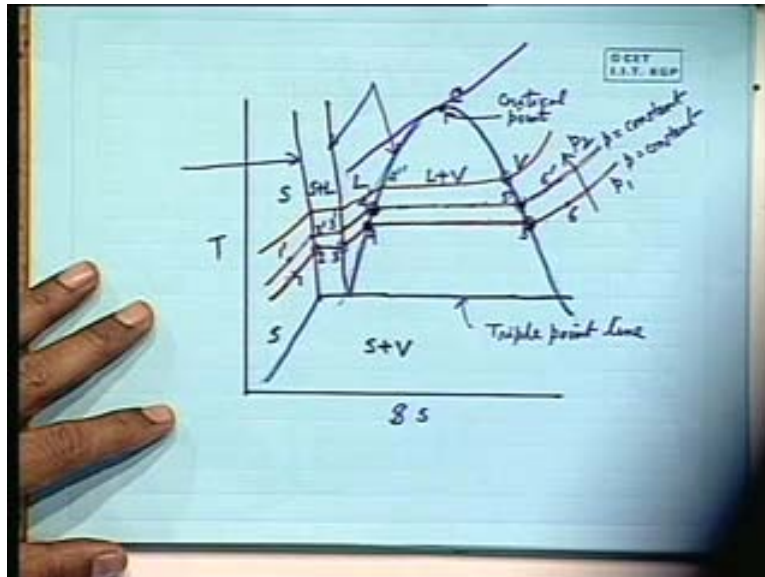
**Basic Thermodynamics**  
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**Lecture No 16**

**Properties of Pure Substances-I**

Good afternoon. In the last class, we were discussing, the phase diagram of a pure substance in relationship to the properties of pure substances and where we ended is the temperature entropy plot in course of phase change of a pure substance.

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We arrived at this diagram, where we stopped last class. So,  $T_s$ ; the temperature and specific entropy plot is like this. This is the vapor dome. Typically, these are the saturated liquid lines for boiling or vaporization. This is the locus of point force which we designated as 0.4, the saturated liquid state for vaporization.

Similarly, this is the locus of saturated vapor points; that means, this is known as vapor line. This is similarly, the saturated liquid line for solidification and this is the saturated solid line for melting.

**This red line**, these are the constant pressure lines. One thing we have appreciated that a constant pressure looks like this. At constant pressure, if temperature increases, entropy

increases during this sensible heating part of a substance. This is the vapor phase; the gas phase, this is the liquid phase and this is the solid phase. While in coat surface change, both pressure and temperature remains constant. So, a temperature pressure line runs parallel to the s axis, because T is the ordinate; that means, it becomes constant temperature also.

Similarly, this is the triple point line which will come afterwards. This thing is like this. This is the figure for phase diagram in Ts plot. One thing is that this is saturated liquid and we are not much interested on this part. We are interested on liquid and liquid vapor. The saturated liquid line for vaporization hills only towards the right. That is because at higher pressures, when the pressure is increased, the saturation temperature is increased and it takes more heat. Therefore, the entropy content in the system is much more. Therefore, the line hills towards the right.

For an example, if this is one atmospheric pressure line. So, for water, 100 degree Celsius. If this is a five atmospheric pressure line, then this temperature may be something around 150 degree Celsius. So, water has to be heated to 150 degree Celsius. So, the entropy is more, but here the saturated vapor line hilling towards left in the similar way, as it happened in case of pv diagram.

This is because of that entropy. **The entropy is lower here compared to here, though the temperature is higher here.** Why entropy is lower? That is because at this higher pressure and temperature, the latent heat which is the difference between the enthalpy at this point and this point which will be again explained in hs diagram.

Latent heat is less. Again, I am giving an example that if it is 100 degree Celsius water. If this line is one atmospheric pressure line then this is 100 degree Celsius vapor. So, difference in enthalpy between this and this is the latent heat; that means, the entropy change is because of the latent heat absorption. Latent heat is taken at the constant temperature. When we change the pressure, for example, at five atmospheric pressure, let us consider five atmospheric pressure, probably the temperature is 130 degree Celsius or 140 degree Celsius.

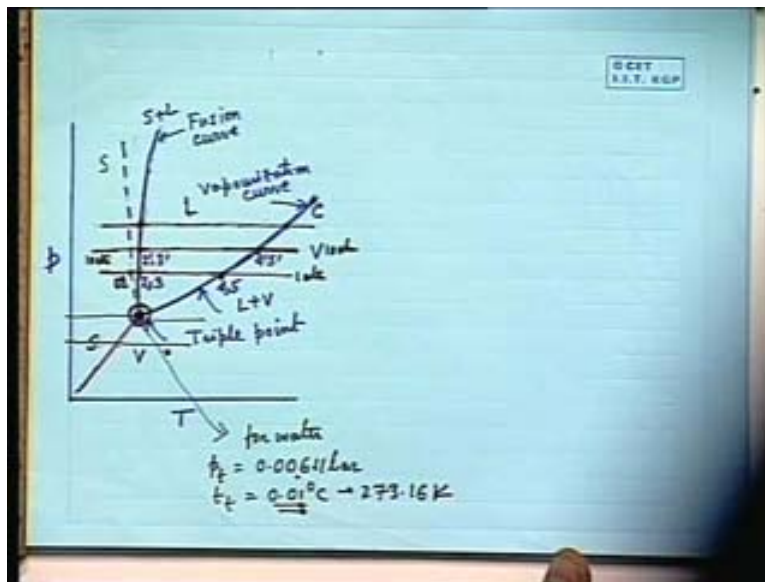
So, at high temperature, this point is there. But at the same time, the latent heat of vaporization reduces as we go on increasing the pressure. So, the heat which is given to vaporize this liquid to the vapor is less. So, the change in entropy is less so that the

absolute entropy is decreasing as we go on increasing the pressure. That is why, in Ts plot, this saturation vapor line hills towards the left.

In pv plot, it hills towards the left. This is because the specific volume decreases because of the compressibility. But here it is other way that is specific entropy is reduced when we increase the pressure. This curve hills towards left and ultimately it creates the vapor dome meeting at a point known as the critical pressure.

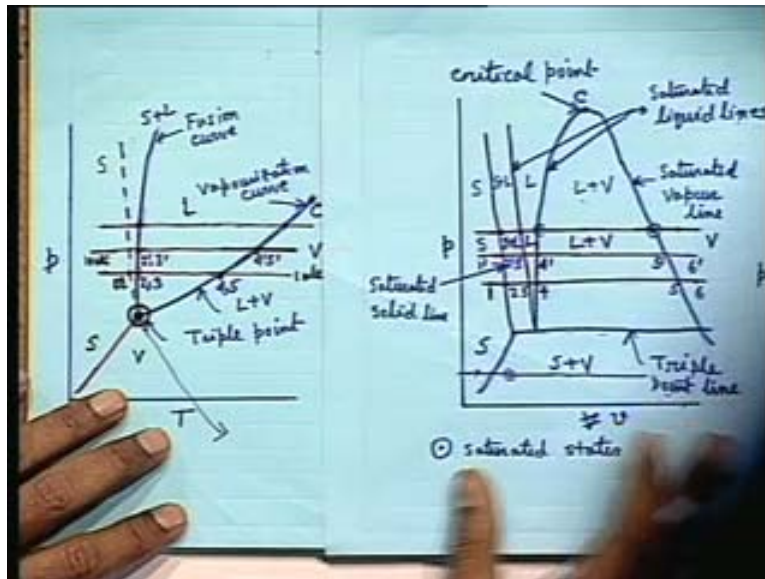
If we draw a constant pressure line like this, only in the liquid part, the critical pressure line is like this. So, this is precisely Ts plot in the phase diagram. Now, I come to this pT.

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Now to understand this pT plot very clearly, I think we should compare with it pv plot.

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This is the  $p-v$  plot. Now, at any constant pressure, if we heat, this is the saturated solid, saturated liquid. In this case, when the phase change takes place, these two points, two ends of the saturation state, solid and liquid similarly here liquid and vapor are space tapered. This is because these specific volumes are different. We are placing it on  $v$  axis. They are same in pressure and temperature, but vary in specific volume. For an example, if we consider water. So, this pressure one atmospheric pressure, this temperature 100 degree Celsius and this temperature 100 degree Celsius, but their specific volume varies. This temperature 0 degree Celsius and this also 0 degree Celsius, but their specific volume varies. When we do it for  $p-T$  plane, then two saturated states at the extreme two phases, they coincide to a point, because they corresponds to a single point with pressure and temperature.

Similarly, for the vaporization curves also, the four, five point, they are the extreme ends of the two saturated points. They also coincide. This curve is known as fusion curve and all the points on this curve represent this mixture of solid and liquid that means this zone. This part is the solid and this is liquid. Again, these points, four, five points and four dash five dash, all these are on single curve. This is known as vaporization curve.

Now, if we draw this line that is the solid liquid point on  $p-T$  diagram at different pressures, we will see that this curve is very steep; that means, the influence of pressure. If we consider the temperature, this temperature of solidification or melting is very less.

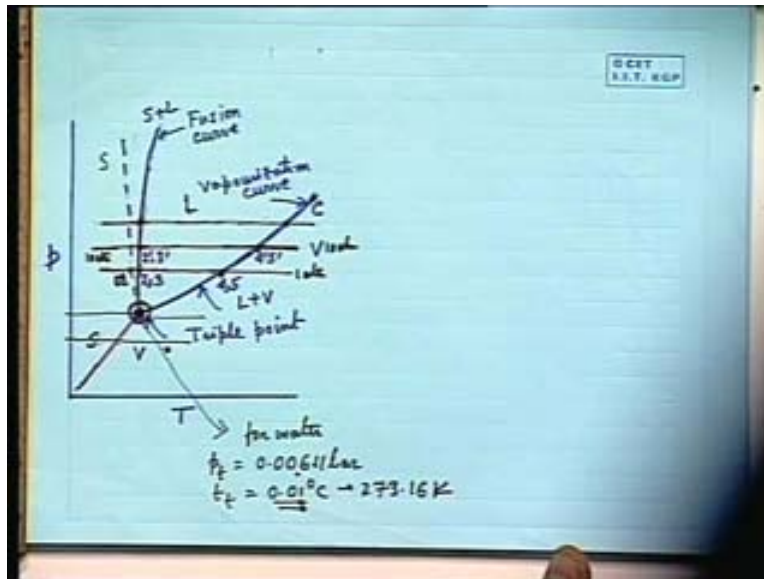
Except for water, it has a positive slope; that means, if we increase the pressure, temperature for melting to the corresponding pressure, saturation temperature for melting or solidification increases very little. But for water, the behavior is little different. as we go on decreasing the pressure, the melting temperature or solidification temperature increases. But in the cases, the decrease and increase is very small so that this curve is very steep. This is the gift of the nature so that these two curves meet at a point. Whereas this curve is very flat which means the pressure has a dominant influence on the vaporization temperature.

Let this is the one atmospheric pressure and if this temperature is 100 degree Celsius, if we change the pressure to ten atmospheric pressure then there will be substantial change in the temperature for vaporization.

So this curve is relatively flat, whereas for water it is not so; for melting it is not so. If it is one atmospheric pressure, it is melts at ten at 0 degree Celsius. If we change the pressure to 10 atmospheric pressure, it will melt at the lower temperature. This is a peculiarity of water, but that lowering of temperature will be very small and very less than the 0 degree Celsius. So this curve is curve steep, whereas this curve is very flat. So, there is an opportunity that these two curves meet at a point. This point is the triple point. So, below this point, we state a solid and vapor.

I am giving an example, one atmospheric pressure; water is boiling at 100 degree Celsius. If we go on reducing the pressure, the boiling temperature or saturation temperature goes on drastically decreasing. Whereas, if we go on reducing this pressure on saturated solid, water or saturated water which is being solidified, or saturated solid water which is melting, this increase in temperature is very small. So, there is an opportunity where they meet at a point and this point for water, the value of this point is triple point of water.

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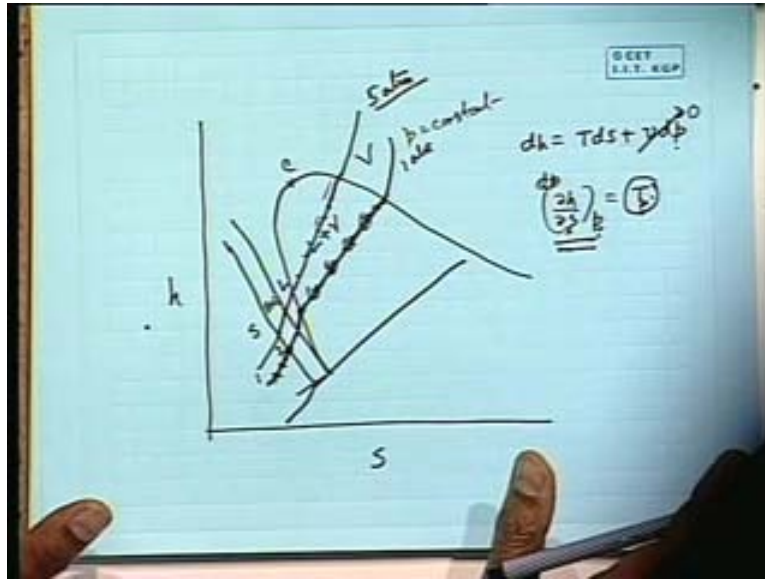


This value  $p_t$  is 0.00611 bar. We know bar, ten to the 10 to the power 5 Pa and corresponding temperature is 0.01 degree Celsius. 273.16, 273.15 is the conversion plus 273.15. Therefore, point 273.16 K. When we reduce the pressure from one atmosphere to this atmosphere, water boils at this temperature.

At the same time, when we reduce the pressure from one atmospheric pressure to this pressure that means this pressure, water also solidifies at this temperature. So, this is the meeting point. So, below this pressure, if we heat solid water, it will directly transfer into vapor. This process is known as sublimation.

Therefore, the saturation states in  $p_t$  diagram appear at points and the locus of that points are known as saturation curve, fusion curve. This is vaporization curve. Now, let us draw the  $h_s$  diagram. If we draw, we will see that it will look like this.

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If we draw the hs diagram enthalpy, entropy diagram, it will look like this. It will be little like same type of thing. Now, when we increase the enthalpy, for example when we heat from one to two that means solid region, when we heat both, its enthalpy will increase at constant pressure; p is equal to constant.

Again, we think of a constant pressure heating, then the pressure to enthalpy will increase and entropy will increase. So, qualitative trend will be like this. When we heat it at a constant pressure and temperature, because of the phase change this is solid plus liquid, this is liquid similar way now we know this thing that is why I am going little fast. So, it also increases, but it is a linear curve.

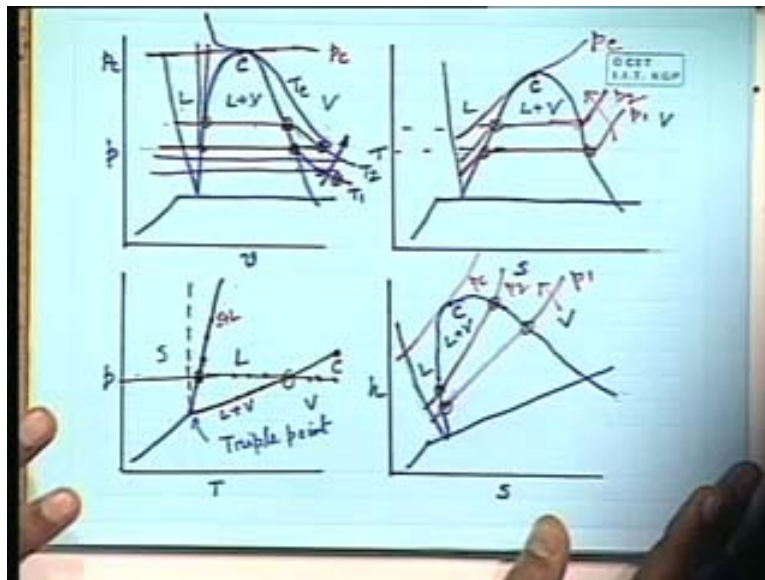
Similarly, in sensible heat part, there is an increasing trend but when the phase change is there, this is linear. How we get this thing? let us see that. In hs diagram, at constant pressure, we know that dh is equal to Td s plus v dp. Now, at constant pressure, this is 0. Therefore, del h divided by del s is a very important relationship and it is equal to T. At constant pressure, del h divided by del s at constant p is equal to T; that means, slope of a curve in hs plane at constant pressure. A constant pressure line in hs plane, the slope at constant pressure line in hs plane at any point is equal to temperature of the system.

When we go on heating, at each and every point on sensible heating part, the temperatures are changing; increasing. So, this curve is with increasing slopes tip. So, if we draw this thing qualitatively, it will tell us that our concept is clear, whereas when we

draw this curve in this portion, it is constant because  $T$  is constant. When phase change is taking place, each and every point  $T$  is constant during the phase change; solid to liquid or liquid to vapor. So,  $\Delta h$  divided by  $\Delta s$  at constant  $p$  is constant; that means, it is linearly increasing. As we go on heating, both the enthalpy and entropy is changing.

If we draw another curve, constant pressure at a higher pressure, then **this** curve will have a greater slope. If we show this linear curve in the phase change diagram, do not draw parallel to **this**. It is diverging type because slope of this curve is more than that because **this** is equal to temperature. So, saturation temperature is more than **this**. For example, this is one atmospheric curve, all these points correspond to 100 degree Celsius temperature; that means, slope corresponds to this 100 degree Celsius. Whereas if it is of five atmospheric pressure, if the saturation temperature is 150 degree Celsius; that means, this temperature is more that means slope of this line, linear element is more. So, they are diverging in nature. Now, we can construct the  $h-s$  diagram. Now we should compare these four diagrams. That is very important. How do we compare?

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Compare means if we look, no question of comparisons. But if we look then it will be clear see  $p-v$  diagram. So I am only drawing the liquid, liquid vapor and this is the liquid line, this is liquid vapor.

These red lines are the constant pressure line whereas **these lines** (Refer Slide Time: 15:36) are the constant temperature lines, isothermal lines. If we want to understand the



isothermal line, at any point here, if we move in this direction, at constant temperature, moving in this direction means we are increasing the pressure. Number of constant pressure lines intersects. If we move an isothermal compression, we come to this point; that means, we are coming to the liquid. That means compressing a gas, we can come to the liquid.

For example, this is the atmospheric pressure line. So, this temperature is 100 degree Celsius. So, this is the saturation temperature. Now if **this (Refer Slide Time: 16:21)** 100 degree celsius line extends here and even at some point **here**. For example, here whose pressure is lower, and then one atmospheric pressure; that means, it is in vapor state. If we compress that vapor to one atmospheric pressure then only it will become liquid because 100 degree Celsius water at some atmospheric pressure is a vapor. Similar is the case at this intersection; that means, this is one atmospheric pressure and the corresponding isotherm is 100 degree Celsius. This is one atmospheric pressure, but this is an isotherm at a higher temperature. This is at a higher temperature, for example, 150 degree Celsius.

If we compress it at certain stage, where the pressure will be the corresponding saturation pressure for this temperature and it starts condensing, this is the link. That is why, the isotherms are like **this and this is (Refer Slide Time: 17:15)** coinciding with the constant pressure lines. Here, the isotherms are very steep upwards, because if we make an isothermal compression, water is incompressible. There is a very little change in  $v$ . So, these are the isotherms in  $p-v$  plane.

Similarly, in  $T-s$  plane, the isotherms are like that. We have already appreciated and **sorry** isobars are like that. Isotherms are the lines parallel to  $s$  axis and these points are the saturated points and this gap is the change in the entropy. This is the  $p-T$  diagram and This is the  $h-s$  diagram. **(Refer Slide Time: 17:45 to 17: 54)**

So, these four diagrams, if we see at a time then these points are the saturated points. These points coincide here in  $p-T$ , saturated point. One thing is clear, in saturated state, this point shows that pressure and temperature are interlinked. When we fix the pressure, temperature is automatically fixed.

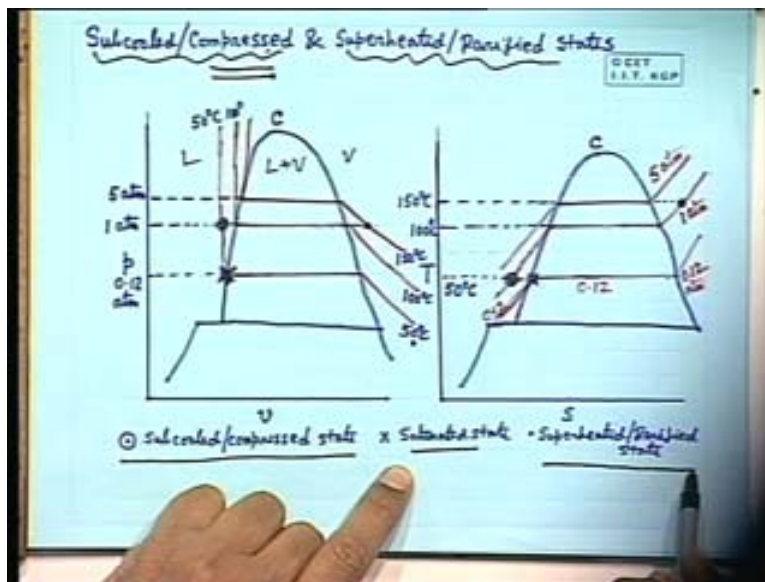
If we see the Gibbs phase rule, that Gibbs phase rule can tell us what is the number of independent variables required in fixing the state of a system. That depends upon the

number of components and the number of phases. When the numbers of phases are two, they exist in equilibrium; then the pressure and temperatures are uniquely connected. When pressure is fixed, temperature is fixed. Only one variable is required to fix this state of the system.

For example, liquid and vapor, can co-exist only in a pair of pressures and temperatures; not at all pressure. For example, if this be the pressure here, so, this has to be the temperature. (Refer Slide Time: 18:57) Then only solid and liquid can coexist in equilibrium. This be the temperature and this pressure, any other temperature either it will be vapor or it will be liquid. At a pair of pressures and temperatures, only the equilibrium between the two phases are possible.

This is the  $T_s$ , this is the  $h_s$ . (Refer Slide Time: 19:20) These points are the saturated states and there is a change in this specific volume during this change of phase. There is a change in the entropy; there is a change in the enthalpy. That is why, these points are space tapered. But in  $pT$  diagram, they are the points. These points are known as saturated states.

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Now, with respect to this, let us see, what is known as sub cooled or compressed, and superheated and rarefied state; this is another concept. It should be clear that sub cooled or compressed; these are the synonymous things, or superheated and rarefied state. A very concrete example I have shown here. Let us consider the  $pv$  and the  $Ts$  diagram.

In pv diagram, first this base line pressure that is one atmospheric pressure. Let this be the one atmospheric pressure, the isotherm which coincides with one atmospheric pressure in the vapor dome. This is liquid, this is liquid plus vapor; vapor should be 100 degree Celsius that means this temperature is 100 degree Celsius.

If we have a liquid, for example, 50 degree Celsius; let us first locate here. So, correspondingly in Ts diagram, let us consider that this is the similar one atmospheric pressure line. So, this is one atmospheric pressure line and obviously, this temperature is the 100 degree Celsius.

Now, if we have 50 degree Celsius water at one atmospheric pressure, that is known as sub cooled liquid, because its temperature is lower than the saturation temperature corresponding to that pressure at one atmospheric pressure. The 100 degree Celsius water is the saturated water for vaporization; that means its saturation temperature is 100 degree Celsius.

It is below the saturation temperature; 50 degree Celsius. These can be shown here. This lies on another isotherm which is at 50 degree Celsius. This state is known as sub cooled because this temperature is below the saturation temperature and the degree of sub cooling difference is 50 degree Celsius.

At the same time, this is known as compressed state. Why a sub cooled state is the compressed state? We can think from other angle that at this temperature, if we want to vaporize this water then we have to reduce the pressure; so, 50 degree Celsius. That means, if I now go like this then we will see that this 50 degree Celsius isotherm; that means, if I follow this line that means I am reducing the pressure. So, if I go on reducing the pressure, there will be a point where this 50 degree Celsius saturation temperature.

At that point, the pressure is 0.12 atmosphere. This I have taken from the table. 0.12 atmospheric pressure, water boils at 50 degree Celsius. This point is at a compressed state; that means, at a higher pressure corresponding to this saturation pressure of its existing temperature. From that angle, this point is a compressed state. Here, it is at 50 degree Celsius.

So, at 50 degree Celsius, if we go like this then it becomes the saturation state. So, through that point there is a constant pressure curve which is 0.12 atmospheric pressure. A sub cooled state is the compressed state. This is because its temperature is lower than

the saturation temperature corresponding to its existing pressure, or its pressure is higher than the saturation pressure corresponding to the existing temperature. So, that is why a sub cooled and compressed state; this is saturated state. Similarly, superheated state is a rarefied state.

Let us consider at one atmospheric pressure a point in the vapor region. Let this point is 150 degree Celsius .We have steam at 150 degree Celsius; one atmospheric pressure. So, superheated steam and degree of superheat is 50 degree Celsius, because it is 50 degree Celsius more than the saturation temperature. Thus, the reverse of the sub cooled state.

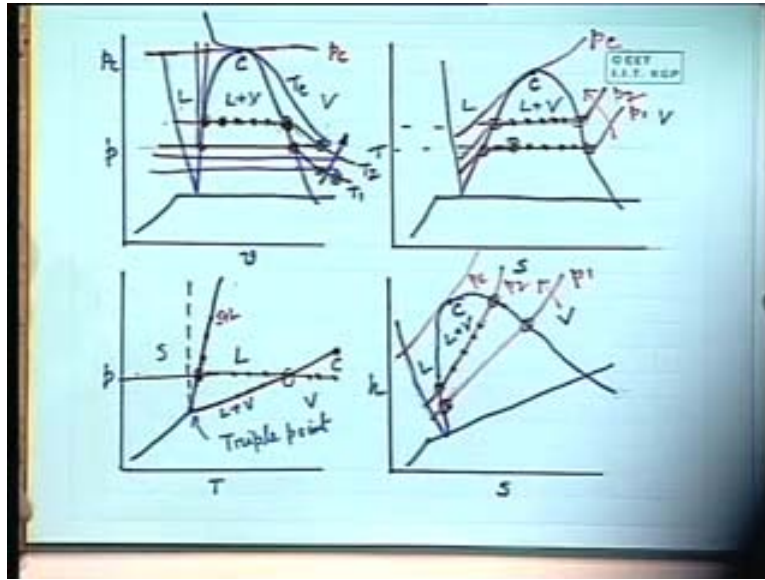
Therefore, this is superheated. If we cool it at constant pressure then it has to come to 100 degree Celsius for condensation. So, how to show this point here? This point is the one atmospheric pressure. So, we just extend this point and we see this cuts an isotherm. We have to extend this pressure line and the intersection of this pressure line with the 150 degree Celsius line. This is the point here.

This is a superheated state. Similarly this is a rarefied state because if we have to condense this point then I have to move in this direction. When we move in this direction, at 150 degree Celsius, not in this direction and the same temperature, if I have to now condense, this has to move in this direction so that it becomes saturated here. (Refer Slide Time: 24:32 to 25:00) This pressure line is the higher pressure line, five atmospheric pressure line.

This is 50 degree Celsius for which the five atmospheric pressure line is the saturated pressure. 150 degree Celsius steam can be condensed if I increase the pressure to five atmospheric pressure. It is at a relatively lower pressure that means it is a rarefied state. Its temperature is more than the saturation temperature corresponding to the existing pressure, or its pressure is lower than the saturation pressure corresponding to the existing temperature so that the superheated state is a rarefied state. There are two states; sub cooled or compressed state, and superheated or rarefied state, where the sensible heating and cooling takes place.

Now, we have seen that in these four diagrams.

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These are the saturated states and the properties are well fixed, all fixed; that means, this have got pressure and temperature, but other properties, specific volume of saturated liquid is fixed and specific volume of saturated vapor is fixed. This vapor is known as dry saturated vapor that means completely dry vapor.

Here, the entropy is fixed. This entropy is fixed, this enthalpy is fixed, and this enthalpy is fixed. (Refer Slide Time: 26:25 min) What are these state points which show different values of specific volume, specific entropy or even specific enthalpy, but at the same pressure and temperature within the vapor dome?

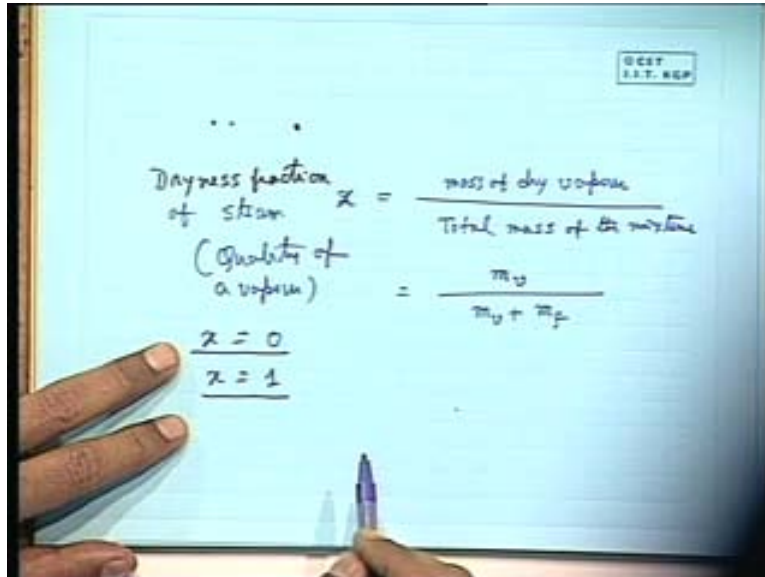
What are the different points showing the different values of specific volume, showing the values of specific entropy, showing the different values of specific enthalpy within the vapor dome but at the same pressure and temperature indicated. They indicate physically a mixture of the two phases and the mixture composition is varying.

For example, at this point it is full water when we plot in this direction. This point is mixtures of water and vapor and as we go in this direction, the mixture composition, the vapor constituents increases and here it is full of vapor. Therefore, all these points are specified by a mixture composition and all these points in the vapor dome represent a mixture of the two phase. (Refer Slide Time: 27:11 to 27:33 min)

In a container, we may have both water and steam, but this mixture of water and steam, the composition may vary and that is represented by the state point. This is a pure

component. This is a single phase. These are pure components, but these are a mixture of two phases. Therefore, to specify any property for these state points, we will have to specify the mixture composition and that is known as dryness fraction of a liquid vapor mixture.

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Handwritten notes on a whiteboard:

Dryness fraction of steam  $x = \frac{\text{mass of dry vapour}}{\text{Total mass of the mixture}}$

(Quality of a vapour)  $= \frac{m_v}{m_v + m_f}$

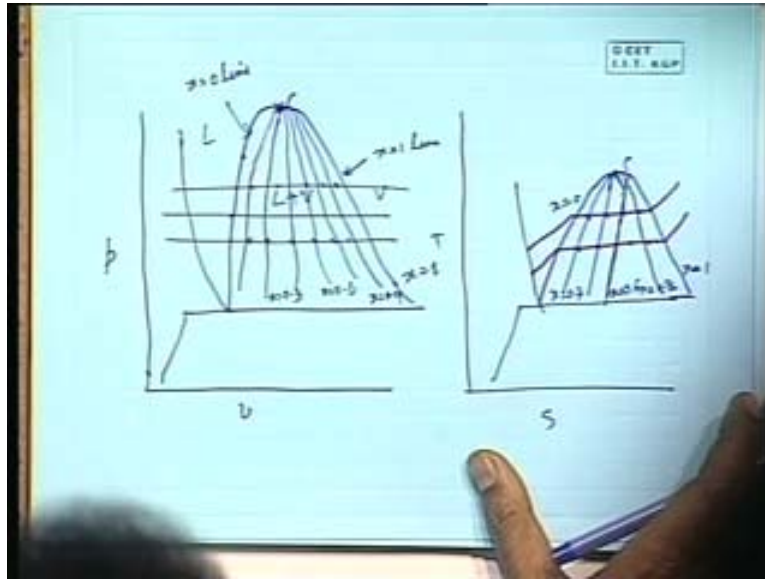
$x = 0$

$x = 1$

We consider here the steam and water. So, with respect to this, there is a dryness fraction of steam is equals to that and it is denoted as  $x$  which equals to the mass of dry vapor, steam or vapor divided by the total mass of the mixture.

The mass of dry vapor, let us denote  $m_v$  and total mass of the mixture; this is a mass of dry vapor plus the mass of the liquid  $m_f$ . At saturated liquid state the value of  $x$  is zero. At saturated vapor state the value of  $x$  is one. This is sometimes known as quality of a vapor or quality of steam. That means  $x$  is equal to zero is the saturated liquid line and  $x$  is equal to one is saturated vapor line.

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Therefore, now we can make different line like this; rather, I will draw this here. If we draw the  $p-v$  diagram like this, we are interested in the liquid plus vapor into vapor. This is  $c$ . At any pressure, we have specific volume depending upon the value of  $x$ . These are the  $x$  is equal to zero line. This is  $x$  is equal to one line and in between we have different  $x$ . We can draw locus of constant  $x$ , with different values of  $x$ . They all meet at critical point; this is  $x$  is equal to one. Let this is  $x$  is equal to 0.9; that is  $x$  is equal to 0.6,  $x$  is equal to 0.3, finally  $x$  is equal to zero.

Similar is the case for  $T-s$  diagram also. A  $T-s$  diagram looks like this. **Sorry, diagram why but doesn't matter the scale is different.** So,  $T-s$  diagram also, these are the constant pressure lines so that we can show different dryness fraction points having various entropies. We can draw at different temperature or pressure lines. These are all coinciding. These are all coming from the same point  $x$  is equal to 1,  $x$  is equal to 0 and various values of  $x$ ,  $x$  is equal to 0.8,  $x$  is equal to 0.6 like that  $x$  is equal to 0.3. These are the constant  $x$  curves constant quality.

**Yes**

**[Conversation between Student and Professor - Not audible ((31:51 min))]**

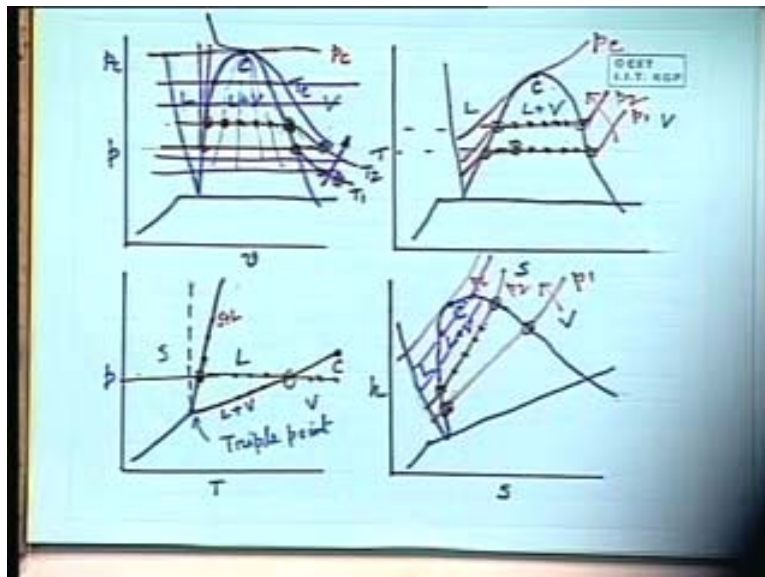
$x$  at a critical point; that value of  $x$  at a critical point. I will explain what it is? The critical point is very difficult to understand. What is the value of  $x$  at critical point? Because all  $x$

values are meeting at the point, the value of  $x$  is not defined at the critical point. This is the answer.

The value of  $x$ ; geometrically all the  $x$  constant,  $x$  lines or different values emerge from critical point. Mathematically, one can see that the value cannot be defined at critical point. So, physically and both mathematically, the answer is that value of  $x$  is not defined at the critical point.

In relation to that I will explain what is a critical point? So far, we have studied the vapor dome phase diagram, how we can represent the state points in the phase diagram, in an isotherm, in an isobar, What is sub cooled or compressed state? What is superheated or rarefied state? Now I will explain what is a critical point.

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The critical point is the point where the saturated liquid line and the saturated vapor line merges. Just follow these three diagrams, not in  $pT$  diagram. When we increase the pressure in  $p-v$  diagram, the difference in specific volume is going to be reduced.

Initially, the specific volume of liquid is more than that of the vapor, but as we go on increasing the pressure, the difference between the specific volume of the liquid and the vapor is going to be reduced.

Ultimately at  $c$ , there is no change in the specific volume of liquid and vapor is the first observation. Second observation here in  $Ts$  diagram, the change in the entropy between



these two points is going to be reduced. But before that it will be more appreciating that the change in the enthalpy between the two state points are going to be reduced.

What does it mean physically? What is this change in enthalpy imply? The heat added to this? If we write the steady flow energy equation, enthalpy of this dry vapor minus enthalpy of the liquid is the amount of heat added. Specific enthalpy difference is the amount of heat added per unit mass.

This is precise latent heat. As we go on increasing the pressure, the latent heat is reduced. The vapor enthalpy and liquid enthalpy are coming close together. It requires a very less heat to become the vapor and ultimately at the critical point it becomes 0.

From these three diagrams, obviously, the entropy change is 0. At critical point, the conclusion is that the properties of the dry saturated liquid and the properties of the dry saturated vapor become exactly the same and liquid does not take any heat to vaporize.

That means that except the critical point, that means below the critical point, there is a distinct phase transition. When it gives the heat to water after taking sensible heat at a constant pressure, it attains a temperature. At that temperature, there is a time when the liquid is getting converted to a vapor.

How do you know that it is going from a very dense medium to a very light and verified medium which we distinguish as vapor? It takes some time. That is because it takes some finite amount of heat which is the latent heat. If we measure the properties like specific volume, enthalpy, entropy, internal energy then there is a finite change in that property.

Therefore, the phase change process is defined where they have distinct phases and there is a time taken for a given amount of a particular phase is to be converted to other phase having different properties from the earlier phase and taking some finite amount of heat known as latent heat. But at critical point, all these differences are 0.

If we go on heating at the critical pressure, here at critical pressure, for example, here if we go on heating water at the same critical pressure, slowly water is heated. At some temperature, it is defined here, where automatically it flashes into vapor. It automatically flashes; very difficult to understand. They are the temperature physically thing is like that, slowly the density of the water. For example, if we think in terms of the density, one property specific volume gradually changes and there is no discontinuity.

It is very difficult to recognize liquid from vapor within in a distinct transition zone. The specific volume is slowly increasing and there is a smooth transition. We cannot distinguish from one distinct state of the phase to another distinct state of the phase is a continuously increasing function or a continuously decreasing function. At a very difficult point before which that is the distinct phase after which there is another distinct phase. This is defined below the critical point, because there was a discontinuity.

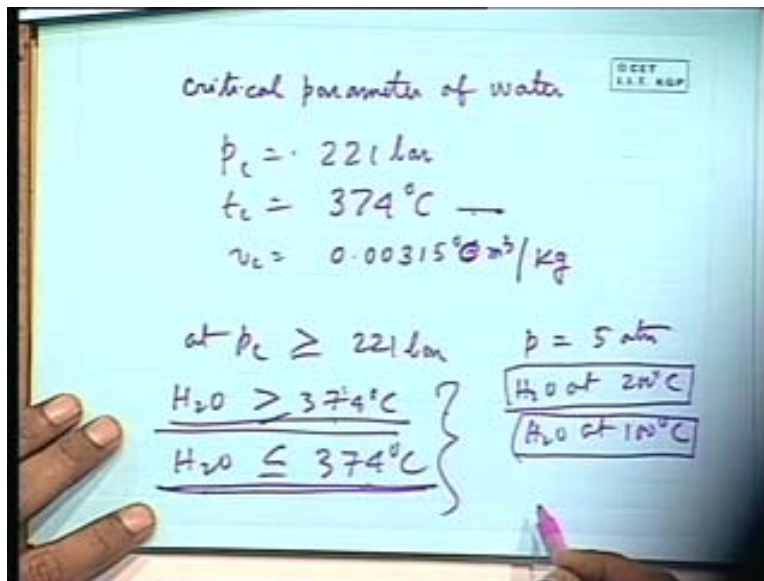
If we plot the specific volume verses time then temperature. Then at a constant temperature, specific volume, there is a sudden jump. For an enthalpy there is a sudden jump. There is a discontinuity but there is no discontinuity. Liquid automatically converts into vapor. **This is the book definition. But we should not define anything like that.** There is no distinction between liquid and vapor. Critical point of a component; like that, they remain as a component. So, there is no distinction between liquid and vapor in the critical point.

Critical point for example, at same isotherm if we go and compress the vapor, we go on compressing the vapor with this; that means, the specific volume is decreasing and it continuously goes on decreasing. Here, if specific volume is decreased and here at the same temperature, there is a drastic change in specific volume.

There is a discontinuity while the temperature remains the same. We can define two distinct phases at critical point, beyond the critical point, at and beyond the critical point there is no distinction between the two phases, absolutely there is no distinction between the two phases. One phase automatically transferred to other phase.

**For example, water at critical point if we define above critical pressure water at this temperature, water at that temperature having a property of this, having a property of that** but there is no distinction at all. Now, I tell the values like that, for example.

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We can understand better critical properties, critical parameter of water. This is the information many of we know that  $p_c$  is 221 bar approximate values. I am not going for the decimal point.  $t_c$  is 374 degree Celsius and  $v_c$  is 0.00315 degree Celsius m cube per kg.

[Conversation between Student and Professor - Not audible ((39:29 min))]

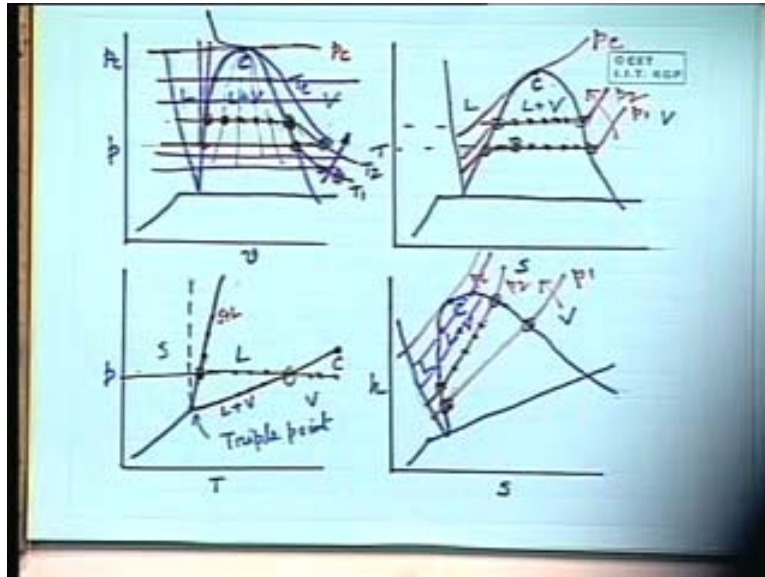
We can give it in Kelvin, but we can express in  $t_c$  also does not matter.

[Conversation between Student and Professor - Not audible ((39:37 min))]

374 degree Celsius and not the Kelvin. When I am writing Celsius, it is Celsius not the Kelvin. We can convert it into Kelvin by adding 273, but sometimes this is the convectional value. So, usually we give terms of the Celsius.

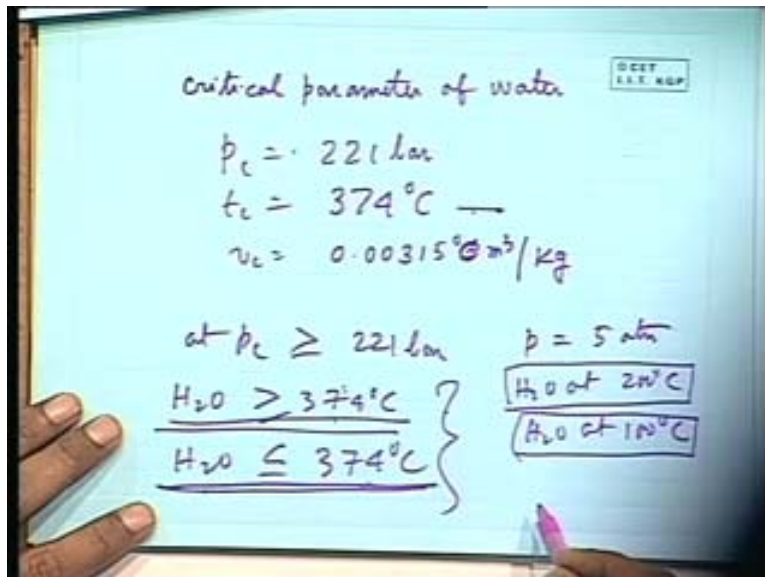
Now, see that to understand what the physical concept is.

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If one tells again I am coming here, that at this point and this point what is the difference? This value is greater than 374 degree Celsius. This value is less than that, less than that 200 degree Celsius. But, the pressure is 221 one bar or even at a higher pressure.

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At pressure,  $p_c$  greater than is equal to 221 bar.  $H_2O$  greater than 374 degree Celsius or even equal to  $H_2O$ , is not wise. **This is the concept; many books do not make it so clear. It is wise to tell, not to tell that whether this is liquid or that means this is liquid and this is vapor. This is water below 374 degree Celsius water above 374 degree Celsius.**

It has definite properties. So, there is no distinction between liquid and gas, but on the other hand, if  $p$  is equal to five atmospheric pressure,  $H_2O$  at 200 degree Celsius,  $H_2O$  at 100 degree Celsius, then this is steam vapor and this is liquid water. Though this has definite properties, because when we go from this to this at this atmospheric pressure, then there is a phase transition. But at critical point, there is no phase transition. Beyond the critical point there is no phase transition; system is unique by its component. So, the definition of phase change, identification of phases, all these things are not valid.

Many books write many languages I am telling you firmly.

The liquid automatically converts into vapor. There is no difference. If an experimenter sees that it is very difficult for him, tell “yes”. Here is the discontinuity. When a liquid is being boiled and going to vaporization, how do you distinguish? Because it distinguishes from a specific volume, there is the dense medium and there is a line. We tell this is a vapor and this is a liquid. But if it goes on continuously changing without any discontinuity in a specific volume, no experimenter can tell, “yes. This is the point, where I tell a particular phase is being converted to another phase below this point. This is a different phase beyond this point this is a different phase, no difference. No latent heat is required”.

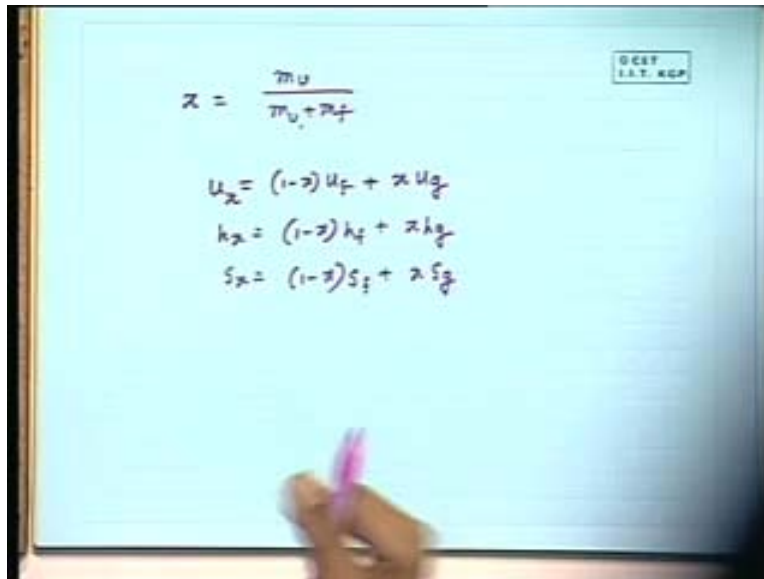
The phase transition is not defined at and above the critical point. I will be very happy because, these are very important things I will you.

These concepts are very much related to cryogenic applications, cryogenic rocket engines or other, where the liquid oxygen are used at more than critical conditions. They are vaporized. So, there is no distinct phase for that when we do the calculations for heat transfer and other things. we try to recognize that there is no such continuous change of phase.

There are many applications where liquid is used above the critical points, critical pressures heating of the liquid or cooling of the liquid takes place. There liquid as it is that means it is recognized by its component only that is no distinct phase transition.

Now, very important thing to come down to the reality; we know that at any intermediate points the composition is specified by  $x$ .

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The whiteboard contains the following equations:

$$x = \frac{m_u}{m_u + m_f}$$
$$u_x = (1-x)u_f + xu_g$$
$$h_x = (1-x)h_f + xh_g$$
$$s_x = (1-x)s_f + xs_g$$

Dry vapor divided by dry vapor plus fluid. Therefore, the extensive and also the corresponding intensive properties depend on this intensive property and the specific extensive properties. Extensive properties are the properties depend on the mass and therefore, in a mixture of two phases, the extensive property will depend upon the composition.

What is the internal energy, enthalpy or entropy of a mixture of water and a steam at a particular pressure and temperature? What is the composition? I know these values for the steam, dry steam at that pressure and temperature, because this end of the curve. I know this value for the saturated liquid at that pressure and temperature, but if we tell a mixture of that, then we need the value of  $x$ .

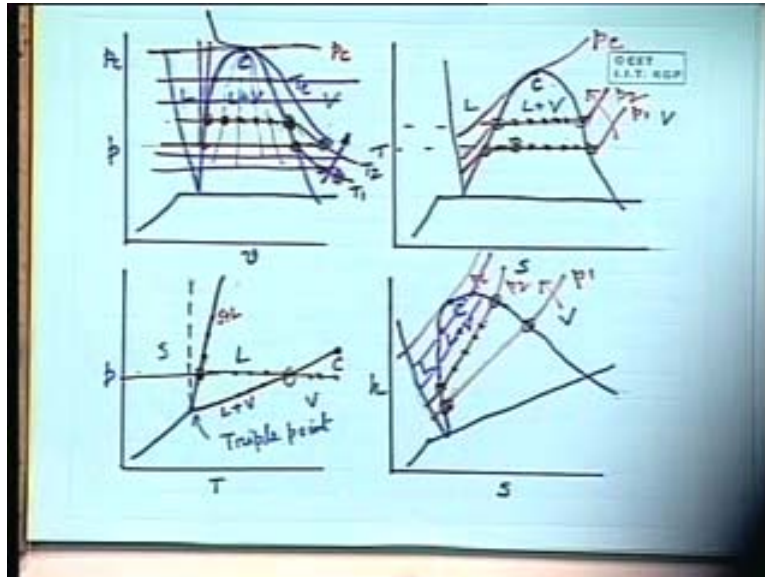
Then this is simply at class four five level calculations that if you define. We can write immediately all such properties; specific internal energy for any quality or dryness fraction  $x$  is one minus  $x$ . Before that,  $f$  is the conventionally used subscript denoting the properties at saturated liquid states and  $g$  is the conventionally used subscript to denote the properties at dry vapor. Therefore, it will be  $x$  into  $u_g$ .

I think there is no disagreement with that, it is simply a primary school job.

This is the contribution from liquid side and this is the contribution from the vapor side, dry vapor side. Similarly, all intensive property corresponding to the extensive properties; these are specific internal energy, specific enthalpy, and specific entropy.

If I know the values of these properties specific internal energy, enthalpy, specific entropy at two saturated state points of the two phases, then I can find out the values for a mixture of these two specified by  $x$ . I require another one parameter, more parameter  $x$  to determine this. So, this is very important thing.

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There are tables for all these properties at saturated state, end states, in the superheated vapor region and also in the subcooled state for each and every substance. But for our work, we are much more interested for all common work with water.

Water is a very common fluid which is used in practice. While, it is faced and very common example is a steam power plant. So, the table which tabulates the properties at saturated states, and also the superheated rarefied or compressed sub cooled state are known as for water steam tables. I think you develop practice in your house to see these steam tables I tell you how it looks like. Again it is a primary school level education but you must know that a steam table documents the thing this way. There are two types of steam tables.

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Saturated Steam Internal Energy

Pressure $p$ MPa	Temperature $t$ °C	Sp Volume		Sp Enthalpy			Sp Entropy	
		$v_f$ m <sup>3</sup> /kg	$v_g$ m <sup>3</sup> /kg	$h_f$ kJ/kg	$h_g$ kJ/kg	$s_f$ kJ/kgK	$s_g$ kJ/kgK	
0.1	99.63	1.043	1.694	417.46	2675.5	1.3026	7.3594	

$v_{fg} = v_g - v_f$        $u_{fg} = u_g - u_f$   
 $u_f$        $u_g$   
 $u_g - u_f$

One is the steam table for saturated steam and this table is made of two ways; one way is the pressure as the left column; that means, it goes on writing the pressure from very low value. More tabulating the pressure then the corresponding saturation temperature, for example, I am giving pressure is the 0.1 M Pa which is the atmospheric pressure almost equal to atmosphere pressure then the corresponding saturation 99.63. Then they tabulate specific volume  $v_f$  in m cube per kg, specific volume  $v_g$  cm cube per kg. Otherwise, if we put it in the same unit, there has to be some 10 to the power minus 3 or like that. Sometimes, the units are changed. This cm cube per kg has typical value 0.1.

This is the specific volume for the liquid, specific volume for the dry vapor. This is the value corresponding to this pressure for water. The specific enthalpy for liquid, saturated for saturated dry vapor. Similarly, the specific entropy for liquid and specific entropy for saturated vapor, this is a typical value for 0.1MPa.

Now the pertinent question comes. I know many of you are eager to ask that how do you calculate this value?

Chandrasekhar what is your question? Do you have any question? How do you calculate this value? Why not so? That means you must know the difference.

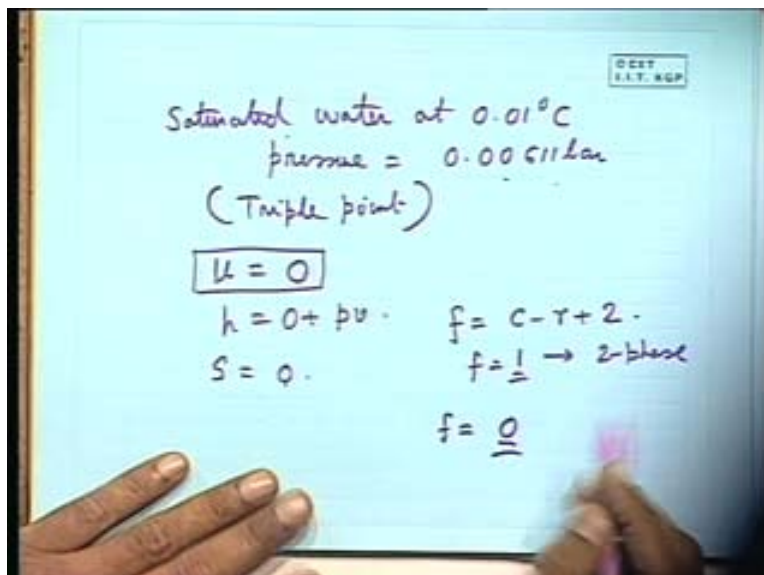
If I give a table depending upon, these are locations. This is the value of the potential energy. Where is that datum? Whenever I give an assigned value of the enthalpy, value of the entropy



Similarly, the value of the one thing is missing I am sorry, I am sorry what is missing? internal energy, very good internal because this is such a short paper to write internal energy.

Similarly, there will be  $u_f$   $u_g$ , sometimes in many steam tables the difference is also written. For example,  $h_{fg}$ .  $h_{fg}$  has got a very much physical significance. That is the latent heat. Sometimes, they give  $v_{fg}$ , they give  $u_{fg}$  that is  $v_g$  minus  $v_f$ , that means, the change in the specific volume. Usually  $v_g$  is much higher than  $v_f$ .  $u_g$  minus  $u_f$  so I am sorry, so, these values also are not there. So, this way saturated steam tables are generated. So, what is the difference? I have to know the reference datum. Where from these values have been calculated? The reference value is like this.

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Saturated water at 0.01 degree Celsius that means it is triple point, pressure is 0.00611 bar. This is the saturated water at this temperature means its pressure is this. That means water at this temperature and pressure is saturated. It can convert in to vapor, at the same time, if we extract heat it will convert to ice, it is a triple point; both the three phases existing to equilibrium.

Two phases can exist into equilibrium at several states, but this state of a restriction that pressure and temperature are not independent; they are dependent. If pressure is fixed, temperature is fixed. There may be many states, but with couple values of pressure and temperatures. But in triple point, the state is uniquely fixed; that is only unique state. So,

three phases can exist into equilibrium only at a single phase that comes from the Gibbs phase rule. So, at this saturated water condition; that means triple point, this is typically triple point.

I am going probably little fast I don't know, if you have got any doubt you can ask me question.

Triple points we consider the internal energy is 0,  $h$  is a small value,  $h$  is 0 plus  $pv$ .

So, with the internal energy, because we know from the beginning of the thermodynamics the internal energy is introduced in terms of its difference.

Now, a potential energy changes in terms of its different gravitational potential energy. Always it is defined in physics in terms of its difference. Therefore  $u$  is 0,  $u$  is the absolute value. To designate the absolute value of  $u$  at a state point, we require a reference  $u$ . Similarly entropy, entropy is also 0; that means, internal energy entropy are made 0 at this condition. Now, Gibbs phase rule if we remember is equal to  $c$  minus  $r$  plus 2.

What is  $c$ ?

[Conversation between Student and Professor - Not audible ((52:05 min))]

$c$  is the number of components,  $r$  is the number of phases.

If the number of the components is one and phase is two, then this  $f$  is equal to one. That means two phase system. The variance is one; that means, if one parameter is fixed intensive property state is fixed.

Steam air co-existing equilibrium at one atmospheric pressure that means sufficient condition is told, science does not require more thing. So, one atmospheric pressure means everything is known, 100 degree Celsius corresponding volume, corresponding enthalpy, and internal energy or the steam water system existing at equilibrium at 100 degree Celsius.

Only one parameter is required. If it is a triple point, what is  $f$ ? One  $c$  is 3; therefore, that is 0. For triple point state, variance is 0; triple point is a unique state we cannot have any variance. For all substance, there is a unique state. While the three phases of the substance coexist in equilibrium that is the triple point. So, with this, we tabulate the values which are documented in the steam table.

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Saturated Steam Internal Energy

Pressure $p$ MPa	Temperature $t$ °C	Sp Volume		Sp Enthalpy			Sp Entropy	
		$v_f$ m <sup>3</sup> /kg	$v_g$ m <sup>3</sup> /kg	$h_f$ kJ/kg	$h_g$ kJ/kg	$S_f$ kJ/kgK	$S_g$ kJ/kgK	
0.1	99.63	1.043	1.694	417.46	2675.5	1.3026	7.3594	

$v_{fg} = v_g - v_f$        $u_{fg} = u_g - u_f$   
 $u_{fg} = u_g - u_f$

Superheated steam table, for saturated steam table, superheated steam table again I tell the saturated steam table with pressure. We get temperatures corresponding the value specific volume, internal energy, specific enthalpy and specific entropy. These tables are made in two ways; one pressure corresponding temperature, another temperature wise corresponding pressure.

For that the interpolation job is little bit eased; we do not have to too much Interpol it. Sometimes, we require some temperature. So, we have to find out what is the saturation pressure. Then we can see the temperature table that depends upon water and steam at 150 degree Celsius coexisting in equilibrium.

If there is a pressure table, we may not have 150 degree Celsius. So, we have to Interpol it. So, we see temperature wise, there we will see that 150 degree Celsius and the resolution between the two pressures and temperatures are usually 20 degrees, 50 degrees depending upon the table.

Left side pressure or left side temperature, corresponding saturation temperature or saturation pressure and all the values of specific volume, specific enthalpy and specific entropy for two end points that means two saturated states. For superheated steam table, the documentation is made like that, but we have to look the steam table **and it will develop practice while solving problem which I will do in the next class.**

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Superheated steam Table

$p = 0.1 \text{ MPa}$  ( $t_{\text{sat}} = 99.63^\circ\text{C}$ )

State	$v$ ( $\text{m}^3/\text{kg}$ )	$u$ ( $\text{kJ}/\text{kg}$ )	$h$ ( $\text{kJ}/\text{kg}$ )	$s$ ( $\text{kJ}/\text{kg K}$ )
Sat	1.694	2506.1	2675.5	7.3594
100°C	-	-	-	-
150°C	-	-	-	-
200°C	-	-	-	-
250°C	-	-	-	-

↓ 300°C

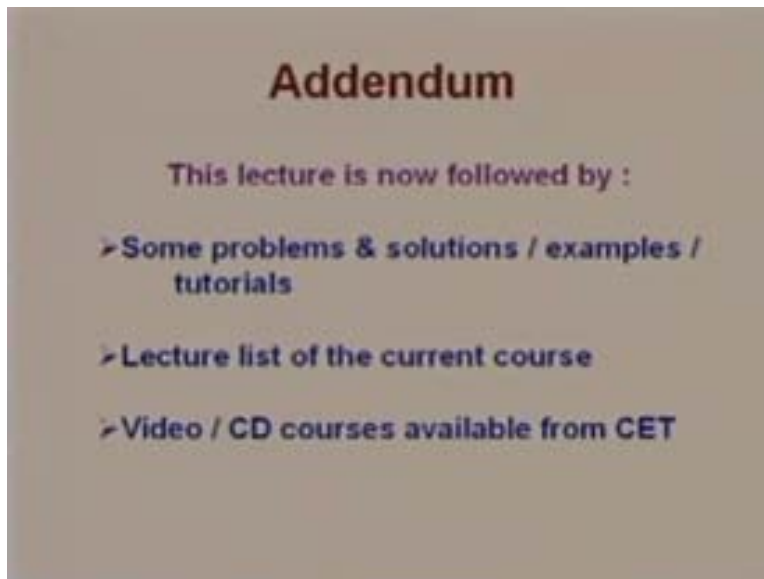
Superheated steam table; what do they do? In a superheated state, we know for a given pressure there may be number of temperature. For example, one atmospheric pressure steam may exist at any temperature starting from 100 degree Celsius, 150 degree Celsius, 120 degree Celsius, and 300 degree Celsius. It does not matter until and unless it goes to the plasma state.

At a given pressure, it starts like that; on the top, it rises the saturation temperature corresponding to that pressure. Then it tabulates specific volume, internal energy, enthalpy and entropy of the superheated vapor at that state.

First they tabulate saturated state. These are the saturated state values which will coincide with the values for the dry vapor in the saturation steam table. Then they tabulate with different temperatures; that means, if we find out the properties of superheated steam at 250 degree Celsius and go on 500 degree Celsius and all this. So, after certain limit, that limit depends upon our usable working range.

Clear? Okay!

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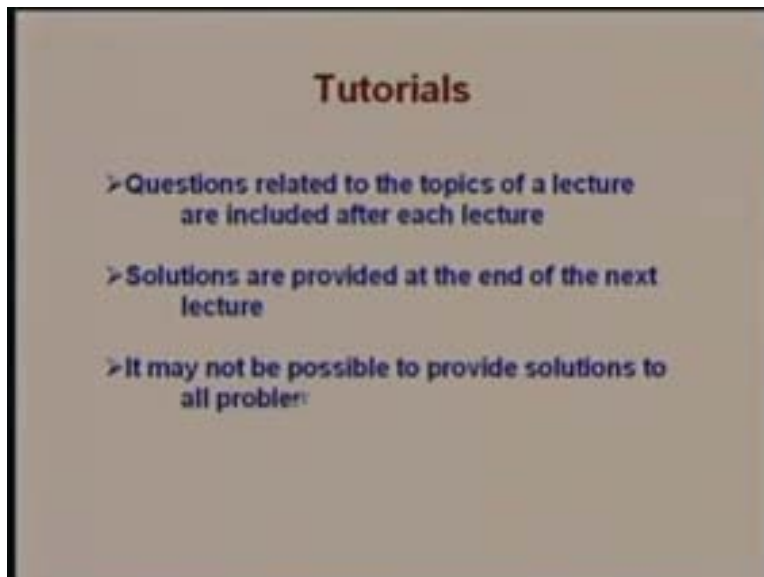


**Addendum**

This lecture is now followed by :

- Some problems & solutions / examples / tutorials
- Lecture list of the current course
- Video / CD courses available from CET

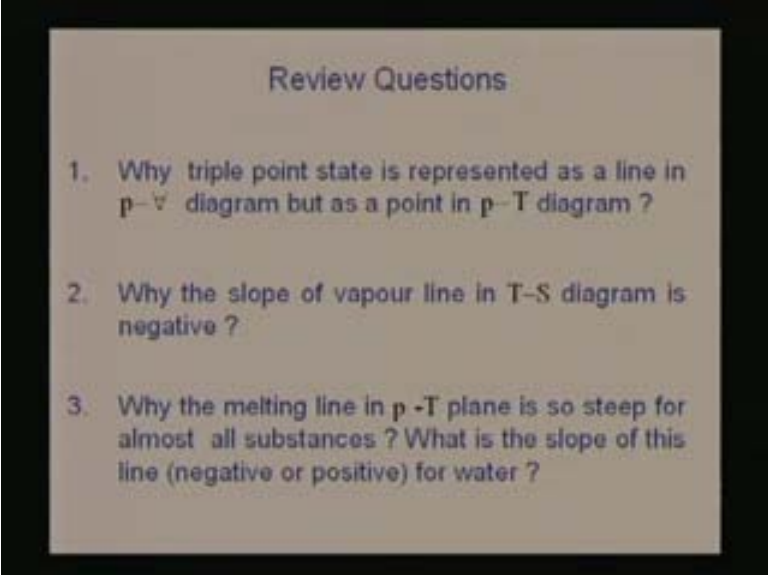
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**Tutorials**

- Questions related to the topics of a lecture are included after each lecture
- Solutions are provided at the end of the next lecture
- It may not be possible to provide solutions to all problems

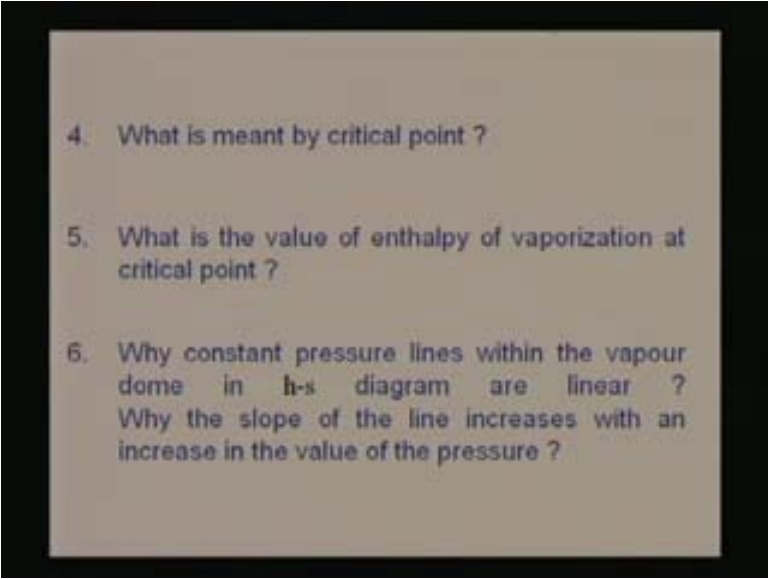
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Review Questions

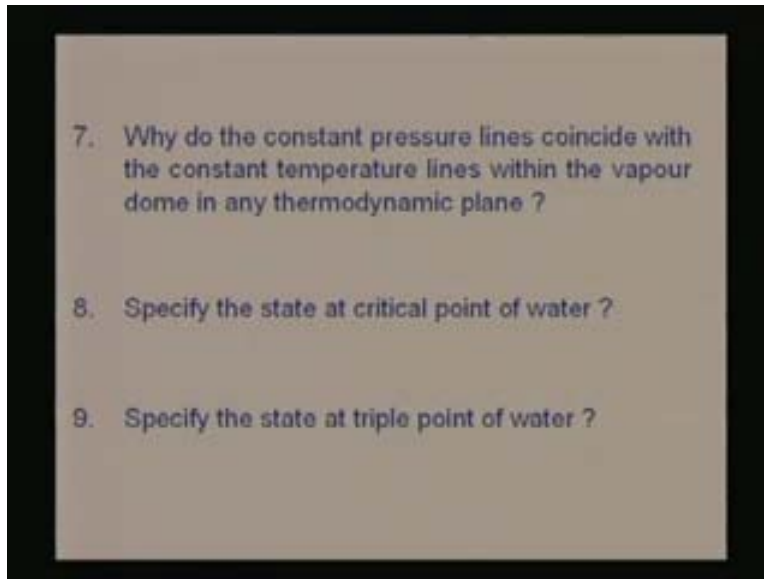
1. Why triple point state is represented as a line in  $p-v$  diagram but as a point in  $p-T$  diagram ?
2. Why the slope of vapour line in  $T-S$  diagram is negative ?
3. Why the melting line in  $p-T$  plane is so steep for almost all substances ? What is the slope of this line (negative or positive) for water ?

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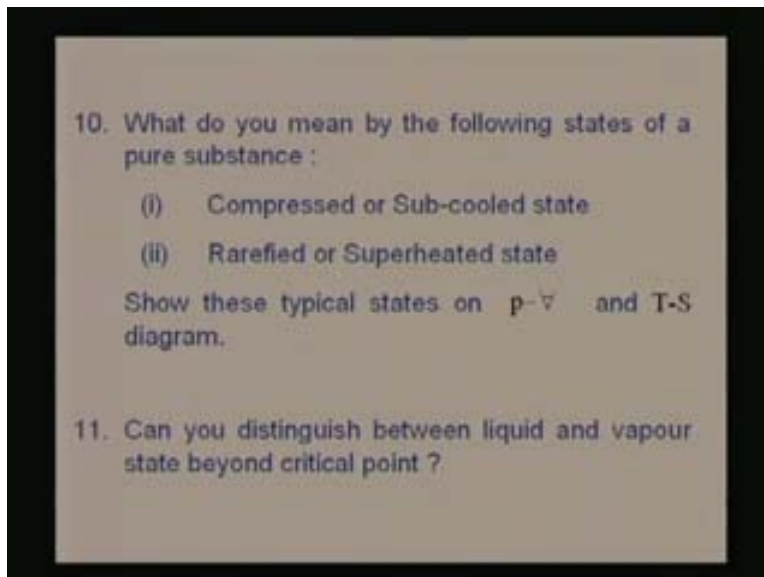


4. What is meant by critical point ?
5. What is the value of enthalpy of vaporization at critical point ?
6. Why constant pressure lines within the vapour dome in  $h-s$  diagram are linear ? Why the slope of the line increases with an increase in the value of the pressure ?

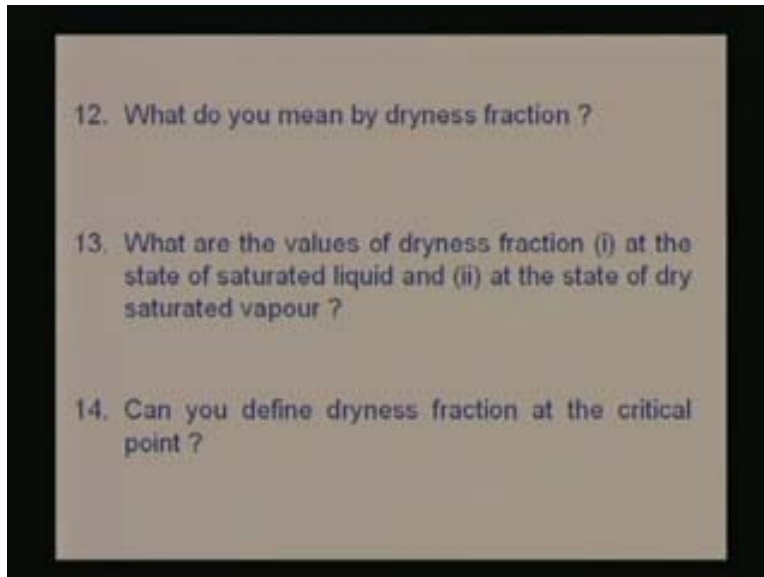
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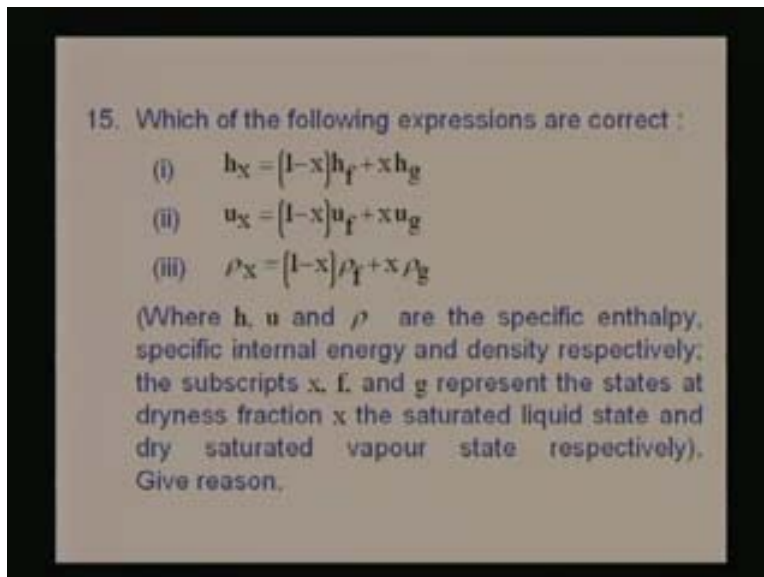


12. What do you mean by dryness fraction ?

13. What are the values of dryness fraction (i) at the state of saturated liquid and (ii) at the state of dry saturated vapour ?

14. Can you define dryness fraction at the critical point ?

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15. Which of the following expressions are correct :

- (i)  $h_x = (1-x)h_f + xh_g$
- (ii)  $u_x = (1-x)u_f + xu_g$
- (iii)  $\rho_x = (1-x)\rho_f + x\rho_g$

(Where  $h$ ,  $u$  and  $\rho$  are the specific enthalpy, specific internal energy and density respectively; the subscripts  $x$ ,  $f$ , and  $g$  represent the states at dryness fraction  $x$  the saturated liquid state and dry saturated vapour state respectively). Give reason.



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16. A rigid vessel contains 1Kg of a mixture of saturated water and saturated steam at a pressure of 0.15MPa. When the mixture is heated, the state passes through the critical point. What is the volume of the vessel ?

17. What happens when a substance is heated at a pressure below that of its triple point pressure ?

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Answer to the above questions are given at the end of Lec No. 17

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Answers of the Review Questions given at the end of Lec. No. 15

(Answers to objective / short Questions are only given. Answers to routine descriptive Questions are omitted)

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2. Enthalpy.

3. Irreversible process.

4. No.

6. Joule Kelvin coefficient.  $= \left( \frac{\partial T}{\partial P} \right)_h$

10. Zero.

17. One.