Basic Thermodynamics

Prof. S.K Som

Department of Mechanical Engineering

Indian Institute of Technology, Kharagpur

Lecture - 17
Properties of Pure Substances-I

Good morning to all of you. We were discussing about the properties of matter and the phase diagrams during the change of state. Almost, we are at the end of this discussion.

So, today, we will continue the same thing.

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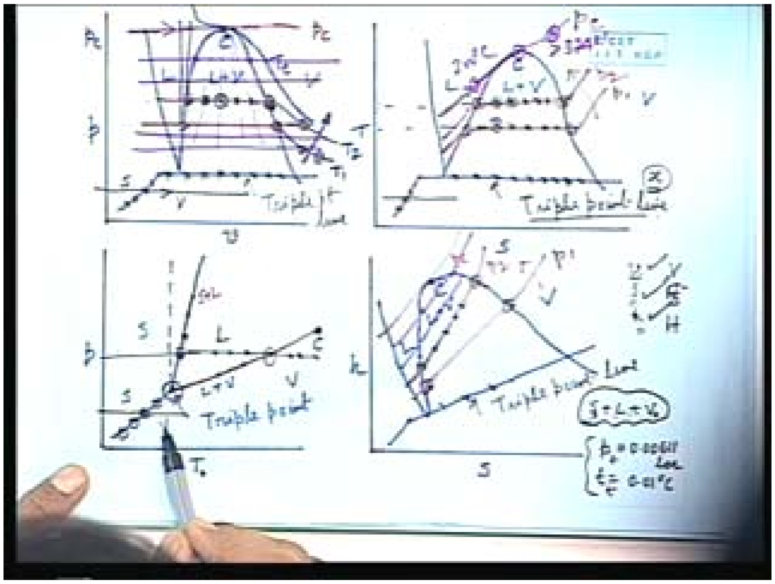

So, just in continuation, we like to have a look on this figure that is the typical pv, Ts, pT, hs diagram to show the states in different thermodynamic plane during change of phase; liquid and liquid vapor and vapor, only liquid vapor two phases. So, these things have already been discussed.

Now, before closing this discussion on this phase diagram, I like to emphasize one point. at the end of last class, the time was not there which I forgot to emphatically mention. These are the saturation states for liquid and vapor. Similarly, the states are available for solid-liquid transitions also. So, these states are being specified by either pressure or temperature.

When pressure is fixed the corresponding isotherm, temperature is fixed which are known as saturation properties. The temperature corresponding to the pressure is known as saturation temperature for that pressure.

Similarly, when the temperature is fixed, the pressure is fixed. Same way, the pressure is known as the saturation pressure corresponding to the temperature. Another thing which we noticed in this diagram is that these are the points which represent the different mixtures of different compositions of liquid and vapor. One thing is true that though the pressure and temperature are fixed for these two saturated states that mean the saturated liquid states, saturated vapor state, saturated liquid state and dry saturated vapor state. Similarly, dry saturated liquid state, dry saturated vapor state; but one thing is that all the points here are varying with specific volume. They are varying with specific entropy and the specific enthalpy also.

These state points represent a mixture of liquid and dry vapor. To fix a particular point, we require an additional information which is the dryness fraction x, or the quality which is defined as the total fraction of the mass of the total mixture as the dry vapor. That means x is the ratio of the mass of the dry vapor to the mass of the total mixture. x is equal to one is this line, x is equal to zero is this line. (Refer Slide Time: 03:42)

These points are specified by x. So one thing has to be understood that the saturation states can be specified by pressure and temperature, but this wet condition that these are the points known as the wet vapor. Wet vapor are the saturated states but with a different composition of mixtures of dry saturated liquid and dry saturated vapor. To know the specific volume, specific entropy, specific enthalpy, we require the dryness fraction x. Otherwise, during this saturated states this will vary from a value corresponding to the saturated liquid to a value corresponding to the dry saturated vapor. So, this is very important thing.

Similar is the case for triple point, but here we have pT. Again, these two points along with all these points coincide to a single point, because the entire saturated states considering all the wet vapors within the vapor dome are squeezed to single point, because they refer to a single pressure and temperature. Solid liquid, this is also a liquid vapor. So in this case, these two are these points.

Similarly is the case for triple point. Triple point is the point where solid, liquid and vapor can co-exist into equilibrium. They refer to a single pressure and temperature which are unique for a given substance. But at the same time, the composition may change; that means, solid, liquid and vapor, the mixture composition can change. Composition means what will be the fraction of solid mass? What will be the fraction of liquid mass? or What will be the fraction of vapor mass? Therefore, even if there is a unique pressure and unique temperature. For example, in case of water, what is this? p_t t_t is 0.00611 bar. Similarly, for this is 0.01degree Celsius (Refer Slide Time: 05:44)

Even if this is unique but the specific volume, specific entropy similar is the case specific enthalpy. They are varying depending upon the composition. See in the pv diagram, this is the line. That is why in the pv diagram, a triple point appears as a line, the way the saturation states appear as a line.

Similarly in Ts diagram, this is known as sometimes triple point line (Refer Slide Time: 06:08). So, point means straight, so triple point straight line whereas this is indicated by a point in pT diagram. Similar is the case in hs diagram, triple point line usually written like this (Refer Slide Time: 06:22). That means this represents a line. Why because these three intensive properties are the specific values of the extensive properties like volume, entropy and enthalpy. These typical intensive properties depend upon the fraction. In case of two phase saturation states, this is defined as a dryness fraction or quality. Here, no such parameter is defined. But one has to remember that there may be various combinations of these or there may be various compositions of solid, liquid and vapor, depending upon which the three properties will vary so that the triple point state is represented by a line in the pv diagram.

It can have infinite number of specific volumes. It can have any specific entropy. So, this point represents states of three phases coexisting in equilibrium, but with different values of specific volume, specific entropy but the temperature is fixed; similarly the enthalpy.

Below this point, if we heat at constant pressure, solid is converted to vapor. So, these are the points where solid vapor are in equilibrium. So, it is either saturated solid or saturated vapor line corresponding to sublimation in forward or backward direction. These are at the saturated sublimation state. So, this is also at constant temperature. This is sublimation. Similarly, this point represents that. Here, if we transfer, it will be solid to vapor. This is the point saturated states for sublimation; that means saturated solid for sublimation, saturated vapor for sublimation.

Now, after that we will discuss one practically important thing that when we take steam, sometimes, it is very important. I just explain, how to measure the dryness fraction of steam that means if we have a wet steam having certain dryness fraction, how to measure the dryness fraction, because we know, if we have a wet steam,

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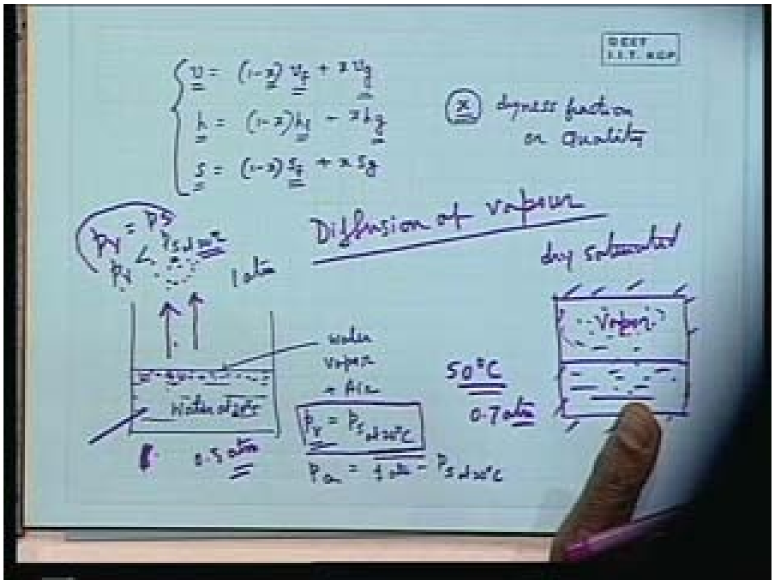

If we have a wet steam, we know that its property like specific volume is find out as 1 minus x into $_f$ plus xv_g, where v_f is the specific volume of the saturated liquid and that is dry saturated gas.

Similar is the case for enthalpy; 1 minus x into h_f plus xh_g, where h_f is the enthalpy at the saturated liquid and h_g is the enthalpy of the saturated vapor. Similar is the case of s; 1 minus x into s_f plus x s_g, where s_f is the entropy of the saturated liquid and s_g is the entropy of the dry saturated gas.

Therefore, to specify these properties of a wet steam, we have to know x; the dryness fraction or the quality. If we have a wet steam of some dryness fraction or quality, to determine these values which are very important at this moment at this stage how important are those values in calculating heat and work transfer in a system that change these properties play what important role to determine, what is the reversibility of the system? So, these three very important properties have to be found out. We have to know x. So, x has to be specified.

This value, dryness fraction or quality, this parameter is determined experimentally. How do we measure the dryness fraction or quality of steam? But before that I like to tell one very important thing which we will not find in any book of thermodynamics. Sometimes this question I asked in the laboratory classes. This is a very interesting question try to understand.

When we will read heat transfer, these things will be made a little clearer that as we have heard as since your school days, there is a difference between boiling and evaporation.

There are so many points. Probably, a little understanding we have mugged up all the points. There are six-seven points. Difference between evaporation and boiling, but the major point is that evaporation occurs at any temperature. If we have a liquid, just I like to mention this thing in this context of thermodynamics so that some concept is clear at this level.

If we have a liquid at any temperature, for example, today the room temperature is 20 degree Celsius. If we take water at one atmospheric pressure and 20 degree Celsius, we know that it will not boil. Because we know saturation temperature corresponding to one atmospheric pressure is 100 degree Celsius. So, until and unless there is a 100 degree Celsius temperature of the water, it will not boil, because the boiling will not take place but what will happen? Water will continuously be converted into its vapor stage.

For an example, if we keep the water in the room and if we come after five days or six days, we will see all the water has been converted into vapor. This is an evaporation process which is spontaneous; that means, whenever there is a liquid open to a surrounding at a gaseous ambient, for example, air in this case, then water molecules from the surface will always be converted into vapor. This is known as evaporation. Continuously water is being evaporated and this evaporation process will be enhanced if the water temperature is being raised. If water is at 20 degree Celsius, there will be some rate of evaporation.

If water is at 40 degree Celsius, the rate of evaporation will be increased. What is this physical process? What for the evaporation takes place? Let me explain.

Whenever there is water kept in a container with a free surface, always there will be an adhering water vapor with the free surface. This vapor is always at dry saturated state. If the concentration of the vapor in the atmosphere free string that means at a far distance from this free surface in the undisturbed atmosphere is less than this concentration then the vapor will flow. This is known as molecular diffusion. The vapor pressure is less, concentration less means vapor pressure is less.

Again, I am giving an example. Let me see this way. There is a pot. There is water at 20 degree Celsius. This concept may take sometime. So, just on the free surface, there is a layer of both water vapor and air mixture. So, it is a mixture of water vapor and air.

What is the pressure of the water vapor p_v? That pressure will be the saturation pressure corresponding to 20 degree Celsius. This water vapor will be at the saturation pressure at 20 degree Celsius. Otherwise, this water vapor will not be in equilibrium with this water. This water vapor is at the saturation pressure corresponding to the existing temperature. Since the total pressure is one atmospheric pressure, the partial pressure of the air which is mixed with the vapor and adhering to the free surface will be the one atmospheric pressure minus p_s at 20 degree Celsius. So, the total pressure become equals to the atmospheric pressure. The partial pressure of the water vapor equals to the saturation pressure at 20 degree Celsius known as vapor pressure.

Now, if the vapor present in the atmosphere is such, depends upon its total amount such that its saturation pressure that is p_v is less than the saturation pressure at 20 degree Celsius. Then the water vapor will diffuse, because it is the vapor pressure gradient which allows the diffusion of water vapor from the surface to the atmosphere. If the vapor pressure present in the atmosphere is less than the saturation pressure at 20 degree Celsius. For an example, saturation pressure at 20 degree Celsius let 0.5 atmospheric pressure. So if such vapor pressure or the partial pressure of the vapor in the undisturbed atmosphere is less than 0.5 atmospheres, then there will be a vapor pressure potential which will drive this liquid vapor to flow to the atmosphere. This is known as diffusion of vapor. The rate of diffusion is given by fix law and these things. These are molecular diffusion.

When the diffusion will take place, automatically it will make the equilibrium. The molecules of water in the liquid state will be detached from the surface and will be generated. To maintain the equilibrium at this pressure, because some mass is going from here, (Refer slide time: 15:47) so this has to be balanced by further mass to retain this vapor pressure at the surface so that continuously evaporation will take place. So, the conversion of water into vapor from the free surface is guided by the diffusion. If diffusion is somehow chocked or closed, for example, I make the atmosphere in such a way that p_v equal to p_s that means 0.5 atmospheric pressure. In that case, no vapor will flow and therefore, no water molecule will be converted into vapor. No evaporation will take place.

What is the situation in p_v is equal to p_s? 20 degree Celsius is the room temperature. So, corresponding saturation pressure is 0.5 atmospheric pressure. So, vapor in the atmosphere of such quantity that the partial pressure equals to 0.5 atmospheric pressure. The saturation pressure corresponding to the room temperature pertains to be condition of 100 percent relative humidity. So, in 100 percent relative humidity, there will be no diffusion of vapor from a water surface to the ambient so that water will not be evaporated; evaporation will be stopped.

If we heat the water, this temperature will increase. So, when the temperature will increase, for example from 20 degree Celsius to 50 degree Celsius, then the vapor pressure, the partial pressure of the water vapor adhering to this water will be increased. That will be the corresponding saturation pressure at 50 degree Celsius. For example, let it be 0.7 atmospheric pressure. So, vapor pressure gradient will be more, whereas the vapor pressure here will be less than more is the potential. So, more will be the rate of diffusion and more will be the evaporation.

Now, one thing is true that this is happening from the surface. It is a surface phenomenon. So bulk of the liquid, nothing happens. These remains as the liquid and vapor is being transformed from the surface. Molecules from the surface are being converted into vapor. So, it is the surface phenomenon.

Therefore, one very important thing is that this vapor is dry saturated vapor. Sometimes, I ask this question that there is a pot and there is water and this is insulated. For example, let the water evaporate. It may be at any temperature, even at room temperature also. There will be always a vapor, because of the evaporation. At any instant of time, the liquid level may go down. It may be infinitely slow process if this temperature is equal to the temperature of the vapor. But ultimately at some point, it will be stopped when the saturation pressure corresponding to this vapor will be equal to the saturation pressure at that temperature.

This ambience will be fully saturated so that no evaporation will take place. Whatever may be the condition I am not going into that detail but if I ask what is the state of the vapor? It is dry saturated, because this vapor will never contain any liquid in it. But what happens when we heat air to its boiling temperature?

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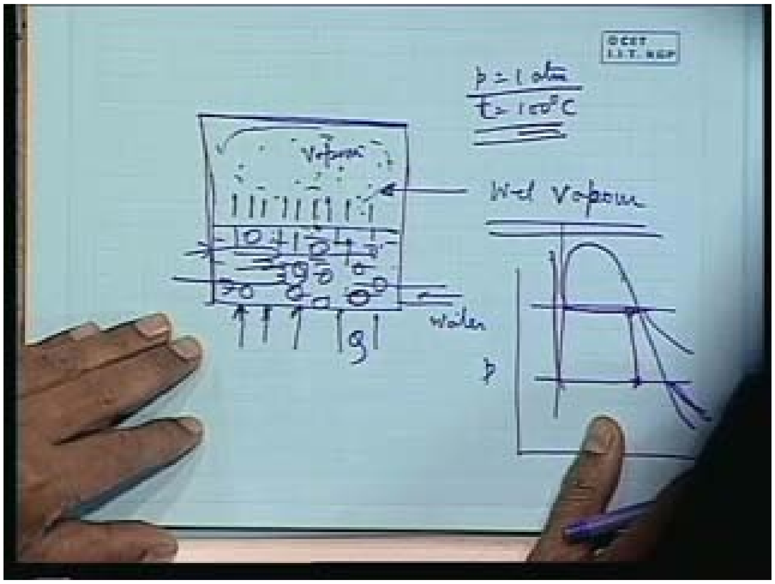

If I have water here, let us consider a closed box, some water is there. I heat it by immersing some heater or heat is supplied from the surface or from the bottom. This is the surface of the bottom of the closed box. If the temperature is reached to the boiling temperature, let p is equal to one atmospheric pressure and t is equal to 100 degree Celsius then boiling will start.

This boiling phenomena start from the bulk of the liquid. So, until and unless heat the liquid bodily, not from the surface but we have to heat it such a way that heat comes through the bulk of the liquid; that means, we have to heat from the bottom of the surface or we have to immerse a heater like this so that the temperature will be reached at saturation temperature and then boiling will occur. Boiling is a phenomenon, a similar phenomenon, but here the vapor will be generated more violently from the bulk of the liquid.

We can see vapor will be generated from all points, even from the bottom, where the heat is supplied. If we heat it from the bottom, they will create a vapor bubble like that. This is being lighter than the water that will go up and ultimately there is a collapse of the vapor bubble, because the pressure is released. Here the pressure is less, here the pressure is more. (Refer slide time: 20:18) So, bubble will be collapsed and ultimately the vapor will be generated and diffused to the atmosphere. So, this will be full of vapor at any state, if we boil the liquid and also continuously we supply water and boil it. So, we will say always water is being boiled which is a bulk phenomenon, body phenomena.

Boiling starts and a particular temperature is reached; that is, the saturation temperature related to the pressure at one atmospheric pressure. The vapor is generated within the liquid and this vapor is coming up and collapse of vapor and the vapor is coming out and this is the full of the vapor zone. This happens in a boiler drum, in a power plant and this vapor is always wet vapor. This is one of the very important things, when we will read the applied thermodynamics the steam power plant. Your teacher may ask you I don’t know.

This very important thing that this vapor is always wet vapor. Why because when the vapor comes from the body, main body of the liquid and it collapses and goes out, it always carries or entrants’ small liquid particles with it. So, this vapor always is a mixture of vapor and liquid. That is known as the wet vapor which may have a dryness fraction which may vary from some value to some value but it is not equal to one. This is a wet steam.

It is more important that when we heat water in a closed vessel which is the case of a stream drum in a steam power plant. If we go on adding the heat, the pressure will increase. So, corresponding saturation temperature will increase, but the vapor will be always under condition of wet vapor. It will never be a dry vapor. Very simple example is that if we draw the pv diagram and if we are below the critical pressure, this is the constant pressure line. This is the temperature isotherms. These are the isotherms. (Refer slide time: 22:15)

This chapter is very interesting you will have to think.

If we go on heating, it is a constant volume heating. So, its pressure will increase that means it goes like this. So, this is one isotherm. (Refer slide time: 22:30) Pressure and temperature will increase, but it will remain as wet steam until and unless some point is reached. It is very near to critical point when the steam becomes dry saturated. But usually within the working range, it is always that if we go on heating, the phenomenon will be such that the vapor will be generated from the bulk of the liquid. It is one characteristic feature of evaporation and they will burst at the free surface and will escape as vapor from the free surface will always carry an entrained liquid. Therefore, it is a wet steam.

If in a power plant operations, we require a superheated steam at the entry to the turbine; that I will explain. In a power plant, after boiler, there is a turbine where from the mechanical work is being generated, where steam at high pressure and temperature expands and because of the expansion, these expansion takes place as the steam flows through a series of blades. That is the principle of turbo machines. So, that expansion takes place and by the way of rate transfer of the angular momentum from the steam, as it flows through the blade to the blades, mechanical work is developed. That is a different chapter all together.

When the requirement is that for some practical considerations, the inlet state of the steam to the turbine should be superheated. If we go on adding heat, the steam drum will not do anything. It will always produce a wet steam. Whenever we take the steam from the steam drum which is being accumulated above the free water surface, because of the heat to the water, it will be always wet steam. So, we will have to take the steam and we will have to make the separate arrangement, where this steam is heated by some heat source.

Usually, it is done by taking the flue gas that is the burnt products of combustion. We allow that to flow to extend the heat or by adding in another electrical heater. So, separate heating arrangement should be done at constant pressure so that the wet steam becomes dry saturated then superheated. If we take steam from steam drum in any power plant, that is a wet steam and if we visit any power plant, we see there is no super heater. That is known as super heater only when steam is taken from the boiler drum. It is being used for the turbine or for any other purposes; this steam is a wet steam.

For process industries, we do not bother; we take the steam from the steam drum and use it because there probably a wet steam will do the service but for power plant processes that I will explain afterwards when I will be discussing the vapor power cycle, we require state of superheated steam at the end to the turbine. So, superheated steam is required. There is an additional heat exchanger; that means, steam from the drum is taken and it is being heated separately to make it superheated and that is known as super heater. This is the physics that whenever we boil a liquid in a close container and generate vapor at the in the upper zone, beyond the free surface or the separating surface of the liquid and vapor, that vapor will be always a wet vapor.

Whereas if we have liquid in a close container, do not boil it, do not raise its temperature to saturation temperature, keep it as it is at any temperature below the saturation temperature, within the room temperature. We do it, but it will be infinitely slow process, very slow data operation. We will see, after sometime, there will be a vapor enclosed within this space. Because of evaporation that vapor is at dry saturated state.

Since this is the case of boiling water and collecting the vapor at the upper level of this free surface of water is in the boiler and we are very much interested to know what the dryness fraction of this steam is. Now, that is why, the measurement of dryness fraction comes into picture because we will get interest only if I tell this thing.

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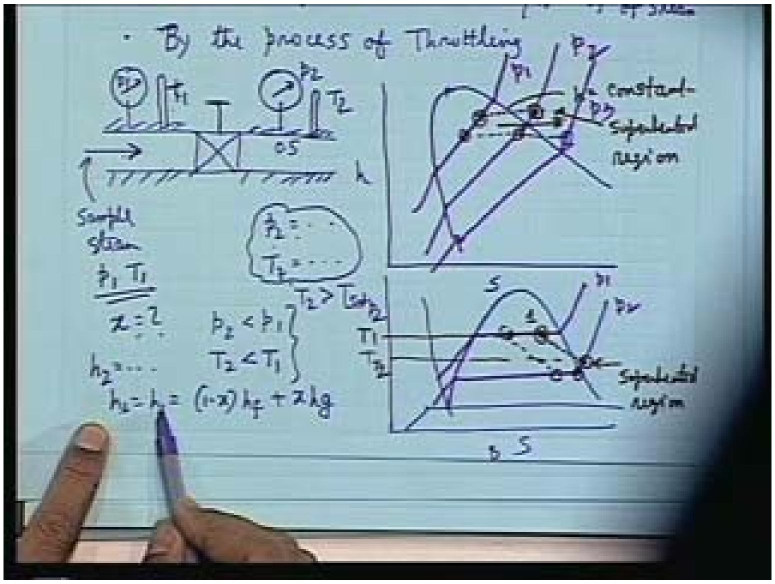

That is measurement of dryness fraction or quality of steam: Very simple thing, I will tell only the philosophy. I will not draw a very nice picture and all these things of the equipment.

One method, very common method is by the process of throttling. What is throttling? As we have heard, throttling is that if we take the steam, now the diagram is like this; simple insulated pipe. So, in the upstream, we take the sample of steam. It is the sample steam whose pressure and temperature is p_1 and T_1 respectively, whose pressure and temperatures correspond to the saturation values; that means, in one atmospheric pressure 100 degree Celsius. That means the sample steam is at saturated state, but not at dry saturated state. It has got x.

That means saturated liquid, dry saturated vapor and in between states, we will tell saturated state or wet saturated state. Simply, we will tell saturated states with dryness fraction x; that means, this pressure and temperature represents the corresponding pair for the saturated state. Now, we are interested to find out x. What is done in a process of throttling? There is a throttle valve which throttles the steam; I have already told what a throttling process is. We measure the pressure p_2 and the corresponding temperature T_2 after throttle. We measure p_2 and $T_{2.}$

Now, we will see that after throttling, the steam temperature is reduced. Its inversion point is such for water vapor that with after throttling or with throttling the temperature always decreases; pressure decreases temperature decreases. Both these things are reduced. That means p_2 is less than p_1 similarly T_2 is less than $T_{1,}$ but what happens we know. Even if this temperature is reduced, this steam becomes superheated; that is the philosophy.

Let us draw hs diagram. It will be very clear. This is the critical point. So, this is the constant pressure line. Let this be the pressure p_1 and this is the pressure $p_{2.}$ So, our initial point was somewhere here. When we throttle it, though we cannot show the throttling process but by a dotted line we can show the constant enthalpy line. The constant enthalpy line is this. This goes like this. This is h is equal to constant. So, the state point will move along this line. (Refer slide time: 29:29 to)

Why? First, this enthalpy has to be constant. So, this line has to be parallel to s axis. From the entropy principle, the entropy of this system will have to increase, because in isolated system there is no heat transfer. So adiabatic system, the entropy must increase. It is the irreversible process. Entropy of the isolated system or an adiabatic system of an inverse has to increase. So, this will be in this direction. If we draw a horizontal line from this point towards the right means increasing it then we will arrive at this point.

We see one thing categorically. This point temperature may be low but it is in the superheated region. Let us make it clear more from the corresponding Ts diagram also which will make it more clearly in Ts diagram.

If you have any difficulty here in understanding you tell m. A Ts diagram here, if we draw the TS diagram, this is the liquid line, I am not drawing all these things very clearly

In TS diagram, this is the constant pressure line that means this is p_1, this is p_2. This is the point one has some dryness fraction. Enthalpy constant, here we do not know that at there is no enthalpy parameter in one of the axis of this diagram, but we know the entropy must increase so that the line will be like this increased entropy. If we plot this, here the temperature is reduced. This is the initial temperature T_1. This is the final temperature T_2. But this T_2 is more than the saturation temperature corresponding to the existing pressure. This is a super-heated region. (Refer slide time: 31:48 to 32:43)

Now the question comes, always it will be super-heated? No, it depends upon the initial state; that means, if the initial state is somewhere here, after throttling it may not come to super-heated that means it depends upon the initial state and the pressure up to which it is throttled. But one thing is sure; when we throttle it from any initial state to any pressure, its quality is increased.

Super-heated means quality more than one. Mathematically, quality greater than one is superheated state; that means, the quality of the steam is increased that means the wetness fraction of the steam is reduced. Dryness fraction of the steam is increased, but whether it will be superheated or not depends upon its initial state and the pressure up to which it is throttled. Therefore, depending upon the initial state of this steam that means pressure and temperature, our throttling has to be made in such a way that it has to be throttled to that pressure so that after throttling, it may go to the superheated region.

If our initial pressure state is that then I will throttle it at least up to this value and this is the pressure line. I will have to throttle up to p_3 pressure. The pressure after throttling has to be judiciously decided so that after throttling the quality is increased beyond the value of one; that means, it has to be in superheated region, because if it goes to superheated region, then we know the value of enthalpy directly from the table. At this point p, T, we know the enthalpy, entropy specific volume at saturated liquid and dry saturated vapor.

To find out the enthalpy, entropy specific volume for wet vapor, we have to know x. Without that we cannot know. That is the thing which is done here, to find out the air, but when it is superheated, from the superheated table h_2 is known because it is a unique state at this pressure that this T_2 will be more than this saturation temperature corresponding to p_2.

For example, if we throttle a wet steam at one atmospheric pressure at 100 degree Celsius, if we throttle it to 0.5 atmospheric pressure then its temperature may be reduced from 100 degree to 90 degree, but at 0.5 atmospheric pressure, saturation temperature is 60 degree that means 30 degree superheat. By absolute value of the temperature, it is reduced but it is still in superheated zone, because the saturation temperature corresponding to the reduced existing pressure is still lower.

Now, when we know the superheated state, we know h_2, and this h_2 is equal to h_1, this part is primary school level thing, 1 minus x into h_f plus x h_g if we leave this to a school boy, he can tell yes, I can find out x because this enthalpy remains constant that I have told you earlier in a throttling process, if we write this steady flow energy equation, enthalpy before and after is same. So, h_2 is h_2 is 1 minus x into h_f plus x h_g. These things we know since we know the pressure and temperature. This arrangement is known as throttling calorie meter.

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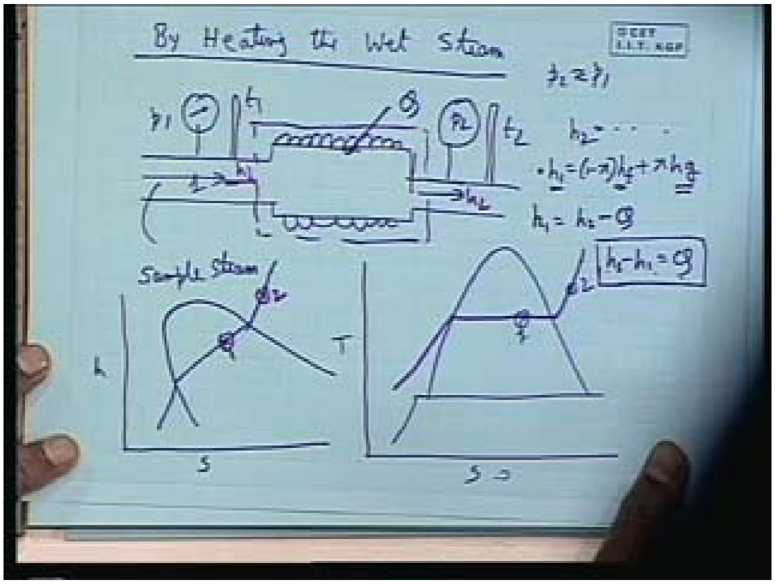

With the similar philosophy, another process is there which is known as by heating the wet steam, there is nothing usually I tell the students to read it at home but here I do it because the documentation is there of this teaching for the outside students also. Similar is the case and it is heated electrically. That is why it is known as electrical calorie meter.

So, there is a test section like that which is an electrical heater, steam is coming, it is heated electrically by wrapping electrical wires in this, and this is being heated. It is Q. I know the pressure p_1. This is the state one. I know the temperature T_1 after heating, the constant pressure heating p_2 and it is superheated.

If I draw the diagram in hs, ts any diagram can make, hs diagram, only one pressure, pressure is unique. So, this pressure and this p_2 is $p_{1,}$ except for the frictional loss. So, this is a short section. If frictional loss is there, there is no expansion. p_2 is p_1 that means it is one and this goes to two, a constant pressure heating. ts diagram does not matter you can draw. In examinations, you will be asked to draw the diagram. So you develop your practice also in drawing diagram, ts diagram it is like this. ts diagram we draw the constant pressure line like this. This will be like this. So the point is here. So it will be simply heated. So, there is the heating. Entropy increases in both the cases, because of the heating. Therefore, we see that it is by heating we are keeping it to superheated region.

We know the pressure, the temperature, so we know $h_{2.}$ So, h_2 is now fixed, because it is the superheated state. How to find out h_1 now? It is not throttling process. h_2 is not equal to h_1. So, we have to find out h_1 because h_1 is 1 minus x into h_f plus x h_g. So, these things I know because I know this p_1 T_1.

How to relate h_2 with h_1? In this case, h_1 is equal to

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No no no not c_p delta T. Simply h_1 is h_2

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Plus Q or minus Q?, because h_2 minus h_1 is Q, if we write the steady flow energy equations, h_1 and this is h_2 So, h_2 minus h_1 is the heat transfer.

Simply the steady flow energy equations h_2 minus h_1 is Q. Is it clear?

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If I know h_2 and if I can measure the heat transfer that electrical heater is there. I can know the power input so that from which I can know what is the heat Q coming to this steam? So, h_2 minus h_1 is Q.

After this, I will close this discussion on this phase diagrams of a pure substance by solving simple two problems.

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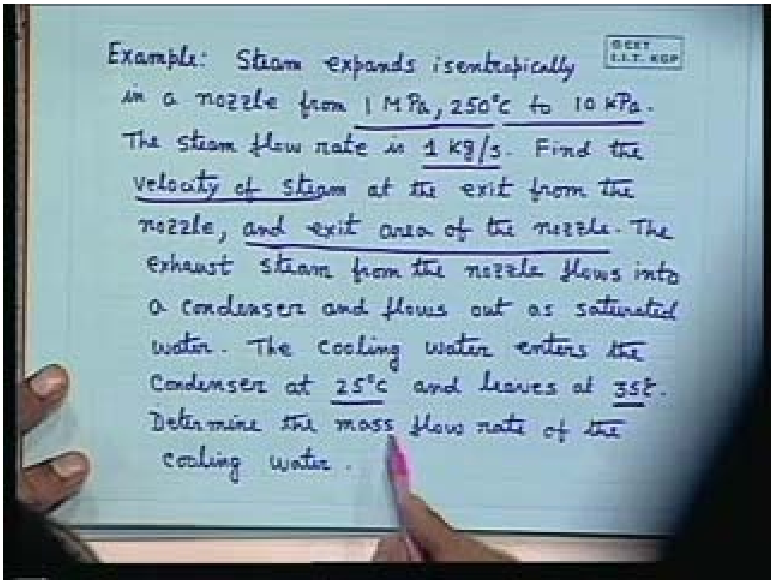

Example: Steam expands isentropically in a nozzle from 1 MPa, 250°C to 10 kPa. The steam flow rate is 1 kg/s. Find the velocity of steam at the exit from the nozzle, and exit area of the nozzle. The exhaust steam from the nozzle flows into a condenser and flows out as saturated water. The cooling water enters the condenser at 25°C and leaves at 35°C. Determine the mass flow rate of the cooling water.

Let us see the first problem, which is a direct application of the throttling calorimeter, throttle valve for measuring the quality of the steam. What is this problem? Example, a sample of wet steam from a boiler drum, so that is why I explained all these thing, in problems you will see that boiler drum, so you have to understand what is this otherwise these words will not be understandable by, does not matter, you can solve the problem, at 3 M pa that means it is a wet steam. Whenever we tell wet steam at 3 M pa mean it is saturated region, but wet means its temperature is known. Temperature is this saturation temperature corresponding to 3 M pa is put, through a no do not ask anytime sir pressure is giving temperature is not giving but it is within wet steam.

Wet means a dry saturated steam at 3 M pa, but if all adjectives are omitted only steam at 3 M pa we show anywhere, we can see a problem like that how can I understand that steam is wet, dry saturated. So, if the steam is super-heated then 3 M pa pressure is not sufficient. I have to be given with temperature but whenever wet steam is given that means it is saturated state with some dryness fraction, is put through a throttling calorimeter in which the pressure and temperature are found; that means, this is the pressure and temperature after throttling. So what is the quality of steam?

After throttling this data is given, whether the problem is well posed or not that we can check from the steam table. If we see this steam table, we will see that 120 degree Celsius the saturation temperature corresponding to 0.1 M pa is less than 120 degree Celsius and for this problem it is very easy to say without going for steam table. 0.1 Mpa is atmospheric pressure, is almost the atmospheric pressure for which the saturation temperature is 99.6 degree Celsius, approximately 100 C. So, this is super-heated. We can see coolly from the steam table, what is the value of h_2? h_2 is like this, my nomenclature is like this, two is this section, one is this section, this is the throttle bar. So, h_2 corresponds to 0.1 M pa, 120 degree Celsius. If we see this steam table, h_2 will be 2716.28 kilo Joule per kg.

Sometimes, we have to make an interpolation, because as I have told at different pressure, these steam tables are given values for different temperatures. They give v, h, s. There temperature may be 100, 150. So, in between we have to linearly interpolate. That interpolation is valid. So, linear interpolation has to make because at exactly at 120 degree Celsius. We may not read this steam table to find the exact value, I have also interpolate it. It is given at 100 degree and 150 degree Celsius. So, this is the value of h that means h_1 is also h_2 is equal to 2716.28 and that equal to 1 minus x into $h_{f.}$

Now, again, this is rate from the superheated steam table. Go to steam table for saturated steam then at 3 M pa, find out the value of the enthalpy at the liquid state which is $h_{f.}$ I am directly writing the value 1008.42 plus x into the value of 2804.2; that means, this is h_f and this is h_g which is read from the steam table for saturated steam at 3 M Pa. So, this gives x is equal to 0.951. This is a straight forward application. Another problem, I will solve.

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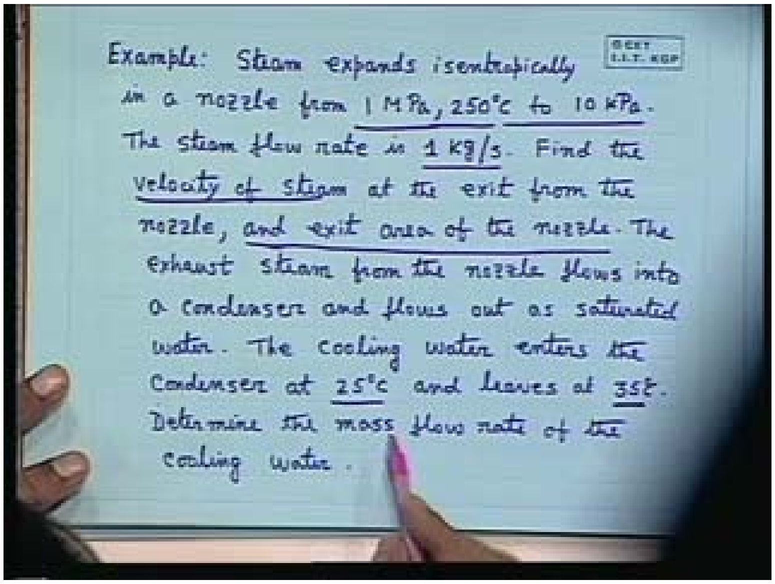

Example: Steam expands isentropically
in a nozzle from 1 MPa, 250°C to 10 kPa.
The steam flow rate is 1 kg/s. Find the
velocity of steam at the exit from the
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exhaust steam from the nozzle flows into
a condenser and flows out as saturated
water. The cooling water enters the
condenser at 25°C and leaves at 35°C.
Determine the mass flow rate of the
cooling water.

Steam expands isentropically in a nozzle from 1 M Pa at 250 degree Celsius to 10 k Pa. The steam flow rate is 1 kg per second. Find the velocity of steam at the exit from the nozzle, so, velocity of steam is required; the exhaust steam from the nozzle and the exit area of the nozzle. The exhaust steam from the nozzle flows into a condenser and flows out as saturated water.

Condenser, there is a heat exchanger where this steam is condensed then flows out as saturated water. Who takes the heat from the steam? The cooling water which enters the condenser at 25 degree Celsius and leaves at 35 degree Celsius is heated which takes the heat from the steam to condenser. Determine the mass flow rate of the cooling water. We have to find out three quantities. First, again I read the problems.

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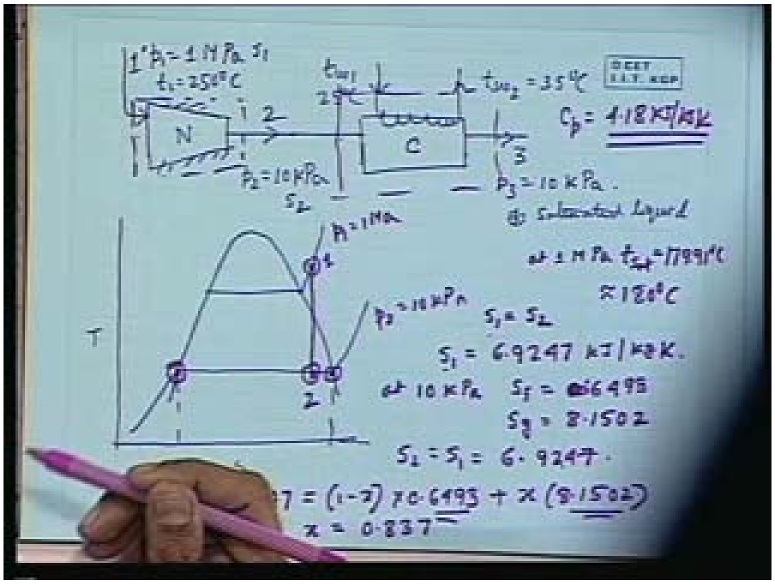

Now, let us first draw the diagram. There is a nozzle. So, steam enters the nozzle. This is the first condition. The steam enters in 1 M pa. So, this is the state one. p_1 is 1 M pa and t_1 is 250 degree Celsius, nozzle is insulated because isentropic expansion. This is two. So, two, condition is that p_2 is equal to 10 k Pa then it goes to a condenser. There is cooling water. Cooling water enters at 25 degree Celsius. So, cooling water let tw_1 25 degree Celsius and going tw_2 water at 35 degree Celsius. Steam coming at three, which is at this same 10 k Pa, p_3, there is no pressure drop, because this is a steady flow and saturated liquid. So, this is the condenser, this is the nozzle. So, this is the problem.

How I will solve? This is an isentropic. Let us then draw the entropy of state two will be same as the entropy of state one. If I am asked to draw this diagram in Ts diagram which may not be necessary but still I am drawing this that let this is $p_{1.}$ 1 M pa, this is p_2 10 kPa. So, now, starting point is 1 M pa, 250 degree Celsius. First of all, if we have shown this diagram on Ts plane then we have to see that inlet state point is one.

Initially, in this case, inlet state point will be uniquely frozen; that means it has to be in superheated region. If we see this steam table, we will see that at 1 M Pa, the saturation temperature t saturated is equal to 179.91 that mean approximately 180 degree Celsius that we can verify from this steam table for saturated state. It is superheated steam so that this point is here.

Usually, this type of expansion, after the isentropic expansion, the point comes to a wet vapor in the reduced pressure that is pressure after expansion. How do we know that this point is wet?

So, first, we have to find out what is the entropy, because the main catch of the problem is that it is isentropic; that means, entropy at the initial state is equal to the entropy of the final state is two. So, if we find the entropy at the initial state then we will see the specific entropy is equal to s_1 is equal to 6.9247 kilo Joule per kilo gram. This is the entropy. See this steam table, at 10 k Pa pressure, s_f is equal to 0.6943 kilo Joule per Kelvin and s_g is 8.1502 kilo Joule per kilo gram Kelvin.

Now, this s_1 is this that means s_2 is s_1 is six point sorry

six no it is six point ah all right it is point six okay it is all right I am sorry it is all right. So, see this is 6.9247.

One thing that specific entropy is more than that of the liquid; much more. It is 0.6493, whereas this is more than entropy of this point, but it is less than this. This is 8.1502 and this is 0.6493. So, this point is somewhere in between; that means, this point is in the wet region. Then if we can find out x, how we can make 6.9247 is equal to 1 minus x into 0.6943 plus x into 8.1502 which gives the value of x. The value of x is equal to 0.837. This is the value of x which is being found. How to find out the velocity?

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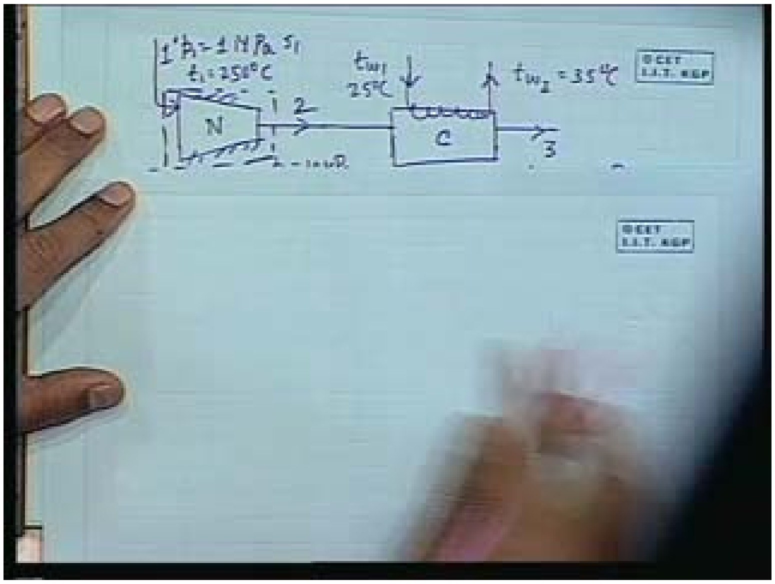

Velocity will be found out if we write this steady flow energy equation. What will be that?

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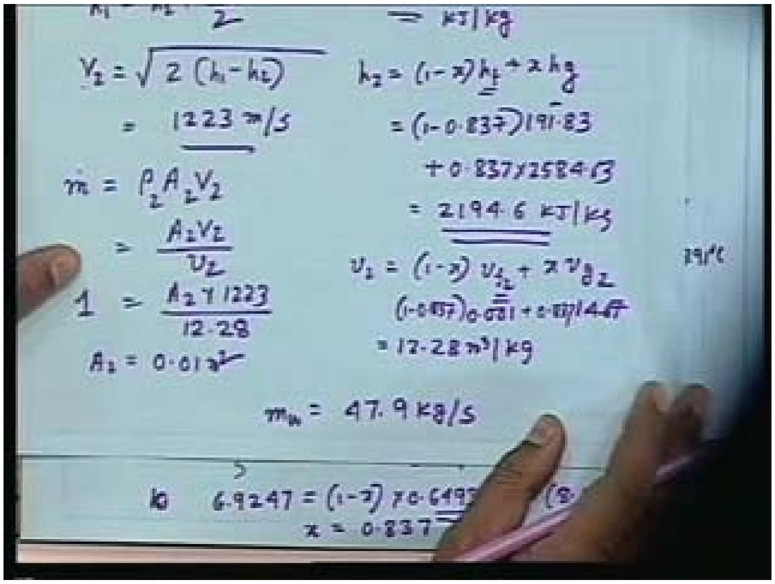

$V_2 = \sqrt{2(h_1 - h_2)}$

$= \underline{1223 \text{ m/s}}$

$\dot{m} = \rho_2 A_2 V_2$

$= \frac{A_2 V_2}{v_2}$

$1 = \frac{A_2 \times 1223}{12.28}$

$A_2 = 0.01 \text{ m}^2$

$h_2 = (1-x) h_f + x h_g$

$= (1 - 0.837) 191.83 + 0.837 \times 2584.63$

$= \underline{\underline{2194.6 \text{ kJ/kg}}}$

$v_2 = (1-x) v_{f_2} + x v_{g_2}$

$(1 - 0.837) 0.001 + 0.837 \times 14.67$

$= 12.28 \text{ m}^3/\text{kg}$

$m_w = 47.9 \text{ kg/s}$

$6.9247 = (1-x) \times 0.649$

$x = 0.837$

h_1 is equal to h_2 plus into v_2 square by 2; steady flow energy equation, because heat transfer, wet transfer, nothing is there. So, take care of the kinetic energy, initially kinetic energy is negligibly small. It is simply v_2 is root over 2 into h_1 minus h_2.

How to find out h_2? Question is that h_1 is known, because h_1 is read again from the steam table by which we rate the entropy 2942.6 kilo Joule per kilo gram. So, h_1 is rate from this steam table, h_2 is simple; we know the pressure 10 k Pa. Since we know x, we can know any property provided. We know h_f, h_g that is found from the saturated steam table at 10 k Pa pressure.

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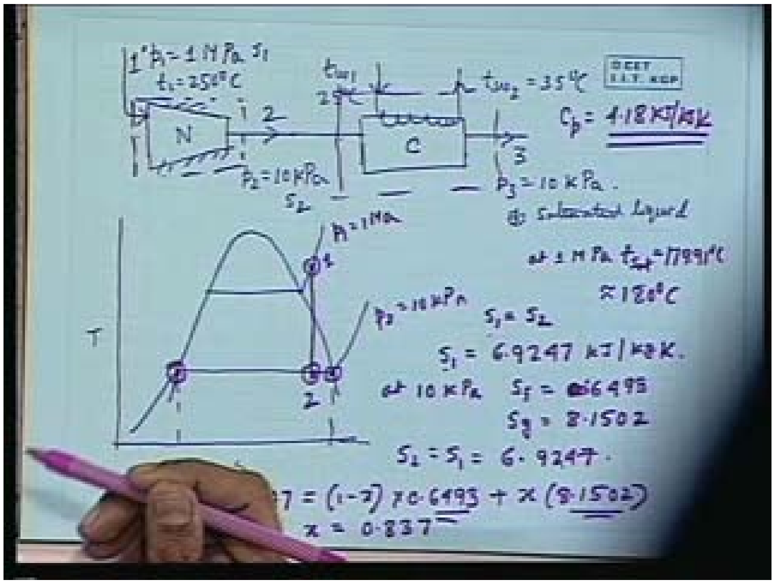

1: $p_1 = 1\,MPa$, s_1
$t_1 = 250°C$
t_{w_1} 25°C
$t_{w_2} = 35°C$
$C_p = 4.18\,kJ/kgK$
$p_2 = 10\,kPa$, s_2
$p_3 = 10\,kPa$.
③ Saturated Liquid
at 1 MPa $t_{sat} = 179.91°C$
$\approx 180°C$
$s_1 = s_2$
$s_1 = 6.9247\,kJ/kgK$.
at 10 kPa $s_f = 0.6493$
$s_g = 8.1502$
$s_2 = s_1 = 6.9247$.
$7 = (1-x) \times 0.6493 + x(8.1502)$
$x = 0.837$

The way we found out these entropy values for liquid and dry saturated vapor.

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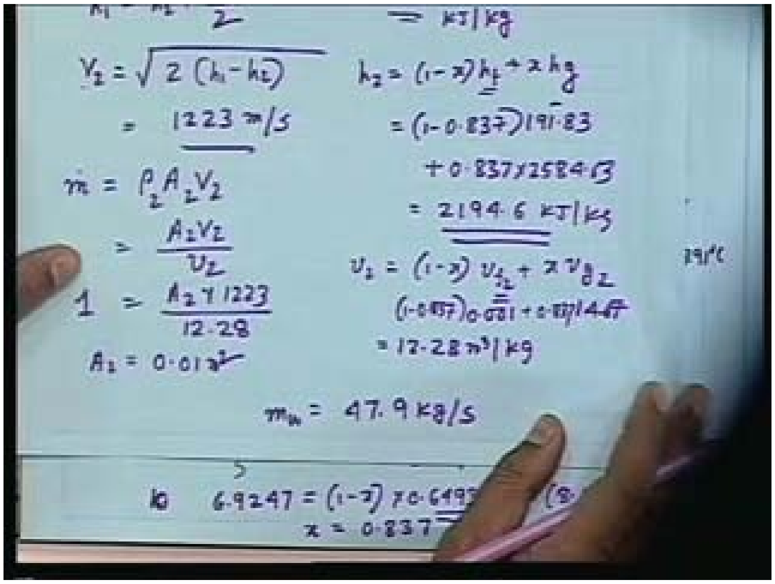

$= kJ/kg$

$V_2 = \sqrt{2(h_1 - h_2)}$
$= 1223\,m/s$
$\dot{m} = \rho_2 A_2 V_2$
$= \frac{A_2 V_2}{v_2}$
$1 = \frac{A_2 \times 1223}{12.28}$
$A_2 = 0.01\,m^2$

$h_2 = (1-x) h_f + x h_g$
$= (1-0.837) 191.83$
$+ 0.837 \times 2584.63$
$= 2194.6\,kJ/kg$
$v_2 = (1-x) v_{f_2} + x v_{g_2}$
$(1-0.837) 0.001 + 0.837 \times 14.67$
$= 12.28\,m^3/kg$

$m_w = 47.9\,kg/s$

$6.9247 = (1-x) \times 0.649$
$x = 0.837$

Similarly, we find out and it is very simple that means 1 minus 0.837 into h_f, h_f has been found out as 191.83 kilo Joule per kilo gram plus 0.837 into 2584.63. So, that becomes equal to 2194.6 kilo Joule per kilo gram. So, if we put this value of h_2 and these values of h_1, where v_2 will come, 1223 meter per second.

How to find out the area? Area is like this; if we write the mass flow rate at any section we know from fluid mechanics equation, it is rho two into A_2 into V_2. Here, V_2 A_2 is the area rho two, rho two is v_2, and again v_2 is 1 minus x into v_{f2} plus x v_{g2}.

So, we have to read v_{f2} and v_{g2} and we can find out. These v_{f2} will be 0.001 and v_{g2} will be 14.67. So, we put the value of x. It is 1 minus 0.837 and it is plus 0.837, we get the value of v_2 as 12.28 m cube per kg. So, if we put this value of v_2, if we put the value of this velocity and m is 1 kg/s is A_2 into 1223 divided by 12.28 and so A_2 is equal to 0.01 m square.

I think time will be up. Some time is there? Two minutes.

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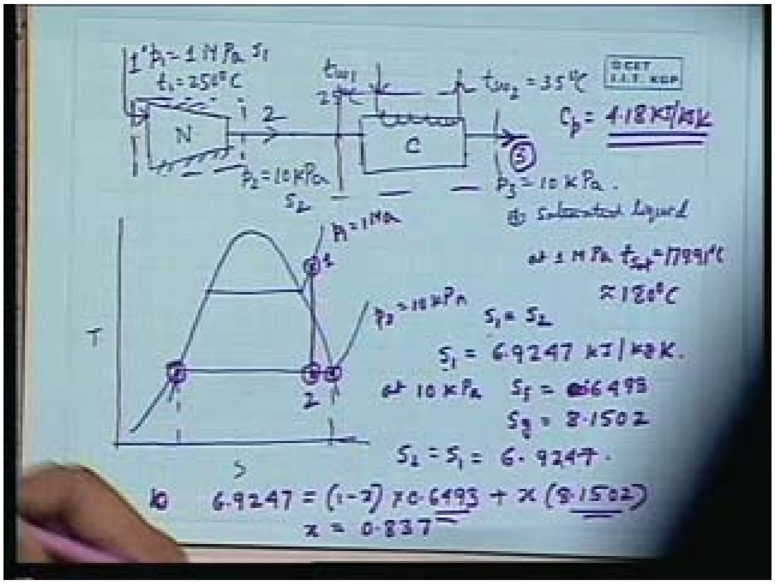

So that next part, I can if some time is there then I can complete the next part, next part is, what is the mass flow rate of the water? I can go time is up

Two minutes are there, so therefore time is up.

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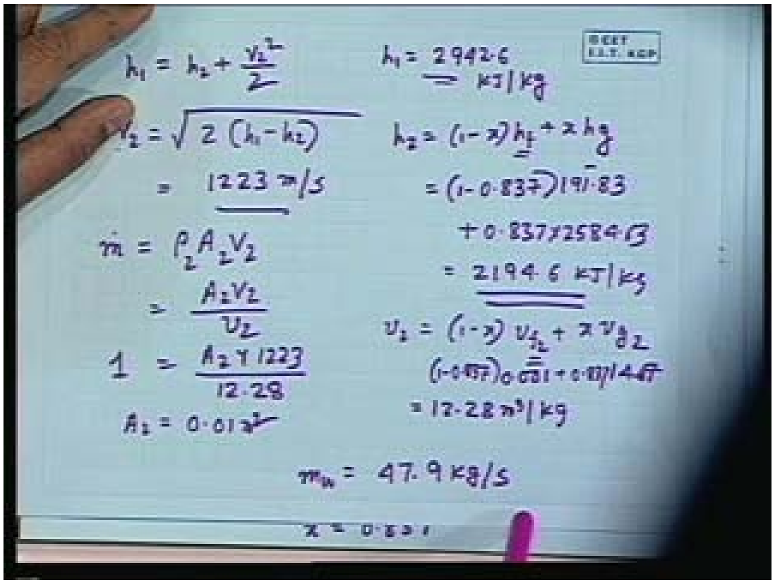

$h_1 = h_2 + \frac{V_2^2}{2}$

$V_2 = \sqrt{2(h_1 - h_2)}$

$= 1223$ m/s

$\dot{m} = \rho_2 A_2 V_2$

$= \frac{A_2 V_2}{v_2}$

$1 = \frac{A_2 \times 1223}{12.28}$

$A_2 = 0.01 m^2$

$h_1 = 2942.6$ kJ/kg

$h_2 = (1-x) h_f + x h_g$

$= (1-0.837)191.83 + 0.837 \times 2584.63$

$= 2194.6$ kJ/kg

$v_2 = (1-x) v_{f_2} + x v_{g_2}$

$(1-0.837)0.001 + 0.837 \times 14.67$

$= 12.28 m^3/kg$

$m_w = 47.9$ kg/s

$x = 0.837$

So, next part is that to find out the mass flow rate of cooling water, the answer is m_w. This is left as an exercise 47.9 kg/s.

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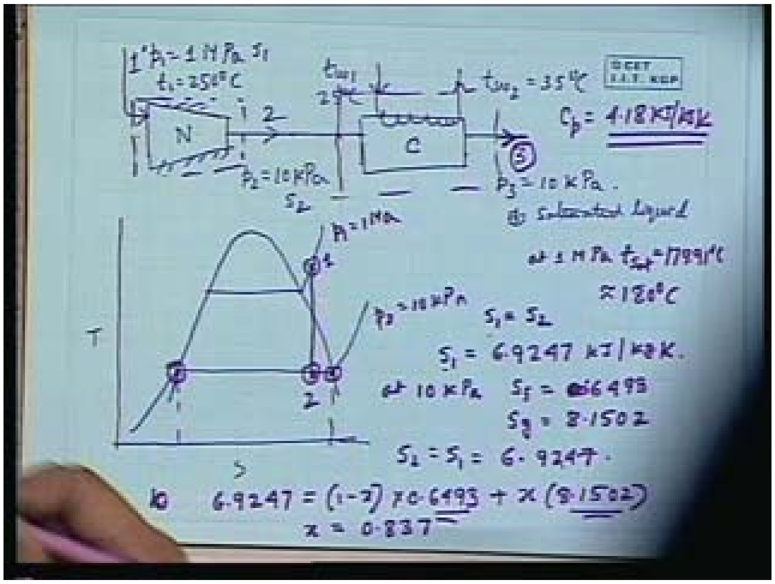

$c_p = 4.18$ kJ/kgK

③ Saturated Liquid

at 1 MPa $t_{sat} = 179.91°C$

$\approx 180°C$

$s_1 = s_2$

$s_1 = 6.9247$ kJ/kgK.

at 10 kPa $s_f = 0.6493$

$s_g = 8.1502$

$s_2 = s_1 = 6.9247$.

$6.9247 = (1-x) \times 0.6493 + x(8.1502)$

$x = 0.837$

We will have to make an energy balance here and assume that c_p of water as 4.18 kilo Joule per kilo gram Kelvin. So, we assume this c_p. So, c_p delta t is the heat taken up by the water and the change in enthalpy is the heat given up by the steam.

So, it comes with the saturated water. So, three corresponds to the enthalpy of the saturated water and h_2 we know. So, we write the energy balance and get the mass flow rate of the water whose value will be 47.9 kg/s

Okay! All right, thank you.

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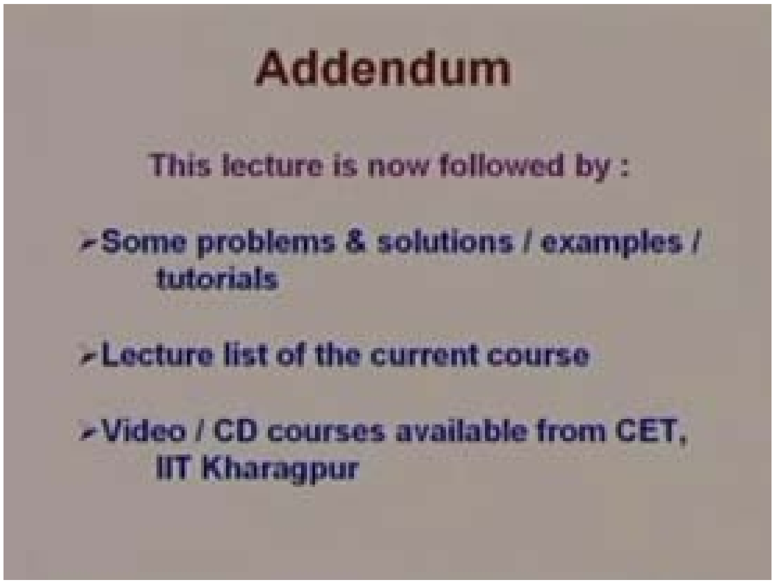

Addendum

This lecture is now followed by :

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

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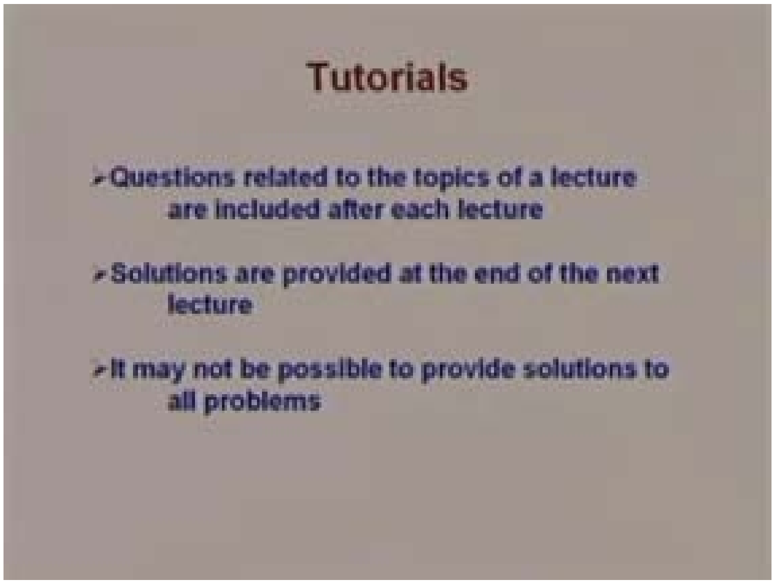

Tutorials

- 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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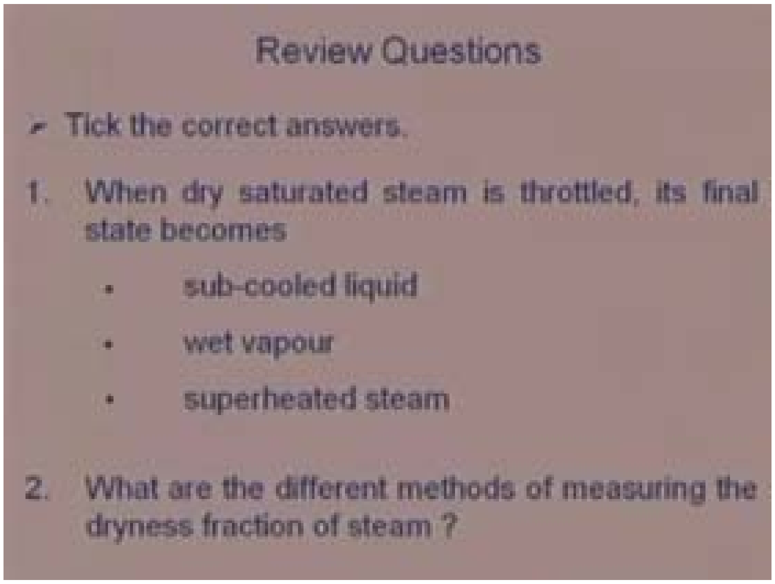

Review Questions

- Tick the correct answers.

1. When dry saturated steam is throttled, its final state becomes
   - sub-cooled liquid
   - wet vapour
   - superheated steam

2. What are the different methods of measuring the dryness fraction of steam ?

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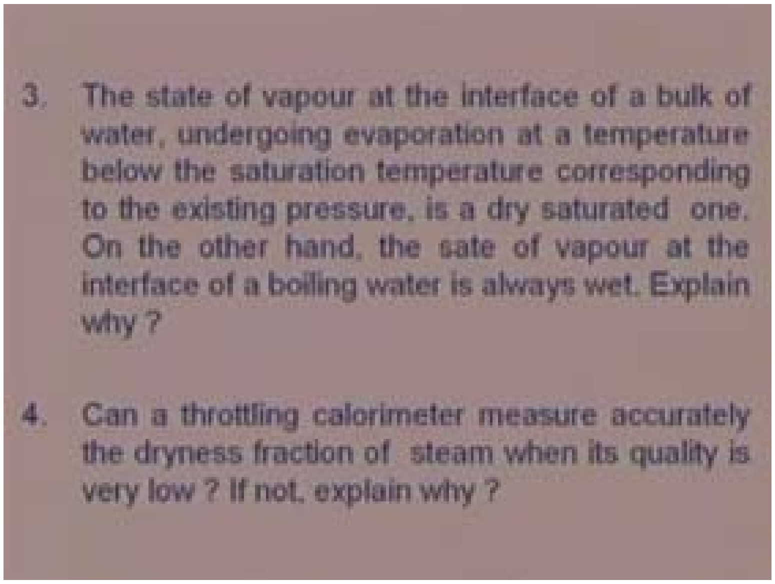

3. The state of vapour at the interface of a bulk of water, undergoing evaporation at a temperature below the saturation temperature corresponding to the existing pressure, is a dry saturated one. On the other hand, the sate of vapour at the interface of a boiling water is always wet. Explain why ?

4. Can a throttling calorimeter measure accurately the dryness fraction of steam when its quality is very low ? If not, explain why ?

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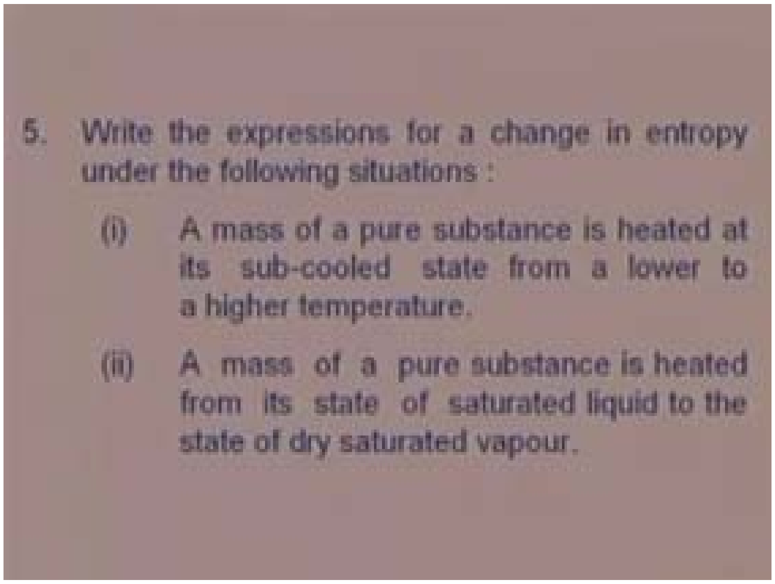

5. Write the expressions for a change in entropy under the following situations :
    (i) A mass of a pure substance is heated at its sub-cooled state from a lower to a higher temperature.
    (ii) A mass of a pure substance is heated from its state of saturated liquid to the state of dry saturated vapour.

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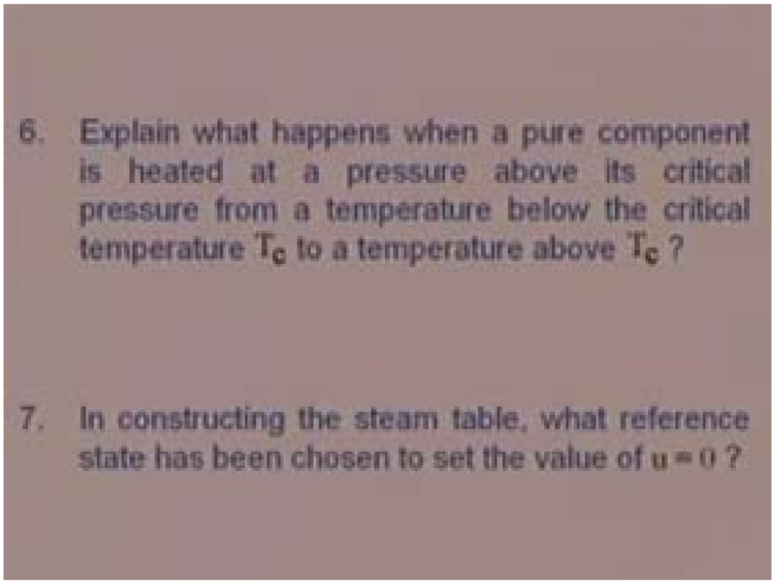

6. Explain what happens when a pure component is heated at a pressure above its critical pressure from a temperature below the critical temperature T_c to a temperature above T_c ?

7. In constructing the steam table, what reference state has been chosen to set the value of $u = 0$?

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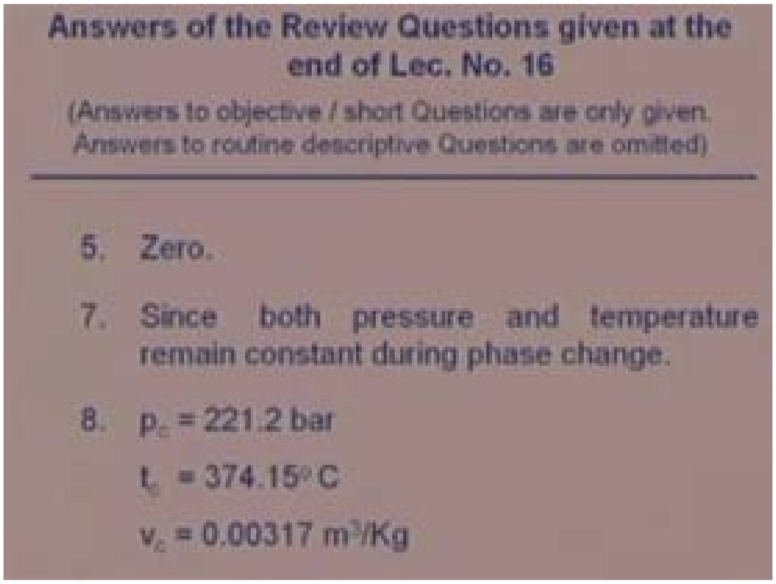

Answers of the Review Questions given at the end of Lec. No. 16

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

5. Zero.

7. Since both pressure and temperature remain constant during phase change.

8. p_c = 221.2 bar

t_c = 374.15° C

v_c = 0.00317 m^3/Kg

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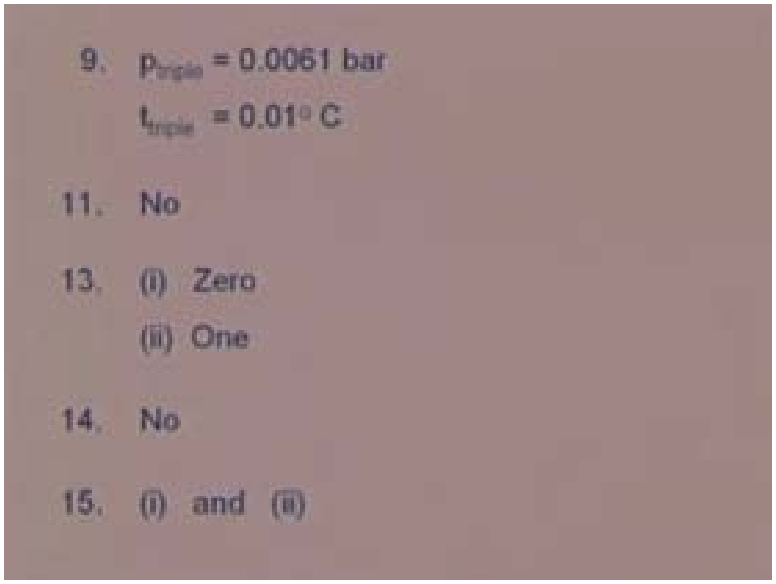

9. p_{triple} = 0.0061 bar

t_{triple} = 0.01° C

11. No

13. (i) Zero

(ii) One

14. No

15. (i) and (ii)