Engineering Thermodynamics

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Lecture - 49

Gas-Vapour Mixtures: Psychrometric chart. Applications

This is the third and the concluding lecture on Gas-Vapour Mixtures. In the first two lectures, we started off by looking at a general mixture of ideal gases. In the second one, we restricted ourselves to making that approach applicable for one particular case, which is air plus water mixture.

Now, we will look at this mixture from a different perspective, particularly something that is relevant in air conditioning. The science of this is called psychrometry. So, we will first look at the psychrometric chart, what it is, what it means and how to use it; and following that we will look at some applications that will conclude this module on gas mixtures.

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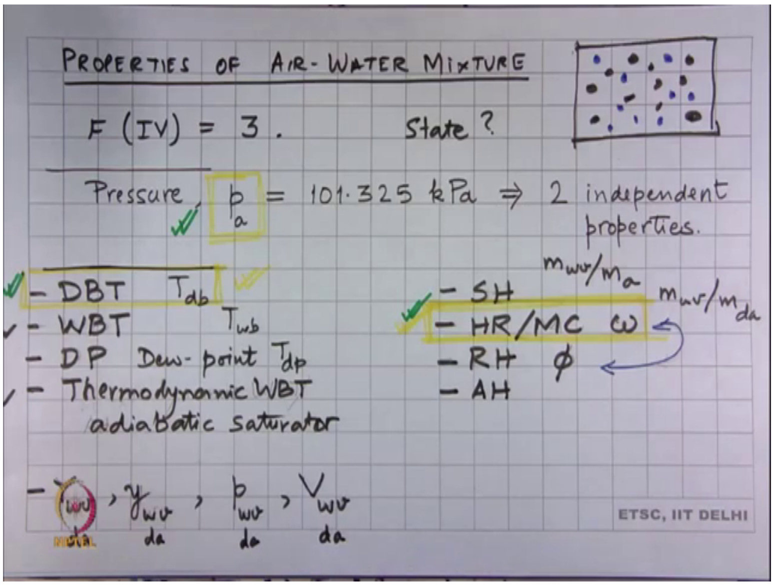

PROPERTIES OF AIR-WATER MIXTURE

$F\ (IV) = 3.$ State ?

Pressure ✓✓ $p_a = 101.325\ kPa \Rightarrow 2$ independent properties.

✓ - DBT T_{db}
✓ - WBT T_{wb}
- DP Dew-point T_{dp}
✓ - Thermodynamic WBT
adiabatic saturator
- $\overset{}{w_v}$, $y_{\frac{wv}{da}}$, $p_{\frac{wv}{da}}$, $V_{\frac{wv}{da}}$

- SH m_{wv}/m_a
✓ - HR/MC ω m_{wv}/m_{da}
- RH ϕ
- AH

In an earlier lecture, we had come across an expression from the number of degrees of freedom of a system, which may also call as the number of independent variables that are there. And this we saw that for an air water mixture, this value is 3. This tells us that we need to have three independent properties to fully specify the state of an air water mixture.

Now, the question that we are posing is which are these three properties, and if there any other combinations of any three properties which one is a more preferred one, which is used by practicing engineers. So, to answer that question, we look at the first part of it. And we realize that we are dealing with ambient air. Actually the first property that get fixed up is that the air pressure or the moist air pressure as we have called it p subscript a. This is 760 millimetres of mercury, which is 1 atmosphere which is 101.325 Kilo Pascal's. So, one property got fixed.

So, we are now left to get two more independent properties to completely specify the state of an air water mixture. So what options do we have? In this previous lectures, we have come across a large number of properties. And so we will just list them out, and then ask can any two of those be used to satisfy this requirement to completely specify the state of the system, so that is what we need to do, how do you specify the state, and which are those properties that would do the job for us.

So, here the listing of those properties that we have come across, the first thing of course we came about was the dry bulb temperature. This is the temperature of air, as it is measured by an instrument sitting in air. Then we looked at another property, this was the wet bulb temperature which we said that if that air is adiabatically cooled by evaporating water in it, then what is the lowest temperature that it will get that temperature is that wet bulb temperature or the thermodynamic wet bulb temperature, which we then say that is slightly different from WBT. So, this is the ideal case which we will get from an adiabatic saturator, but we do not use an adiabatic saturator for making practical measurements in day-to-day engineering, what we use is a wet bulb thermometer with the (Refer Time: 04:34) that gives us the WBT. And for practical purposes, we say that these two are identical.

Yet another temperature property that we came across was the dew point, which is the temperature at which moisture will condense, if that air sample were to be isobarically cooled, so that is a dew point temperature. So, a WBT is always going to be between DBT and the dew point, so these are the temperatures that we had.

And we are defined a various symbols for this T db for this, T wb, T dp like that. Then we came across many properties by which we can quantify the composition of the mixture which was the mass fraction say of water vapour. And similarly, for dry air or the molar fraction for water vapour, and dry air or we could get the partial pressure of water vapour or the partial pressure of dry air, and the volume the partial volume of say water vapour or partial volume of dry air.

So, again we have many more options coming up here. And they are all describing the same system, we are looking at which is a system in which there is air, they are the air molecules, and then there are water. Then we came across another set of properties which told us something about what we call humidity. So, we had one definition which was specific humidity, which was mass of moisture in a kilogram of the air.

Then we looked at humidity ratio or moisture content, symbol omega which was mass of water vapour per mass of dry air, this was mass of water vapour per mass of air. But, since the difference between these two in the denominator is very small, because the mass of water vapour in the mixture is very small. The values would be very close, but to keep matters clear we say that the two are not exactly identical, we cannot substitute omega, and call it specific humidity, we will not do that.

Then we defined relative humidity with the symbol phi, which was the mass of vapour in the atmosphere with divided by mass of vapour that would be required to saturate the air at the same temperature. And then we also had another term, which was the absolute humidity. So, this is the options that we have, so many temperatures humidity, and so much of combinations. The question is are all they independent or are some of them connected to one another. And that answer that question got partly answered, when we looked at various expressions that we derived.

And for instance, we saw that these two are uniquely related to one another. So, if you specify one, the other is specified. Similarly, we can show that the others are also interrelated to these. So, if we do all of that, we say we will look I do not need to specify all of that, but then if I do specify omega and phi, then that is really only one property being specified ok.

So, what are the combinations of properties that we will use which makes life easy. And what has been done is that the first property that is chosen is something which is easily measurable, and which can very quickly make sense, and that is the DBT. So, this is the second property, pressure was our first property. And then the other property which is taken as independent, and is useful in the way engineering of air conditioning systems is done is omega. So, here we have conversed to three independent properties, which is; which are the pressure, the dry bulb temperature, and the humidity ratio or the moisture content. So, if we specify these three, then the state of the system is completely uniquely specified.

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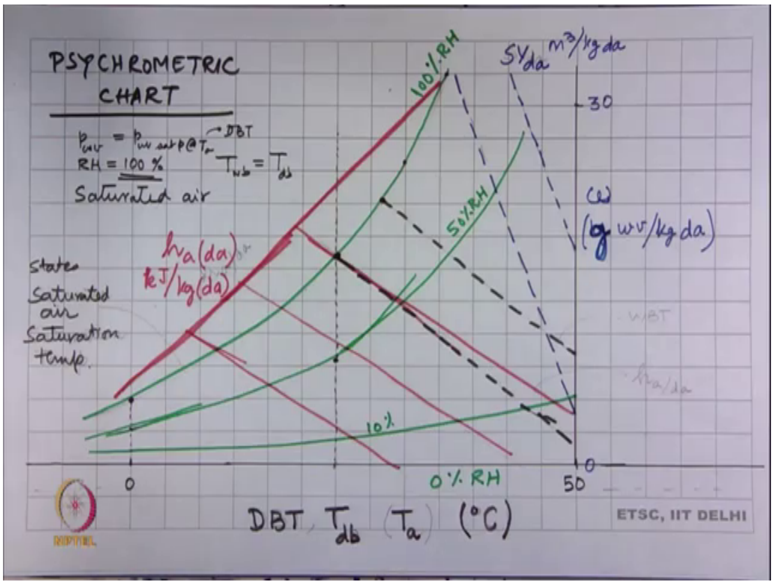

So, let us see now what happens? We had a various expressions for these properties. And the idea is that can we make it into a chart that is easy to use, and we can use it for doing engineering calculations such a chart is called the psychrometric chart.

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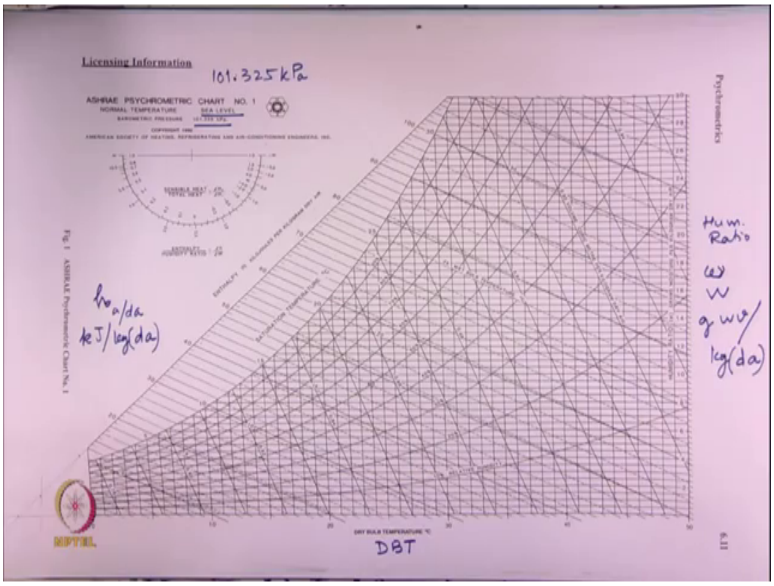

And this is the actual psychrometric chart that has been that is available in various books and other materials. So, now, we will spend some time trying to understand, what this chart is and what it is telling us and what is the basis from which this chart came about. So, we start with by looking the fact that this is the x-axis, and there is 0 here, then 10, 20, 30, 40, 50 going this way, this is the dry bulb temperature the DBT.

So, the x axis is DBT, and the y axis you can see here the small numbers which has 2, 4, 6, 8, 10 all the way going to 30 is humidity ratio w, grams moisture per kilogram dry air. So, this is what we have called omega, some people call it W, this is grams of water vapour per kg of dry air. So, if this scale is increasing left to right, and this is increasing from bottom to top, we could easily have made this scale like any classical graph that we plot this axis over here, and the x axis over there, nothing would have been lost.

The graph would still be exactly the same except that you would see a big empty space on one corner of the graph which cannot be used for anything else, what we are seeing here is that this empty space that was there has been used to put on the sketch there, which is again useful in solving the problems over here.

Now, this is what the two axis on this psychrometric chart are and this entire chart have been said that this is a normal temperature at sea level, and barometric pressure is 101.325 k P a. So, this chart is valid only even the pressure is 101.325 kilo Pascal. If there is a small plus minus 5 10 percent change this way that way it is not going to make too much of a difference. But, if it is going to be down to 50 kilo Pascal’s or 30 kilo Pascal’s or may be 10 1000 same say 500 kilo Pascal’s which is compressed air. Then in that case bit be little more worrying in using this particular chart for getting those properties. So, this is for 101.325 k P a, which is good enough for almost all practical applications in air conditioning, and many industrial applications as well.

So, now let us see, what are all these lines here, there is a one set of lines which are going like this. There is another set of there is another axis over here, which is enthalpy is kilo Joules per kilo gram of dry air. So, this is a third axis which is h a on the dry air basis, which is kilo Joules per kg of dry air, this was also dry air. So, if you look at these lines which are going this way, these are lines of constant enthalpy. And this axis being DBT means, all this vertical lines, these are lines of constant dry bulb temperature. And horizontal lines parallel to the x axis are lines of constant omega ok. So, this is humidity ratio or moisture content.

Besides these we see some more lines say a line like this one here. And say a second line which is going like this, and here (Refer Time: 14:49) line which is going like that. So, if you look at what is written on these, it says relative humidity. So, this is a line of constant relative humidity 10 percent, line of constant relative humidity 20 percent, 30, 40 like that up to this extreme line, which is line of 100 percent humidity.

And of course, this horizontal line the x axis itself, where omega is 0 is the line of 0 percent humidity. So, this is relative humidity lines and then we have this dash lines going over here like this. And there are many of these dash lines, it is here which looks almost parallel to the constant enthalpy lines, but they are not. Because, you can see here, the dash line goes slightly above the solid line. This dash line is says wet bulb temperature. So, these are lines of constant wet bulb temperature. And then there is a third family of lines, which are little more steeper which are going like this here. And this has numbers like 0.88, 0.9, 0.92, and this is volume in cubic meter per kilogram of dry air, so that is what these lines are.

So, the graph looks somewhat cluttered with so many lines on it. So, we will look at each one of these individually, and say how to why does graph look like this which are the equations that are being put together to make this graph. And then we will see how to use this how to interpret this. So, what we are doing is we made the x axis here 0 to 15 degree Celsius. So, like that original graph this is DBT or in our symbol system, we had called it T db or in all the equations, we have called it T subscript a. And the units is degree Celsius, this is the important to keep in mind.

The graph goes in that case from 0 to 50 degree Celsius, but there is no real reason why, it should not go before this or after this. So, if you have air at minus 10 degree Celsius, and you want to do heating cooling or humidification of that air how do you do it or what is the temperature is more than 50 degree Celsius, like what would happen say in the Rajasthan desert. Now, 55, 56 degree Celsius is not uncommon though the same set of equations can be extended, and this graph can be extended to both sides. This particular graph is done, just because this is the typical range of temperatures that people have to work with in designing air conditioning systems.

But, there are other graphs that you will see where instead of 0 to 50, it goes say 0 to 80 degree Celsius. And these days of course all of this has been programmed, and you get nice online resources or programs or interactive software, where you can do all the things which we are talking of doing manually ok. So, the y axis was 0, and the temperature scale, this is the omega, humidity ratio kilograms of wet vapour per kilogram of dry air going from 0 to 30.

The reason I put this numbers is to just to get an idea, what sort of numbers that we dealing with here order of magnitude. So, somewhere in the middle would be say 15 or maybe here would be 10. So, you got basically sorry this is not kg, this is g this is grams of water vapour per kilogram of dry air. And it tells you again that is like of the order of 10 or 15 grams in 1 kilogram of air which is very small; 1 percent.

Now, let us say if I take a DBT, and I draw a line. So, here is a line that we can make, this is a line of constant dry bulb temperature. So, what is telling is that if I pick up a point on this line, it means that the dry bulb temperature is this much, and this much is the moisture content. So, the question is if we keep going up for here, I get this value for here, we get this value, for here we will get this value. So, this basically tells you that give me a DBT, and for every state there will be a value of omega.

But, what we have learned is that for a given dry bulb temperature, there is a limit to how much moisture air can hold. Any additional moisture will cause it to precipitate, and that is what we called as saturated air, beyond that we cannot have a state which has more moisture than that. So, there is an upper limit to which this line can go, and that line limit we can say is here where air is saturated.

And when we say air is saturated, it means that at this point relative humidity is 100 percent or phi is equal to 1. The partial pressure of water vapour is equal to the partial pressure of the corresponding saturation pressure at the T, which is your T a or which is your in this particular case for this point T a is nothing but DBT the dry bulb temperature. So, there these states are not possible, so that is one thing we got.

And now we could do the same thing for every temperature say take 0 degree Celsius, and we will get this point, we take anywhere here 30, 35, 40 degree Celsius, and we start getting these points. And you start seeing that you get a locus of points, which are telling you that the air is saturated. So, we have this line coming up here. And this is a line of saturated air states, these are the states where we have saturated air.

And the temperature is the saturation temperature, it also means that this state point the T db is what it was is this axis, because it is 100 percent, because this is saturated air 100 percent relative humidity, the wet bulb temperature is also the same. So, this particular point also replaces tells us that the wet bulb temperature is exactly the same thing which is your T a or T db, and all of these because relative humidity is 100 percent.

So, this also tells us that this is a line of 100 percent relative humidity. So, beyond this no states are possible, and that is why this graph beyond this is all empty, so that is one thing we got. Now, we can do another thing we said were look, we will do the same thing, but now that we know what is 100 percent relative humidity; I can calculate, and say what is the value of omega for 50 percent relative humidity.

So, if you do that we will get some line over there or state over there, the omega here corresponds to 50 percent relative humidity. Similarly, we can do that for each one of these, and that will create another line which will be like this. And this would be the line of 50 percent relative humidity. And like that we can continue making lines all the way down there, and this could be say 10 percent relative humidity. And then this line the axis itself is 0 percent relative humidity. So, in between we can draw more lines, as you saw on the graph for every 10 percent change of relative humidity there is a line, so that is one set of lines that we got. And what it basically means is that each point here corresponds to omega for the saturation vapour pressure; simple as that.

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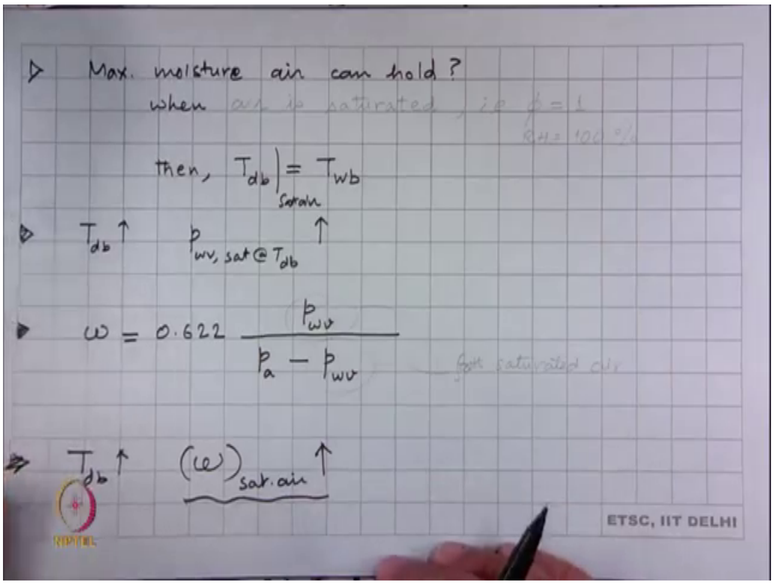

▷ Max. moisture air can hold ?

when air is saturated, i.e. $\phi = 1$

$RH = 100\ \%$

then, $T_{db}\Big|_{\text{satn}} = T_{wb}$

▷ $T_{db} \uparrow \quad p_{wv,\, sat @ T_{db}} \uparrow$

$$\omega = 0.622 \frac{p_{wv}}{p_a - p_{wv}} \quad \text{— for saturated air}$$

$T_{db} \uparrow \quad \underbrace{(\omega)_{\text{sat. air}}} \uparrow$

Now, we let us look at the constant enthalpy lines, and for that let us go back, and see the relations that we had. So, before we do that, we just recap that on this graph, as the air is saturated, dry bulb temperature is wet bulb temperature only at saturated air. As the dry bulb temperature increases, the parts; the saturation pressure of water vapour at that temperature also keeps on increasing which is the reason, why this graph is going up, and does not go down like this or does not become flat.

And then we calculated omega based on this 0.622 into this relation, where it was a partial pressure of water vapour and at 100 percent relative humidity state whatever was there we could get that, so that is how we got the other state points. This plot also tells us again that as DBT increases, the ability of the air to hold moisture is also increasing because of this graph, so that is what it is as dry bulb temperature increases, the humidity ratio at which air becomes saturated that also increases. So, it is a monotonic increase in this. So, this was the iso relative humidity lines.

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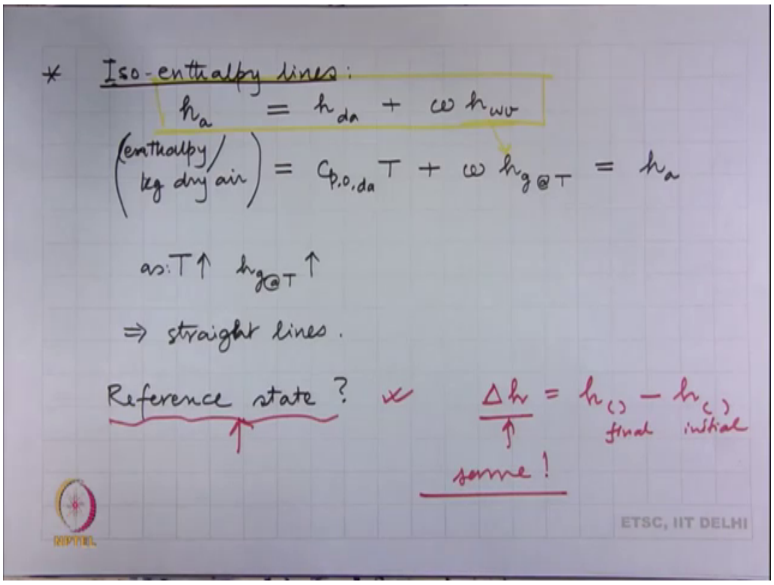

* Iso-enthalpy lines:

$$h_a = h_{da} + \omega h_{wv}$$

$$\left(\frac{\text{enthalpy}}{\text{kg dry air}}\right) = c_{p,0,da} T + \omega h_{g@T} = h_a$$

as $T \uparrow$ $h_{g@T} \uparrow$

$\Rightarrow$ straight lines.

Reference state? ✗ $\Delta h = h_{(\,)} - h_{(\,)}$ final initial

same!

Now, we look at iso-enthalpy lines; that means lines of constant enthalpy. And what we have here is that where in expression which said that specific enthalpy of air which is the enthalpy on kg per dry air basis where; so, in general, we have this expression that enthalpy of air is specific enthalpy of dry air plus omega times specific enthalpy of water vapour.

And then if we simplified, divided this we got from dividing by mass of the dry air, then h d a can be written as specific heat of dry air times the temperature, and this is omega times h g, which is the dry saturated vapour specific enthalpy at that particular temperature. So, we have this expression. And now we say that if h a is constant, which is what is there on the left hand side say this is equal to h a.

And if I keep h a constant select at T, and then calculate the omega, we will get the state point. And this tells you that as T increases omega has to keep decreasing, so that is a qualitatively, we get that. This expression also tells us, it is pretty much like a linear behaviour. So, we get this one that when we plot this, we will get a bunch of straight lines. So, here is the; a straight line that we will plot, say this is with enthalpy.

So, these are the lines these are the lines of constant enthalpy, and this is the same value here. The axis work on enthalpy is made on this side, and this is h a on dry air mass basis kilo Joules per kg dry air. So, this is that particular line that we got. And that was the basis, why these lines are slope like this, and why they are straight. So, like this there are whole bunch of lines that we get.

The only question left with specific enthalpy is that to get the value of h here, we need a reference state. So, depending on what reference state one picks up based on that all these will get added, and it will come there. If you use that different reference state, the number values will all change, but the corresponding lines will all remain the same.

So, different charts I have used a different reference states, somebody has used minus 20 degree Celsius as the value for setting h as 0, but that should not worry us because, in most calculations, we will be worried about the change in enthalpy which will be enthalpy at some state minus enthalpy at initial state. So, this would be a final state enthalpy, this could be say initial state enthalpy of the outlet and inlet enthalpies.

So, irrespective of what reference value is used, the difference will always be the same. So, to that extent we do not have to worry us to what these are, but if there are two peoples solving the same problem using two different charts, where the reference states for enthalpy are different, individual values that they will keep getting a different. But, in the end all calculations were there are a difference of enthalpies coming in those values will be identical, so do not need to worry too much about it at that point, so that is what we have for specific enthalpy.

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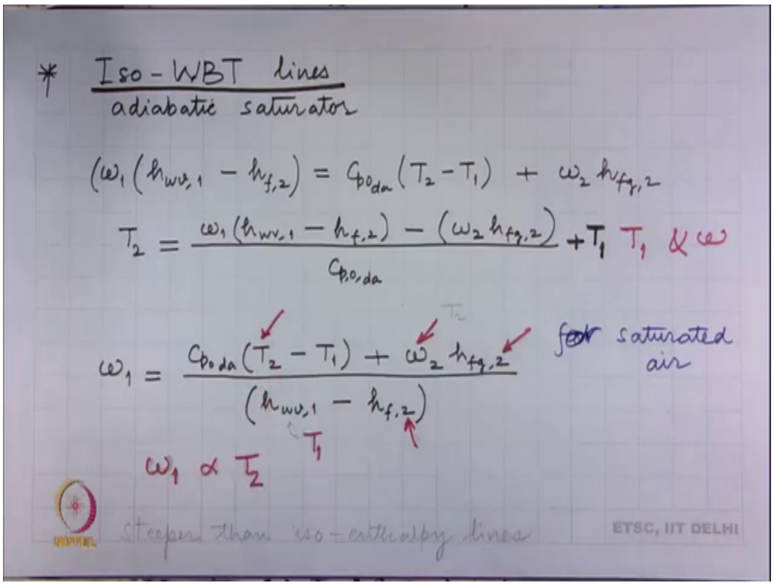

* Iso - WBT lines

adiabatic saturator

$$(\omega_1 (h_{wv,1} - h_{f,2}) = c_{p0_{da}} (T_2 - T_1) + \omega_2 h_{fg,2}$$

$$T_2 = \frac{\omega_1 (h_{wv,1} - h_{f,2}) - (\omega_2 h_{fg,2})}{c_{p,0,da}} + T_1 \quad T_1 \ \& \ \omega$$

$$\omega_1 = \frac{c_{p0\,da} (T_2 - T_1) + \omega_2 h_{fg,2}}{(h_{wv,1} - h_{f,2})}$$

for saturated air

T_1

$$\omega_1 \propto T_2$$

steeper than iso-enthalpy lines

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Now, let us look at how do we get the iso wet bulb temperature lines. So, basically what we are saying is the way, we can the expression we got for wet bulb temperature came from the adiabatic saturator, where we said that you got air and we are putting water in it, to produce a saturated state, where the water temperature is the same at the saturated state temperature and that temperature is what is the in thermodynamic wet bulb temperature what we would also continue to call it as the wet bulb temperature. When you do that, this was the expression for energy balance that we got after invoking the mass balance.

And this can be rearranged that T 2, which is the wet bulb temperature or the thermodynamic wet bulb temperature, this is given by this expression omega 1 into enthalpy of water vapour in inlet state 1 minus h f which is the saturated liquid state at temperature T 2 into omega 2, which is the saturated state humidity ratio times the specific enthalpy of evaporation h f g at temp temperature T 2 divided by specific heat of dry air.

So, if we rearrange this and put this as omega 1 as function here, this is the expression we get. And when we look at this expression, we see a couple of things. If we say that this is T 2, if we specify it. Once T 2 is specified, omega 2 gets specified, if we know because we know T 1, h f g 2 gets specified, because this is dependent on T 2. So, this is nothing but a thermodynamic property. So, this is only a function of T 2. This is only a function of T 1, and this is again only a function of T 2.

So, what one can do, and we can see from this expression is that omega 1 in ways proportional to T 2. So, what one can do is we say that ok, if I keep the wet bulb temperature constant which is T 2 is constant then what is the relation between T 1 and omega, which this expression tells us. So, if you do that sorry this and there has to be one more term after this, this is the plus T 1. So, this expression tells us that we can expect a linear behaviour between these two lines.

And that is what we see here on the psychrometric chart that lines of constant wet bulb temperature would be lines which are going like this, they start from here, and they would be going like that. So, like that there will be many more lines over there, they all start here, and these lines continue like that. At this point the DBT and WBT are the same. So, if this was a 20 degree Celsius DBT, this line is 20 degree Celsius WBT. So, like this we get lines which are which look almost to be same as the iso-enthalpy lines, but they are slightly more steeper than the constant enthalpy lines, so that tells you this yet another line.

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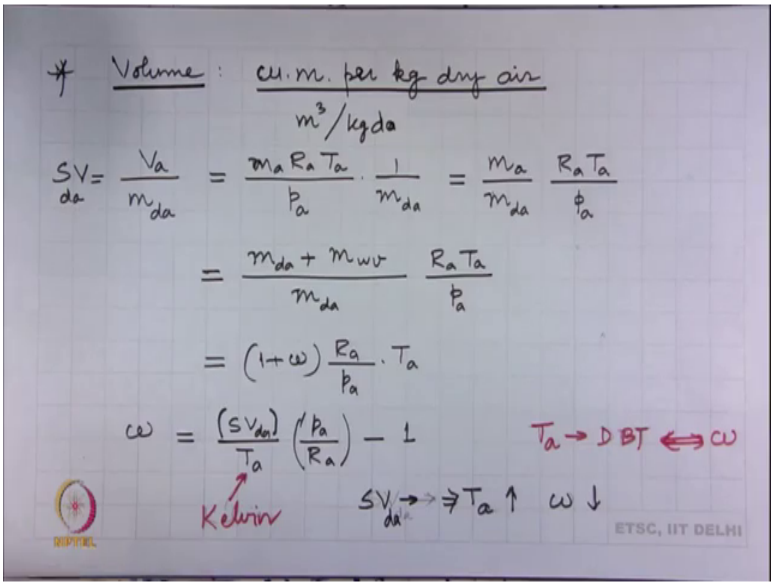

* Volume : cu.m. per kg dry air

$m^3/kg\,da$

$$SV_{da} = \frac{V_a}{m_{da}} = \frac{m_a R_a T_a}{p_a} \cdot \frac{1}{m_{da}} = \frac{m_a}{m_{da}} \frac{R_a T_a}{p_a}$$

$$= \frac{m_{da} + m_{wv}}{m_{da}} \frac{R_a T_a}{p_a}$$

$$= (1+\omega) \frac{R_a}{p_a} \cdot T_a$$

$$\omega = \frac{(SV_{da})}{\underset{\nearrow}{T_a}} \left(\frac{p_a}{R_a}\right) - 1$$

Kelvin

$T_a \rightarrow DBT \Longleftrightarrow \omega$

$SV_{da} \rightarrow \ni T_a \uparrow \quad \omega \downarrow$

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And finally, we have a lines for the specific volume. So, this is cubic meter per kg of dry air, meter cube per kg da. So, this we can write specific volume with on dry air basis is V a upon m da V a can be written as m a R T a by p a into 1 upon m da. And when you simplify that, we can write mass of air the mass of dry air plus mass of water vapour. And then you simplify it, and this becomes 1 plus omega R a by p a times T a or omega is the specific volume divided by the ambient temperature into p a upon R a minus 1.

Now, unlike all the other expressions, where temperature was in degree Celsius, because we use the ideal gas equation of state one must realize that this temperature has to be in Kelvin. So, what it tells us is that for a given value of specific volume, these are one to one connection between the DBT and omega. So, what we are seeing is that for a given specific volume on dry air basis, so if this is constant, this implies that T a increases, omega decreases, and it does so in a linear fashion.

So, we go back to our chart then we begin to see yet another set of lines, which is these lines. So, these are lines of constant specific volume on dry air basis meter cube per kg dry air. So, we have all the we know all the equations from which we got this using the equations, we can make our own computer programs, if we need b or we can use that in some other calculation or then we can go back to the chart which is been created by using those equations, and use this directly from the plot.

Now, let look at some typical numbers that we are looking at starting with DBT of course is a 0 to 50 degree Celsius, humidity ratio 0 to 30 grams per kilogram of dry air specific enthalpy is of the order of like here, it is 20, 30 going to 100 kilo Joules per kg of dry air depending on whatever was the zero state that was used. Numbers will be of the same order, maybe of consistently by 10 or 20 something like that. This is the line of 100 percent humidity, and also with the line of saturated air.

So, this also tells you the saturation temperature which is also essentially basically WBT with 100 percent humidity that is what saturation temperature is. And then we saw lines of constant humidity 90, 80, 70 like that. And then we got these lines which is your wet bulb temperature lines here, and this has exactly the same magnitude as the DBT. And you can see that the 20 degree WBT line, here this line starts at the point where the 20 degree DBT line meets the saturated state. So, here that is 25, then 30 like that.

And then we had the constant specific volume lines, which is here the number here is 0.92 meter cube per kg of dry air, and so and like that this is 0.9, 0.88, and if we keep going down this is 0.82, this is point 0.8. So, recall that is specific volume is this, the density of this will be the reciprocal of that. So, as the temperature keeps coming down, and humidity keeps coming down, the air gets more and more dense. And this is of course the case, when pressure is constant.

So, this is what this chart has, there is one more thing here, which we will not go into detail here, but that the subject of a further full fledged course on air conditioning, which is that this little thing that has been put over here. What it shows is like a semicircle in, and some cases, there is not showing this thing. There is a line on this side, which gives the same values. And it says inside sensible heat to total heat ratio that means, if we are going from state 1 to state 2 that particular inclination will tell us, what is the ratio of sensible heat to total heat, which is sensible heat plus the latent heat.

So, it starts vertical line, it is 0, and as it go this way it becomes 1. So, if it is going to 1, and one this way, one of which will be that means, there is no moisture being addition that sensible heat over total heat is 1 that means, all the heat is only incoming as sensible heat, so the line has to be parallel to this line. If there is only if it is 0 that means sensible heat addition is 0, only latent heat addition is there, then the line has to be here vertical line. And any inclined line in between will tell us what the ratio of these two, and that is helpful in making various air conditioning calculations, for now we will not go into the details of it, but that completes our discussion of the psychrometric chart.

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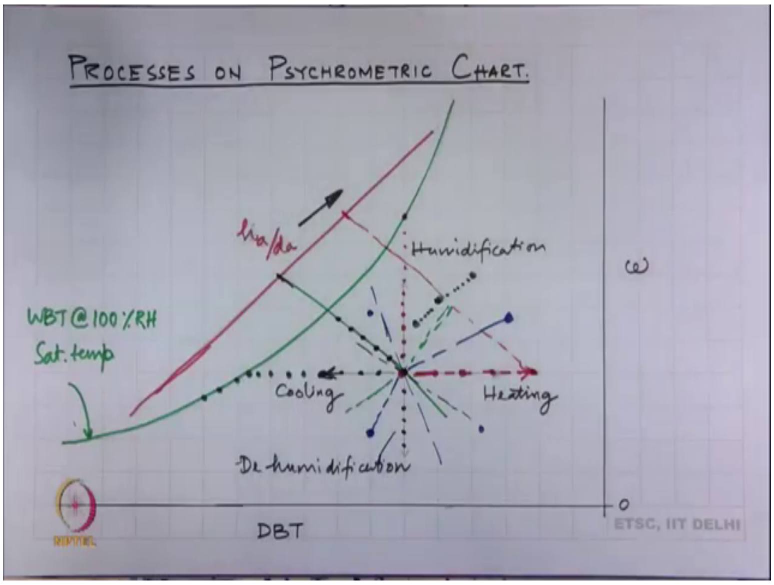

Now, we move on us, what is the type of procedures that we can see in this. So, here arethe axis as before DBT and omega, and we have let the saturation temperature line or the 100 percent humidity line over there. And we have the third axis, which was the specific enthalpy line h a over d a, this was the saturation temperature which is nothing but WBT at 100 percent relative humidity.

So, now what it tells us is that if we have a state say air in this room, then we can say that we know the DBT we measured it say, and either we know omega or we know the relative humidity. So, if the relative humidity was there, it would pass through a line over there something like that. This is the relative humidity line or if you knew the WBT, then we could have used the WBT line to mark it or if you knew the specific volume, we could have used the specific volume line and mark the state. So, specific volume line would have gone something like this.

So, we can uniquely identify the state or even if it was not DBT, if it was say omega and R H, we could still say that this was the omega, this much is the R H the state lies here corresponding DBT, WBT are this much. So, this is our initial state. And now we say what is the type of procedures that can be shown on this picture, and we have shown four arrows over here, so let us go on with one by one with them. First look at what happens when the series of change of states happens, and it comes to say this point or this point or this point or this point. So, what has happened in this case is that the DBT has increased, but omega has remained the same.

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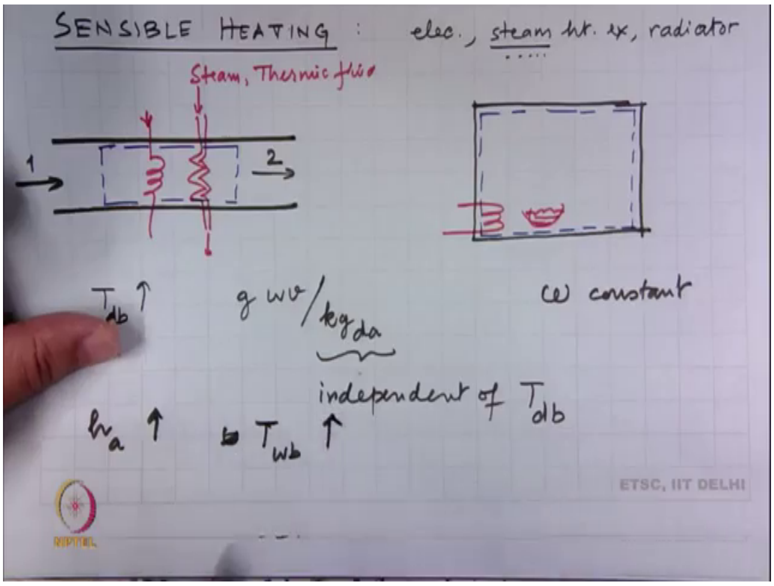

So, this is our first application that we have seen that this is what we call sensible heating. So, this can be accomplished, and practically this is done so by various ways. One is that we have a duct in which say air is flowing, and to heat it we have simplest thing an electric coil, we pass current through this. So, this air goes in, this duct is insulated, it goes in at state 1, comes out at state 2, the only thing that was done that was heat was added to this system.

Another way where the same thing happens is what one does in the house in cold days is that we have a room and in this we put an electric heater, and heat up this air, and assume that the walls are adiabatic. The other option could be that we have a thing where there is small drink or hot and that is giving away heat. So, this is a close system, where heat is being given. This is an example of an open system, where the air is being heated.

This heating could be done electrically or it could also be done by putting it, through a set of heat exchanger pipes through which we could have steam or any other hot fluid like a hot thermic fluid, which is flowing which heats the air. Then all these cases all we are doing is there is only sensible heat addition taking place, and the states that we are seeing happening here is goes from here to any of these states on this line.

So, the hallmark of this is that in sensible heating the dry bulb temperature increases and because we are neither adding moisture nor removing moisture from this control volume. So, we need to define that, so this is say the control volume or in this case this is our control mass. We did not add moisture, we did not remove moisture, so the amount of moisture in the system remain same that means, grams of water vapour is the same, and this is grams of water vapour per kg of dry air also remains the same.

Now, remember because we are doing it on dry air basis, this is independent of the temperature. And that is one of the reasons, why more of the property that we are looking at are expressed in terms of dry air and not in terms of the total amount of air, so that is what it tells us that because this is fix no moisture is added or removed, it means that omega is constant, so that is one thing that is come out.

The second thing is see that as the state goes this way that lines of enthalpy are going of that way, if you read here, the enthalpy is increasing in this direction. So, when you do heating h of a increases, and that we can calculate from that. And the same time, we can also see that lines of wet bulb temperature which are these dash lines, even those lines go up.

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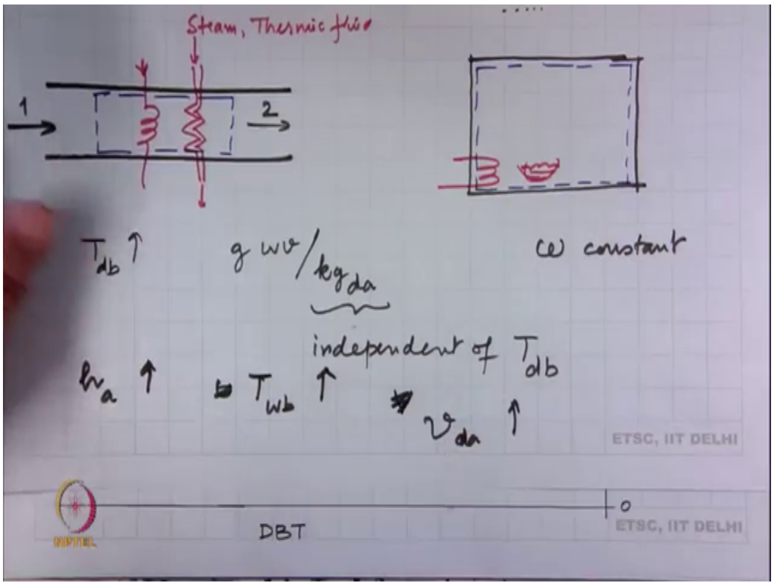

So, we can say that that wet bulb temperature also increases, and as this blue lines would go they are going to the right, it tells us that thus volume or that this the specific volume per kg of dry air, this is also increasing; air is expanding. So, that is the first application processes that we are looking at and what we are saying is that we can get the enthalpy of this state by going to this graph, and reading it from there this one.

And the final states it was there we see what is the specific enthalpy line that is going through this, and go to the state. And this difference is the change of enthalpy during this process. So, this is the process this is the way, we will do calculations for all the other changes that we are coming across. So, this is a case which is purely of sensible heat addition, which I we saw earlier in that picture on this side, the ratio of sensible heat to total heat is 1.

Now, let us look at the second application, where we are going to do sensible cooling only. So, what we are doing is what we are saying is that this was the state, and we cool it, and we realize all these states which are coming up here, and so this becomes the final state over there. We can do the same type of a calculation over here, remove the line here, and get the final enthalpy on this side. So, specific enthalpy is now decreased.

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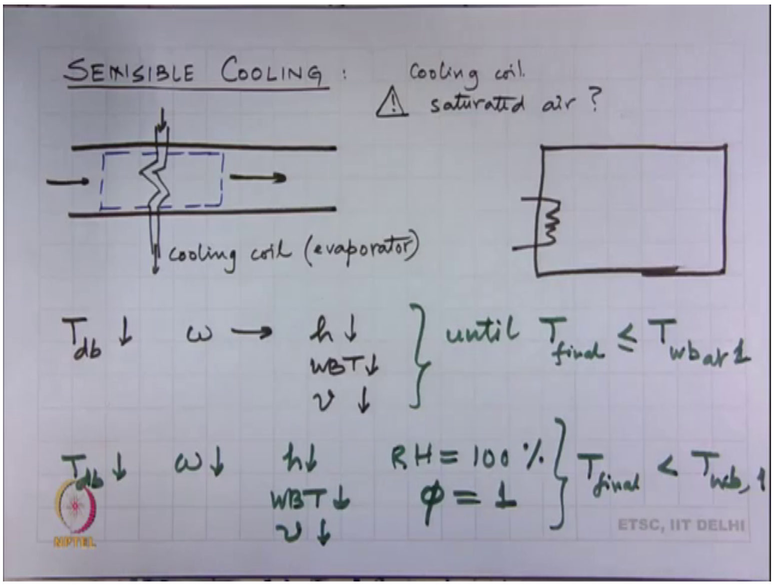

$T_{db}\downarrow \quad \omega \rightarrow \quad h\downarrow,\ WBT\downarrow,\ v\downarrow \Big\}$ until $T_{final} \leq T_{wb\,air\,1}$

$T_{db}\downarrow \quad \omega\downarrow \quad h\downarrow,\ WBT\downarrow,\ v\downarrow \quad RH = 100\%,\ \phi = 1 \Big\}\ T_{final} < T_{wb,1}$

And by same type of arguments that we did for the heating case, what we do is when we are looking at sensible cooling place the same thing happens. And here the way the engineering works out is that we have a duct into which say we are putting a cold fluid which cools the air, as it flows over this, this is our control volume. And this air is going through this. The close systemic equivalent of this is that we have a chamber in which we have done this type of a coil; heat exchanger coil, which is taking heat away, and this being the control volume this is being cooled.

So, what is happening in this case is exactly the opposite of what happened earlier that dry bulb temperature decreases, omega remains the same, h decreases, WBT decreases, specific volume decreases. But, there is a little caution on this particular generalization is this goes like that. We can continue on these states continue cooling until it hits this points that means, we have cooled it to the point that air has now become saturated. So, up to this point everything that we said so far is perfectly fine.

Now, what happens, if you continue cooling it further; and this is where the situation becomes tricky, in that any further cooling will not cause just at cooling effect, but will also cause moisture to precipitate. So, the states will then start following this line. So, what is happening now is that all of this process that we wrote here all of this is good until the final state T final is less than or equal to the wet bulb temperature.

Further cooling, what we see is that of course T db, the dry bulb temperature will fall down. Omega begins to come down, because now the points are coming below it. h of course is coming down, WBT is coming down, v is coming down, but R H is 100 percent. So, phi remains constant at 1. So, this is what is going to happen, when the final temperature is less than the wet bulb temperature at the initial state say 1.

And so we now in a slightly different situation that we are also having precipitation. So, this is what when actually sees happening, and this coil that I have drawn here. This could be nothing but the cooling coil of an air conditioner; a window ac or a split ac or what we may call this as the evaporator of the system.

And we know that when the humidity in the air increases, which is the we are now coming to the monsoons and we are trying to cool air firstly the air temperature does not come down too much, because all that energy is done to precipitate the water out. And one can see that from the air conditioner, there is lot of water dripping out all the time. This is also an issue, when we do cooling of a room, where there are people inside, where you are breathing and giving out moisture.

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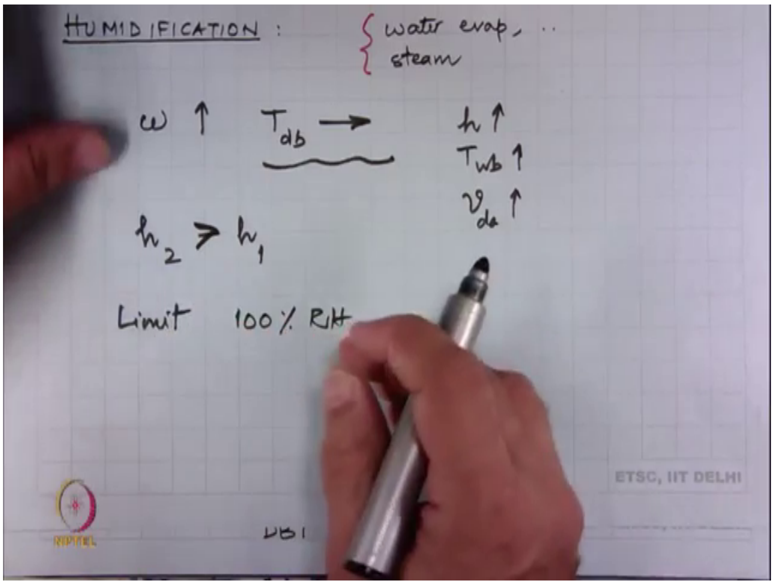

Now, we look at two other processes one, where we do pure addition of humidity that means, we started from this state, and we start going in these states, this is called humidification. And this can be either done by evaporating water, and heating it or by introducing steam in it. So, when we do that what we are seeing on that particular chart, the psychrometric chart tells us that we are adding moisture in such a way that omega increases, but the dry bulb temperature is held constant. And while we do that this specific enthalpy is increasing, and so is the wet bulb temperature and the specific volume for dry air.

So, in this sense what you are seeing is that final enthalpy h 2 minus h1 or h 2 is greater than h1 on that graph we can see that. So, just by adding moisture also, we are increasing the enthalpy of air, even though the dry bulb temperature is remaining the same that is what is called the latent heat being added. Again we can go keep going up on this graph, and there is a limit to it we can do is that we hit 100 percent humidity. So, there is an upper limit to which you can keep humidifying the air at constant temperature that once you have reached 100 percent relative humidity, then the process has to stop, so there is a limit.

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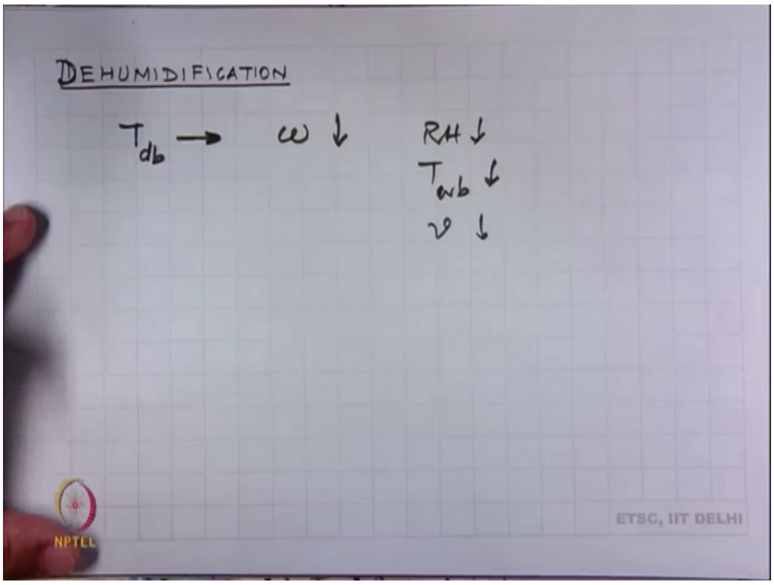

DEHUMIDIFICATION

$T_{db} \rightarrow$ $\omega \downarrow$ $RH \downarrow$

$T_{wb} \downarrow$

$v \downarrow$

The opposite of this are the series of states going down here, which is dehumidification. So, we have a dehumidifier something say that absorbs the moisture gets the air out, and that what we are doing there. Again here T db remains constant, while omega is decreasing. And with omega decreasing, R H is coming down. Dry wet bulb temperature is coming down, the air is becoming more dense, so that is these types of processes.

And then finally, you could have combinations of these processes, for example so now we can summarize on this, this is a heating process, this is cooling, this is humidification, and this is dehumidification. So, because still now have combinations of these, and we will just plot it to give a flavour of what is happening that we could be starting from this state, and going and coming to this state which would be heating and humidification or we could be starting from this state, and coming over here which would be cooling and dehumidification or we can have a state going over there or going over there from this. So, these combinations will come, and that is the type of calculations one would do in a air conditioning system.

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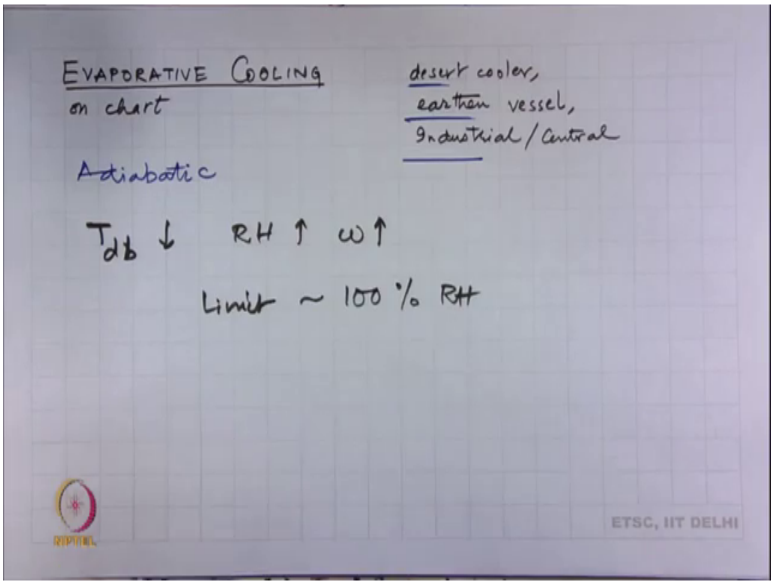

EVAPORATIVE COOLING
on chart

desert cooler,
earthen vessel,
Industrial / Central

Adiabatic

$T_{db} \downarrow$ RH $\uparrow$ $\omega \uparrow$

Limit ~ 100 % RH

ETSC, IIT DELHI

Then one more process, we will look at which is evaporative cooling. As we have seen what happens in a desert cooler or in a earthen part, and in many industrial cases, where you spray water into the air before taking the air in. What we are doing here is, because it is adiabatic, something again to the adiabatic saturator that we have already studied. The processes that this particular system will follow, they will lie on the constant enthalpy line which is here, and so this is what will be the states which the evaporative cooling process will take.

So, we can see here that when evaporative cooling takes place, this is going there because of that the dry bulb temperature keeps coming down, relative humidity increases, and so does omega. And there is a limit that you can only do that much cooling, until you get to 100 percent relative humidity, after that nothing is possible which is what also even see on the graph that if the temperature is high, and the humidity is low, one can do a lot of cooling.

But, if it is say like 45 degree Celsius and 20 percent humidity, it will be here. If you do iso-enthalpy cooling, it will come there. But, with 35 degree Celsius and 80 percent humidity, number of cooling you can do, and get a drop in temperature is very small and that the reason, why evaporative coolers are not effective, when humidity becomes very high.

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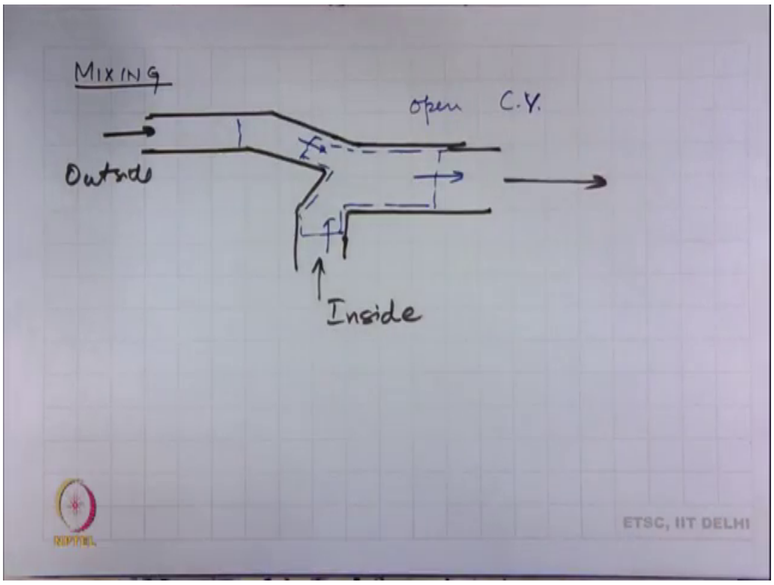

Another application of this is where you have two streams of air of different conditions mixing together. And this is was typically happens in air conditioning systems, we take some air from inside the air conditioning space, and some from outside, and we mix the two, and then we do the further cooling of this, so that way you are replenishing the oxygen and removing the carbon dioxide from the air where people are there.

So, what you are doing is now you have a different type of a system here. So, we can say that this is the control volume, this is something going in this goes in there, this comes out, and you are basically adding two streams to get a third stream. This is a type of an open system, so we will apply the control of control volume approach to this, write the equations and solve them for three states. We can see this mixing operation on this, there will be two states, and the third state comes in between there. So, this is air coming at one point, air coming there, and this is a say third point coming there, where we cannot draw the process by a solid line, because it is mixing is an irreversible process. So, we can say that this is happening there, and this comes from there to there, and this is the final state.

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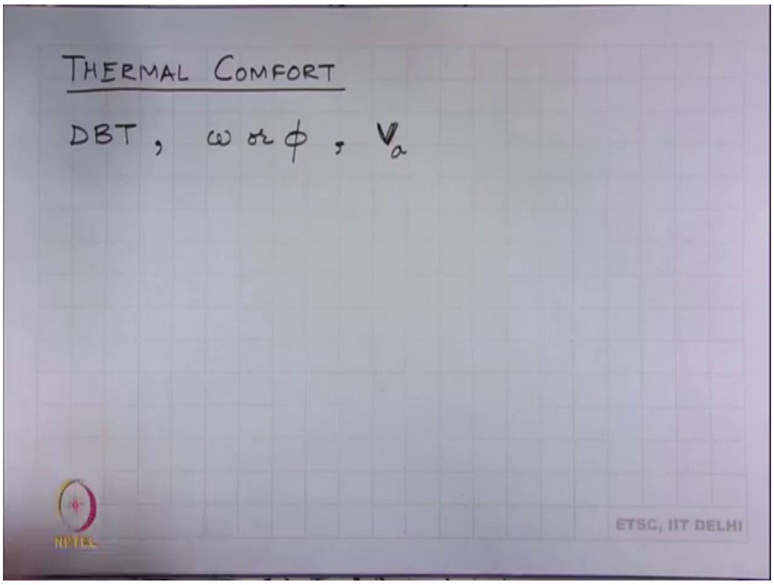

THERMAL COMFORT

DBT, ω or ϕ, V_a

Finally a word were to about why this we all studied in the first place, it has to do everything with thermal comfort. And it is not just thermal comfort say in a house or a office, but this could also be thermal comfort on say manufacturing floor or thermal comfort in an some industrial environment, where there are many other factors coming in.

And we say that what quantifies thermal comfort is the DBT, and omega or relative humidity, and see the air velocity. So, what we have in comfort charts, and we can see this on the psychrometric chart. The ideal condition is given by this little dot which is 25 degree Celsius and 50 percent humidity. So, everybody thinks that if we have this; that is the most comfortable thing for all of us, but then it is always a range, we say that it should be between these humidity’s and this WBTs. So, we end up making a region here which says that this is the most comfortable condition, then you go slightly away from it little less comfortable, you go out more uncomfortable, and then like that it goes on. And we are all quite familiar with this that when we have 45 degree Celsius temperature, and very low humidity we are sitting somewhere here we are way out of the comfort zone.

So, now this is becomes an important thing, because with increasing air conditioning. It basically says that most of the electricity being consumed in the grid on a very hot day by domestic and commercial industry office spaces, is for air conditioning like 60 percent of the energy, 50 percent of the electricity. So, if you want to become more energy efficient, lower carbon footprint, the emphasis is can we do air conditioning with less energy consumption.

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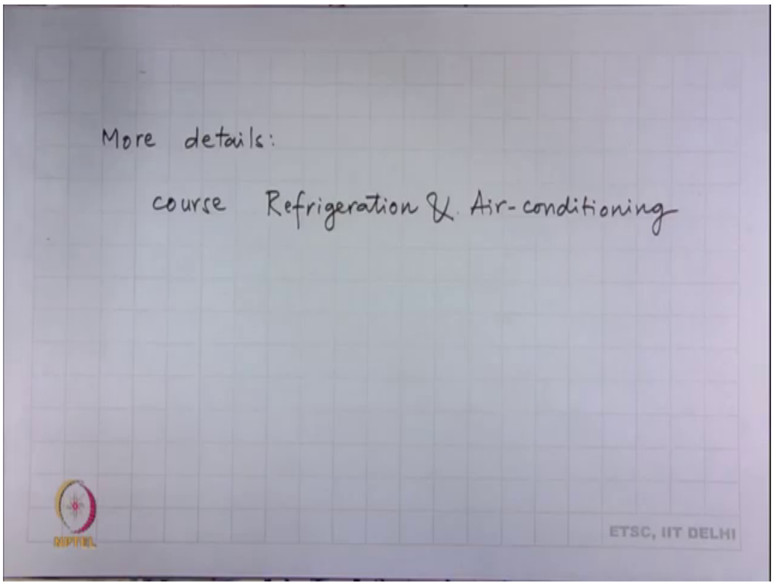

More details:

course Refrigeration & Air-conditioning

So, with conclude here with the saying that we have introduced various concepts of mixtures and psychrometry. More details, we can learn in an advance course on Refrigeration and Air-Conditioning and what we have learned here are the basics which are; which will remain unchanged later on.

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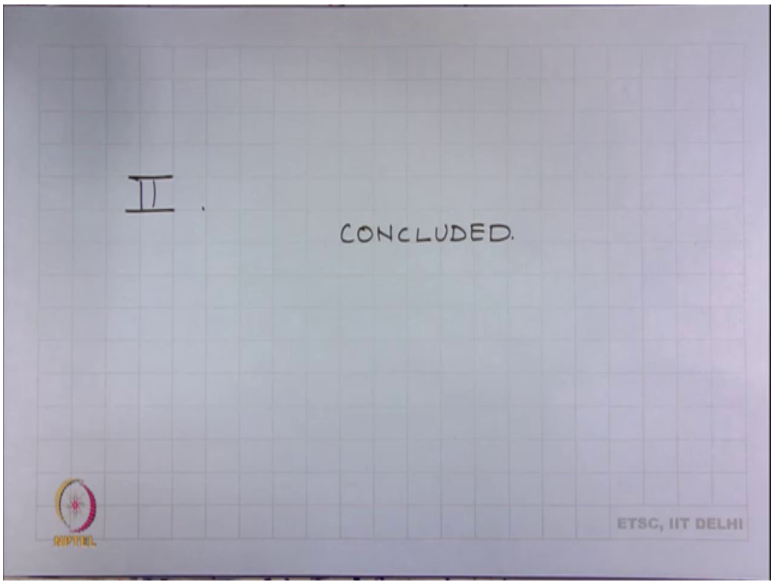

II. CONCLUDED.

So, with this we come to the conclusion of this lecture, we started off by looking at ideal gas mixtures, then gas vapour mixtures, and psychrometry and its applications. So, this ends this second module of second part of thermodynamics and we will stop the lecture here.

Thank you.