Engineering Thermodynamics
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Lecture - 48
Gas-Vapour Mixtures: Properties. Conservation of mass and energy

This is the second module on Gas Vapour Mixtures and psychrometry. In the previous lecture, we had looked at what is a air or moisture its components being dry air and water vapour and then we looked at how to quantify the properties of that. And we came across three terms which was absolute humidity, specific humidity and humidity ratio. Now to proceed further, we need to look at an important concept which is what is the maximum amount of moisture that air can hold for a given temperature. This is to say that when does air become saturated, so that is the question.

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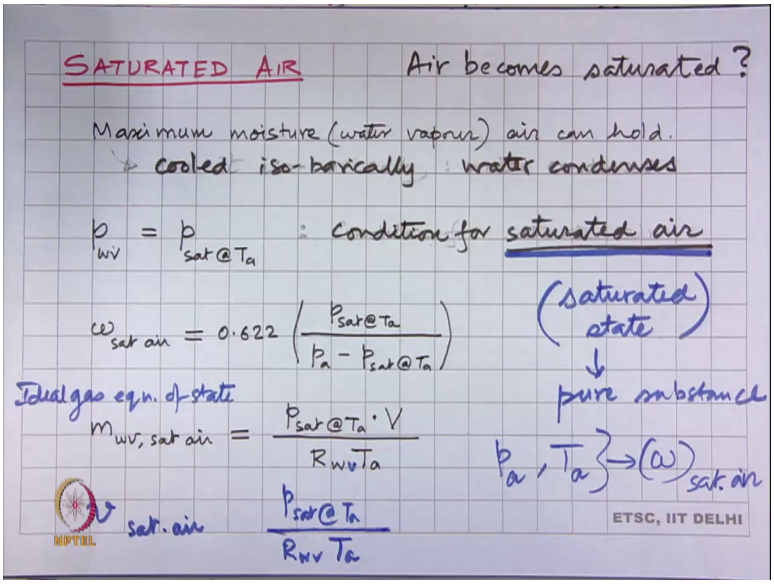

SATURATED AIR

Air becomes saturated?

Maximum moisture (water vapour) air can hold.

→ cooled iso-barically : water condenses

$p_{wv} = p_{sat@T_a}$: condition for saturated air

$\omega_{sat\ air} = 0.622 \left(\frac{p_{sat@T_a}}{p_a - p_{sat@T_a}} \right)$

(saturated state)
↓
pure substance

$p_a, T_a \} \rightarrow (\omega)_{sat.\ air}$

Ideal gas eqn. of state

$m_{wv,\ sat\ air} = \frac{p_{sat@T_a} \cdot V}{R_{wv} T_a}$

$v_{sat.\ air} \quad \frac{p_{sat@T_a}}{R_{wv} T_a}$

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We know from common experience that we keep putting moisture in to there at some point the air cannot hold on to that vapour, that vapour becomes liquid or a solid. If it becomes liquid, it precipitates out as a fog or a mist or as rain. If it gets cold enough that it precipitates out, it get becomes ice and then go into snow and all that. So, these are the type of phenomena once is in the atmosphere right even otherwise we see that in daily life in many cases.

For example in your in a closed room or a car or a bus and cold outside, then we soon start seeing fogging happening on the glass is telling with that inside the air is not able to hold onto anymore moisture as soon as it sees a cold surface it is precipitating out. So, we say that maximum amount of moisture that air can handle or hold is that if it is cooled isobarically. That means, you have this saturate air and it constant pressure we cool it, then if immediately water condenses then we say that that air is saturated. So, that is called saturated air which means that at that point the partial pressure of water vapour is equal to the saturation pressure at that particular temperature.

So, this is the condition at which we can have saturated air or remember that what we have defined now as saturated air as a very different meaning from what we have used. So, far in thermodynamics which was the saturated state this could be a saturated vapour saturated liquid or a saturated solid, but all of those definitions were always in the context of a pure substance.

We are now looking at a new idea I have to say how can you saturate a mixture which is what saturated air actually means. So, earlier relation that we are derived for relative humidity. We now know that the vapour pressure is equal to the saturation pressure at the temperature. So, it is p sat at the ambient at the air temperature or p a minus p sat at T a. So, which means that if the pressure is known p a and the temperature is known T a then everything on the right side of this equation is known and then we can say that from these two we can calculate omega that would be there if the air were to be saturated.

So, this is something that comes out of this equation and if you want to know how much is the mass, then we can say that mass of saturated air using the ideal gas equation of state that what we have done here. Mass of water vapour for saturated air is the saturation is the pressure partial pressure of water which in this case with the saturation pressure at T a multiplied by the volume upon the gas constant for water vapour divided by in T a.

So, again so, now what happens is as far as this part goes or if you can even say that what the specific volume in that case, then we get p sat at T a divided by R w v into T a. So now, if this equation there is only one variable T a. So, once you say that this is the air temperature then we can say what is the specific volume of air that will be there in the saturated state.

So, that is one part this is an important concept what is saturated air and we will now start using it in defining more terms. Before we do that let us see what the property diagram tells us.

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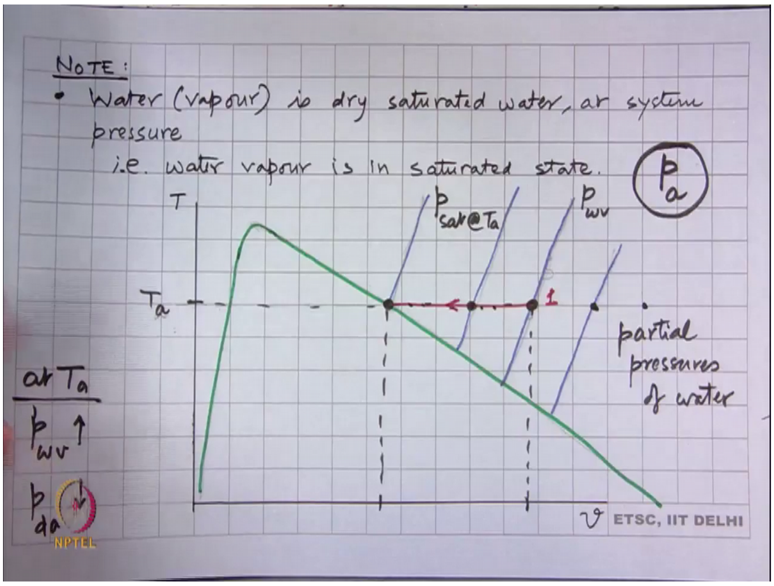

NOTE:

- Water (vapour) is dry saturated water, ar system pressure
  i.e. water vapour is in saturated state.

So, here I have drawn T v diagram instead of the usual T s diagram and shown here is this is the saturation dome this line is the saturated vapour line and lines of constant pressure on this will be these lines here. So, let us take a state here and say well if this is the state that is state we come back here and say this state it is T a. We know then that this line is a particular line which will be p w v, so, there are different values of the pressure.

So, what we are saying is that the maximum amount of moisture that air at T a can hold will be the case when that vapour is dry saturated. So, if we go say to a state like this or to a state like this at the same temperature, there is no problem. All this moisture the air can hold though the partial pressure of air which is p w v for a this is this is all for a particular p it can hold this much of partial pressure of water. If you goes this direction we first come to this point which is also in the sense that at this partial pressure you cool it will go down like this, so, it is not going to precipitate.

But if you keep going further down and you come to this point where now you have dry saturated vapour at T a any cooling will immediately cost precipitation to take place. So, this is the what it will be this is the what you called just now p sat at T a. So, this is the line which is at this temperature it represents the saturation line. Specific volumes can be obtained by going down this graph and seeing these values there or from tables and charts we can do this. Please remember one thing that these pressures that are being talked of here are partial pressures of water.

And although we are looking at the T v diagram we are looking at the T v diagram for one component of air, where the mass fraction by it is very small. So, that is why wrote there that this is at p a we are looking at all of these things happening. So, if the partial pressure of water vapour increases p a is constant, it would mean that as you are saturating it the partial pressure of water vapour at a given temperature T a; this goes up and partial pressure of dry air will come down.

So, this is the type of process that we are looking at from this state which was state a say 1 we came down by kept on say adding moisture to the air at the same time keeping the temperature constant we could reach up to this point at which point if you add more moisture, it will precipitate ok.

So, this is the depiction of the process on a chart and again remember that this is for water vapour component of air, there will be a similar chart for air as well. And what intuition tells us that we are looking at the pressure of water is actually is a partial pressure of water which is very small compared to the total pressure of air. So, now, we have an idea of what is saturated air and this gives us a reference point to define some more properties of air.

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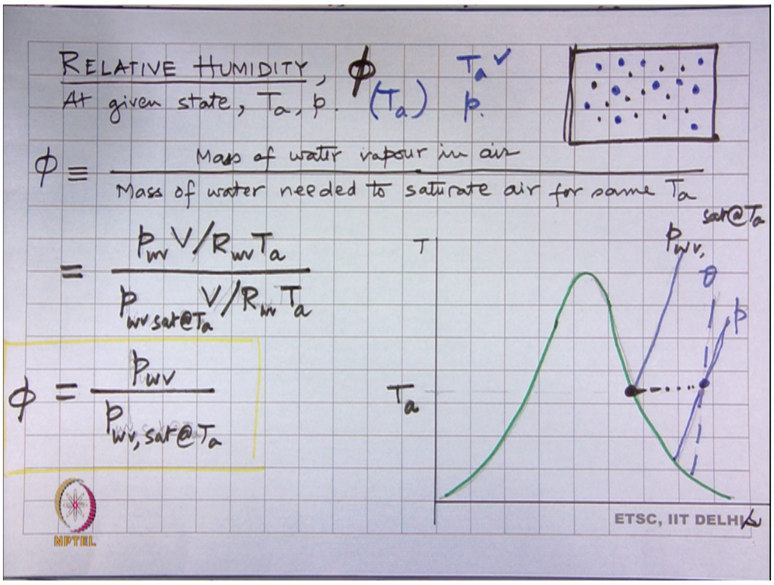

RELATIVE HUMIDITY, ϕ (T_a) T_a ✓ p

At given state, T_a, p.

$$\phi \equiv \frac{\text{Mass of water vapour in air}}{\text{Mass of water needed to saturate air for same } T_a}$$

$$= \frac{p_{wv} V / R_{wv} T_a}{p_{wv\, sat@T_a} V / R_{wv} T_a}$$

$$\boxed{\phi = \frac{p_{wv}}{p_{wv,\, sat@T_a}}}$$

The first and the most frequently used one that we keep coming across all the time is relative humidity or phi. So, at a given state which is at ambient T a and pressure p or we can call that p a relative humidity is defined as the mass of water vapour in air divided by the mass of water needed to saturate the air at the same T a. So, what you are saying is this is the system, in this we have at certain amount of air and in this we already had some amount of water. Then we maintain the same T a at the same pressure and keep adding more moisture to it.

The maximum amount of moisture that we can add that is saturate the air that is the point where that extra mass that we added that got added to the original mass of air in this volume which is the total mass of water that is needed to saturate air for the same temperature. So this is not the extra mass of water to be added, but the total mass of water in saturated air that what it is and in both cases phi is defined as at the same temperature.

So, we can now invoke the ideal gas equation of state for water and write these things as p w v into V upon R w v into T divided by p w v saturated at T a times V divided by R w v times T. So, what we have here we have said mass of water vapour in the air is nothing, but mass of water vapour.

So, this is w v times the volume of this upon the gas constant for water into T; T is we can write as T a in the denominator is the saturated condition where the pressure becomes the saturation pressure at T a and that is put here and we simplify this and we get in the denominator.

Partial pressure of water vapour in the saturated state when air is saturated in the numerator partial pressure of water vapour, so, phi is a ratio of two pressures. So, this is purely or number without any units and this is what it means that what is at this temperature how much water vapour is there in the air and what is the maximum amount of water that this particular temperature air can hold. So, we can see on the T s diagram.

So, what we have here are two pressure lines that we solve in the previous picture, this is your constant pressure line this is another constant pressure line and the same line also we can plot the constant volume line and this is our state. And what we are saying here is that what was the mass of water here which is this pressure in the numerator this p and if it were to be saturated it would go like that it come to this state which is the saturated state at the same temperature and at this pressure this is your p w v saturated at T a.

So, this pressure divided by this pressure is the relative humidity. So, it is quite different from the other definitions of humidity that we have come across so far and this is the one which is purely a ratio.

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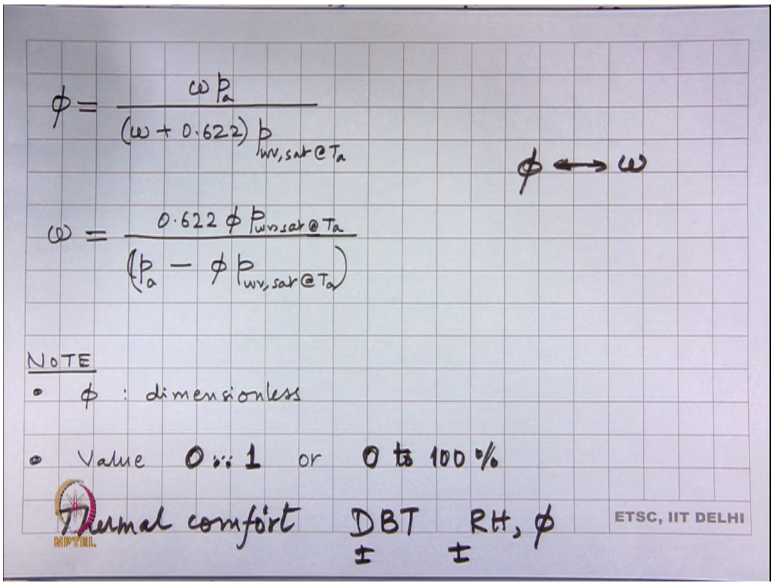

$$\phi = \frac{\omega p_a}{(\omega + 0.622)\, p_{wv,sat@T_a}}$$

$$\phi \leftrightarrow \omega$$

$$\omega = \frac{0.622\, \phi\, p_{wv,sat@T_a}}{(p_a - \phi\, p_{wv,sat@T_a})}$$

NOTE

- ϕ : dimensionless
- Value 0 ... 1 or 0 to 100 %

Thermal comfort DBT ± RH, ϕ ±

And so, we can then write this taking that expression we can write this in terms of omega which is omega times the ambient pressure upon omega plus 0.622 times the partial pressure of water vapour or you can turn around these things and say that the humidity ratio is 0.622 times phi times saturated pressure at T a upon ambient pressure minus specific humidity sorry this is a relative humidity multiplied by saturation pressure at T a.

So, what this thing is telling us all is that there is a one to one relation between phi and omega. So, you can calculate any one of them and using this relation, you can calculate the other. So, these are not two independent properties next we know that phi is dimensionless if the ratio of two pressures or ratio of two masses and its value lies between 0 and 1 or typically as we see in reports it is between 0 and 100 percent and this is one of the indicators of comfort. So, if you are looking at thermal comfort it has largely been defined in terms of DBT and Relative Humidity some people call it RH or we can also call it phi.

And everybody has decided that in an air conditioned room there is a range of DBT and RH combinations. So, its DBT would be say 25 degree Celsius plus minus 1 or 2 degree Celsius relative humidity would be say 50 percent plus minus 10 percent. So, you would say that this is the ideal comfort condition where we have said that the air velocity in that particular space is very small less than like 0.1 meter per second. Clearly we see our daily experience that is quite different in that you often use ceiling fans where the air or even desert coolers which give out away air at a large velocity there the velocity is go up to like 2 to 0.5 meters per second in which case thermal comfort becomes a function of this, this and the air velocity.

So, this is the case when air velocity is very very small and that is what the ideal case is supposed to be. Next we look at the enthalpy of air, will be already had a relation for enthalpy of dry air, we had an enthalpy of water vapour relation.

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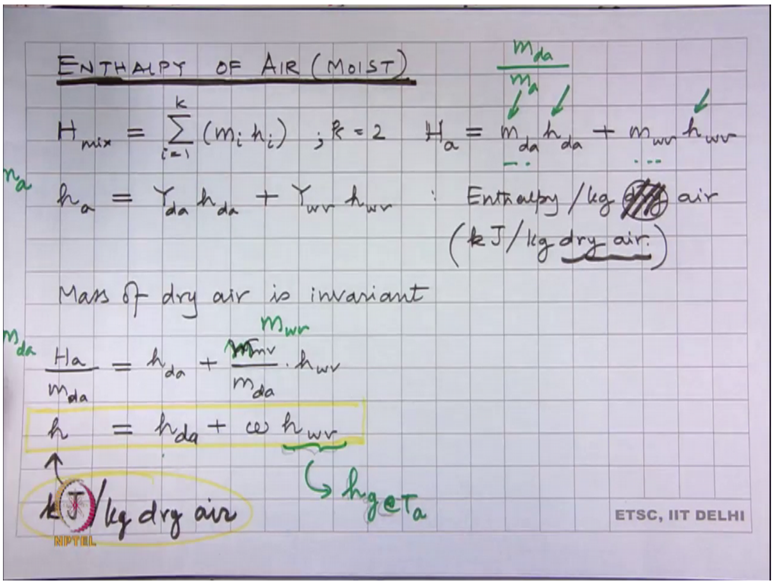

ENTHALPY OF AIR (MOIST)

$H_{mix} = \sum_{i=1}^{k} (m_i h_i)$; $k = 2$ $H_a = m_{da} h_{da} + m_{wv} h_{wv}$

$h_a = Y_{da} h_{da} + Y_{wv} h_{wv}$: Enthalpy / kg air

$\frac{m_{da}}{m_a}$

(kJ/kg dry air)

Mass of dry air is invariant

$\frac{H_a}{m_{da}} = h_{da} + \frac{m_{wv}}{m_{da}} \cdot h_{wv}$

$\boxed{h = h_{da} + \omega \underbrace{h_{wv}}_{\hookrightarrow h_{g@T_a}}}$

kJ/kg dry air

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Now, we ask the question using those two is it possible to calculate the enthalpy of air what the moisture. So, we have that for two component system the extensive property and of enthalpy is mass of each component multiplied by its specific enthalpy. So, this is for dry air plus m for water vapour multiplied by specific enthalpy of water vapour.

How to get these two we already got expression for that and this we know that this can be related to humidity, now various types of humidity and then from there you can get this. Now to make it into a specific enthalpy there are two things which should be possible if we divide throughout by the mixture mass which is m a then H a becomes small h a m d a becomes mass of dry air or mass of air which is the mass fraction of dry air times specific enthalpy of dry air.

And similarly for this one it becomes Y w v times h w v. So, this is now enthalpy of air per kg of air; air means moisture, but we would like to know what is specific enthalpy per kg of dry air. So, what that what we do is we divide both sides by mass of dry air. So, you get H a by m d a is equal to h d a plus this is m water vapour upon mass of dry air into h w v which gives us that h now referenced on dry air is h a plus omega h w v. So, this is an important relation that we have got.

And the units here of h is not just that we are saying it is kilo Joules per kg, but it is kilo Joules per kg of dry air and recall how we are going to get h; sorry this is h d a here and h w v which is the water vapour enthalpy this is as we have just argued few minutes back this is h g at T a. So, this is another important relation that will be used in problem solving, it is this property which is listed in the psychometric chart and in the tables. For the same reason that in many applications dry air mass remains constant whereas, the mass of moisture mass keeps going up and down ok.

So, we have h reference per kg of dry air; it is important to remember this part. Now that we have a definition of what is saturated air, we will define yet another thing which is the dew point or T with the subscript d p.

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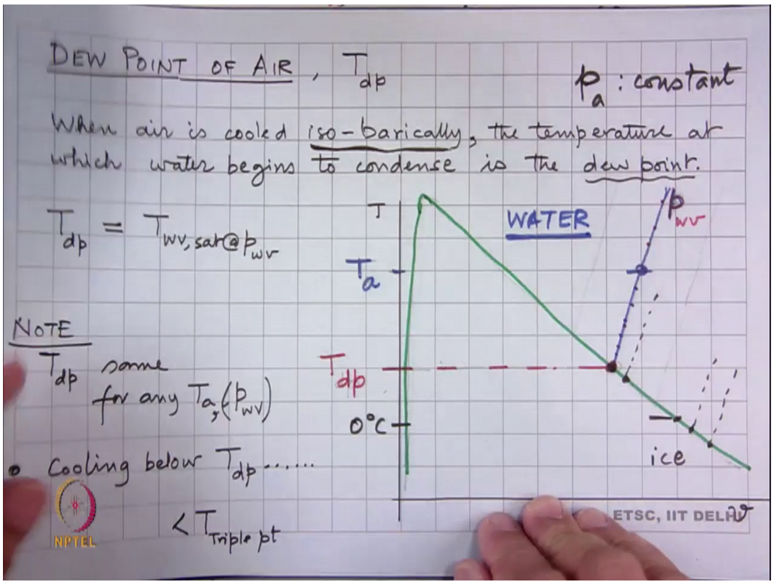

DEW POINT OF AIR, T_{dp}

p_a : constant

When air is cooled iso-barically, the temperature at which water begins to condense is the dew point.

$T_{dp} = T_{wv, sat@p_{wv}}$

NOTE

T_{dp} same for any T_a, (p_{wv})

- Cooling below T_{dp} ......

$< T_{Triple\ pt}$

So, what is dew point is when air is cooled isobarically; that means, at constant pressure ,the temperature at which water begins to condense is called the dew point. So, it is on this is the T v diagram. So, let us see what we seen on that. So, on this we have us given state which is put here it is at this pressure here. This is p, p p a which I why we want to call it, the temperature at this state comes here this is T a and we are looking at the properties of water.

So, what we are seeing is that this is the state that we had and we are saying when air is cooled isobarically; that means, if you go this way it is heated isobarically. These states it is cooling isobarically. So, this is what we are interested in that if you keep cooling it we will reach this point where any further cooling will cause precipitation. So, this is the limiting point and this is what we can then say that this point the temperature corresponding to this point is T dew point. So, what this graph tells us also is that dew point is nothing, but the saturation temperature at this pressure that is what this point is this is the dry saturated vapour line.

So, T d p is for water vapour the saturation temperature at the partial pressure of water vapour. So, you can say this is p or you can call this p w v. So, as long as the partial pressure of water vapour is this whether the dry bulb temperature is there, there or here the dew point does not change it is the same, its only when the partial pressure of water vapour goes up or goes down that the dew point will change. So, what happens if you do cooling beyond this point? So, you have a system where you kept cooling it at constant pressure it became air got saturated at this temperature.

More cooling, air cannot hold any more moisture; some of the moisture condenses and false out if the temperature is above 0 degree Celsius and the new state that it gets will now start going here which would mean that some of the water vapour in the mixture got out as liquid at to have equilibrium. You cannot have subcooled liquid in thermodynamic equilibrium with a saturated vapour. So, what would happen is that because some of the water is gone out the partial pressure of air will decrease, it will come here and this will be the new condition.

And if go down all the way say this is 0 degree Celsius and if you cool any further than this, then this moisture will not go to the liquid phase, but will start precipitating out as a ice. And clearly what you are seeing here is that the partial pressure of water in the air is continuously decreasing as you are cooling it. The total pressure is still the same which means that the partial pressure of air the dry air keeps going up. So, all of this is happening when this isobaric process is there; that means, p a is constant or just p if you want to call it.

So, this is what is happening if you heat it there is no issue; it there is no chance of precipitation, it will just keep going up that line. So now, we got yet one more property for a mixture which is the dew point. So now, let us see what happens how we can show these things on property diagram.

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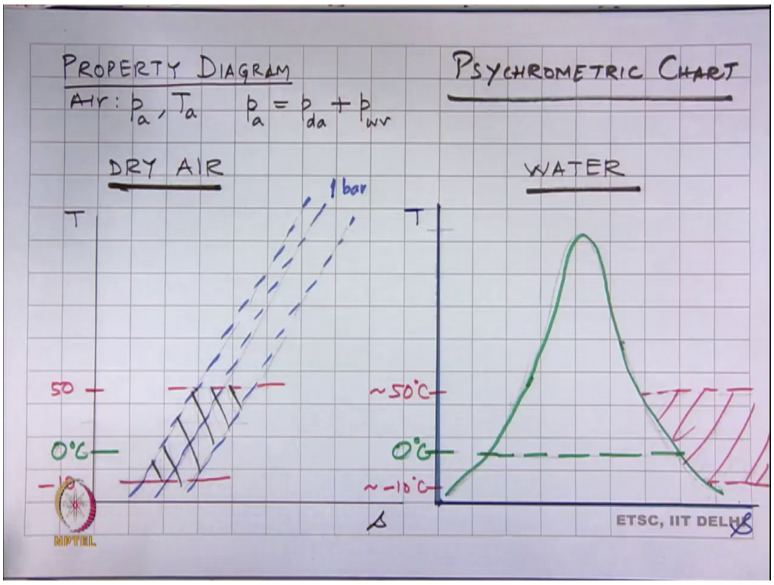

The difference here compared to what was there in pure substances that property diagram here for cannot be one diagram we have two components, we have two very different properties. But the process is going on is the same initial pressure and temperature was something in the final pressure and temperature is something we know that both the whole mixture has gone through that change.

So, we make one property diagram for dry air and another for water. So, this T s diagram for air here is the T s diagram for water and in this case we have drawn here the line of 0 degree Celsius, this is 0 degree Celsius; for air or dry air this is an ideal gas. So, there is no question of showing any saturation line from this water in the pressures and temperature that we are looking at is very close to the dome. So, you have this line as the 0 degree Celsius line and the states as we said earlier that we are studying are belonging in this region over here.

This point is of the order of 50 degree C some point here of the order of minus 10 degree C. So, you have this you have this and this is our region of interest same temperatures get mapped onto this diagram. So, you come here to 50 degree C and minus 10 over here and you have this line, but now this is a these are isobars. So, this could be say isobar for 1 bar this could be say 0.5 or something like that and then this is a isobar for some other case. So, the air conditions that we are looking at are in this region.

So, our points are moving in these two regions simultaneously and that is what only showing what happens to the water is good enough to understand what happens to water, but it also important to show it onto the dry air plot and say what is happening to air or so. And we combine both these and later on we will see this into what is called the psychrometric chart ok; so, this is what we have come for so far.

We need some more definitions to be done, but before we get those terms to be define we need to have a handle on the conservation equations for gas vapour mixtures.

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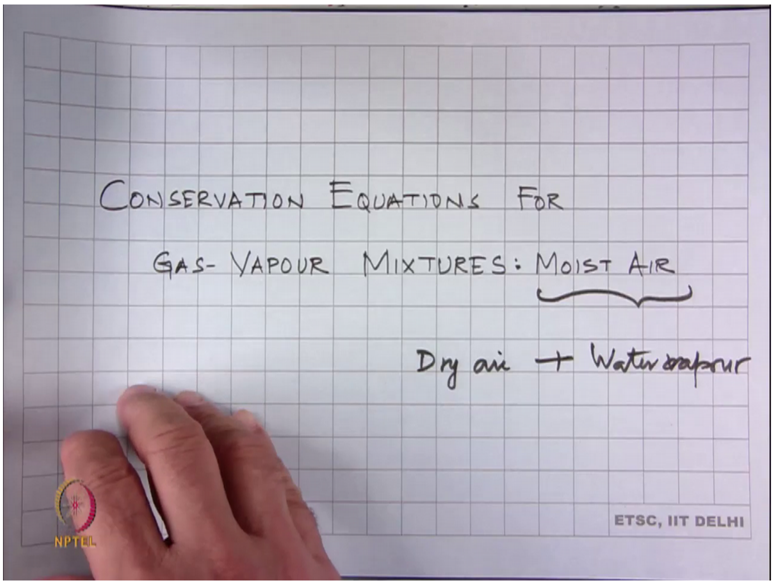

CONSERVATION EQUATIONS FOR

GAS- VAPOUR MIXTURES: $\underbrace{\text{MOIST AIR}}_{\text{Dry air + Water vapour}}$

So, that is what we will do now, we had earlier written conservation equations first for a pure substance for a closed system and then open system then we developed and extended those equations for a mixture of gases. And now we will further restrict those things to look at mixture of look at moist air which is a mixture of dry air plus water vapour.

So, the forms are very similar all we have to do is make some substitutions to make sure that we are using the right terms for the mass and the right terms for the properties of that mass.

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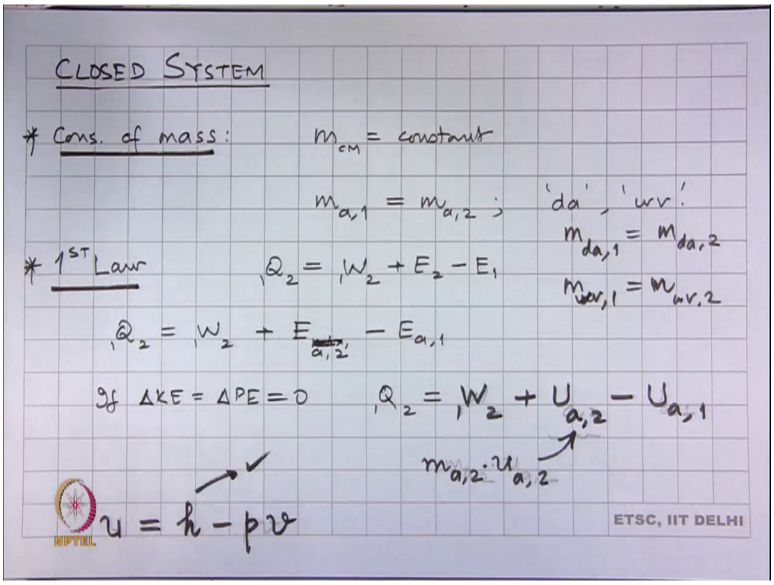

CLOSED SYSTEM

* Cons. of mass: $m_{cM} = \text{constant}$

$m_{a,1} = m_{a,2}$; 'da', 'wv':

$m_{da,1} = m_{da,2}$

$m_{wv,1} = m_{wv,2}$

* 1st Law $\quad {}_1Q_2 = {}_1W_2 + E_2 - E_1$

$${}_1Q_2 = {}_1W_2 + E_{a,2} - E_{a,1}$$

If $\Delta KE = \Delta PE = 0$ $\quad {}_1Q_2 = {}_1W_2 + U_{a,2} - U_{a,1}$

$m_{a,2} \cdot u_{a,2}$

✓

$u = h - pv$

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So, here we have a closed system for which the conservation of mass is m c M is equal to constant which also means that within that system the mass of dry air will remain the same. So, mass this in the control mass is mass of air, but then it also tells us that since it is closed mass of dry air in state 1 is equal to mass of dry air in state 2 and similarly mass of water vapour in state 1 is equal to mass of water vapour in state 2. So, that is the conservation of mass.

And now, we look at the 1st Law where everything remain same except that E 2 minus E 1 term which was there for a pure substance we now qualify that E of a 2 a 1, where a is the mixture. And if kinetic and potential energy changes are 0, then we can say that the heat transfer during the process in internal energy of the air at state 2, internal energy of the air at state 1 which here becomes mass of air at state 2 multiplied by specific internal energy of air at state 2.

So, air is now the mixture and how to get U the so far we have only looked at specific enthalpy with that in each case we will have to go back and use the definition u is equal to h minus p v and h for h we had relations in terms of temperatures ok. So, that is what we will have to apply when you are looking at mixture in air water mixtures in a closed system.

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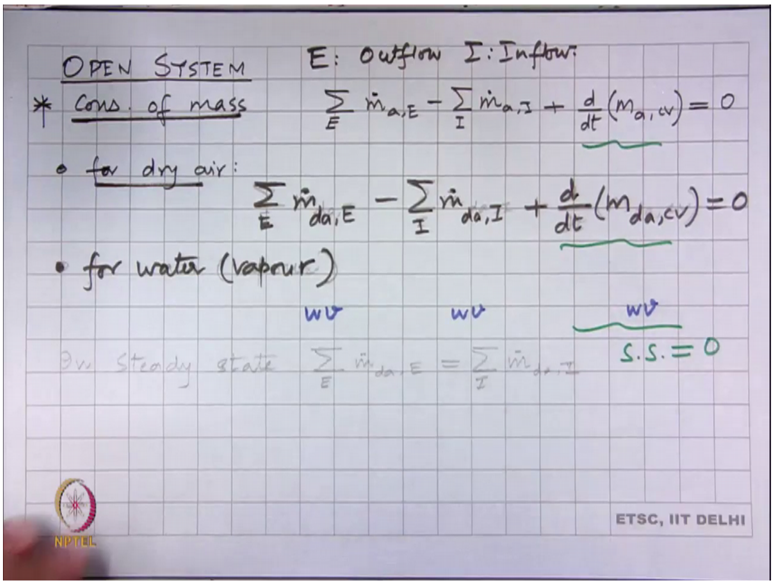

OPEN SYSTEM

E: Outflow I: Inflow

* Cons. of mass

$$\sum_E \dot{m}_{a,E} - \sum_I \dot{m}_{a,I} + \underbrace{\frac{d}{dt}(m_{a,cv})} = 0$$

- for dry air:

$$\sum_E \dot{m}_{da,E} - \sum_I \dot{m}_{da,I} + \underbrace{\frac{d}{dt}(m_{da,cv})} = 0$$

- for water (vapour)

wv wv $\overbrace{\text{wv}}$

S.S. = 0

In steady state $\sum_E \dot{m}_{da,E} = \sum_I \dot{m}_{da,I}$

And now the 2nd law it said that S 2 minus S 1 is greater than equal to the integral from T 1 to T 2 of delta Q by T, now S becomes S of a which is air minus S a at 1 greater than or equal to the same integral. So, that is the 2nd law applied to a closed system. Now we come to open systems and say what happens here conservation of mass we have to add the extra subscripts to say that mass flow rate at every outflow or inflow is mass flow rate of air. So, m dot a at E; E is every outflow and I is every inflow.

So, air outflow rates minus air inflow rates plus rate of storage of air in the control volume is 0, but remember air has got 2 components now. So, we could write a conservation equation for dry air which says that mass flow rate of dry air at each exit minus the same thing done at the inlet plus d by d t of m d a of the control volume is equal to 0. And we can write a similar equation for water vapour and all you have to do is in all these da’s that we have written here we just substitute those by w v.

So, when you talk of conservation of mass in the pure substance it was only one equation here as we looked at mixtures it is a number of components plus 1 that is a number of conservation equation for mass and that what we have here a conservation equation for air, conservation equation for dry air and conservation equation for water vapour and all three have to be simultaneously satisfied. A in study state this terms will become 0 and life will become a bit simple, so, this and this in steady state these terms will be 0. So, there is a little extra complication coming in when we look at the conservation of mass for an open system.

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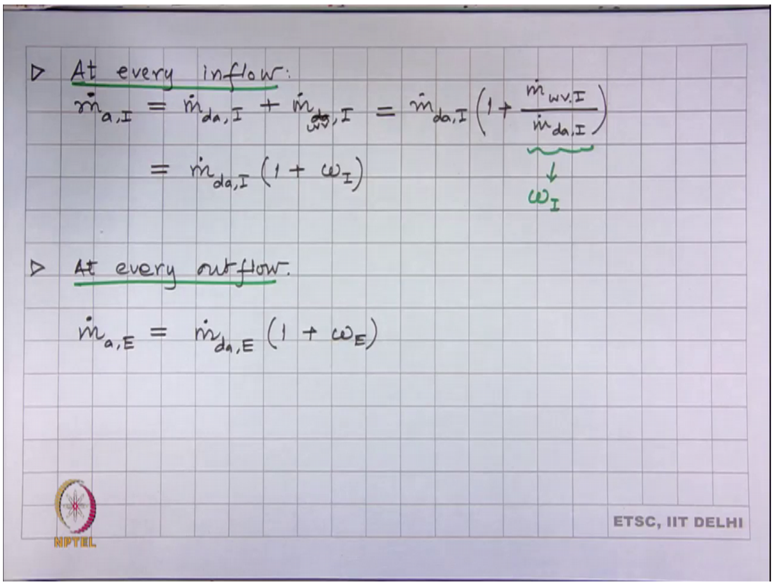

▷ At every inflow:

$$\dot{m}_{a,I} = \dot{m}_{da,I} + \dot{m}_{\underset{wv}{\cancel{da}},I} = \dot{m}_{da,I}\left(1 + \underbrace{\frac{\dot{m}_{wv,I}}{\dot{m}_{da,I}}}_{\downarrow\ \omega_I}\right)$$

$$= \dot{m}_{da,I}(1 + \omega_I)$$

▷ At every outflow:

$$\dot{m}_{a,E} = \dot{m}_{da,E}(1 + \omega_E)$$

At every inflow we have mass flow rate of air it will be mass flow rate of dry air plus mass flow rate of water vapour. So, if we take out m d dry air mass flow rate out it becomes 1 plus the ratio of these two mass flow rates which is mass flow rate of dry air at the inlet in bracket 1 plus omega at the inlet condition. So, this was mass of water vapour divide per mass of dry air and the flow rate definition remains the same. So, this became omega at the inlet state. So, this is important to get because now we are able to express it in terms of the dry air mass flow rate.

Similarly, for every outflow we can express the mass flow rate of air at every outflow mass flow rate of dry air at that outflow into 1 plus omega at the same condition. So, these are 2 equations which will become handy when we solve problems. We then look at conservation of energy or the 1st law.

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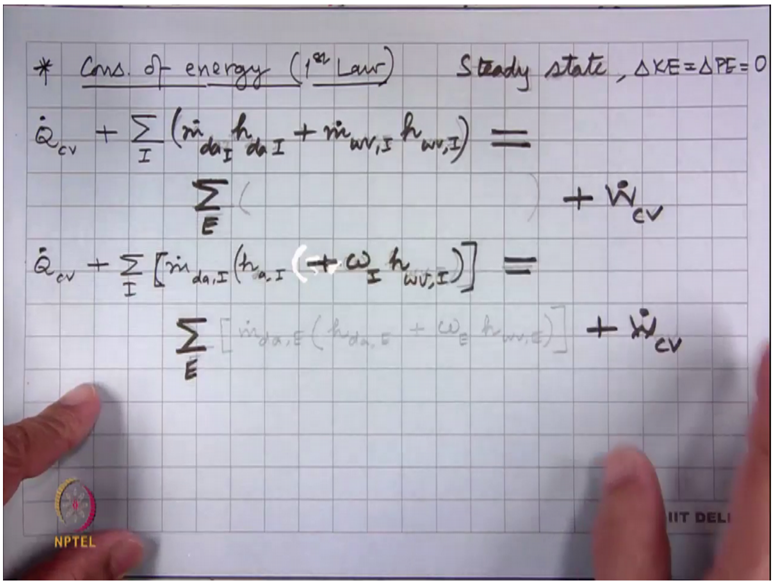

* Cons. of energy (1st Law) Steady state, $\Delta KE = \Delta PE = 0$

$$\dot{Q}_{cv} + \sum_{I} \left(\dot{m}_{da_I} h_{da\,I} + \dot{m}_{wv,I} h_{wv,I}\right) = \sum_{E} \left(\qquad \right) + \dot{W}_{cv}$$

$$\dot{Q}_{cv} + \sum_{I} \left[\dot{m}_{da,I} \left(h_{a,I} + \omega_I h_{wv,I}\right)\right] = \sum_{E} \left[\dot{m}_{da,E} \left(h_{da,E} + \omega_E h_{wv,E}\right)\right] + \dot{W}_{cv}$$

So, now this expression is exactly same as it was before and we are going to write it for steady state and delta KE equal to delta PE equal to 0. And so, when we do this in the terms which was in the brackets we are ignoring kinetic and potential energy changes. So, what would have been here is m dot a and h a we can break that up and write in terms of m dot d a at every inlet h d a at every inlet plus m dot water vapour at that same inlet h water vapour at that inlet and equated to a similar summation for the exit side plus work transfer across the control volume.

So, this expression we can get m dot d a out and write this a h dot d a 1 plus omega I h w v I and you get a similar expression on the other side which is for every exit flow rate the same thing, where I you get replaced by E plus the work transfer rate. So, steady state delta KE delta PE equal to 0 almost all the problems we will look at we will assume that this is the case and then equation to be used then becomes this one; otherwise we have the full equation there plus unsteady term that would come in the steady state were not there.

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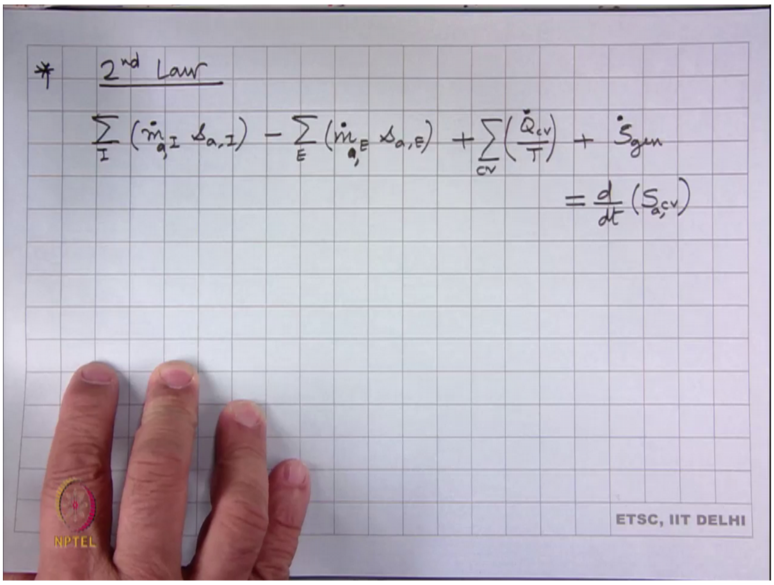

* 2nd Law

$$\sum_{I}(\dot{m}_{a,I}\, s_{a,I}) - \sum_{E}(\dot{m}_{a,E}\, s_{a,E}) + \sum_{CV}\left(\frac{\dot{Q}_{cv}}{T}\right) + \dot{S}_{gen} = \frac{d}{dt}(S_{a,cv})$$

The 2nd law equation becomes we just substitute that with every inflow for air m dot this should be m dot a at every inlet into s with the specific entropy at of air at every inlet. This is m dot a at exit into multiplied by specific entropy of a at each exit plus summation of Q dot c v upon T plus rate of generation of entropy is equal to rate of storage or depletion of air entropy in the control volume.

So, basic equation is still the same we are just putting properties for mass flow rate and the properties of the substance with those of moist air. We will now look at the last thing which is what is called an adiabatic saturation process because that leads us to the definition of one very important term and that is where we will then stop.

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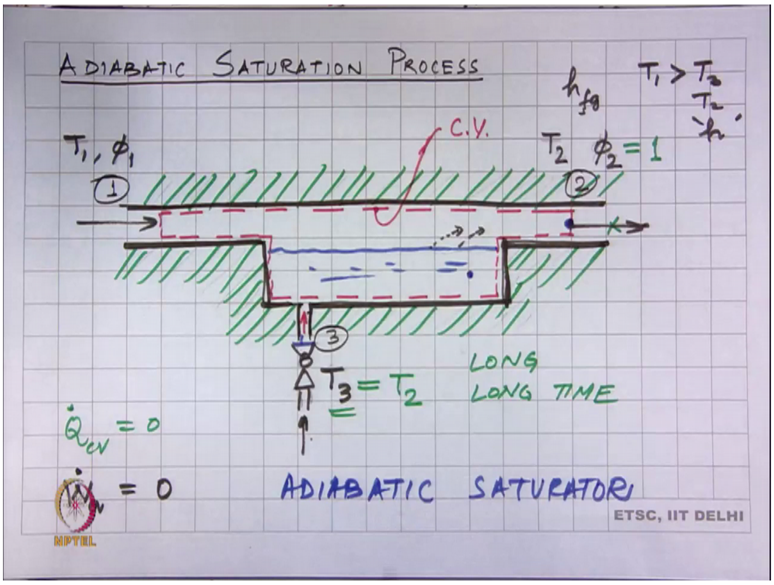

So, what we are looking at is what is an adiabatic saturation process and say if one way to do that is to have a chamber into which you have inflow of air at T 1 and phi 1s relative humidity and comes out at state 2 where temperature is T 2 and humidity phi 2. But you also do another thing which is to make it flow over a bed of water which is continuously being filled from here.

So, this is water coming in at state 3 temperature T 3, but device like this and this whole thing is insulated. So, we say that all of this is insulated, so, this is adiabatic; that means, there is no heat transfer to anything here. Now, we know from experience like a device like a desert cooler then what you are doing is if you keep running this for a sufficiently long period of time the temperature will keep decreasing, the air will keep getting more and more humid as it comes out.

Then there will be a time where if you are able to control two things which is control the flow rate here and to control T 3 and this is very long and for a long time then we can say that this air is completely saturated. So, it is T 2 and phi 2 with phi 2 becoming 1 and we further restrict by saying that the water that is being put here at T 3 we have able to control the temperature and say we will be now putting water at temperature T 2.

So, now what has happened is that this whole system this is completely insulated there is no heat transfer. So, q dot c v is equal to 0, before that it is define the control volume. So, we will say that the control volume is here. So, that is the control volume there is one inflow here one outflow here and one inflow here so, at this point and for this control volume not only is adiabatic, but also there is no work transfer taking place w dot c v is also 0. So, under this condition and you kept this as T 2 and outcoming air finally, reaches the same temperature and gets completely saturated at temperature T 2.

So, this is what we have done, we have done at through an adiabatic process we have saturated the incoming air where phi 1 could be less than 1, but now we are getting temperature has gone down to T 2 and relative humidity is 1.

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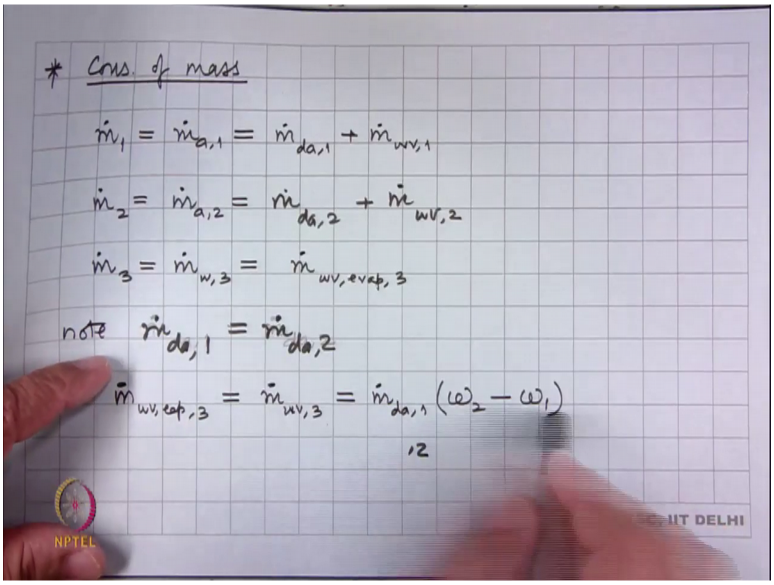

* Cons. of mass

$$\dot{m}_1 = \dot{m}_{a,1} = \dot{m}_{da,1} + \dot{m}_{wv,1}$$

$$\dot{m}_2 = \dot{m}_{a,2} = \dot{m}_{da,2} + \dot{m}_{wv,2}$$

$$\dot{m}_3 = \dot{m}_{w,3} = \dot{m}_{wv,evap,3}$$

note $\dot{m}_{da,1} = \dot{m}_{da,2}$

$$\dot{m}_{wv,eap,3} = \dot{m}_{wv,3} = \dot{m}_{da,1}(\omega_2 - \omega_1)$$

,2

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So, another now we apply the conservation of energy and the conservation of mass to this system there 3 state points 1 2 and 3 m dot at 1 is m dot a at 1 which is mass flow rates of dry air and water vapour at 2 it is only air and we can write a similar equation like this which will be m dot d a at 2 plus m dot w v at 2 and m dot 3 is equal to w 3 which is nothing, but the evaporation rate.

So, what is happening in this is that this water vapour evaporating into it and it is cooling this thing now because it has this is the h f g involved in it. At the same time, there is heat transfer taking place from T 1 to this because T 1 is greater than T 2 or T 3 there is sensible heat transfer h heat transfer coefficient to this, but as a whole this system is perfectly insulated.

Now, because the mass flow rate of dry air has not changed from inlet to outlet we can say that m dot d a 1 is equal to m dot d a 2 and so, mass flow rate due to evaporation which is 3 is m dot d a 1 or it could be m dot d a 2 multiplied by omega 2 minus omega 1. Omega 2 and these are the moisture contents of the air, so, these are absolute numbers this is not a fraction.

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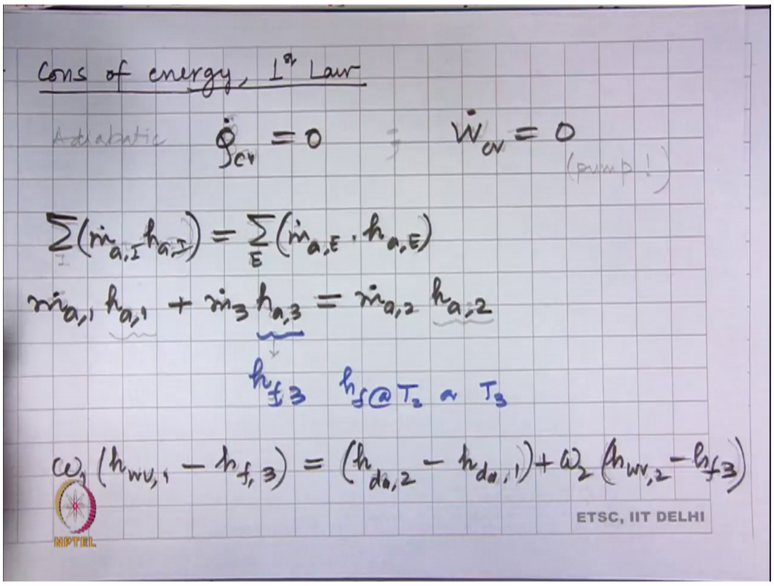

Cons of energy, 1st Law

Adiabatic $\dot{Q}_{cv} = 0$; $\dot{W}_{cv} = 0$ (pump !)

$$\sum_I (\dot{m}_{a,I} h_{a,I}) = \sum_E (\dot{m}_{a,E} \cdot h_{a,E})$$

$$\dot{m}_{a,1} h_{a,1} + \dot{m}_3 h_{a,3} = \dot{m}_{a,2} h_{a,2}$$

h_{f3} $h_{f@T_2} \sim T_3$

$$\omega_1 (h_{wv,1} - h_{f,3}) = (h_{da,2} - h_{da,1}) + \omega_2 (h_{wv,2} - h_{f3})$$

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We now apply the conservation of energy with already have said that Q dot c v and W dot c v are 0 we and then we apply the 1st law m dot a inlet into h a inlet is similarly we can write this expression for the outlet condition m dot a E times h a E. And when we simplify this you get m dot a at 1, h a at 1 plus m dot 3 h a at 3 this is equal to m dot a of the outflow multiplied by specific enthalpy of air at that condition.

Now, what has happened is that this thing is what we were putting in and we were putting in at T 3 which is in the long run equal to T 2 which is the saturation temperature of water. So, this is h f at 3 which is h f at T 2 or you can call it T 3. So, when we simplify this further we will get the expression that omega 1 into h w v 1 minus h f 3 is equal to h d a 2 minus h d a 1 plus omega 2 h w v 2 minus h f 3. So, that is the expression we have got and we will now just do a little bit of simplification on this.

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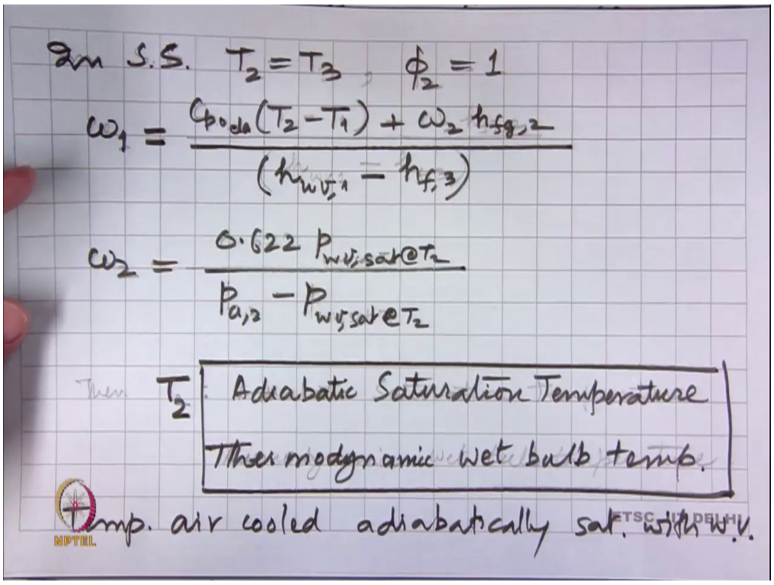

In S.S. $T_2 = T_3$, $\phi_2 = 1$

$$\omega_1 = \frac{c_{p0,da}(T_2 - T_1) + \omega_2 h_{fg,2}}{(h_{wv,1} - h_{f,3})}$$

$$\omega_2 = \frac{0.622\, P_{wv,sat@T_2}}{P_{a,2} - P_{wv,sat@T_2}}$$

T_2 : Adiabatic Saturation Temperature

Thermodynamic wet bulb temp.

Temp. air cooled adiabatically sat. with w.v.

And invoking that in steady state T 2 is equal to T 3 phi 2 is equal to 1. And we can simplify this and we get 2 relations; one relation which is omega 1 a C p 0 dry air multiplied by T 2 minus T 1 plus omega 2 h f g at temperature 2 divided by h w v 1 minus h f 3 and omega 2 is equal to phi 0.622 partial pressure of water vapour saturated at T 2 divided by p a at 2 minus p water vapour saturated at T 2.

And this is where we will try to come is that now we have T 2 which is an important parameter that has come out this is called adiabatic saturation temperature, also this is what is called the thermodynamic wet bulb temperature. So, that is the important of this whole exercise that we have now come across the thing that if we can saturated saturate air in an adiabatic process then we generate cool it down to a temperature which is called the wet bulb temperature.

So, this is what it is the thermodynamic wet bulb temperature or the adiabatic saturation temperature the temperature to which air will be cooled when it is adiabatically saturated with water vapour. And that is what we experience you have use this say in desert coolers or keeping things cool while in earthen pots water stay cool by evaporation.

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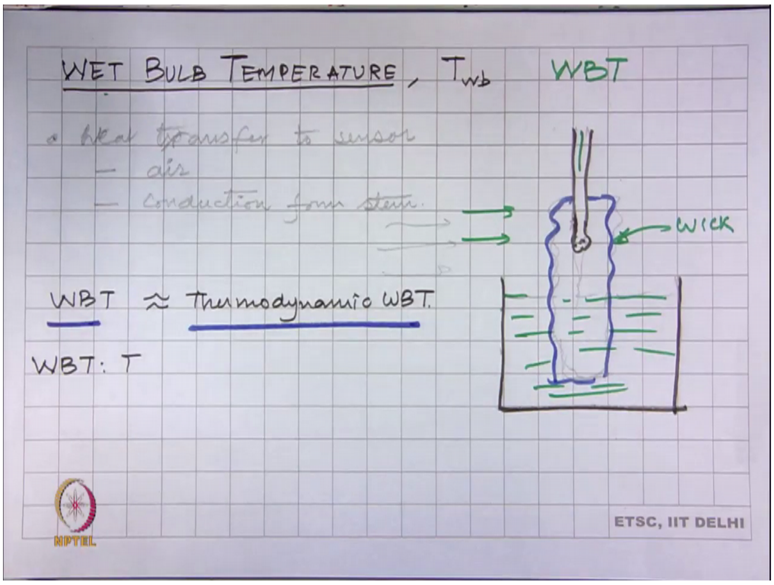

WET BULB TEMPERATURE, T_{wb}

WBT

- heat transfer to sensor
  - air
  - conduction from stem.

WBT ≈ Thermodynamic WBT.

WBT: T

And we call this is the thermodynamic wet bulb temperature because it practically slightly different from the wet bulb temperature T w b which is what we measure in a lab where we take a sensor and we take this sensor and rapid radar around it a porous cloth a fibrous material although which is kept in a container which has got water vapour in it liquid water in it.

So, this is all liquid water and this is what we can call it as a wick or a porous fabric and this will let it remain in air or blow air slightly over it. The as the water evaporates, it generates a saturated condition and the temperature indicated by this is what we call the wet bulb temperature or T w b or often called WBT.

This is slight, if you were to measure the temperature in that experiment that we did the this whole device this is called an adiabatic saturator. And T 2 either can be measured as the DBT of this or we can measure the temperature of this water both are at the same temperature and that is what will give us what is the thermodynamic wet bulb temperature. So, this is a perfectly an adiabatics process this is not perfectly adiabatic in the sense that there will be some conduction through the stem and because air is flowing over it and air temperature is more than this. There will be some heat transfer taking place to this to the bulb.

Because of this the wet bulb temperature that we measure is slightly greater than the thermodynamic wet bulb temperature, but for all practical purposes we use this and say that wet bulb temperature is approximately the same as the thermodynamic wet bulb temperature. So, this is yet another important property that we have come across and we will conclude by showing it on the T s diagram where this is the saturation vapour line,.

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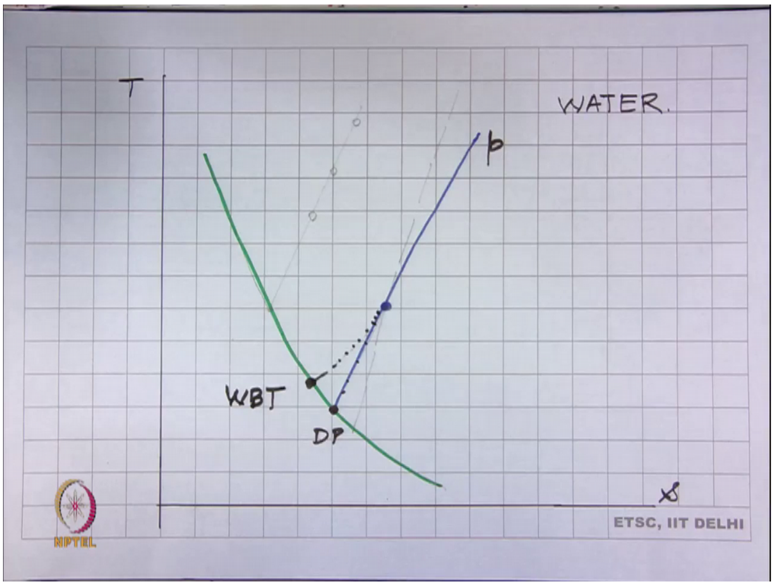

This was the pressure at which the air was working this was our initial state and what we did was if he had cooled it at constant pressure. So, this is isobar if you had cooled it like this you would have reached the dew point this is a dew point.

But in a adiabatic process we went across like that and reach this point which is the wet bulb temperature. So, that is the difference and with that we come to the end of this lecture and we now realize that we have all the necessary tools to tackle practical applications of air water mixtures.

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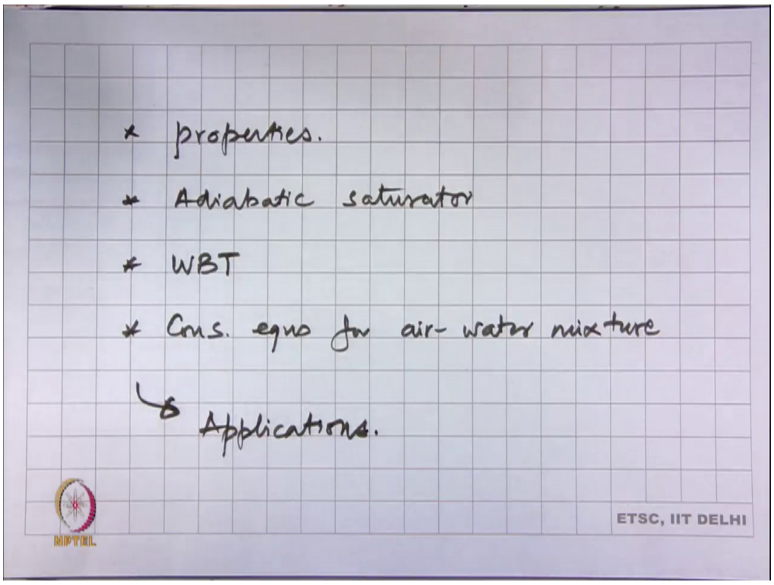

- * properties.
- * Adiabatic saturator
- * WBT
- * Cons. eqns for air-water mixture
  - ↳ Applications.

So, we defined a whole bunch of properties then we came across a new thing which was the adiabatic saturator and from there we got the wet bulb temperature and now we are also put in the process the conservation equations for air water mixture. And so, with all of this we can now look at applications which will take will take up a few applications in the next lecture. So, at this point we will conclude this lecture.

And thank you.