Applied Thermodynamics
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Module - 05
Refrigeration and Air-Conditioning System
Lecture - 41
Air Conditioning Processes

Dear learners, greetings from IIT, Guwahati we are in the MOOCS course Applied Thermodynamics, module 5 Refrigeration and Air-conditioning system.

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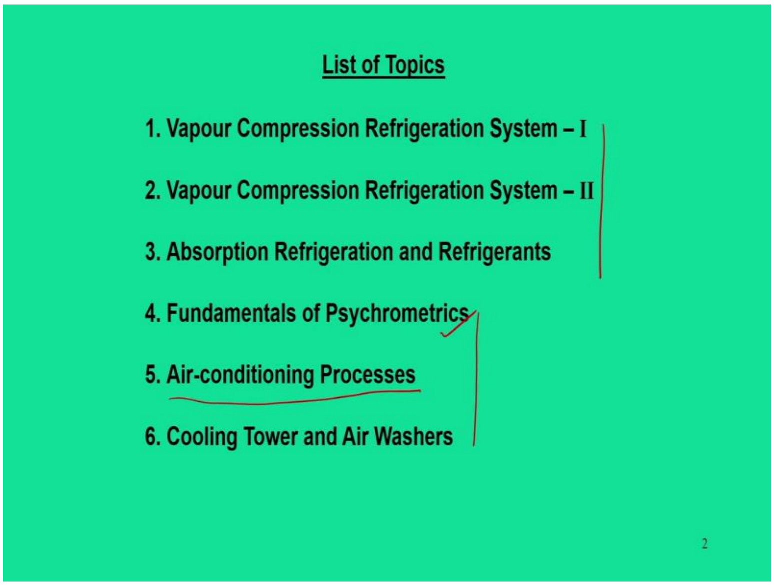

Till this point of time, we have covered the concepts of refrigeration that is vapour compression system and vapour absorption systems, side by side we discussed about refrigerants, and then we started with air conditioning systems. So, in the first lecture we covered the fundamentals of psychrometrics which is a very important concept in air conditioning systems, where we deal with moist air and its properties.

Now, in today's class, we will be discussing about air conditioning processes and moreover our attempt would be to discuss about the thermodynamic aspects of all air conditioning processes, and side by side we will try to see that how the moist air properties is going for a change for the requirement of air conditioning systems.

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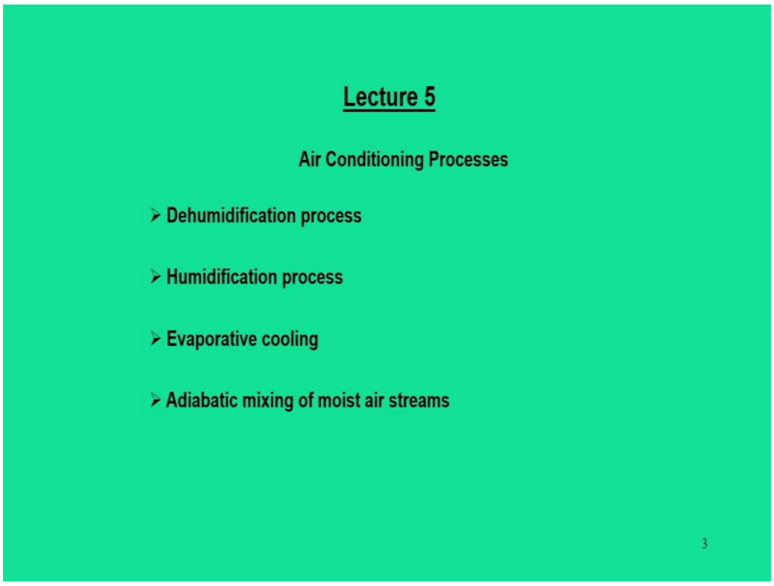

So, if you actually think about air conditioning processes, there are four fundamental processes: dehumidification processes, humidification processes, evaporative cooling and adiabatic mixing of moist air stream. And, I mentioned in my earlier lectures that when you deal with air conditioning processes, try to control simultaneously temperature as well as humidity.

Now, another aspect is that while controlling humidity side by side there is a possibility that temperatures can increase or decrease. So, basically when we deal with humidification processes, our main intention is to remove moisture from the air and when you do a humidification processes; that means, we add moisture in the air. So, in the process either we have to add steam or you have to use water.

And, since there is a variation in temperatures of air and water in the name of increasing dehumidification or humidifications, there is also possibility that temperature also is going to change. So, in that sense the humidification and dehumidification processes always involves heating or cooling coils depending on the requirement.

So, basically it is a dehumidification with heating or dehumidification with cooling or humidification with heating or humidification of the cooling. So, this comes in a single go when you deal with humidification or dehumidification processes. Another important aspect is the evaporative cooling.

This evaporative cooling process is nothing but which is similar to a adiabatic saturation processes. And the last segment of air conditioning processes it could be adiabatic of mixing of two air streams. So, prior to this, in our basic thermodynamics, we all deal with two air streams and they try to mix or there may be multiple air streams and they try to mix and after mixing they go as a single entity.

And, through these processes, there are various changes in the properties of air. But, here this mixing will be mainly focusing for moist air streams. When you deal moist air streams, that means, we have to deal dry air as well as water vapours simultaneously. Till this point of time, we have discussed exhaustively what is a moist air, what are the different processes, humidifications, humidity ratio.

Here temperature could be a dry bulb, wet bulb or dew point temperatures, then we also have humidity ratio, we also know relative humidity and side by side other properties like enthalpy entropy can be calculated. And, while dealing this calculation processes, we also have introduced a chart which you call as a psychrometric chart.

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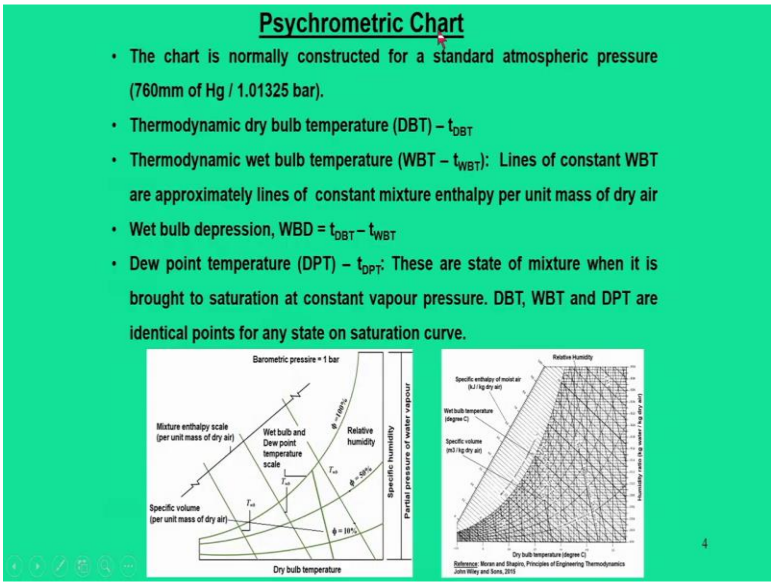

In fact, this psychrometric chart is the backbone of air conditioning systems because this particular chart gives all information which is required for a moist air in a common applications. So, the single chart will give you the properties like, wet bulb temperature, dry bulb temperature, specific volume, enthalpy, humidity ratio, relative humidity. So, I am not going into deep details, but these are very much required to study or to understand the different air conditioning processes.

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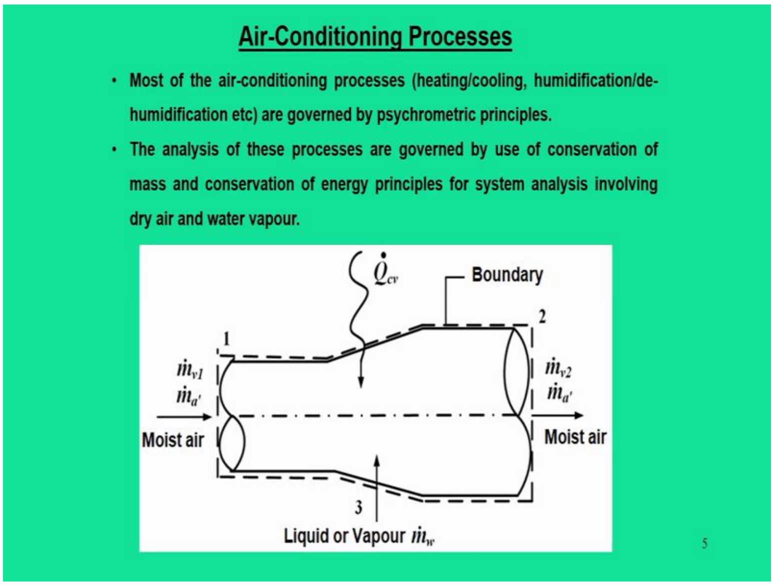

Now, when you start this air conditioning processes, we start with the basic energy balance equations. Of course, we have mass balance equations, when I talk about mass there are two possible masses, one is mass of air and other is mass of vapour. So, the analysis of air conditioning processes is governed by conservation of mass and energy principles for dry air as well as water vapours.

So, for example, if you talk about a domain in which the moist air enters and also in some segment or some exit location, the moist air goes out of the domain. And, we choose a control volume. So, there could be a possibility of heat interaction; of course, we do not deal about work interaction here. So, there could be a possibility of heat interaction, but if you take adiabatic systems, this heat interaction is not allowed.

And, of course, most of the situations, when you change the properties of moist air, either water is removed from the air or water is sprayed into the air or air comes into contact with water so, as to increase the humidity or in some way mass of water vapour will keep on increasing or decreasing.

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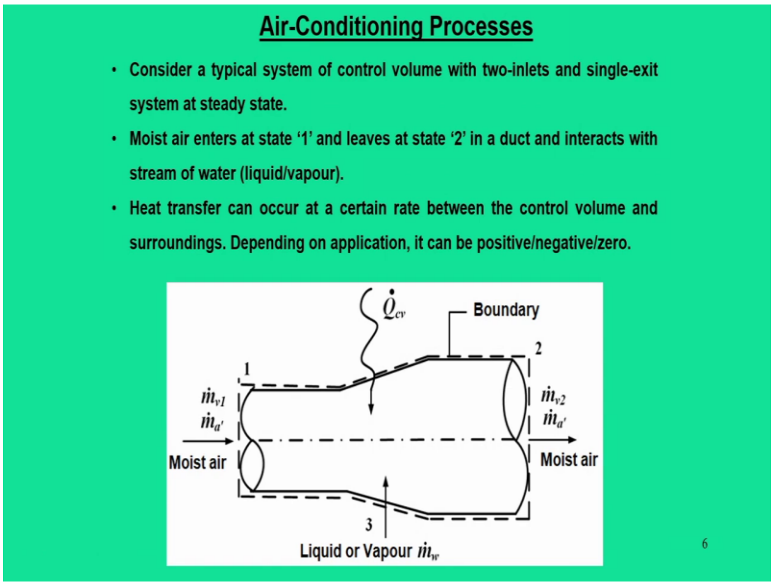

So, to analyze such systems, we consider there are three different state 1, 2 and 3; 1 is inlet state; 2 is exit state and 3 will always be either adding mass or water into the system or take out of this system. Heat transfer can occur in the certain volume to the surroundings depending upon the application it can be positive, negative or 0.

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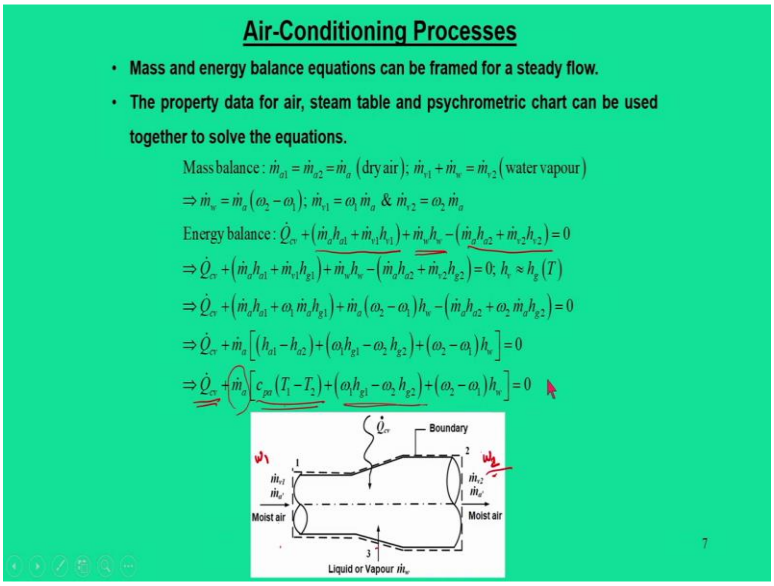

So, for a very general domain, one can use this mass and energy balance equations have been a steady flow situations. First thing we talk about mass balance, typically when you talk about mass moist air part, the air part do not change. $\dot{m}_{a1} = \dot{m}_{a2} = \dot{m}_a \ (\text{dry air})$ What changes is the addition of water and when you add water the mass of vapour increases.

So, the mass of water vapour changes and this mass of water vapour from the basic definition we can bring humidity ratio into account. So, through this humidity ratio, we can correlate the relation between mass of water vapour and mass of dry air. $\dot{m}_{v1} = \omega_1 \dot{m}_a$ & $\dot{m}_{v2} = \omega_2 \dot{m}_a$ So, likewise we can frame a mass balance equations the amount of mass which is getting added into the system is equal to $\dot{m}_a (\omega_2 - \omega_1)$; ω_2 and ω_1 is nothing but the humidity ratio at the exit and at the inlet.

And, then we can also write down the energy balance equations. So, energy balance equations takes into account what are the energy interactions possible first is Q_{cv}; that means, heat addition that gets added here. And, one part that comes from the inlet because there are two inlets one for the moist air inlet at state 1, other is moist air inlet at the state 3 in the form of water. So, when you multiply its mass with their specific enthalpy, we can get the total energy and this the energy that leaves through this exit stream and this gives a negative sign.

$$\dot{Q}_{cv} + (\dot{m}_a h_{a1} + \dot{m}_{v1} h_{v1}) + \dot{m}_w h_w - (\dot{m}_a h_{a2} + \dot{m}_{v2} h_{v2}) = 0$$

Now, here we can simplify these equations by considering this ω_2 and ω_1 into picture and ultimately we can frame a very common equations which is a energy balance equations. And, here this energy balance equation has basically four parts: one is Q_{cv} that gets added into the system, and here entire thing that goes common is the mass of dry air and because mass flow rate of dry air does not change.

And, this contribution of this air has two aspects – one is through the process of changing there is also temperature change. So, the change due to energy that gets added through air only; other part is for the water vapours, when we multiply $\dot{m}_a$ with ω, we get in the form of the energy associated with water vapour.

Here g stands for the gas phase for the state 1 and state 2 and the difference in the humidity ratio is multiplied by enthalpy of water because this is in the water form. So, enthalpy must be calculated at temperature which is available at state 3. So, this is the very basic equations that we are going to use for all fundamental air conditioning processes which we will be dealing now.

$$\dot{Q}_{cv} + \dot{m}_a \left[c_{pa} \left(T_1 - T_2 \right) + \left(\omega_1 h_{g1} - \omega_2 \, h_{g2} \right) + \left(\omega_2 - \omega_1 \right) h_w \right] = 0$$

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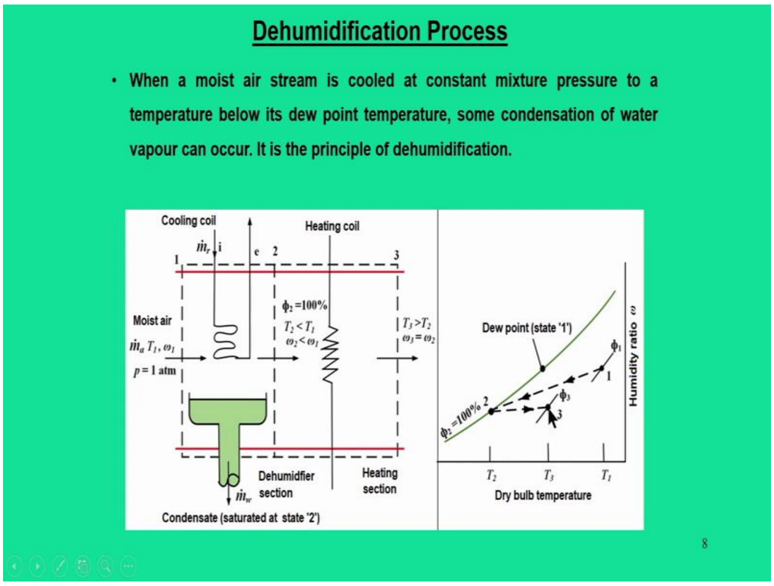

And, the first fundamental processes is the dehumidification process. So, when a moist air steam is cooled at a constant mixture pressure to a temperature below the dew point temperature, some condensation of water vapour can occur and this principle is called as a dehumidifications.

Now, how I can dehumidify? That means, you have to cool this temperature below dew point temperature. In fact, we have a deliberately discussed about how a dew is formed in our previous lecture, and with that concept, we can use this particular concept to design a dehumidification processes.

What a typical process dehumidification looks like is that we have a chamber. We can assume that there is a control volume sections and these control volume sections has two part one is a dehumidifier section, other is a heating sections. Basically what is a user requirement is something else and user requirement is maybe at state 3 and moist air is available maybe at the inlet state.

So, we have to design a system such that from the available state of the moist air to be changed to the user requirement state. So, one way that we have to do this thermodynamically that you have to rely on this psychrometric charts. How I can design my dehumidification processes such that I can just fix them in the psychrometric charts. And if it is not possible to fix this psychrometric chart, then such a system is not possible.

So, what we normally do is that for a given available stream, we can then locate that as a state 1 and for that state 1 we know ω and T_1. And, correspondingly if you go along same humidity ratio line, we will reach the saturation line which is the dew point for that situation.

Now, what this dehumidifier do? Normally, to do this dehumidification you have to remove water vapour. So, for that thing you have to use a cooling coil and this air is allowed to interact this cooling coil. That means, this cooling coil we have to use such a way that when this air gets interact with this, then it will reach the dew point temperature.

When the dew point temperature is reached, water vapours gets condensed and they come as a condensate and the rest of the desired air they can go and leave this section 2. Now, when doing so, not necessarily in that process we will be able to achieve the humidity but we cannot control the temperatures. So, then we have to do some kind of heating or cooling coil. So, here heating coil has been used, so that temperature can be as desired depending on the final state.

So, one way is to locate this is that, you have to bring down that state 1 to the saturation curve where we will remove all the condensate in the form of water vapour, then subsequently we have to heat to reach the desired state. So, this is only possible way that we can achieve this dehumidification processes.

And we also know that there is also a change in the temperatures, but other possibilities could be 1-2-3, but 1-2-3 we cannot directly draw on the psychrometric chart. So, 1-2-3 is not the physical way of dealing with these processes because we cannot make the condensation unless and until we reach the saturation point. So, that is the reason we have to take this long path from 1 to 2 then again come back to 3.

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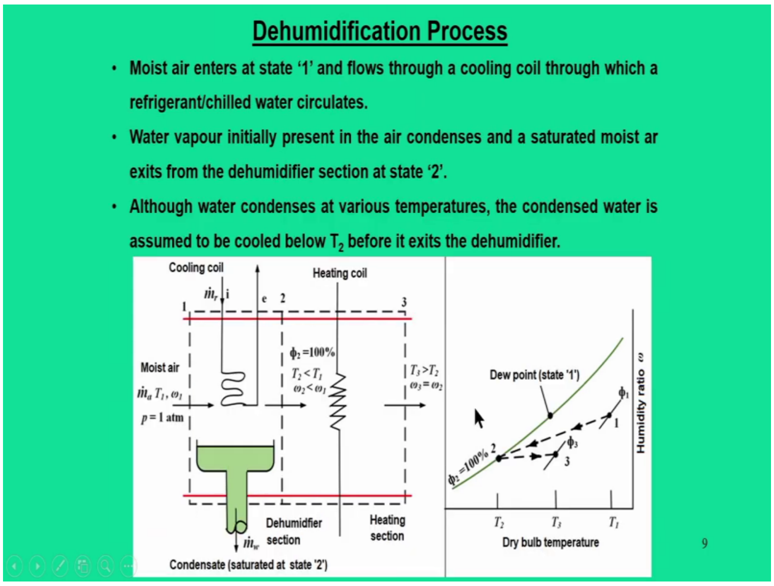

This is how I have already explained how the water get condenses and the condensate gets cooled below this temperature T_2.

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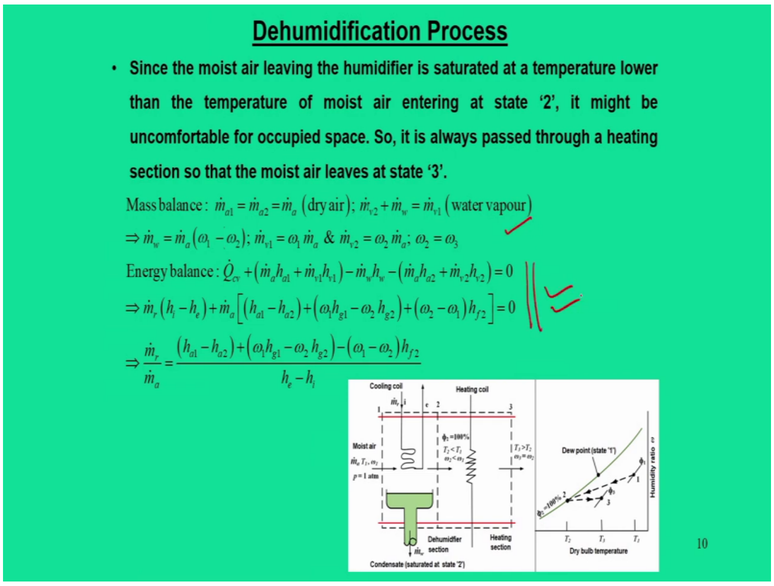

And, for these kind of systems we can use this similar way the mass and energy balance equations. First the mass balance equation for air that remains same. Water vapours it is $\dot{m}_{v1} + \dot{m}_w = \dot{m}_{v2}$. So, the equation is written in a way that if the water gets out, that is what a plus sign. But, however, when you deal with these things, ultimately the negative sign will indicate that water will come down. So, in this way we can frame this energy and mass balance equation.

$$\text{Mass balance: } \dot{m}_{a1} = \dot{m}_{a2} = \dot{m}_a \ (\text{dry air});\ \dot{m}_{v1} + \dot{m}_w = \dot{m}_{v2} \ (\text{water vapour})$$

$$\Rightarrow \dot{m}_w = \dot{m}_a (\omega_2 - \omega_1);\ \dot{m}_{v1} = \omega_1 \dot{m}_a \ \&\ \dot{m}_{v2} = \omega_2 \dot{m}_a;\ \omega_2 = \omega_3$$

$$\text{Energy balance: } \dot{Q}_{cv} + (\dot{m}_a h_{a1} + \dot{m}_{v1} h_{v1}) - \dot{m}_w h_w - (\dot{m}_a h_{a2} + \dot{m}_{v2} h_{v2}) = 0$$

$$\Rightarrow \dot{m}_r (h_i - h_e) + \dot{m}_a \left[(h_{a1} - h_{a2}) + (\omega_1 h_{g1} - \omega_2 h_{g2}) + (\omega_2 - \omega_1) h_{f2} \right] = 0$$

$$\Rightarrow \frac{\dot{m}_r}{\dot{m}_a} = \frac{(h_{a1} - h_{a2}) + (\omega_1 h_{g1} - \omega_2 h_{g2}) - (\omega_1 - \omega_2) h_{f2}}{h_e - h_i}$$

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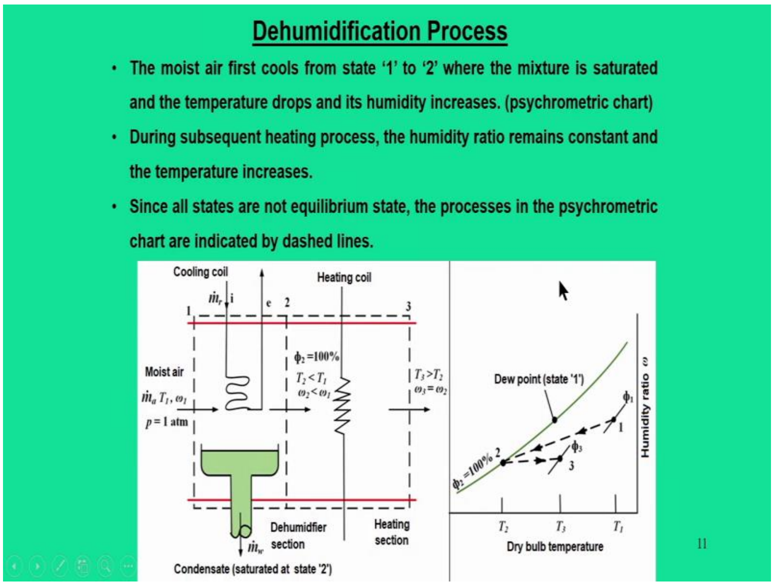

Then moving further this dehumidification processes, the other important aspect is that we have to locate these states 1 and 2 in the psychrometric chart, so that that we can ensure the feasibility of a dehumidification processes. If all these states are not equilibrium states, the processes are indicated by dash lines.

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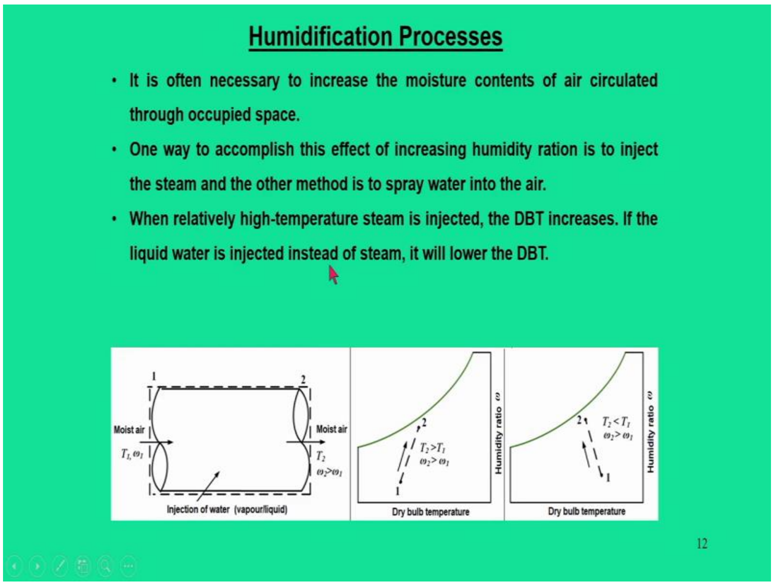

The next processes that comes as a humidification processes. So, humidification processes is just opposite to the dehumidification processes. Here we have to add water vapour into the moist air. So, this addition of water vapour into the moist air is possible by two means: one is if you can add in the form of a water vapour, other way is that we can add in the form of liquid; that means you can spray as a liquid jet or you can spray as a steam jet.

So, there are two ways in which we can add it. Now, when we are in state 1 that is moist to air at state 1, what happens when steam is added? So, when steam is added, obviously the humidity increases and of course, the temperature also increases. So, when a high temperature steam is injected, this dry bulb temperature increases.

So, this ensures that addition of either water vapour or steam always increases humidity ratio, but when a steam is added, the temperature of air goes up and this can be denoted in the psychrometric chart that point 1 goes to point 2 in this direction with increase in the dry bulb temperatures. Other way is that if I add water into this moist air, the dry bulb temperature is going to drop.

So, when it drops; that means, water is added and temperature drops. So, this is the very basic fundamental thing that we should know that when a relative high temperature steam is injected, the dry bulb temperature increases; if liquid water is injected, then it will lower the DBT.

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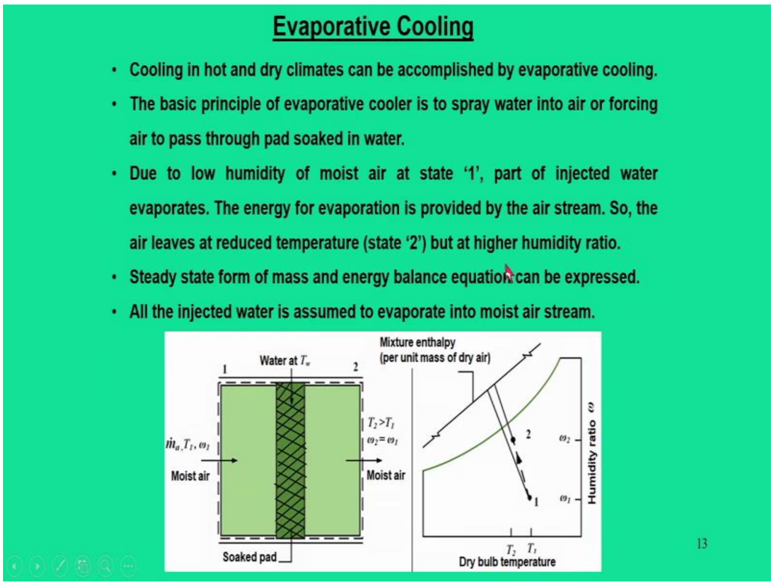

Now, another important aspect is evaporative. So, this is something similar to a adiabatic saturation processes. Where we require this evaporative cooling? The cooling in hot and dry climates can be accomplished by evaporative cooling. Normally, evaporative cooling gets the advantage that when we have a very hot and dry climate, then evaporative cooling gives a better results.

The very basic principle of evaporator cooler is to spray water, this is something like cooler you are using in our household applications that its a evaporative cooler to spray water into the air or forcing air to pass through a pad soaked in the water. Now, due to a lower humidity of moist air at state 1, the part of water injected gets evaporated and because evaporation causes cooling this is the fundamental principle.

So, the energy transfer for evaporation is provided by the air steam. So, the air leaves at a reduced temperatures, but at a higher humidity ratio. That means, humidity ratio can be increased, but temperature is lowered and for this case also we can form steady state form of mass and energy balance equations and all injected air is assumed to be evaporated into the moist air stream.

Now, if you look at this particular domain, so, what we have is a control volume where we have a soaked pad. Soaked pad means it is basically soaked with water and air is forced to pass through these things and in this process the temperature drops in this case.

So, T_2 is less than T_1. So, dry bulb temperature drops, in the psychrometric chart, the process goes from 1 to 2 in this direction and in this way if you can actually locate the state point and find the enthalpies, then we can see that enthalpy at state 2 is higher than that of state 1.

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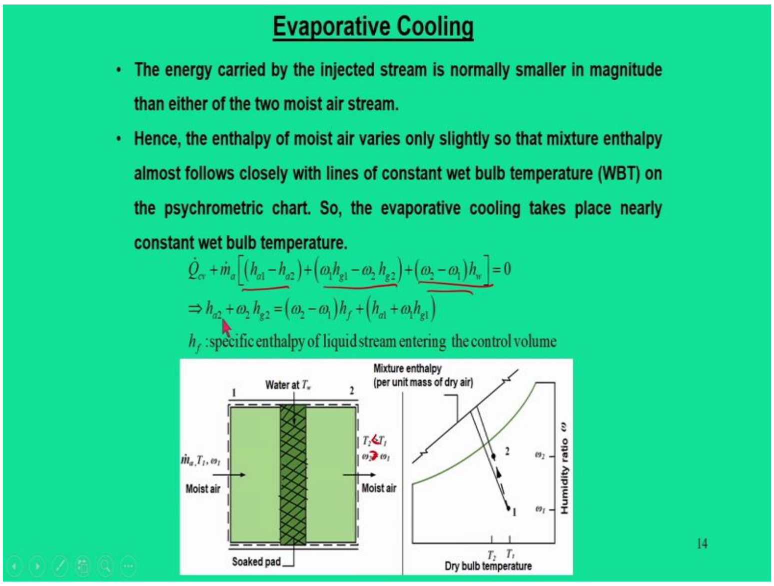

Then this energy balance equation can be applied here as well. So, when we apply this energy balance equation, it has three entities; one is moist air that enters water at T_w and moist air that leaves. So, we can write this energy balance equations that is $\dot{Q}_{cv} + \dot{m}_a\left[(h_{a1} - h_{a2}) + (\omega_1 h_{g1} - \omega_2 h_{g2}) + (\omega_2 - \omega_1)h_w\right] = 0$. So, T_2 is less than T_1 and ω_2 greater than ω_1.

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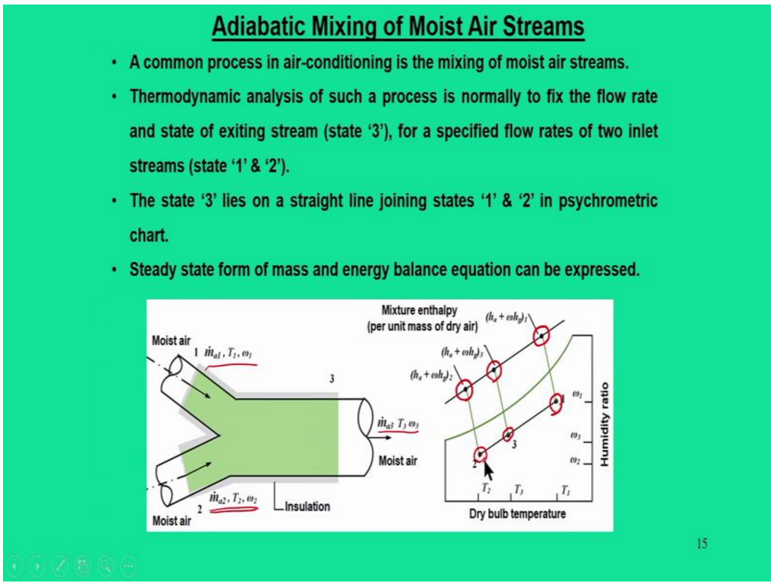

The last part is the adiabatic mixing of two moist air stream. Theoretically possible that we can have a one stream, two stream or multiple streams of air which comes and they try to mix and they goes out. And, in most of the cooling application or air conditioning application normally there are two moist air streams that comes through different inlets.

And, they may be at different states. Now, when they come and mix and finally, after mixing they go as a single entity at a conditions m_{a3}, T_3, ω_3 such a systems you have to locate them in a psychrometric charts. To do that mainly we have to find out the enthalpies which the moist air is carrying. So, enthalpy is the very vital factor.

So, a state point 1 can be located based on the data available T_1, ω_1 and state 2 can be located based on the data T_2, ω_2. So, we can join this state 1 and 2 and obviously, the state 3 will fall any point on this line. So, from this, we can locate the enthalpy values and finally, we can find out what is the condition 3. Now, a very basic point is that why the point 3 will lie on this line.

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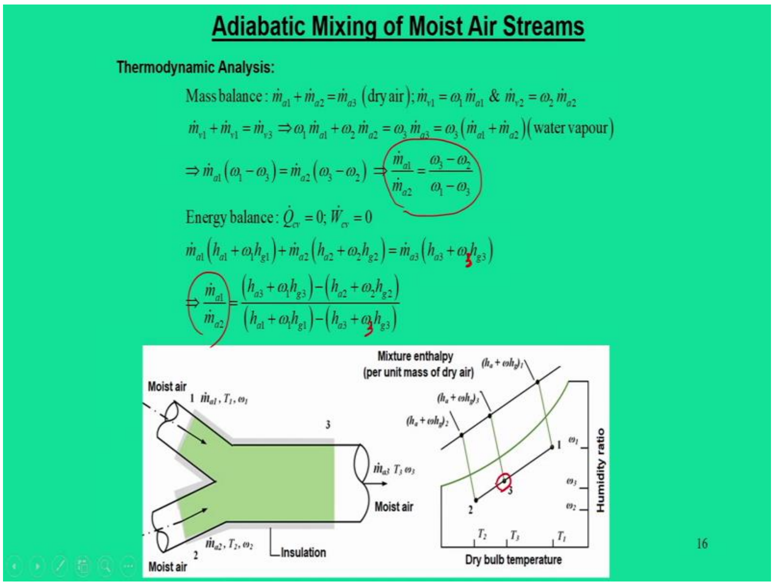

So, to prove that we have to rely on this mass balance and energy balance equation. So, mass balance equation we can write $\dot{m}_{a1}+\dot{m}_{a2}=\dot{m}_{a3}$ and that is for dry air and for moist air we can introduce the humidity ratio which can correlate the mass of water vapour with mass of dry air. $\dot{m}_{v1}=\omega_1\,\dot{m}_{a1}$ & $\dot{m}_{v2}=\omega_2\,\dot{m}_{a2}$

Then we can also do the mass balance equations for water vapour and we can finally, land off a equation $\frac{\dot{m}_{a1}}{\dot{m}_{a2}}=\frac{\omega_3-\omega_2}{\omega_1-\omega_3}$. So, this is not nothing but a linear relation.

Similar way another equations we can find out $\frac{\dot{m}_{a1}}{\dot{m}_{a2}}$ from this enthalpy equation. So, because this is adiabatic mixing $\dot{Q}_{cv}=0;\ \dot{W}_{cv}=0$. So, rest of the things which are left with that $\dot{m}_{a1}\left(h_{a1}+\omega_1h_{g1}\right)+\dot{m}_{a2}\left(h_{a2}+\omega_2h_{g2}\right)=\dot{m}_{a3}\left(h_{a3}+\omega_3h_{g3}\right)$.

So, ultimately we can use these particular relations here and we will find that the mass of air 1 and 2, they form a ratio with respect to this enthalpy values at different states and this linear relation proves that the point 3 will always lie on this straight line.

$$\frac{\dot{m}_{a1}}{\dot{m}_{a2}}=\frac{\left(h_{a3}+\omega_1h_{g3}\right)-\left(h_{a2}+\omega_2h_{g2}\right)}{\left(h_{a1}+\omega_1h_{g1}\right)-\left(h_{a3}+\omega_1h_{g3}\right)}$$

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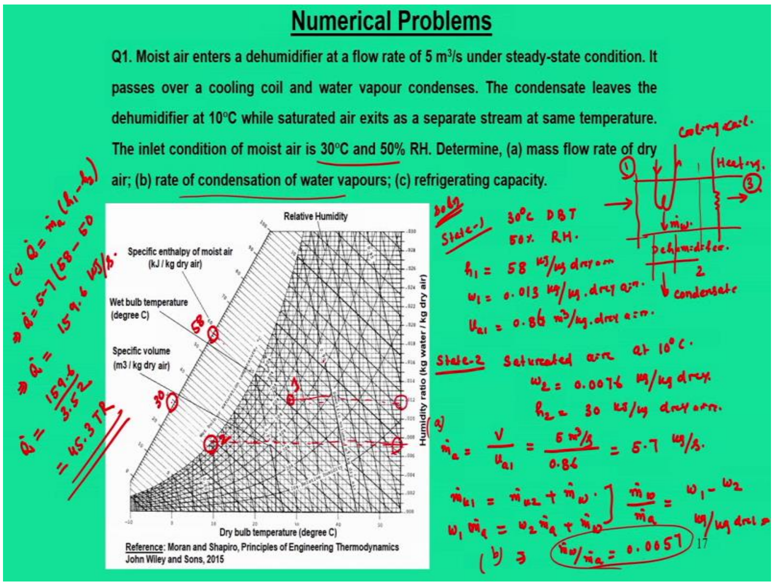

These are all about the different psychrometric processes and how different psychrometric properties that can be used for designing air conditioning systems. So, now we will discuss some of the numerical problems which is based on certain air conditioning processes that we discussed so far. So, the first one is nothing but dehumidification processes.

So, for this dehumidification processes, we have to locate the states of moist air in the psychrometric chart. So, this typical dehumidification processes can be rewritten in this way that we have a dehumidifier section and we have a heating section. And, we have a cooling coil and through this cooling coil, we have a container carrying condensate. So, moist air enters, it is interacting with this cooling coil, when it interacts with the cooling coil, the water vapours comes down as a condensate. And, finally, the air that goes out into a heating section just to control the temperatures.

So, we can locate the states as 1, state which is leaving, the condensate is 2 and the state that is leaving is 3. So, what is given? State 1 30°C DBT, 50% RH. So, we can roughly locate the state somewhere here.

And, for this, we can actually find its values; h_1 = 58 kJ/ kg dry air. We can also find out ω_1 0.013 kg/kg dry air. So, we know this state and of course, we can find the specific volume 0.86 m^3/ kg dry air.

So, state 2 is nothing but the saturated air at 10°C. So, for this, this value would be ω_2 0.0076 kg per kg dry air and this enthalpy value is close to 30.

$$\dot{m}_a = \frac{V}{v_{a1}} = \frac{5}{0.86} = 5.7\text{kg/s}$$

$$\dot{m}_{v1} = \dot{m}_{v2} + \dot{m}_w; \omega_1 \dot{m}_a = \omega_2 \dot{m}_a + \dot{m}_w \Rightarrow \frac{\dot{m}_w}{\dot{m}_a} = \omega_1 - \omega_2 = 0.0057\text{kg/kg dry air}$$

So, this is the rate at which the condensation takes place and mass flow rate of dry air we already evaluated that is first part; second part what is the rate of condensation of water vapour, we can say 0.0057 kg of condensate that comes per kg of dry air and third thing that we have to find out refrigerating capacity.

$$\dot{Q} = \dot{m}_a \left(h_1 - h_2\right) = 5.7\left(58 - 30\right) = 159.6\text{kJ/s} = 45.3\text{TR}$$

So, this is the problem that we use for dehumidification processes. So, the very basic bottom line that we locate the state points 1, state point 2, by locating the state points we calculated the properties values, enthalpy, specific volume and use them in the calculations.

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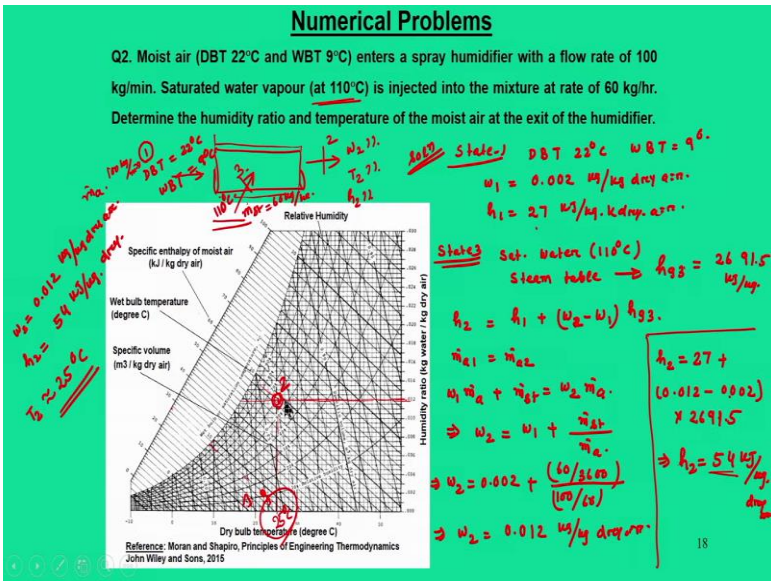

The next problem is on spray humidifier and here the data that is given moist air which is given with DBT of 22°C and WBT of 9°C enters this spray humidifier with a flow rate and saturated vapour at 110°C is injected to the mixture at a rate 60 kg/ hour.

So, you have to calculate humidity ratio and temperature of moist air at the exit of the stream. So, we can draw these simplified version of the problem that we have a situation in which moist air enters this control volume and state 1 DBT 22°C, WBT 9°C, saturated water vapour at 110 degree centigrade. So, it is a steam. So, this enters at 60 kg per hour and the moist air that enters 100 kg/minute and what is leaving state we do not know. So, we also have to find enthalpy because without enthalpy we cannot find the temperatures.

$$\text{State-1: DBT } 22°\text{C} \;\; \text{WBT } 9°\text{C} \Rightarrow \begin{array}{l} \omega_1 = 0.002\text{kg/kg dry air} \\ h_1 = 27\text{kJ/kg dry air.K} \end{array}$$

$$\text{State-3: Sat. Water } 110°\text{C} \Rightarrow h_{g3} = 2691.5\text{kJ/kg}$$

$$h_2 = h_1 + (\omega_2 - \omega_1) h_{g3}$$

$$\dot{m}_{a1} = \dot{m}_{a2}$$

$$\omega_1 \dot{m}_a + \dot{m}_{st} = \omega_2 \dot{m}_a \Rightarrow \omega_2 = 0.002 + \frac{(60/3600)}{(100/60)} = 0.012\text{kg/kg dry air}$$

So, state 2 will lie on this horizontal line which is 0.012. For exact location we need another parameter.

$$h_2 = h_1 + (\omega_2 - \omega_1) h_{g3} = 27 + (0.012 - 0.002) \times 2691.5 = 54\text{kJ/kg dry air}$$

$$@\, \omega_2 = 0.012, h_2 = 54 \Rightarrow T_2 \approx 25°C$$

So, you can see how easy you can locate this point on the psychrometric chart. One thing I need to emphasize these numbers may not be exact, but it will give an approximate estimate, when you look at the psychrometric chart.

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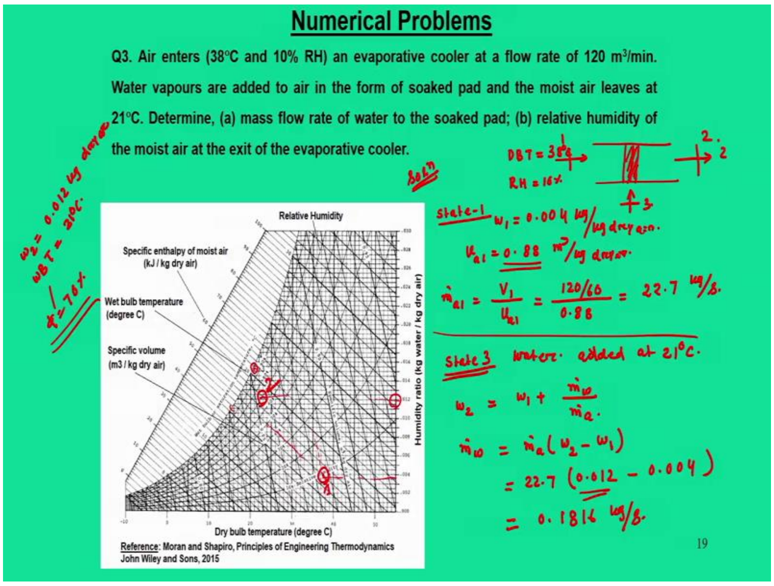

The 3rd question is on evaporative cooler this is also we studied today. So, in this evaporative cooler the concept goes that the air is allowed to pass through a soaked pad in which the moisture gets added into this air and by virtue of its the moist air exits from the evaporative cooler.

So, very basic bottom line of philosophy of this evaporative cooler is that we have to rely on adiabatic saturation processes, we have to think about what is the wet bulb temperature at the end of the processes because along this adiabatic process wet bulb temperature does not change.

To do that, we have to first draw the simple system we have some kind of soaked pad, which is kept which gives the water at state 3, moist air enters at state 1, leaves at state 2. So, entry state DBT 38°C, RH 10 percent. So, the point 1 is located. So, we can write ω_1 = 0.004 kg/kg dry air and specific volume v_{a1} could be 0.88 m^3/ kg dry air.

$$\dot{m}_a = \frac{V}{v_{a1}} = \frac{(120/60)}{0.88} = 22.7\text{kg/s}$$
$$\omega_1\dot{m}_a = \omega_2\dot{m}_a + \dot{m}_w \Rightarrow \dot{m}_w = \dot{m}_a(\omega_1 - \omega_2) = 22.7(0.012 - 0.004) = 0.1816\text{kg/s}$$
$$@\,\omega_2 = 0.012, \text{WBT} = 21°C \Rightarrow \phi = 70\%$$

So, this is how we are going to locate the state 1 and 2 in the psychrometric chart get the properties and then use them to solve the problems. So, here we have attempted three problems – one on dehumidification processes, other is humidification processes, third is evaporative cooling processes. So, next class we will talk about similar problem on a adiabatic mixing process. So, with this I conclude this lecture for today.

Thank you for your attention.