Applied Thermodynamics
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Module - 05
Refrigeration and Air-Conditioning System
Lecture - 42
Cooling Tower and Air Washers

Dear learners, greetings from IIT Guwahati, we are in the Applied Thermodynamics course module 5 Refrigeration and Air Conditioning Systems.

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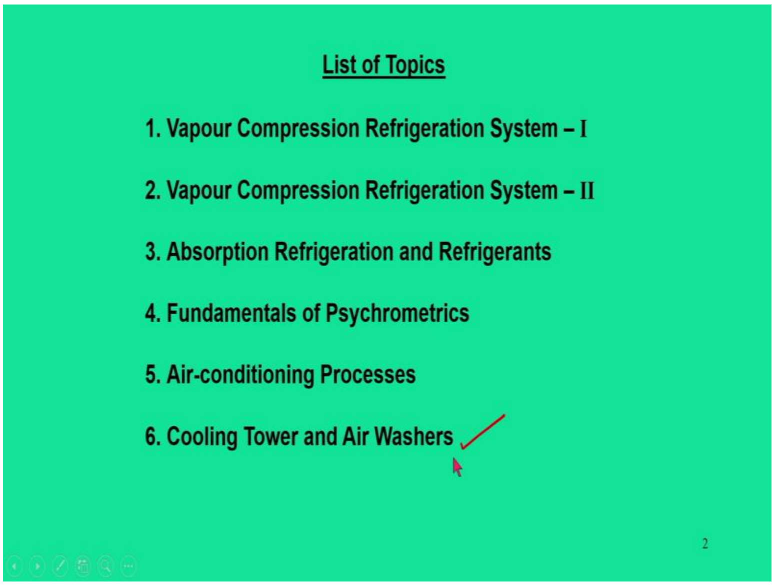

Till this point of time we have covered 5 lectures on this module, the first 3 was focused towards refrigeration systems, that is vapour compression systems and vapour absorption refrigeration systems. In addition to that we have discussed about refrigerants their applications, their designations and their commercial names.

And in last two lectures we dealt with fundamentals of psychrometrics and how those concepts are used for air conditioning processes. So, in the air conditioning processes, we discussed about humidification, dehumidifications, evaporative cooling, adiabatic mixing and side by side we discussed how the properties of moist air is going to change for certain processes.

Today in the same line we will discuss about cooling towers and air washers. So, this is again a application oriented with respect to air conditioning applications and to some extent you must have aware of cooling tower applications in the steam power plant. And also in the similar line there is air washers.

So, this air washer is nothing but a conceptual things; that means, in a layman sense we say it is washing of air. Now, while doing the washing processes, there are requirements that what are the need for the users, accordingly air can be conditioned to fit into the required applications.

So, when I mean conditions, it means the properties of moist air that is its dry bulb temperature, wet bulb temperatures, humidity ratio, relative humidities, all these needs controlled in some fashion. So, that we can achieve a desired air conditioning requirement. So, this is the last segment of these lecture series on this module that is refrigeration and air conditioning. So, we will be dealing with mainly cooling tower and air washers.

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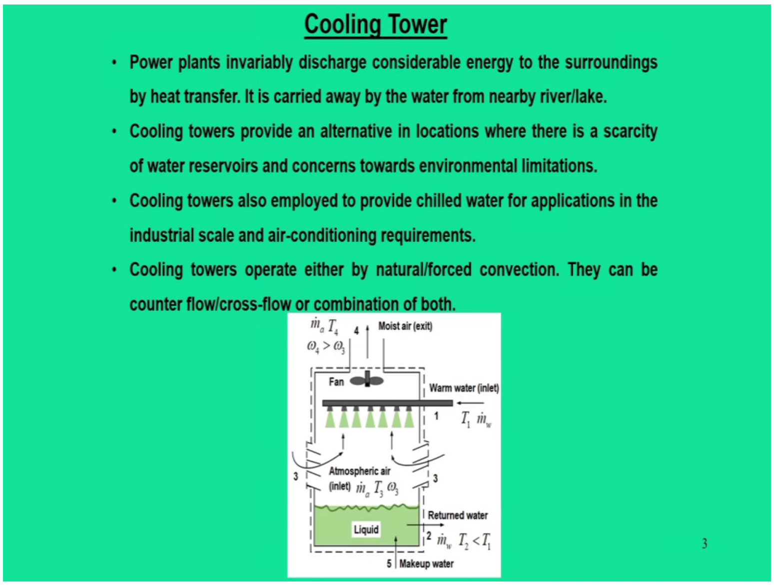

So, although we have seen that cooling tower applications is one of the important aspects in a steam power plant, but side by side we are fitting into psychrometrics because this cooling tower requires the knowledge of moist air and how the air conditions can be controlled so that we get the required applications.

When you dealt with cooling tower for steam power plant applications, there main focus was to cool the warm water that is left from the condenser of a steam power plant and then that water needs to be conditioned. That means, we call this as that returned water that goes to the condenser back again. So, it is basically circulating water and controlling the environment of water or desired condition of water which needs to be re-circulated again to the power plant.

So, this is how the philosophy of steam power plant requires the knowledge of cooling tower, but other approach is that if our application is oriented towards the requirement of moist air at the exit. That means, when you dealt with cooling tower for steam power plant applications we really not do not bother what is the exit condition of air, what is the inlet condition of air. Normally the inlet condition of air is atmospheric and we do not really bother about the exit condition of the moist air that comes out.

Rather we are mainly dealt with requirement of returned water that needs to be sent back to the power plant, but side by side other way of looking at is that through this water circulations, it is also possible to control the condition of moist air that comes out from this cooling tower.

So, there is two possibilities or two applications that we can use this moist air; one way is that you can use this water, which is returned back from the cooling tower. So, this is the way two broad sense of requirement or applications for cooling tower. Just to give the brief introduction about the cooling tower.

So, the power plants invariably discharge considerable amount of energy to the surroundings by heat transfer. So, it is carried away by water or nearby lakes. So, normally the release of water from a steam power plant goes directly to the river or pond or lake nearby. Many a times what happens when there is a scarcity of water then people explore the possibility of a cooling tower.

That means water which is supposed to be exhausted, that needs to be recirculated. So, that is what conditioning of water is required because it is a recirculated water. So, in a close cycle circuit when the water needs to be recirculated in a steam power plant, the role of cooling tower is very vital. So, cooling tower provides an alternative in locations, where there is a scarcity of water reservoirs and concern towards environmental limitations.

Of course they are also used to employ chilled water for applications in the industrial scale and air conditioning requirements. Cooling tower as either operate by natural or forced convection and they can be counter flow, cross flow or any combination of both. So, this is how the schematic of cooling tower is represented. So, what we see here is that there is a fan. So, in this case, it is a forced convection methods where it sucks the air from the bottom.

So, you can see air enters to the tower at state 3 through these passages and because the fan rotates it sucks the air from the bottom and the air outlet goes in the top. So, when the air goes out, it is now moist air. When the air enters it is normally atmospheric air at certain conditions. Now, when the air goes out it has contains some water vapour at state 4 we say ω_4 humidity ratio which is higher than ω_3.

Now, how this humidity ratio increased because we are spraying water or warm water, typically at condition 1 warm water is inlet and it is in a spray form. So, by doing this spray, we are essentially breaking this content of water into tiny droplets. So, that heat transfer processes can be enhanced.

So, in that sense the tiny droplets gets absorbed in the air. So, by the by virtue of it, the humidity ratio of air increases and side by side when it comes back, the water is again collected at the bottom of the tank, which is in the liquid state. Now, again whatever condition air that comes out and stored is returned back. And typically the mass flow rate of water that comes in and mass flow rate of returned water, they are normally same.

I mean in a cooling tower they are maintained constant, but by virtue of it, temperature drops because it was initially sent as warm water at T_1 and the returned water has temperature less than T_1, that is the main requirement as the returned water temperature needs to be less here. And side by side we also have a provision of makeup water what is the makeup water requirement.

Now; obviously, when the air interacts with this, it takes out moist, humidity ratio is increased. That means some of the water vapours gets absorbed in the air and as a results the concentration of water, which is supposed to be there, it comes out.

So, there is some provision that we need to add the makeup water. And the requirement of makeup water is nothing but the increase in the humidity ratio that is $\omega_4 - \omega_3$

multiplied by the mass flow rate of air that much amount of makeup water is required here.

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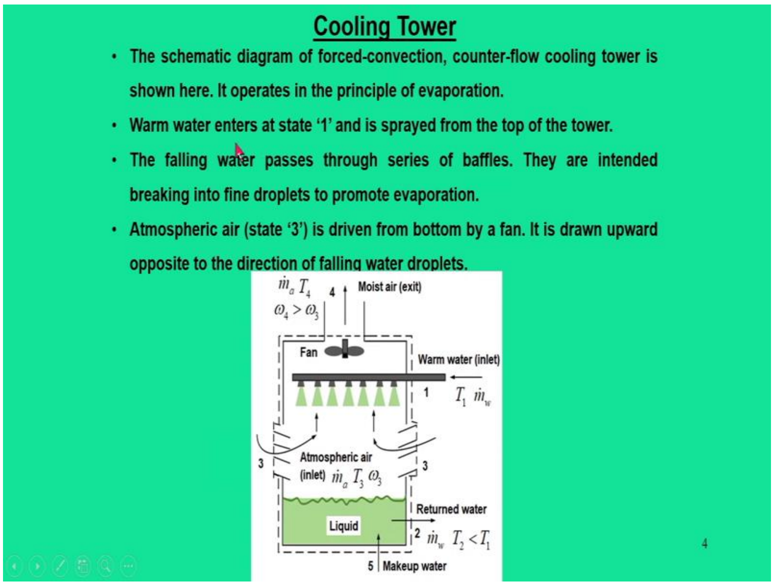

So, already I have explained this fact that warm water enters at state 1 and spread from the top of the tower, falling water passes through the series of baffles and they are mainly intendent in breaking the droplets to promote evaporations. Atmospheric air at state 3 is driven from the bottom by a fan and it is drawn upward opposite to direction of the falling water droplets.

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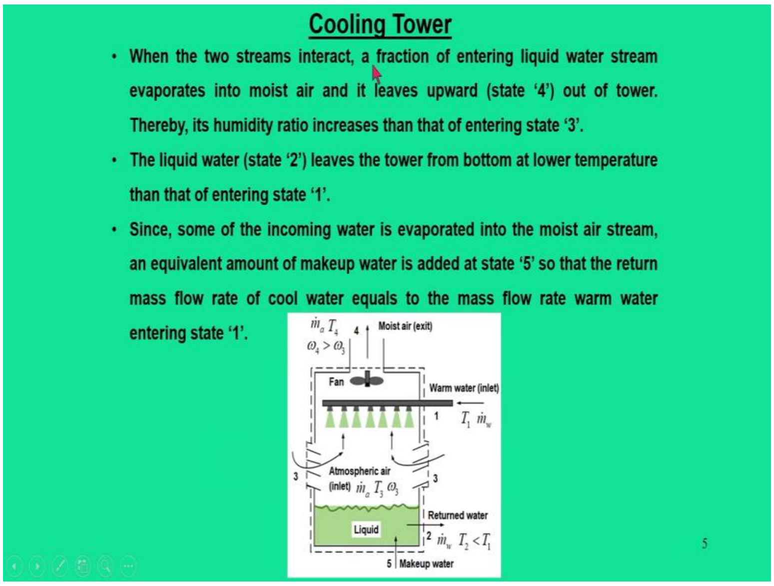

Now, when two streams interact a fraction of air entering liquid water stream evaporates into moist air and leaves upward at state 4, that is out of the tower. So, by this process the humidity ratio increases from its entering state that is 3. Now, liquid water at state 2 leaves the tower from the bottom and at lower temperature than that of state 1. Now, since some of the incoming water is evaporated into moist air stream; so, an equivalent amount of makeup water is added at state 5. So, that return mass flow rate of cool water equals to the mass flow rate of warm water entering at state 1. So, basically we need to control $\dot{m}_w$, to control $\dot{m}_w$ we need to provide makeup water. This makeup water is required because some of the water droplets or water vapours are carried away by the air.

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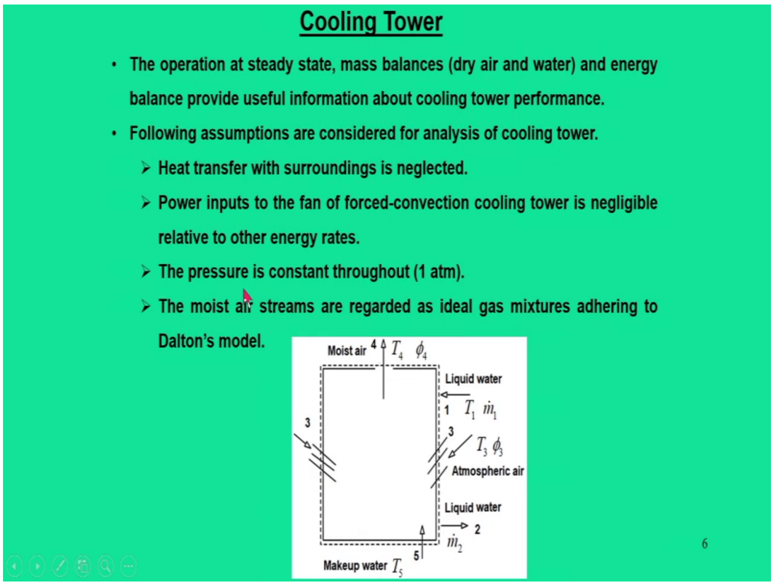

Now, let us see that how we can do some modelling analysis for a cooling tower. So, one way of looking at these process is that we just simplify in a control volume container where at state 3 air enters and it is mainly at atmospheric air. And its conditions are normally defined in terms of relative humidity. And when it goes out its condition is T_4 or we can some way say it is humidity ratio at state 3 or state 4.

Liquid water enters at a conditions T_1 and $\dot{m}_1$, liquid water leaves out at $\dot{m}_2$, makeup water is added at of course, that should be at different temperature T_5 and $\dot{m}_5$. So, to do this analysis we make certain assumptions, those assumptions are heat transfer with surrounding is neglected.

Power inputs to the fan of forced-convection of the cooling tower is negligible relative to the other energy rates. Pressure is maintained constant throughout that is one atmosphere, moist air streams are regarded as the ideal gas mixture adhering to the Dalton's model. So, you can also apply Dalton's law of partial pressures.

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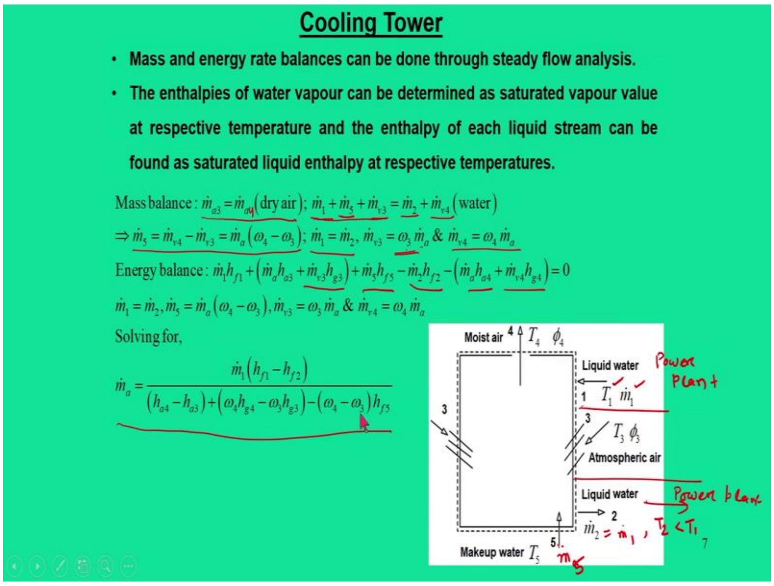

Now, here the main mathematical equations that is used here and that is mostly mass and energy balance in a steady flow operation. And here one of the main intention or application for the cooling tower design is that, we try to see that what is the amount of air that is going to be reused for this cooling tower.

Typically these derivations are made with respect to a power plant application, that is steam power plant applications where liquid water at certain flow rate and temperature is allowed to enter the tower. And we expect that same flow rate of water that has to be released or returned back to the power plant, but at a different temperature or lower temperatures.

So, if you allow the temperature of water that comes from the power plant is at condition T1 and $\dot{m}_1$. And when the water goes out that means, returned water again back to power plant we expect that $\dot{m}_1 = \dot{m}_2$ that is same flow rate and of course, $T_2 < T_1$ that is the requirement for the power plant that temperature should be lower than this.

And to have this problem we require certain quantity of air flow rate that has to be pumped into the tower. So, this is done through a fan and we are controlling that fan and through that air can be sucked into the tower. And the air conditions could be like T_3 $\phi_{3,}$ the inlet state and T_4 and ϕ_4 is the exit state.

So, the first equation that we are going to use that $\dot{m}_{a3} = \dot{m}_a \; (\text{dry air})$ that is air flow rate remain same maybe in 4 and 3 are equal. $\dot{m}_1 + \dot{m}_5 + \dot{m}_{v3} = \dot{m}_2 + \dot{m}_{v4} \left(\text{water}\right)$

So, from this equations we can say that we expect $\dot{m}_1 = \dot{m}_2$, that means, water flow rate should be remain same and $\dot{m}_{v3} = \omega_3 \, \dot{m}_a$ & $\dot{m}_{v4} = \omega_4 \, \dot{m}_a$.

So, from this equations when you simplify we can find out the amount of makeup water required at state 5, $\dot{m}_5 = \dot{m}_{v4} - \dot{m}_{v3} = \dot{m}_a \left(\omega_4 - \omega_3\right)$. Now, similar way we can do the energy balances $\dot{m}_1 h_{f1} + \left(\dot{m}_a h_{a3} + \dot{m}_{v3} h_{g3}\right) + \dot{m}_5 h_{f5} - \dot{m}_2 h_{f2} - \left(\dot{m}_a h_{a4} + \dot{m}_{v4} h_{g4}\right) = 0$. Energy balance at state is water that is in the liquid state. So, h_{f1} is the enthalpy of liquid water at state 1.

And the second part is air, it has two components, it is $\dot{m}_a h_{a3} + \dot{m}_{v3} h_{g3}$. So, it is in the vapour state. So, state 5 and 2 is again in the liquid state and state 4 is air plus water vapour. So, it is $\dot{m}_a h_{a4} + \dot{m}_{v4} h_{g4}$.

Now we have, $\dot{m}_1 = \dot{m}_2, \dot{m}_5 = \dot{m}_a \left(\omega_4 - \omega_3\right), \dot{m}_{v3} = \omega_3 \, \dot{m}_a$ & $\dot{m}_{v4} = \omega_4 \, \dot{m}_a$. So, after putting this, energy balance equations can be solved for m dot a. So, this equation can now be solved for m dot a. Now, if you look at this $\dot{m}_a$ that is nothing, but the mass that enters into the cooling tower.

$$\dot{m}_a = \frac{\dot{m}_1 \left(h_{f1} - h_{f2}\right)}{\left(h_{a4} - h_{a3}\right) + \left(\omega_4 h_{g4} - \omega_3 h_{g3}\right) - \left(\omega_4 - \omega_3\right) h_{f5}}$$

$\dot{m}_1$ is water that enters the tower. So, you can find a ratio that is $\dot{m}_a$ by $\dot{m}_1$. So, this is nothing but the ratios in terms of their enthalpies. So, this is a simple expression we can have mass flow rate of air required for the cooling tower. Another equation that we have to use that how much mass of makeup water is require for the tower.

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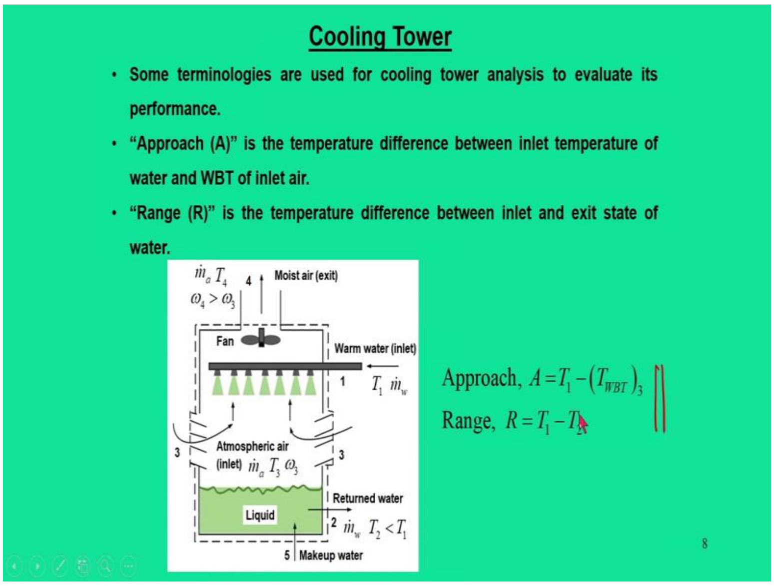

We also use some terminologies in the cooling tower for the design perspective point of view, one is approach that this approach is nothing but the temperature difference between inlet temperature of water in this case is nothing but T_1 and WBT of inlet air at state 3.

The other parameter of interest is the range, this range is the temperature difference between the inlet and exit state of water. Range is nothing but with respect to water and approach is nothing but the inlet temperature of water and wet bulb temperature of inlet air. So, these two expressions are very vital.

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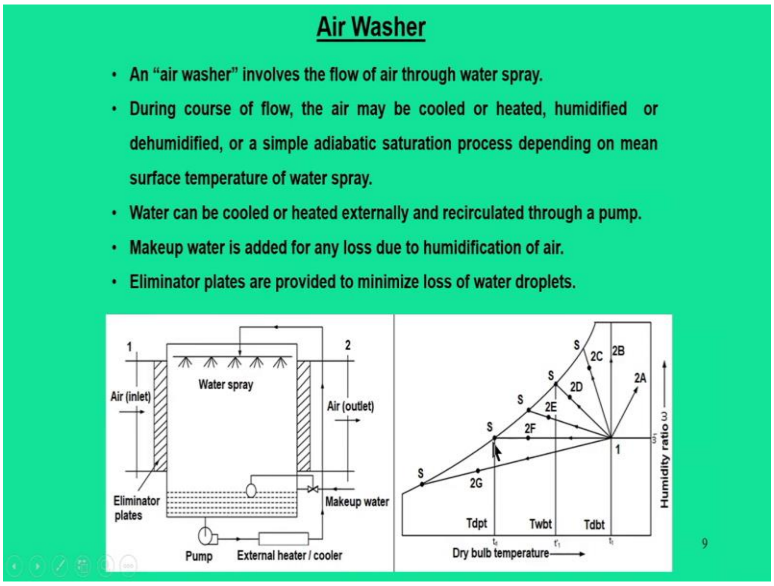

Next important aspect, we are going to deal with the air washers. So, air washer in a Layman sense means we are washing the air for a conditioning process. So, to get this conditioning processes, while washing we can have the state of air at different positions in a psychrometric chart.

So, based on that we can say what is the actual air conditioning processes that happens. And in fact, this air washer philosophy concept in thermodynamics sense will let you know that this concept can be used throughout the air conditioning applications.

So, although it is just a concept, but we can schematically represent in this fashion. So, air washer involves the flow of air through water spray. So, during the course of the flow, what may happen? That air maybe cooled or heated humidified or dehumidified or simply adiabatic saturation depending on the mean surface temperature of the water spray.

So, in our last lecture we talked so many processes like humidification, dehumidifications, heating, cooling, adiabatic saturations, evaporative cooling, mixing. So, all these processes are possible, now we will try to locate these thermodynamic states in a psychrometric chart and if it is possible to locate then such a process can exist. Now if it exist, practically how you can achieve this?

So, that is the concept of air washer. So, if it is a feasible process in a psychrometric chart, I mean how we can achieve this. So, this is how it is represented conceptually by this process. So, a similar concept as like cooling tower, but it is presented in a different context. So, we have a container and in the bottom of the container we have some water. And this water is pumped and there is a external heater or cooler.

That means this is a arrangement where we can have heating process as well as cooling processes, water can be pumped and when it is pumped, on the top we can spray the water. Means we can enter water, we can make a tiny droplets and try to spray. And through this process we have also a passage in which air can come in. That means, air may enter at state 1 and it goes at a state 2.

So, from 1 to 2, many thermodynamic processes possible. So, air can be only humidified that means, there is no change in temperature, air can be dehumidified. That means, we can regulate the spray so that we can take out the water vapours or that means, exit state of water will have less humidity less than inlet state.

The other possibilities air can be heated. So, there is a provision of heating and air can be cooled, there is a provision of cooling. So, all these processes are possible and we have also the provision that water can be cooled or heated externally and there is a recirculated pump. That means, it can be also circulated in the circuit and the eliminators plates are provided to minimize the loss of water droplets.

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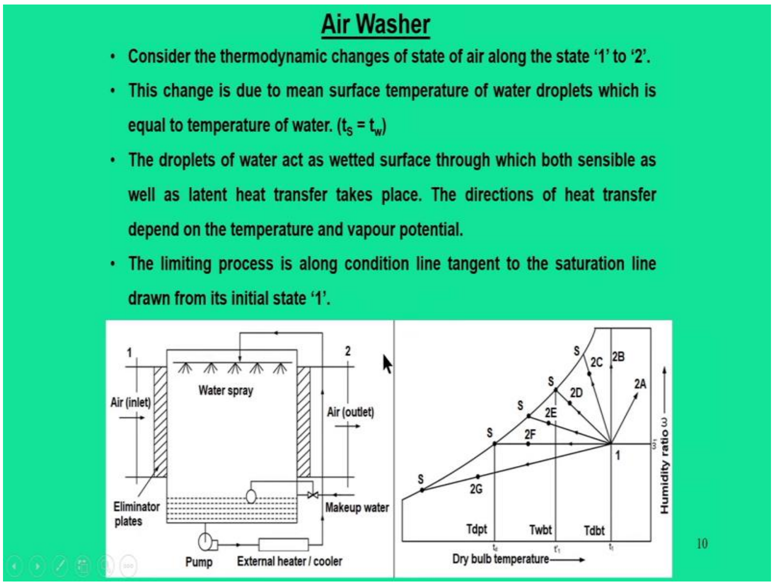

Now, here we are trying to analyze that how you are going to model our the conditioning air. So, consider a thermodynamic changes of state of air when it goes from the state 1 to 2. This change is due to mean surface temperature of water droplets which is equal to temperature of water. So, here you are assuming that surface temperature of water droplets is equal to the water temperatures which exist at that state.

And the droplets of water acts as a wetted surface. That means they act as wetted surface through which both sensible and latent heat transfer can take place and the direction of heat transfer depends on the temperature and their vapour potential, whether they have ability to transmit water vapours or they have ability not to transmit the water vapour.

So, under those conditions, it depends the direction of heat transfer, but there is a limiting processes and of course, when you talk about the ability of transferring these things. Then in such cases those processes can be designated in a psychrometric charts.

But the limiting process is that along the condition line tangent to the saturation line drawn from its initial state. So, if you draw a line tangent to the saturation line and from its initial state that is the limiting processes we can. That means, we cannot go beyond this saturation line, because that is the limiting case for a psychrometric chart drawn at the atmospheric conditions.

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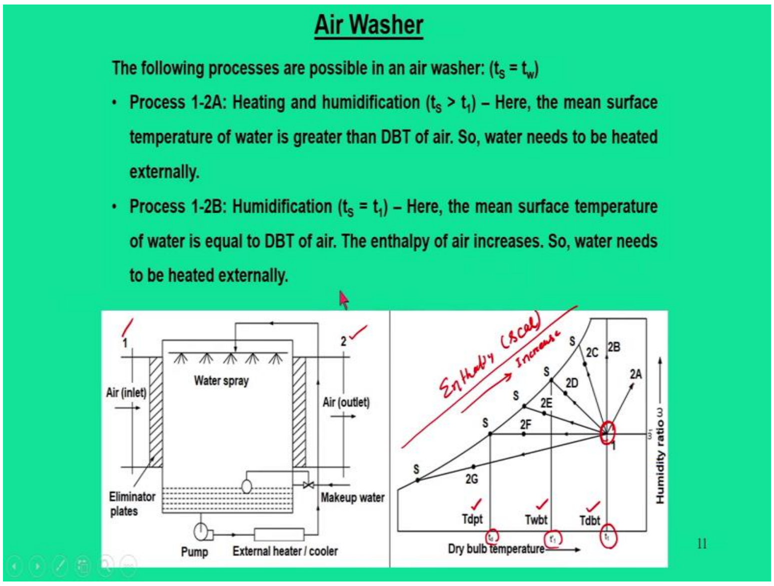

Now, let us say that we are at state 1 which is denoted in the psychrometric chart. And state 2 can be any other location on the psychrometric chart and that is designated as 2.

Now, here I have noted at A, B, C, D that means, state 2 are different locations in the psychrometric chart and that is represented here. So, if I say a process 1 to 2A, through this process humidity increases and the temperature also increases.

So, the process is called heating and humidifications and in this process the water surface temperature is greater than t_1 and here also there are 3 temperatures, t_1 is nothing but dry bulb temperature, $t`_1$ that is nothing but wet bulb temperature, t_d is nothing but dpt.

So, these 3 temperatures we will be frequently using. So, in a heating and humidification process t_s is greater than t_1, but physically the mean surface temperature of water is greater than the dry bulb temperature of the air.

So, water needs to be heated externally. Now, to achieve this process, this water when circulated from the pump has to be heated through this external heater. That means, if you want to achieve this process, we have to heat this air. If you talk about the process 1-2B, that means, we are going in a constant dbt line upwards and in this process dry bulb temperature does not change, but humidity increases.

So, it is a process of humidifications where $t_s = t_1$, t_1 is nothing but dry bulb temperature; the mean surface temperature of water is equal to dry bulb temperature of air. So, through this process, enthalpy of air increases. So, this is enthalpy axis in the psychrometric chart and in this case it is increase in the enthalpy. So, in the process 1-2B, the mean surface temperature of water is equal to dry bulb temperature of air, enthalpy of air increases. So, water needs to be heated externally.

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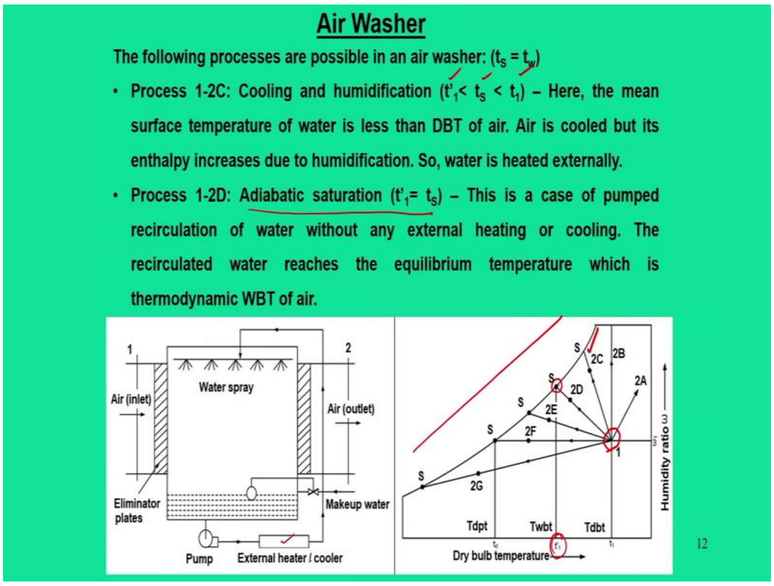

Now, moving to process 1 to 2C, here we can see the temperature drops but air is getting humidified. So, it is a cooling and humidification. So, wet bulb temperature $t`_1 <. t_s < t_1$.

So, the mean surface temperature of water is less than the dry bulb temperature of air. So, here air is cooled, but its enthalpy increases due to humidification. Of course, here also the enthalpy increases with respect to point 1 that is initial state. So, water is heated externally.

Now, moving to process 1 to 2D. So, it is a situation where we are going along a adiabatic saturation process. So, this adiabatic saturation process means we are going along a constant enthalpy line. So, we reach this point S and we reach wet bulb temperature for that air at state 1.

But our process terminates at 2D. So, for process 1 to 2D, $t`_1 =. t_s$ and this is a case of pumped water recirculation without any external heating or cooling. So, the external heater or cooler has no role when you are going in the process 1 to 2D. The recirculated water reaches the equilibrium temperature which is the thermodynamic wet bulb temperature of air.

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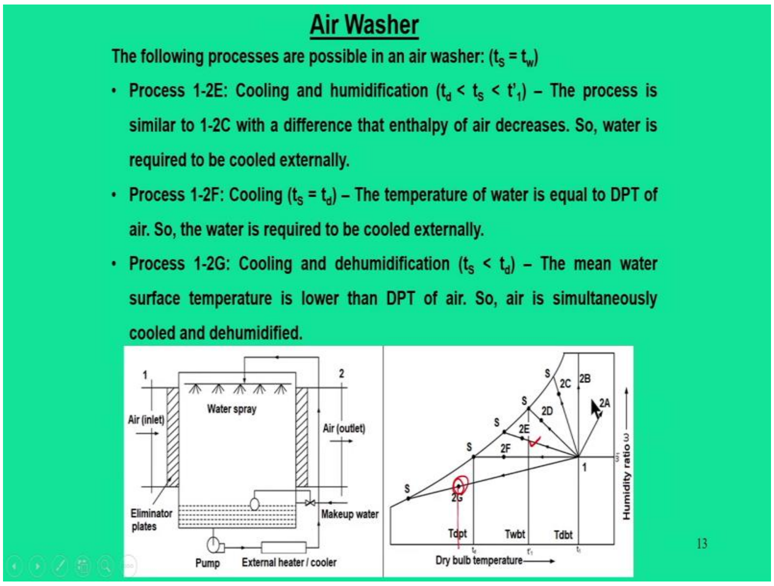

Then we have other two processes that is 1 to 2E. So, it is a cooling and humidification process, temperature drops and humidity ratio increases. So, here the process is similar to 1-2C, but with a difference that enthalpy of air decreases and water is required to be cooled externally.

Now, moving further when you are moving along a process 1 to 2F, that means, we are moving along constant humidity ratio line. So, in that way we reached $t_s = t_d$ that means, temperature of water is equal to dew point temperature of air. So, the air is required to be cooled externally.

And the final process is 1 to 2G. So, here it is a cooling and dehumidification process, so $t_s < t_d$. So, here the mean water surface temperature is lower than the dew point temperatures. So, the air is simultaneously cooled and dehumidified.

So, by this cooling dehumidification process, air is simultaneously cooled and dehumidified. That means, here there is no role of external heater or cooler because air is simultaneously cooled and dehumidified. So, these are the possible means of psychrometric processes.

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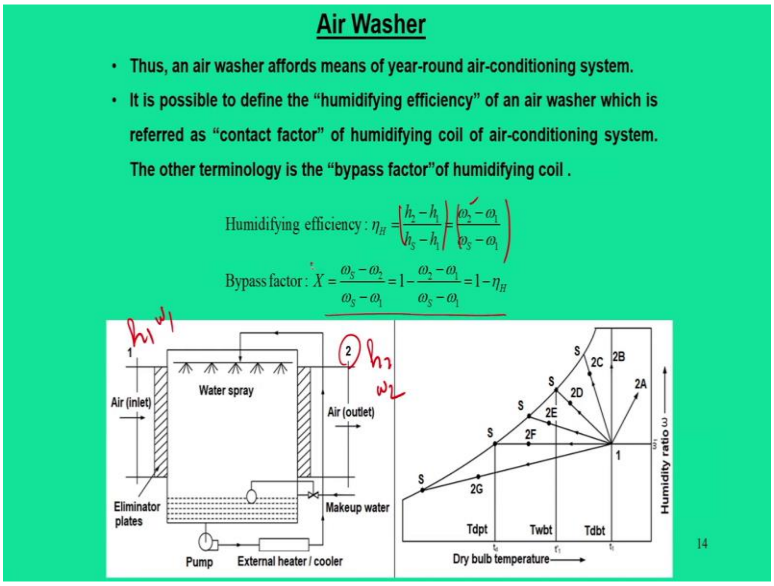

So, any process you choose on this that is 1-2A, 2B, 2C, 2D, 2E, 2F, 2G and if you are able to locate those states and if they are feasible in the psychrometric chart and such a process exist, then we can use it for air conditioning requirement. So, that is the novel innovativeness, through the concept of air washer, we says that air washer provides affordable means of year round air conditioning systems.

So, there is some other term people use here in terms of air conditioning systems, one way is that we talk about humidifying efficiency of an air washer or which is also referred as contact factor of a humidifying coil in a air conditioning systems. We can define this humidifying efficiency η_H is nothing but actual change in the enthalpy divided by the maximum possible enthalpy change. So, other factor would be actual change in the humidity ratio to the maximum possible change in the humidity ratio.

$$\eta_H = \frac{h_2 - h_1}{h_S - h_1} = \frac{\omega_2 - \omega_1}{\omega_S - \omega_1}$$

So, other terminology would be a factor what we call as X, which is nothing but bypass factor. $X = \frac{\omega_S - \omega_2}{\omega_S - \omega_1}$. So, if you arrange this particular fashion then we can say $X = 1 - \eta_H$.

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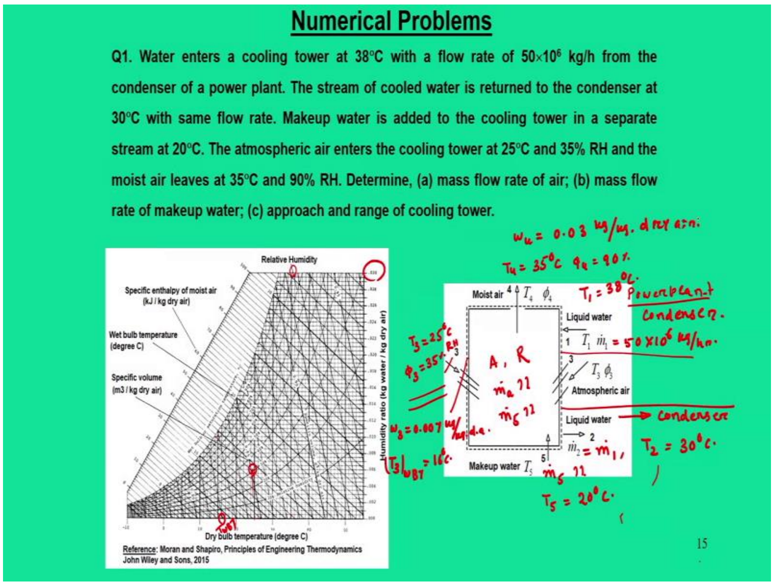

So, with this I conclude this air washer as well as the cooling towers. Now, we will try to solve some numerical problems what we have discussed so far. So, the first problem is based on the cooling tower for which we have already made the modelling and this is the schematic diagram of this cooling tower.

This particular problem is mainly dealt with a realistic power plant with some numbers where water enters a cooling tower at 38°C with a flow rate of 50 x 10^6 kg/hour from a condenser of a power plant.

So, if you look at this schematic figure, this liquid water comes from the condenser for which $\dot{m}_1 = 50\times10^6$ kg/hr; $T_1 = 38°C$. Stream of cooled water is returned to the condenser at 30°C, but with same flow rate.

So, this circulated water again returns to condenser. So, $\dot{m}_2 = \dot{m}_1$ and your temperature requirement has to be 30°C. And makeup water is added to the cooling tower in a separate stream. But it is at temperature T_5 that is 20°C. Now, air comes at state 3.

So, atmospheric air enters at 25°C and ϕ_3 = 35 %. Moist air leaves at condition 4, T_4 is equal to 35°C. So, it is a just 10 degree increase in the temperature and ϕ_4 is 90 %. So, air gets humidified by 90 percent.

So, we have to find out $\dot{m}_a, \dot{m}_5$ and of course, approach A and range R. Now to solve this problem first thing that we need to condition of air at state 3 and 4 for which you have to refer the psychrometric chart and for all liquid conditions we have to refer steam table data.

$$@T_3 = 25°C, \phi_3 = 35\% \Rightarrow \omega_3 = 0.007 \text{kg/kg dry air; DBT=}16°C$$
$$@T_4 = 35°C, \phi_4 = 90\% \Rightarrow \omega_4 = 0.03 \text{kg/kg dry air}$$

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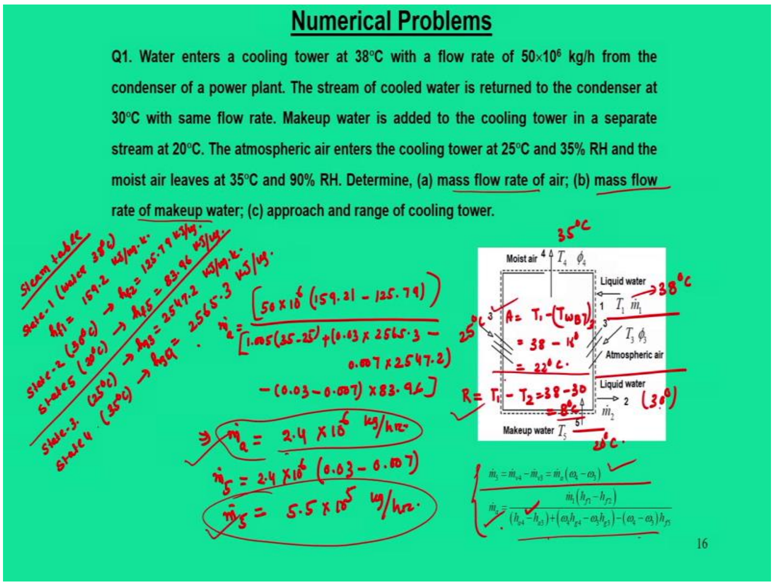

From steam table:

State-1 @Water 38°C: $h_{f1} = 159.2 \text{kJ/kg}$

State-2 @Water 30°C: $h_{f2} = 125.79 \text{kJ/kg}$

State-5 @Water 20°C: $h_{f5} = 83.96 \text{kJ/kg}$

State-3 @ 25°C: $h_{g3} = 2547.2 \text{kJ/kg}$

State-4 @35°C: $h_{g4} = 2565.3 \text{kJ/kg}$

$$\dot{m}_a = \frac{\dot{m}_1 \left(h_{f1} - h_{f2}\right)}{\left(h_{a4} - h_{a3}\right) + \left(\omega_4 h_{g4} - \omega_3 h_{g3}\right) - \left(\omega_4 - \omega_3\right) h_{f5}}$$

$$\dot{m}_a = \frac{50\times 10^6 \left(159.21 - 125.79\right)}{1.005\left(35-25\right) + \left(0.03\times 2565.3 - 0.007\times 2547.2\right) - \left(0.03 - 0.007\right) 83.96} = 2.4\times 10^6 \text{kg/hr}$$

$$\dot{m}_5 = 2.4\times 10^6 \left(0.03 - 0.007\right) = 5.5\times 10^5 \text{kg/hr}$$

$$A = T_1 - T_{WBT}\big|_3 = 38 - 16 = 22°C$$

$$R = T_1 - T_2 = 38 - 30 = 8°C$$

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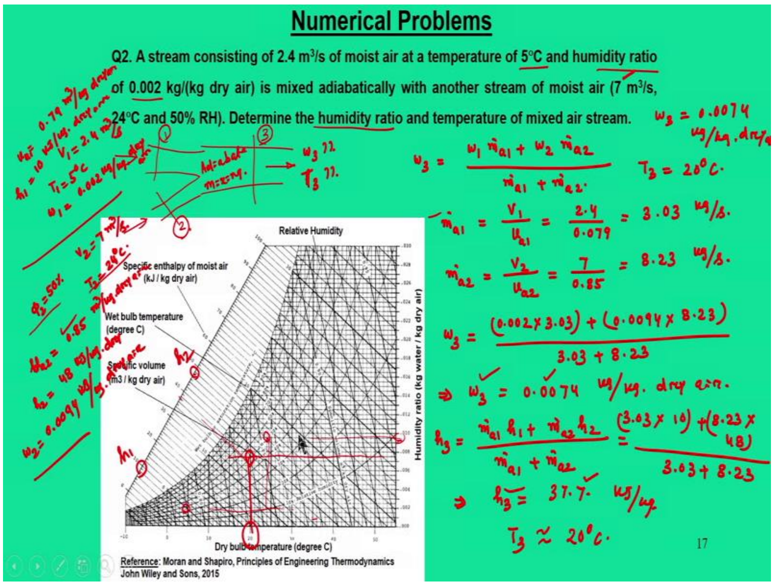

And there is another problem probably this problem which you would have solved in the last lecture. So, this was a problem in which there is adiabatic mixing of two streams. So, you have state 3, state 1, state 2; two streams at state 1 and 2 mix then goes as state 3, so this mixing we call as adiabatic mixing. So, the formulation of this problem which we have already done in our last lectures, but due to the limitation of time I could not solve a problem. So, here we will just try to see if this problem can be solved.

So, here the problem is that are two streams one is coming at 2.4 m^3/s, other is coming at 7 m^3/s. So, we can say V_1 is 2.4 m^3/s and V_2 is 7 m^3/s and the stream 1 has temperature 5°C, humidity ratio 0.002 kg per kg dry air.

And stream 2 has 24°C that is T_2 as 24°C, we have ϕ_2 is 50 percent and we require ω3 and T_3.

$$@T_1 = 5°C, \omega_1 = 0.002 \Rightarrow v_{a1} = 0.79\text{m}^3\text{/kg dry air; } h_1 = 10\text{kJ/kg dry air}$$

$$@T_1 = 24°C, \phi_2 = 50\% \Rightarrow v_{a2} = 0.85\text{m}^3\text{/kg dry air; } h_2 = 48\text{kJ/kg dry air}$$

$$\dot{m}_{a1} = \frac{V_1}{v_{a1}} = \frac{2.4}{0.79} = 3.03\text{kg/s; } \dot{m}_{a2} = \frac{V_2}{v_{a2}} = \frac{7}{0.85} = 8.23\text{kg/s}$$

$$\omega_3 = \frac{\omega_1 \dot{m}_{a1} + \omega_2 \dot{m}_{a2}}{\dot{m}_{a1} + \dot{m}_{a2}} = \frac{(0.002 \times 3.03) + (0.0094 \times 8.23)}{3.03 + 8.23} = 0.0074\text{kg/kg dry air}$$

$$h_3 = \frac{h_1 \dot{m}_{a1} + h_2 \dot{m}_{a2}}{\dot{m}_{a1} + \dot{m}_{a2}} = \frac{(10 \times 3.03) + (48 \times 8.23)}{3.03 + 8.23} = 37.7\text{kJ/kg}$$

So, from the intersection point of ω_3 and h_3, we can drop a vertical, we get T_3 as 20°C.

So, this psychrometric chart helps to locate the moist air states and we can calculate all the properties of moist air stream using this psychrometric chart. So, with this I conclude this particular lecture today that is cooling water and air washer and side by side we also completed module number 5 that is refrigeration and air conditioning.

Thank you for your attention.