POWER PLANT SYSTEM ENGINEERING

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Module 2

Lec 18: Cooling Towers

Dear learners greetings from IIT, Guwahati. We are in the MOOCs course Power Plant System Engineering, module number 2, Vapour Power System part 3. So, this is the last lecture of this module, in which we will be concentrating on one of the important component of the steam power systems that is cooling towers. So, before we start discussion on cooling towers, we will try to see basic background regarding various aspects of the power systems. First thing is the requirement of circulating water system. So, here we will try to see that the main job of this cooling tower is to cater the needs of water requirement at various locations of the steam power system.

So, that is the reason, we call this as a circulating water systems. So, there are different classifications to it. We will try to discuss them like once through mode, closed mode and combination mode. Then we will try to see the basic concept of the circulating water systems that is from the beginning when we start the concept of how to circulate the water at different components of the steam power system.

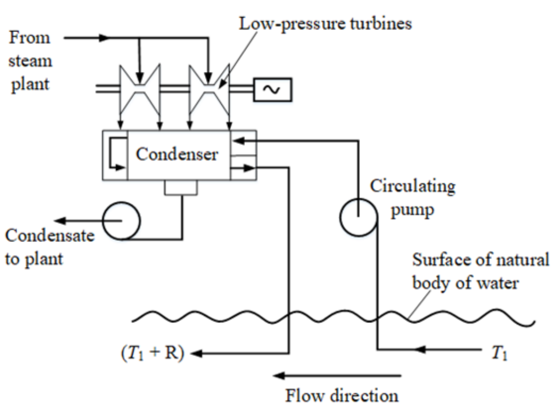
Then people started with various ideas such as cooling legs, cooling ponds, dry cooling towers. So, these were the initial concepts for circulating water systems, but over the period of time, the modern power systems use wet cooling towers. So, wet cooling towers takes the advantage of air plus water. So, main aspects of this cooling tower is to take out heat during the condensation process. So, in the wet cooling tower, we use combination of air and water and take the advantage of temperatures for water as well as air with the psychrometric concepts. And under this heading we will have mechanical and natural draft type. So, basic difference between these two is that in mechanical type, we use different types of draft fans like forced draft fan, induced draft fan where you take the advantage of height of the cooling tower or design the cooling tower for a large height to take the advantage of density difference of air and that makes the circulation of air possible for a given location and requirement. And one of the most important aspects of this wet cooling tower is basically the mass and energy balance equation that needs to be solved, but for that things we require the psychrometric terminology and we will try to see that how that psychrometric terminology will help us in doing the various calculations for a wet cooling tower. This is the overall view of this cooling tower section. Now, let us briefly talk about the need of the circulating systems.

The first and foremost concept if you recall our Carnot cycle and basic Rankine cycle which means that for a given power output from the turbine, we require heat addition in the boiler, we also require some pump work and finally, heat is rejected in the condenser. Now, heat rejection is a must because based on the Carnot cycle concepts, when you say this is a heat engine, which operates in a cycle and this heat engine cycle is nothing, but this particular thermal circuit of the steam power systems and in which one of the way of heat rejection is the heat rejection in the condenser. Now, where does this rejected heat go? It goes out to this cooling water. So, one of the important concept is that for certain work output from the turbine, we must reject heat to the surrounding and here the surrounding can either be air or the water which circulates in the condenser. So, this is the basic need of the circulating water systems and mainly for the condenser unit.

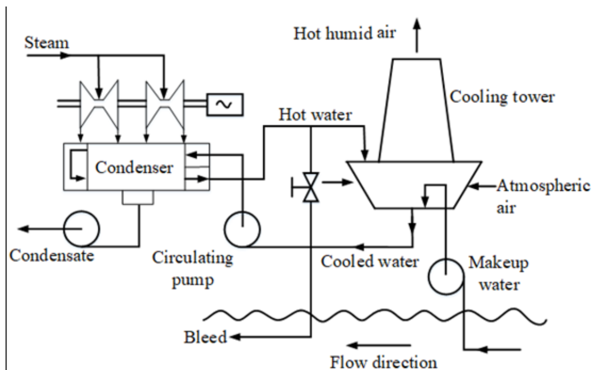
Now, let us try to understand more basics of the Carnot cycle. So, if we just make some estimate considering these parameters like the heat rejection from the Carnot cycle is $\dot{Q}_r$, heat addition rate is $\dot{Q}_a$ and work output is $\dot{W}$ with a cycle efficiency, η. Then for every case let us say, we are trying to get 100MW of power with various efficiencies of the Carnot cycle. So, one thing you can notice here is that by using this calculations with certain efficiency for a given work output, if we can make a correlations of how much heat we are rejecting to the surroundings or heat rejection rate, then you can say for 100 MW, we have to reject about 400MW for small old industrial unit. For fossil power units, we must reject 300MW and for nuclear power plant it is less, but whatever may be the case we can see that heat rejection is a must requirement of the Carnot cycle. But the extent of heat rejection depends on the nature of power plant that we study.

Another important aspect is that we can say there is an improvement of 7% efficiency that is from 0.25 to 0.33 which results 33% savings in heat rejection and again our improvement of efficiency from 0.33 to 0.4 results in 25% savings of heat rejection.

So, the bottom line is that we must reject heat and heat rejection quantity is about 4 times of the work output from the plant at the same time. This means, the requirement of cooling water is almost used may be close to 4 times the amount of power which is going to be delivered from the plant unit. So, for this huge requirement, we must have a proper circulating water system. Normally, this circulating water system is considered in variety of ways. The circulating water system is based on three concepts- once through mode, closed systems and combination systems.



Once-through circulating-water system



Closed mode circulating water system with wet cooling tower

Let us try to understand what is this once through mode circulating water systems. So, if you see this figure, we can see the condenser in which exhaust from the plant comes from the turbine. So, this heat must be rejected to the cooling fluid. Now, here the cooling fluid can be the circulating water and this circulating water can come from natural body of water, it may be a lake, it may be a pond, it may be a river. So, you can have a circulating pump that can enter and this condensate again can be discharged back to this same river or same water bodies, but at a higher temperature. So, initial temperature is T_1, but the final temperature is $T_1 + R$ with some addition of heat and again the condensate goes back.

Here what we see is that the heated water goes out again to the same water body. Many a times it poses ecological damage of this water system of the river. So, that is the reason, this particular method is not generally employed. So, we move on to closed mode. So, the closed mode means that you use a separate unit called as cooling tower, which does all kinds of water treatment before it discharges to the water bodies. So, the closed mode of circulating water system means first you take the water and send it to the cooling tower, treat it, then send it to the condenser, again from the condenser you take back the hot water, again treat it and finally, discharge it to the water bodies. So, that way entire treatment is normally done in this cooling tower only, so that the ecological system of river is not affected.

So, when you take the once through systems, the discharge system can be lake, river or ocean and this discharge can be a surface discharge, submerged discharge or diffuser type of discharge, but there are various advantage and disadvantage of each method. But most effective way is the diffuser discharge system, in which we can get the water out in a controlled manner through the nozzles operated in a long pipe, so that ecological aspects of water bodies remains unaffected. Again in the closed loop mode, the essential requirement is this cooling tower, which we will discuss more in details in the subsequent part. But here, apart from this cooling tower options the earlier option for heat disposal system could be a spray pond or spray canals. So, there are other substitutes of cooling devices.

Now, combination systems either operates in once through mode or it can be operated through a closed mode. So, the combination system operates in a both modes like once through mode and a closed mode. We have extra device here that is a valve and that valve operates in such a way that if the water has to be discharged directly to the water bodies then this valve becomes operational, so we run the system in a once through mode. If you want the water to be treated then the valve has to be operated that means, entire water that comes out from the condenser goes directly to the cooling tower. After treatment it again gets discharged.

So, basically speaking that in both the cases if your initial temperature T_1 which it takes from the water and when you do it in a once through mode the final temperature will be $T_1 + R$, but when you do this combination mode the final temperature will be $T_1 + TTD$ and this TTD is the terminal temperature difference which is nothing, but the temperature at the exit of the cooling tower and the source temperature. So, TTD is a very vital term that is difference between the exit temperature of the tower and the source temperature at which it enters. And there is another term which is called as range. Range is defined as the temperature rise across this condenser. So, we will discuss more details when you come back later in our analysis of wet cooling tower.

Now, let me give you some basic background on earlier systems. When there was no concept of wet cooling tower, then people started using the concept of cooling legs, which is the oldest and, but simplest type of techniques for artificially rejection of heat from the steam power unit. So, what we normally do is that we can prepare an artificially made lake that means, you can prepare an area into which we dispose the water and in the lake we allow maximum residence time for this water so, that it cools down naturally. So, while cooling naturally, it can cool by evaporation or convection by wind or thermal radiation to the sky. So, through these means the water gets cooled and, but the net effect of the cooling is lake is not constant because over the lake area there could be variation of large water temperature differences and climatic conditions. So, ultimately for this kind of modeling, we come across expression which normally gives equilibrium temperature of one cooling lake. With dependence from our heat transfer analysis, we can do it and that talks about this particular exponential expressions.

Expression for equilibrium tempertaure, $\frac{T_c - T_e}{T_h - T_e} = e^{-\frac{UA}{\dot{m}c}}$;

Heat dissipation rate, $\dot{Q}_r = \dot{m}c(T_h - T_c)$

T_e:Equilibrium temperature; T_c&T_h:Temperature of cold and hot water, respectively

c:Specific heat of water; $\dot{m}$:Mass flow rate of water; A:Lake surface area.

U:Overall heat transfer coefficient $\left(= 62.4\dfrac{\text{W}}{\text{m}^2.^0\text{C}}\right)$; $\dfrac{UA}{\dot{m}c}$:Non-dimensional parameter$(= 1.173)$

And we have one more term which is called overall heat transfer coefficient and of course, we have another non dimensional parameter that is $UA/_{\dot{m}c}$ which is mostly most frequently used in the heat exchangers for heat transfer analysis. So, this is what we say as equilibrium temperature expressions for a cooling lake and once you have this, we can also find out what is the heat dissipation rate.

The other concept is like a spray canals which is also similar to the water cooling tower concept. In this the water is sprayed into air above this surface and the flow pattern is such that it goes in a channel. Through this process, heat transfer takes place again due to evaporations, conduction of air, partial radiations.

But another parameter that gets popped into here is the weather conditions. Since air comes into picture here, air dry bulb temperature (DBT) and wet bulb temperature (WBT) are also needed to be considered. So, here we also use a similar governing equation and the notations are given.

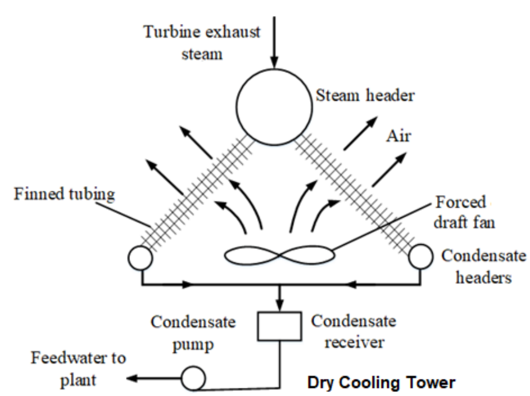
Simplified governing equation, $\dfrac{T_c - T_{WBT}}{T_h - T_{WBT}} = \exp\left(-\dfrac{N[1-f]r[NTU]b}{c}\right)$

T_{WBT}:Wet bulb temperature of atmospheric air

T_c&T_h:Temperature of cold and hot water, respectively

c:Specific heat of water;N:Number of nozzles

b:Rate of change of enthalpy with temperature



Dry Cooling Tower

f:Allowance for correction of local WBT with elevation

r:Ratio of nozzle flow rate to recirculation water flow rate

However, this is just an introduction of this, but now in all modern steam power systems, we normally do not use this old concept of spray canals or artificial pond. So, we normally choose direct method of using the circulating water system through cooling towers.

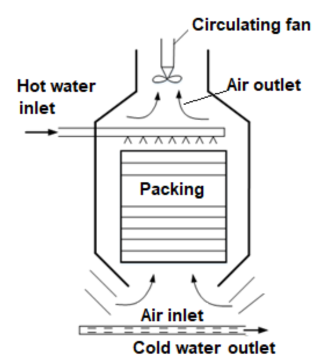
So, when you say cooling tower, there are two types, one is dry cooling tower & other is wet cooling tower. So, the first one is the dry cooling tower, in this schematic figure we can say that, the air and water do not mix with each other rather the circulating water is passed through the finned tubes, in which cooling air is passed. So, heat rejection from the cooling water is in the form of sensible heat to the cooling air. Since we do not look into the concept of water vapor so, wet bulb temperature of air does not apply here. The term that is most important here is initial temperature difference (ITD).

$ITD = T_f - T_a$; Economicalrange,10^0Cto16^0C

T_f:Temperature of fluid entering the tower

T_a:Temperature of outside air

The next method is the wet cooling tower. In fact, wet cooling tower is a widely used methods and in this wet cooling tower the heat rejection or heat dissipation process has following mechanisms.



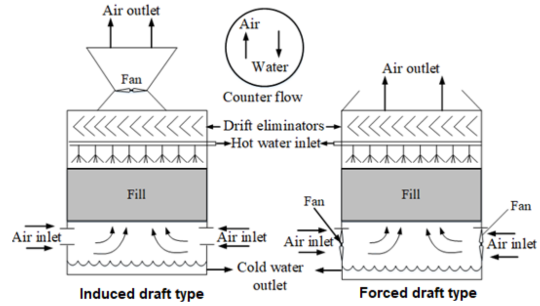
1. First is addition of sensible heat to the air that means, air temperature increases when it takes the heat from the exhaust of the turbine.
2. Then we take the advantage of evaporation of portion of heat to the circulating water itself.
3. Then addition of sensible heat to the natural water bodies that means, we take the advantage of water bodies as well as increasing the temperatures.

So, for a wet cooling tower concept, if you look at the figure here, the hot water inlet which normally comes from the exhaust from the turbine, are sprayed. Now, when they are sprayed, they are passed through a packing or fills. That means, it is just a kind of an arrangement, where the entire slug of water gets splitted through series of nozzles and they are allowed to spray through the packing or fill. And from the bottom air gets sucked through this packing. Thereby when air gets in contact with this hot water, it absorbs heat that means, its temperature also increases. So, water vapor concentration in this air keeps on increasing until it gets saturated. Once it is saturated, it cannot absorb further mixture, but when air goes up again, it comes in contacts with water & its temperature goes up. Thereby keeps on soaking the water vapors from the hot water. So, through this process at the end of this outlet, we get the air which is almost heated and saturated that means, air does not have any more tendency to absorb any moisture from this water. So, through this concept, we take the advantage of increasing the temperature of air at the same time the water vapor concentration in the air is also increased.

So, thereby air has two temperatures right now. At the starting point it has a dry bulb temperature and it has certain wet bulb temperature, but finally, air is completely saturated that means, both dry bulb and wet bulb temperature of the air becomes equal. So, through this process we take the advantage of air plus water vapor in which we take the advantage of heat rejection process from this hot water unit.

Now, considering whatever I have explained, we have to look into the upper limit of this air outlet. And this upper limit of air outlet is nothing, but the saturated air. Saturated air means air does not have any capability to absorb any more water vapors. So, evaporation of the cooling is stopped and such a things where we have saturated water and that temperature we call this as an adiabatic saturation temperature or wet bulb temperature of the ambient air.

So, this is the concept of the wet cooling tower system. Now, these wet cooling tower system is classified by two ways one is a mechanical draft or



Mechanical draught cooling towers

draught type and other can be a natural draft or draught type. And when they operate in either form, they can be a counter flow type or a cross flow type.

Now, let us understand these mechanical draught type cooling towers. So, here if you look at these figure, mechanical means we are artificially allowing the air to enter into the tower. So, there are two possibilities of air entry. Normally air enters from the bottom as shown in this figure. So, either it can be a forced draft type or induced draft type. So, in a forced draft type, we introduce a fan which is at the entry of the air in the tower. So, thereby we are forcing the air to enter into this tower. And at the outlet the hot air goes on its own because it is already hot air and its density is less so, it goes naturally. But the main disadvantage in this process is that, there is a tendency of this fan to introduce a back pressure and due to this back pressure the air distribution issues in the film arises. There is possibility of leakages and recirculation of air back to the tower. That means, after recirculation, if sufficient pressure is not maintained, air again try to reverse back towards this main inlet.

So, that is the main disadvantage of a forced draft type cooling tower, but other options to remove these ambiguities is to consider this fan at the exit level. So, at the outlet level you use a fan and that fan is nothing, but induced draft type. So, basically you suck the air whatever is coming and create a pressure difference in between that means, the pressure difference is felt in the entire tower and by virtue of this pressure the air gets sucked in from the bottom and there is hot air goes out at the outlet. And through this process there is other advantage that happens is that mixing of water with air is very much possible in this field or packing. This is the most important advantage for an induced draft type tower. Second advantage is that the issue of back pressure does not arise. So, because of these advantages, most of the wet cooling towers are normally induced draft type and of course, it is a mechanical draft type cooling tower. But main advantage is low capital cost, construction cost, small physical structures & of course, assured supply of quantity of air at all loads and all climatic conditions.

The other way or other concept of wet cooling tower is to consider a natural draft type. So, basically the issue of fan is either induced draft or forced draft does not apply here.

Here you take the advantage of the driving pressure as a density difference.

So, in other words, you use the concept of rising a height of tower that means, you increase the height of the tower in a manner so that in a tall tower we can get the advantage of density difference of atmospheric air and the hot humid air inside this cooling tower.

So the Driving pressure for natural draft cooling towers, $\Delta p_d = (\rho_o - \rho_i)gH$

g:Acceleration due to gravity

ρ_o& ρ_i:Densities of outside & inside air H:Height of the cooling tower above the fill

So, essentially the height H is nothing, but height which is just above this field. So, of course, this is the empty space, but this empty space is required to maintain this density difference. In that way we take the advantage of the atmospheric air and air inside this cooling tower to create this density difference.

In fact, this natural draft type cooling towers has huge structures and the tower body above this water distribution systems is an empty shell of circular cross sections, but with hyperbolic vertical profile. And this structure is mostly preferred and they are made out of reinforced concrete and because it gives superior strength, greater resistance to the wind loading at as compared to any other configurations. And moreover if you want to see the difference between the mechanical draft and natural draft cooling tower, the essence of using a natural draft cooling tower is that they are suited for cool and humid climates for which we have low WBT that means, low wet bulb temperature and high relative humidity. When we have advantage of having low WBT and high condenser water inlet and outlet temperatures, when there is a heavy winter loads that means, in a winter environment or in the cooling areas, where we have this kind of climatic conditions, then the choice of natural cooling tower is taken into account. But for other places mostly mechanical draft type and that uses induced draft fan are mostly preferred.

Another approach of designing for wet cooling towers is to take into consideration of the parameters called as approach and range. For example, mechanical draft cooling towers use low approach and broad range of water flow whereas, natural draft types are preferred for long approach and broad range of water flow.

Now, till this point of time we have seen all types of cooling towers, but most preferred cooling towers is wet cooling towers and here we will try to understand how the heat is taken by the circulating water system as well as from the air. So, for that viewpoint we require the knowledge of psychrometrics and we will try to understand how the psychrometric analysis or terminologies help us in framing the governing equations.

Essentially the wet cooling tower calculations involve mass and energy balance based on the steady flow and steady state equations. And there are three fluids which are involved here, one is cooling water, second is dry air and third is water vapours associated with this dry air. In addition to this, there is also a term humidity which plays very important role and other assumption is that water vapours in the air is always at a very low pressure. So, we treat them as a gas mixture. So, instead of water vapour we use it as an ideal gas mixtures in which we can use this ideal gas model for this analysis of water vapours.

So, there is a term which is called saturated air. Saturated air is a condition of air in which the air cannot accept any more water vapours at a given temperature. So, this can be obtained from the steam table. That means, we all know that for every saturation temperature, there is a saturation pressure and vice versa. Any drop in temperature in the saturated air will lead to condensation. So, a newer cooling air would also be saturated. An increase in the temperature of the saturated air would make it unsaturated that means, it can accept more water vapours. Once it condenses, it cannot accept any more water vapour that means, I have to add new air into it. But any increase in the temperature of the saturated air will make it unsaturated. So, that way we can accept more water vapours. So, that is the controlling parameter that we can have in this wet cooling tower concept. So, we take the advantage of this and do our analysis. And all our conditions are given below, based on which the psychrometric calculations are normally done.

For saturated air at 15^0C & $p = 1.01325$bar

Partial pressure of water vapour, $p_v = p_s = 0.01765$bar

Partial pressure of dry air, $p_a = 0.9956$bar

At that temperature, from the steam table we will find the partial pressure of water vapours and also the partial pressure of dry air which is the difference between these two.

There is another term, called as relative humidity. So, relative humidity is equal to the ratio of partial pressure of water vapour in the air to the partial pressure of water vapour that would saturate the air at that same temperature. So, this is a non-dimensional term. Then we have absolute humidity, humidity ratio or specific humidity, they are all same term and it is the ratio of mass of the water vapour in the air to the mass of the dry air. So, the saturation pressure increases rapidly with temperature at all vapour pressure. So, the warm air can hold more moisture than the cool air. That means, when the temperature increases, it can hold more moisture.

The other term is called as degree of saturation. So, it is the ratio of actual specific humidity to the saturated specific humidity. So, again it is a non-dimensional term. Now, for air, we have three temperatures one is called as dry bulb temperatures (DBT), other is wet bulb temperature (WBT), third is dew point temperature(DPT). So, if you recall this temperature entropy diagram property table for water at any locations, if you locate the state, the corresponding temperature you call that as a dry bulb temperatures.

Now, what you do? You try to measure the temperature of air by putting this bulb of this thermometer keeping it wet. So, that way the temperature recorded by the thermometer would be less than this dry bulb temperature. So, we are going along a particular constant pressure line and we are reaching one location which will be at WBT temperatures. Now, by putting this dry bulb temperature if you keep on cooling the air and we will reach at the saturation curve and that point the air is no longer able to accept any more moisture. That means, air is going to condense. So, water vapour in the air is going to condense. So, we call this temperature as dew point temperature of air. So, psychrometric term has three temperature dry bulb temperature, wet bulb temperature and dew point temperature. So, this is what we have explained here.

Main important aspect in this cooling tower analysis is the wet bulb temperature. If the air is relatively dry, water would evaporate from the gauge at a rapid rate resulting the cooling of the bulb. So, we record this as a wet bulb temperature. If the air is humid, evaporation rate will be slow. So, that means, wet bulb temperature approaches to dry bulb temperature. We also call this wet bulb temperature as adiabatic saturation temperature. Then dew point temperature means the point at which the water vapour in the air begins to condense. So, it is the equilibrium or saturation temperature corresponding to that partial pressures. And for a saturated air, all the temperatures that means DBT, WBT and DPT are equal.

So, whatever you have discussed so far a complete analysis of psychrometric terminology we can define by these expressions. So, here relative humidity ratio of partial pressure of water vapour to the saturated pressure, then specific humidity which is mass of the water vapour to the mass of dry air.

Relative humidity, $\phi = \frac{p_v}{p_s}$; Specific humidity, $\omega = \frac{m_v}{m_a}$

And considering this ideal gas assumptions for water vapours, we can write down this gas equations for water vapours and for dry air separately. So, based on this we can get the expression for specific humidity in terms of pressure of water vapours to the pressure of dry air. Then we can obtain the expression of degree of saturation that is $\left(\frac{\omega}{\omega_{\max}}\right)$ and this $\omega_{\max}$ is obtained by putting p_v in place of p_s in the expression for maximum specific humidity.

Maximum specific humidity at $T = T_s, \omega \frac{m_s}{m_a}\left(\frac{p_s}{p - p_s}\right)_{\max}$

With ideal gas assumption, $p_v V = m_v R_v T \& p_a V = m_a R_a T$

$$\Rightarrow \omega = \frac{m_v}{m_a} = \frac{p_v R_a}{p_a R_v} = \frac{p_v\left(\frac{\bar{R}}{M_a}\right)}{(p - p_v)\left(\frac{\bar{R}}{M_v}\right)} = 0.622\left(\frac{p_v}{p - p_v}\right)$$

Degree of saturation, $\mu = \left(\frac{\omega}{\omega_{\text{max}}}\right) = \left(\frac{p_v}{p_s}\right)\left(\frac{p - p_s}{p - p_v}\right)$

Water vapours :Pressure(p_v),Mass(m_v),Saturation pressure(p_s)

Gas constant, $R_v = \frac{\bar{R}}{M_v}$; Molecular weight,$M_v = 18$

Dry air:Pressure(p_a),Mass(m_a),Gasconstant, $R_a = \frac{\bar{R}}{M_a}$; $M_a = 28.96$

Universal gas constant, $\bar{R} = 8.314 \frac{\text{kJ}}{\text{Kmol.K}}$

Arbitrary condition :pressure (p),temperature(T),volume(V)

Now, with the psychrometric terms, we are now able to analyze the concept of psychrometric analysis. So, here there are three fluids one is cooling water, dry air and water vapours in the dry air. So, you take a model which we call as a steady state steady flow model for a cooling tower in which there is a hot water entry and cold water out again cold air entry and hot air out.

And when you say air it has two parts one is dry air part for which enthalpy is h_{a1} and the enthalpy for water vapour is represented as h_{g1} corresponding its ω_1. Similarly for hot air out we have h_{a2}, ω_2 and h_{g2} .So, we take the advantage of the difference in the specific humidity of air which absorbs more and more moisture as it passes within this tower.

So, now, you can frame the complete equations for the energy balance for a cooling tower with this concept.

Energy balance, $\left(h_{a1}+\omega_1 h_{v1}\right)+W_A h_{wA}=\left(h_{a2}+\omega_2 h_{v2}\right)+W_B h_{wB}$

Approximation for enthalpy difference for dry air

$h_{a2}-h_{a1}=c_p\left(T_2-T_1\right)$

Use steam tables at respective temperature, $h_v=h_g$ & $h_w=h_f$

Mass balance per unit mass of dry air, $\omega_2-\omega_1=W_A-W_B$

$\Rightarrow \omega_1 h_{g1}+W_A h_{fA}=c_p\left(T_2-T_1\right)+\omega_2 h_{g2}+\left[W_A-\left(\omega_2-\omega_1\right)\right]h_{fB}$

Driving pressure for a natural draft cooling tower

$\Delta p_d=\left(\rho_o-\rho_i\right)g\,H$

Outside & inside air density,

$\rho_o=\dfrac{p-p_{v1}}{R_a T_1}+\dfrac{p_{v1}}{R_v T_1};\ \rho_i=\dfrac{p-p_{v2}}{R_a T_2}+\dfrac{p_{v2}}{R_v T_2}$

h_a & h_v: Enthalpy of dry air and water vapours, respectively

R_a & R_v: Gas constants dry air and water vapours, respectively

h_w :Enthalpy of circulating water; ω: Absolute humidity

W : Mass of the circulating water

H :Height of the tower above the fill

Subscripts 1 & 2 refer air inlet & exit

Subscripts A & B refer circulating water inlet & exit

So, energy balance at the inlet we can have $h_{a1}+\omega_1 h_{v1}$ and for water inlet we have $W_A h_{wA}$. So, W stands for mass of the circulating water per unit mass of dry air. And then again on the outlet side we have air outlet and water outlet. And of course, here $h_w$stands for water because there is hot water and cold water, and their temperatures are different. Then at 2, air is almost saturated. So, considering this most of this data a given problem can be obtained from the steam table and using this equations.

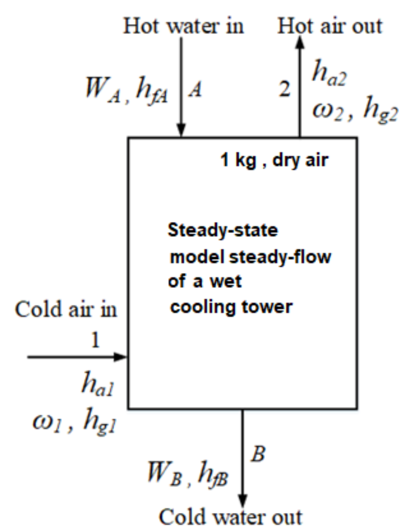
The approximation for dry air analysis is the enthalpy difference for air which have a dry part other part is water vapour.

Now, difference between h_{a1}& h_{a2} is associated with this difference that is $C_p(T_2-T_1)$. So, once you know this inlet and exit condition of air we can find the enthalpy difference for air. So, air and water vapours has to be treated differently. Of course, the mass balance equations it is nothing, but dry air mass remains unchanged. The difference between the specific humidity will give you the water vapour that gets added into this air. So, this is about the final equations for energy in this form which is nothing, but your working equation for solving the problem. So, you must remember this.

Another part of this cooling tower design that we also expect a pressure difference. So, the pressure difference normally is achieved from the outside air whose density is ρ_0 and from the inside air whose density is ρ_i. And this ρ_0 and ρ_i has two components one is for dry air other is for vapour. So, it is treated differently, both the density calculation is treated differentially. First part consist of calculation for air dry & second part for water vapours. That means, this is for outside air, similar way we can have the density difference for the inside air and this entire analysis will give you the density difference that occurs between the outside air and the inside air. And this density difference with this height will give you the driving pressure for a natural draught type cooling tower.

So, this is all about the entire analysis for draft cooling towers. So, with this analysis let me frame this particular problem with some numerical data. So, whatever analysis we have done so far, we are now going to use for this numerical problems with appropriate data for a specific case which is a natural draught type cooling tower.

Q1. A natural-draft cooling tower with a range of 11°C receives 360000 gal/min of circulating water at 32°C. The outside air is at 15°C, 1.01325 bar and 50% relative humidity. The exit condition of air is saturated at 27°C. Calculate, (a) the amount of makeup water to compensate for evaporation; (b) volume flow rate of outside air; (c) height of the cooling tower for a pressure losses of 72.5 N/m^2



So, the problem statement is as this. You recall our schematic model in which we have hot water in, cold water out, cold air in, hot air out. So, from this figure and data, let's write down different conditions.

So, let us see the case of the hot air in.

$\dot{W}_A = 360000 \text{ gallons/ min} = 22714 \text{ kg/min}$

$T_A = 32°C$

So, at this temp conditions, from the steam table we can find out $h_{fA} = 134.14$ kJ/kg

Then for hot water out, we have $\dot{W}_B$ which is the amount of water vapour which gets absorbed per kg of dry air.

$W_B = [W_A - (\omega_2 - \omega_1)];$

Temperature at the outlet, $T_B = 21°C$, as Range $= T_A - T_B = 11°C$; $h_{fB} = 88.14$ kJ/kg

So, this is for water part. Now, let us consider outside air part.

Temperature, $T_1 = 15°C$; Pressure, $p_1 = 1.01325$ bar ; Relative humidity, $\phi = 50\%$

From Steam table, Saturated pressure, $p_{s1} = 0.01705$ bar

We know, $\phi = \dfrac{p_{v1}}{p_{s1}} = 50\%$; Then at this temperature, $p_{v1} = 0.008525$ bar

Then further information we can calculate

$$\omega_1 = \frac{0.622\, p_{v1}}{p - p_{v1}} = 0.005277 \text{ kg / kg dry air}$$

From Steam table, using vapor condition at $T_1 = 15°C$; $h_{g1} = 2258.9$ kJ/kg

$h_{a1} = C_p T_1$

In similar way hot air out is exit condition of air is saturated.

$T_2 = 27°C$; $p_{s2} = 0.03567$ bar ; $\omega_2 = 0.02268$ kg / kg dry air; $p = 1.01325$ bar

Total pressure remains same.

Using Steam table, corresponding to $T_2 = 27°C$; $h_{g2} = 2550.8$ kJ/kg

$h_{a2} = C_p T_2$

So, at all locations we have all the data. Then we can use our working equation.

$$\omega_1 h_{g1} + W_A h_{fA} = C_p(T_2 - T_1) + \omega_2 h_{g2} + [W_A - (\omega_2 - \omega_1)]h_{fB}$$

$$\Rightarrow (0.005277 \times 2258.9) + W_A(134.14)$$

$$= 1.005(27 - 15) + (0.02268) \times (2550.8) + [W_A - (0.02268 - 0.005277)] \times 88.14$$

$$\Rightarrow W_A = 1.23 \text{ kg by kg dry air}$$

But our question is to find out the makeup water. So, from this we can find out what is the amount of dry air requirement, $\dot{m}_a$.

$$\dot{m}_a = \frac{\dot{W}_A}{W_A} = \frac{22712.4}{1.23} = 18465\frac{\text{kg}}{\text{s}} \approx 1.1 \times 10^6 \text{kg/s}$$

a) So, first part of the question

$$\dot{m}_{mak} = \dot{m}_a(\omega_2 - \omega_1) = 1.1 \times 10^6 \times (0.02268 - 0.005277) = 19143.3 \text{ kg/min}$$

b) Then we have this second part is the volume of the flow rate of outside air.

$$\text{Outside density}, \rho_o = \frac{p - p_{v1}}{R_a T_1} + \frac{p_{v1}}{R_v T_1}$$

$$\text{Inside density}, \rho_i = \frac{p - p_{v2}}{R_a T_2} + \frac{p_{v2}}{R_v T_2}$$

$$R_a = \frac{8314}{28.96} = 287\frac{\text{J}}{\text{kg.K}}; \;\; R_v = \frac{8314}{18} = 517.4\frac{\text{J}}{\text{kg.K}}$$

Now with all the data we can get $\rho_o = 1.22 \text{ kg/m}^3$; $\rho_i = 1.203 \text{ kg/m}^3$

Then volume flow rate outside air requirement would be

$$\dot{m}_{out} = \dot{m}_a(1 + \omega_1) = (1.1 \times 10^6) \times (1 + 0.005277) = 1.105 \times 10^6 \text{kg/min}$$

$$\text{Then volume flow rate}, \dot{V}_o = \frac{\dot{m}_{out}}{\rho_o} = 0.9 \times 10^6 \text{ m}^3/\text{min}$$

The second part analysis is done for the volume flow rate of outside air.

c) For third part, height of the cooling tower for a pressure losses of 72.5 N/m^2

$$\Delta p_d = (\rho_o - \rho_i) g\ H$$

$$\Delta p_d = 72.5 \frac{\text{N}}{\text{m}^2};\ \ g = 9.81 \frac{\text{m}}{\text{s}^2};\ \rho_o = 1.22\ \text{kg/m}^3;\ \ \rho_i = 1.203\ \text{kg/m}^3$$

$$\Rightarrow H = 435\ \text{m}$$

So, for a natural draught cooling tower with this data, we require a cooling tower having height of 435 meter for continuous operation of air to maintain this density difference. So, it is a huge structure normally done in the reinforced concrete. So, this is all about the numerical problem associated with this wet cooling tower. So, with this I conclude this lecture and with this the module 2 is closed. Thank you for your attention.