POWER PLANT SYSTEM ENGINEERING

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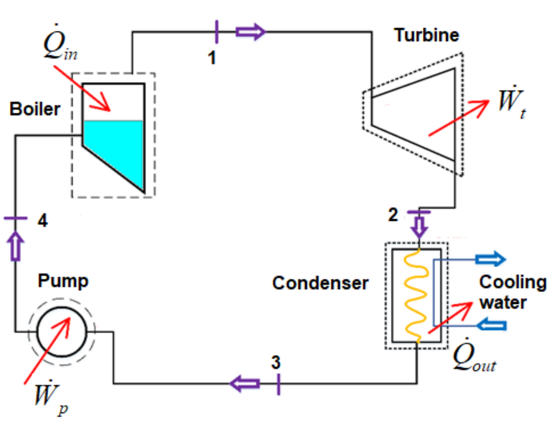
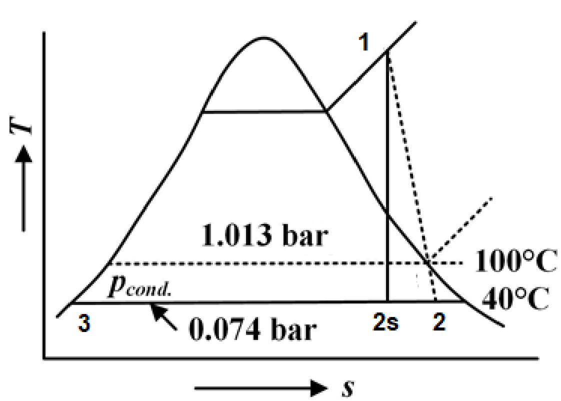
Module 2

Lec 16: Steam Condenser

Dear learners, greetings from IIT, Guwahati. We are in the MOOCs course Power Plant System Engineering, module number 2 that is Vapor Power System part 3. In today's lecture, our main focus would be on steam condenser. So, the under this heading, we will try to discuss the following components that is condensate- feed power systems. Then we will talk about two types of condenser- one is direct contact type and other is the surface condensers. So, both the condensers will be discussed exhaustively in this lecture.

But before you enter into those condenser details, let us try to understand the first basic need what we call as a condensate and feed water systems. So, look at this particular diagram or thermal circuit which consists of boiler, turbine, condenser and pump. In fact, this thermal circuit we discussed in one of the earlier lectures that is beginning of module 2. So, on for this thermal circuit, our main target is that we are going into details of this condenser unit.





So, why do you require this condenser units? That is mainly because if you recall this T-s diagram that is temperature entropy diagram based on Rankine cycle of steam power systems, what we see is that the turbine inlet condition is at state 1 and the steam expands in the turbine and finally, it comes to the state 2. So, after the expansion of the steam in the turbine it reaches to the state 2. Now, while reaching its state 2, the steam condition is either in a superheated regions or in the liquid vapor region. But this steam has to release the heat in a unit, what is called as condensers. Now, another essential requirement is that more and more you can expand in the turbine, then the output from the turbine will be higher and that is possible, if we operate the condenser at lowest possible pressure. So, this means that during the expansion process from 1-2, one can stop this expansion process at any intermediate points on this diagram, but the lowest possible point will yield maximum turbine output. In other words, if a condenser is operated at the lower pressure, then work output or enthalpy difference that is between h_1 and h_2 will be increasing. So, that is the reason, we require this condenser to operate at very low pressures.

Second requirement of the condenser in the steam power plant is that the output from the condenser is again fed to the pump and it gives necessary feed water to the boiler. So, that is the reason we also require a feed pump that takes the water from this outlet of the condenser or you call this as condensate and then it gives water to the pump for a higher pressure, the pressure in the water reaches to the boiler pressure.

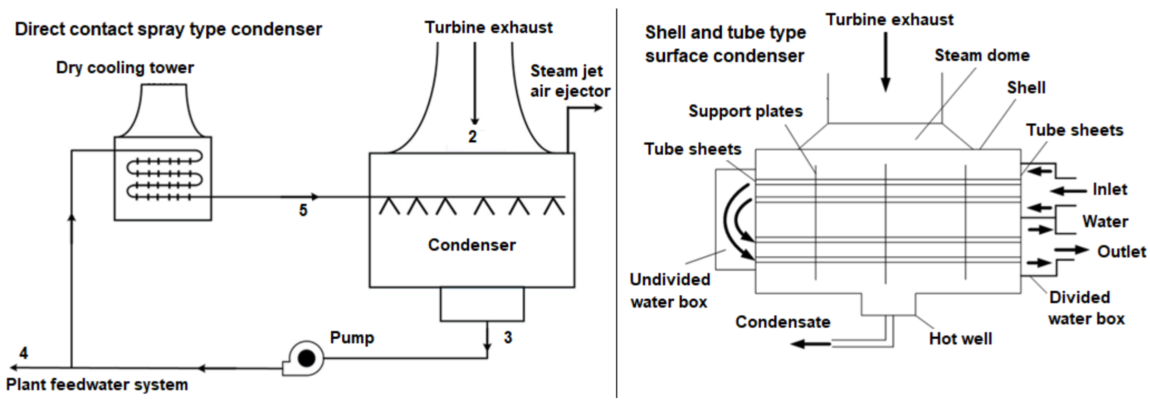
So, this is the main requirement. This outlet from the condenser is usually called as condensate. But feed water is another term. This condenser has to also supply required amount of feed water to the pump. So, that is how two things are coupled together when dealing with the condensers. However, we are going to treat them separately. So, in this lecture we will mainly focus on the primary part that is condensers. In the subsequent lecture we will talk about feed water systems. Because the feed water can come from variety of ends, it can come from the turbine end or one can get from the condenser end. That part will be discussed in the separate lecture. But our main role in this lecture is that we are going to deal with the important component that is condenser. Its main role is to condensate the exhaust from the turbine to recover high quality of feed water for reuse in the cycle. As you can see at state 3, the condensate or the high quality feed water gets circulated in the cycle.

The most important part is that turbine work is higher when the condenser is operated at lower pressure. And mostly we say that if you can operate the condenser pressure mostly in the vacuum, then we can maximize the enthalpy output. So, some of the additional requirement for the condenser is that by lowering the back pressure in the condenser by few units, it gives additional advantage of increasing work output from the turbine, improved plant efficiency and of course, reduction of the steam flow. And thermodynamically it is also important to use the lowest cooling-water that is available for use.

For example, to get this heat out from the turbine exhaust we require the cooling-water to get circulated in the condenser. So, in other word, it means that when you take this inlet temperature of the cooling-water, it should be at par with the water availability at that location, where the condenser is installed. The main purpose of feed water is to improve this cycle efficiency by heating the condensate to 200 to 250℃. So, in the later point of these things, we will see that when you take out the condensate that mean we do not really bring back to atmospheric temperature rather that condensate we try to leave them at around 200 to 250 ℃. So, that at the entry to the boiler, the boiler load will come down. If you allow the condensate or feed water at this 200 to 250℃ and then supply water before returning to the steam generator.

Then these feed water systems are mainly of two types, one is direct close type and open type, which we will talk later in the next lecture. But our main target is a very basic point that we have to look into the steam condenser unit and this steam condenser unit should operate much below the atmospheric pressure. For example, normally the saturation pressure at 40℃ , we is called as condenser pressure and that is typically 0.074 bar. So, this is the standard way, how all the steam turbine operate. And one must understand that the atmospheric pressure is much above this condenser pressure. So, this is the reason why we say that always vacuum condition is maintained in the condenser.

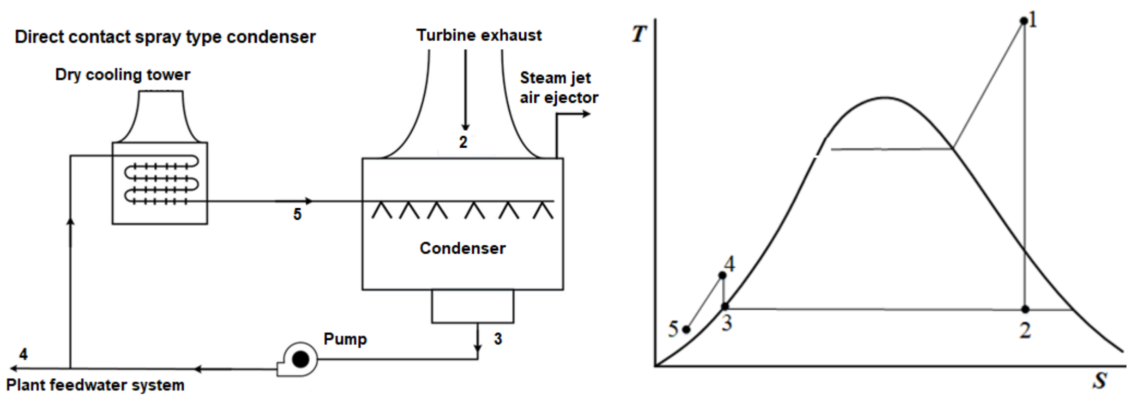
Then let us see the types of condenser. There are essentially there are two types of condenser, one is direct contact type other is surface condenser. In the direct condenser type, both the cooling-water and the condensate are allowed to mix whereas, in a surface condenser these two fluids are treated as two different entities. For example, normally the exhaust from the turbine is either superheated steam or it is liquid vapor region or mix region steam with desirable quality about 80-90%. So, in a direct condenser, we do not restrict the mixing of steam. It means that if you look at this figure the exhaust from the turbine is at state 2 and the circulating water that enters to the condenser is at state 5 and both are allowed to mix in the condenser and the mixture leaves at state 3.



So, this is what we call as a direct contact type condenser. That means, two fluids that enters into the condenser, they mix and the resultant stream comes out as a condensate. Whereas, a surface condenser type which is normally used in most of the modern power plant, uses a shell and tube type heat exchanger. You can see a turbine exhaust in picture. So, the turbine exhaust is in the steam dome which is in this location and this normally enters to the shell side that means, this dome is connected to the shell and entire shell is occupied with this turbine exhaust. But we do not allow the circulating water to mix with the steam. So, in that case, what should we do that is we have some inlet water temperature segment in which the water enters and then it continuously move in this condenser multiple times as a single pass, two pass, three pass or any number of passes. So, that the entire heat which is available at the exhaust of the steam from the turbine gets trapped by this circulating water. That means, at the end our outlet temperature of the circulate reaches to a maximum value. So, that is the reason we ensure that the water passes through multiple tube sheets and we call them as a two pass, three pass, four pass like that. So, in that sense, there is maximum utilization of heat when steam releases heat to the cooling water.

So, the surface condenser are essentially the shell and tube type of heat exchanger in which the primary heat transfer mechanisms are condensing the saturated steam outside the tubes and the forced convection heating of the circulating water inside the tubes. So, the majority of the power plant use the surface condenser because effectiveness of heat transfer becomes higher.

Now, let us try to understand about these steam condensers separately. So, first let us start with a direct contact type steam condenser. In one of the variant the direct contact type condenser is called as a spray condenser.



So, the spray condenser uses a dry cooling tower, which is not nothing, but a water reservoir that stores water at normal room temperature or atmospheric temperature and it supplies the water to the condenser unit. Now, during this supply, water is sprayed inside the condenser from the top and at the same time we also allow the turbine exhaust to pass through this medium and through this process we have steam and water and the mixing of both steam and water takes place. At the end of these things, most of the steam that releases the heat to this water and the resultant part which is collected at state 3 and called as condensate and then it is fed to the feed pump. Now, here at point 3 there are two components, one goes at state 4 and other again return back to the cooling tower at state 5. So, as you can see here after the turbine exhaust, we are now at point state point 2, the thermodynamic state where the quality of the steam is around 85- 90%.

So, process 2- 3 happens in a condenser. So, through this process of heat release, the vapor becomes liquid at that saturated pressure and temperature and we reach at the state 3 that is condensate which is collected from the outlet of the condenser unit. Now, at 3, water has to be pumped into this. So, basically from state 3, one part goes to state 4, other part can leave at state 5. State 5 means there is further lower temperature, because 2-3 happens at 40℃ and state 5 is normally close to water temperature, which is available for use in the cooling tower around 15 - 20℃. So, state 5 is at further lower temperature.

And that same water again enters into the condensing unit. Now, here most important thing we need to find out is the mass flow of water requirement for a given quantity of steam. And that is called as ratio of circulating water to the steam flow rate. From this we can frame mass balance equation and energy balance equation for this spray type condensers. Here we can see that $\dot{m}_2$ which is the exhaust from the turbine is equal to $\dot{m}_4$ which normally leaves.

Mass balance of the system: $\dot{m}_2 = \dot{m}_4; \dot{m}_3 = \dot{m}_2 + \dot{m}_5$

Energy balance of the system: $\dot{m}_2 h_2 + \dot{m}_5 h_5 = \dot{m}_3 h_3$

Ratio of circulating cooling water to stream flow: $\frac{\dot{m}_5}{\dot{m}_2} = \frac{h_2 - h_3}{h_3 - h_5}$

Now, from these two equations we can find a ratio that is the ratio of circulating water circulating cooling water to the steam flow, which means that for a given unit of steam flow what is the requirement of cooling water. And this is the most vital part and it decides the load of the condensers. And based on that load of the condenser all other parameters like how many number of tubes, what is the number of pass required, how many passes we need to do, then further what outer diameter and inner diameter of the tube; all the things can be designed.

The next important part or segment for direct contact condenser is a barometric condensers. So, normally, if you look at the previous spray type condenser, they use pump. Now, in order to replace this pump, initially people have thought of putting a tailpipe of certain height and this tailpipe tries to replace the requirement for the pump.

So, necessary pressure difference is achieved by using a tail pipe and this tailpipe height is sufficiently high. And we take the advantage of barometric height which is 'h' to take care about the pressure difference.

Presure differential in tail pipe $\rho g H = (p_{atm} - p_{cond}) + \Delta p_f$

Frictional pressure drop: $\Delta p_f = f\left(\frac{H}{D}\right)\left(\frac{\rho V^2}{2}\right)$

ρ:Density of mixture; g:Acceleration due to gravity

H:Height of tail pipe; D:Diameter of tail pipe

V:Velocity of flow in tail pipe**;** f:Friction factor

This pressure differential is nothing, but the difference between atmospheric pressure and condenser pressure, further it has to also take care of the frictional pressure drop in this pipe. And that frictional pressure drop is related to the friction factor, height and diameter of the pipe, velocity of the flow in the pipe. So, when we know all these things, we can calculate the pressure differential based on this height.

This is one part, second thing is that here this cooling tower arrangement is like baffles that means, there are multiple number of baffles, so the water continuously gets in contact with the exhaust of the turbine. Another important aspect of this thing is non-condensable. For example, water, which gets condensed goes out of this through the tailpipe and whatever non-condensable remains, they have to be taken back through a steam jet air ejector system. So, this is what we call as unwanted parts as far as the condenser requirement is concerned. And the role of the tailpipe of this mixture is to compress the mixture to atmospheric pressure in the hot well by virtue of static head and thus replacing the need of the pump. This is one aspect what we call as barometric condenser and here also both exhaust from the turbine and the cooling water, they are allowed to mix.

Now, another design of this barometric condenser is referred because many a times we also require very long tail pipe because the pipe is of constant length and diameter. So, that variations can be regulated by keeping a diffuser type design in the tailpipe. So, essentially the tailpipe is replaced with a diffuser type design that involves a throat which is the minimum area section and side by side this geometry of the shape is a kind of a diffuser where the water gets through this process where we get desired pressure difference across this diffuser. So, here also the cooling water and turbine exhaust, they are allowed to mix in a cascade arrangement so that proper mixing is possible.

So, we require various cascades to enhance the heat transfer from the turbine exhaust to the cooling water. So, here also there are provisions that we must use the steam jet air ejector to remove the unwanted non-condensable gases. Now, if you just compare both barometric and jet type condensers, they have almost similar designs, but very basic difference is that, the tailpipe requirement of barometric condenser is close or less than 10 meters. So, that length gets reduced if you go for a jet type of condenser.

Now, we will move on to next type of condenser which is called as surface condenser. So, I mentioned earlier the surface condensers are shell and tube type heat exchangers, in which the primary heat transfer mechanisms are condensing the saturated steam on the outside of the tubes and force convection heating of the circulated water inside the tube. Here we see that there is a shell, the shell means it contains the steam dome and in the entire unit we have steam, but the water enters into the condenser through multiple tube sheets and through this process the heat transfer takes place. So, steam gets condensed and the condensate is collected in the hot well, which is below the shell. So, in this process we get much more or enhanced heat transfer or the mechanism of giving high quality circulating water to the boiler. So, that is the advantage of surface condenser.

So, there are some standard information for steam condensers that is when the steam condensates its volume decreases. So, that means, we have very few tubes, smaller passes to drain the water into the hot well. And this hot well acts as a reservoir that receives the condensate, with a capacity equal to the total condensate flow at a particular time. For this surface condensers, normally copper tubes of diameter 1-3m is used and their length is typically 25m. These dimensions are preferred for a large scale power plant. Number of passes determines the size and effectiveness of condenser. So, which means that enhanced heat transfer is possible, if you allow this steam to move inside the condenser in multiple times and that what we call as a pass.

So, for a given water velocity, you can try to link the pressure drop. That means, for a given flow rate of inlet velocity of water, let us say it is 2m/s and if you go for two pass type system that means, you allow the water to circulate two times then we have a larger pressure drop. So, that means, for two pass systems we have a larger pressure drop. Second thing is that when you increase the number of passes we will land of having higher pressure drop. Higher pressure drop means more effectiveness of the condenser and through this process the condenser size also will gets reduced. In other words, it means single pass condenser will have a larger size than that of a two pass condenser. A single pass condenser with same number of tube and size with same water velocity requires twice the water flow than the two pass condenser. So, it reduces half of the temperature rise and it has lower condenser pressure. So, that is the reasons in many cases most power plant prefer single pass condenser when the requirement of thermal pollution is essential. But in terms of water requirement and pumping requirement, we generally prefer two pass condensers because the single pass condensers involves higher cost. So, a balanced approach in number of passes essentially decides the size and cost of the condenser.

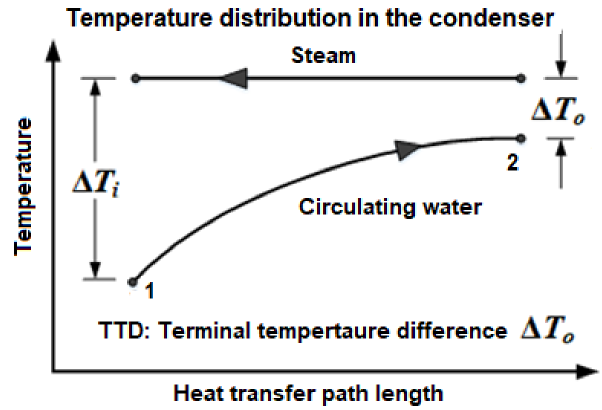
Another important aspect of this surface condenser, we are now going to see, which is called as Deaerator. It means that in a steam and vapor fire power cycle, it is important to remove non-condensable gases that gets accumulated in the systems. We have been emphasizing the fact that there are non-condensable gases, which are non-avoidable at the turbine exhaust. So, those non-condensable gases has to be relieved or released. And what are these non-condensable gases? Firstly these are nothing, but mostly air that leaks from the atmosphere at various portion of the cycle. Secondly, there could be decomposition of water to hydrogen and oxygen, which are mostly predominant in the nuclear power plants. So, these things has to be removed in the condenser. They have to be removed because the presence of those gases adds partial pressure.

And through this, when they have their own partial pressures that way the total pressure of the system increases. This is the first demerit of these non-condensable gases. Second demerit is that the blanket of heat transfer surfaces means, these non-condensable gases creates a kind of insulation blanket on the heat transfer surfaces and thereby the overall condensing heat transfer coefficients decreases. So, that is the reasons these non-condensable gases has to be removed. Another thing is that if there is chemical presence in the non-condensable gases, then they can add to corrosion.

For example, presence of oxygen adds corrosion to heat transfer surfaces. When there is a corrosion, the overall heat transfer coefficient drops. Then the performance of the condenser will also drop down. So, most of the fossil fuel power plant requires the guaranteed oxygen concentration to be less than 0.005 cm^3/L. So, essentially the role of oxygen in a condenser is very significant because it adds to corrosion, it drops overall heat transfer coefficients passively and they have their own partial pressure. So, to suppress all these things, we require an additional unit that is called Deaerator and that is normally used in the surface condenser.

Then another study that we are going to do because most of the steam power systems they use surface condensers, so we will try to focus our attention on some of the important parameters and mainly we will call this as a heat transfer analysis. And this heat transfer analysis requires the knowledge of the condensation of steam & how it takes place. So, for example, if you see the surface condenser diagram, we have two streams, one is exhaust from the turbine that enters through the steam dome into the shell, other is the cooling water that enters at the inlet and comes from the outlet.

And since the turbine exhaust which is close to the saturated vapor steam and inside the condenser whose role is to condense means, there is no change in the temperature rather there is a release of latent heat of vaporization for the steam. So, the heat of the steam is being taken away by circulating water. So, if you have inlet temperature of water as 1 and as it takes away the heat, its temperature at state 2 increases. So, thermodynamically or you can say through heat transfer if you plot a graph for temperature versus heat transfer path length, either in terms of area or length then we have two temperature differences, one is ΔT_i at the inlet & ΔT_o at the outlet.



So, it is essentially the arrangement of a counter flow in which one fluid is condensing while temperature of other fluid is increasing. So, one temperature is ΔT_i at the inlet & other temperature is ΔT_o at the outlet. And normally this ΔT_o from the condenser view point mainly for surface condenser, is called as terminal temperature difference (TTD). So, this parameter is very vital because it adds to the cost, sizing and performance of the condenser. So, more & more this temperature difference is that means, if you have a very higher temperature at the outlet that means, performance of the condenser is very good. So, that is the reason the terminal temperature difference is kept as low as possible and typical number is close to 3℃ that means, the difference between the steam and the outlet temperature of the circulating water should be in the range of 3℃.

Second important aspect is that, at a given temperature difference at the inlet, larger TTD results in large LMTD and smaller area. There is an increase in the water flow because this water temperature rise is reduced. Smaller TTD will result in larger condenser area with reduced water flow and higher exit temperatures. And because of this larger size, that means, our design is not perfect, so we call this as an oversize condensers and it will invite higher capital cost. So, in the condenser design this TTD is very much vital in designing various components of the condenser.

Now, to design the various component of condensers, there are some standard calculations and that is supported by heat transfer modelling and this standard is proposed by the heat exchange institute standards for steam surface condensers.

Heat load on condenser, $Q = UA(\Delta T_m)$;

Logarithmic mean temperature difference in the condenser, $\Delta T_m = \frac{\Delta T_i - \Delta T_o}{\ln\left(\frac{\Delta T_i}{\Delta T_o}\right)}$

Total outside tube surface area, $A = n\pi d_o l$

$l \& d_o$:Length and outer diameter of the tube; n:Number of tubes

V:Circulating water velocity in the tubes at inlet

ΔT_i:Difference between saturated steam temperature and inlet circulating water$\left(11^0\text{C} \text{to} 17^0\text{C}\right)$

ΔT_o:Difference between saturated steam temperature and outlet circulating water$(\sim 3^0\text{C})$

So, this simplified equation is called as heat load on the condenser. Now, in this equation only U is not known to us.

U:Overall condenser heat transfer coefficient based on outer tube area

Now, this U is a function of various parameters and the proposal given by this heat exchange standard says that overall heat transfer coefficients can depend on various factors. What are the factors?

C_1:Dimensional factor depending upon tube outer diameter
C_2:Dimensionless correction factor for circulating water inlet temperature

C_3:Dimensionless correction factor for tube material and gauge

C_4:Dimensionless cleanliness factor

& this is proportional to the square root of velocity.

$U = C_1 C_2 C_3 C_4 \sqrt{V}$

So, if you are interested to design a steam condenser, then we have to look into all these parameters and then accordingly we can calculate the overall heat transfer coefficients. However, in our course this value will be mostly given for the condenser calculations.

Then moving further, the next part that we require is, how much heat is being carried out by the water. And that is required with the condenser load, Q. We also require the other important parameter like the mass flow rate of the circulating water that is nothing, but the temperature differential that we are supposed to achieve that is $T_2 - T_1$. Another parameter also required here is the pressure drop in the condenser that is Δp

Mass flow rate of circulating water, $\dot{m}_w = \dfrac{Q}{c_p(T_2 - T_1)}$

Pressure drop in the condenser, $\Delta p = \rho g H$

Q: Heat load on the condenser; H:Mano metric head

ρ:Density of water; c_p:Specific heat of water

T_1: Inlet temperature of water $\left(\text{typically,2.1 to 2.5}\,\dfrac{\text{m}}{\text{s}}\right)$

T_2:Exit temperature of water;g:Acceleration due to gravity

So, these two parameters are also very vital in the designing of a surface condenser. Now, finally, this is the overall picture that how surface condenser designs details are taken into account. However, other important aspect which is very vital and we are not following in this lecture is the kind of cooling that happens in the condensers and this is called as a film wise condensation in horizontal tubes. So, we have seen that there are tubes in which the water flows inside. And if you take the cross section of this tube where water gets circulated in the tubes, at any particular instant if you see the water temperature is t_w and there is another dome which is called as saturation temperature of water because outside we have steam and inside we have water, so there is a layer and we call this as a condensate film. And there is a thickness, δ, which engulfs about the diameter of the tube in which water is there. So, this particular concept, we call this as a film wise condensations that is different part altogether, in which also comes the design of steam condensers.

Another kind of knowledge that we require in the design of the condenser is heat transfer mechanisms which means conduction through tube walls, forced convection inside the tube at varying temperatures and then also you need to evaluate heat transfer coefficient as various parts of the condensers that is at shell and tube inner and outer surface. And both of the things will give you the heat load on the condenser and additionally this heat load must be removed by the feed water. And that is the reason condensate and feed water are taken together. And all non-condensable has to be taken out from the condenser unit by a component called as a steam jet air ejector.

So, considering all these things together, we can say that heat transfer mechanisms in a condenser is quite complex, but what we have presented here is a very simple way so that numerical problems can be attempted.

So, with this we conclude. However, before you close this lecture, let us try to understand some of the numerical problems which are part of this lecture.

Q1. A surface condenser receives 240 tonnes/hr of steam at 40°C with 88% quality. The cooling water enters at 32°C and leaves at 38°C. The pressure inside the condenser is 0.078 bar and the velocity of circulating water is 1.6 m/s. The tubes of the condenser have 25 mm outer diameter with thickness 1.25 mm. Determine, (a) the rate of flow of cooling water; (b) the rate of air leakage into the condenser; (c) length and number of tubes. Take overall heat transfer coefficient as, 2560 W/m^2.K.

So, the first problem is on surface condenser, its design and calculations. So, the problem statement goes like this. The surface condenser receives 240 tons of steam at 40℃ with 88% quality. The cooling water enters at 30℃and leaves at 38℃.

The pressure inside the condenser is 0.078 bar, velocity of circulating water is 1.6 m/s. The tubes of the condenser have 25 mm outer diameter and thickness 1.25 mm. We need to find out what is the rate of flow of cooling water, air leakage into the condenser and length and diameter of the tubes.

So, essentially we can draw the schematic, what we have shown earlier is that we have tubes in which water enters and leaves. The tube has outer diameter 25 mm, thickness is 1.25 mm. Now, water inlet temperature is 32℃, outlet temperature is 38℃. Steam enters at 240 tons/ hr. And here quality of the steam is 88% and this condenser pressure is 0.078bar.

Condensation takes place on the surface, overall heat transfer coefficients for this tube is $U_0 = 2560\ \mathrm{W/m^2}$.K. So, this is the problem. So, we need two diagrams, in first diagrams let us see how that expansion process takes place in the turbine and where you stand. So, if you say T-s diagram, there is a dome. So, the state that enters in the condenser at 2 and it leaves at 3 and this temperature is 40℃.

Second part is that we also need to see, how the condensation happens across this heat exchanger length. So, if you say temperature versus path length that is A_0 or l in this direction, then steam condenses in this manner. So, this is a counter flow heat exchanger and cooling water temperature increases. At outlet this is ΔT_oor TTD and at inlet it is ΔT_i . So, from the data that is given we say T_{c1} temperature is 32℃, T_{c2} is 38 ℃ and condensation takes place at 40℃ that is T_{sat}.

So, these three diagrams will give you most of the information. So, having drawn these diagrams, we will be now able to solve this particular problem. So, let us see the given data,

$x_2 = 88\% = 0.88$

We also have data at 40℃, we can calculate the value of h_{fg} using saturated temperature steam table.

At 40°C, (steam table) $h_{fg} = 2407$ kJ/kg

Then we can say the condenser load, $h_2 - h_3 = x_2(h_{fg}) = 2118.2$kJ/kg

Once we know this, then we can perform energy balance for cooling water and steam.

Energy balance, $\dot{m}_s(h_2 - h_3) = \dot{m}_c C_{pw}(T_{c2} - T_{c1})$

So, we have all the data, $T_{c1} = 32$°C ; $T_{c2} = 38$°C ; $C_{pw} = 4.187 \frac{kJ}{kg.K}$; $\dot{m}_s = 240$ ton/hr

$$\dot{m}_s = \frac{240 \times 1000}{3600} = 66.66 \text{ kg/s}$$

So, by inserting these value we get

$$66.66(2118.2) = \dot{m}_c \times 4.187\ (38 - 32)$$

a) ⇒ Rate of mass flow of cooling water, $\dot{m}_c = 5620.5$ kg/s

Now, for the second part rate of air leakage into the condenser. So, if you take this total condenser volume is V and that total volume can be calculated as per below equation.

Total Volume, $V = \dot{m}_s v_2$

Now, here we require specific volume of the steam that is v_2.

$$v_2 = v_f + x_2\, v_{fg}$$

At 40°C, from steam table, $v_2 = 0.001008 \frac{\text{m}^3}{\text{kg}}$; $x_2 = 0.88$; $v_{fg} = 19.544 \frac{\text{m}^3}{\text{kg}}$

So, from this we can calculate, $v_2 = 17.2 \frac{\text{m}^3}{\text{kg}}$; we also have,

$$\dot{m}_s = 66.66 \text{ kg/s}$$

b) Then we can use the ideal gas equation.

$$p_{air}V = \dot{m}_{air}R_{air}T$$

Now, next question is to find out this p_{air} . Now, this condenser operates at total pressure which consists of saturated pressure plus air pressure which is already existing in this condenser.

$p = p_{sat} + p_{air} = 0.078$ bar

p_{sat} $(at\ 40°\text{C}) = 0.07375$ bar

From this we can calculate, $p_{air} = 0.00425 \text{ bar} = 0.425 \text{ kN/m}^2$

Now we have, $R_{air} = 0.287 \frac{\text{kJ}}{\text{kg. K}}$; $T = 40°\text{C} = 313 \text{ K}$; $V = \dot{m_s}\, v_2$

So putting this number in the equation, $p_{air}V = \dot{m_{air}} R_{air} T$

$\Rightarrow 0.425 \times 66.66 \times 17.2 = \dot{m}_{air}\ (0.287)(313)$

$\Rightarrow$ Rate of air leakage , $\dot{m}_{air} = 5.42$ kg/s

So, this solves the second problem part.

c) The third part of problem is that, we need to calculate the length and number of tubes. So, for that reasons we have to bring the overall heat transfer coefficient.

$Q = U\, A_0\, \Delta T_m$

$$\Delta T_m = \frac{\Delta T_i - \Delta T_e}{\ln\left(\frac{\Delta T_i}{\Delta T_e}\right)} = \frac{8-2}{\ln\left(\frac{8}{2}\right)} = 4.33°\text{C}$$

Data given, $U = 2560 \frac{\text{W}}{\text{m}^2\text{. K}}$

$Q = \dot{m}_s(h_2 - h_3) = 66.66 \times 2118.2$

$$\Rightarrow A_0 = \frac{66.66 \times 2118.2}{2.56 \times 4.33} = 12738\ m^2$$

We know, $A_0 = n\pi d_o l$

Here, n is not known l is also not known. To find this, we can link this mass flow rate of cooling water $\dot{m}_c$.

$$\dot{m}_c = \left(n\frac{\pi}{4}d_i^2\right)\rho V_w\ ;$$

$$\text{Water velocity}, V_w = 1.6\,\frac{\text{m}}{\text{s}};\ \text{density of water}, \rho = 1000\,\frac{\text{kg}}{\text{m}^3};$$

$$\text{Already evaluated}, \dot{m}_\text{c} = 5620.5\,\frac{\text{kg}}{\text{s}};\ d_i = \text{d}_0 - 2t = 25 - 2.5 = 22.5\ mm$$

So, in this equation all are known.

$$\dot{m}_c = \left(n\frac{\pi}{4}d_i^2\right)\rho V_w\ \Rightarrow n = \frac{5620.5}{\left(\frac{\pi}{4}\right)\times(0.0225)^2\times 1000\times 1.6} = 8834$$

So, number of tubes we got, now only length is not known.

We know, $\quad A_0 = n\pi d_o l$

$$\Rightarrow l = \frac{A_0}{n\pi d_o} = \frac{12738}{8834\times\pi\times(0.025)} = 18.35\ \text{m}$$

So, this entire problem discusses about how you need to go for a condenser design.

Q2. In a direct-contact spray condenser, find the ratio of circulating water to steam flow for the condenser pressure of 0.07 bar and turbine exhaust of 90%. The cooling tower cools water to 15°C.

The second problem is a very simple one. So, this emphasizes the important aspect that is, the ratio of circulating water to steam flow rate. So, circulating water is $\dot{m}_5$ in a direct contact type condenser and this steam rate is $\dot{m}_2$.

So, in the diagram, we have one condition at state 5, second condition at state 3 and third condition is at state 2. So, for a spray condenser to you calculate the mass and energy balance, you can recall our equations that is

Mass balance : $\dot{m}_3 = \dot{m}_2 + \dot{m}_5$

Energy balance: $\dot{m}_3 h_3 = \dot{m}_2 h_2 + \dot{m}_5 h_5$

This 2 equation gives, Ratio of circulating cooling water to stream flow: $\frac{\dot{m}_5}{\dot{m}_2} = \frac{h_2 - h_3}{h_3 - h_5}$

So, first thing is that condenser operates at 0.07 bar.

Saturated steam table at 0.07 bar; $h_{fg} = 2407 \frac{\text{kJ}}{\text{kg}}; T_{sat} = 40℃ ; h_f \ (at\ 40℃)$

$= 162.2 \ \frac{\text{kJ}}{\text{kg}}$

Condenser exhaust from turbine, $h_2 = h_f + x\ h_{fg} = 162.2 + 0.9 \times 2407$

$= 2328.5 \frac{\text{kJ}}{\text{kg}}$

$h_3 = h_f$ at $40℃ = 162.2 \frac{\text{kJ}}{\text{kg}}$

$h_5 = h_f$ at $15℃ = 65.26 \ \frac{\text{kJ}}{\text{kg}}$ (obtained from steam table)

Now, after inserting this value we can say get

$$\frac{\dot{m}_5}{\dot{m}_2} = \frac{h_2 - h_3}{h_3 - h_5} = \frac{2328.5 - 162.2}{162.2 - 65.26} = 21.83 \approx 22$$

This means the circulating water has to be 22 times higher than the steam flow rate, which is quite high for a steam power system. So, this gives you the important concepts and numerical problems based on this lecture today. With this I conclude this session. Thank you for your attention.