Thermal Engineering: Basic and Applied
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Lecture - 40
The Role of Condenser in Power Plant

I welcome you all to the session of thermal engineering basic and applied. Today we shall discuss about the role of a condenser in a steam power plant. If we recall then we can understand there are a few major components in a steam power plant and we have discussed about all those components like boiler, turbine, condenser and a feed water pump. We have discussed about the boiler because boilers are essential. And this particular component is there in a steam power plant to produce or to generate steam. Then steam which is produced in the boiler is taken to the turbine and while steam flows through the turbine, it does work on the rotating part of the turbine and we get work output. After doing some work that steam is again taken to another device that is the condenser where steam releases heat and again after releasing heat steam is condensed into water and that water is recycled back to the boiler.

So, now today we shall discuss about 2 important objectives or roles of the condenser in a steam power plant. And to understand that let us again draw the schematic diagram of the steam power plant and we shall try to map the processes in a T-S plane.

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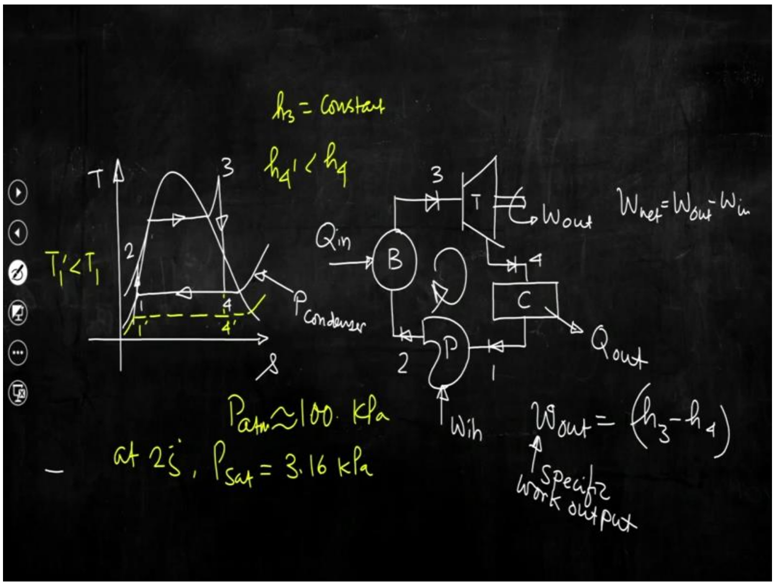

So, we have drawn the steam power plant schematically in the slide. We will see that condenser play an important role. So, there is a turbine from which we get work output. Then there is the feed water pump. We need to supply some energy to the pump and upon receiving heat, the feed water which is supplied by this pump to the boiler gets converted into steam and that steam is taken into the turbine but not directly into the turbine.

We have discussed that steam is taken to the turbine via flow nozzles. The sole purpose of the nozzle is to produce steam Jets and when steam Jets impinge upon the turbine blades which are mounted on the shaft of the turbine, the turbine wheel rotates and we are getting work output. Now there is the condenser wherein steam or exit steam of the turbine is taken, that steam releases heat and gets converted into water and that water is taken or pumped back to the boiler. So, now if we try to draw all these processes in this T-S plane considering that this particular unit is operating following Rankine cycle with superheated steam. So, that steam is superheated beyond this point and we can see all these processes that is 1- 2- 3- 4.

Now I would like to discuss first 1 important objective of having this particular unit that is condenser in a steam power plant. From this particular schematic let us consider a hypothetical case that this particular unit is not there. So, feed water would be pumped by this feed water pump to the boiler, upon receiving heat from an external source that water will be converted into steam that steam will be taken into the turbine and the turbine will produce work. Now after doing work let us consider that the steam will not be again taken to the condenser instead that steam will be discharged into the ambience means any place.

Then we can understand that if we would like to discharge the steam into the ambience then the steam will be discharged at the atmospheric pressure. When it is discharged to the ambience then the saturation temperature corresponding to atmospheric pressure is 100°C. So you can understand that when steam will be discharged into the ambience at the atmospheric pressure the steam temperature will be 100°C degree. And at that temperature steam will be converted into water. Now this particular process is not allowed because of this environmental constraint because we cannot really discharge steam water mixture which is having 100°C temperature to the ambience. Second thing is that if it is a case then again we have to supply feed water for each time and that is also not an economical design of the power plant.

So, essentially we need to have this cyclic processes such that steam that comes out from the turbine will be taken into this condenser. Upon releasing heat that steam will be condensed into water of course saturated water and that water will be taken back to the boiler. So, this is how this particular steam power plant works. Now we can understand that means condenser plays a major role to convert steam into the water, so that we can operate this particular unit in a cyclic manner. So, this is one of the most important objectives.

Now we can also recall the second law of thermodynamics, Kelvin Planck statement which says that it is not possible to construct a device that will operate in a cycle and produce net work while exchanging heat with a single temperature thermal reservoir. So, now let us again look at this particular schematic diagram. So, if we consider that boiler is only the thermal reservoir wherein heat is supplied then we may get net work because $W_{net} = W_{out} - W_{in}$. So, even if we try to get net work output but second law of Thermodynamics puts a restriction that there must be a place where heat should be rejected if you would like to operate the unit in a cyclic manner. So, this particular unit condenser should be there. So, condenser will be there if we need to run this system in a cyclic manner. So, this particular component acts like a heat sink and steam rejects heat in this particular component. So, this is one of the important objective. Now if we look at another most fundamental objective of having condenser in a steam power plant then we need to look at this T-s plane.

$$\text{Specific work output}, w_{out} = (h_3 - h_4)$$

So, that is the enthalpy drop of steam inside the turbine and that is the specific work output. As I said you that this pump will handle only liquid. Now if the liquid is having high temperature then again there will be some problematic issues to handle that hot liquid by this pump. Because pump blades material will be having certain permissible thermal stress or thermal stress bearing capacity. So, if the temperature of the working fluid is higher than the temperature which is allowed when this particular blade is selected I mean that the blade can withstand, then if we now use this pump to handle that particular liquid which is having high temperature blade material may fail.

So, our objective should be to reduce the temperature of water which is available at the exit of the condenser. Now if you would like to reduce the temperature of the water then enthalpy h_4 would be less and this is also good thing, because higher the enthalpy drop of steam inside the turbine, more will be the specific work output.

Now consider this is the T-s diagram, we can understand that the condenser pressure which is also known as turbine back pressure that is the pressure at the exit of the turbine. Now for example if this condenser pressure is atmospheric pressure, then the saturated liquid at point 1 that would be available at the inlet of the pump will be having temperature 100°C. So, basically we can understand that if we do not have this particular unit condenser and by any means if we try to condense the steam at the atmospheric condition, then temperature of the saturated liquid that would be available at the inlet of the pump will be having high temperature. So, that liquid with that high temperature will create a few problematic issues to run the pump in a long run.

Second thing, if we still use any device wherein steam will be condensed into the liquid at the atmospheric pressure then you can understand that enthalpy at state point 4 will be relatively high and if that enthalpy is high then this enthalpy drop will be reduced and specific work output will be reduced. So, the ideal situation should be that the temperature of the liquid at the inlet of the pump should be in the range of 25-30°C. It may also be 20°C.

Now if we consider that the liquid at the inlet of the pump should be 25-30°C temperature then at 25-30°C temperature saturation pressure is way less than the atmospheric pressure. So atmospheric pressure $P_{atm} = 101.3$ kPa that means close to 100 kPa. So, at that pressure temperature of water would be 100° saturated temperature. So, we need to reduce the temperature of the water at the inlet of the pump and that would be 25-30°C and at that temperature saturation pressure is much less than atmospheric pressure.

Now at 25°C ; $P_{saturation} = 3.16$ kPa which is significantly lesser than the atmospheric pressure. So, that means the entire condensation process will be conducted at a pressure which is way less than the atmospheric pressure and if we need to perform this particular process we need this particular component that is the condenser.

And if we do like this then in the T-s diagram there will a state point 1', so temperature of 1' that is $T_{1'} < T_1$ and the corresponding saturation pressure also will be is substantially lesser than the atmospheric pressure. So, this is this would be good for the power plant. Because now there is a point 4' due to that the specific work output will be more because $h_{4'} < h_4$.

So, we will be having high enthalpy drop that means if we can design the system in such a way that during entire condensation process or this entire phase change process, steam will be converted into saturated liquid in a condition where pressure will be substantially less than the atmospheric pressure then we can understand that the specific work output will be more because enthalpy drop will be more. Here h_3 is fixed, so $h_3 = \text{constant}$ for this case. So, now since the pressure is way less than the atmospheric pressure, we need to have a special device that will operate at this pressure and this is what is done in a condenser.

So, you can understand condenser is having 2 important objectives. First of all it allows the entire unit to operate in a cyclic manner. It also allows to reduce the turbine exit pressure or back pressure of the turbine so that the total enthalpy drop will be more & specific output will be more. And also the temperature of the condensate at the exit of the condenser should be near about 25-30°C so that the pump will not be having any problematic issues to handle that liquid. So, these 2 are the important objectives.

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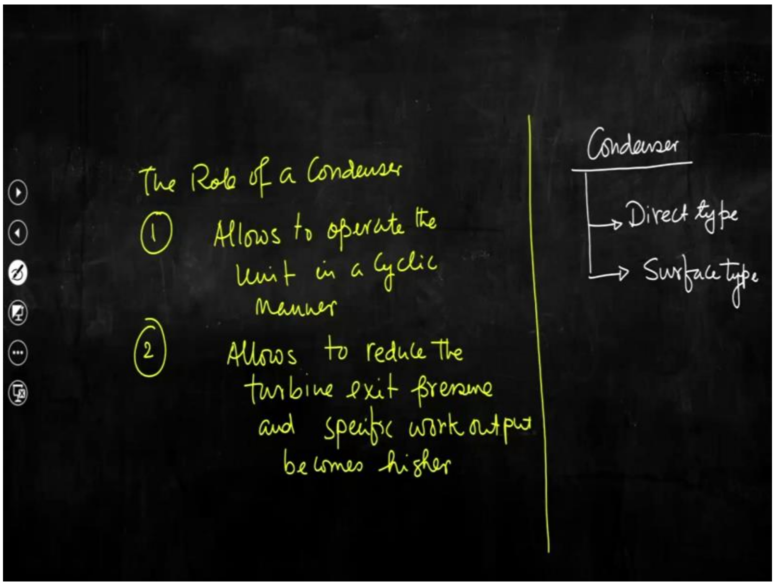

So, the role of a condenser

1) It allows to operate the entire unit in a cyclic manner
2) It also allows to reduce the turbine back pressure that is the exit pressure of the turbine and which in turn allows to have more specific work output.

So, now let us look at the different types of turbine. So, there are 2 broad classes of condenser and the first type is direct type and second one is surface type. So, from the name of the first type that is direct type we can understand from the schematic depiction is that in the condenser steam will be condensed into the saturated liquid. That means the flowing steam will release heat and for that we need to have one cooling medium.

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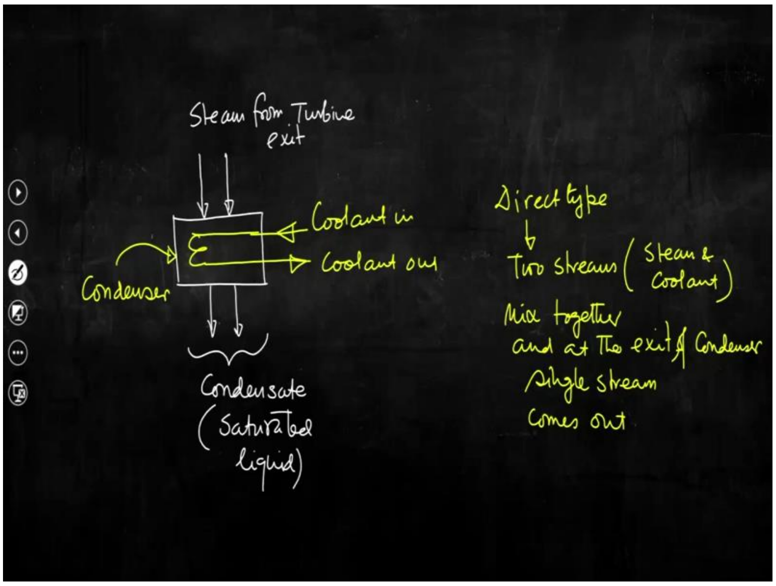

So, let us try to draw this unit again. To this condenser steam comes out from the turbine exit and we will be getting condensate saturated liquid at the exit of the condenser. Because we would like to use pump so this is the saturated liquid. Now this process is basically a heat exchanging process. So, that means we need to circulate coolant and the coolant in and coolant out has been marked in the schematic.

So, the condenser is a type of heat exchanger in which 2 different steams exchange heat. Now the flowing steam can be allowed to mix with the coolant directly, if it is the case then it is a direct type condenser. If we allow coolant to flow through the tubes and steam will flow over the tubes, so that the 2 streams will not be allowed to mix directly, then this is the surface type condenser.

So, in direct type condenser 2 streams will be allowed to mix together and eventually at the exit of the condenser we will be getting a single stream and it is designed accordingly, so that the amount of steam after mixing with the coolant will produce this saturated liquid. Second type is surface type, in which 2 streams are not allowed to mix together rather from the convenience of maintenance and cleaning purpose we need to flow coolant through the tubes while steam will flow over the tubes and in this process, heat exchange will takes place and steam will be converted into saturated liquid. So, this is called surface type. So, once again direct type means 2 steams that is Steam and coolant mixed together and a single stream comes out at the exit of the condenser.

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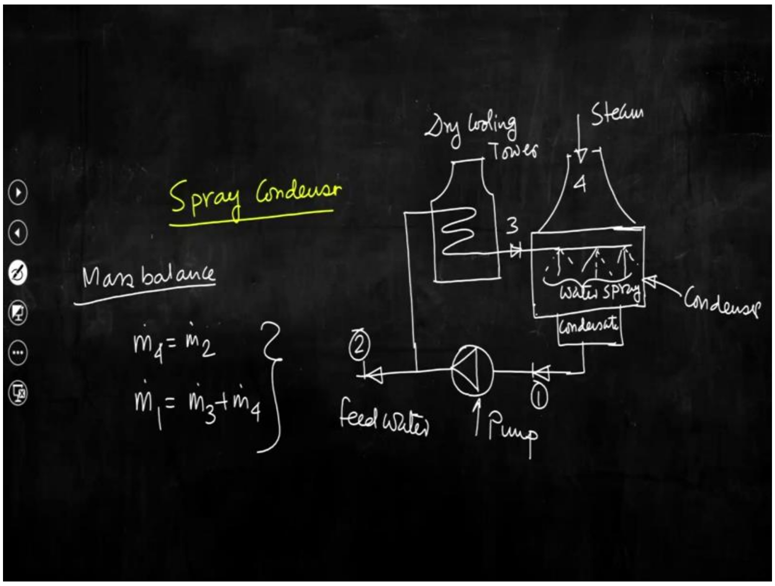

Now let us discuss about one particular direct type condenser just for the sake of understanding how this particular type works. So, there are different types available in the category of direct type. So, one particular type is spray condenser. So, now let us try to draw the schematic. There is condenser, pump and dry cooling tower drawn in the schematic.

So steam at the exit of the turbine is taken into this condenser & this is of direct type. What we can see that steam flows through the condenser and in the flowing steam this water is sprayed. So, water is sprayed into the flowing steam as if these 2 streams are now mixing together and eventually we will be collecting condensate.

Now that condensate is again pumped back to the dry cooling tower and that water is again sprayed into the steam part of that condensate is pumped to the boiler as the feed water. It is very important. We have named 1, 2, 3, and 4 in the schematic. So, you can understand that the condensate after collecting in this basin that condensate will be pumped and a part of that condensate will be pumped back to the boiler as the feed water and the amount of that feed water will be equal to the amount of steam, while remaining condensate will be pumped back to the dry cooling tower. Here in again that condensate will be having relatively higher temperature. And that condensate will release heat to the air and after releasing heat that condensate will be again sprayed into the flowing steam.

So, this is a continuous process. So, if we try to have a simple mass and energy balance analysis then we will come to know the amount of water that is needed to be supplied per kg of steam to get the saturated liquid at the inlet of the pump.

Mass balance

As I said you that mass flow rate of steam should be equal to mass flow rate of feed water. So

$$\dot{m}_4 = \dot{m}_2 \;\; \& \;\; \dot{m}_1 = \dot{m}_3 + \dot{m}_4$$

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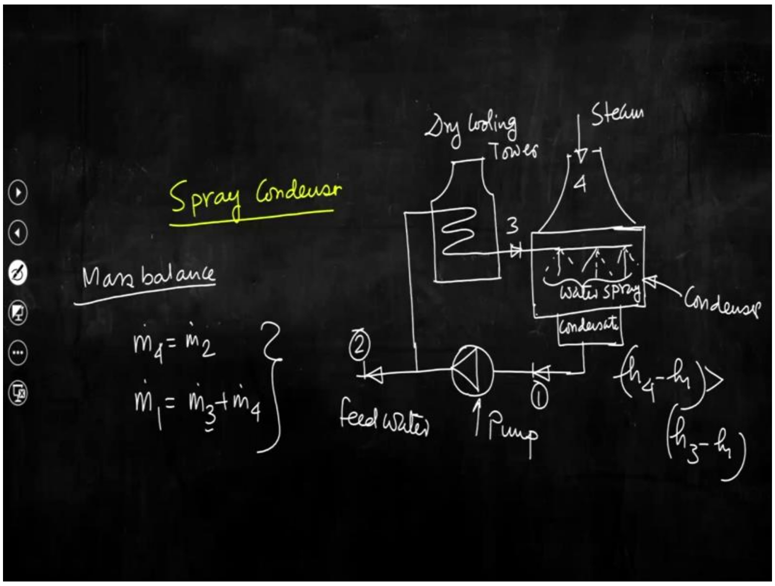

Energy balance

So we can write enthalpy of the steam that is available at the inlet of the condenser plus enthalpy of the coolant that is available at the inlet of this condenser is equal to total enthalpy available with the condensate that is collected in the basin.

$$\dot{m}_4 h_4 + \dot{m}_3 h_3 = \dot{m}_1 h_1$$

$\dot{m}_4 h_4$ = Energy available with the flowing steam

$\dot{m}_3 h_3$ = Energy available in the flowing coolant

$\dot{m}_1 h_1$ = Total energy which is available with the condensate that is collected in the basin

$$\dot{m}_4 h_4 + \dot{m}_3 h_3 = \dot{m}_1 h_1$$

$$\Rightarrow \dot{m}_4 h_4 + \dot{m}_3 h_3 = (\dot{m}_3 + \dot{m}_4) h_1; \text{From mass balance}$$

$$\Rightarrow \frac{\dot{m}_3}{\dot{m}_4} = \frac{(h_1 - h_4)}{(h_3 - h_1)} = \frac{(h_4 - h_1)}{(h_1 - h_3)}$$

Now if we go back to the previous slide we can understand that $(h_4 - h_1) > (h_4 - h_1)$ because steam is having high enthalpy than the enthalpy available with the coolant at the inlet of the condenser. So, that means certainly enthalpy of the condensate will be higher than the enthalpy of the coolant which is available at the condenser in because that coolant will take away a certain amount of heat from the flowing steam.

So, we can understand that $\dot{m}_3 > \dot{m}_4$. So, that is what I was you know discussing few minutes back that this particular unit will be designed in such a way that the amount of coolant flow will dictate that the condensate which should be available at the inlet of the pump should be saturated liquid.

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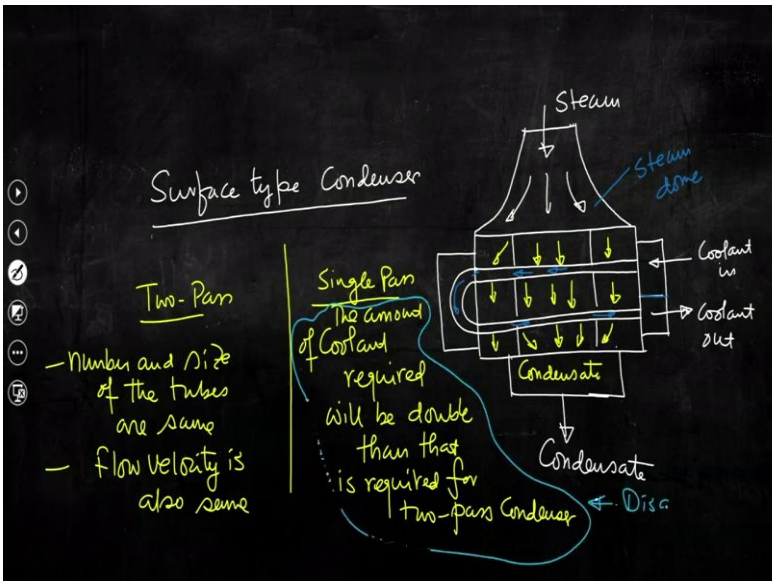

Now let us look into to the surface type heat exchanger or surface type condenser as I said you that the condenser is a type of heat exchanger. So, it is a surface type heat exchanger. Now if we try to recall in surface type condenser because of its name, it is designed in such a way that 2 streams will not mix together that means 2 streams will be exchanging heat while they are passing through the condenser without getting mixed.

So, now we have drawn the schematic of this particular type in the slide. So, we can see from the schematic that coolant is taken through the tubes. Basically I am writing coolant because coolant may be water or it may be any oil and in most of the cases coolant is water. The coolant flows through the tubes and steam passes over the tubes. Since the coolant is having low temperature so, the tube surface is having low temperature. When steam passes over the tubes or when steam is in contact with the cold surface, it condenses and eventually we will be collecting condensate. So, you can understand that this is a mechanical arrangement, coolant is allowed to flow from right to left or left to right depending on the design. So, the flow direction of coolant is marked in the schematic.

This is called two pass surface type condenser as the coolant which is entering into the tube at the top passes from right to the left, again there is a bend tube and through this main tube which is connecting the top and the bottom tubes that coolant again passes from left to the right and eventually goes out. So, this is called two pass surface type condenser.

Now it is not mandatory that always condenser will be 2 pass condenser but single pass condenser is also fine. In case of a single pass condenser, this tube will be having 1 inlet and 1 outlet. So, tubes are not connected by using this bend tube. So, there may be even 2 tubes for a single pass condenser but coolant will flow from the right to the left and it will go out.

In this case we can understand that coolant passes through the tube which is placed at the top and when it is coming out from the condenser again taken to the condenser through another tube. And finally it comes out and it is taken for further heat exchange purpose. So in this case we can understand that there are 2 boxes available; 1 box is placed at the right and this is called divider. When coolant is coming from the external source that coolant will be having lower temperature, so this coolant will not be allowed to mix with the coolant which is going out from the condenser and that is why this divider is given. And this left box is provided to accommodate this bend tube.

You can understand we need to hold the tubes inside the condenser, so mechanical arrangements will be there. There is a steam dome that has been marked in the schematic. Now this particular design is there because we are allowing steam to have more or less uniform distribution when it flows through the condenser and if we do not provide this particular shape part then steam will be having almost non-uniform distribution.

And then the tube which is adjacent to the condenser side walls will not be in a position to be in contact with the steam and the performance or efficiency of the heat exchanger will be reduced. So, this is a Surface type heat exchanger and this is most widely used condenser in a power plant.

So, direct type condensers are not widely used but surface type condensers are most widely used in the power plant. Now I would like to discuss one important point here that instead of 2 pass condenser if we use single pass condenser then there will be an important benefit at the cost of one disadvantage that I like to discuss.

So, now let us compare two pass vis-a-vis single pass. As I said you for the single pass coolant will come in and go out and coolant will not be again directed into the condenser using this bend tube. So, now if you are trying to compare the performance of two pass condenser vis-a-vis single pass condenser, then we need to have we need to have a common basis. So, basically we consider that number and size of the tubes will be same and velocity of coolant when passes through the tubes is also same then the amount of coolant needed for the single pass will be just double than the amount of coolant needed for this two pass. So, this is the disadvantage.

But the advantage is that for a single pass, rise in temperature of the coolant will be even half than the two pass. If the rise in temperature of the coolant is even less, then we can reduce the turbine back pressure & we can reduce the condenser pressure. If we can reduce the condenser pressure further then looking at the T-s diagram, we can understand that the specific work output will be more. So, this is the difference between two pass and single pass condenser. So, if I now ask why this is disadvantage because if we need more coolant then the pumping power will be more. So, this is the disadvantage.

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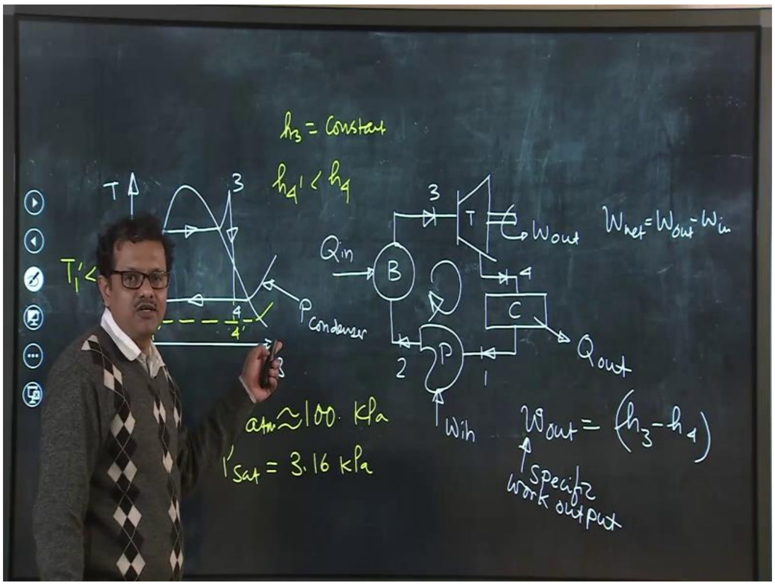

Now the advantage for single pass is rise in coolant temperature will be half. So, basically if the rise in coolant temperature is reduced, we can again lower the back pressure. So essentially we will be getting saturated liquid. So, if the rise in temperature is reduced that means the saturation temperature will be reduced. So, if we reduce the back pressure or condenser pressure, specific workout will be more but let me tell you one important thing. Maybe we can reduce the turbine back pressure or we can lower the condenser pressure further and further to get specific work output, but we will be having another important disadvantage at this particular point that is the turbine exit. So this particular point is now going away from the saturated vapour line that means the steam quality at the exit of the turbine will be having high moisture content. So, we will be having the problem from the perspective of turbine blade erosion.

So, though we can increase the specific work output by lowering the condenser pressure by using single pass condenser as temperature rise will be less, but the quality of steam at the turbine exit will be poorer and turbine blade erosion problem will be there. So, this is the comparison between 2 pass and single pass condenser.

Now finally I would like to discuss one important point that is if we look at this particular type of condenser then you can understand from today's discussion that condenser plays an important role from 2 different perspectives. First of all it allows to run the unit in a cyclic manner and also it allows to operate the turbine at a low turbine back pressure so that the specific workout output will be more.

But if you would like to have coolant available at the inlet of the pump at temperature maybe 25°C or 30°C, so that the saturation pressure at that temperature is way less than the atmospheric pressure that means the entire unit will run or operate at a pressure which is way less than the atmospheric pressure. So, though all these parts are connected through mechanical components since the unit is running at a pressure which is way less than the atmospheric pressure, air leakage problem will be there. So, air will leak into the condenser through different joints and also there is a possibility that when steam is coming out from the turbine that steam is having some amount of air which has already leaked into the steam through the turbine flanges.

So, steam is already having air and also air will leak into the condenser because condenser pressure is much less than the atmospheric pressure, so that air will create 2 problematic issues.

1) When steam is in contact with the cold surface of the tube, steam will condense but since air is non-condensable that air will create a thin film around the tube surface, so, it will reduce the heat transfer capacity.
2) So, this is very important point. If air leaks into the condenser through different joints then the vacuum pressure will be reduced. So, the pressure at which condenser is operating will be reduced. So, that means the turbine back pressure will be reduced and turbine work output will be reduced. So, if air leaks into the condenser and then the pressure inside the condenser will be again go off which in turn will reduce the turbine

back pressure and will reduce the enthalpy drop. So, turbine specific work output will be reduced.

So, these 2 are the problematic issues because of the air leakage into the condenser. So, air removal arrangement should be there. Not only air can leak into the condenser through the joints but also some air will come with the steam itself because already air has leaked into the steam at the turbine exit through turbine flanges. So, air removal part also should be there, otherwise it will create the problematic issues. So, with this I stop here today and we shall continue our discussion in the next class. Thank you.