Applied Thermodynamics
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Steam Power System
Lecture - 11
Regenerative Cycles

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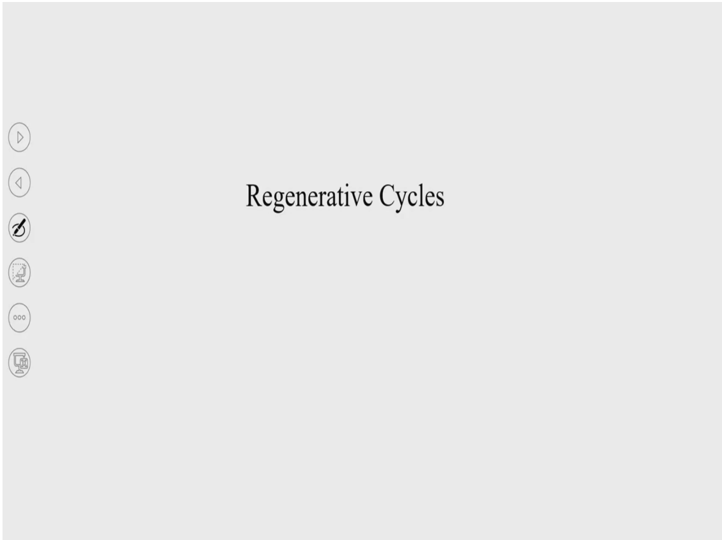

Today we shall start discussing on the Regenerative Cycle. You know that in the last class we have discuss about ideal regenerative cycle and we have seen that using this regeneration method we can achieve efficiency of the cycle closer to the ideal Carnot cycle. And in fact, by illustrating a very simple mathematical exercise we could establish that the efficiency of the ideal regenerative cycle is almost equal to the efficiency of the ideal Carnot cycle.

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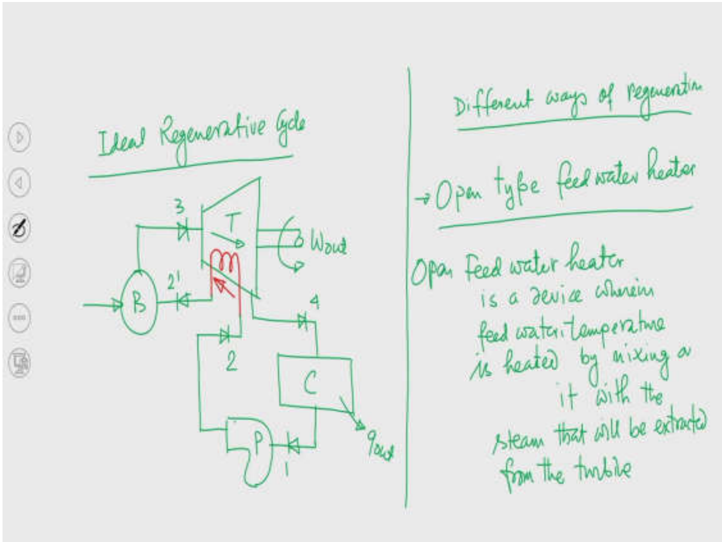

So, just for the recapitulation I am drawing this schematic. This is what we have discussed in the last class that here the collected condensate is pumped to the boiler by allowing the condensate to pass through the reheat coil. So, it is not a case that the collected condensate will be directly pump to the boiler, but it is definitely pumped to the boiler for generation of steam, but it is allowed to pass through the heating coil which is placed inside the turbine.

Now we have discussed that here probability will be there that the steam while expanding in the turbine at the outlet, quality may fall because it not only is doing work but probability will be there that enthalpy of the steam will fall further and if the quality of the steam deteriorates, then it would be very problematic as it may lead to the turbine blade erosion. So, considering that today we will be discussing different ways of regeneration.

In fact, the concept is remaining same that before feed water enters into the boiler its temperature will be increased, essentially to increase the average or mean temperature of heat addition. As idea is that if we can heat up the feed water before it enters into the boiler; then, perhaps that much fuel required for that much of heating inside the boiler can be saved.

Now, as using this method as I told you that this method will also invite another problem of having turbine blade erosion as the steam quality will be very poor at the exit of the turbine. So, now, you are thinking of different ways of regeneration. First way is open type feed water heater.

So, the concept is we have to heat up the feed water before it enters into the boiler. So, instead of heating the feed water in a coil which is placed inside the turbine, we can heat the feed water by adopting several other means, but our attention will be not to deteriorate the quality of the steam as it leaves the turbine. So, here let me draw this schematic depiction.

So, the feed water heater is a device wherein feed water temperature is heated by mixing or passing it with the steam that will be extracted from the turbine.

So, we can have increase in feed water temperature by mixing the feed water with the steam that will be extracted from the turbine or by passing the feed water in a counter clockwise or into the tube and passing steam over the tube. So, if we just mix the feed water with the steam that will be extracted from the turbine and that is a device which is known as open feed water heater.

So, open feed water heater is a device wherein feed water which is pumped from the condenser will be allowed to mix with the steam that will be extracted from the turbine. Since it will be allowed for direct mixing, it is call open feed water.

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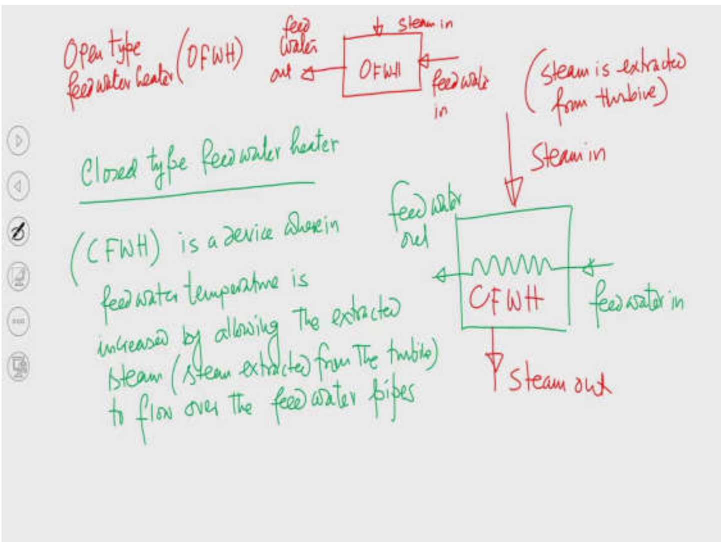

Now, another is closed type feed water heater. So, closed type feed water heater is a device wherein feed water temperature is increased by allowing the extracted steam from turbine over the feed water pipe. Now, as feed water moves from its inlet to outlet through the coil which is placed in this heater and steam is allowed to pass over the coil and as steam temperature is high, so, heat transfer will take place and we can increase the temperature of the feed water.

Now, you can understand in open type feed water heater there is no outlet for steam. So, the steam coming from turbine is allowed to mix directly with the feed water that is taken to this heater. So, this is called open type.

So, we will be discussing soon that using either open type feed water heater or closed type feed water heater, we can bring efficiency of the regenerative cycle closer to the ideal Carnot cycle efficiency at the same time we can eliminate the problem of having reduction in the steam quality at the exit of the turbine.

Let we draw this schematic depiction and also the T s diagram. Then we will try to explain that we can increase the efficiency of the cycle and which will be closer to the ideal Carnot cycle efficiency, but at the same time we do not have any problem related to the deterioration of the steam quality at the exit of the turbine.

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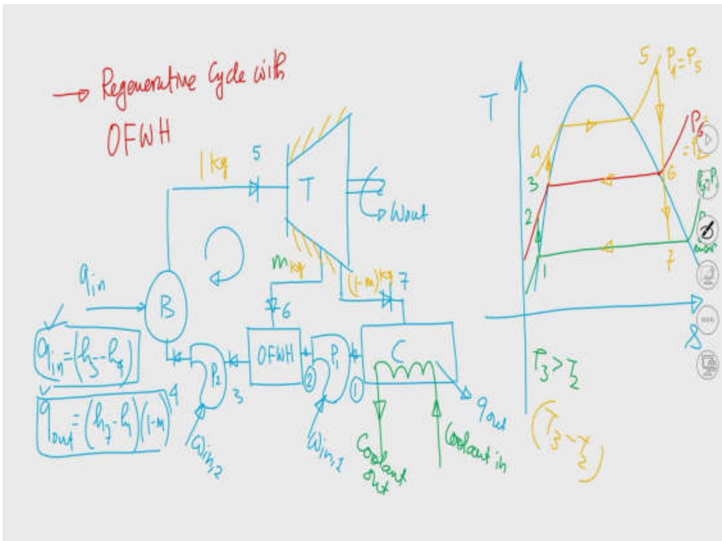

So, first I will be discussing about open type feed water heater. So, regenerative cycle with open type feed water heater. Let me draw the schematic depiction. We must have boiler. Heat is given to convert feed water into steam and we will be having turbine, this is turbine output.

Now, exit steam will be taken to this condenser. So, this is coolant in and this is coolant out. We will be discussing this part again and this is open type feed water heater and we will be having one pump.

So, this is w_{in}. So, steam will be extracted from the turbine and it will be allowed to mix with the feed water which is pump to this heater. And finally, we have to have another one pump to supply.

Now, so, this is w_{in2}, this is w_{in1}. So, you can see this is the schematic depiction. Now, if you try to compare the schematic with the schematic depiction that we had for the ideal regenerative cycle, here feed water is not allowed to pass through the heating coil which is placed inside the turbine instead, a part of the steam after doing certain amount of work is extracted.

So, when steam is generated it is having high enthalpy and steam will be allowed to expand in the turbine, so that we will be getting work output. So, now, question is here when steam is expanding in the turbine, after doing certain amount of work a small fraction of steam is extracted. The amount of steam that will be extracted will depend that will be discussing.

So, now certain amount of steam is extracted from the turbine and steam is allowed to mix with the feed water which is pumped from the condenser and after mixing definitely the feed water temperature will increase and that feed water again will be pump back to the boiler.

Now, the collected steam will be having steam pressure. So, basically if you need to have efficient mixing of feed water and steam, the feed water pressure will be definitely equal to the steam pressure. So, we need to build up pressure of feed water equal to that pressure at which steam is extracted, so that we will be having efficient mixing. So, after mixing again the pressure will not be equal to the boiler pressure. So, what we need to do? We need to pump the collected mixture, I mean feed water with steam. So, it is basically again saturated liquid. So, as I told you that amount of steam that will be extracted from the turbine that will depend because we need the quality of liquid.

So, basically at point 3, thermodynamic state will be saturated liquid. So, at point 3 again we will be having pump, so that we will be getting saturated liquid having higher temperature that we need to again pump it back to the boiler. The pressure at point 3 is not equal to the pressure at point 4, rather it is boiler pressure.

So, we need to increase the pressure and that is why second pump is coming. So, let me tell you, the first pump is essentially to increase pressure, so that we will be having efficient mixing of the feed water to the extracted steam, because steam which is extracted from the turbine is having certain pressure.

So, we need to increase the pressure that is why first pump is coming. Second pump is coming because after mixing we will be we need to extract steam in such a way that at the outlet of the open type feed water heater we will be having saturated liquid.

So, that saturated liquid pressure is not equal to the pressure at which the boiler is operating. So, we need to increase the pressure again. So, that is why second pump is coming. So, I think you have understood the necessity of these two pumps in the context of the cycle. So, if you try to draw the T s diagram it will be clear.

So, 7 to 1 that is constant pressure heat rejection that is condenser pressure. So, let us first draw the condenser pressure, $p_7 = p_1 = p_{condenser}$.

Now, we are having one pump. So, pressure at point 2 will be definitely higher than pressure 1 that is why pump is required. Why we are developing this pressure because we need to have efficient mixing. The steam which is extracted from the turbine is at an intermediate pressure. So, that is not equal to the condenser pressure and definitely higher than the condenser pressure.

So, this is an intermediate pressure p_6. So, 2 is the outlet of the first pump that is the temperature of the feed water.

We want the feed water temperature will increase. So, at point 3 temperature will be definitely higher than temperature point 2 and that is why you are mixing with the extracted steam. So, this is you know point 3. On the top of that as I told you the amount of steam that will be extracted from the turbine for mixing with the feed water will be such that the liquid will be saturated liquid at the outlet of the open type feed water heater.

So, this is state point 3, right. So, state point 3 is lying on the saturated liquid line; so that means, the amount of steam we are extracting will be selected in such a way that we will be getting saturated liquid at the exit of the open type feed water heater, but you can see temperature at 3 is greater than temperature point 2. So, it basically you can see T_3 is greater than T_2.

That is what our objective is, because we need to increase the temperature of feed water. Now, finally from 3, we need to increase pressure again and that will be the boiler pressure. Say boiler is operating at this pressure $p_4 = p_5 = p_{boiler}$.

So, we will be discussing in one class that why 3 to 4? So, process 3 to 4 that is occurring inside the pump that is reversible adiabatic process then why this temperature is increasing that is nothing but the frictional heating; so slight increase in temperature.

So, though I could not show according to scale, but 3 to 4 the slight increase in temperature that is only due to frictional heating. So, at state point 3 it was saturated liquid corresponding to that pressure, but when we are trying to build up pressure to boiler pressure that is why second pump is coming essentially to meet the boiler pressure.

Now, temperature corresponding to boiler pressure is sub cool liquid because boiler pressure is something else which is definitely higher than $p_3 = p_6$. So, that is sub cool liquid. Now, from 5 to 6 and 5 to 7. So, this is very important now say steam is heated at here. So, this is point 5. Now, steam is allowed to expand isentropically. So, this is point 6 and this is point 7.

So, this is the T-s diagram. So, when steam is passing through the turbine it does work and it is allowed to expand reversible adiabatically. So, this is there is no heat loss and we are assuming the processes is internally reversible. So, we can say that is reversible adiabatic process. So, that is nothing but isentropic.

So, the pressure at point 6 is not equal to pressure at point 1 that is why second pump is coming, because pressure at point 2 must be equal to pressure at point 6. So, this is $p_6 = p_2$.

So, I am telling this because having one extra pump will involve additional installation cost as well as operational cost, but yet we need to have this additional pump only to increase pressure of the feed water to that of the extracted steam pressure so that efficient mixing can be ensured.

So, that is why first pump P1 is there and feed water pressure is increased from pressure p_1 to pressure p_2.

And finally, 6 to 7. So, remaining steam will expand isentropically and it will expand up to the condenser pressure 6 to 7. So, I mean certain amount of mass, say m kg steam is extracted after it does certain amount of work. If 1 kg of steam is flowing through the cycle and if we extract m kg of steam for increasing feed water temperature then 1-m kg of steam is expanding isentropically and it is eventually going to condenser for releasing heat to this heat sink and this is coolant in and this is coolant out. So, this is complete description of the open type feed water heater. In this case we can increase efficiency because eventually you are increasing temperature of feed water from point 1 to point 2 and then from point 2 to 3. So, we can increase the efficiency of the cycle as mean temperature of heat addition will increase.

See had this open type feed water not being there in the cycle then the temperature of feed water entering the boiler would have been Temperature at 3, but this much amount of temperature $T_3 - T_2$ is increasing without supplying additional amount of fuel. If the case would have been like this that we would like to increase this additional amount of temperature inside the boiler then additional fuel cost would have been associated with this, but that is not the case. So, we are increasing this amount of temperature only by having this arrangement and by doing so, we can save fuel and the cycle efficiency will increase.

So, as I told you this is very crucial that the amount of steam that will be extracted after it does certain amount of work in such a way that at the exit of the open type feed water heater will be saturated liquid. So, if you try to do energy balance across these open type feed water heater only to understand what will be m. So, let us do this energy balance or steady state steady flow equation to the mixing process in feed water heater.

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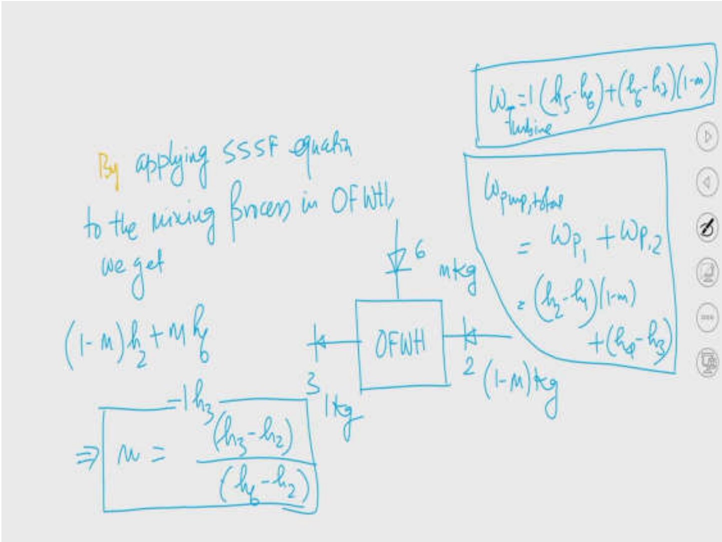

So, by applying steady state steady flow equation to the mixing process in open type feed water heater, we get what? So, this is open type feed water heater, what is the state point? This is 2, here we are having 1-m kg of steam. Here we are having 6, we are having m kg of steam and this is the point 3.

So, now m_1 kg of steam is extracted and here 1- m_1 kg of feed water is coming from the condenser. So, you can understand that 1- m_1 kg of steam is allowed to expand isentropically and it is eventually going to condenser to release heat. I mean following second law of thermodynamics we have learned that there must be a heat sink otherwise it is very difficult to operate the cycle for the system in a cyclic process.

So, 1- m_1 kg of feed water that will be pump by this pump P_1 to the open type feed water heater. So, just now by applying this steady state steady flow energy equation to the mixing process in open type feed water heater what we can write? We can write $(1-m)h_2 + mh_6 = h_3$

So, m_1 kg of steam is allowed to mix with 1- m_1 kg of water and we need to find out the amount of steam that will be mixed in such a way that will be getting 1 kg of water at the outlet that is what our objective is.

So, if we try to do it then we will be getting $m = \frac{h_3 - h_2}{h_6 - h_2}$. So, this is the fraction of steam that should be extracted from the turbine essentially to have 1 kg of water at the exit of the open type feed water heater.

Now, for this particular cycle what is q_h or q_{in}? $q_{in} = h_5 - h_4$ that is heating inside the boiler right. And $q_{out} = (h_7 - h_1)(1-m)$. So, 1-$m_1$ kg of steam is allowed to go to the condenser. So, the heat rejection will be $(h_7 - h_1)(1-m)$.

So, what is w turbine? let me tell you 1 kg of steam is doing work up to h_5 - h_6 remaining 1-m kg of steam is doing work h_6-h_7. So, $w_{turbine} = (h_5 - h_6) + (h_6 - h_7)(1 - m)$

So, what is w pump? $W_{pump} = (h_2 - h_1)(1 - m) + (h_4 - h_3)$

So, to summarize today's discussion we have discussed about one method of regeneration in which we have seen that without inviting the problem of having high moisture content of the steam at the exit of the turbine we can increase the efficiency of the cycle following this regeneration method, but of course, several issues are there that is we require additional pump also the open type feed water heater.

So, installation of an open type feed water heater as well as the extra pump. So, the increase in efficiency will be justified from the perspective of the additional cost involved with the installation as well as operational cost of the open type feed water heater and one extra pump.

But it is seen that the increase in efficiency using open type feed water heater at is very high. We can increase the number of feed water heaters, so that efficiency can be increased. So, increasing the number of open type feed water heater, we can increase the efficiency of the regenerative cycle and the efficiency will be as good as the ideal Carnot cycle.

But as I told you we should have a compromise rather we should have a judicial balance between the increase in efficiency vis a vis the cost associated with the installation as well as operation of this open type feed water heater and one additional pump.

So, it is seen that for the high power plant at least the number of open type feed water heater can be used is 8. So, we can use maximum 8 heaters for a large plant to increase the efficiency of the cycle and the efficiency will be as good as the ideal Carnot cycle efficiency.

So, with this I stop here today and in the next class I will just briefly describe about the schematic of the closed type feed water heater and then we will proceed to the next topic.

Thank you.