Thermal Engineering: Basics and Applied
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Lecture – 16
Analysis of Regenerative Steam Power Cycles

I welcome you all to the session and today we shall discuss about the regenerative steam power cycles. So, if we try to recall in the last class we have discussed about the ideal regenerative cycle and we have seen that the efficiency of the ideal regenerative cycle is equal to that of the Carnot cycle. So, before going to discuss the regenerative power cycles, let us briefly review whatever we have discussed in the last class.

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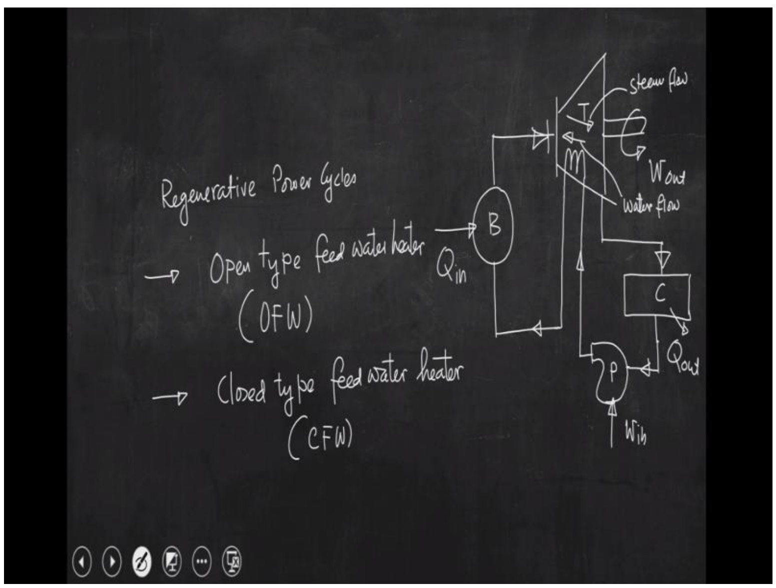

So, we tried to discuss about the ideal regenerative cycle in the last class. And we have critically analyzed that the efficiency can be increased using the special arrangement. That means, if we can circulate this feed water through a coil which is placed inside the turbine and the flow of feed water is in the direction which is opposite to the steam flow direction in the turbine then we can increase the temperature of feed water before it enters into the boiler and if we can do so, then average temperature at which heat is added to the cycle can be increased, which in turn increases the efficiency of the cycle. But at the same time, we have also discussed that by this arrangement though theoretically you can see that the efficiency can be increased and the efficiency will be as good as the Carnot efficiency, but making such an arrangement in real applications is not a an easy task. Rather it involves both operating cost as well as initial cost. So, accounting for these difficulties essentially from the perspective of the operation of the cycle, in fact the plant there are several other methods by which this regenerative principle can be used to increase the efficiency of the cycle. What are those?

Let us now briefly discuss about several other avenues. See the temperature of feed water should be increased to increase the efficiency. So, instead of circulating this feed water through this coil which is placed inside the turbine, why we cannot look for several other avenues. Like you know that steam which is passing through the turbine is having high temperature and high enthalpy. At the cost of this expansion inside the turbine, we will be getting work output, but temperature of steam will reduce. So, if we can allow steam to expand isentropically and if we try to bleed or extract steam at different points from turbine and then we allow that steam to be mixed with feed water.

I mean, if it is not possible for direct mixing, why we cannot design a device wherein this extracted stream will be allowed to flow over the stream of feed water. And essentially by virtue of heat exchange, temperature of feed water can be increased. Since regenerative cycle is not a practically viable method, we can look for other ways by which the efficiency can be increased by using the regenerative principle. One method is the extraction or bleeding steam from the turbine. Here from the steam stream the temperature can be used to supply to the feed water. This is what we have studied in heat exchanger. So, the idea is to extract steam and that steam should be allowed to get mixed with the feed water in this case. We shall discuss that if it is possible. If we allow the extracted steam to be mixed with the feed water then the temperature of feed water can be increased. And such an arrangement is known as open type feed water heater in short OFW.

So, in this case, why we are saying open? Because extracted steam will be allowed to be directly mixed with the feed water, which is taken from the pump, before it goes into the boiler. So, these 2 streams will be allowed to mix, so, that temperature of the feed water can be increased. But, we shall discuss today that you if this particular arrangement that means, if direct mixing of these 2 streams creates problem, I mean definitely from the operational point of view, then we also can look for other arrangement like cross flow type heat exchanger.

So, the extracted bled stream should be allowed to pass through a device and feed water should be allowed to pass through the feed water tube. And if we allow steam to pass over the feed water, then tube by the virtue of heat exchange phenomenon we can increase the temperature of the feed water. Such an arrangement, where these 2 streams are not allowed to mix directly is known as close type feed water heater (CFW)

Now we shall discuss these 2 different you know types of regenerative process in today's class and first we shall take up OFW.

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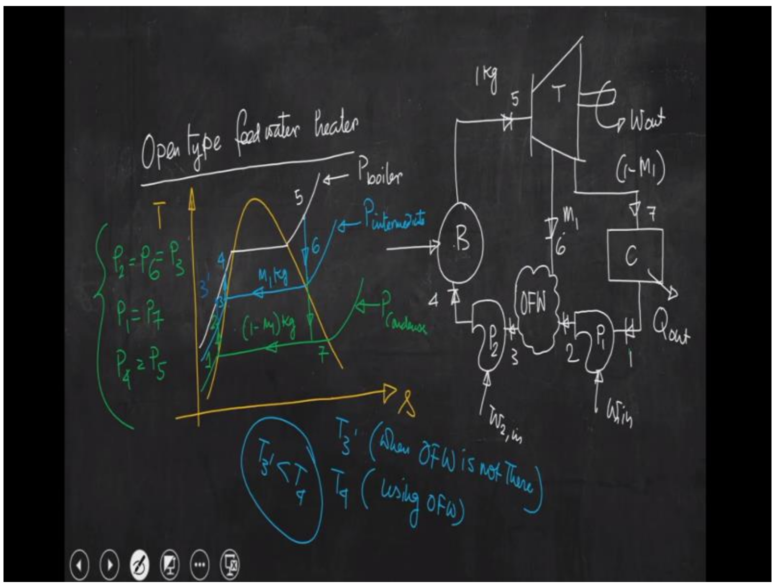

Open type feed water heater

Let us briefly discuss this using the schematic diagram and then we shall analyze the effect by representing the processes in T-s plane. So, you know there are 4 major components Boiler, Turbine, Condenser and Pump. The second law of thermodynamics puts a restriction that there must be a heat sink, essentially to run this device in a cyclic manner. Then we can have this device in which extracted steam will be allowed to mix with the feed water which is coming from the pump. So, the schematic depiction in slide is exactly what we have discussed in the context of previous slide that the streams should be extracted from the turbine. And this is not the stream which is taken exactly at the inlet of this turbine rather steam is allowed to expand isentropically.

And then at an intermediate pressure some amount of steam should be extracted. What would be that fraction of steam, which will be extracted that we will discuss today. But, so, basically after doing certain amount of work, the steam should be extracted at an intermediate pressure and that steam should be allowed to mix with the feed water which is pumped from the condenser into this device. So, this device is basically open type feed water heater.

So, now we will apply what you have studied in fluid mechanics. We know that the 2 streams are coming and one stream is having high temperature and high pressure. So, if we need to have efficient mixing of these 2 streams, then we cannot directly take the condensate into this device. Because the feed water which should be taken to this particular device should have pressure which is equal to the pressure at which steam is extracted, otherwise mixing will not be efficient.

So, to ensure that the efficient mixing, pressure of the feed water should be equal to that of the stream which is extracted. And for that a pump is coming into the picture which is P_1 as per the schematic. If we do not use this pump and we directly take the collected condensate to this open type feed water heater, then mixing will not be efficient and if mixing is not efficient, heat exchange will not be efficient. Main idea is to have efficient heat transfer between these 2 streams and that is why we need to ensure that these 2 streams should be mixed at a given pressure and that pressure is equal to the pressure at which stream is extracted because it is at high pressure. So, after mixing you know that the temperature of the feed water will increase as the feed water is mixed with the extracted stream and to build up that pressure of feed water this pump is used.

And after mixing we really do not know, it could be water or it could be a mixture. So, whatever the case may be, we will discuss that soon. That mixture will be again pumped back to the boiler. So, you know boiler is operating at a pressure, which is definitely not the pressure this mixture is having. So, we need to have another pump essentially to develop the pressure of the mixture which is equal to the boiler pressure. So, this another pump is P_2. So, the complete schematic depiction of the regenerative power cycle having open type feed water heater is shown in the slide. So, I hope you have understood why these 2 pumps are required for the smooth as well as efficient operation of the plant using these arrangements. So, the pump P_2 is required to build pressure of the mixture which is coming from the open type feed water heater, so that the pressure would be raised to the boiler pressure. And the first pump P_1 is essential to build up pressure of the feed water to ensure the efficient mixing between these 2 streams. So, you know this is the description here I was telling that you know that the steam you are extracting from the turbine and feed water is coming from this condenser I mean condensate is coming from condenser.

So, basically from our previous discussion, we know that the thermodynamic state at point 1 is saturated liquid, because pump cannot handle 2-phase mixture. So, pressure of the saturated liquid is raised by this pump to the intermediate pressure at which steam is extracted.

Now, what would be the thermodynamic state of the mixture after mixing? Would it be 2-phase mixture? No, because again the pump cannot handle 2-phase mixture again. So, the mixture which we shall get from the open type feed water heater should be pumped back to the boiler, because the pressure of this mixture is less than the boiler pressure. So, we need to develop pressure that is why the second pump is there. And if we need to pump this mixture back to the boiler to complete the cycle, then definitely the thermodynamic state at point 3 should be again saturated liquid.

So, the fraction of steam that should be extracted from the turbine at any point, while steam is expanding isentropically inside the turbine, will depend based on the criteria that is the quality of mixture at the exit of open type feed water heater should be the saturated liquid. So, this fraction is m_1. So, if we consider 1 kg of steam is flowing then remaining $1 - m_1$ kg of steam will be allowed to flow isentropically. So, if we consider 1 kg of steam is flowing and it is entering into the turbine and we need to extract m_1 kg of steam then the calculation of m_1 should be based on the condition that is quality of the thermodynamic state of the mixture at state 3 should be the saturated liquid. So, remaining $1 - m_1$ kg of steam will expand isentropically as usual up to the condenser pressure and the cycle will be completed.

So, let us quickly draw the T-s diagram. Now, you know that this is regenerative power cycle so, this is modified Rankine cycle, so steam is superheated beyond point 3. So, when we shall draw the T-s diagram, we should look at the schematic depiction. You should not memorize otherwise you will be doing mistake while drawing the T-s diagram. So, you know that when steam is expanding inside the turbine, some amount of steam is extracted from the turbine at any point and it is allowed to expand isentropically at an intermediate pressure. So, we can consider that intermediate presser is $P_{intermediate}$ and stream is expanding isentropically up to this point 6. So, try to understand it is not necessary that whether the point 6 should be on the superheated region or on the saturated vapour line that criteria we have to design. Because our entire objective is to increase the temperature of the feed water heater. So, higher the temperature of steam, extracted from the turbine, higher will be the temperature of feed water heater. At the same time you also need to ensure that if we take steam depending on the position at which steam is extracted and we allow that steam to expand then that intermediate pressure is very important.

If the state point 6 is on the saturated vapour line, we will be getting some kind of heat from the extracted steam and that should be supplied to the feed water heater. If the point 6 is in this superheated region and we take that steam and if we allow the feed water to mix with that steam, we will be getting another heat transfer between these 2 streams. So, that is based on the requirement.

So, this is $m_1$kg of steam is taken to the open type feed water heater wherein the collected condensate is pumped and these 2 streams will mix together to ensure efficient mixing. That's why we are having this extra pump. And finally the thermodynamics state at point 3 would be the saturated liquid. So state points are plotted on the T-s diagram.

And now the remaining steam will as usual expand inside the turbine isentropically up to the condenser pressure. So, the state at 1 is saturated liquid and it will be again pumped back to state point 2. So, basically this feed water and collected condensate should be pumped to raise the pressure up to that intermediate pressure that is P_6.

$$P_2 = P_6 = P_3$$

$$P_1 = P_7$$

$$P_4 = P_5$$

So, now try to understand that had this (OFW) arrangement not there in the circuit, we would have obtained the feed water temperature at 3' that is at the inlet of the boiler, if the operating pressure of the boiler is remaining same. So, I would like to tell you that if the operating pressure of boiler is same that is $P_4 = P_5$ then making use of this arrangement, the temperature of feed water at the inlet to the boiler is now T_4.

But, what I was telling that had this arrangement not been there in the circuit, we would have obtained the temperature of feed water at the inlet to the boiler that is at 3'.

$$\text{Temperature of Feed water} = T_{3'} \text{ (when OFW is not there)}$$
$$\text{Temperature of Feed water} = T_4 \text{ (using OFW)}$$

So, using this arrangement, we could increase the temperature of feed water before it enters into the boiler. So, when you would like to compare, we should have a common basis of the comparison. So, if the boiler and condenser these 2 are operating at a given pressure, say, P_5 and P_7. In that case, it is because of this arrangement, we could increase the temperature of feed water up to this point that is T_4. But in absence of this arrangement, we could get the temperature of feed water at the inlet to the boiler that is $T_{3'}$. So, definitely $T_{3'} < T_4$. So, it is because of this increase in temperature by making use of this arrangement efficiency of the regenerative power cycle can be increased.

So, that is the objective of having such an arrangement. So, try to understand that we are increasing the temperature up to T_4, but this increase in temperature is not associated with the additional fuel cost. So, this is not due to the additional supply of heat that is given to the boiler instead this is by taking some amount of heat from the flowing steam inside the turbine.

So, we should be careful while we are extracting certain amount of steam from the turbine. The fraction of steam should not be substantial amount of the total steam flow rate, otherwise w_{out} will be compromised. So, we should be careful while extracting steam from the turbine. So, now we should find, what should be the fraction of m_1. The condition is that fraction of m_1 should be selected in such a way that the state at 1 should be the saturated liquid. So, to obtain m_1 we need to apply steady state steady flow equation to the mixing process inside the Open type feed water heater.

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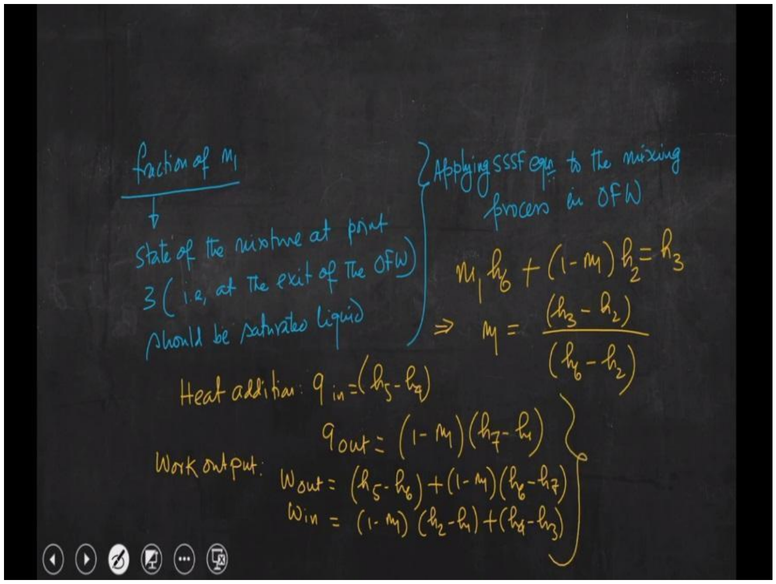

So, the important & only criteria that we should keep in mind while calculating m_1 is that state of the mixture at point 3 that is at the exit of the Open type feed water heater should be saturated liquid. So now let's apply the steady state steady flow equation to the mixing process in OFW. So, we know that 1 kg of steam, taken from the turbine into the Open type feed water heater has enthalpy h_6 and $1 - m_1$ kg of feed water which is taken from the condensate has enthalpy h_2.

$$m_1 h_6 + (1 - m_1)h_2 = h_3$$

As at state 3 we will be getting working substance $= m_1 + (1 - m_1) = 1kg$

$$\Rightarrow m_1 = \frac{(h_3 - h_2)}{(h_6 - h_2)}$$

So, if we can calculate enthalpy at different state points, then we can calculate what should be the fraction of steam to be extracted from the turbine.

$$\text{Heat addition}, q_{in} = h_5 - h_4$$

$$\text{Heat Rejection}, q_{out} = (1 - m_1)(h_7 - h_1)$$

These expressions will be required while solving numerical problems. So, if you know q_{in} and q_{out} you can directly calculate the thermal efficiency of the regenerative power cycle. Nevertheless, we also need to know the work input and the work output. If we supply 1 kg of steam in the turbine, then 1 kg of steam will expand from h_5 to h_6 and remaining $(1 - m_1)$ kg of steam will expand from h_6 to h_7.

$$\text{Work output}, w_{out} = (h_5 - h_6) \times 1 + (h_6 - h_7) \times (1 - m_1)$$

$$\text{Pump work}, w_{in} = (1 - m_1)(h_2 - h_1) + (h_4 - h_3)$$

So, these are very important. If we apply steady state steady flow equation to different devices, we will be getting the similar expression. This expression will be very much useful while solving numerical problems.

So, you know if you would like to summarize today's discussion, we have discussed about the ideal regenerative power cycle. Though we had discussed this in the previous class, today we have briefly touched upon that and we have discussed the limitation of this. Perhaps the limitations associated with this particular arrangement are the motivation for this arrangement that is Open type feed water heater.

So, using this particular arrangement, we had seen that this helped us to increase the temperature of the feed water which would be supplied to the boiler. And this additional heat which is not supplied to the feed water is not by burning coal or burning fuel instead, that heat is taken from the steam which is flowing through the turbine.

So, once can argue that if we do not extract this $m_1$kg of steam, then this steam would have done further work and w_{out} would have increased. That is true, if we do not extract this amount of stream, then, this steam will be doing additional work and w_{out} will increase but, by extracting this amount of steam, we could increase the temperature of feed water. Not only that but also the amount of heat that must be rejected, will decrease. So, the overall impact would be to raise the efficiency of the cycle. So, by extracting steam, momentarily you can find that we are going to compromise w_{out}, but this steam will increase the temperature of feed water before it enters into the boiler, which in turn will increase the efficiency by increasing the average temperature of heat addition.

And had this steam been allowed to expand in the turbine, I do agree that it would have obtained more amount of work from the turbine, but at the same time the heat rejection amount would have increased. So, perfectly designing this system and perfectly calculating the fraction of steam that should be extracted, if we can run the plant then, the overall impact would be the increase in efficiency of the cycle. And it is very important that till now we have shown only one feed water heater, it is possible to extract steam at different points from the turbine. And it is seen that if we can have 8 such arrangement, then efficiency of the regenerative power cycle would be exactly equal to the Carnot cycle. So, with this discussion, I stop here today