Thermal Engineering Basic and Applied
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Lecture – 17
Regenerative Steam Power Cycle with Closed Feed-Water Heater, Ideal Working Fluid

In this class, we shall discuss about the regenerative steam power cycle with closed type feed-water heaters. In the last class, we have discussed about the regenerative steam power cycle and we have seen the use of feed-water heater and that was open type feed-water heater. So, today we will try to just recall exactly what we have discussed in the last class.

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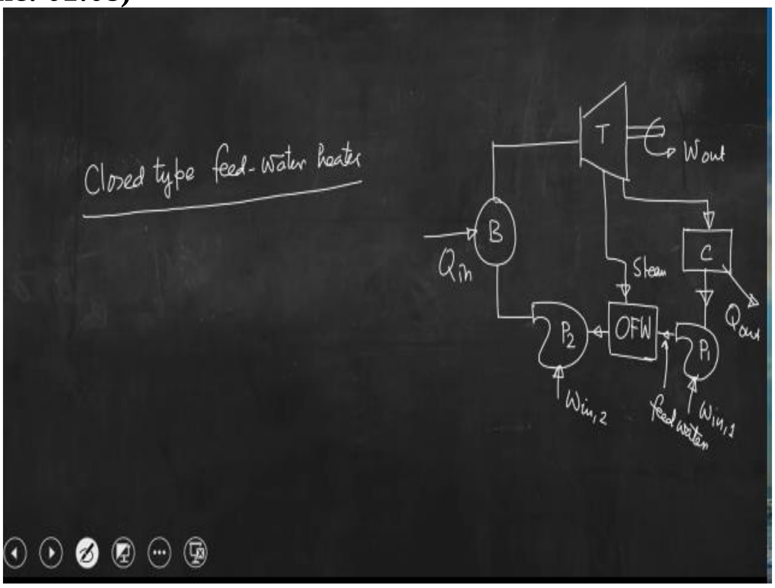

So, this is the schematic depiction of the regenerative steam power cycle with open type feed-water heater. We have seen this device which is essentially heat exchanger and in this extracted stream from the turbine is allowed to mix with the feed-water which is coming from the condenser. So, the collected condensate would be pumped to this device wherein the extracted steam will be allowed to mix properly. Now, whether it is open type feed-water heater or closed type feed-water heater, these devices are basically heat exchangers. So, you know that by making use of these, we could establish that the efficiency of the cycle can be increased. And we have discussed that if more than one such device can be integrated with the circuit, then efficiency of the regenerative power cycle can be increased and efficiency would be closer to the Carnot cycle efficiency. But, you know that practical limitations are there because of the initial cost as well as the cost involved with the operation of this device. So, accounting for these difficulties, the number of feed-water heaters is limited to 8 and not more than that.

So, these 2 streams that is extracted stream and feed-water are mixing together in an open ambience. This is a closed device, but here open ambience means these 2 streams are directly mixing and there is no any interface. So, that is why the name open is coming. Now, today we shall be discussing about the closed type feed-water heater. In this closed type feed-water heater the extracted steam will be allowed to pass over a circuit or a coil and feed-water will be allowed to pass through the coil. So, this is essentially a cross flow type heat exchanger. So, let me draw the circuit here only.

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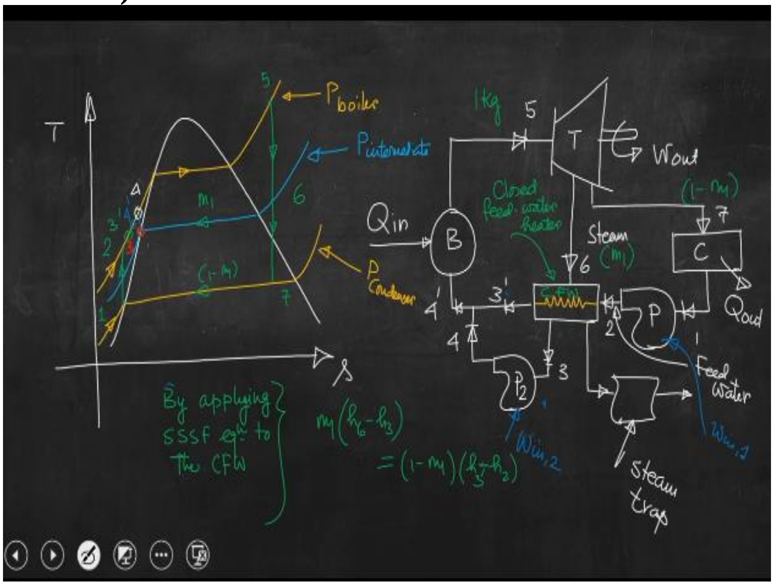

So you know there is boiler and turbine. Now, here we will be having one feed-water heater and steam will be taken to this feed-water heater from the turbine. So, I have drawn the coil through which this feed-water will be pumped. Then there is a condenser and a pump, which is responsible to develop pressure. So, the collected condenser will be pumped by this pump at the boiler pressure.

If we go back to the previous slide, in OFW, 2 streams are mixing together and definitely the steam which is extracted from the turbine is having different pressure than the pressure at which the feed-water is supplied to this open feed-water. Now, it is because of this reason, the second pump was there, but in this case since the feed-water will be allowed to pass through the coil and if we can design properly and select pump accordingly, then this pump will be able to cater feed-water even up to the boiler pressure. So, there is no need of having additional pump as of now.

So, the idea is that this is a cross flow heat exchanger in which feed-water is needed to be heated by the steam which is extracted from the turbine. So, the steam which is extracted from the turbine will be allowed to pass over this coil and during this flow process heat exchange will take place and feed-water will gain heat from the extracted steam and we can increase the temperature of feed-water. So, when steam is allowed to pass over the coil, it will lose heat and that heat will be gained by the feed-water. And then what will happen; the steam will be condensed.

So, again there are 2 ways, if we need to supply that condensed steam to the feed-water line, then definitely we need to have an additional pump and that is why, this additional pump will be required. So, it is named P_2 in the schematic. So, you can understand that collected condensate will be pumped back to the feed-water line and eventually we will be getting mixture at the inlet of the boiler.

So, basically the steam, water mixture will be pumped to the boiler and we have identified several state points that is 1, 2, 3, 4, 4', 3', 5, 6 and 7. Previously we have discussed that requirement of additional pump is not there in the circuit. But now we can see this pump is required, but requirement of this pump can be eliminated, if we use steam trap. So, from the name itself you can understand that it is a device which will trap steam and will allow liquid to pass. So, the collected steam can be again cascaded back to the condenser using a throttle valve. So, if we can use this steam trap, then the requirement of additional pump can be eliminated, which is not advisable considering the cost associated with its operation as well as initial cost.

So, this requirement of additional pump can be avoided, if we use steam trap and this device will only trap the steam and will allow liquid to pass. The steam which is collected can be cascaded back to the condenser using a throttle valve. So this is the idea. So, this is the regenerative steam power cycle using a closed type feed-water heater. Why it is closed type? You can understand that different streams are not mixing directly together rather the feed-water is passing through the coil, while steam is allowed to pass over the coil. And during this process heat exchange takes place and the feed-water temperature can be increased before it enters into the boiler. And that is the objective of this particular cycle. So, somehow we are increasing the temperature of feed-water and that temperature rise is not coming from the combustion means that heat is not supplied into the boiler by burning fuel. But this amount of heating is done by extracting steam from the turbine.

Again I am repeating. When we extract steam that means, we are not allowing that steam to do work. Had we allowed that steam to work in the turbine, we would have obtained more amount of work from the turbine. But we are not going to do that, instead we are extracting the steam to heat up the feed-water. But, you also need to keep in mind that if we allow that steam to do work in turbine, then perhaps the amount of heat that must be rejected in the condenser would increase. So, from that point of view it is quite possible to increase the overall efficiency, though we are sacrificing some amount of work by extracting steam from the turbine.

So, our next objective should be to draw the T-s diagram, which will help us understand more about this cycle. So, in the T-s plane drawn in the slide, we are trying to draw all the processes. From there we will come to know about all the processes by which eventually the efficiency of the cycle is getting increased. So, we have plotted the boiler pressure, condenser pressure, intermediate pressure. Now, this is the amount of stream which is extracted from the turbine at an intermediate pressure. State points 5, 6 & 7 have been plotted too.

Now, If 1 kg of steam is allowed to go to the turbine from the boiler and if we extract m_1 kg of stream from the turbine, then remaining $(1 - m_1)$ kg of steam will be allowed to expand isentropically and to go into the condenser.

So, we have extracted m_1 kg of steam from the turbine and remaining steam is again, expanding isentropically up to the condenser pressure that is 6-7. This m_1 kg of the steam is extracted but before that this amount of steam has done work on the rotating part of the turbine while expanding isentropically in the turbine that is 5-6.

Now, again try to apply your common sense because pump cannot handle 2-phase mixture so, the thermodynamic state at point 1 is saturated liquid. Now what about the pressure at point 2, 3', 4' and 5? Try to understand that this is not the open type rather this is closed type. So, this pump is responsible to build up pressure and that is the pressure at which boiler is operating. So

$$P_2 = P_{3'} = P_{4'} = P_5$$

That means 2, 3', 4', 5 points will lie on the boiler pressure line.

So, the question arises will the entropy at 4 be higher than the entropy at 4' or vice versa? This is very important. So, now point 3 is again on the saturated liquid. So, pump is used to supply the condensate, though this is 2-phase mixture, but point 3 is on the saturated liquid line. I have point 3, 3' in the T-s plane. So, you know this pressure at 3' is definitely higher than pressure at 3 and that is why the requirement of additional pump 2 is coming into the picture. So, you know point 3' is on the feed-water line so the corresponding pressure is the boiler pressure while the point 3 is on the saturated liquid line, so the pressure is high.

Ideally point 3', 4' and 4 all these points should coincide. But if you apply your common sense you know that m_1 kg of the stream is extracted from the turbine and it is then allowed to pass over the coil. During the process, the extracted steam releases heat and that heat is absorbed by the feed-water while the steam is collected at point 3 that is essentially condensed steam.

So, water is one stream, whose temperature should be increased by taking heat from another stream that is allowed to pass over the coil. So, it is very unlikely that the temperature at 3' should be equal to temperature at 3. But it can. So, temperature at 3 is definitely higher than 3'. Though I could not represent these points at per scale, but you should keep in mind that the temperature at 3 should be slightly higher than temperature at 3' otherwise heat transfer would not be justified and that is what you have studied in heat transfer course. So, this temperature at 3' should be slightly lesser than the temperature at 3 otherwise, efficient heat transfer will not be justified.

So, next is what about 4? Now entropy at 4 should be slightly higher than the entropy at 3' and 4' because temperature at 3 is high and that is again pumped. So, while we are pumping it is because of this viscous heating, temperature will increase a little more.

So, you know entropy at state point 4 should be higher than the entropy at state point 3' and 4'. So temperature at 3' prime is less than temperature at 3 and entropy at 4 should be higher than entropy at 3' and 4', though the points 3', 4' prime and 4 should coincide but theoretically they should not.

So, since the temperature at point 3 is high and condenser stream is again pumped. So, because of viscos heating temperature will increase a little more and as a result of which entropy at 4 should be even higher than the entropy at 4' and that is what you can see from the TS plane.

So, basically this 3-4 is isentropic process because that is again reversible adiabatic pumping process. So, I should show work input $w_{in,2}$ and $w_{in,1}$ to the respective pumps in the schematic.

So this is all about the description of the regenerative power cycle with closed type feed-water heater. Again I am telling, had this arrangement not been there in the circuit, the temperature of feed-water would have been T_2 before entering into the boiler. But, because of this complex arrangement, we could increase the temperature of feed-water before it enters into the boiler up to 4'. So, it is because of this increase in temperature of the feed-water, the average temperature of heat addition increases, which in turn increases the efficiency of the cycle.

Now, again one important issue is what should be the fraction of steam that should be extracted. In the context of the open type feed-water heater, I have discussed that you have to keep in mind that the thermodynamic state at the inlet to pump 2 should be the saturated liquid. So, that was the key for the calculation of the fraction of steam that should be extracted in OFW.

So, again, if we were to calculate the fraction of steam that is extracted from the turbine essentially in the context of this closed type feed-water heater, then we can again apply steady state steady flow equation to this closed type feed-water heater and then we can easily calculate.

Closed type feed-water heater

So, let's apply steady state steady flow equation to the closed type feed-water heater. So, basically the enthalpy of the feed-water of $(1 - m_1)$ kg increases from 2-3' prime. As ideally this is heat balance, so, the gaining of the enthalpy by the feed-water is equal to the enthalpy loss of the extracted steam.

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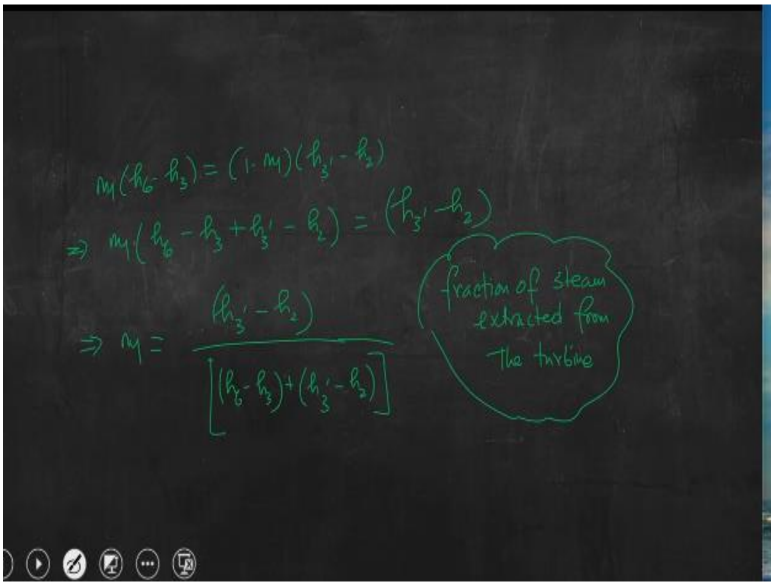

$$m_1(h_6 - h_3) = (1 - m_1)(h_{3'} - h_2)$$
$$m_1(h_6 - h_3 + h_{3'} - h_2) = (h_{3'} - h_2)$$
$$m_1 = \frac{(h_{3'} - h_2)}{[(h_6 - h_3) + (h_{3'} - h_2)]}$$

So, this is the expression of the fraction of steam extracted from the turbine. So this is the important part. I am not going to write the expression of $q_{in}, w_{out}, w_{in,1}, w_{in,2}, q_{out}$. Because, you can calculate again all these expressions by applying steady state steady flow equation to the process which is there in the boiler, turbine, condenser and these 2 pumps.

Now, we have discussed about several issues related to several cycles starting from the Carnot cycle that is the ideal cycle. We have discussed about the limitations of the Carnot cycle then simple ideal Rankine cycle, Rankine cycle with several modifications and then we have discussed about the regenerative Rankine cycle. And we have seen that by making use of this regenerative principle, it is possible to increase the efficiency of the cycle which should be almost equal to the Carnot cycle efficiency. It is not so easy to achieve the efficiency which would be as good as the Carnot efficiency, but of course, it can be increased closer to the Carnot efficiency.

So, we have so far discussed about the cycle and we have seen that the working substance of the cycle is water and steam, water mixture to be precise. So, now we shall deeply discuss about the ideal working fluid.

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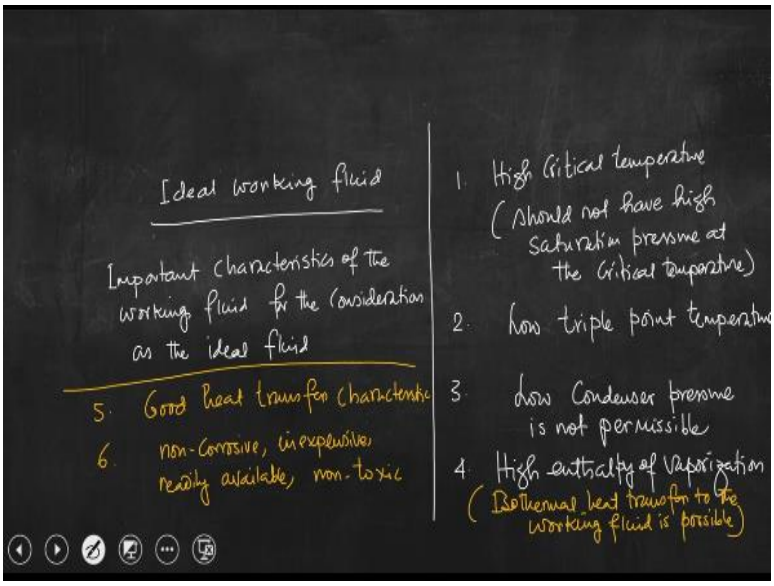

Ideal working fluid

You know that water is predominantly used as the working fluid in the vapour power cycle though it is not an ideal fluid. Because water is having a few drawbacks to be used as the ideal fluid. But, the concept of another cycle that is known as binary cycle will be an attempt to overcome those shortcomings of water and make water as an ideal fluid. So, though water is not an ideal fluid, but it is predominantly used. Considering this, now time has come to understand the important characteristics of the working fluid for the consideration as the ideal fluid.

So let me repeat again. As of now water is used as the working fluid for all the cycles we have discussed till now. Though it is used predominantly, but water cannot be considered as an ideal fluid because water has few drawbacks. But the concept of binary cycle would be an attempt to overcome those shortcomings, so that water can be considered as the ideal fluid for the vapour power cycle. That particular cycle will be discussed in the coming classes. Now let us briefly discuss about the important characteristics of the working fluid for the consideration as the ideal fluid.

Important characteristics of the working fluid for the consideration as the ideal fluid

1) High critical temperature.

So, about critical temperature you have studied in thermodynamics. Now, if the critical temperature is above the metallurgical allowed temperature or maximum temperature to be precise, then isothermal heat transfer is possible at the maximum temperature. Because, we have seen from the cycles that when heat is supplied in the boiler for the conversion of water into the steam, the low temperature heat addition is not desirable one, because it lowers the average temperature at which heat is added. So, if I now come to the Carnot cycle, you have seen that, if we can increase the temperature at which heat is added that is the isothermal heat transfer when fluid changes the phase. So, basically we cannot increase the temperature inside any device above the metallurgical allowed maximum temperature as the material which is used to fabricate the device will start melting. So, if the critical temperature is above the metallurgical allowed maximum temperature, then isothermal heat transfer is possible at the maximum temperature as the fluid changes its phase.

So, this is very important. If the critical temperature is very high and we can have isothermal heat transfer at the maximum temperature, then we can closely reach towards the Carnot cycle. But at the same time we have to keep in mind that the working substance with high critical temperature should not have high saturation pressure.

2) Low triple point temperature.

If, triple point temperature is below the cooling medium temperature, then solidification can be avoided. So, let me tell you once again you know that we need to reject heat in the condenser in which cooling water is circulated and I have discussed all the condensers are operating at a pressure which is less than atmospheric pressure. If we reduce the condenser pressure perhaps we can allow steam to expand even more in the turbine. But, the problem is that if the condenser pressure is well below the atmospheric pressure, then air leakages will be there. And in addition to that you know that pressure at which condenser will be operated depends on the temperature of water which is available in the site.

So, if we can have one working fluid whose triple point temperature is even less than the temperature of the cooling medium, then solidification problem can be avoided.

3) Low condenser pressure is not permissible.

So, low condenser pressure is not permissible that is what I have discussed earlier, that it will create another problem of having air leakage into the condenser. And if that is there, then we need to have again de-aeration, which is nothing but the removal of air from the feed-water, otherwise, it will start corrosion in the boiler tube.

4) High enthalpy of vaporization.

High enthalpy of vaporization that is HFG, then isothermal heat transfer to the working fluid is possible.

5) Good heat transfer characteristics.

You know that good heat transfer characteristics means heat transfer coefficient should be high, so that it can carry maximum amount of heat. Because essentially what you have understood from the discussion till now is that heat is added in one part of the cycle and in other part, heat is rejected and by this course of heat addition and heat rejection, we are getting work output. So, the working fluids should have high heat transfer characteristic or good heat transfer characteristics.

6) Non-corrosive, inexpensive, readily available and then non-toxic

The last point is quite common. You have studied in the context of heat exchanger, which fluid is used. It should not be corrosive, it should be readily available, inexpensive and non-toxic. Because you know this working fluid is allowed to pass through the coils and tubes in the boiler. So, if these properties are not there in the working fluid, which is should be chosen, then it will again invite cost associated with the regular maintenance of different parts of the steam power plant.

So, to summarize today's discussion starting from this open type feed-water heater which we have discussed in the last class, let's make a comparison between these 2. So, open type feed-water heater is relatively simple in design. Since, it does not involve any complex design, so the maintenance cost open type feed-water heater circuit is also less. Only one problem in this circuit is that the requirement of pump 2 is must. But if we go to the closed type feed-water circuit, then it has complex design, maintenance as well as the initial cost of for the circuit is relatively higher than the open type feed-water circuit. But this additional pump is not essential for the circuit, instead we need to use steam trap.

So, these are the basic comparison between the open type feed-water and closed type feed-water circuits in the context of the regenerative steam power cycle. And finally, we have discussed about the important characteristics of the ideal working fluid which is commonly used in the steam power cycle. So, with this I stop here today and we shall continue our discussion in next class about the binary cycle. Thank you.