Thermal Engineering: Basic and Applied
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Lecture - 15
Regenerative Principle of Steam Power Cycles

I welcome you all to this session of thermal engineering and the topic of our today's discussion is the regenerative principle of steam power cycles. So, today, we shall briefly discuss about the regenerative principle, but before going to this it would be important if we discuss why this regeneration is important in the context of the steam power cycle.

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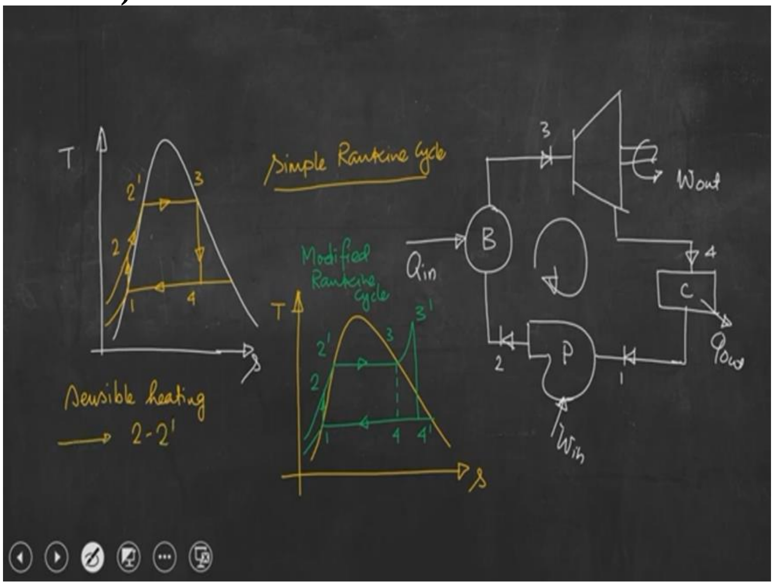

So, if we try to recall the schematic depiction of a steam power plant then we have seen that there are 4 major components. And we have seen that all the processes can be represented or can be analysed using the simple Rankine cycle. We can also draw the T-s diagram of the simple Rankine cycle. And we can also go for the modification of the simple Rankine cycle by superheating the steam beyond point 3 and try to draw the T-s diagram for the modified Rankine cycle. What we can see from these 2 diagrams that whether the plant is operated following the simple Rankine cycle or the modified Rankine cycle the important issue is the segment at which heat is added at a lower temperature that we can name 2-2'.

So, you know the sensible heating that is 2-2'lowers the temperature at which heat is added to the cycle and it is because of this factor, thermal efficiency of the Rankine cycle or modified Rankine cycle becomes lesser than that of the Carnot cycle.

So, idea is somehow we need to eliminate this particular component or increase the temperature at which heat is added in the boiler. There are 2 components that is sensible heat transfer that is 2-2' and remaining either 2' -3 or 2' to 3' depending on whether it is simple Rankine cycle or modified Rankine cycle.

If we can improve the heat addition at 2-2' or if we can eliminate this part at all, I mean, if we can eliminate this low temperature heat addition inside the boiler, then efficiency of the plant can be increased the way by which, we can increase the heat addition at a higher temperature into the cycle for which efficiency of the cycle be higher. It is very unlikely that the efficiency would be equal to the Carnot efficiency. But, attempt can be taken to increase the efficiency of the simple Rankine cycle or modified Rankine cycle up to that of the Carnot cycle efficiency. So, this could be made possible by making use of the regenerative principle.

So, let me repeat it. We have understood from previous classes that efficiency of the cycle, which is used to describe the processes in a thermal power plant, is less than that of the Carnot cycle efficiency. Attributable factor for such a decrease in efficiency is the sensible heating component that is 2-2'. So, this segment, which is nothing but the heat addition at a low temperature eventually lowers the average temperature at which heat is added to the cycle and which in turn results in the reduction in the thermal efficiency. So, we need to understand that if we can eliminate this segment or if we can reduce the low temperature heat addition, then efficiency can be increased. Though it cannot be made equal to that of the Carnot efficiency, but at least efficiency can be increased and this could be made possible by making use of the regenerative principle.

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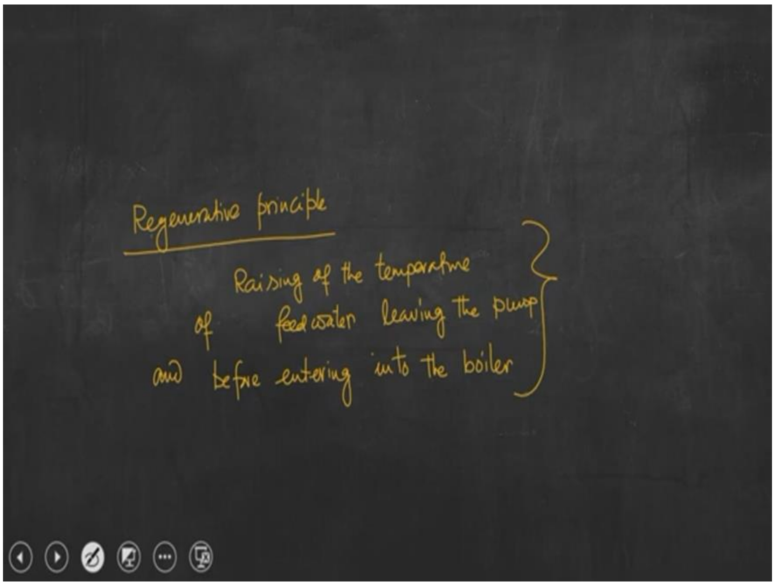

Regenerative principles

So, this is nothing but raising of the temperature of the feedwater leaving the pump and before entering into the boiler. So try to understand from this schematic depiction that inside this process 2-3 or 2-3' if it is super-heated even beyond point 3, one point is there inside the boiler that is 2'. So, the state point 2 is at the exit of the pump or inlet to the boiler, but state point 2' is inside the boiler wherein the heating is due to sensible heat transfer. And if we can eliminate this portion or reduce this portion, we can increase the efficiency.

How can we make it? We can increase the temperature feedwater which is leaving the pump, but before it enters into the boiler. We can make such an arrangement, so, that temperature of feedwater before entering into the boiler can be increased and perhaps the heat required for such an increment or increase of the temperature of the water inside the boiler, which essentially comes from the fuel combustion can be eliminated.

So, try to understand if we can make an arrangement so, that the temperature of feedwater leaving the pump and before entering the boiler can be increased up to 2' but to increase the temperature, required heat should not come from the combustion of fuel. Instead that heating can be completed through a special arrangement. One such arrangement is that we can allow feedwater to go through the turbine following a counter flow heat exchanger arrangement, as if water is allowed to pass through the turbine in the direction opposite to the steam flow and that water should be taken into the boiler for further heating. If we can do so, we can increase the temperature of feedwater before entering into the boiler.

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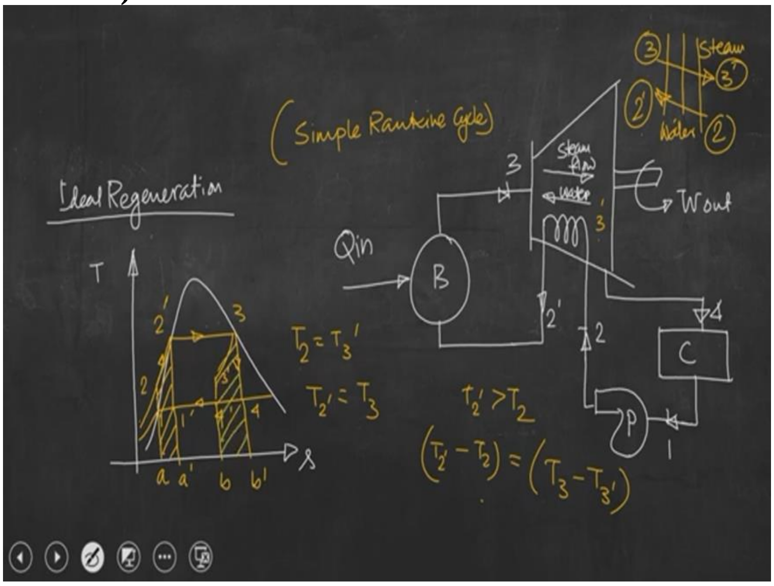

Ideal regeneration method

So we can draw the schematic for the power plant as shown in the slide and can mark 1-2-2'-3-4. So we have an arrangement in this schematic. So, you can distinguish the feedwater flow direction, & the steam flow direction. So, in this schematic we can see that instead of taking the feedwater which is pumped, directly into the boiler, it is now circulated through this special arrangement. And this arrangement is placed inside the turbine. Feedwater is allowed to flow in the direction which is opposite to the direction of the steam flow. And while water is flowing through this coil, it will take certain amount of heat from the flowing steam and that heated water will be now taken into the boiler for further heating.

So, in this arrangement here also we need to supply heat Q_{in}. But the required heat which essentially comes from the combustion of fuel will be less than that what is needed for this particular case (simple Rankine cycle). So, if we consider the size of the plant is same, the mass flow rate of steam per cycle is also same for both the cycle then to get equal power output, the heat supplied to the boiler for the ideal regenerative cycle would be less. And we can increase the efficiency of the plant because thermal efficiency is essentially the function of Q_{out} & Q_{in}.

So, this is the ideal regenerative cycle. While I am discussing about the favourable aspect of this particular cycle, I also should also discuss about the demerits. You have studied in heat transfer course that this is a counter flow heat exchanger. So steam is flowing in the left to right direction while pertaining to this particular arrangement water is flowing in the reverse direction. While these 2 streams are allowed to flow in this device, and as steam is having high enthalpy so, they will exchange heat and as a result of which water coming out from this coil will be having high temperature.

Now, issue is that if we make such an arrangement essentially to increase the efficiency of the cycle, then again we are going to invite additional costs involved with the maintenance of this coil, because of its complex geometry. So, maintenance of such an arrangement could be again difficult, though the idea is very good that we can take certain amount of heat from one part of the cycle and we can use that heat to heat up the working substance in another part of the cycle. This process is nothing but regeneration, as if we are regenerating the heat to increase the efficiency of the cycle.

Let me tell you once again that the idea is we can reduce Q_{in} which is supplied by burning fuel and to do that, this is the simple arrangement which is also known as ideal regeneration method. Though efficiency can be increased, but for this increment of efficiency, we are going to have special arrangement. The regular maintenance as well as initial costs of such complex arrangement should be justified with the increase in efficiency before this particular arrangement is considered in practical scenario.

So, what we understand from this process is that there are basically two working substance water and steam, and the idea is to take heat from the working substance of one part of the cycle and use that to heat up the working substance in another part of the cycle. In that way we can reduce the quantity of heat that should be supplied from the external source by burning the fuel. So, this is the concept, though this is not really feasible in practical scenario accounting for the complex geometry of the system, we can find out several other avenues by which efficiency of the cycle can be increased. What are those?

So, let us briefly discuss about the T-s diagram and we can see why such an arrangement will increase the efficiency of the cycle. So, let’s try to draw the T-s diagram for simple Rankine cycle 1-2-2'-3-4. Now, we are trying to discuss about the ideal regeneration method by superimposing you know the different state points which are needed to properly describe the processes in this circuit.

So, you know, this 2-2' is the heating which should be done inside the boiler. Now, pertaining to this particular configuration of ideal regenerative cycle, we can see that the heating is done inside the turbine through this special arrangement, instead of heating inside the boiler. So, you can understand $T_{2'} > T_2$. At the cost of getting the higher temperature of feedwater before it enters into the boiler, we need to compromise the steam temperature or steam of quality as well. So, this amount of heat that is $T_{2'} - T_2$ will definitely come from the expansion of steam rather enthalpy of the steam.

$$T_{2'} - T_2 = T_3 - T_{3'}$$

So, while steam is expanding, the steam temperature should drop up to $T_3 - T_{3'}$ inside the turbine itself. So, the 3' state point should be inside the turbine where the temperature would be less than T_3, but this 3' prime temperature should be even greater than T_4 depending on the location of this coil. So, if we would like to increase the temperature of water by this $\Delta T = T_{2'} - T_2$ this ΔT will come from the flowing steam.

So, we can assume the process is reversible. If the process is reversible, we can take any cross section and the temperature of water and temperature of steam will be equal. If heat addition process that heating of the feedwater is reversible and you know water is flowing in the opposite direction to the steam flow then at any cross section temperature of steam and temperature of water would be equal. If that is the case, we can write that

$$T_2 = T_{3'} \text{ and } T_{2'} = T_3$$

So, if we assume that the process is reversible then at any section, the temperature of water and steam are equal. So you understand that if the process is reversible then at any section even at the inlet and outlet also the temperature of water and temperature of steam will be equal.

Now, in this T-s plane we could not show the process 3-3'. We have shown 3-4 over here that is isentropic expansion, but 3-3' process we could not show here. We have also shown 2-2' here. Since these 2 temperatures are equal, the path which should be followed by steam for this drop in temperature will be identical to the path which is followed by this water for the rise in temperature when passing through the coil. So remaining 3'-4' will be again isentropic.

So, now let’s draw T-s diagram for this regeneration again. As shown in the slide, we can mark the points 1, 2, 2', 3, 3', 4, 4'. We can also extend those points on X-axis and mark a, a', b, b' as shown in the slide.

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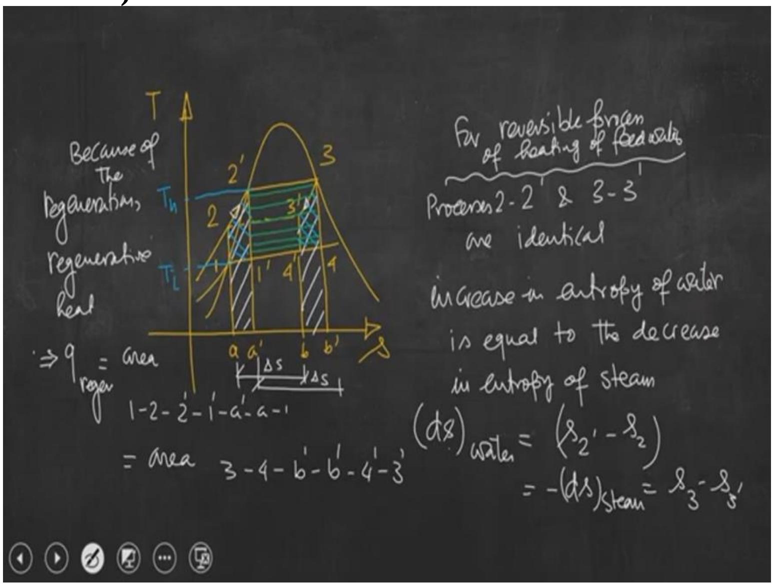

So, now if I hatch this portion a-a'-2'-2, then this represents the regeneration. I have mentioned that the processes 2-2' and 3-3' are identical for reversible process of heating of feedwater. So, basically we know that at any cross section the temperature of steam and water are equal then we can write that increase of entropy of water would be equal to the decrease in entropy of the steam. So we can tell that increase in entropy of water that is

$$(ds)_{water} = (s_{2'} - s_2)$$

$$(ds)_{steam} = (s_3 - s_{3'})$$

So, you can understand increase in entropy of water is equal to decrease in entropy of steam. So, now the regeneration, the regenerative heat = q_{regen}.

$$q_{regen} = \text{area of } 1 - 2 - 2' - 1' - \text{a}' - \text{a} - 1 = \text{area of } 3 - 4 - \text{b}' - \text{b} - 4' - 3'$$

So, these 2 areas are equal that we can see from the schematic because the process 2-2' and process 3-3' are same. And also it could show that increase in entropy of water is equal to decrease in entropy of steam. So, it is because of this reduction in temperature or heat, we can regenerate that heat so, this is the regenerative heat.

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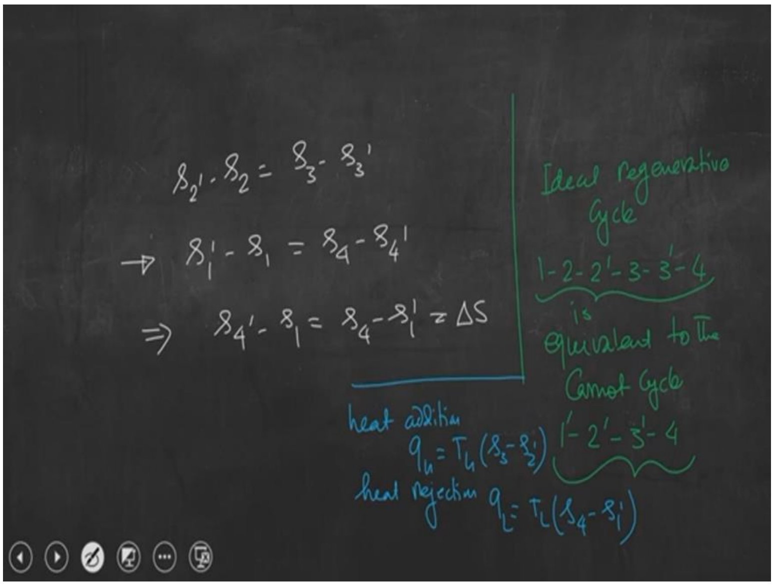

$$s_{2'} - s_2 = s_3 - s_{3'}$$

From the T − s diagram, $s_2 = s_1 \; and \; s_{2'} = s_{1'}$

Similarly, $s_3 = s_4 \; and \; s_{3'} = s_{4'}$

$$\Rightarrow s_{1'} - s_1 = s_4 - s_{4'}$$

$$\Rightarrow s_{4'} - s_1 = s_4 - s_{1'} = \Delta s$$

So, from the T-s plane, so, this $ab = \Delta s$ and also this $a'b' = \Delta s$. If we look at this TS diagram we can say that ideal regenerative cycle is 1-2-2'-3'-4'. So, this is equivalent to the Carnot cycle which is 1'- 2'- 3'- 4. So, basically why because you know this is $s_{4'} - s_1 = s_4 - s_{1'} = \Delta s$. So, you know, this particular segment this is equal to this.

Since these 2 areas (1-1'-2'-2 and 3-3'-4'-4) are equal that is basically regenerative heating. Because if we reduce this one, so, if we subtract this area from this ideal regenerative cycle, and if we add this area, then you can understand 1'-2'-3-4 you will be getting. So, if we subtract this area from this ideal degenerative cycle and if we add here, since these 2 are equal, we are getting new cycle and that is the Carnot cycle.

So, 1'- 2'- 3'- 4 is the Carnot cycle. So, in conclusion, it is because of this ideal regeneration cycle heat is added at a constant temperature and heat is rejected at constant temperature. Now,

Heat addition for Carnot cycle , $q_h = T_h(s_3 - s_{2'})$

Heat rejection for Carnot cycle , $q_l = T_l(s_4 - s_{1'})$

$$s_3 - s_{2'} = s_4 - s_{1'} = \Delta s$$

So, we can conclude that the efficiency of the ideal regenerative cycle seems to be equal to that of the Carnot cycle. So, ideal regenerative cycle is equivalent to the Carnot cycle in which heat addition is at constant temperature T_h and heat rejection is again at constant temperature T_l. And it is because of this regeneration, at least we could eliminate this segment (2-2') so that the average temperature of heat addition becomes lower. So, by making use of this regeneration, we can increase the efficiency of the cycle.

A very important part is that this regeneration not only improves the efficiency of the cycle, but also provides a convenient means of deaerating the feedwater. Let me tell you briefly. I have discussed this issue that condensers are operated at a pressure which is less than atmospheric pressure. So, when the steam is taken to the condenser, chances are there for leakage of air into the condenser from the ambience. So, the feedwater which would be collected and again will be pumped back to the boiler will be having some air. But if we cannot de-aerate feed feedwater. So, it should not be a proper design, if we do not think about the removal of air from the feedwater before it enters into the boiler, because presence of air in the feedwater start initiate corrosion of the boiler pipe. So, that is again very detrimental from the perspective of the boiler operation.

This regenerative cycle not only improves the efficiency that we have seen from today's discussion, because we could show that the ideal regenerative cycle is equivalent to the Carnot cycle in which constant temperature heat addition is there and constant temperature heat rejection is there, but also provides a convenient means of de-aerating the feedwater before it enters into the boiler. That part will discuss in the next class.

But before coming to the conclusion, let me tell you, though we could establish that the regenerative cycle efficiency is as good as Carnot cycle efficiency, but such an arrangement which we have discussed today is not a practically viable solution. So, there are several other ways by which the temperature of feedwater can be increased before it enters into the boiler and those aspects we shall discuss in the next class. So, with this I stop here today, we shall continue our discussion on this particular topic in the next class. Thank you.