**Applied Thermodynamics**
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**Steam Power System**
**Lecture - 10**
**Improvement in Rankine Cycle Efficiency: Regenerative Methods**

I welcome you all to the session of Applied Thermodynamics, and today we shall discuss about the Regenerative Method.

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We have discussed about the improvement of Rankine cycle efficiency and in the context of this aspect we have discussed about super heating and also reheating.

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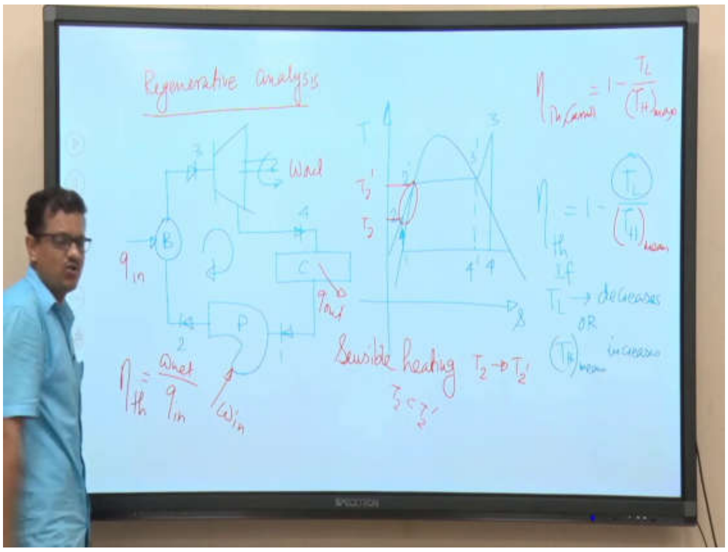


Now, if we draw the T-s diagram we see; you can see that the state point 3` is the state of steam before it enters into the turbine. This is for the ideal Rankine cycle.

Now, as we have discussed that we can go for the super heating by which we can increase the temperature of steam beyond point 3` and we can super heat up to point 3.

Now, in both the cases you can see either steam will start expanding in turbine from 3` to 4` if we do not go for super heating the steam. But if we go for super heating the steam beyond point 3` then steam definitely will expand from 3 to 4 that is in the turbine.

See, here our objective should be to increase efficiency. So, there are two ways, either by decreasing $T_L$ or by increasing $(T_h)_{mean}$ but as I told you in the in previous classes that we really cannot decrease $T_L$. We can increase the mean temperature of heat addition.

So, if we look to increase temperature of steam beyond 3`, we are essentially increasing the average or mean temperature of heat addition. We can definitely super heat steam that is not bad, because it not only improves the efficiency, but also increase the quality of the steam. So, it is advantageous from the perspective of the life time of the turbine blade.

So, cannot we look at one important point that is regenerative analysis? What do we mean by regeneration? Now, if we look at this particular part that is heating from $T_2$ to $T`_2$; we are having this component of heating that is this sensible heat transfer. So, this heating takes place at a relatively lower temperature. So, you know that is $T_2 < T`_2$; that is quite obvious because you are pumping liquid that is also at normal temperature. Now we are heating, so basically we are increasing temperature of the feed water which is being fed by the pump to the boiler and that heating takes place at a relatively lower temperature.

And we have discussed in previous classes that this part of heating lowers the average or mean temperature of heat addition. So, definitely we can look into all these aspects like super heating steam and then reheating, but why cannot we look at this particular aspect; cannot we think about increasing the temperature of the feed water before it enters into the boiler?.

If we do so, then perhaps we can increase the mean temperature of heat addition which in turn will approach towards $(T_H)_{max}$ that we consider for ideal Carnot cycle. So, $\eta_{thermal,Carnot} = 1 - \frac{T_L}{(T_H)_{\max}}$.

Now, our objective should be to increse this mean temperature of heat addition in the ideal Rankine cycle. If $(T_h)_{mean}$ becomes closer to $(T_h)_{max}$ we can reach the ideal Carnot cycle efficiency. Now, as I discussed we can go for super heating and reheating, those aspects we have already discussed. But we really cannot ignore this part of heating from $T_2$ to $T`_2$.

So, cannot we increase the temperature of feed water so that the sensible heating component can be reduced. And if we can reduce this low temperature sensible heating then it will increase this $(T_h)_{mean}$ closer to $(T_h)_{max}$ and we can increase the efficiency of the cycle.

So, the idea is to reduce the low temperature heating of the feed water. So, our objective should be to increase the mean temperature of heat addition by reducing or eliminating.

If we can eliminate it that is well and good, if we cannot eliminate it we can reduce. So, if we can reduce this amount of low temperature sensible heating we can raise the average temperature of heat addition and it will eventually be closer to the $(T_h)_{max}$ so that we can achieve almost the Carnot cycle efficiency. And this could be made possible by making use of the regenerative analysis.

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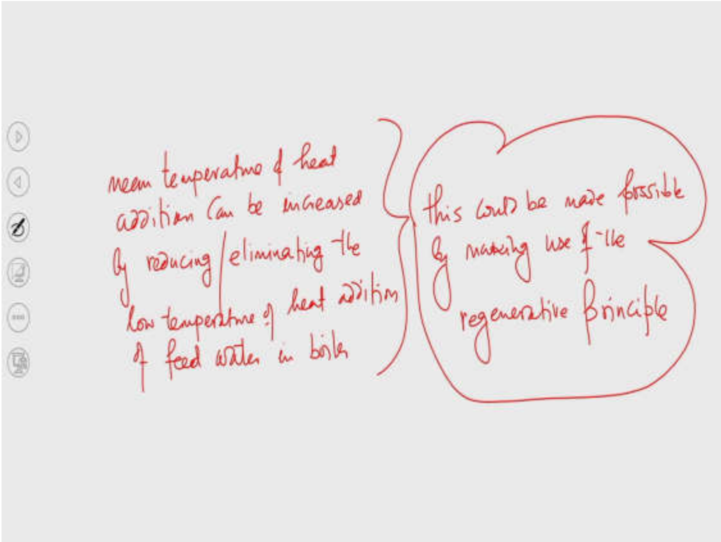


So, mean temperature of heat addition can be increased by reducing or eliminating the low temperature of heat addition of feed water in boiler. And this could be made possible by making use of the regenerative analysis, regenerative principle. So, what is regenerative.

So, now when feed water is pumped to boiler, so before it goes to boiler if we can increase the temperature of feed water by some other means then perhaps we can increase the mean temperature of heat addition. See, when feed water is pumped to the boiler and essentially you are supplying heat to the boiler. Now, upon receiving heat from the combustion of coal, if it is coal fired boiler, the water temperature first will increase from $T_2$ to $T`_2$. Now, if we somehow can provide temperature; the feed water temperature will be $T`_2$ then perhaps this amount of temperature increase will not be there in the boiler and we can save the fuel cost. And in that case we can increase the efficiency, because net work divide by net heat input that is nothing but the $q_{in}$ is equal to the efficiency. So, if we can reduce the $q_{in}$ then efficiency can be increased and it will be closer to the ideal Carnot cycle efficiency.

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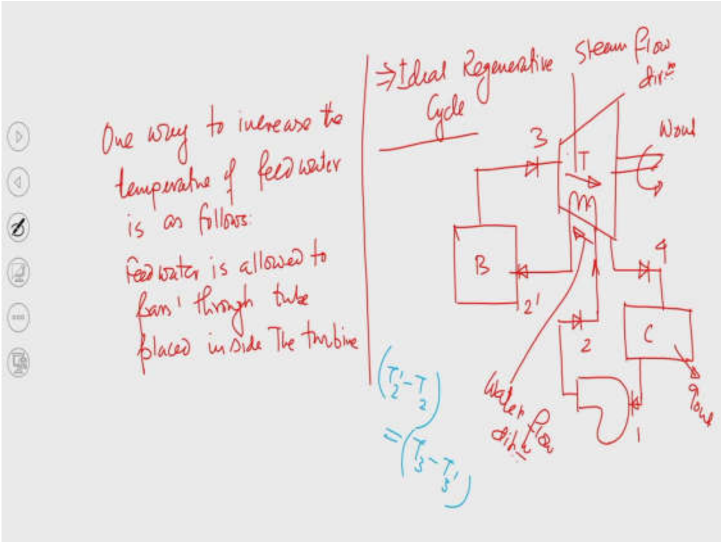

So, one way to increase the temperature of feed water is as follows. So, feed water is allowed to pass through tube placed inside the turbine. So, let me draw the schematic depiction that will help you to understand what I would like to discuss now.

So, this is boiler and then this is turbine. So, you will be getting $w_{out}$ and the steam will expands and it will be collected. It will be allowed to pass through condenser wherein we will be having heat rejection. And then it will be collected and that collected condensate will be pumped.

So, this is a special arrangement; I mean if you now compare this schematic with the previous one; in this case directly the condensate collected from the condenser is pumped back to boiler without taking that particular water into the turbine. But, here what we can see? We can see the condensate that is collected will be pumped through a circuit which is placed inside the turbine.

So, when water is allowed to pass through the circuit which is placed inside the turbine and steam is expanding. So, this is basically a counter flow type heat exchanger. Turbine will now is acting as a dual performer. So, basically turbine is allowed steam to expand and while steam is expanding it does work on the rotating part of the wheel we are getting work output. On the other hand since this circuit is placed inside the turbine and water will flow in the opposite direction to this steam flow.

So, the turbine is now acting as a work producing device, it is also now acting as a counter flow heat exchanger. So, when water is passing through the turbine through the circuit where the direction of water flow is in in the opposite direction to the steam flow and the water will be heated by taking heat from the expanding steam.

So, there will be heat transfer. Heat will be transferred from the expanding steam because steam is having high enthalpy. So, that temperature will be transferred from expanding steam to the water, eventually when water will be entering into the boiler that is the thermodynamic state at 2`. So, water temperature at state point 2` will be definitely higher than the water temperature which it had at state point 2.

So, now you can see that perhaps by taking heat from the expanding steam we can save the fuel which would have been required to increase the temperature from $T_2$ to $T`_2$, if we had passed water directly to the boiler. So, in that way we can increase the efficiency of the plant and this is called ideal regenerative cycle.

Now, using this ideal regeneration method, we are still having one important disadvantageous feature. Which is that? When steam is expanding in this direction definitely it will exchange heat with the water that is flowing in the reverse direction.

While exchanging heat, steam temperature may fall at the exit of the turbine. So, the possibility of having high moisture content of the steam which will leave from the turbine will be there and it may lead to turbine blade erosion. The concept is that to take heat from one part of the cycle and that heat will be added to the working substance in another part of the cycle.

So, the ideal regenerative cycle is though not feasible because maybe we can increase temperature of water from $T_2$ to $T`_2$. To increase that temperature, we may reduce the steam temperature and the quality of the steam leaving the turbine may be vulnerable to the turbine blade erosion.

So, instead of allowing water to pass through the turbine what we can say? Because ultimately steam will be in contact to the tube which is placed inside the turbine; so, the concept is we can take certain amount of heat from one part of the cycle and that heat will be utilized to increase temperature of feed water in another part of the cycle and that is nothing but the regeneration.

So, we do not require additional amount of fuel to heat up that feed water rather we are taking certain amount of heat from one part of the cycle and that heat will be utilized to increase the temperature of feed water in another part of the cycle and that is nothing but regeneration.

So, since this is having one serious problem that the life time of turbine blade may hamper. So, knowing fully that quality of the steam may deteriorate at the exit of turbine, so, we cannot go for this particular method. But still there are so many other method.

What are the methods? Instead of allowing water to pass through the coil which is placed inside the turbine what we can do, we can have a separate chamber in which water will be allowed to mix with certain portion of steam that will be extracted or bleed.

So, we can have steam bleeding or steam extraction and may be after doing certain work we can extract certain amount of steam from the turbine. And we can allow that steam to be mixed with the water or condensate which is coming from the condenser. In that way we also can increase steam temperature. Now, if we do like this perhaps the problem expected problem of having turbine blade erosion can be avoided.

So, let us draw the T-s diagram.

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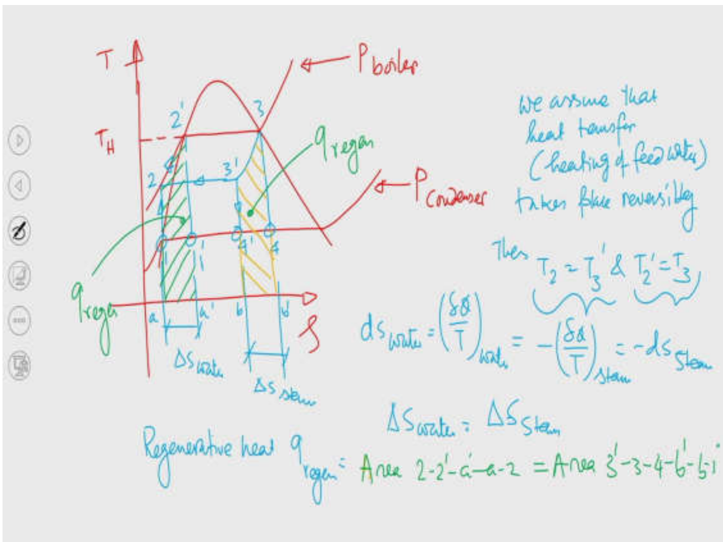

So, now try to understand 2 to 2` that heating will be done, but that heating will not be there in the boiler rather that will be there inside the turbine by using by making use of this special arrangement.

Now, you know that when steam expands inside the turbine steam temperature will fall because of this particular heating. So, $T_2' - T_2 = T_3 - T_3'$ assuming that the processes of heating is reversible inside the turbine. So, now, let me explain you. So, you can see the temperature of water increases from $T_2$ to $T`_2$ and temperature of steam will drop from $T_3$ to $T`_3$ prime. If it is internally reversible process, so, that is quasi static process. So now, if that is the case we can write heating of feed water takes place reversibly, then $T_2 = T_3' \text{and} T_2' = T_3$ .

So, this is very important to understand. If you assume that the heat transfer takes place reversibly, then these two temperatures will be equal and in that case the path followed by steam and water will be exactly equal.

So, if the process is reversible then if you draw a line, at any point steam temperature must be equal to the water temperature, quasi statically they are in equilibrium condition.

So, at any point between the heating and cooling process temperature of steam and water will be equal. And as a result of which the path followed by steam will be exactly equal to the path followed by the water. Now, we can write $ds_{water} = \left(\frac{\delta Q}{T}\right)_{water} = -\left(\frac{\delta Q}{T}\right)_{steam} = -ds_{steam}$ .

You have studied second law, so heat will be gained by water which is allowed to pass through the coil. So, entropy of water will increase, but there will be transfer of heat from the flowing steam. So, entropy of the steam will decrease. We have written this formula because we have considered this is reversible process. So, there is no entropy generation.

We can write $\Delta s_{water} = \Delta s_{steam}$ . So, this is possible if we consider this heating and cooling processes are reversible process. There is no entropy generation. So, this is highly for the reversible process and you can see the minus sign has come only because of the reduction entropy. So, the gain in entropy by water is equal to the loss of entropy by the steam. So, this is the equation.

Now, you can see after expanding, steam temperature will drop from $T_3$ to $T`_3$ and the remaining expansions takes place isentropically that is 3` to 4`.

Now question is, what is regenerative heat? So, you can understand regenerative heat that is QΔs; this is 2-2`. So, since the processes are reversible; so, this area under this process line will give you the regenerative heat. So, heating is equal to the cooling.

So, that is nothing but area under the curve 2-2`-a`-a-2 = 3`-3-4-b`-b-3`. So, from this T-s diagram can we write that $\Delta s_{water} = \Delta s_{steam}$ . $\Rightarrow s_1' - s_1 = s_4' - s_4 \Rightarrow s_4 - s_1' = s_4' - s_1 = \Delta s$

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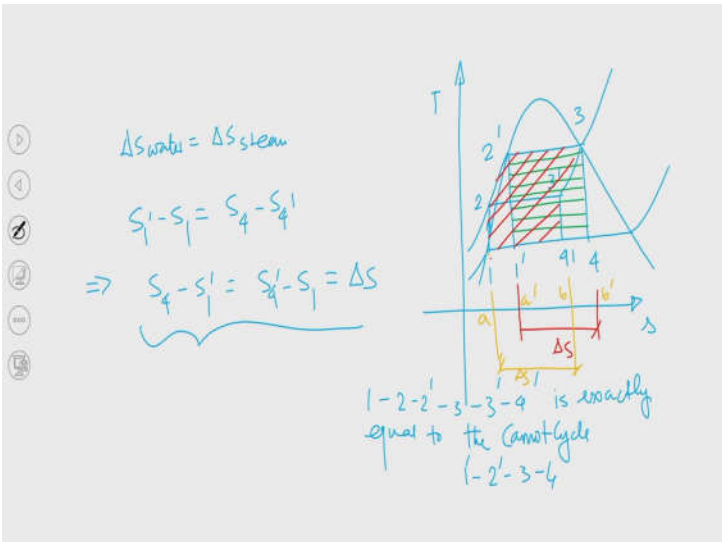


So, the ideal regenerative cycle is denoted by 1-2-2`-3-3`-4`. Carnot cycle is exactly equal to the 1`-2`-3-4. Since $\Delta s_{water} = \Delta s_{steam}$; from this T-s plane the area 1`-2`-3-4 will be equal to the area 1-2-2`-3-3`-4`. What does it mean? It indicates that efficiency of the ideal regenerative cycle is equal to the ideal Carnot cycle.

So, we are doing this exercise essentially to establish that by doing this regenerative principle we can increase efficiency of the cycle closer to the ideal Carnot cycle. So, from these simple mathematical analysis we can prove this with only one important assumption is that the heating of water and cooling of steam inside the turbine will take place following reversible process.

If we can do so, that means if we make that processes infinite slow, then we can show that the efficiency of the ideal regenerative cycle will be equal to the efficiency of the Carnot cycle. For all the cases for both the cases heat rejection is remaining same. So, efficiency of the ideal regenerative cycle will become closer to the ideal Carnot cycle; this is only possible because of the increase of the mean temperature of heat addition.

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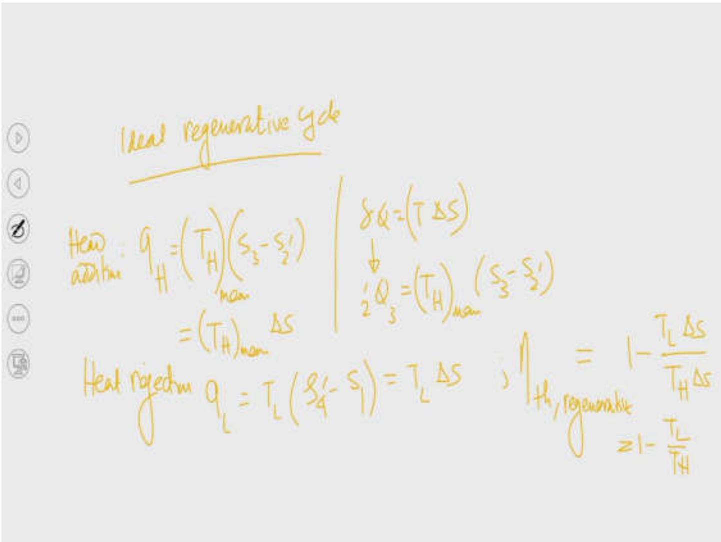


For the ideal regenerative cycle, we can write $\delta Q = T\Delta s$. So, if we integrate the to this process then ultimately we will get ${}_{2'}Q_3 = (T_H)_{mean}(s_3 - s_2')$. So, this is nothing but $(T_H)_{mean} \Delta s$. So, this is now this is heat addition. Similarly heat rejection $q_L = T_L(s_4' - s_1)$ that is nothing but $T_L \Delta s$.

See these two ΔS are equal that is we have already proved $s_4 - s_1' = s_4' - s_1$. So now, efficiency will be $\eta_{\text{th,regenerative}} = 1 - \dfrac{T_L \Delta s}{T_H \Delta s}$.

So, this is not Carnot so I cannot write $1-\frac{T_L}{T_H}$ rather we can write $1-\frac{q_L}{q_H}$. So, that is nothing but $1-\frac{T_L}{T_H}$. So, we have been able to establish that only by having this regeneration, we could increase the efficiency of the ideal regenerative cycle and we could increase up to the Carnot efficiency.

So, if you try to summarize by doing this simple mathematical analysis we have been able to establish that by increasing temperature of feed water before it enters into the boiler, we can increase the efficiency of the cycle up to the extent of the Carnot efficiency.

So, though the ideal regenerative cycle may not be feasible in practice, because of its disadvantageous feature that moisture content of steam leaving the turbine will increase and it may lead to turbine blade erosion. But there are several other means by which we still can have regeneration and those aspects we will be discussing in the next class.

Thank you.