Applied Thermodynamics
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Steam Power System
Lecture - 09
Improvement in Rankine Cycle Efficiency: Reheating and Regenerative Methods

We shall start our discussion today on the Reheating and Regenerative cycles. We have discussed in the previous class about the modification of Rankine cycle essentially to increase the efficiency.

Now, what we have seen from yesterday's class is that one way to increase the efficiency of the ideal Rankine cycle is to increase the boiler pressure or to increase the temperature of steam leaving the boiler, that is to super heat the steam.

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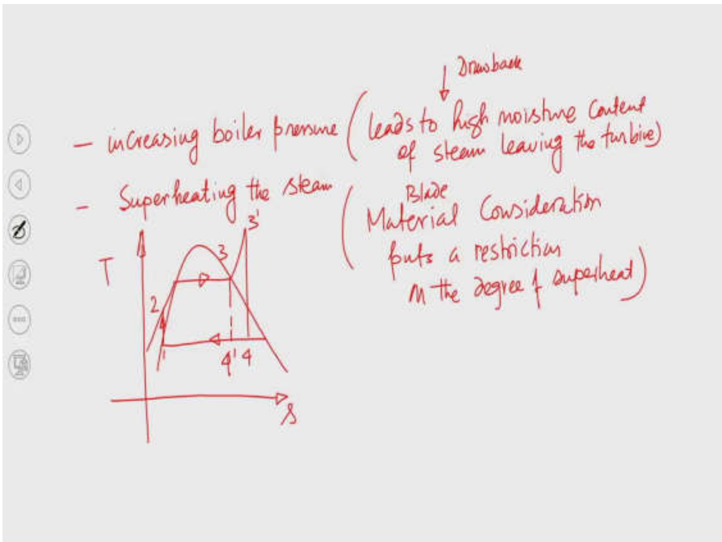

So, we have seen that whether we try to increase the efficiency of the cycle by increasing boiler pressure; we can increase the efficiency by 3 to 4 percent.

But at the cost of that increase in efficiency, we are going to invite another problem of having high moisture content of steam at the exit of the turbine. So, this leads to high moisture content of steam leaving the turbine. So, this is one important drawback.

For super heating the steam, we have seen that we can increase the efficiency; we can increase the equality of the steam at the exit of the turbine. Now, if we increase the temperature of steam beyond 3, that is if you would like to have super heated vapour by increasing steam temperature, how we can do? We discuss that we can allow steam to pass through the super heater.

So, we can really increase the quality of the steam at the exit. But the question is, maybe we can increase the efficiency also the quality of the steam leaving the turbine can be increased? But the problem is the turbine material consideration.

So, material consideration puts a restriction on the degree of superheat. So, we can increase the temperature of steam beyond point 3, but the degree of super heat by which the steam temperature can be increased is not arbitrary.

So, we have constraint that is imposed by the turbine blade material. So, considering these two aspects, we have discussed about ideal Rankine cycle and we have also discussed about these two important issues by which we can really increase the efficiency of the simple Rankine cycle.

There is also another way by how we can increase the efficiency of the simple Rankine cycle is by lowering the condenser pressure; but that aspect we will be discussing when we will be discussing about condenser.

So, we can reduce the condenser pressure but we cannot even go beyond a particular value, that we will be discussing. So, for the time being at least we should know that, we really cannot increase boiler pressure or we really cannot increase the temperature of steam leaving the boiler to the extent possible. We are having restriction considering the blade material of the turbine. So these are not the viable solution.

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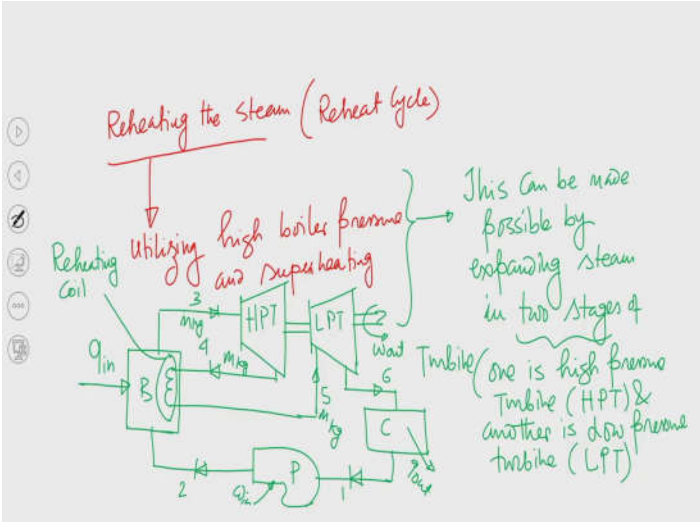

Another important method is reheating, reheating the steam, this is called reheat cycle. So, this is even very simple, We can reheat the steam. So, basically reheating the steam, it is accomplished by increasing boiler pressure.

So, basically it is utilizing high boiler pressure and super heating. So, from the previous discussion we have seen that, increasing boiler pressure also leads to increase in efficiency; but it leads to the deterioration of the quality of the steam leaving the turbine.

Super heating also leads to increase in efficiency; but as I discussed that from the perspective of the turbine blade consideration, we are having even some kind of restrictions. So, now, we can use the combination of these two, that is high boiler pressure as well as super heating the steam to increase efficiency and that is nothing, but reheating.

So, the concept of reheating which I have written over here, utilizes both high boiler pressure as well as super heating. And we will see that utilizing this concept, we can increase the efficiency of the cycle by 4 to 5 percent without compromising the quality of the steam at the turbine outlet.

So, now let me draw the schematic depiction. So we are trying to utilize the combination of high boiler pressure and super heating the steam, essentially to increase the efficiency of the cycle without compromising the quality of the steam.

To implement that, what we need to do? So, this can be made possible by expanding steam in two stages.

So, one is high pressure turbine, that is HPT, and another is low pressure turbine, that is LPT. So, essentially that steam which is coming out from the boiler will be allowed to pass through two different turbines; first one is high pressure turbine and then after doing work in the high pressure turbine, that steam will be taken back to the boiler and it will be allowed to pass through a coil which is placed inside the boiler. And then again, the steam will be taken to low pressure stage turbine. And finally, we will be getting work output from the turbine.

And finally, when the steam is coming out from the low pressure stage turbine, it is taken as usual to a condenser and from the condenser, the collected condensate is pumped back to the boiler, so this is what is the schematic depiction.

So, as I told you, steam will be allowed to expand. So, we will be using super heating steam. So, we will be using super-heated steam, while it expands in the high pressure stage turbine. So, the steam which is coming out. So, boiler will be operated at high boiler pressure and also the steam which is which will be coming out from the boiler is the super-heated steam, not the saturated steam. So, when steam is expanding in the high pressure stage turbine, it does work on the rotating part.

So basically the shaft of the high pressure and low pressure stage turbine is common. So, now, after expanding steam is taken back to the boiler, we are having one reheating coil.

So, the name reheating is coming from the fact that after expanding steam in the high pressure stage turbine, steam is taken back to the boiler, wherein it is allowed to pass through this reheating coil. So, basically it is passed through a coil, where it is reheated. So, that is why the name reheating is coming.

Now, after this heating, again steam is taken to the low pressure stage turbine and it does work again and finally, the process is as usual that we have discussed many times. So, question is, if we do this practice; perhaps this is the common practice which is followed in modern steam power plants.

We can increase the efficiency because first of all boiler is working at high boiler pressure. So, if I draw the T S diagram which will help us to understand the increase in efficiency without compromising the quality of the steam in a more convenient way.

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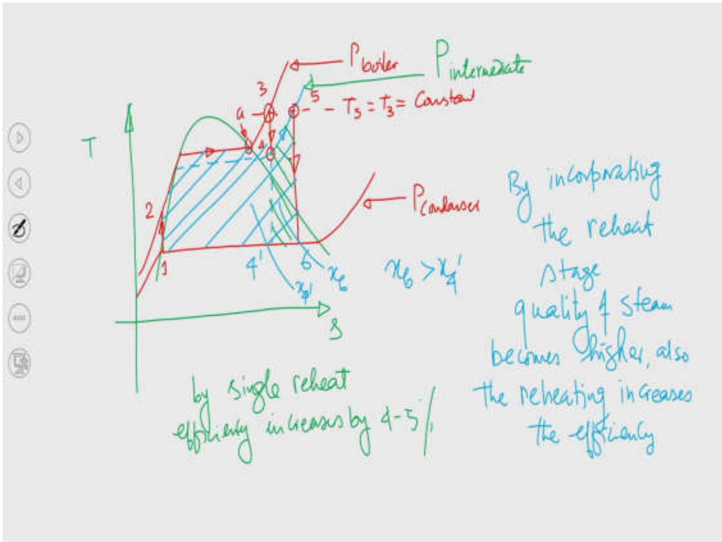

I will be using different colours to represent different processes; So, you understand process 6 to 1 that is the condensation process. So, we will be having two different pressure; one is boiler pressure, other is the condenser pressure.

So, this is constant pressure line in T S plane, so this is $P_{condenser}$. We will also have one pressure line that is boiler pressure line. So, this is P_{boiler}. So, as I told you that process 1 to 2 that is reversible adiabatic process, work done that is nothing but *-vdp*. In fact, again I am telling, for both the reversible adiabatic and reversible isothermal processes; the work done is *-vdp*, it is not *pdv* work.

So, the process 1 to 2 is pumping process that is reversible adiabatic process or isentropic. Now, the boiler is operating at high boiler pressure and steam is reheated.

So, the point ‘a’ is the saturated vapour, but we are allowing the temperature of steam to increase beyond point a, that is you are trying to have super heating.

So, say this is the point 3. Now, from this thermodynamic state point 3, steam is taken to high pressure stage turbine and it does work. So, when steam is entering into the high pressure stage turbine, it will expand; it will expand up to an intermediate pressure.

So, when steam is expanding in the high pressure stage turbine; it does work on the rotating part of the turbine. It is taken back to this coil for reheating. So, it is expanded up to an intermediate pressure isentropically.

So, say this is point 4. Then steam is reheated again inside the boiler and is this allowed to pass through this coil. So, the pressure is not the boiler pressure, but somehow it is an intermediate pressure.

So, the steam is heated preferably up to that super heat temperature. So, this is point 5. Point 5 is the inlet state before it enters into the low pressure stage turbine. So, the temperature of point 5 is preferably equal to the temperature of point 3, otherwise it will not be justified.

So, when steam is taken back to the boiler and it is allowed to pass through this heating coil; it is reheated up to the temperature which is equal to the temperature of steam before it enters into the high pressure stage turbine. So, basically it is designed in such a way that T_5 should be equal to T_3.

Then it is expanded in the low pressure stage turbine isentropically. So, this point is 6. So, we try to understand that we are utilizing high boiler pressure essentially to increase the efficiency, we are also allowing steam temperature to go beyond point a, that is your super heating.

Now, if we superheat and also we are using high boiler pressure; the concept of these two we are utilising over here. But, if we allow the steam from point 3 without reheating, then say it reaches 4`; try to understand if we do not include this reheating stage and if I allow steam to expands from point 3 isentropically, then the quality of the steam will be $x`_4$.

Now, quality of the steam is x_6. So, definitely $x_6 > x`_4$. So, though we are using high boiler pressure, but still we are not going to compromise the quality of the steam; by incorporating this reheating stage. So, by the reheat stage, quality of steam becomes higher, also the reheating increases the efficiency.

So, this is what we wanted to discuss. So, see only by having one reheat stage, we can increase the quality of the steam; you also can see the total area under the process line 1-

2-3`-4-5-6-1 will give the net work output.

Had steam been allowed to drop to expand isentropically from point 3 to 4 prime; we had to compromise the work done that I can show by this hashed portions say this is the extra amount of work that we are getting.

So, we can see the area shown by the hashed portion is the additional amount of work we are getting; not only that because of this extra amount of w_{net}, cycle efficiency will increase, we also can improve the quality of the steam leaving the turbine. So, a single reheat stage, increases efficiency by 4 to 5 percent.

So, you can say that, we can increase the number of reheat stage more than 1. So, boiler is operating at high pressure, steam is super heated up to point 3 beyond point a, steam is taken to the high pressure stage turbine and it is allowed to expand up to an intermediate pressure that is P_5 and then it is taken to that heating coil and reheated up to the temperature point 4, preferably it is designed.

So, the reheating stage is designed in such a way that after reheating, temperature should be equal to the temperature of steam at the inlet of high pressure stage turbine. And then steam is finally, expanded isentropically up to point 6.

Now, question is, if we can increase efficiency by 4 to 5 percent by having only one reheat stage; we can increase the reheat stage may be more than 1, but we cannot.

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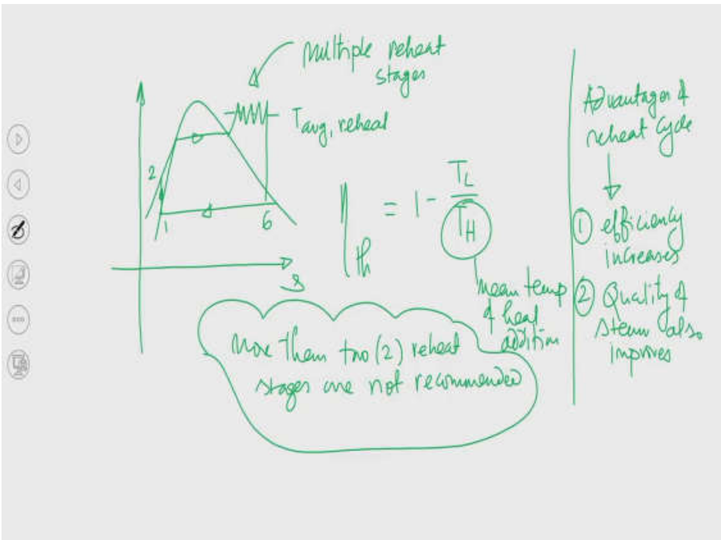

Now, say we can have multiple reheat stage but this T average of reheat do not change.

So, you know that efficiency of any Rankine cycle or heat Rankine cycle is nothing but $1-\frac{T_l}{T_h}$.

So, our objectives should be to increase the average temperature or a mean temperature of heat addition and to decrease T_L. Now, though if we are trying to have multiple reheat stages; can we really increase the mean temperature of heat addition? No.

Though we can increase multiple reheat stage, but average temperature of heat addition is remaining almost constant. In fact, that is what I have highlighted, that when steam is reheated; it is designed in such a way that, reheating temperature is T_5 will be equal to T_3.

So, basically though we can increase efficiency by 4 to 5 percent having one reheat stage; but multiple reheat stages will not increase efficiency in that proportion, because the average temperature of reheating is remaining same and that is the same order of magnitude.

Since average temperature of reheating is of the same order of magnitude as that of the super heating. So, you can understand, if we have only super heating up to point 3; then average temperature will be having equal to the average temperature even after having one reheat stage.

So, this is one of the important drawback that we really cannot go beyond 1 or 2 superheating. So, practical aspect is that we can go up to maximum 2 reheat stages, not more than 2 reheat stages.

Maybe we can go up to 3, 4 or 5 reheat stages; but the gain in efficiency even after having 4 or 5 reheat stages will not be justified by the cost associated with the incorporation of 5 reheat stages. So, from the practical point of view more than two reheat stages are not recommended. So, this is very important that it is essentially from the cost comparison or cost analysis.

So, this is very important, but one disadvantage is that, we cannot increase more than 2 reheat stages. But what are the advantages? Advantages is that efficiency increases; 2) quality of the steam increases improves.

The most important part is, efficiency will increase that we can see from the schematic depiction, from the T-s diagram that because of the hashed area; quality of the steam also will increase that, we can see from this T-s plane.

Now try to understand one important thing; this much amount of additional net work output we are getting for the same steam flow rate.

So, if we had say m kg of steam at point 3, here also we are having m kg, here also we are having m kg. So, from our one of the previous classes if we try to recall that, since for the same steam flow rate, w_{net} increases; so signifying a low SSC specific steam consumption rate, thereby an a smaller plant.

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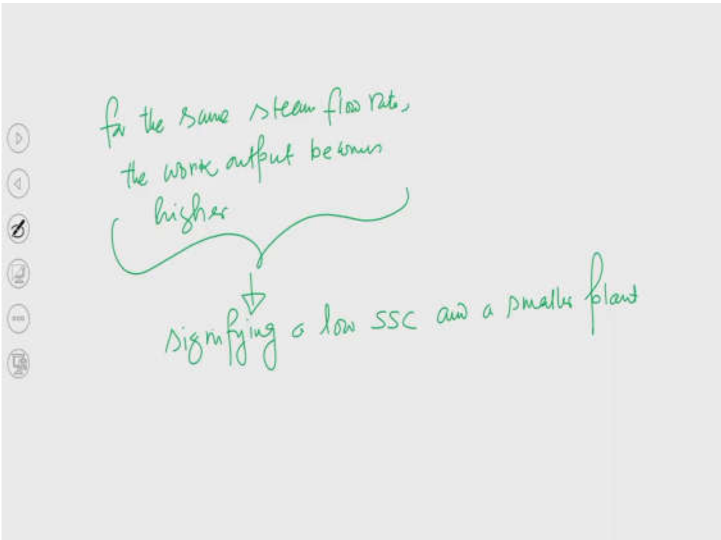

So, for the same steam flow rate, the work output becomes higher; low SSC, thereby a smaller plant. In addition of these two features, that is efficiency increases and quality of the steam also improves; it will also have low SSC; so, smaller plant. If the plant is smaller, installation and operational cost will be less.

Now, one important point I would like to discuss that, we have discussed that we really cannot go beyond 2 reheat stages, I mean from the practical point of view. As I discussed that you can go up to 5, but it should be justified.

So, the cost associated with the installation as well as operation should be justified from the increase in efficiency that we are getting out of these five reheat stages. So, having a comparison cost analysis, it is observed that more than two reheat stages are not recommended. However, now question is, we have discussed in the last class that super heating can also increase the work output, also it increases the quality of the steam.

Now, question is, we could not stick to that particular aspect; in fact super heating really is a very feasible way of increasing efficiency of the Rankine cycle, only constraint is the turbine blade material. So, from today’s discussion we can see, if we can have a particular specific turbine blade material which can withstand high temperature; then perhaps super heating will be more viable than reheating stages.

So, having even one reheat stage, you have to have pipeline, you have to have two different stages of turbine, you have to have one heating coil. So, installation cost as well as operational cost will be high.

But question is, if we can have a specific turbine blade material, which can withstand high temperature; then perhaps it is not required to go for the reheating method, instead we can use the super heating stage.

So, though reheating provides all these favourable features; even then if we can have a specific material which will be used to fabricate turbine blades and if that particular material can withstand high temperature, then super heating will be more viable than the reheating stage. So, with this I stop here today and we shall continue a discussion in the next class.

Thank you.