Steam Power Engineering
Prof. Vinayak N. Kulkarni
Department of Mechanical Engineering
Indian Institute of Technology Guwahati

Lecture -06
Rankine cycle with heat theory and example

Welcome to the class. Till time we have seen that there is Rankine cycle and there can be a Rankine cycle basically without any superheat but it has a certain issues such that it will have problem in the turbine exit since the dryness fraction is very low. So, we have thought to additional superheat; so Rankine cycle plus superheat is also seen and then it has been seen that the Rankine cycle with super heat leads to a turbine work out put.

And then it has basically lead it has basically higher work ratio so but it as also been seen that it is not always possible to have the superheat existing. If we are going to use the water as source of heat then it is not possible. If we have flue gases or liquid metals then it is possible. Then, still if you want to have higher efficiency with superheat then we have to have certain attachments and among that attachment we have one thing which is called a Rankine cycle with reheat. So, topic of discussion at this moment is Rankine cycle with reheat.

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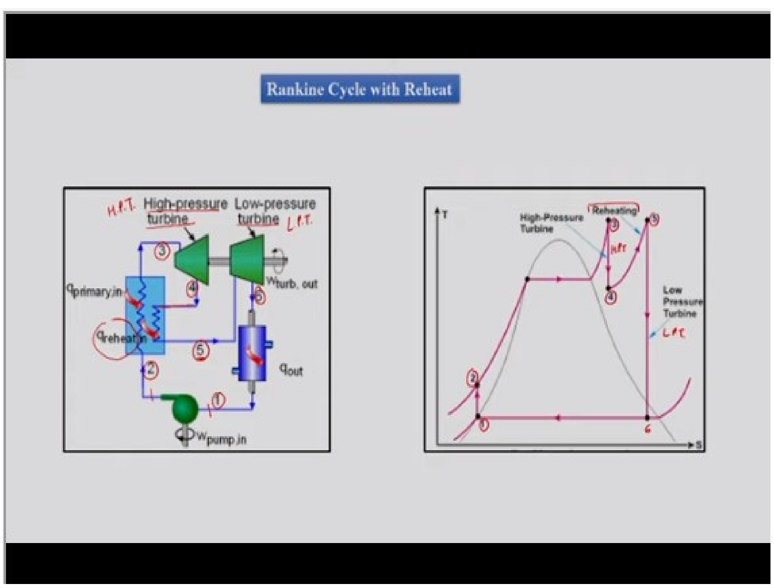

So, the same Rankine cycle as what we have seen where we have wanted to as pump where the water will get pumped from low pressure to high pressure. Once it gets low pressure to high pressure pumping then it will go to the steam generator or boiler where it will get heat addition from the external source like flue gases. And then it will get expanded into the turbine which we call it as high pressure turbine or what we call HPT high pressure turbine.

In the isentropic expansion of high pressure turbine we know that enthalpy of the steam will decrease and we will come to lower enthalpy state which is 4 from the initial state at 3. Here, instead of expanding the steam completely till the pressure of condenser we will heat the steam in heater again as at isobaric condition and in that heater is called as reheater that heater is called as reheater.

So, steam will get reheated from station 4 to station 5 or state 4 to state 5. Then, this steam is supplied to the low pressure turbine and the steam is supplied to low pressure turbine; so low pressure turbine has intake at 5 and then it will expand till the state 6 but state 6 at this moment with single reheat we are reheating only once. So, at the single reheat state 6 corresponds to the pressure of the condenser pressure so we have condensation from state 2 to 1.

So, we can see that there is reheating in the Rankine cycle where we are providing once reheating once to the steam. So that we have only 2 turbines which is high pressure turbine and low pressure turbine. The point to be noted over here that with super heating we were entertaining or we were having only one turbine. So, complete expansion was taken place in only one turbine but when we are talking about reheat we are having 2 turbines in case of 1 reheat or if there are 2 reheats then we will have 3 turbines.

So, such that we will have multiple turbines for the expansion and between 2 turbines we will always have heating of the steam at constant pressure. So, in case of single reheat we have the $T-S$ diagram like this as usual we have 1 to 2 has pump and after 1 to 2 has pump we have heat addition in the boiler from 1 to 2 is pump heat addition in the boiler from state 2 to 3, 3 to 4 is basically our high pressure turbine and 4 to 5 is reheating and 5 to 6 is the low pressure turbine and 6 to 1 is condenser.

So, this how we have our steam power cycle operating when we are having only one reheat. So, this how the steam cycle should work if we expect the reheating to be happening only once. Now, instead of 1 reheat if we plan to have 2 reheats then in such case we can have a schematic to be drawn like this.

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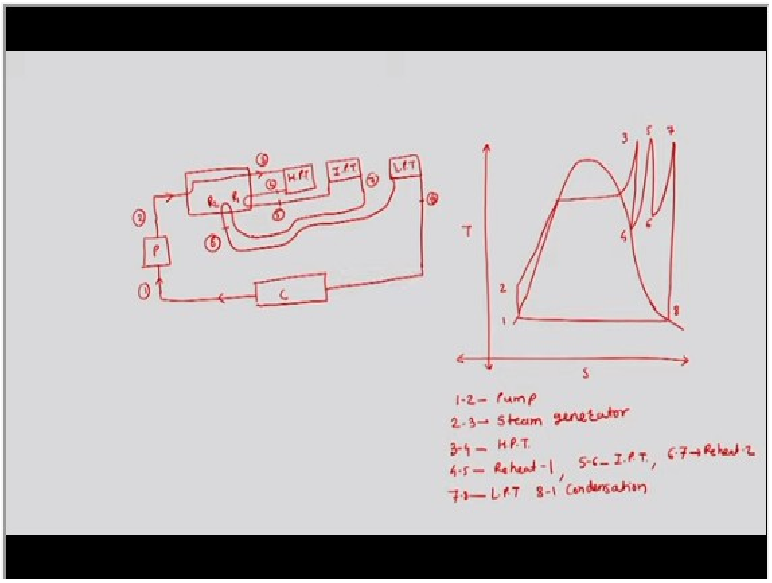

Basically, we will have a pump; pump from station 1 to station 2 after the pump we will have a steam generator from 2 to 3, then after the steam generator we will have turbine which is basically high pressure turbine. Then high pressure turbine steam will be heated and then it will be given to an intermediate pressure turbine. So, 3 to 4 is an expansion, 4 to 5 is first reheat what we will call it as R1 and then 6 to 7 is intermediate pressure turbine.

Then in case of intermediate pressure turbine we will have secondary heat where steam would get reheated from 7 to 8 this is R2. And then it will supplied to the low pressure turbine and from low pressure turbine steam would go to the condenser from 9, 8 to 9 is an expansion and then from condenser it will go the pump. So, this is how a travel of steam would be there; there in that case we can draw the $T-S$ diagram for the steam power plant.

In this case we will have usual dome then we will have 1 to 2 is pumping process, then we will have 2 to 3 is first reheat, then we will have 2 to 3 is heat addition in the boiler, then we will have 3 to 4 first reheat and then we will have 4 to 5 a second reheat 4 to 5 is intermediate pressure turbine, 5 to 6 is our second reheat and 6 to 7 is 3 to 4 is first expansion in high pressure turbine, 4 to 5 is reheat one, 5 to 6 is intermediate pressure turbine, 6 to 7 is reheat two.

And then we entered enter into the 8 which is exit to the low pressure turbine or entry to the condenser. So, here we will have 1 to 2 as pump, 2 to 3 as steam generator and then we have 3 to 4 as high pressure turbine then we will 4 to 5 as reheat 1, then we have 5 to 6 as intermediate pressure turbine, then we have 6 to 7 as reheat 2 and then we have 7 to 8 as low pressure turbine and then we have 8 to 1 as condenser.

So, this is how we will have a schematic or expansion in case if we have multiple or more than one reheats existing and we will analyze now what will happen if we have reheat in the Rankine cycle.

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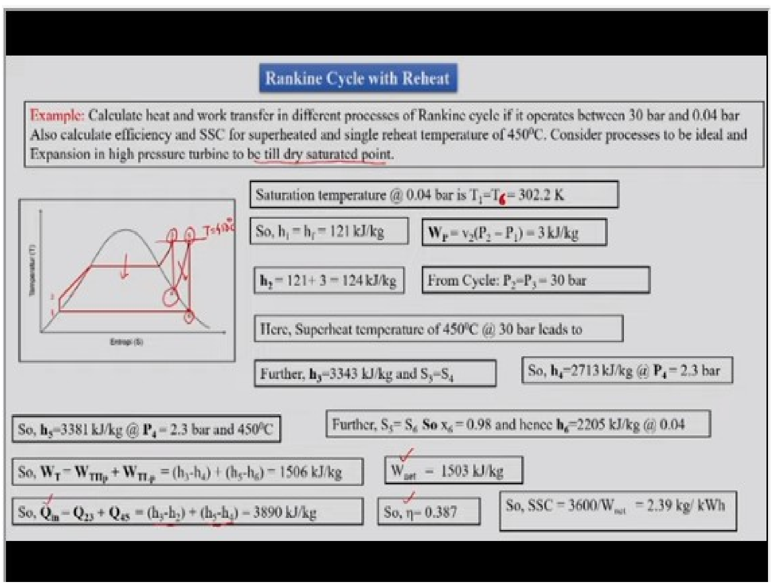

So, for that let us consider the same example where we are told that we have to suppose find out heat and work interaction in the Rankine cycle which is operating between 30 bar and 0.04 bar, 30 bar and 0.04 bar. Here, reheat is told to be single and reheat temperature maximum is said to be 450 degree Celsius, superheat temperature is also said to be $450°C$. Now, all the process are said to be ideal and then we have to find out the work and heat interaction and also specific steam consumption.

One more point to be noted here that expansion in high pressure turbine is still dry saturated point. So, as per our usual notation 1 to 2 is pump, 2 to 3 is boiler, 3 to 4 is expansion in high pressure turbine and as it is mentioned it is till dry saturated point so 4 is a dry saturated point. And then 4 to 5 is reheat we are told that this temperature is $450°C$ so now having known this we can find out.

So, initial thing what we know is T_1 is equal to basically $T_1 = T_6 = 302.2 K$ and then we have $h_1 = h_f = 121\, kJ/kg$. We can find out pump work(W_P) by the same formulae as we what we say specific volume $W_P = v_2(P_2 - P_1)$ we get heat as 3 kJ/kg. So, we know $h_2 = 124\, kJ/kg$ From the cycle we have $P_2 = P_3$ so what we should do is.

We should go to the steam table we should to go to the 30 bar pressure and then we should go to the super heat part of the steam table then we will find out the $450°C$for 30 bar in superheat and then we can know what is h_3 enthalpy at 3 is known to us. Parallelly, we will monitor the entropy at point 3 but we know $S_3 = S_4$. We have no information about pressure or temperature at point 4; we are just given that dryness fraction at $4(x_4)$ is 1.

From this information and known S_3 we can find out which pressure has the saturation entropy of steam is equal to $S_3 = S_4$. So, from that we came to know that pressure is P_4 that is 2.3 bar and that enthalpy is 2713 kJ/kg. So that's how we know the enthalpy at the entry to the reheater 1 now we have single reheater. But then we will again go to the saturated part of the steam table corresponding to 2.3 bar there we will see the temperature at $450°C$ for that we will find out the h_5 which is 3381.

Now, we also monitor S_5 since $S_5 = S_6$ we can find out what is the $x_6$since we know pressure at 6 is 0.04 bar. So, from that we came to know that $x_6 = ¿0.98$, enthalpy at $6(h_6)$ is basically 2205 kJ/kg. So, now by all these means we have found out all the corners of the steam power cycle which is Rankine cycle. Then we can find out turbine work basically turbine work is high pressure turbine plus low pressure turbine work.

So, turbine high pressure, turbine low pressure high pressure turbine is $h_3 - h_4$, $h_3 - h_4$and high low pressure turbine is $h_5 - h_6$, so from that we get turbine work(W_T) as 1506. We get net work (W_{net}) as $W_{net} = W_T - W_P$ which is 1505 then we can get $Q_{¿}$. The major point to be remembered here that we have 2 heat additions; 1 heat addition into the steam generator between pressures 2 to 3(Q_{23}). and also we have heat addition in into the reheater between process 4 to 5 (Q_{45}). So, $Q_{¿} = Q_{23} + Q_{45}$.

So $(h_3 - h_2) + (h_5 - h_4)$, it leads to $Q_{¿} = ¿3890\ kJ/kg$. We know W_{net}, we know $Q_{¿}$ we can find out efficiency it turns out to be 38.7%. We know W_{net}so we know $\frac{3600}{W_{net}}$; so we find out specific steam consumption so this is how we can solve an example for reheat cycle.

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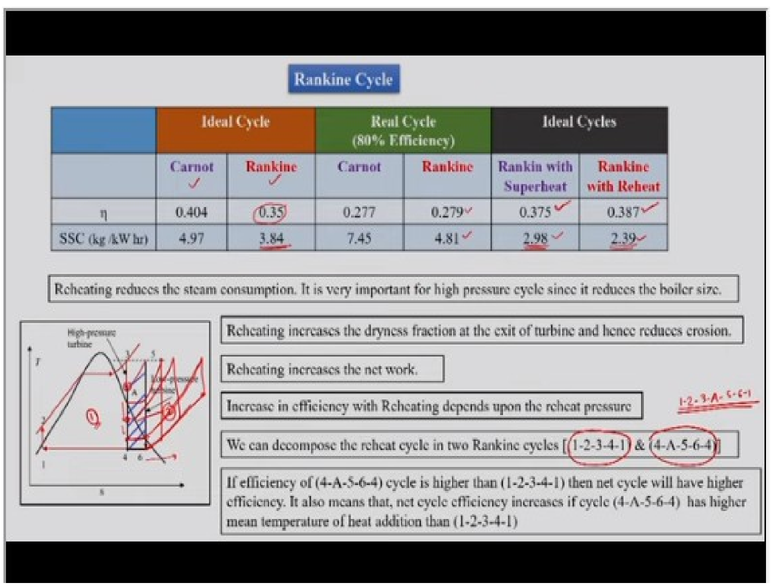

But this example was mainly to compare the different examples in the same between same boiler and condenser pressure so we have solved. We have seen that there is ideal cycle for Carnot and for Rankine where we did not considered any efficiency or with other consider 100% deficiency of components we did not consider any super heat or any reheat for Rankine that time. We saw that Rankine cycle efficiency was less for pressure of ours which is 30 bar and 0.04 bar between condenser and boiler.

But, as we said that there are eight there are components which are non ideal 80% deficiency then we got Rankine cycle as higher efficiency and it has as expected lower specific steam consumption always. But, when we added superheat then in case of super heat Rankine cycle efficiency is basically improved and that is 37.5 with ideal conditions. But, it got further improved when we added reheat and that became 38.7.

But, superheat actually decrease specific steam consumption from 3.84 to from ideal case 2.98 and it further decrease to 2.39 when we consider reheat. So, this is how the evolution or improvement of the cycle is happening when we consider initially Carnot cycle then Carnot cycle has to work inside the dome with the constraints of isentropic processes for work and constant temperature for heat addition.

Then we had certain efficiency and specific steam consumption but when we said that now supposed to use with Rankine cycle for the steam power plant then we got efficiency as 0.035 or 35%. But we got improved specific steam consumption since we do not have to use the compressor we can use boiler so W_{net}got increased. But, when we said that no we do not have ideal components we have real components with 80% efficiency then we got lot of decrement in Carnot cycle efficiency and specific steam consumption got improved rather increased.

But Rankine cycle efficiency did not decrease to the extend where Carnot cycle decreased. But, in case of ideal as we see if you use super heat then Carnot Rankine cycle efficiency improved further and with reheat got further improved. Having said this what is the outcome of reheat? So reheating reduces specific steam consumption. We can see that specific steam consumption was 3.84 without superheat which got decrease to 2.98 with superheat but with reheat it got decrease to 2.39.

So, this is very important points since we need actually reduced size of the boiler if we got to higher and higher pressures of the boiler then reheating increases the dryness fraction at the exit of the turbine. It was expected since we are hiding; adding the heat so we are going towards the right hand side of the steam cycle. And since we are going towards higher and higher temperature at lower pressures we are going to have lower dryness higher dryness fraction close to 1 if we have reheat.

This point we should be noting since we have we were saying that we were not supposed to have reheat super heat which is not supposed to have superheat if we are having high pressure water as the source. But in that case we can have reheat possible since reheat is going to happen at lower pressures and then we will have sufficient temperature difference and then in such case we can further increase the efficiency. Reheating increases the net work since turbine work increases then we have increase in efficiency with reheat as we can see over here.

But it is not always possible that we will have increase in efficiency with reheat we can see that when we can have increase in efficiency. Let us consider the cycle 1, 2, 3, 4, 3, A, 5, 6, 1. Our basic cycle is 1, 2, 3, A, 5, 6, 1 this is our basic cycle. Let us decompose this basic cycle into 1, 2, 3, 4, 1 and 4, A, 5, 6, 4 into these 2 cycles; this is cycle 1 and this is cycle 2. Now when can we have increase in efficiency with reheat?

Now when once we decompose the cycle we can know that there can be efficiencies of 2 cycles. Cycle efficiency of cycle 1, efficiency of cycle 2. If efficiency of cycle 2 is greater than efficiency of cycle 1 then obviously integration of 1 and 2 will have higher efficiency. What does it mean? This point A need not be here this point A can be here so in that case we will have reheat like this; this point A can be here in that case we will have reheat like this.

So, we will have basically in this case we will have reheat like this, in this case we will have reheat like this and then accordingly we will come down. So, point A is not fixed they can be anywhere we can have reheat very close to 4 also. So then in that case we will have expansion like this so efficiency of cycle 2 has to be seen if efficiency of cycle 2 is higher; then efficiency of cycle 1 then integration of 1 and 2 will always have higher efficiency.

What is the problem? Here problem is as we take the reheat pressure to be lower and lower then we can see that we have to first add latent heat and then we have to add sensible heat. But in this phase we would too much right and then in going too much right we will have basically to heat rejection. We will have to start heat rejection at very large temperature and then cycle 2 would have lower efficiency.

Since, heat addition is mean temperature of heat addition is low, mean temperature of heat rejection is high so due to this lower temperature of heat addition mean temperature of heat addition and higher temperature of mean temperature of heat rejection leads to lower efficiency of cycle 2. So, since cycle 2 has lower efficiency if we reheat at lower and lower pressures Rankine cycle integrated will have lower efficiency.

So, as it is said that mean temperature of heat addition of cycle 2 is important and if it is higher than cycle 1 then obviously we will have higher efficiency of integrated cycle. So, what is happening?

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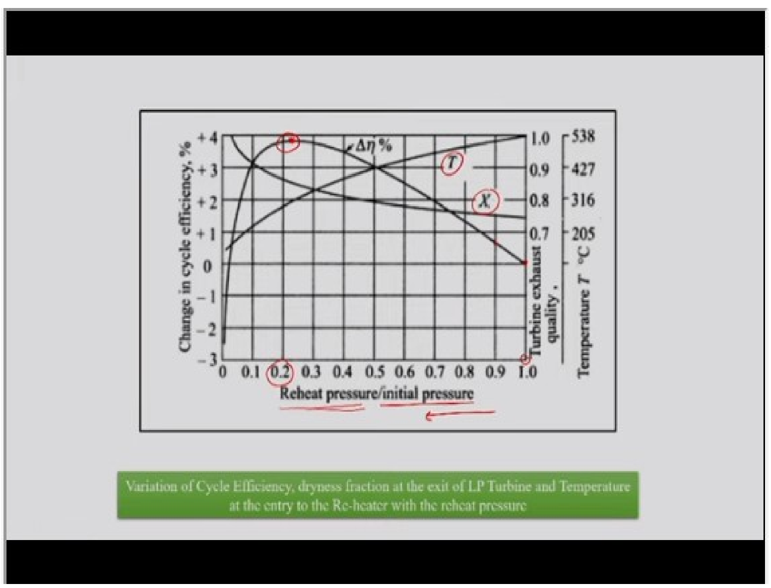

As what we saw that if reheat pressure and initial pressure, initial pressure means that high pressure turbine pressure and reheat pressure is the pressure at which we are going to reheat. If it is 1 that ratio is 1 means we are not reheating so we have certain efficiency if we reheat at a pressure which is closed to the boiler pressure then we will start heating higher and higher efficiency and this is how the reheat pressure is decreasing so we will get higher and higher efficiency.

At a particular reheat pressure around this region which is point 2 we get we are getting basically highest efficiency. So, these numbers are specific to the example what we are solving. But in general it is true that the initial or higher pressures of reheat we will have higher efficiency or increase in efficiency. But if we try to have reheat at lower pressure then we will not have increase in efficiency.

We can always see that this is the dryness fraction at the exit of the turbine is always increasing as we decrease the reheat pressure okay. So, this is the temperature at which we are reheating if we are decreasing if we are doing the reheat at higher temperature pressures then we have higher reheat temperature and this is decreasing. So the take away from reheat part on the Rankine cycle is that if we want to have higher work output from the Rankine cycle or we want higher net work from the Rankine cycle we should adopt the reheat cycle reheat cycle also use good dryness fraction at the turbine exit.

But we might not have increase in efficiency with reheat so reheat is adopted in the Rankine cycle to increase the net work. It is not generally adopted to increase the efficiencies since it is not guaranteed. This is the take away from reheat cycle of the reheat of the Rankine cycle. So, having this part known now we have covered Rankine cycle simple one, Rankine cycle with superheat and Rankine cycle with reheat. The next attachment to the Rankine cycle we will see it in the next class. Thank You.