**Steam Power Engineering**
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**Lecture -05**
**Rankine Cycle with Superheat**

Welcome to the class. So we are in the phase of solving examples and understanding by that mechanism that how to improve a particular steam power cycle or what are the dependencies of the steam power cycle. So, in that case we have solved example for Carnot cycle and then we understood that how the boiler pressure governs the efficiency of Carnot cycle? How condenser pressure governs the efficiency of Carnot cycle and then how to increase?

How much we can increase the condenser pressure or how much we can decrease the condenser pressure and how much we can increase the boiler pressure. This is what we had seen in last class. Now, we will try to understand in the same umbrella the factors for the boiler for the Rankine cycle. So, we know that this is our Rankine cycle where we have pumped boiler turbine and condenser.

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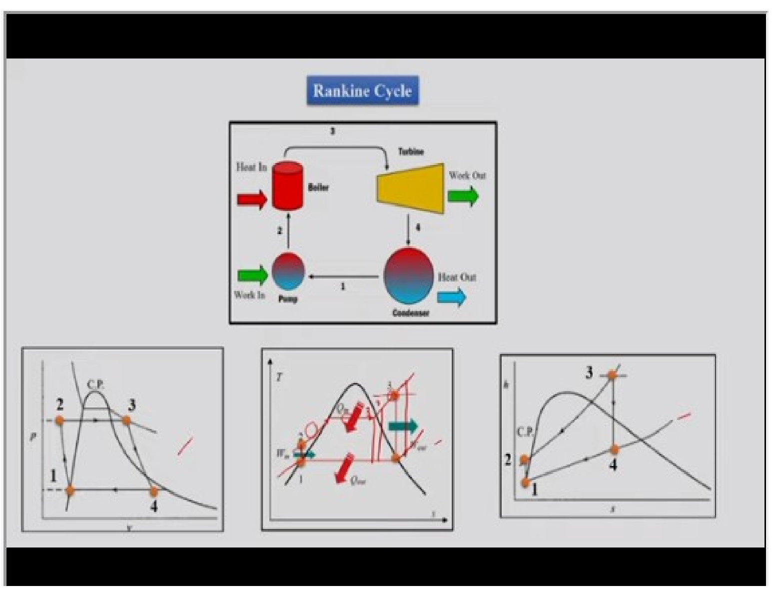


We have drawn Rankine cycle earlier where this was $P-V$ diagram for the Rankine cycle, this is $T-S$ diagram for Rankine cycle and this is $h-S$ diagram for Rankine cycle. As per this diagram we have 1 to 2 as liquid, 2 to 3 as liquid plus liquid in some part and liquid plus vapor in some part and vapor in other part. And 3 to 4 is complete vapor or and then 4 to 1 is liquid plus vapor this is what we had drawn till time.

But, we might not had the heat to the extent that we have added over here we might stop heat addition in this state. So our point 3 can be here, our point 3 can as will be here and further our point 3 can be away from here as well. But in such case if we come down then we have to come down in this manner such that the condenser line becomes constant pressure. So, we have these different Carnot cycle possible different ways by which we can draw Carnot cycle and those depends upon the given constraints on a power plant.

So, knowing this fact we can solve example for the simple Rankine cycle. Obviously we mean over here that the different Rankine cycles are possible based upon the constraints of the plant.

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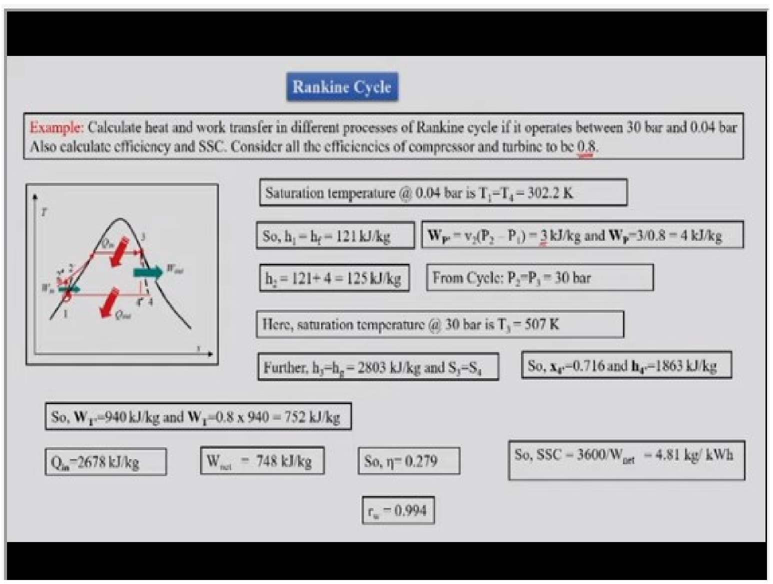


So, if we go and solve the same example which states that we have given with 30 bar of boiler pressure and 0.04 bar of condenser pressure. We are supposed to find out the efficiency on specific steam consumption so this is out typical Rankine cycle. So, we are also given with the boiler, the turbine and compressor pump efficiencies as 80%. So, the 1 to 2'which would have been the the ideal process. Now becomes 1 to 2, 3 to 4'which would have been the ideal process has now become 3 to 4.

We know saturation temperature corresponding to 0.04 bar is 302.2 kelvin so at point 1, $T_1$ is known to us, $T_4$ is known to us and other $T_{4'}$ is also known to us. So, $h_1 = h_f = 21\, kJ/kg$ which is given to us from the steam table we know it. Then we can find out ideal pump work. Ideal pump work is specific volume at point 2 into $\Delta P$ is the high pressure rising by the pump.

So, this is the saturation vapor pressure, saturation specific volume into $\Delta P$ so we get pump work$(W_P)$ to be 3 kilo joule per kg. But we know that efficiency is 80% so it becomes 4 kilo joule per kg pump work. That is how we can calculate $h_2$ so we know $h_1$, we know pump work. So $W_P + h_1 = h_2 = 125\, kJ/kg$. We know that $P_2 = P_3 = 30 ¿$. Here saturation temperature corresponding to 30 bar is 507 kelvin.

So, we know that we are told that this is a Rankine cycle and we are not told anything about point 3. So, what we have done is we have taken point 3 on the saturation line. So, we know that the pressure at 3 is 30 bar so this enthalpy at 3 is the saturation enthalpy of vapor corresponding to 30 bar which is 2803 $kJ/kg$. Then using that we can find out $x_{4'}$ and hence we can found find out $h_{4'}$. It is same as what we solved in the last example for Carnot cycle.

So, we know what is turbine work which is ideal and so we know what is turbine work which is actual $Q_{¿}$ or here it changing and that is $h_3 - h_2$, now $h_3$ is known, $h_2$ is known so $Q_{¿}$ is 2678 $kJ/kg$. Now, we know turbine work, we know pump work we can find out $W_{net}$ it turns out to be 748 $kJ/kg$. Thus we know $W_{net}$, we know $Q_{¿}$ we can find out efficiency and it is 27.9. Specific steam consumption is 3600 upon $W_{net}$ and it is 4.81 $kg/kWh$.

Work ratio; this is very important parameter to be noted and it is $\frac{W_{net}}{W_T}$ and it is 99.4% or 0.994 a huge work ratio for Rankine cycle.

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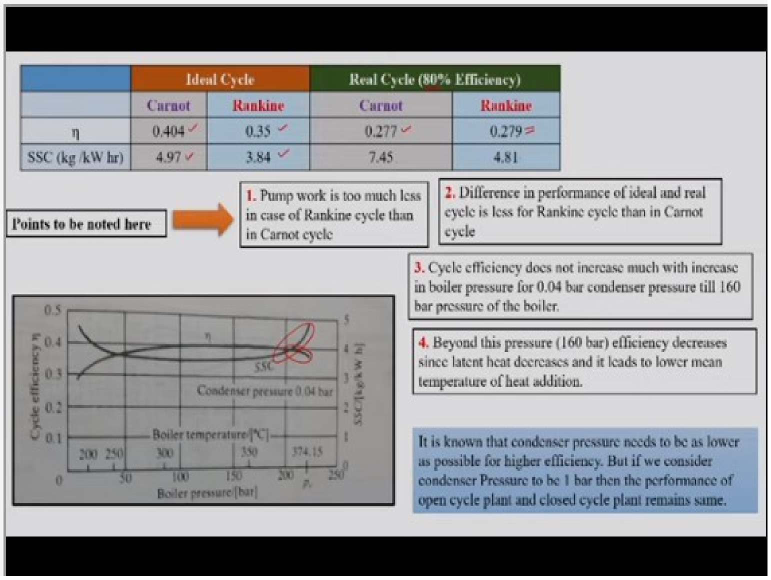


If we see the examples what we solved for Carnot and Rankine cycle we would have solved suppose the ideal case. Then efficiency was 35% for Rankine but the same ideal efficiency for Carnot cycle is 40.4% specific steam consumption was 4.97 and specific steam consumption is 3.84 in case of Rankine cycle. But Carnot cycle has in case of non ideal components 80% efficiencies of pump or compressor and turbine.

Its efficiency becomes only 27.7% where Rankine cycle crosses the efficiency of Carnot cycle and its efficiency 27.9%. The specific steam consumption for Carnot cycle increases a large amount and it becomes 7.45 if we have non-ideal parts. But there is minor increment in specific steam consumption for the Rankine cycle when we say that it is having non-ideal components. We can see that some points pump work is too less in case of Rankine cycle than the compressor work of Carnot cycle.

Difference in performance of ideal and real cycle is less in case of Rankine cycle than the Carnot cycle. The efficiency of Rankine cycle if would have solved these example for different boiler pressures for the same condenser pressure then it initially increase but then it does not increase much at higher boiler pressures. Initially, specific steam consumption decreases but then there is not much change in specific steam consumption and then we have later decrement in efficiency and we have increment in specific steam consumption.

We have to mind one thing that we are solving this for the same condenser pressure of 0.04 and we are saying turbine inlet is dry saturated point. Here one thing is happening that we have cycle efficiency for the Rankine cycle is not changing much beyond 160 bar it actually it is having minor change in efficiency. Further, efficiency decreases and that decrement in efficiency has a prominent reason that at higher pressures actually latent heat decreases for the steam power plant.

But our point 3 is always frozen on the dry saturation point of the 30 bar pressure or the corresponding to the boiler pressure. Here we are adding heat into the boiler which is $h_3 - h_2$ that has two components one is in the economizer which is a same sensible heat and other is in the evaporator which is in the latent heat part. As we increase the boiler pressure the latent heat is decreasing and the economizers load is increasing and evaporators load is decreasing.

So at a point beyond 160 bar the amount of heat added into the evaporator becomes so low in comparison with the heat added into the economizer or sensible heat such that mean temperature of heat addition decreases. And since mean temperature of heat addition is decreasing due to lower amount of latent heat we have decrease in efficiency and hence further we have increase in specific steam consumption.

Here, one point to be noted that if we have the condenser pressure in the same example if we would keep the boiler pressure to be same and if we increase the condenser pressure and by means we keep the condenser pressure to be one bar. Then the Rankine cycle what we are thinking at this moment as a closed cycle would have same performance as a locomotive based Rankine cycle where the cycle is operating as a open cycle where the steam at the exit of the turbine is released to the atmosphere.

So, this is what a point of discussion for Rankine cycle. Now, we are at a point where we have seen that Rankine cycle has certain efficiency when we start the Rankine cycles operation for the turbine at the dry saturation point. But, now let us consider that we are not having the start of the turbine or entry to the turbine as dry saturated, we are saying that entry to the turbine is superheated.

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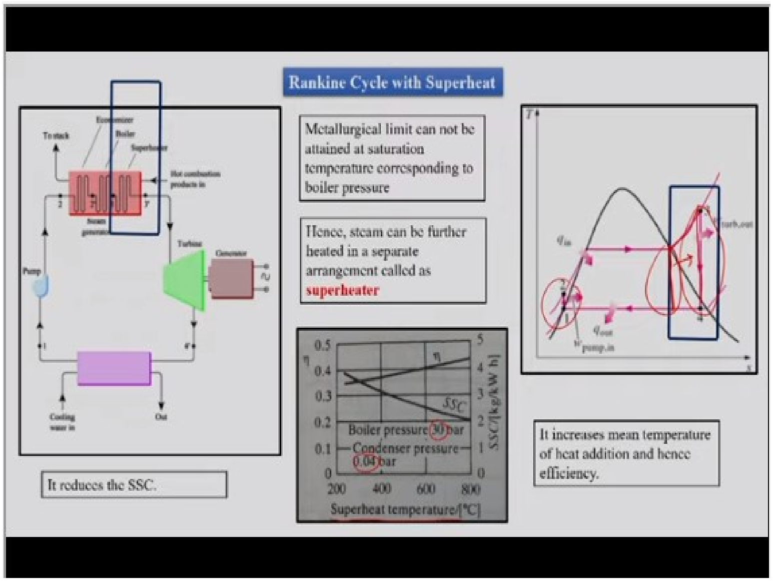


So, if we have so then how much is the amount of heat we can add such that we can have sustained operation of the turbine. Then we should remember one point that there is a metallurgical limit and it corresponds to the materials temperature which are engaged in handling high temperature steam. So, there are boiler and high pressure turbine elements which are exposed to this high temperature.

So, there is a limit due to that temperature but yes below that temperature we can heat the steam. Hence steam can be heated below the metallurgical limit such that it would cross the saturation point and it would get superheated and the component which would heat in the steam generator is called as superheater. So we have seen that economizer is there, evaporator is there and now we are adding superheater so this is the superheater.

So we have superheater also added into the boiler which will give super heat to the steam. So, we instead of stopping at the point here we moved ahead to the superheat region and then we have added superheat to the steam into the superheater. So, what would happen? Having superheat it increases the mean temperature of heat addition for the Rankine cycle. So, since mean temperature of heat addition is increasing we have increase in efficiency of the Rankine cycle it reduces the specific steam consumption.

So, basically we are having more $W_{net}$ and specific steam consumption is $\frac{1}{W_{net}}$, we have deduction in specific steam consumption. This is how for the previous example if we would have added superheat then we would have thought that the specific heat consumption would decrease like this for the given boiler pressure of 30 bar and then condenser pressure of 0.04 bar that efficiency would increase like this and specific steam consumption would decrease like this if we would superheat at different temperatures.

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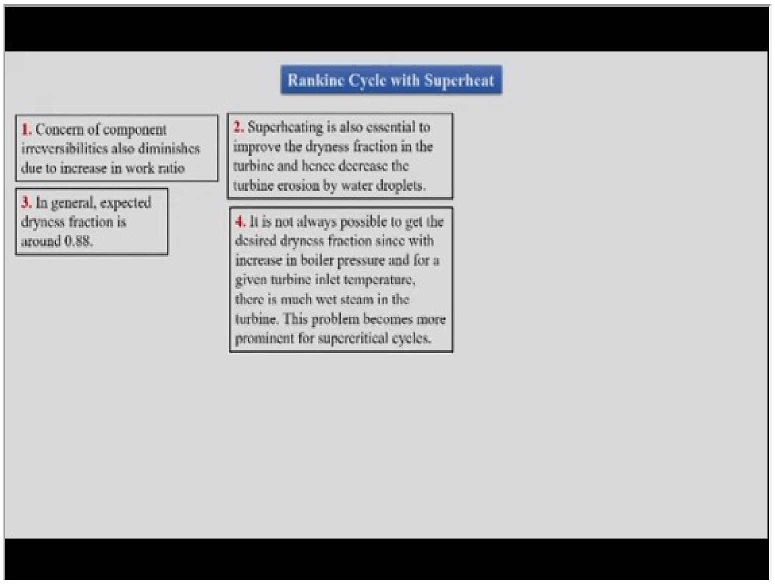


So, there are certain points to be noted with superheat that concern of component irreversibility's gets diminished with increase in work ratio. As what we can see that earlier we had stopped for the Rankine cycle over here, we have turbine over here but now due to addition of superheat we have got turbine over here. So what has happened turbine work has got increased from here to here but pump work is same so turbine work has increased, so net work has increased. But we know that Net work upon turbine work is work ratio.

So, since work ratio is increased our problem of irreversibility is solved more. We had seen in previous class that the work ratio if it is higher then the cycle becomes more and more insensible or less sensible towards the component efficiency. So having superheat we do not have too much bother about the component efficiencies superheat is also essential to improve the dryness fraction.

We had seen that at the exit to the turbine if we would have the entry to the turbine as dry saturated steam so the turbine outlet are point 4 would remain in the inside the dome. But if we would have superheat then we will go close to the dry saturation point. But we expect to have dryness fraction to be in general around 88% or 0.88 at the exit to the turbine this has one implication. Basically, if we have the steam power plant like this where we have stopped somewhere here.

So, if we have the entry to the steam into the turbine over here and if we have expansion like this then we have only vapor over here and we have liquid plus vapor over here. So, this liquid component is also flowing over the turbine and since this liquid component is flowing over the turbine we would have more erosion of the turbine blades. So, we want lesser and lesser liquid component into the turbine blade so for that expected dryness fraction at the outlet of the turbine is 88% such that most part of the turbine would have exposure to the steam or vapor only.

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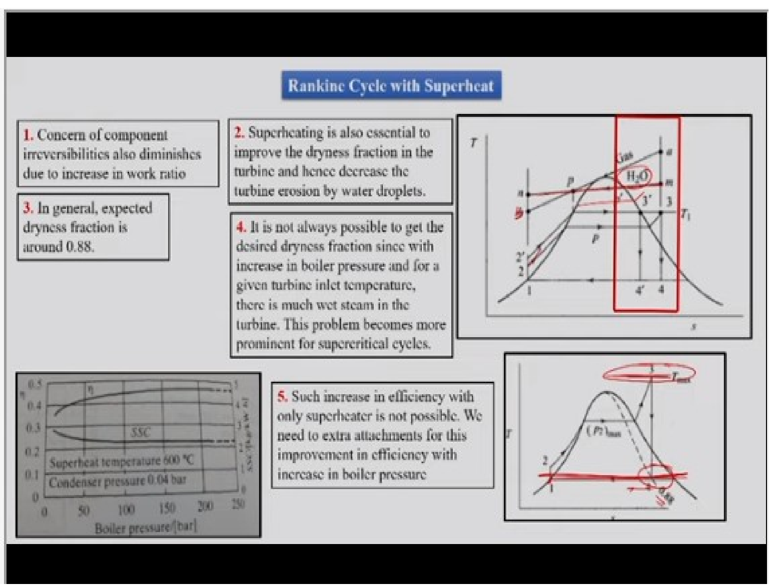


So, we are expecting that our dryness fraction has to be in the range 88% but is not always possible to attain this dryness fraction only with superheat basically. So, if we consider a typical example that who is supplying the heat to the water such that water is getting heated. Now if we are having gas which is like this and this gas is coming from a state to b state and gives its heat to the water.

In this case what would happen is water would get heated we can heat the water since we have lot of temperature difference between water and the gas it is possible. But now instead of gas if we have high pressure water, heavy water which is supplying the heat as in case of nuclear power plant. Then we cannot have higher and higher superheat possible with water as the medium which is the source of heat.

So, in such if we want to go at higher pressure then lesser and lesser amount of superheat is possible and at certain pressure we would not have superheat possible with certain water with high pressure water which is giving the heat but in case of gases yes it is possible. So the point to be noted over here that we although want superheat as a desirable entity to have mm higher cum higher work ratio which would lead to the no issues with the internal irreversibility and also we want to have our turbine to be safe from the erosion but it is not always possible.

So, this is a Rankine cycle which tells us limits so there is a freezing at this level due to metallurgical limits of the material which is getting used for boiler and turbine. Turbine has a problem that turbine rotates so in the case of rotation it undergoes compression and expansion as a cyclic phenomenon so there is a fatigue involved in the turbine design. Further it is exposed to high temperature so the strength of the turbine would reduce in the case of fatigue and further it is exposed to high temperature.

So, there this becomes delicate fact to note so there is a limit due to metallurgical sense for the high temperature whatever we can go. There is a limit in this site where we can go, we cannot go below 88% further there is a limit for this line itself that we know that we are using natural resources for cooling in the condenser. So, this pressure is the corresponding saturation pressure for the atmospheric temperature of those natural resources. So this is how our Rankine cycle gets constrained from different facts.

So, if we want efficiency to be continuously increased and specific steam consumption to be continuously decreased it’s not possible only with superheat because it depends upon the source which is going to give heat. But yes it is possible to increase the efficiency and decrease the specific steam consumption if we have certain extra attachments to the existing Rankine cycle whatever we are talking about. We will see those attachments down the line.

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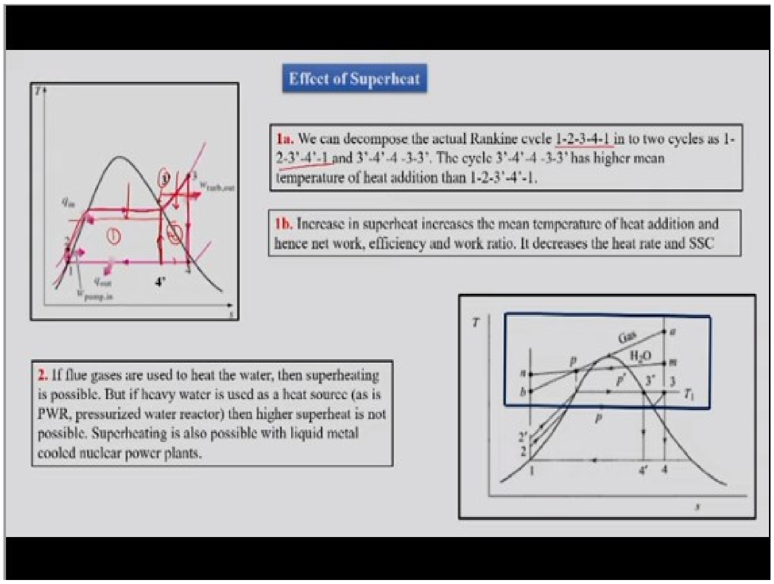


So, effect of superheat we can decompose the existing Rankine cycle which is 1, 2, 3 ,4 into 2 cycles. One cycle is 1, 2, 3'and 4 so this is 3'and other cycle is 4', 3', 3 and 4. Basically, in sense of cycle we are decomposing our Rankine cycle which is 1, 2, 3, 4, 1; 1, 2, 3, 4, 1 into 2 cycles , One is 1, 2, 3', 4',1 and other is 3', 4 other is 3', 4',  4, 3, 3' or other way 4', 3', 3, 4, 4'.

So these are the two cycles which we are decomposing our basic cycle this is for our understanding. So, here we are having certain mean temperature of heat addition for cycle 1 then this is cycle 2. So, cycle 2 has mean temperature of heat addition somewhere here. Here we are adding heat in this cycle and here we are adding heat in this cycle. So, for cycle 1 mean temperature of heat addition is close to the dry saturation temperature and here it is more than dry saturation temperature.

Now, this these two cycles are clubbed mixed together to form our basic Rankine cycle and hence since this cycle 2 has higher mean temperature of heat addition we practically get more mean temperature of heat addition in the presence of superheat. So, superheat increases the mean temperature of heat addition and hence it increases the net work, increases the efficiency and it increases the work ratio. We have discussed this point that the possibility of super heat is there if we have gases as the source.

Further, we if have water high pressure water like pressurized reactors, water reactors it is not possible to have super heat always. But we can have again super heat possible if we have liquid metals available for us for the source.

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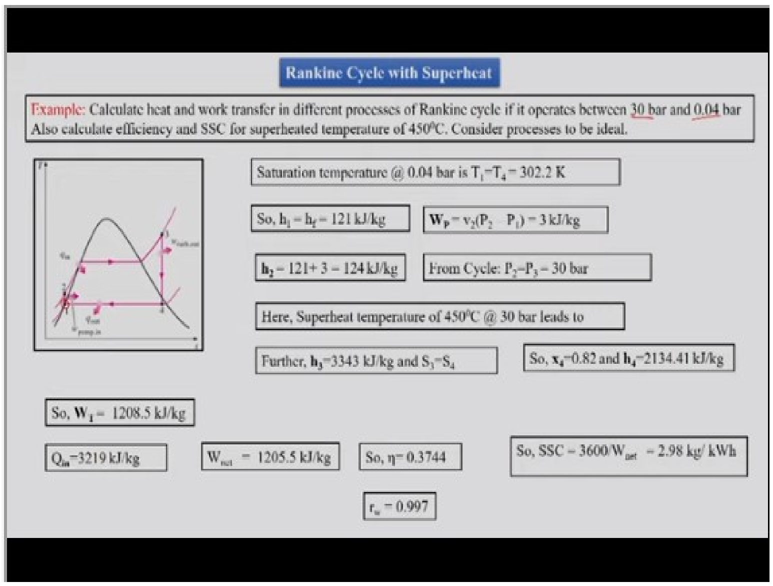


So, we will solve the same example as what we solved earlier but now we will see what will happen to the efficiency and work transfers and heat transfers in the Rankine cycle if we have $450\,°C$ as the super heat here we have 30 bar and 0.04 bar as the pressures as told earlier so now this is our Rankine cycle. We know that point 1 is 0.04 bar so we know condition at one. We know condition at 1 so we know enthalpy at 1. We know pump work but, in this example, we are not told with efficiency.

So we will take 100% efficiency of pump so we know pump work, we know enthalpy at 2 from the pump work and $h_1$ then we can actually we need to know only 3. We know that at pressure at three is 30 bar so what we should we do is we should go the steam table. But now instead of going to the saturation part of the steam table we have to go to the super heat part of the steam table and in superheat part we have to see to the 30 bar and different temperatures.

In the different temperatures we have to see $450°C$ and then we get the enthalpy at 3 which is 3343 $kJ/kg$ and then we also have to see entropy at 3. Knowing entropy at 3 we know entropy at 4 so from that we can find out dryness fraction at 4 which is 0.82. So we know what is enthalpy at 4 then we can find out turbine work which is $h_3 - h_4$, we can find out $Q_{¿} = h_3 - h_2 = 3219$.

Then we can find $W_{net} = W_T - W_P$then we can find out efficiency which is 37%. We can as well as find out specific steam consumption which is 2.98 $kg/kWh$. We have work ratio as 0.997 for the Rankine cycle with super heat. So, we have seen that with super heat efficiency has got increased we have got lower specific steam consumption we have further got higher work ratio thus super heat is advisable if it is possible.

We also have seen that there are limitations on the Rankine cycle based power plant based upon the source of heat and further based upon the source of or sink of it. We have also seen that we are expected to have dryness fraction at the exit of the turbine to be 88% so that we can save the turbine blades from the erosion. With these understanding we end the discussion with Rankine cycle with super heat and then next discussion we will see that there are some extra attachments which would lead to higher efficiencies of the Rankine cycle or which might lead to higher efficiencies of the Rankine cycle which is not possible only with superheat. Thank you.