Engineering Thermodynamics
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Module 07
Lecture No 48
Rankine and Carnot Vapor Power Cycles

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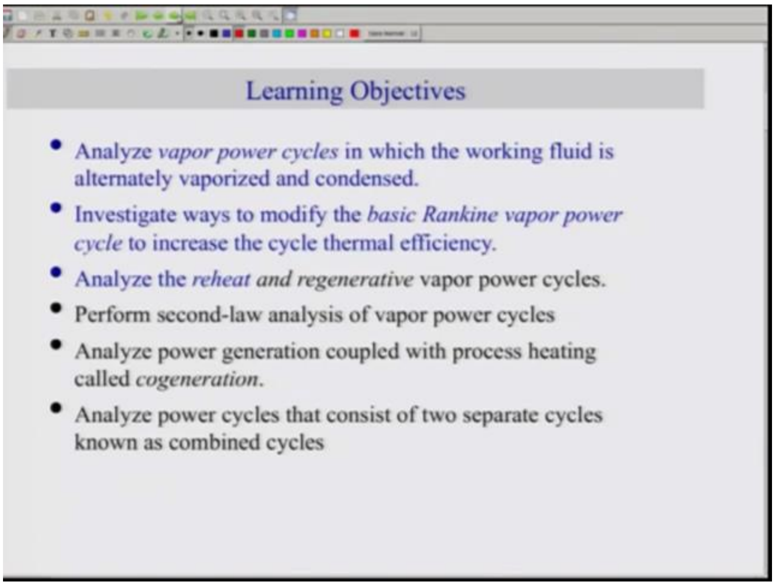

Welcome back we are going to start new topic it is on vapor power cycles. So let me just go through the objective of this particular chapter so let us try, I will start with the analysis of the vapor cycle in which basically the working fluid is alternatively vaporized and condensed, it does not remain in the gas state all the time as in the case of the gas power cycles. We will try to first analyze the particularly based on Carnot cycle and followed by introducing the Rankine cycle and then certain aspects of such Rankine cycles issues and how one can increase its efficiency by reheating.

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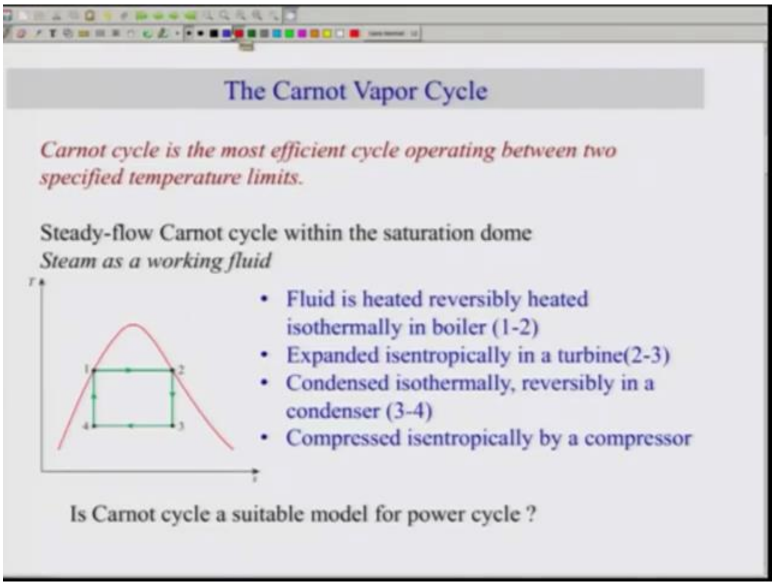

So let me start with the basic alternative vaporized and condensed cycle that is your vapor power cycle in the form of Carnot cycle. Now a Carnot cycle is the most efficient cycle which we know which operates between 2 specified temperatures limits okay. Now that means it is very obvious that one would like to make use of Carnot kind of cycle for the case of vapor power cycle and in this case we can start with the Carnot cycle by considering this saturation dome and the cycle operates within this dome and because of the fact that the vapor cycle means for alternating vaporized and condensed cycles or hence it has to be within the saturation dome so that is what to be made use of Carnot cycle.

We considered steam as a working fluid, now let me just refresh the Carnot cycle particularly in this form. This is on a TS diagram, so 1 and 2 is the process where the fluid is heated reversibly, isothermally in a boiler okay this is where your Q in is being supplied using a boiler okay at a constant temperature. And 2 and 3 is basically where the steam is expanded isentropically having a constant entropy okay and 2 is your saturated vapor, it gets expanded creating final state 3 where it is a mixture of vapor and liquid and finally 3 to 4 is a process where it is condensed isothermally reversibly in a condenser that means there is a Q out of it okay.

And then the 4, from 4, it is compressed isentropically by a compressor in order to get the back to the original state which is saturated liquid. Now, it is very clear that the Qin depends on the enthalpy change from 1 to 2 and essentially we cannot raise the temperature because as you increase the temperature, Q in will decrease because of the fact that the enthalpy difference between 1 and 2 will decrease. Thus this limits the maximum temperature one can use in a saturated liquid or saturated dome as in the case of the way we have demonstrated here and we know that efficiency of a cycle increases if you increase the temperature at which heat is being supplied.

So thus this limits the temperature at which we can as a Carnot cycle, so in addition the issues related to the turbine which has difficulty in operating the mixtures similarly the related to compressing the mixture. Thus the question is, is Carnot cycle a suitable model for power cycle and we know based on our current just discussion that there are issues related with such Carnot operation under saturated dome okay.

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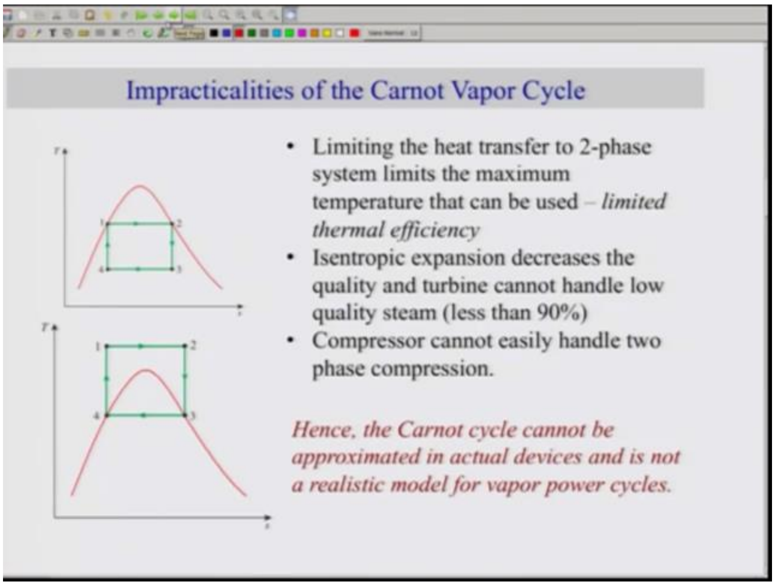

So let me just summarize these impracticalities of the Carnot vapor cycle, so as I already mentioned that using Carnot cycle in saturated dome has impracticalities and that is it limits the heat transfer 2 phase system okay, which is basically it limits the maximum temperature that can be used and thus it has a limited thermal efficiency okay and of course the turbine has issues that means turbine cannot handle low quality steams so what we prefer 3 as close as saturated vapor line. Similarly, compressor cannot easily handle 2 phase compression and thus we also prefer 4 to be as close as saturated liquid line so these are the impracticalities of the Carnot vapor cycle. One can try to avoid this by considering the 1 to 2 process that means iso thermal heating process at super critical condition.

However, the problem in this case would be the boiler has to operate at different pressure all the time. That means the boiler has to operate at different pressure okay along this line and this would be difficult as far as the practicality goes okay and hence it is not so easy to that.

Second is that you can avoid of course this 2 phase issues of handling from turbine from here 2 to 3 but from for 4 to 1 for the pump, the pump has to operate at very high pressure and because it has to compress from 4 to 1 and this is also impracticality and hence the Carnot cycle cannot be a approximated in actual devices and it is not a realistic model for vapor power cycles.

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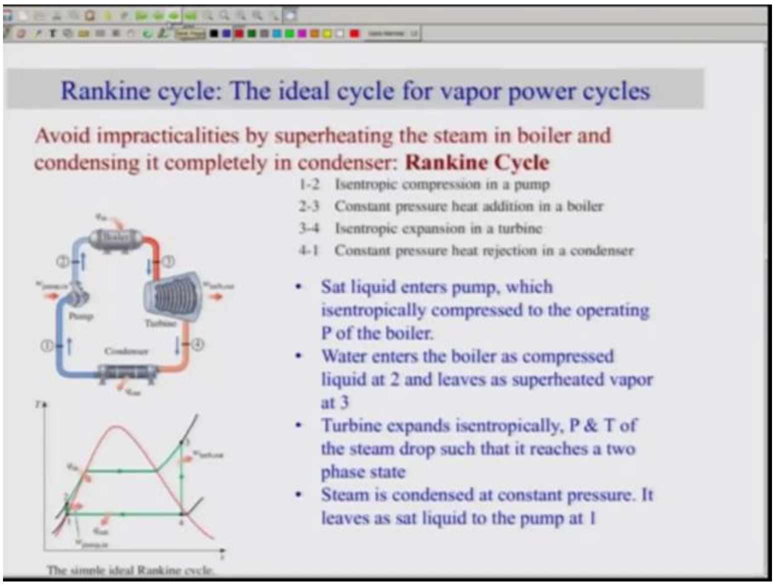

Uh so we will try to come up with another cycle which is more practical and this is where we are going to introduce Rankine cycle which is the ideal cycle for vapor power cycles so what is does, it avoids impracticalities by super heating the steam and the boiler and condensing it completely in condenser okay, so let me just summarize this cycle first. So here the 1 to 2 is your isentropic compression in a pump okay followed by a constant pressure heat addition in a boiler followed your isentropic expansion in a turbine okay which is 3 to 4 followed by constant pressure heat rejection in a condenser.

Okay one can describe this process on TS diagram and let me describe this first, so we will start with 1 which is this okay so the 1 condition is saturated liquid okay, it enters the pump and where it isentropically compress to the operating pressure okay which is this, so this is the boiler pressure okay. So it reaches up till 2 that means 2 is at a boiler pressure, this is at boiler pressure okay and water enters the boiler at a compressed liquid at 2 and leaves AS a super heated vapor so this becomes super heated so this is your super heated okay.

Here the turbine expands isentropically such that the P and T of the steam draws and reaches the 2 phase system so the 4 is the 2 phase system okay and here 4 to 1 is the steam gets condensed pressure and it leaves a saturated liquid to the pump at 1 okay, so this is at saturated liquid. So naturally 4 to 1 is the work pump in and this is W turbine out and this is your Q in, in the boiler, Q out from the condenser, so this is the summary of the Rankine cycle involved in this. Okay so now we are can consider the energy balances for each particular device involved in the Rankine cycle considering it to be steady flow devices.

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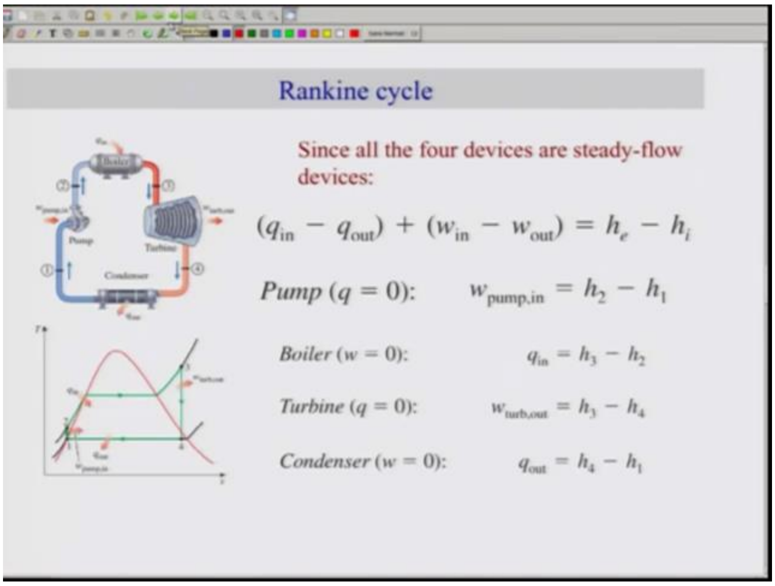

One can simply write these are energy balance equations and consider each particular device so for the case of pump, considering it to be adiabatic okay the work here, is simply the enthalpy change between 2 and 1 so that is how the work of the pump in. The boiler, there is no work involved in that okay, there is no boundary work, no other work so your Q in is simply the enthalpy change between 3 and 2 okay. Turbine of course, it is also adiabatic and in this case in idealized condition and this is your turbine workout which is nothing but your enthalpy change between 3 and 4. Condenser, there is no work involved in that and hence Q out is simply the enthalpy change between 4 and 1 okay.

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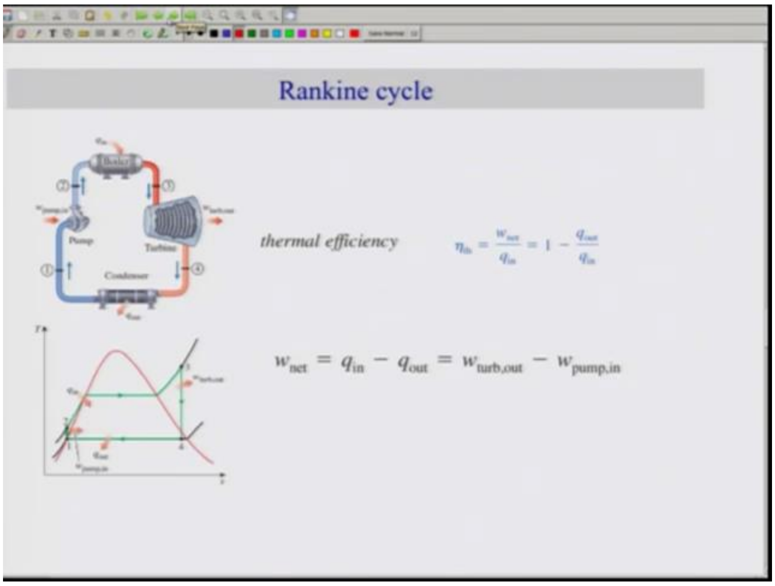

So now one can also make use of this balance as well as the overall information on the work net and calculate the thermal efficiency, so we know the thermal efficiency is nothing but the W net out divided by Qin based on the energy balance, it is nothing but 1 - Q out by Q in. Now W net is simply Q1 - Q out, it is nothing but Q turbine out - W pump in okay, so based on the information available; one can plug in this and calculate the thermal efficiency of the Rankine cycle okay. Now what we discussed as of now is only the idealized Rankine cycle, but we know the irreversibilities are associated with such Rankine cycle and the fact that the many the devices involve irreversibility so we will just try to understand the deviation of the actual vapor cycle from the idealized Rankine cycle.

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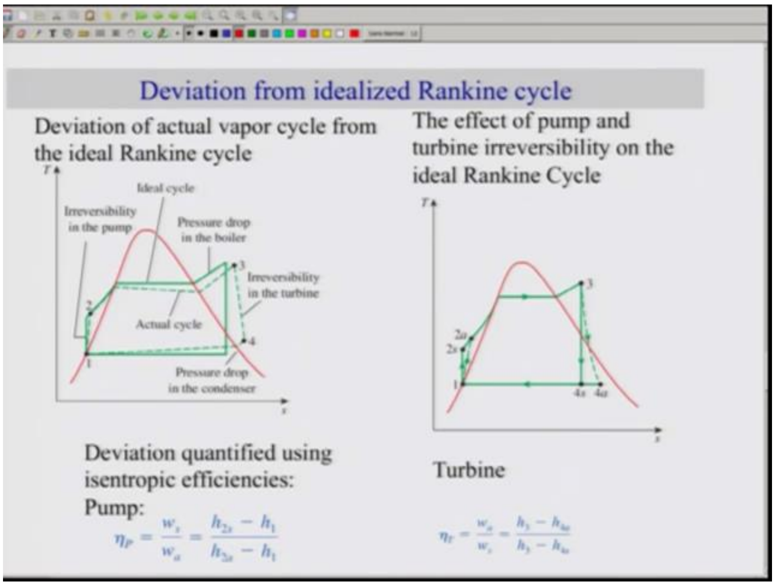

So here the solid line is the your idealized cycle and the dash line is basically the cycle continuing irreversibility, so from 1 to 2 there is a deviation from the idealized or isentropic process okay because of the irreversibility in the pump and similarly there could be a pressure drop in the boiler and thus it may not be constant temperature within the saturated dome condition. Similarly, there could be the irreversibility in the turbine and hence it may not be isentropic so that is why it follows this dash line and similarly there could be a pressure in the condenser.

Based on the simply the irreversibility associated with the pump and turbine, one can come up with the more simplified diagram on TS where we just consider the irreversibility here where from 1 and 1 to A represent the actual path because of the irreversibility and 2S represent the isentropic path for the pump okay. Similarly 3-4S is your isentropic expansion for the case of idealized turbine and 3-4A is for the case of actual turbine and due to the irreversibility, it will follow this dash line okay, so one can also utilize this information in the form of isentropic efficiency which will quantify this deviation.

So isentropic efficiency for pump is nothing but your ratio of the work, isentropic work and the actual work and this can be written in terms of change in the enthalpies okay. Similarly for the case of turbine, it will be opposite the actual workout would be less than the isentropic work. On the other hand, for the case of the pump, the actual work has to be more than the isentropic work so that means your Etas P and Etas Taus are going to be less than 1 and this can be related to their changes in the enthalpies okay.

Now we have already discussed the fact that we can increase the efficiency of such cycle if we can increase the temperature at which the heat is being supplied or decrease the temperature at which heat taken out from the condenser and if it is supplied at high temperature in the boiler, so we will try to understand how this can be achieved within this Rankine cycle, so average fluid temperature should be as high as possible during heat addition and as low as possible during heat rejection okay.

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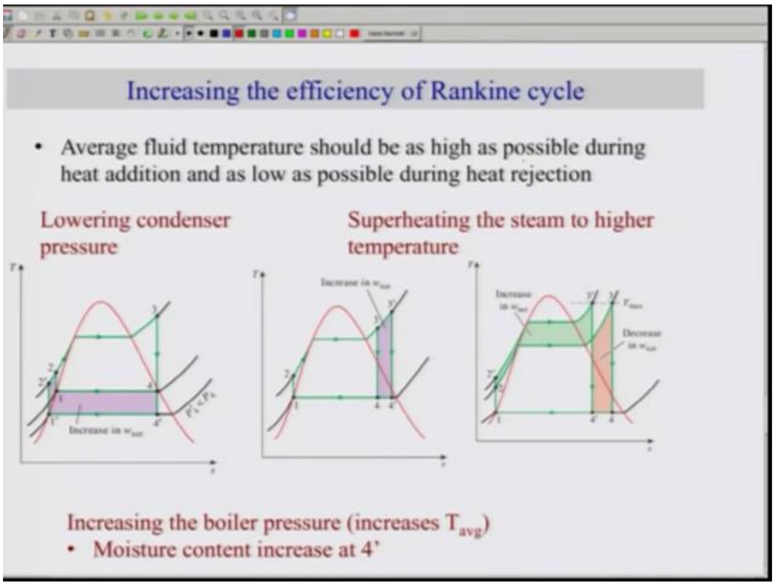

We can achieve this by first considering the case of lowering condenser pressure okay, so let us assume that you have condenser operates at P4 okay and so new pressure if it is lowered, let us say P dash 4, this will increase the area which is basically the increase in the Wnet okay and thus the efficiency will increase okay. Similarly, one can also increase the temperature at which the 3 is that means the exit of the boiler that means increase the superheat the steam to a higher temperature, now this will also increase the network okay.

You can achieve the same effect by increasing the boiler pressure, so either increases this to here or you can increase the boiler pressure which will be the case of this okay. By doing that you can also increase the Wnet, but of course there would be decrease in Wnet because this line which is the isentropic line will shift to the left from 4 to 4 dash and this is the amount which will get reduced okay. But this steam acts super heating the steam to a high temperature is limited by the metallurgical constraints that means the container should be able to sustain that much heat okay.

There is another problem due to this increased boiler pressure, if you increase the boiling pressure to achieve this high temperature as well as to increase this work net, this 4 shifts to 4 dash which means the moisture content of 4 dash is much higher than 4 okay so the quality is reduces okay and this creates problem for the turbine because turbine has a difficulty in operating to face mixture okay. So we can try to avoid it okay so that means how can we take the advantage of the increased efficiency at higher boiler pressure without facing the problem of excessive moisture at the final stages of the turbine.

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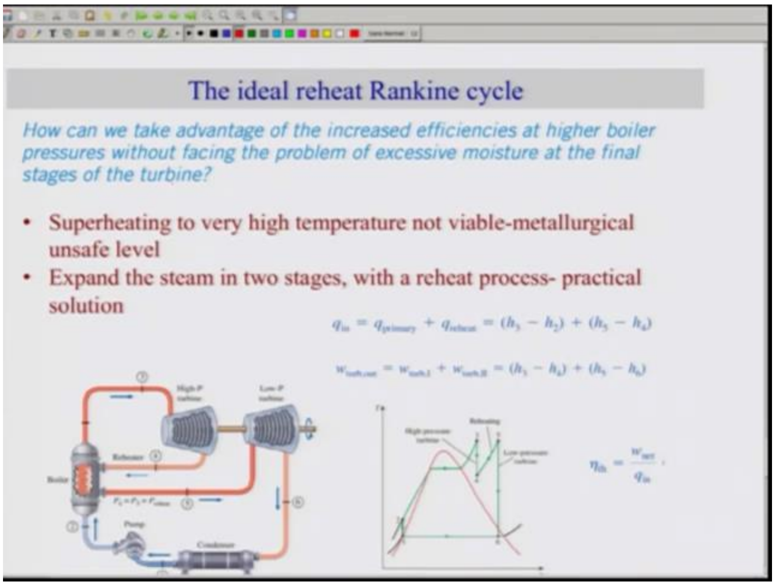

So what we can do is, we can expand this steam in 2 stages, so instead of going down here okay what we can do is, we intermediately we can stop here and take out the steam and reheat again so you can have this one turbine here and another turbine, so 1 turbine works at high pressure because this is at higher pressure okay and the other turbine works at lower pressure because this line here which is reheated is at a low pressure that is why you have 2 turbines okay and that is why you have this 1 from 2 to 3 it goes and the steam is taken out, it is being reheated the exit T5 is taken to the low turbine okay.

And from here you have 6 and 6 undergoes condensation using a condenser completing the whole cycle. So reheating increased the quality okay and reduces the excessive moisture at the final stage and increases the performance of this particular Rankine cycle. Now, one can understand that there is 2 specific heat supplied, 1 is at this end which is at the primary heat okay, which is from 2 to 3 and other one is at during the reheating process so this is Q primary + Q heat.

It can be directly related to the enthalpy change at different points. 3 to 2 is for the primary heat and 5 to 4 okay is corresponding to reheat and similarly there are 2 turbines, hence we have 2 works associated with that which also can be related directly to the enthalpy change and overall the efficiency can be written in the same way as we have written earlier okay. You can increase the average temperature of this because here the average temperature depends on the temperature of this and as well as here so this whole path from here to here corresponds to the increasing changes in the temperature so you can take the average temperature.

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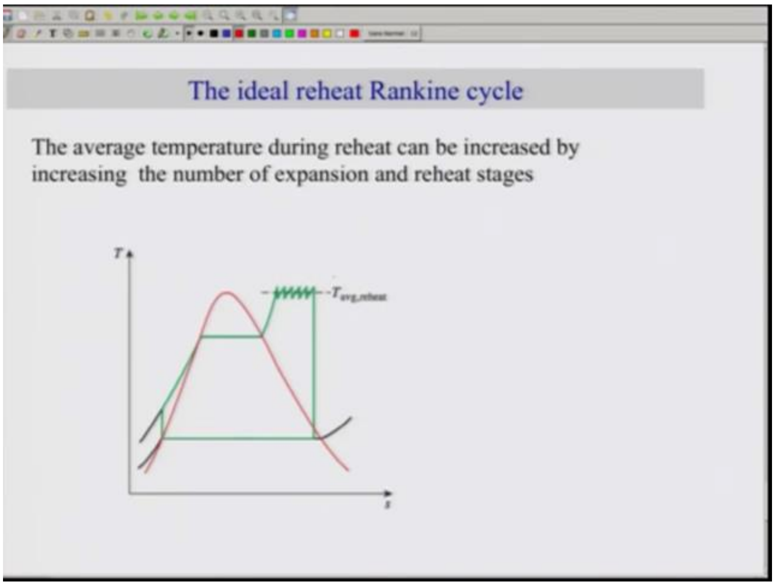

Now this average temperature further can be increased by increasing the number of reheat and number of expansion so this is an idealized or kind of a limiting case where the T average is quite high and which essentially means the efficiency will be quite high for this case so for this you will have to increase the number of the expansion on reheat stages okay in order to have very high temperature during reheat okay. Or this is basic concept that we need higher average temperature of where the heat is being supplied okay.

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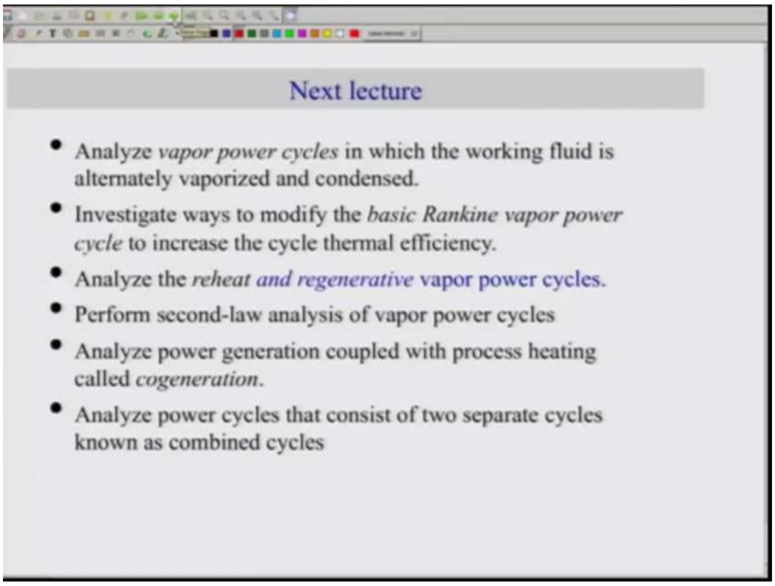

So that will be the end of this lecture so we will be looking at regenerative vapor power cycle and another analysis of this Rankine power cycle okay in the next lecture. We will also consider something called co generation in the next lecture, so I will see you in the next lecture.