Applied Thermodynamics for Engineers

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Lecture – 22
Regenerative Rankine cycle

Hello everyone, welcome for the third time in the week where you are talking about the vapour power cycles. Here over the previous two lectures we have already talked about the ideal Rankine cycle, its different variations or I should say not variations but the different factors that we may have to include in the ideal Rankine cycle to have more practical prediction. Something like the isentropic efficiencies for the turbines and pumps, the possibility of having pressure drop in the boilers and turbines, those factors we have discussed. Then in the previous lecture we have talked about different ways of improving the efficiency of the Rankine cycle just by changing the maximum pressure or maximum temperature or maybe the condenser pressure. And also, we have discussed the option of reheating the steam or I should say by breaking the turbine expansion in two stages with a reheat in between, quite similar to the Brayton cycle.

So, that multi-stage expansion with reheating is one very efficient way of increasing the output from a turbine or from a Rankine cycle. The reheat Rankine cycle gives you higher power output because here we are achieving the expansion in two stages: one at the high-pressure stage from the boiler pressure level to the intermediate pressure level and then the low-pressure stage from the intermediate pressure level to the condenser pressure level. In some turbines we may have even two stages of reheating as well, where we may have two intermediate pressure levels.

So, the net effect of increasing the number of reheating stage or I should say the net effect of increasing the reheat portion in the turbine expansion is to have a net increase in the total power output that we can get from the cycle, because there will be increase in the turbine work output. But the work input requirement for the pump will remain virtually the same. And also, we have already seen that the pump work input requirement is virtually negligible compared to the turbine output.

So, the total output will increase but of course that will also be associated with an increase in the heat input requirement. Because along with the primary hea,t additional amount of heat input also will be required for the reheating part and therefore total heat input will also increase and hence the Rankine reheat cycle or I should say the heat Rankine cycle gives you a higher power output but may not provide any increase in the efficiency.

The efficiency may increase, efficiency may decrease or may demand more or less the same depending upon the level of the intermediate pressure. So, in order to have an increase or I should also add that the biggest advantage of having the reheating is of course on the turbine exit side there will be significant increase in the exit quality of the turbine exit. And therefore the problem of erosion in the later stages of turbine expansion can be eliminated completely.

Now in order to have a higher work output as well as higher efficiency we have to go for something known as a regeneration.

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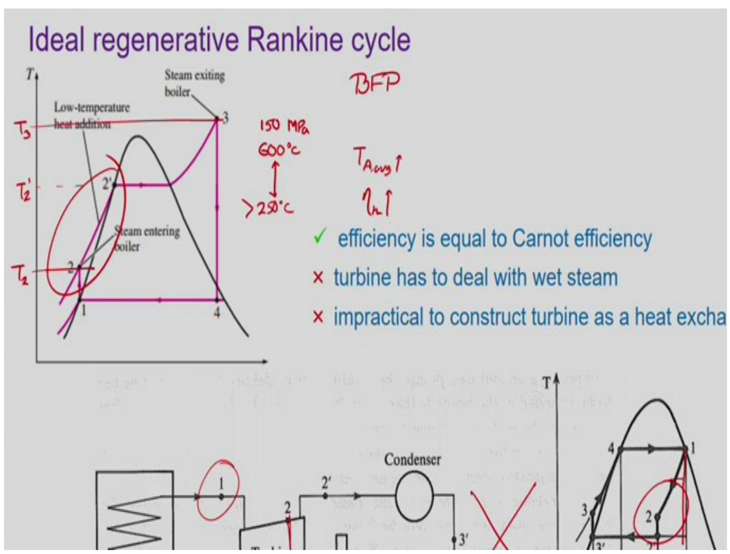

I touched upon this one in the previous lecture. Here as you can see this is an ideal Rankine cycle without any reheating. Here the boiler input power or I should say the boiler operation starts from this stage point 2 and finishes at this point number 3. So, this is your temperature T_2 and this is your temperature T_3. So, the boiler heat addition progresses over a very large temperatures range from T_2 to T_3.

There are several example problems we have already solved you can check out any of the example problems from there. And if we take something like say, our cycle is operating with a maximum pressure of 150 MPa and the temperature of the turbine exit is 600 ^{0}C and the minimum temperature which should correspond to the condenser pressure may be something in the range of 30 ^{0}C.

Then the heat addition progresses over this wide temperature range of 30 ^{0}C to 600 ^{0}C which leads to significant lowering in the average temperature of heat addition. Particularly because of this portion which we can also call as feedwater heating portion. The water coming from the condenser is often called the feedwater. The pump which we are using for this stage 1 to 2 or for the process 1-2 is also called the feedwater pump or boiler feed pump, because its objective is to feed the water back to the boiler so often, we call it a boiler feed pump in short BFP. Now the stream coming out of the boiler feed pump that being such a low temperature compared to the turbine inlet temperature we have a significant lowering in the average temperature of heat addition. And therefore, to increase the net efficiency of this cycle we have to find a way of increasing the temperature of this feedwater from this T_2 level to the saturation temperature level which is this $T_{2'}$.

Where this $T_{2'}$ is nothing but the saturation temperature corresponding to the boiler pressure like in this example 150 MPa. If we can somehow achieve that, that is the water coming out of the boiler feed pump will enter the boiler not with temperature T_2 rather with the saturation temperature corresponding the boiler pressure, then the average temperature will not corresponding to heat addition will not correspond to the 630 ^{0}C rather there will be significant increase in this 30 ^{0}C.

I have forgotten the number but corresponding to 150 MPa your saturation temperature may will be in the range of 250 ^{0}C or even more than that. So, immediately there is a big jump in the temperature level in this boiler operation and so there is an increase in the average temperature of heat addition. $T_{A,average}$ increases and accordingly the thermal efficiency will also increase.

So, that is the idea of regeneration that is to increase the efficiency of an ideal Rankine cycle by incorporating the regeneration where the objective is to raise the temperature of the feedwater coming out of the boiler feed pump from the T_2 level to the saturation temperature corresponding to boiler pressure. But how can you do that? You already have studied the Brayton cycle and there we have seen that the exhaust gases that are going out after the turbine expansion, the heat remaining in that exhaust gas is generally used to raise the temperature of the air before it enters the combustor.

But that kind of option we do not have in case of a Rankine cycle because here nothing is going out in a way. The steam is complemented, it is a perfectly closed cycle and the water or steam whatever we may call the working substance that is bound within the domain of this boundaries. So, the ideal way of achieving the regeneration is something like this: where the water coming out of this feed pump this stage number 3, before it enters the boiler which stage number 4 it is allowed to pass through the casing of the turbine or through the outer surface of the turbine.

And water as it passes through the turbine while it goes through the expansion process but that expansion is no more an isentropic expansion rather during this process its temperature also decreases because of heat addition so its entropy decreases. Even if there is no frictional losses but entropy will decrease. Because you know that entropy of a system can change while in two ways: one is because of heat addition and other is because of irreversibilities.

So, even when there are no irreversibilities, because of a heat transfer I should not say heat addition heat additional rejection. Because of any heat transfer the entropy of substance can change. Now here in the turbine the steam which is coming with state number 1 as that passes through the turbine it loses heat to the feedwater thereby its entropy also reduces. Because the direction of entropy transfer along with heat transfer is the same as the direction of the heat transfer.

So, its entropy reduces as shown on this diagram the turbine expansion starts from this point number one and had there been no regeneration it should have ended up somewhere here. But because of the presence of regeneration its temperature and entropy both reduces. So, it ends up at some point 2. 2 is the point up to which you have this regeneration going on. After this point 2 to 2', it is the normal turbine expansion that is isentropic expansion when it is not in vicinity of any kind of heat water. But process 1-2, that is the turbine expansion can be divided into 2 parts this 1-2 where we have the regeneration going on. That is heat is getting transferred to the feedwater from the steam which is getting expanded in the turbine, and then from stage 2 to 2' which is normal isentropic expansion.

So, this is the most ideal one you can achieve with regeneration. The advantage of this can be we can get the idea by looking at this *Ts* diagram. If we take any cross section of this turbine where the regeneration is going on that is between state 1 to 2 you can see both the feedwater and the steam are more or less at the same temperature, there is infinitely small temperature difference between the two.

And therefore, the heat transfer that is taking place from the steam in the turbine to the feedwater that is happening with infinitely small temperature difference. So, that can be viewed as a reversible heat transfer. And hence the cycle that we have drawn, that is allowing you reversible heat transfer and hence it is a perfectly reversible cycle now. And as this is a perfectly reversible cycle so its efficiency has to be equal to the Carnot cycle efficiency. That is the biggest advantage of this particular ideal cycle with regeneration.

But practically this is not possible. One big problem is that, look what is happening during the turbine expansion. As it is getting expanded, had it been an isentropic expansion something like this of course during the expansion it starts with the saturated vapour but gradually it gets converted to a mixture. And during the regeneration part, again it is getting converted to mixture but the quality is decreasing very rapidly and so the turbine in towards the later stage towards somewhere here has to deal with very wet steam, which is always problematic. There will be significant amount of erosion which cannot be sustained in practical operation.

Another problem is, if we want to have this on the turbine, it will have to act as both a turbine as well as a heat exchanger, which is again very difficult. We always want to have the turbine built in adiabatic mode so that there is no heat loss.

And now you are talking about making it a heat exchanger, so that is also impractical. And therefore, this ideal cycle is not possible in practice. Rather we have to think about some other way of achieving the regeneration. And to have that what is done in practice instead of allowing the feedwater to pass through the casing of the turbine, small amount of steam is extracted from the turbine from during some part of its operation and that steam is supplied to a feedwater heater where it exchanges heat with the feedwater and thereby raising the temperature of the feedwater.

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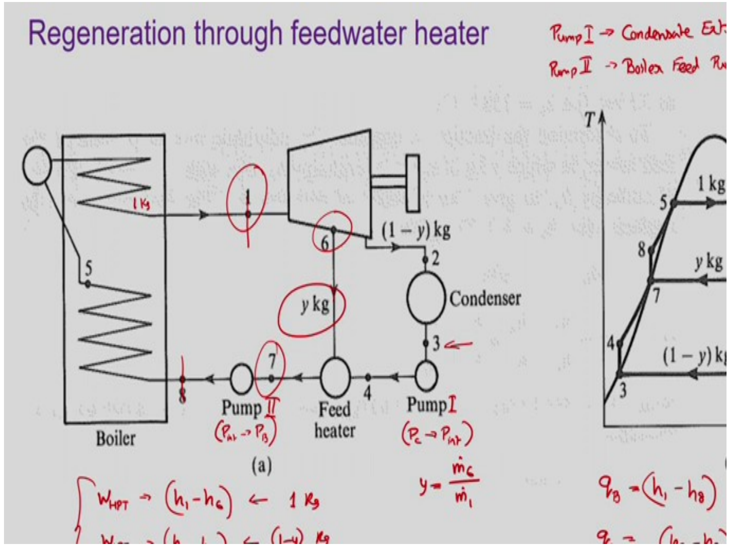

And this is the scheme that I am talking about. So, a small fraction like, if we talk as the initial mass of steam to be equal to 1 kg. Then a small fraction of that, i.e., y kg is taken out at some intermediate pressure level. So, this is the boiler feed pump from there which state 8, the feedwater is entering your evaporator just look at the subsequent Ts diagram. So, this is your state number 8. It is already at the boiler pressure so that the boiler pressure is entering the evaporator and then there it is getting super-heated up to state number 1, which is this particular point. So, this 8-1, this entire thing is happening at the boiler pressure where the feedwater sub-cooled or compressed liquid is getting converted to superheated vapour. Then it is passing through the turbine, but instead of allowing the entire quantity of steam to pass through the turbine at some intermediate pressure level, at this point 6 small fraction is taken out. And the remaining fraction that at one point, the $1 - y$ fraction is allowed to complete the expansion.

Look at the diagram, this is an intermediate pressure that I am talking about where a small quantity has been taken out. Remaining portion is allowed to complete the expansion to reach state number 2. Once it reaches state number 2 then it passes to the condenser. So, that 1 - y fraction gets condensed to reach state number 3 somewhere here. Now that is allowed to pass through a pump where its pressure is raised to that intermediate pressure level.

So, here else we are talking about two pressure levels. This particular pressure line is your boiler pressure line, this pressure line is the intermediate pressure line and this pressure line is the condenser pressure line. So, there are two pumps: the first pump, the pump number 1 is raising the pressure from the condenser pressure level P_C to that intermediate pressure level.

And once it reaches to the intermediate pressure level, now we have a feedwater heater which is nothing but a mixing chamber kind of thing. The condensate that is coming from your pump number 1 and also that y kg of steam that you have extracted often called the bleed steam that is coming from the turbine that is they are allowed to mix in the feedwater heater. And in therefore it forms a mixture of temperature or state 7.

This is the state ideally, in case of ideal reheating the state of the working substance at this point will be of saturated liquid at that intermediate pressure level, that can be controlled by controlling this fraction y. That is, we want in case of ideal regeneration, where you want the magnitude of y to be such that state 7 and correspond to the saturated liquid state at the intermediate pressure level.

Now we have the second pump, where the pressure is raised from this intermediate pressure to the boiler pressure to have reach state number 8, which is sub cooled liquid now. But at elevated pressure and then it processes to the boiler operation. This is also the alternate way or practical way of doing regeneration. In practice any thermal power stations working with steam will be having feedwater heaters where just as shown here, steam will be extracted. And that steam will be used to raise the temperature of the feedwater. You can see there are two pumps that we are talking about pump one is raising the pressure from P_C to $P_{intermediate}$ and pump 2 is raising it from intermediate pressure to the boiler pressure. Pump 1 is taking its input from the condenser and therefore it is often called the condensate extraction pump.

Condensate extraction pump or in short CEP and the pump 2, as it is going to supply the feedwater back to the boiler is called the boiler feed pump, as I just mentioned, or in short BFP. So, in power stations commonly we will find both the pumps in operation: one is the condensate extraction pump which operates at the lower pressure level because it takes its input from the condenser which is at the vacuum pressure and resists it to the pressure of the feedwater that is an intermediate pressure at which the feedwater heater is operating and also the steam has been extracted from the turbine. And the second pump, the boiler feed pump is taking its input from the feedwater and supplying it to the boiler pressure. So, if we want to see a very brief analysis of this entire thing, look at this diagram. Let me remove all these red lines to make it clearer. So, in the boiler the amount of heat that you are adding is equal to:

$$q_B = h_1 - h_8$$

and that heat has been added to the entire mass. So, that has been added to the entire mass, that is 1kg. In the condenser the change in enthalpy is:

$$q_C = h_2 - h_3$$

but look the condenser is not operating on the entire mass rather it is operating only on $(1 - y)$ fraction. So, though the change in enthalpy of the working medium is:

$$= h_2 - h_3$$

but it is operating on $(1 - y)$ kg of condensate per unit mass of the working medium and so while calculating the total heat load of the condenser or heat rejected in the condenser, we have to take into account this $(1 - y)$ fraction.

And what about the turbines? Now there are two stages of turbine expansion you can see. In one stage the high-pressure turbine, the change in enthalpy the high-pressure part change in enthalpy is:

$$W_{HPT} = h_1 - h_6$$

and here it is operating over the entire mass. However, on the low-pressure stage the change in enthalpy is:

$$W_{LPT} = h_6 - h_2$$

but here this is happening over $(1 - y)$ kg. So, if you want to have the total turbine output you have to consider different mass flow rates for different turbines.

And what about the pumps? So, W_P for the first one which is the condensate extraction pump here the change in enthalpy is:

$$W_{P,I} = h_4 - h_3$$

or if we see as we have seen often, we can write this one as:

$$\approx v_3(P_4 - P_3)$$

but this entire thing is operating on $(1 - y)$ kg of mass, because that bled steam has not been mixed with the fluid. But what about the second pump which is the boiler feed pump? Here again the change in enthalpy is:

$$W_{P,I} = h_8 - h_7 \approx v_7(P_8 - P_7)$$

where

P_8 is boiler pressure

P_7 is intermediate pressure

and it is operating over the entire mass because the mixing has taken place, mixing between the remainder of the condensate and the bled steam that has taken place. Similarly, if we want to write an energy balance for the feedwater heater, what you can write?

So, the feedwater is receiving y kg of steam from the boiler at state 6. So, it is in carrying energy:

$$yh_6 + (1-y)h_4$$

it is also receiving $(1 - y)$ fraction of condensate coming from the condensate extraction pump which state 4. So, it is h_6 and h_4 are the two corresponding states and what is the output? The output is

$$= h_7$$

which is having the entire mass into picture. So, this is for the feedwater heater that we are talking about, an energy balance for the feedwater heater. And of course, here y is the mass fraction which we can write as mass flow rate of this bled steam divided by the total mass flow rate:

$$y = \frac{\dot{m}_6}{\dot{m}_1}$$

But this way that we have shown the feedwater heating that is only the theoretical aspect. Practically we can have two kinds of feedwater heaters: open feedwater heater where do we allow the condensate and the bled steam to mix with each other thereby having a direct heat transfer and also the closed feedwater heater where they flow in some shell and tube kind of heat exchanger, that is a condensate flows through pipelines and the steam is allowed to flow outside of that pipe lines on the shell side and therefore there is no direct mixing that is called closed feedwater heater.

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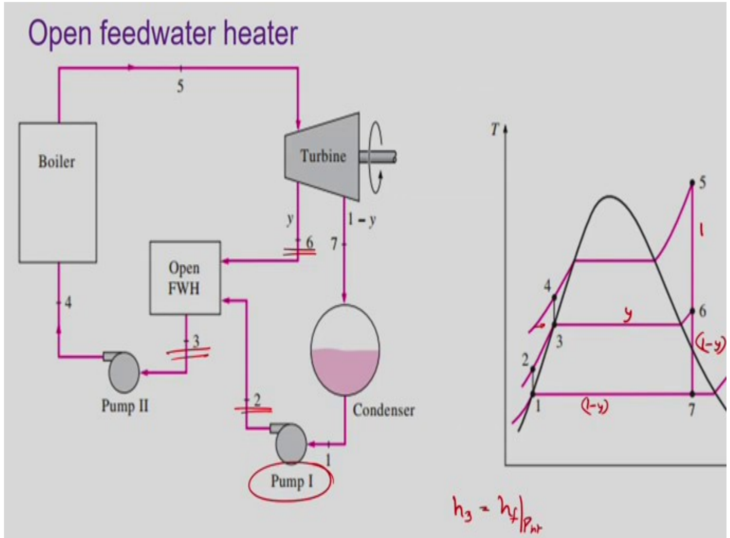

First this is the open feedwater heater in case of an open feedwater heater just the scheme that we have seen in the previous slide. Here the bled steam coming with the state 6 and the condensate coming at this state 2, they are allowed to mix with each other. So, here as I have shown, if the mass here is one then y fraction is flowing through this state 6 and $(1-y)$ fraction is completing the expansion going from 6 to 7. In the second stage of the turbine expansion or maybe the remainder of the turbine expansion and then this y fraction. Of course, we are talking about two stages of turbine expansion but a truly speaking it is a single turbine, just to mention that there are different flow rates we are referring as one high pressure stage and other low-pressure stage. But it is not like reheating where we have two different turbines.

In case of reheaters we have two different turbines, but here we have the same turbine but having different flow rates, lower flow rates I should say on the later stage of expansion. So, this condensate having mass fraction of $(1-y)$ then gets passes through the condenser then through the condensate extraction pump in 1 to 2, this is your condensate extraction pump. And then we have the open feedwater heater which is nothing but a mixing chamber and the exit side of the mixing chamber in case of ideal regeneration cycle is as I have mentioned is of saturated liquid at the intermediate pressure.

So, the magnitude of y has to be selected such that:

$$h_3 = h_f|_{P_{ht}}$$

Here the role of this condensate extraction power is very important because as we are going for direct mixing therefore both the bled steam and the condensate has to be the same pressure. And again, after the mixing takes place, we have to raise the pressure to the boiler pressure level and therefore we need two different pumps. Quite often power stations may have more than one heater and each of the heaters requires a different pump when you are going for open feedwater heaters. Because we have to achieve mixing of feedwater and steam at the same pressure and therefore at each stage the pressure of the condensate that has to keep on increasing to the pressure of the corresponding bled steam.

So, this is the open feedwater heater, open feedwater heater allows direct mixing of the two fluids, therefore it provides very, very efficient heat transfer. And also, another big advantage that we get with open feedwater heater is that, the condenser as we have already seen that works at the vacuum pressure level, i.e., at sub-atmospheric pressure. So, whatever precaution you may take but practically it is always possible for that some amount of non condensable gases from the atmosphere may leak into the condenser and get mixed with the condensate.

Now gases like oxygen and carbon dioxide when that get mixed with the water that can lead to significant amount of corrosion of the corresponding pipes. And therefore, it is mandated to get those gases eliminated from your water stream. And that can be done very easily in this open feedwater heater. In the open feedwater heater as we are talking about the condensate mixing with the bled steam to get a saturated liquid mixture.

So, it is when this mixing process takes place it is generally seen that all those non-condensable gases get separated from this mixture and gets liberated to the atmosphere, thereby giving this state 3 to be virtually free of all those condensates. That is why open feedwater heater has a very important role to play though as we are going to see close to feedwater heater in our next slide.

Though power stations commonly go for closed feedwater heaters several of them but there will be at least one open feedwater heater primarily to achieve this deaeration operation, that is to remove the non condensable gases. And therefore, this open feedwater heater is often also called a deaerator that is its purpose is to deaerate the condensate. This is the open feedwater heater.

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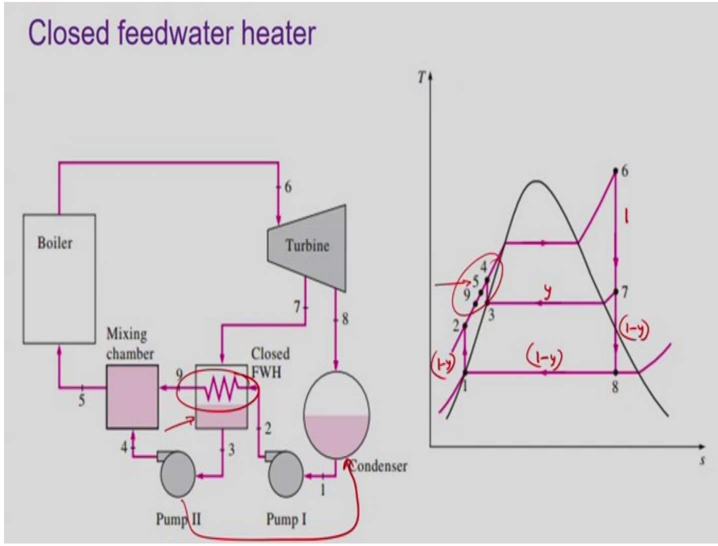

Now you have a closed feedwater heater. In case of a closed feedwater heater the condenser is allowed to flow through these tubes. And the steam which is coming from the turbine extracted from the turbine flows over the outside outer surface of these tubes thereby getting condensed and this bled steam and condensate are never coming in contact with each other. Now the condenser that is formed here in the closed feedwater heater because of the condensation of the bled steam that subsequently can be pumped to a mixing chamber or it can be pumped back to the condenser as well. Or there can be several close feedwater heaters quite often the condensate formed from the bled steam are just allowed to flow back to the lower side over to the feedwater heater which is operating at the lower side. Then in that case we do not need a second pump, we would rather use something called a trap. Trap is an arrangement which operates on throttling. It allows the condensate formed in the closed feedwater heater from the bled steam to throttle back to the lower pressure closed feedwater heater. The condensate from the last feedwater heater is allowed to flow back to the condenser.

Look at the subsequent *Ts* diagram. Here again if one fraction is coming or 1kg of mass is getting expanded in the turbine, y fraction of that is has been extracted at point 7, remaining $(1 - y)$ fraction completes the turbine expansion and then passes to the condenser. Then it passes to the condenser extraction pump also.

So, this state 1 to 2 is also corresponding to $(1 - y)$ fraction, then we have the feedwater heater. But as there is no direct mixing so after the close feedwater heating, they are not going to be at the same temperature rather they will be at the different temperature. Look at this, the state 2 goes to state 9, so the condensate whose pressure which is little bit raised to the boiler feed pump pressure.

It is heated up to temperature 9, whereas the bled steam coming from state 7 loses its heat to form this saturated liquid at state number 3 from where it is pumped back to state number 4 to the boiler pressure level. And then we have a mixing chamber quite similar to an open feedwater heater, where they mix with state 9 and state 4 to give this final state of 5 which then proceed to the boiler.

So, this is what we have in case of a closed feedwater heater. Remember they had the bled steam and the condensate are not coming in contact with each other therefore this heat transfer is less efficient compared to an open feedwater heater. And also requires much more complicated arrangement because we have to arrange for this shell-and-tube kind of configuration, we have to ensure that the steam is not getting leaked into the water stream. But the advantage is here we do not need a separate pump for every feedwater heater.

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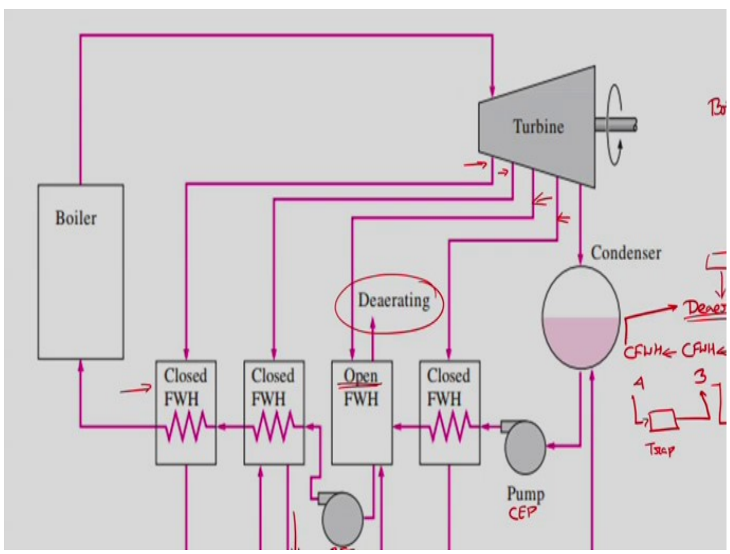

Just look at the arrangement shown here, where we have several closed feedwater heaters. We have four heaters, three of them are closed and one is open. Look at the last one, the one operating with the highest pressure. The condensate here is receiving the steam extracted with the highest pressure from the turbine. So, that steam when that gets condensed then using this trap it is allowed to flow back to the previous feedwater heater which is at a slightly lower pressure because it is using condensate at this pressure which is lower than the first one.

So, here we do not need a separate pump. Now this is from the second close feedwater heater, the condensate coming from the first one is allowed to mix with the condensate formed in the second one and then both of them are allowed to flow through the second trap back to the open heater. In the open heater we are supplying steam at even lower pressure level and also the condensate that is coming from the downstream side they are allowed all allowed to mix with each other. See it is an open feed waterheater so, there everything is allowed to mix with each other and once that mixing has taken place then the final outcome is raised to the boiler pressure level using this boiler feed pump. This is your boiler feed pump. But you do not need separate pumps for the other two closed feedwater heaters.

So, only one pump is sufficient to take the load of all this closed feedwater heaters or to allow the liquid to flow through all the closed feedwater heaters and finally to the boiler. And there is also another closed feedwater heater below this open heater which is receiving steam at the lowest pressure level. And here again the condensate formed is allowed to flow back to the condenser by this trap.

So, we have again just two pumps, one is the condensate extraction pump and another is a boiler feed pump. Now you may question that earlier also here two pumps but see how many heaters? We have here, we are showing four heaters. But still we are using just two pumps, condensate extraction pump you will always be required even if you do not have any feedwater heating. The boiler feed pump is coming because of the presence of the open feedwater heater.

So, we need one condensate extraction pump and then whatever may be the number of open feedwater heaters accordingly number of boiler feed pumps or feed pumps that we may be needing. If there are no open feedwater heater then that condensate extraction pump alone is sufficient because it is directly going to raise the pressure from the condenser pressure level to the boiler pressure level.

But as I have mentioned, mainly to have this deaeration operation we often go for at least one open feedwater heater. Modern power stations you may often find that, you have the condenser, then you have closed feedwater heater 1, then closed feedwater heater 2, then you have another closed feedwater heater 3. We may have a fourth one also, 4 so 3 to 4 stages of closed feedwater heating.

So, the steam coming from the condenser that is allowed to flow through the CEP, condensate extraction pump. From there it flows to the closed feedwater heater number one, from there to the second one, from there to the third one, from there to the fourth one. From the fourth one, now it goes to the deaerator, that is an open feedwater heater. After the open feedwater heater now we need another pump which is your boiler feed pump.

So, from this condenser extraction from outlet till the inlet to the boiler feed from the entire line is operating at that intermediate pressure level which is the pressure of the deaerator. Now after the boiler feed pump, then again we may have several closed type feedwater heater. So, we may have closed feedwater heater number 5, then we may have closed feedwater heater number 6.

Quite often we have a seventh one also enters 7 and then finally it is going to the boiler. That means we are having as shown in this diagram which is very common in several Indian steam-based power stations, we have 8 stages of feedwater heating, seven of them are closed feedwater heaters and one is open heated water heater which is deaerator. Now the deaerator and the first four stages of the close feedwater heating are operating at the intermediate pressure level or the deaerator pressure level.

And the final 3 feedwater heaters, close feedwater heaters plus the boiler is operating at the boiler pressure level. For each of these feedwater heaters the condensate formed from the bled steam are fed back to the lower one through the trap. Like the condensate formed in the closed feedwater heater number 4 that using a trap is fed back to the third one where it gets mixed with the condensate formed here.

So, which is again via trap is fed back to the second one where it gets mixed with the condensate form by the bled steam coming directly to this second feedwater heater. Then we may have another trap which is taking the condensate back to the feedwater heater number one, which combines all these condensates and also mixes that with the condensate of the bled steam coming directly to this.

And finally, this one via trap goes back to the condenser. Similarly, the condenser that is formed in the closed feed heater number 7 that is allowed to flow back to the one at number 6 through a trap where it gets mixed with the bled steam or the condenser of the bled steam coming directly to the 6. So, that condensate that mixture is allowed to flow back to the number 5 through another trap where those two get mixed with the condensate formed individually here.

Finally, that through another trap is fed back to the deaerator. So, for each of the close feedwater heaters we are having a trap which is taking the condensate back to the lower side but you do not need additional pumps for any one of them. That is one big advantage of the closed feedwater heaters and that is the primary reason that we go for the closed feedwater heaters. Also, another big advantage of closed feedwater heating can be that as they are closed in nature, we can have any kind of in addition they are generally much smaller in size compared to the open feedwater heater. And we can feed them anywhere in the orientation of the power stations because they are generally much more compact.

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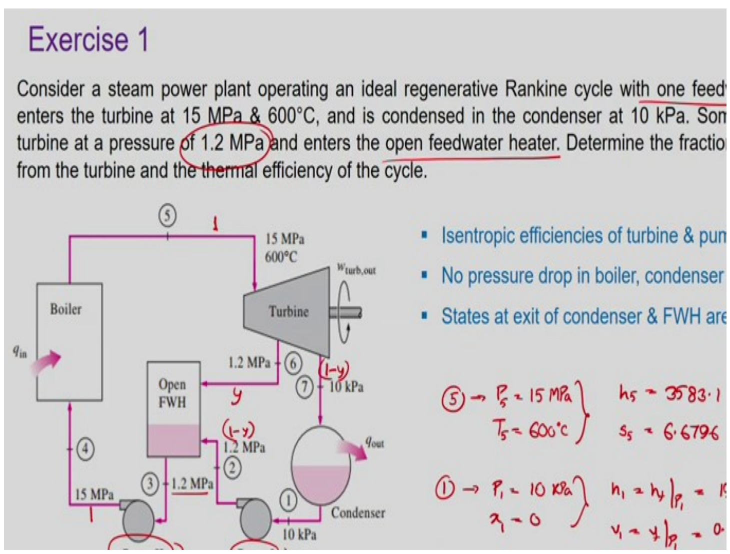

Let us solve one numerical problem to see the effect of this regeneration. Just read the problem carefully. We are talking about a steam power plant operating on an ideal regenerative Rankine cycle with one feedwater heater, just a single feedwater heater we have here. Steam enters the turbine at 15 MPa and 600 ^{0}C and in condensed in the condenser at 10 kPa.

Some steam leaves the turbine at a pressure of 1.2 MPa and enters the open feedwater heater. So, we are talking about an open feedwater heater, it is just a single feedwater heater and there is a open type and this 1.2 MPa is the intermediate pressure. So, here we can note the; I will note down their things later on. Let us read the problem or complete the problem. Determine the fraction we have to determine the fraction of the steam extracted from the turbine and the thermal efficiency of the plant.

So, this is the diagram of the plant. Here we have:

$$P_B = 15\ MPa$$

$$P_{int} = 1.2\ MPa$$

$$P_C = 10\ kPa$$

So, look at the diagram, it is very similar to the open feedwater heater diagram that we have seen earlier. So, steam coming from the boiler with state number 5 with 15 MPa at 600 ^{0}C is fed to the turbine, where it gets expanded at point 6 some amount of steam has been extracted. Let us assume this mass of steam to be equal to y here the total mass is 1 then $(1 - y)$ fraction continues to point number 7 where it goes to the condenser. Then we have this condensate extraction pump as the pump number 1, which raises the pressure from 10 kPa to 1.2 MPa which is the pressure of this open feedwater heater.

So, this condensate at 1.2 MPa pressure and bled steam coming with 1.2 MPa pressure are allowed to mix in this open feedwater heater. So, this condensate is coming with mass fraction of $(1 - y)$ and they form a mixture at the same pressure of 1.2 MPa, here now the mass is back to 1. Where we have the boiler feed pump which increases the pressure from this 1.2 MPa to 15 MPa and feeds it back to the boiler.

Now here you are talking about an ideal regenerative Rankine cycle. So, these are the things that can be assumed, isentropic efficiencies of turbine and pumps are unity because nothing is mentioned and we also we are talking about an ideal cycle. So, they must be having isentropic expansion or compression. No pressure drop in the boiler condenser and feedwater heaters. So, only three pressure levels to be considered. These three only, we do not have to bother about any other pressure levels.

And also states at the exit of condenser and feedwater heater are of saturated liquid. That is important as it is associated only the ideal cycle, in practical cycle they may be sub-cooled or they may be very low-quality mixture as well. So, we have to work out the states.

It is our state number 5, so, for state number 5 we have:

$$h_5 = 3583.1\ kJ/kg$$

I have already noted the values from the tables. And s_5 you know that we need the entropy because you are talking about isentropic expansion. So, it will be coming as:

$$s_5 = 6.6796\ kJ/kgK$$

but point 5 we shall be coming back later on let us focus on point number 1. Point number 1 has:

$$P_1 = 10\ kPa$$

$$x_1 = 0$$

because they are talking about saturated liquid. Then enthalpy,

$$h_1 = h_f|_{P_1} = 191.81\ kJ/kg$$

and specific volume,

$$v_1 = v_f|_{P_1} = 0.00101\ m^3/kg$$

So, you know point number one, then in the pump it is raised to point number 2 and therefore for point number 2 we know that pressure is:

$$P_2 = 1.2\ MPa$$

and this process being isentropic expansion:

$$s_2 = s_1$$

But for pumps as the deal with liquid, so we know that we do not have to think about this isentropic expansion or

$$s_2 = s_1$$

rather we can directly calculate the pump work. So, W_{pump} for this condensate extraction pump should be equal to:

$$W_{P,I} = v_1(P_2 - P_1)$$

and we have already got all the values. So, this will be coming is 1.2 kJ/kg. And if we are looking to have the rate of this pump, the work input rate then you have:

$$\dot{W}_{P,I} = (1 - y)\dot{m}W_{P,I}$$

where the role of this $(1 - y)$ fraction will come into play. Presently you do not need this. So, I am not bothering about the $(1 - y)$ fraction. Once we know this, so using this we can calculate:

$$h_2 = h_1 + W_{P,I} = 193.01\ kJ/kg$$

here 1 and 2 both correspond is the same mass fraction. So, you can directly go for the addition and the value is coming to be 193.01 kJ/kg.

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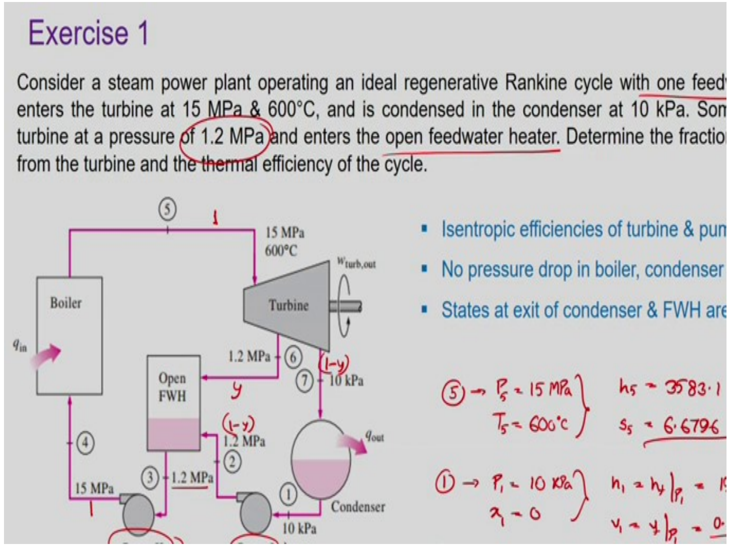

This is the cycle, the *Ts* diagram for the same cycle. The state 1 where we have the mass of one here *y* fraction has been taken out this is (1 – *y*) fraction. This condenser also is operated over 1 - y fraction. So, we have evaluated process 1 to 2. Now look at state number 3. For state number 3, we know that the pressure is the pressure of the open feedwater heater which is 1.2 MPa and as it is an ideal cycle

$$x_3 = 0$$

So, we can easily calculate

$$h_3 = h_f|_{P_3} = 798.33\ kJ/kg$$

and

$$v_3 = v_f|_{P_3} = 0.001138\ m^3/kg$$

So, we are taking six digits after the decimal point practically it is not required. And also look that in the previous case v_1 it was also 0.001 and despite the increasing pressure from 10 kPa to 1.2 MPa, such a large increase it is still more or less the same value. So, there is hardly any change in a specific volume that is logical also. Liquid water is incompressible, that is specific volume or density is independent of pressure which we can see here. So, we know point number 3 now. So we have to now identify the point number 4. Point number 4 corresponds to the boiler pressure level which is:

$$P_4 = 15\ MPa$$

and also, this being isentropic expansion so

$$s_4 = s_3$$

but again we are talking about the pumping operation performed on saturated liquid water or compressed liquid water. So, no need to make use of this:

$$s_4 = s_3$$

rather we can directly calculate the pump work for this 2, to be equal to:

$$W_{P,II} = v_3(P_4 - P_3) = 15.7\ kJ/kg$$

So, it is higher compared to the previous case. For the first pump our work was 1.2 kJ/kg, here it is 15.7 kJ/kg.

But still quite small compared to the turbine work output that you can expect. So, using this we can calculate:

$$h_4 = h_3 + W_{P,II} = 814.03\ kJ/kg$$

Remember this second pump operation has been done on the entire mass of 1, whereas the first pump operation was done on only that $(1 - y)$ fraction. So, if you want to calculate the total power input required then we have to multiply them by separate mass flow rates.

So, we know now point number 4, so 1, 2, 3, 4 unknown to us point 5, is also known to us. So, we can easily calculate the heat input required in the boiler which is:

$$q_B = h_5 - h_4 = 2769.1\ kJ/kg$$

again point 4 and point 5 corresponds the same mass flow rate which is 1. So, we can directly perform this operation without bothering about the mass flow rates.

But we have to talk about the feedwater heating process and also the turbine side. So, we have to identify point number 6 in that case. Look at point number 6, what information are known to us? For point 6, we know that the pressure is that of intermediate pressure that is:

$$P_6 = 1.2\ MPa$$

$$s_6 = s_5$$

So, s_5 we have noted in the previous slide which is 6.6796 kJ/kg.

So, using this we know the value of s_6 now, and if your s_6 is greater than s_g corresponding to P_6 which is coming in this case then we know that it is superheated vapour as shown in the diagram. So, we have to identify this temperature by using the superheated vapour table corresponding to 1.2 MPa and in this particular case I have directly got the number:

$$T_6 \approx 218{,}4°\text{C}$$

which gives you,

$$h_6 = 2860.2\ kJ/kg$$

And what about state number 7? State number 7, the pressure is the condenser pressure which is 10 kPa and

$$s_7 = s_5$$

because this is isentropic expansion. If you combine this you will find that:

$$s_f|_{P_7} < s_7 < s_g|_{P_7}$$

So, it is a mixture calculating this we get,

$$x_7 = 0.8041$$

And putting this number then,

$$h_7 = 2115.3\ kJ/kg$$

So, now you have information about all the possible states. So, how can we calculate the value of this y fraction? Of course we have because you can perform an energy balance over the feedwater heater. So, over the feedwater if we perform an energy balance then we can easily write:

$$yh_6 + (1-y)h_2 = h_3$$

This expression says, look at the feedwater heater, it is receiving bled steam of mass fraction y with state 6 and condense it with mass fraction $(1-y)$ with state 2 and forming mass state 3 with the complete mass.

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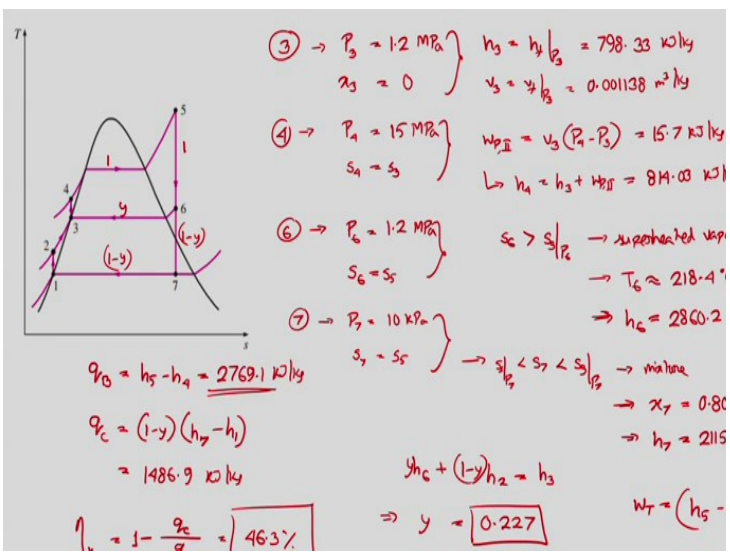

and if you calculate this, we already know the value of h_6, h_2 and h_3 all are there on the slides. So, putting this your h will be coming as 0.227. So, 22.7% of steam has been extracted from the turbine to be supplied to the feedwater heater. And how much is the condenser load? Remember condenser works on $(1 - y)$ mass fraction so, it is:

$$q_C = (1 - y)\,(h_7 - h_1)$$

putting this your value will be coming as:

$$= 1486.9\ kJ/kg$$

So, the thermal efficiency for this plant is equal to:

$$\eta_{th} = 1 - \frac{q_C}{q_B}$$

$$= 46.3\%$$

Just check the lecture of the previous week there we have solved the problem with similar parameters but without regeneration. They are or efficiency or something in the range of 43%. Now as we have gone for the regeneration our efficiency has increased to 46.3%. Of course, we have extracted some steam from the turbine and therefore the net power output from the turbine will be lower. We have not calculated this, but the W_T you can be easily calculated as:

$$W_T = (h_5 - h_6) + (1 - y)(h_6 - h_7)$$

I do not have the calculated value, if you calculate I guess this turbine work will be coming to be slightly lower than what we got in a previous case.

But the amount of energy supplied in the boiler, this particular number that has also come down very, very significantly just compare with the previous problem. That has led to an increase in the overall thermal efficiency of this plant. So, this is an example of how to solve a problem involving feedwater heater.

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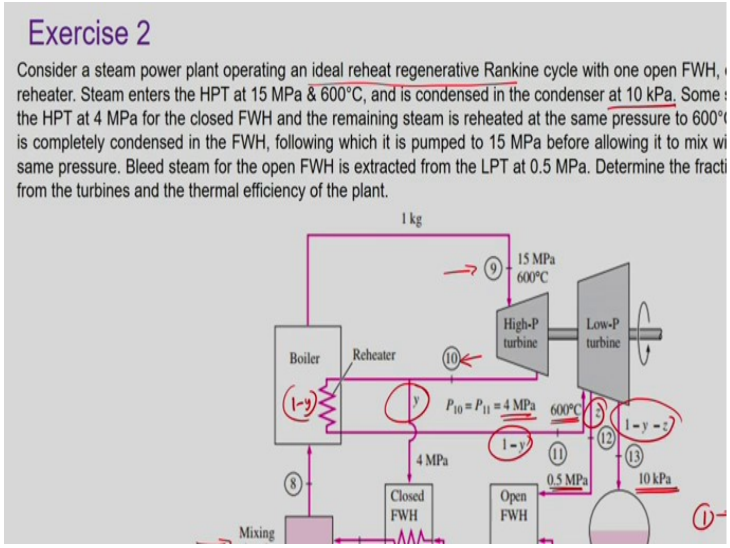

I am going to finish up giving you another exercise I am not going to solve this problem. I am leaving it to you to try on your own, I shall be solving this one in the next class. Also, one additional information, this particular problem is a solved example in the book of Çengel Boles. Please try to solve this one on your own without looking into the book, and also before you start going to the next lecture where I am going to solve this one step by step.

Just read this problem here we are talking about a steam power plant operating on an ideal reheat regenerative Rankine cycle with one open feedwater heater, one closed feedwater heater and one reheater. So, talking about a reheat regeneration cycle, we have reheater and also regeneration plus there are two feedwater heaters one open type and one closed type. This is the cycle diagram for this.

So, the steam that is coming to the turbine, the turbine expansion has been divided into two parts: the high pressure turbine from where steam enters the high pressure turbine in state 9 at 15 MPa and 600 ^{0}C and then it is expanded to some intermediate pressure up to state 2, then it passes through the stage of reheating and it goes back to the low pressure turbine. Let us continue reading the problem.

It is condensed to the condenser pressure at 10 kPa, so this 10 kPa is the final pressure at the exit of the low-pressure turbine and also in the condenser. Some steam is extracted from the high-pressure turbine at 4 MPa for the closed feedwater heater and the remaining steam is reheated at the same pressure to 600 ^{0}C. So, the 4 MPa is the pressure at the exit of the high-pressure turbine and the bled steam for the closed feedwater it is also taken from the same line.

That is here the steam we are not extracting directly from the turbine rather we are extracting it before this, after the steam comes out of the house high pressure turbine and before it enters the reheater, in between you are taking this bled steam, a small fraction y at this 4 MPa pressure. Then the remaining fraction which is $(1 - y)$ that is reheated back to that 600 ^{0}C and supplied to the low-pressure turbine. The extracted steam is completely condensed in the feedwater heater following which it is pumped to 15 MPa before allowing it to mix in the feedwater at the same pressure.

So, it is a closed feedwater heater so it is forming condensate, this condensate is pumped using this particular pump back to the boiler pressure. Where it is mixed with the steam coming from the closed feedwater heater in this mixing chamber, at the same pressure of 15 MPa. Bled steam for the open feedwater heater is extracted from the low-pressure turbine at 0.5 MPa.

So, from low pressure turbine we have this bled line at 0.5 MPa it is coming and getting supplied to this open feedwater heater and the condenser pressure is 10 kPa. So, here another z fraction has been taken out. So, $(1 - y)$ fraction initially, it was 1 which passes through the boiler and the high-pressure turbine, then we take y fraction out to supply to the closed feedwater heater remaining $(1 - y)$ fraction is going to the low pressure turbine and from there z fraction you are taking for the open feedwater heater and $(1 - y) - z$ fraction completes the remainder of the expansion and that is the same fraction that goes to the condenser.

So, we have three pumps to be talked about here. There is the first pump which raises the pressure from 10 kPa to the pressure of the open feedwater heater which is 0.5 MPa. Now mixture from this open feedwater heater is pumped to the pressure of 15 MPa, the boiler pressure, it will be passing with a closed feedwater heater and then to the mixing chamber. And we are not using any trap here rather we are having a third pump which is pumping the condensate in the closed feedwater heater to the mixing chamber. Instead of this we could have easily used a trap to direct this condensate at 6 back to the open feedwater heater thereby you could have saved this third pump and we also never require this mixing chamber.

But in this problem, they are using this third pump and so we have a mixing chamber as well but no trap. So, try to solve this problem on your own. You already know how to calculate. Remember you are talking about an ideal reheat regenerative Rankine cycle. So, the isentropic efficiencies for both stages of turbine and all the three pumps that is 1. There is no pressure loss in the boiler, in the condenser and also in the mixing chamber and in both the feedwater heaters.

No pressure losses and also the exit state 1 and also the exit state for this open feedwater heater that state number 3 that will be of saturated liquid corresponding to that particular pressure level. That is your point number 1 will be having a pressure of 10 kPa and its quality will be 0 because it is saturated liquid. Similarly, for stage number 3, P_3 will be the pressure of this open feedwater heater which is 0.5 MPa and it is also saturated liquid so,

$$x_3 = 0$$

other information is all given. Try to solve this problem on your own, before starting the next lecture or before looking into the book.

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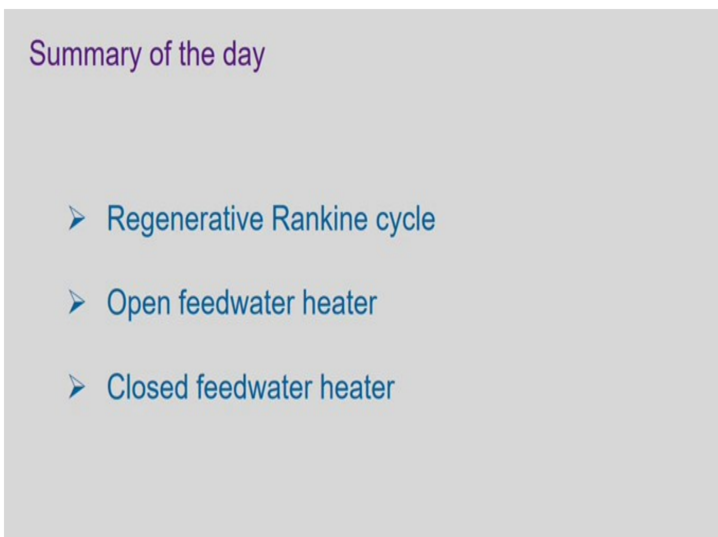

So, today we have talked about the regenerative Rankine cycles, we have seen how it can increase the efficiency, we have discussed from theoretical point of view and also through the numerical example. A regeneration can be achieved with the help of either open feedwater heater or closed feedwater heaters. Practical cycles or practical power stations you know we have both of these kinds, generally, only one open feedwater heater and several closed type feedwater heaters. So, that takes us to the end of today's lecture. In the next lecture we shall we shall be finishing the topic of regeneration, where I shall be solving the problem that I have given here. And then a few other aspects, a few other kinds of vapour power cycles, I would like to discuss. Thank you.