Steam Power Engineering
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Lecture-09
Reheat Rankine Cycle With Regeneration

Welcome, so today we will start with Rankine cycle with regeneration, now till time what we have covered is Rankine cycle simple without any attachment then we talked about Rankine cycle with superheat and then we have said that there is Rankine cycle with reheat. So these 2 things we have seen as an attachment to the Rankine cycle. Now there is a third attachment which is called as regeneration process that we are going to see here onwards.

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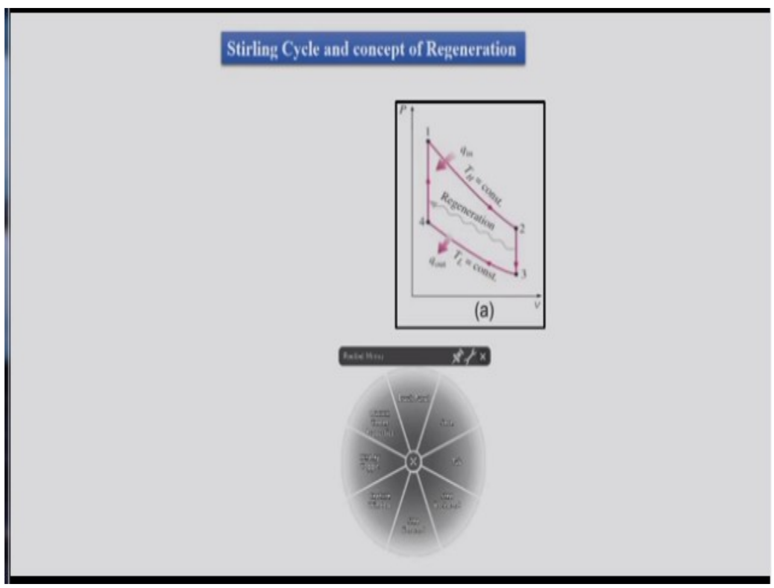

The concept of regeneration is actually taken from the concept which is existing in the sterling cycle. So here we are going to discuss about what is sterling cycle first, thermodynamically we know that sterling cycle is a cycle which is comprised of 4 processes where we will have process 1 to 2 process 1 to 2 as the constant temperature heat addition from the external source.

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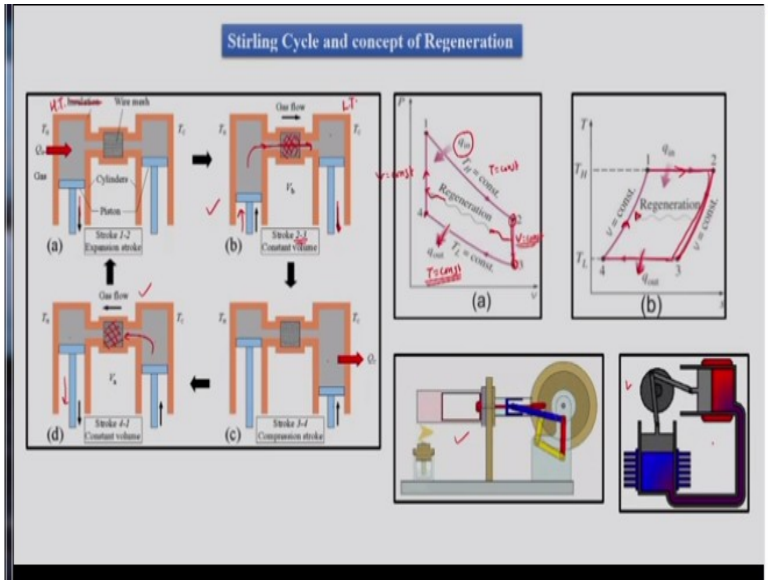

This is little important, this is constant temperature heat addition into the system from the external source, process 2 to 3 is a constant volume process. Here we have V constant, here we have T constant but here process 2 to 3 is V constant but it is heat loss process also. But this heat loss is not to the surrounding, then process 3 to 4 is the q_{out} process at constant temperature to the surrounding.

And then we have process 4 to 1 which is volume constant process but then here we are having heat gain in the volume constant process but this is again not from the surrounding but it is internal it exchange from the process 2 to 3. So practically in sterling cycle we have process 2 to 3 is a constant volume process it is rejecting heat and that heat is gained by this same system part of the system which is executing process 4 to 1.

So this concept is called as regeneration where we are transferring heat from one part of the system to the other part of the system. The same diagram on $T-s$ chart is process 1 to 2 is isothermal heat addition process 2 to 3 is constant volume heat rejection not to that atmosphere process 3 to 4 constant temperature heat resistant to the atmosphere. And process 4 to 1 constant volume heat addition again not from the atmosphere.

So there are engines which are operating in this manner for the sterling cycle they are existing engines. We can see here that these engines can either be 2 cylinder 2 piston engine as in this case or we have 1 cylinder 2 piston engine in other case. There are different versions of sterling cycle based engines, the point to be noted are here in either engines that. Here we are not having any mass transport the system is completely closed in either case.

So it is not like our internal combustion engine where we will have fuel added or we have exhaust. So the same gas, same matter is having heat exchange and work exchange taking place. We can understand the cycle in greater manner if we consider a system of 2 cylinder 2 piston like this. Here the 2 piston motion is in phase they are not moving in the same direction or in the opposite direction but they are motion is in having phase difference.

So for partially for some time they might moving the same direction and for other time they might move in opposite direction as well. So consider the case which is process 1 to 2 which what we are calling it as constant temperature heat addition. So in this case process of heat addition would take place and in the process of heat addition we know that due to addition of it temperature will increase but we want temperature to be constant.

So we will have this heat addition process clubbed with the backward motion of the piston which is in the high temperature zone. So this backward motion is vertically expansion volume is increasing and then heat is return added. But as volume is increasing heat is getting added this 2 things we will get coupled and then we will have constant temperature so this is constant temperature heat addition.

In this case second piston is almost stationary where we will not have much motion of the second piston. But in the process 2 to 3 we have backward motion of the first piston which is trying to push this gas in the second piston or second cylinder and the second cylinder piston is moving backward and this is receiving this gas. This high temperature gas is moving from one cylinder to other cylinder but in this phase this is a wire mesh or this is a buffer in which this hard gas will give it is heat.

And then it will come in this cylinder which is low temperature cylinder, so we get the temperature lower here after the process of constant volume or constant volume. So in this case we will have our piston coming to dead end and most of the gas would have arrived in this cylinder. Then we will have since this cylinder is cooled we will have rejection of heat but rejection of heat would be practically mean to loss of temperature.

But loss of temperature would practically get compensated by compression process and so we will have the temperature to be remaining constant in this case for the gas in the cylinder. But then in the next phase this cylinder as it is moving forward this cylinder will try to come back, so the gas completely will move from this cylinder to this cylinder. And in this phase it will again take the heat which it has given to this wire mesh or buffer such that in the motion of the gas for constant volume process it will regain the heat which is actually left out by the same gas.

So the process which are constant volume processes here we are talking about heat transfer in the constant volume sense but not with the atmosphere. So system is keeping some heat is a buffer which is taking later on. Now this concept of heat addition or heat transfer from the system's different part is translated in the Rankine cycle.

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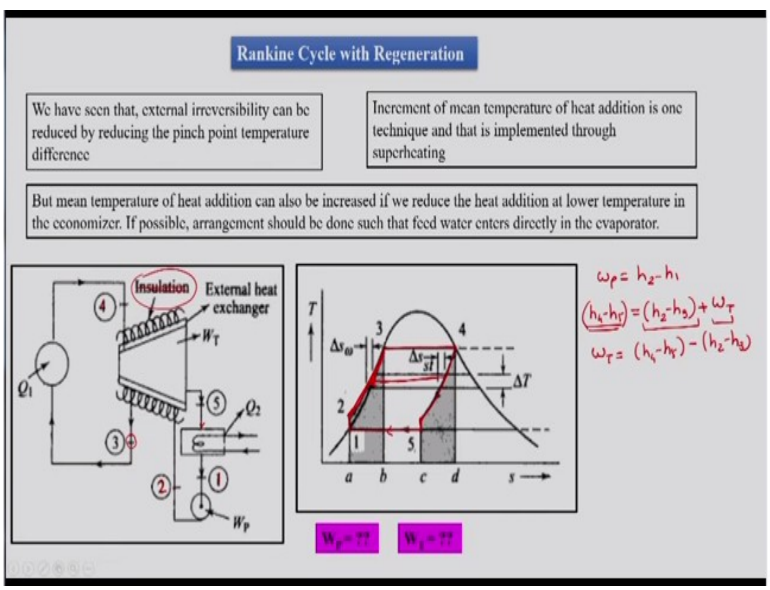

So we have seen that it is possible to have it within the system heat exchange but then why as it regeneration is required. We have seen that externally reversibility can be reduced by reducing the pinch point temperature difference. Pinch point temperature difference we had said that this is the minimum temperature difference between the steam and the fuel gas that temperature difference if you try to reduce then we will have lesser and lesser irreversibility.

Then what we can do to improve the efficiency is we can increase the mean temperature of heat addition. And then for that we were going for super heating but we have also seem that super heating may not be possible always it depends upon the source of heat. So since it depends upon source of heat what we can do is mean temperature of heat addition we can increase by actually reducing the temperature if reducing the amount of heat added into the water in the economizer part.

Since we know in the economizer we add sensible heat and sensible heat is the heat where we are actually having change in temperature. So if we try to remove that part of heat addition then we will just add the saturation latent heat or superheat then those 2 heats will have of higher mean temperature of heat addition. So this is what the argument of regeneration if we can fetch some heat within the system we can give to the economizer.

Then we can bypass the economizer, then the idea in thought is not practical but idea in thought is we have we know that we have pump, pump is with the process 1 to 2. From 1 to 2 we know that it directly goes to the boiler where we have heat addition in the boiler, this is what we were seeing till time. But now what we are saying that no it will not go to the boiler but it will go around the turbine.

Since we know that the steam in the turbine has very high temperature, so since this steam is in the turbine has very high temperature. So that temperature and vortex temperature as finite temperature difference. So due this temperature difference we expect the heat transfer, practically we have insulation in the turbine but in the case when we are saying that we are having heat transfer from the turbine base steam to the water.

We are expecting no insulation and then heat will be transfer due to this heat transfer water will come to this state 3 where it has almost close to the saturation part, it will have the heat which is latent heat getting added into the boiler or steam generator. And then this the water which is the dry saturated or superheated water will get expanded into the turbine and it will come back to the condenser this is a thought experiment.

In this thought experiment we are expecting that we will have 1 to 2 as the pump work and 2 to 3 we are saying 2 to 3 is the heat is getting transferred from the turbine, this turbine is giving this heat such that water is going from 2 to 3. Then 3 to 4 is what we are adding heat into the boiler 4 to 5 earlier turbine was at the nice entropic expansion which is adiabatic reversible. But now we are saying that there is no insulation since there is no insulation the process is not adiabatic.

But there is heat loss entropy will decrease, so we were coming back in this manner and not like vertical line and then we will come to the state like this 5 ok. And then we will have condensation from 5 to 1 this is how the thought ideal regeneration process would exist. Then how to find out pump work and turbine work, it is very simple pump work is same $W_p = h_2 - h_1$ correct, now what is turbine work this is little tricky.

Since what is happening are here is we have $h_4 - h_5$ this is the enthalpy drop of this steam $h_4 - h_5$ enthalpy drop of the steam but what has done with this drop. This drop was helpful for 2 things, thing 1 is to increase the enthalpy of water from h_2 to h_3 + it has done turbine work(W_T). So this and this is the energy values, so this was the energy which was available due to the drop of the enthalpy of the steam in the turbine.

But this turbine based enthalpy drop of this steam has 2 reasons one is heat transfer to the water another is turbine work. So we can know turbine work$W_T = (h_4 - h_5) - (h_2 - h_3)$, so we can find out turbine work.

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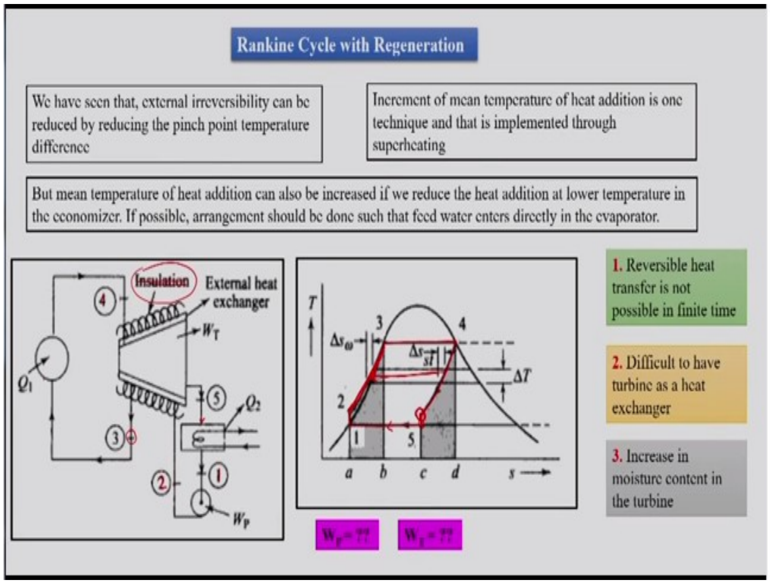

So we actually would find out the turbine work but then the issue which such operation of the Rankine cycle is that reversible heat transfer is not possible in finite amount of time. The process is very fast over here, still we have suppose certain amount of time but in this process we cannot efficiently transfer the heat. So difficult to have turbine as a heat exchanger, so the process of turbine as what we expect is an expansion process.

So we cannot expect turbine also to act as a heat exchanger, so we cannot have an ideal execution of the regeneration process like this what we have just now discussed. Now this also has let one more problem that we have very high moisture content in this state 5. So turbine is experiencing very wet steam since it is wet we are having problem of the life of the turbine, so also it is not a good idea.

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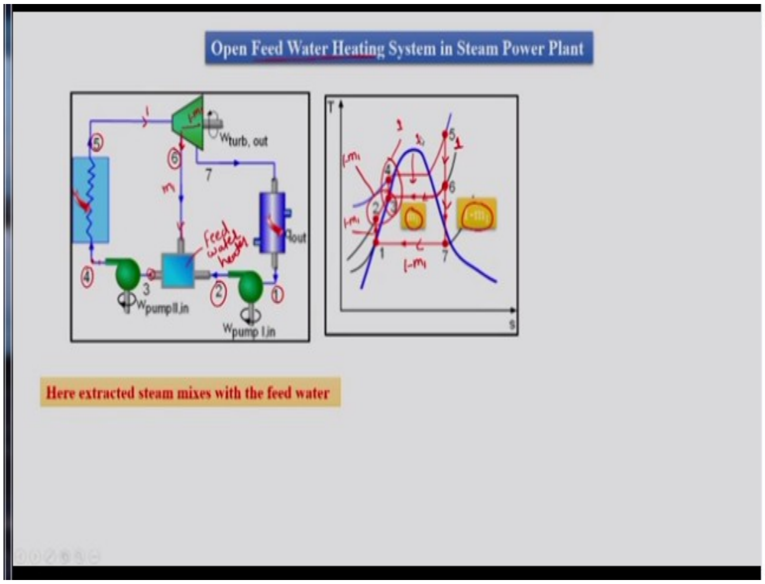

Then there are some other ways by which we can consider regeneration to be possible. The one way is here we can mix the extracted steam directly into the water and the process would be executed in this way. We will have process 1 to 2 in the pump then after pumping in the process 1 to 2 we will have pump to water coming into 1 chamber we call it as feed water heater. So we will have feed water heater, so we will have water coming into the feed water heater and it is basically at certain pressure which is P_2.

But we will extract this steam from the turbine at the same pressure $P_2 = P_6$ and directly mix it with the water. So we have $P_2 = P_6$ and then we will directly mix this steam with the water and then we will get steam at state 3. And at state 3 which is a dry saturated liquid and that dry saturated liquid is basically pumped with further higher pressure rather that is the boiler and then in the boiler we will have heat addition till state 5 from 4.

And then we will have turbine but in the turbine we actually at state 6 we would have extracted some mass m1 but after state 6 we have rest $1 - m_1$ mass is getting flown into the turbine or the expansion process. Initially we had complete 1 kg of mass,1 kg per second mass flowing into the circuit. So this is how the thermodynamic cycle would look like earlier whenever we were drawing $T - s$ diagram for the steam turbine cycle or Rankine cycle.

We never had considered any masses, we have just considered the $T-s$ diagram thermodynamic properties. Since in the complete circuit we have same mass product but now we do not have same mass per unit, what is happening is till this point we have unit mass per unit. But at point 6 we have mass getting split into m_1 mass and $1-m_1$mass and this $1-m_1$mass is reaching to the condenser.

So condenser also has $1-m_1$mass, this pump also has $1-m_1$ mass and this feed water heater also has $1-m_1$mass. But this process 3 to 4 has now 1 kg of mass in pumping and then this boiler also has 1 kg of mass in the process 4 to 5.

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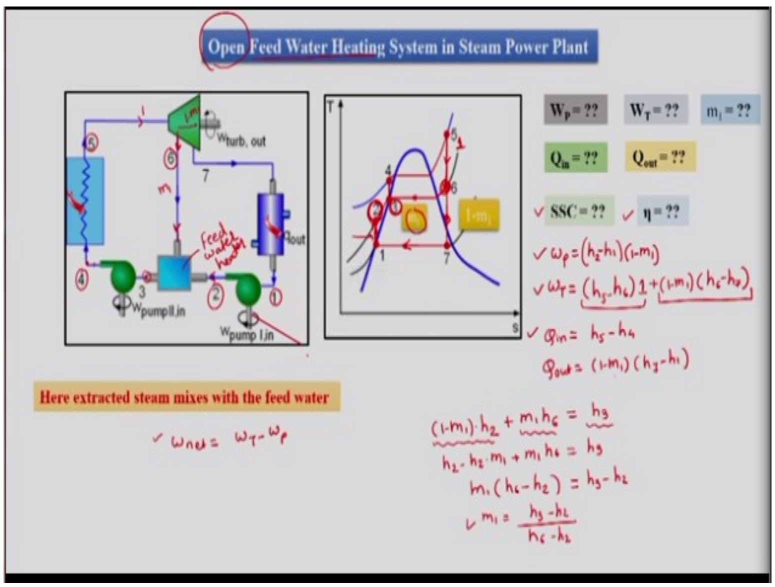

So we have defined masses but rather we have to define masses in this process for the circuit, since it is very essential otherwise the calculation would be wrong since we would learn big conserving the mass ok. So 1 to 2 is a pumping process at state 2 well liquid water comes it has pressure P_2 parallely steam would have come from 5 to 6 state. But pressure P_6 is same as pressureP_2, so we will take n1 mass of the steam at state 6 such that it will lead to a state 3 after mixing with water.

So mass of m1 is very important since the same amount of mass m has to be taken from this steam which would fetch the water + steam mixture to state 3 which is the dry saturated state corresponding to pressure P_2. Then at 3 since steam has mixed with the water we have pumping from 3 to 4 and then we have boiler from 4 to 5 and then we have basically 5 to 6 as complete expansion but then 6 to 7 has rest of the mass which is $1-m_1$ will mix.

And 7 to 1 is a condensation process, so this is something which is realizable, this is something which is practically feasible method of regeneration. But then how to find out pump work, turbine work mass m_1, here pump work finding is simple so we have $W_p = h_2 - h_1$. But this was then enthalpy rise but enthalpy rise was for $1-m_1$ mass. We know in the steam table when we take enthalpy that enthalpy has unit kilo joule per kg or turbine output is also kilo joule per kg.

So for that we have to multiply by kg we are not having unit mass for it so the this pump so condenser pump. So we have to multiply by mass which is $1-m_1$, so then we can get W_p what is W_T here, W_T is simple which we have $h_5 - h_6$ but this is the complete expansion of unit mass. But rest of the mass which is $1-m_1$will expand from h_6 to h_7 this is the expansion of rest of the mass.

So first one first expansion the second expansion such formula we had also consider for reheating where actually we had 2 turbines. But here we have only one turbine but there is change in mass there in reheat we had high pressure and low pressure turbines. Then we can find out basically $Q_{¿}, Q_{¿} = h_5 - h_4$ then Q_{out} is $1-m_1$since condenser has received$Q_{out} = (1-m_1)(h_7 - h_1)$, so now our duty is to find outm_1.

So we have to write mass balance and then we got that m_1 mass is required fetch the water from 2 to 3 after mixing with steam. So we can write the energy balance for this state we know that we have $1-m_1$mass of water at state 2 and that mass of water is mixing so plus with m_1 mass of steam at state 6. And then both of them would go state 3, so this is the mixture total enthalpy, so this is the inlet enthalpy of water + inlet enthalpy of steam, this is outlet total enthalpy.

This is inclusive of all the mass and energy conservation, so we have $h_2 - m_1 h_2 + m_1 h_6 = h_3$. So we have $m_1(h_6 - h_2) = (h_3 - h_2)$, so we have $m_1 = \frac{h_3 - h_2}{h_6 - h_3}$, so we have $m_1 = \frac{h_6 - h_2}{h_3 - h_2}$ sorry we have

$m_1 = \frac{h_3 - h_2}{h_6 - h_3}$, this is mass of steam which is bleder which is taken out from the turbine. Then knowing this mass m_1 we actually can find out all these quantities.

Then we can find out specific steam consumption which needed W_{net} we know $W_{net} = W_T - W_p$ we have calculated W_T , we have calculated W_p then we can calculate specific steam consumption. Similarly we can also find out efficiency since we know efficiency(η) is equal to $\eta = \frac{W_{net}}{Q_{¿}}$ where we have found out $Q_{¿}$ and we have found out W_{net}. But then the feed water heater which we have considered at this moment is called as open feed water heater.

Open, the point to be noted in this feed water heater E is this is open that is why the steam is mixed with water. So there is a mass which is coming inside and then these 2 masses are mix it but the constraint is this $P_6 = P_2$. If pressures are not same then there is irreversibility due to pressure imbalance and then mixing process would become more and more irreversible.

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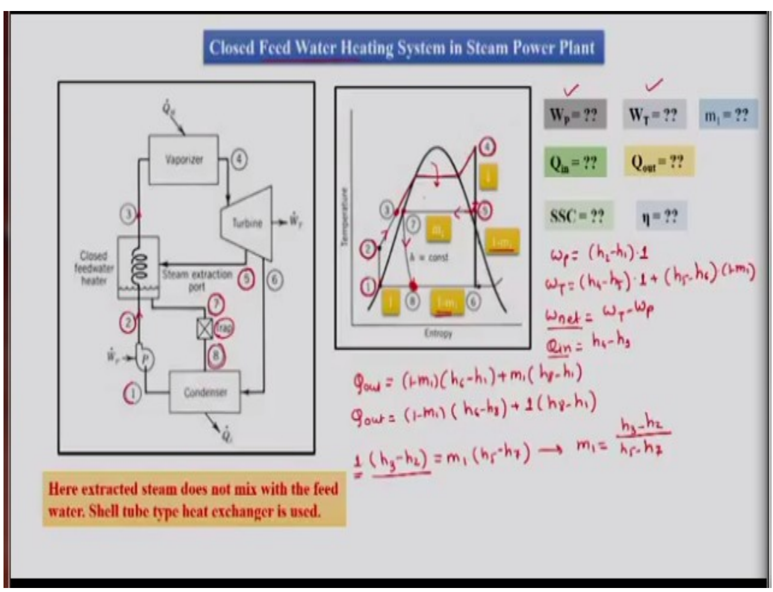

So to avoid this we try to maintain same pressure, then other option is we can have closed feed water heater in the closed feed water heater we know we have pump from 1 to 2. And then we have to go from 2 to 3 due to feed water heating there is a feed water heater. But it is closed type, what do we mean by close type we have water rising it is enthalpy from 2 to 3 where steam is dropping it is enthalpy from 5 to 7, they are not mixing.

Then the steam which has dropped it is enthalpy to 7 is sent back through a trap to condenser, this is mostly a isenthalpic process where we have the trap for sending this steam from state 7 to state 8. So this type of feed water heater is called as closed feed water heater, then how to brought $T-s$diagram. So we have state 1 to state 2 as pumping parallely we have state 4 to state 5 as turbine so here we have in state 5.

Then from 5 we have taken m_1 mass for the regeneration process or feed water heating. So this mass is coming when heating the water from 2 to 3, so we reach here. And water has reached here or steam has reached here which is now which is a saturated liquid. Now this water is sent to the boiler where we are adding heat from the external source and this team is sent back from the 7 to 8 process.

And then we have 4 to 5 as expansion partially in the turbine for the complete mass but rest of the mass $1-m_1$ will expand in the process 5 to 6. And then 6 to 8 we have only $1-m_1$mass into the condenser but at 8 or the mass corresponding enthalpy 8 will be joining this condenser and then we have for rest condensation we have complete mass. This is how we can draw the close feed water heater $T-s$ diagram.

Then here also we have same problem, here we have to find out W_p so we now can find out W_p here pump is handling complete mass. So we have h_2-h_1 complete mass till 1 and then we have W_T, W_T will be same we have $W_T=(h_4-h_5)1+(h_5-h_6)(1-m_1)$. Then this W_p and W_T is find out then we have $W_{net}=W_T-W_p$ we have $Q_{¿}=h_4-h_3$, we have Q_{out} which is this is little tricky.

Since we have 2 different masses, so we have Q_{out} in $Q_{out}=(1-m_1)(h_6-h_1)+m_1¿\text{-}h_1¿$ ok, this can also be said to be equal to that we have $Q_{out}=(1-m_1)(h_6-h_8)+1(h_8-h_1)$. So these 2 formulas are practically same ok then we have to find out m_1, m_1 would be found out here with the constraint that complete mass of water would get heated.

And then it is enthalpy will rise from h_2 to h_3 complete mass of water would have risen it is enthalpy from h_2 to h_3. But for that what steam of mass m_1 has to lose it is enthalpy from h_5 to h_7, so with this formula leads to$m_1 = \frac{h_3 - h_2}{h_5 - h_7}$. This is how we can find out m_1 this specific steam consumption and efficiency can be found out since we know $W_{net}, Q_{¿}$ these 2 things.

Here point to be noted that we did not mix the steam which is extracted from the turbine, we did not mix. So this steam can be at any pressure which we have extracted there is no constraint on the pressure of the steam.