Steam Power Engineering
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Lecture-12
Examples of Regeneration

Welcome to the class, till time we had seen that steam power cycle which is Rankine cycle for us has many components and then how to evaluate there for formals. And how to work out with different interactions like work and heat in the different components, what are the corresponding methods to evaluate what are the optimality conditions and what are the different performance parameters, these were discussed in earlier classes. Now in this class we are going to discuss about steam power cycles and their examples.

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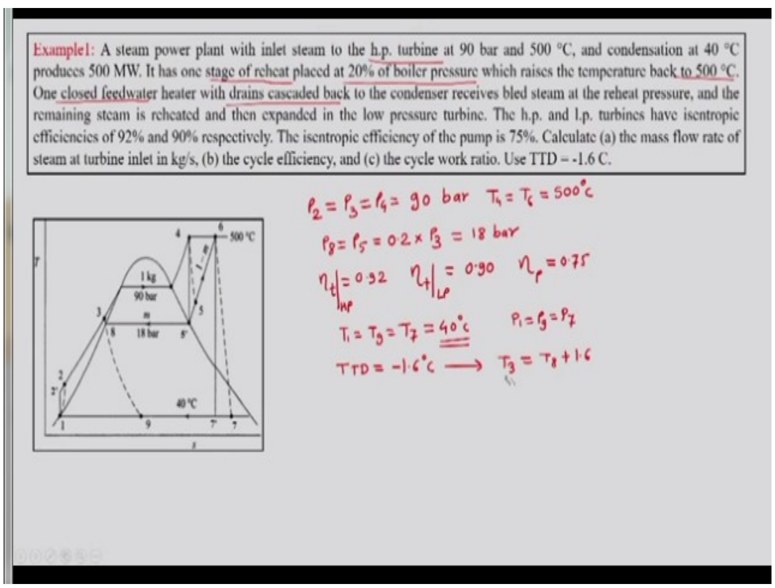

So let us see first example, this example says that steam power plant with inlet steam to the high pressure turbine at 90 bar and $500°C$ and condensation at $40°C$ produces 500 MW of energy. So we are given with 90 bar pressure and $500°C$ are the temperatures of this steam at the high pressure turbine inlet. It has 1 stage of reheat which is taking place at 20% of boiler pressure which rises the temperature back to $500°C$.

So we have 1 reheat, single stage reheat and then reheat temperature is $500°C$, 1 close feed water heater with drains cascade backwards. So we have 1 feed water heater also which is draining cascade backward towards the condenser receives bled from steam at reheat pressure. So reheat pressure we know it is 20% of boiler pressure and the remaining steam is reheated and then expanded in the low pressure turbine h.p and l.p turbines have isentropic efficiencies 92% and 90% respectively.

We have isentropic efficiency of pump which is 75% and then we have to find out mass flow rate of steam at the inlet cycle efficiency and cycle work ratio. So for us this is a typical T-s diagram for this example, so in this example what we know. We know that $P_2=P_3=P_4=90$¿ similarly $T_4=T_6=500°C$, then we know that $P_8=P_5=0.2P_3$ and it is that is why 18 bar.

We are also given that turbine efficiency is if it is HP, if it is HP turbine then efficiency is 92% and if it is LP turbine then efficiency is 90% and efficiency of pump is 0.75. So there are the things which are given to us we are also told that $P_1=P_7=P_9$ is equal to the pressure corresponding to 40 °C. So practically we are given with $T_1=T_9=T_7=40°C$, so we know the $P_1=P_9=P_7$ and that is equal to the pressure corresponding to $40°C$ saturation temperature.

We are also told that TTD = - $1.6°C$, so this implies that $T_3=T_8+1.6$ as per the definition of TTD. So we know TTD is equal to saturation temperature – the exit temperature of feed water saturation temperature – 1.6. So we can know that $T_8+1.6=TTD=T_3$, so knowing this we can start evaluating.

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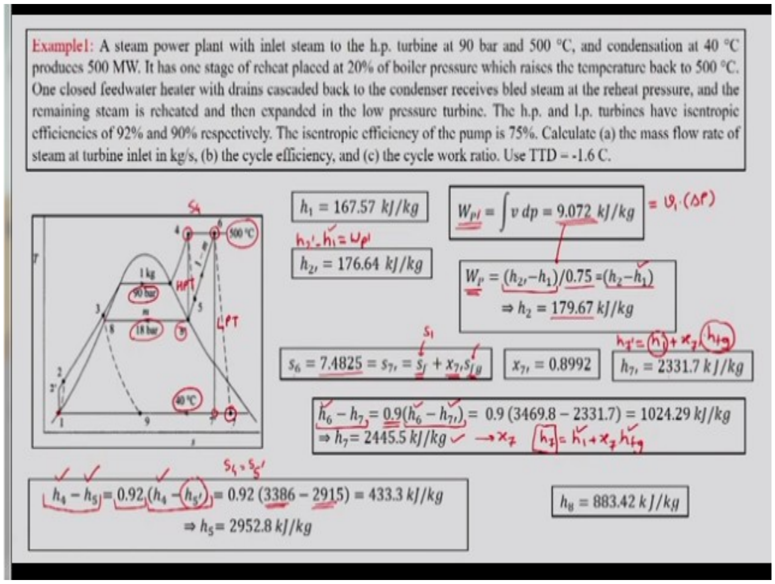

So we know P_1 which is for $40°C$ saturation condition, so we can go to the steam table, go to the saturation temperature part in the steam table find out $40°C$. And then corresponding saturation liquid enthalpy is h_1 and that is 167.57, this is known to us. Then we know that actual pump work is to be evaluated but before that we will evaluate the ideal dash means ideal pump work.

And for ideal pump work we can use $v_1 dP$ and dP is the pressure difference between these pressure corresponding to 40 °C and 90 bar, this pressure difference is dP, v_1 is the specific volume at this state. So thus will give us pump work in actual in ideal case but we know that pump efficiency is given 75%. So that is not the correct work which is actually requiring in pump.

So knowing this we can find out $h_{2'}$ basically $h_{2'}$ is found out from the fact that we know $h_{2'} - h_1 = dP'$, delta P dash is evaluated using this formula h_1 is known then we can find out $h_{2'}$. Then we know that actual pump work is ideal pump work divided by efficiency of pump. So but actual pump work is $h_2 - h_1$, so here ideal pump work divided by 0.7 can be evaluated using this $h_2 - h_1$ within which h_1 is known, so we can find out h_2 and so h_2 is 179.61.

Then we know that S_6, now we are directly coming to the low pressure turbine this is low pressure turbine, this is high pressure turbine. So we know entropy at 6 = entropy at 7' but entropy at 7' $S_{7'}=S_f+x_{7'}S_{fg}$. Basically $S_f=S_1$ and this if we go to liquid saturation entropy corresponding to 40 °C saturation then we can know S_f ,S_{fg} is latent entropy change and that is also given in the steam table, S_6 is we will go to the supersaturated part or superheated part of the steam table will go to the 90 bar pressure.

And 500 °C temperature and then from that we will pick up the entropy, so these things are known to us. So knowing these things we can evaluate $x_{7'}$ and $x_7$turns out to be 0.899, so which can be taken as 0.9. So knowing $x_{7'}$ we can find out $x_{7'}$where $x_{7'}$is practically is equal to $h_f+x_{7'}h_{fg}$ where this h_f is actually equal to h_1.

And h_{fg} is latent change in enthalpy or latent heat, so we know now evaluated the $x_{7'}$. But again we can use efficiency of turbine which is low pressure turbine efficiency is 90% into the ideal turbine work is equal to actual turbine work. So here we now know at 7' we know h_6, h_6 is known to us it is corresponding to 18 bar 500 °C in the superheated part of the steam table.

We know h_6, so $h_{7'}$is known to us from previous step, so similarly we know h_6 here as well and thus these things can be use to find out h_7 which is this point. So knowing h_7 we can find out as well if required the x_7 from the point that $h_7=h_1+x_7h_{fg}$ where h_{fg} is known to us from the steam table where we add used heat over here. And then we know h_1 we had also used it over here h_7 has been calculated then we can find out x_7 if required.

But before that we can find out high pressure turbine, in case of high pressure turbine this actual work is equal to efficiency of high pressure turbine into ideal work. So here ideal work is needing the enthalpy at h5 dash, for that we can go to the stem table superheated part. We can go to 500 °C and 90 bar and then find out the h_4, so h_4 is known and then we can go to the same point and find out S_4.

But $S_4=S_{5'}$, so we know $S_4=S_{5'}$so $S_{5'}$is the entropy corresponding to 18 bar pressure. And then we can find out go to 18 bar part of the steam table find out the entropy at that state which will correspond to entropy of S_4 knowing this that location will have certain enthalpy of the steam which we maybe wet or which maybe dry we will pickup that enthalpy and that enthalpy is $h_{5'}$. So $h_{5'}$ is known to us, h_4 is known to us, $h_{5'}$is known to us from that we can find out h_5, so similarly h_8 is the saturation liquid enthalpy at 18 bar pressure.

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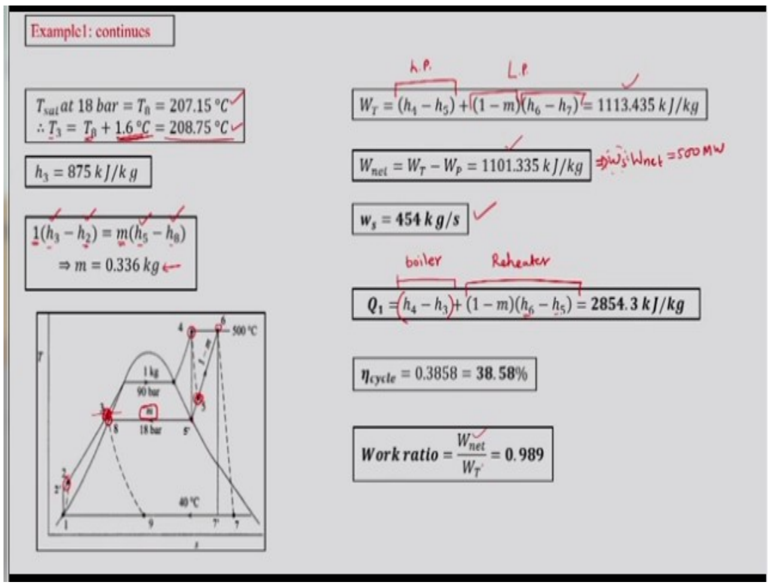

So example 1 is continued, now 18 bar pressure has saturation temperature which is 207.15 °C we had also seen that TTD is given to us. So this is saturation enthalpy saturation temperature + TTD is the temperature at T3. This will be useful to us to find out enthalpy at 3 but this enthalpy is the sub cooled enthalpy corresponding to 90 bar liquid water. This enthalpy would be available again in some steam tables.

Otherwise we could have also approximate it to the saturation temperature as 208.75°C and that saturation liquid enthalpy can also be approximately taken equal to same. Then knowing this we can find out m which is mass given for the bleeding and then that mass is basically can be found out from the energy equation what we are writing that 1 kg of steam is rising it is enthalpy from 2 to 3 at the cost that m kg of mass of bled is losing it is enthalpy from 5 to 8.

So we know now h_3, we know h_2, we know h_5 and we know h_8 from last steps and then we can find out m which is 0.336 kg. This can be helpful for us to find out turbine work and turbine work is $h_4 - h_5$ which is high pressure turbine work h p turbine and then we have $(1-m)(h_6 - h_7)$ this is low pressure turbine. So these 2 turbine works will be added to find out turbine work.

Then net work is turbine work – pump work we had already found out actual pump work, so this will be the net turbine net work of the cycle. But we were told that this net work $w_s W_{net}$ and this is equal to 500 MW. So this will be helpful to us to find out w_s and this w_s is 454 kg per second. Now we can find out Q_1, Q_1 is amount of heat supplied, so amount of heat supplied is $h_4 - h_3$ this is the heat given in the boiler.

So this is heat given in the boiler and then this is the heat which is given in reheater $h_6 - h_5$ and this is Q_1. So cycle efficiency is $W_{net} = \frac{Q_1}{Q}$, so we found out cycle efficiency which is 38.58% then work ratio, work ratio is $\frac{W_{net}}{W_T}$, W_{net} is known to us from earlier step and W_T is turbine work, that is also known from earlier step, then we know work ratio.

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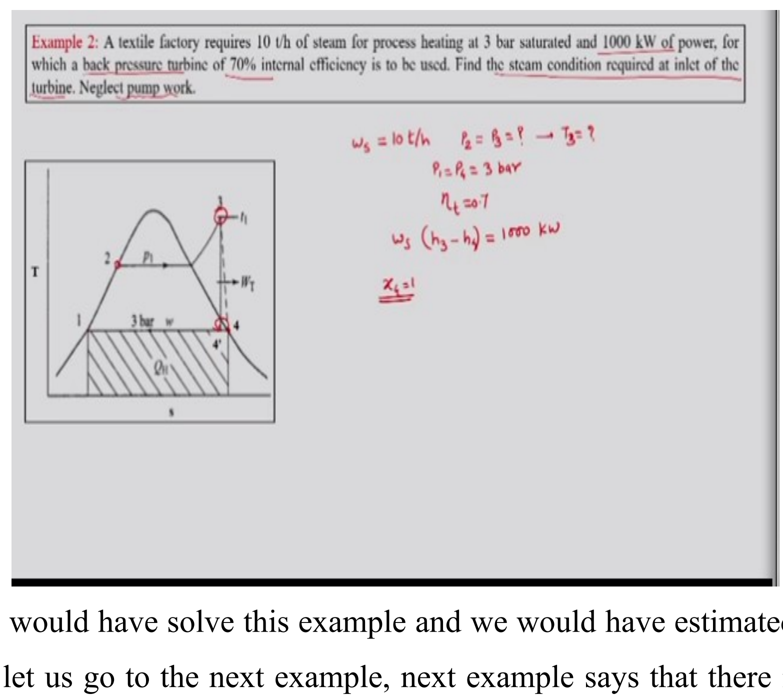

So this is how we would have solve this example and we would have estimated all the necessary parameters. Now let us go to the next example, next example says that there is a textile factory which requires 10 ton of steam per hour for the process heating. So it is a process heating industrial heater is used to heat some object or some matter where 10 ton of steam is considered as the heat source per hour.

And then that heating taking place at 3 bar saturated condition, so steam for the process heating is supplied at saturated condition that is the given fact for us and then the work done is 1000 kilo watt by the cycle. We are obviously using a back pressure turbine and then that turbine has 70% thermal efficiency we are suppose to find out condition of this steam required at the inlet of the turbine we are given that neglect the pump work.

So given this fact we can draw the T-s diagram and this T-s will be like this where we are said that pump work is neglected, so we have not drawn any pump here. Then pump is here itself, state 1 is complete pumping 2 point is purposely shown so as to find out the saturated state corresponding to P_1. So we are told that mass flow rate of steam is given that is 10 ton per hour and then we are given that $P_2 = P_3 =$ ¿found out we are suppose to find out this.

But we are given that $P_1 = P_4 = 3\bar{¿}$ we are also told that turbine efficiency is 0.7, we are also told that $h_3 - h_4$ into mass flow rate of steam is 1000 kilo watt. So this is given fact for us, so we do not know what is the temperature and also we should know T_3. So we do not know where is this state, so logic is that we do not know this state but we know that this turbine is 70% efficient and supply like $x_4 = 1$, supply is saturated.

So this point is saturated, a real point is saturated, so from the real point we will find out ideal point which is $x_{4'}$ from the ideal point we can find out entropy at ideal point. And then we can see that the entropy is at x_3 then we can find out this is the logic of solving this example.

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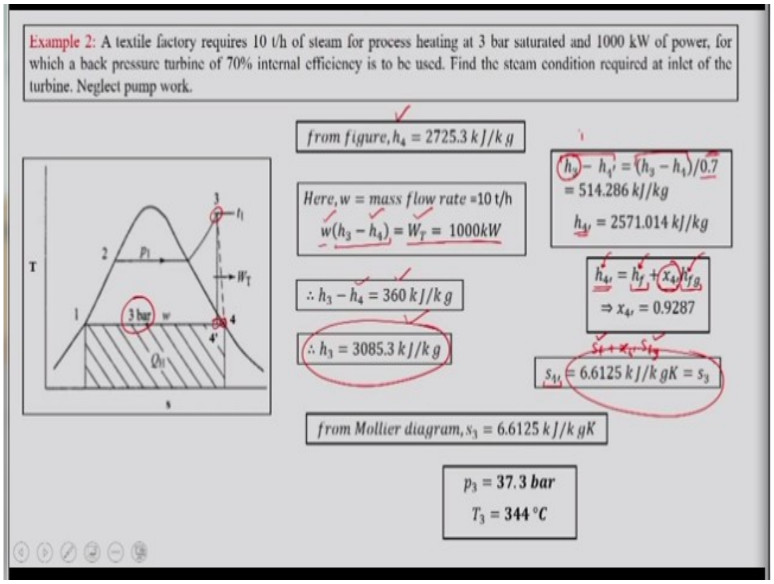

So let us see how we are going to solve this example, so we know that h_4 is a saturation condition and that is at 3 bar. So at 3 bar we can find out saturated steam enthalpy and that is h_4 and then we know that as what we are telling that turbine work is 1000 kilo watt and then that is equal to mass flow rate of steam into change in enthalpy of the turbine. So we know h_4, we know turbine work and we are also given with the steam which is 10 ton per hour.

So knowing this we can find out h_3-h_4 but within that h_4 is known to us, so this will be helpful to find out h_3. So h_3 is known to us, then h_3 is known to us but then we can use the formula for turbine work. So this is the ideal turbine work and this is the actual turbine work divided by the efficiency. So actual turbine work is known, efficiency is known, h_3 is known and we can find out $h_{4'}$ and this $h_{4'}$ will house to 3 bar pressure.

So from this we can say that$h_{4'}+h_f+x_{4'}h_{fg}$, so we can go to 3 bar pressure in the steam table. We can find out liquid saturation enthalpy, we can find out latent enthalpy, we know $h_{4'}$ from previous step then we can find out $x_{4'}$. In the point which is ideal turbine exit, knowing $x_{4'}$ obviously we can find out $S_{4'}$ which is a entropy at 4 and this is again same as $S_f+x_{4'}S_{fg}$which is liquid saturation entropy, this is latent entropy change and $x_{4'}$.

Now $S_{4'}$ is known but $S_{4'}=S_3$, so we know that from the Mollier chart we know Mollier chart is the diagram where y axis enthalpy, x axis is entropy. So we know now enthalpy at 3 is known to us, we know entropy at 3, so knowing entropy and enthalpy we can find out the basically pressure and temperature at state 3. As well if we have not following Mollier chart we can go to the steam table, we can go to the particular entropy.

And then find out for this entropy when we would have enthalpy which is h_3 and then we can take those pressures and temperatures. This point logically at this moment is lying into the superheated part of the steam table.

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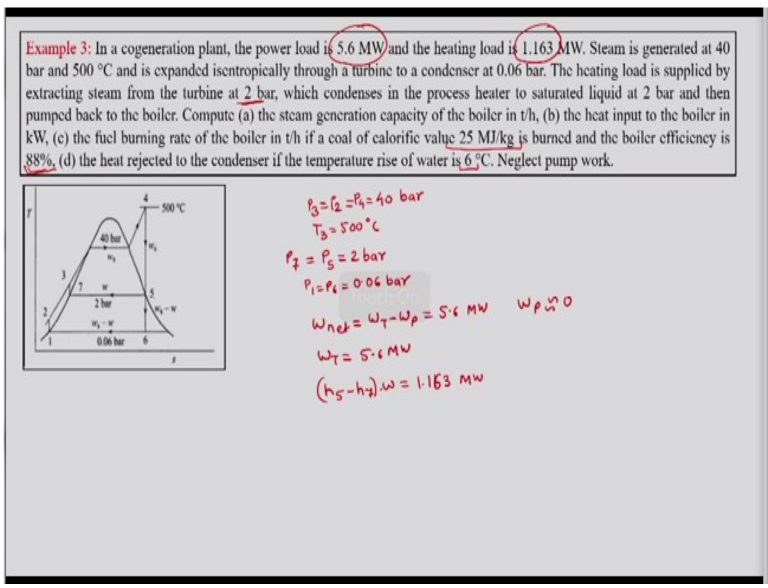

Now let us go to the next example, next example says that there is a cogeneration plant where power load is 5.6 MW and the heat load is 1.163 MW. So this is a cogeneration plant means it is having 2 outputs or 2 objectives one is to generate electricity and one is for industrial heating purpose. So both are given to us, so net work is given to us as 5.6 MW and heating load is also given as 1.163 MW, steam is generated at 40 bar and 500 °C.

And is expanded isentropically through a turbine to condenser at 0.06 bar, the heating load is supplied by extracting steam from the turbine at 2 bar condition. So the heating load is given at 2 bar condition and then the rest of the steam condenses or the steam taken for the industrial heating condenses in the process heater to the saturation liquid state at 2 bar and then pumped back to the boiler pressure.

Basically it is a forward cascading type regeneration except for the fact that this is not used for feed water heating then we are expected to compute steam generation capacity of the boiler in tons per hour, heat input in the boiler and then fuel burning rate in the boiler in tons per hour. We are given that the calorific value of fuel is 25 mega joule per kg of fuel and boiler efficiency is 88%.

So not all the fuel burned is going to give the enthalpy rise for this steam only 88% of the boiler only 88% of the energy liberated from the process of combustion or fuel burning will be use to rise the enthalpy of the steam. And then we are suppose to find out heat rejected in the condenser, if the change in temperature of the cooling water is 6 °C. So let us plot the Ts diagram as per this TS diagram what are the things which are given to us.

We are given that $P_3 = P_2 = P_4 = 40$¿ and $T_3 =$ ¿500 °C, we are also said that the process heating is taking place at 2 bar, so we have $P_5 = 2$¿ and then this is also equal to P_7. We are also told that combustion efficiency is 88% but $P_1 = P_6 = 0.06$¿ these are the given things with us. But we are told $W_{net} = W_T - W_p = 5.6\,MW$ but we are told that pump work can be neglected.

So turbine work is 5.6 MW and heating load in the process heating which is $(h_5 - h_7)w = 1.163\,MW$, this is the given fact for us, so knowing this we can proceed for the example.

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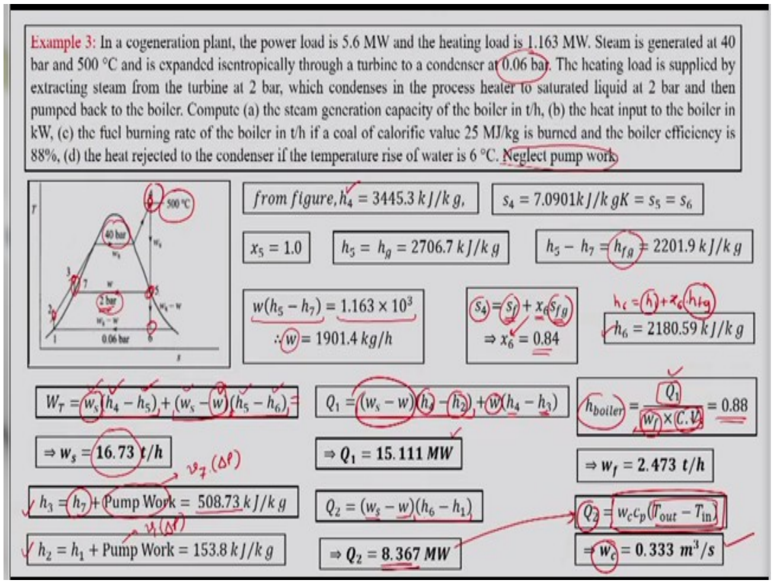

So we can go directly to the steam table at 40 bar and 500 °C and find out h_4 then at the same state we can get the entropy. But this entropy is same as S_5 and S_6 we can use this entropy to find out the condition at 2 bar for the state 5. So what is the enthalpy at 5 we will go to the 2 bar state and then we will find out when this entropy will be equal to S_4 from that we can get the h_5.

Initially turns out that $x_5 = 1$, so it is a liquid it is a vapor saturated state, so we know $h_5 = h_g = 2706.7\,kJ/kg$. This would be giving us $h_5 - h_6 = h_{fg} = 2201.9\,kJ/kg$this is taken from 2 bar which is the latent heat. So as what we are given $w(h_5 - h_4) = heat\,load$, so we can find out w which is the steam required for the process heating. Then we can find out $S_4 = S_f + x_6 S_{fg}$.

And this S_f is corresponding to 0.06 bar S_{fg} is also at 0.06 bar S_4 is known to us corresponding to 40 bar and 500 °C. So we can find out x_6 that is 0.84 we can use this to find out x_6 since $h_6 = h_1 + x_6 h_{fg}$ and this h_1 is at 0.06 bar liquid saturation enthalpy h_5 is 0.06 bar the change in entropy for the phase conversion, knowing this we find out h_6. So turbine work is equal to the total amount of steam getting expanded and loosing it is enthalpy from 4 to 5 before passing w s amount of steam for w amount of steam for process heating.

So $w - w_s$amount of steam is getting expanded from h_5 to h_6 enthalpy drop, so but we know this is equal to 5.6 MW. So here h_5 is known, h_6 is known, h_4 is known, h_5 is known, w_s is known then only we have to find out w and this stands out to be 16.73 tons per hour with obviously would be neglecting pump work. But the pump work to be neglected is the pump which is a condenser pump but this pump is the pump which is pumping of the small amount of steam from the process heating pressure to the boiler pressure.

We know h_7 is the liquid saturation enthalpy at state 7 and then plus pump work and pump work is $\wp = v_7 dP$ where this dP is pressure 40 bar – 2 bar then we can get h_3. We could as well if at all consider pump work here we can consider it is as $v_1 dP$ where delta P is 0.06 bar and 40 bar pressure difference. So we know now h_3 and h_2 both, so heat is added is split like this where $w - w_s$steam is taking rising it is enthalpy from 2 to 4, 2 to 4 is the enthalpy rise for steam which is $w_s - w$.

But small amount of bleed steam for process heating will heating will rise it is enthalpy from 3 to 4. So this is what the total amount of heat given and then this total amount of heat is 15.111 MW. But efficiency of boiler is given as 88% where efficiency of boiler can be said as amount of heat given divided by amount of heat liberated in combustion. So this is calorific value into mass of fuel, so Q_1 is evaluated from earlier state, calorific value is given.

Then we can find out w_f which is 2.473 tons per hour, then $Q_2 = amount\ of\ heat\ rejected = (w_s - w)(h_6 - h_1)$. And amount of heat rejected is 8.367 MW then but amount of heat rejected is equal to mass flow rate of water and into specific heat of water change in temperature of liquid water used for cooling purpose. So this side right hand side is for the cooling water which is used in the condenser to take the heat from the steam.

And to make it liquid saturated and this heat which we are finding out. Now using this we can find out the asked quantity which is the coolant flow rate. So amount of coolant which is flowing into the condenser to take the heat that can be found out since this Δt is given as 6°C. So this is how we can work out and solve the example, so these are some examples which we have solved for the conventional Rankine cycle.

And Rankine cycle with the attachments some like reheater or regeneration are also the examples of back pressure turbine, we will solve some more examples in the next class, thank you.