Applied Thermodynamics
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Steam Power System
Lecture - 21
Numerical Problems: Steam Power Cycle

I welcome you all to this session. And in today's class, we shall discuss about two problems. And we have discussed about Steam Power Cycle and also, we have discussed about the analysis and operation of several components constituting the steam power cycle.

And in this class, we will be discussing two problems. One from the ideal Rankine cycle and another one is from the ideal reheat Rankine cycle. By solving this two problem, we shall see that efficiency of the plant that we have talked about is nothing but the efficiency of individual component. So, efficiency of the thermal power plant depends on the efficiency of the boiler multiplied by the efficiency of the turbine multiplied by the efficiency of the condenser as well as the efficiency of the pump.

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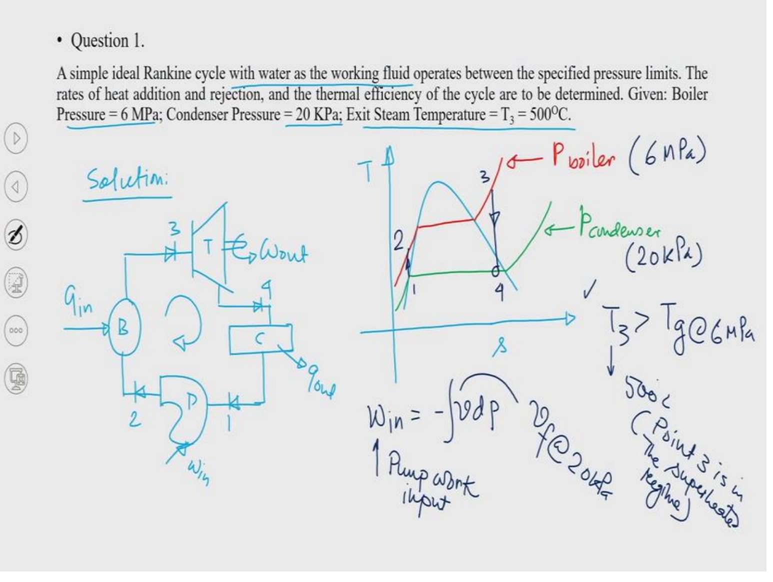

So, illustrating this numerical problem. We shall see that in practical scenario, when a steam power plant is operated then, what will be the maximum efficiency that we can expect. Not only that, we will see that water is allowed to go into the boiler, wherein upon receiving heat, water is converted into steam and then, steam is allowed to go to the turbine. Before it goes into the turbine, it is taken through a flow nozzle essentially to increase the kinetic energy of the steam.

So, at the exit of the boiler and also at the exit of the turbine, we have discussed about steady state steady flow energy equation. From there, we have tried to quantify the amount of heat is being added, amount of work that we are getting from the turbine in terms of the enthalpy.

So, what is the temperature at the exit of the boiler, at the exit of the turbine? We have also discussed the process inside the boiler is a constant pressure process. So, at which pressure boiler is operated. So, all these perhaps will be cleared through the through two different problems that will be solved in this lecture.

So, the first problem is a simple ideal Rankine cycle with water as the working fluid. So, water is the working fluid that operates between the specified pressure limits. The rates of heat addition and rejection, and the thermal efficiency of the cycle are to be determined.

So, this is very important that what is the amount of heat added to the system, the amount of heat must be rejected into the surroundings essentially to allow the system to run in a cyclic manner. And finally, the efficiency of the cycle.

It is given that the boiler pressure is 6 Mpa, condenser pressure is 20kpa, exit steam temperature is 500°C. As I was telling by solving these two different examples, we can see different state different states of the working fluid in the cycle.

So, before going to solve this problem, I would like to give you some important suggestions. What are those? For any numerical problem, be it related to thermodynamic cycle, steam power cycle you have studied about diesel cycle, otto cycle others mechanical, cycles in thermodynamics or if it is a problem related to work and heat or from first law of thermodynamics applied to flow process.

The first objective should be to draw the processes in thermodynamic plane. It is not always true that the thermodynamic plane has to be only Ts plane, it may be pv plane, it may be pT plane, it may be hs plane. So, first objective should be to identify the processes by looking at the problem statement; then, knowing the processes it would be worthy to mimic those processes in thermodynamic plane.

So, in this problem, I mean we can see that it is a simple Rankine cycle. So, just we have drawn the schematic. We can see that we are having heat addition in the boiler and heat rejection from the condenser. So, we need to calculate heat addition and rejection in this cycle. So, we have written all these quantities in the specific form that is all these quantities is per kg of mass flow rate. So, working fluid is water. Anyway, it is given that the cycle operates between two specified pressure limit that is boiler pressure is 6 Mpa and condenser pressure is 20 kpa.

First objective is to draw the schematic and next objective should be to draw the processes. I mean, in boiler that is constant pressure heat addition; turbine that is isentropic expansion of steam. In condenser heat rejection at a constant pressure and finally, to operate this pump that is nothing but reversible adiabatic.

So, we try to represent all these processes in T-s plane as we have to calculate efficiency and also heat rejection and heat addition.

So, as I told you that area under the process line in T-s plane will directly give the heat which is being added or heat is being rejected. So, from the information about the heat being rejected or being added to the system, we can calculate the network output. And if we know the network output and if we know the heat addition, then we can calculate the thermal efficiency.

So, say this is the vapour dome and the cycle is operating between two pressure limits. So, this is the $P_{condenser}$ and another is the boiler pressure. So, this is point 1 and this is point 2.

Now, it is very important, we really do not know whether the state point 3 will be on the saturated vapour line or it will be in the superheated vapour region. State point 3, that is the state point of steam before it enters into the turbine is not known. But it is given as T_3 is 500°C that is exit steam temperature from the boiler. So, boiler is operating between these two pressures. So, basically condenser pressure is equal to 20 kpa and boiler pressure is 6 Mpa.

Now, from steam table we can find saturated temperature T_g corresponding to 6 Mpa and if $T_3 > T_g$, we can consider that the points 3 will be in the superheated regime. Say this is point 3 and then this is point 4.

Now, question is next we have to find out the heat addition, heat rejection and thermal efficiency. Again, we will be applying steady flow energy equation applied to boiler, turbine, condenser and then we will try to calculate the heat transfer and work done.

So, now question is we know that pump work $w_{in} = -\int vdp$. So, this is you know we have discussed that whether it is reversible adiabatic or reversible isothermal process, the expression of work done is $\int vdp$.

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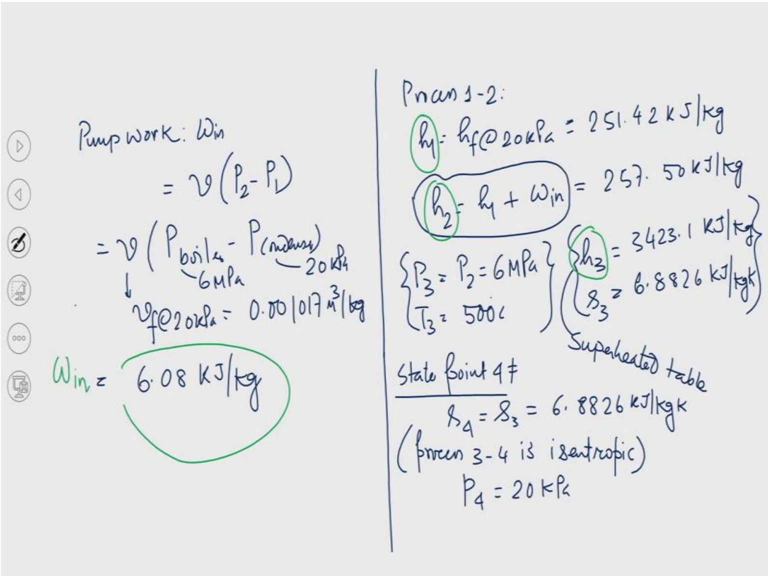

So, $w_{in} = \int vdp = v\left(p_2 - p_1\right)$. So, sole objective of having this pump in this plant is to rise pressure from 1 to 2. So, pressure is increasing from p_1 to p_2. So, p_1 is nothing but $p_{condenser}$ and p2 is nothing but p_{boiler}. So, this is $w_{in} = v_f\big|_{20kpa}\left(p_{boiler} - p_{condensor}\right)$. Point 1 is lying on the saturated liquid line, and hence, v should be v_f at 20 kpa.

So, $w_{in} = v_f\big|_{20kpa}\left(p_{boiler} - p_{condensor}\right) = 0.001017\left(6\times10^6 - 20\times10^3\right) = 6.08\text{kJ/kg}$. This is per kg because we are interested in the specific work input.

As point 1 is lying on the saturated liquid line, so, enthalpy of state point 1 is nothing but the saturated enthalpy of liquid corresponding to 20 kpa and that we will get from steam charts and that is nothing but 251. 42 kJ/kg. So, we need to calculate h_2. We can calculate it by knowing the work input to the pump and enthalpy or state point 1, if I apply steady flow energy equation across the pump.

So, $h_2 = h_1 + w_{in} = 257.5 \text{kJ/kg}$. So, this equation we are getting from the steady flow energy equation applied to the pump, because pump is not a heat interacting device. So, q will be equal to 0. And if we neglect the changes in kinetic and potential energy then, we can write this equation.

Now, next is state point 3. So, heat is added into the boiler. So, we know state point 2 that is h_2, but now we have to calculate our state point 3 and t since, it is given that T_3 is greater than T_g corresponding to 6 Mpa, so definitely from the T-s plane, you can see the point 3 is in the superheated vapour regime. Now, we can calculate h_3 and s_3 from the superheated steam table. So, from superheated table corresponding to pressure 6 Mpa and temperature 500°C, you can obtain h_3 equal to 3423.1 kJ/kg and s_3 is equal to 6.8826 kJ/kg-K.

Now, state point 4; so, 3 to 4 is isentropic expansion process. So, entropy at point 3 and entropy at point 4 will be equal. Again, nothing is mentioned about the state point 4, only we know that the point 4 is on the condenser pressure line; that is called turbine back pressure. So, steam will be allowed to expand up to the condenser pressure. So, $s_3 = s_4 =$ 6.8826 kJ/kg-K, also p_4 = 20kpa. From these two state postulate, we can calculate other properties from the steam chart.

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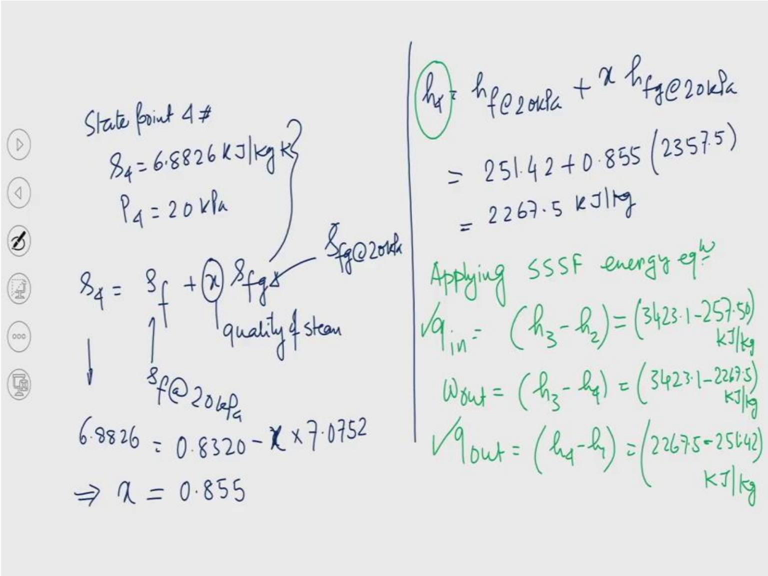

Now, if we go back to the T-s plane. See, point 4 is on the condenser pressure line, but it is inside the vapour dome. So, that is in the two-phase mixture. So, point 4 is inside the vapour dome, it is away from the saturated vapour line. So, we need to find out the quality of the steam.

So, we can write $s_4 = s_f\big|_{20kpa} + x\,s_{fg}\big|_{20kpa} \Rightarrow 6.8826 = 0.832 + x \times 7.0752 \Rightarrow x = 0.855$

So, you can understand quality of the steam is 0.85. So, moisture content of the steam at the exit of the turbine is almost 15 percent.

So, once you have calculated x, we can calculate heat rejection that is nothing but h_4 - h_1. So, we need to calculate enthalpy at state point 4.

Now, $h_4 = h_f\big|_{20kpa} + x\,s = h_{fg}\big|_{20kpa} \Rightarrow h_4 = 251.42 + 0.855 \times 2357.5 = 2267.5\text{kJ/kg}$

Now, we know enthalpy at the 4 different state points, so we can now calculate the amount of heat which is added to the system and the amount of heat which is rejected from the system.

So, just applying steady state steady flow energy equation to all these components, pump, boiler, turbine and condenser:

$$q_{in} = h_3 - h_2 = (3423.1 - 257.5)\,\text{kJ/kg}$$
$$w_{out} = h_3 - h_4 = (3423.1 - 2267.5)\,\text{kJ/kg}$$
$$q_{out} = h_4 - h_1 = (2267.5 - 256.42)\,\text{kJ/kg}$$

So, this is heat in addition to the system per kg of steam and this is heat rejection, then if I multiply with m, we will be getting total heat rejection. So now, there are two different ways by which we can calculate efficiency.

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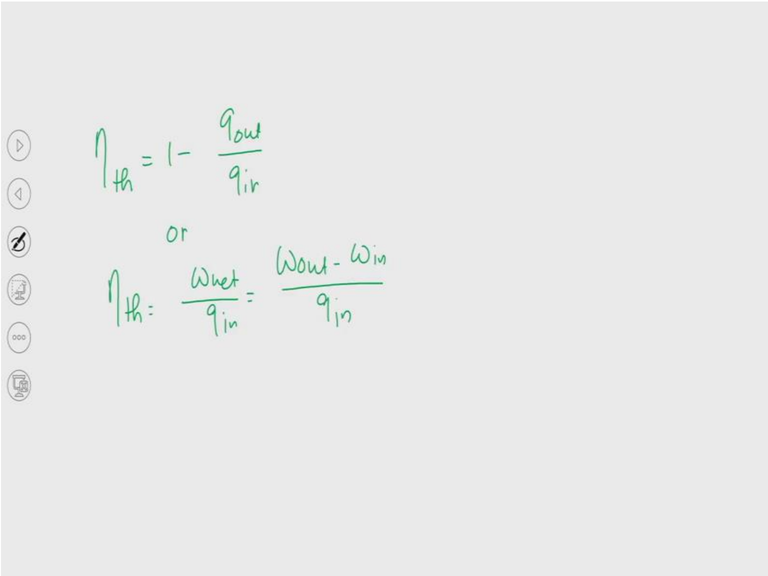

$$\eta_{th} = 1 - \frac{q_{out}}{q_{in}} \quad or \quad \eta_{th} = \frac{w_{net}}{q_{in}} = \frac{w_{out} - w_{in}}{q_{in}}$$

So, this is the first problem we have solved. I have tried to discuss this problem systematically so that you can understand the procedure by which you can solve any other related problem.

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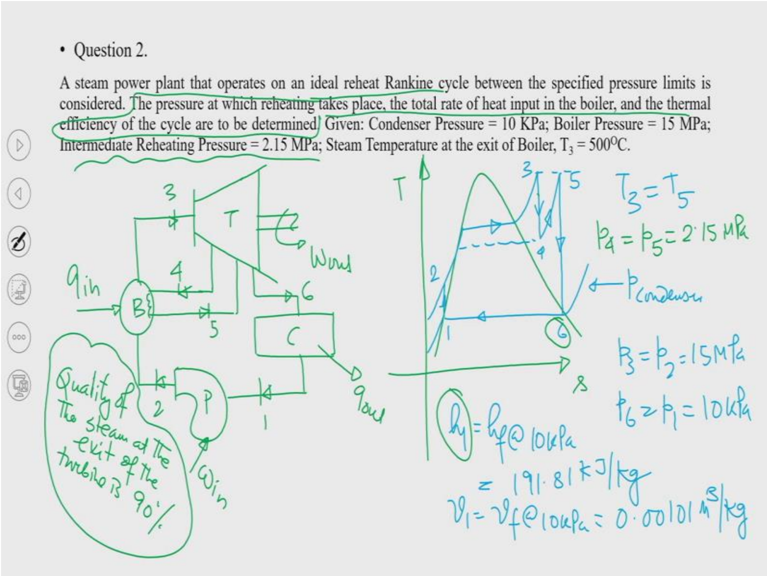

So, the next problem is a steam power plant that operates on an ideal reheat Rankine cycle between the specified pressure limits. The pressure at which reheating takes place, the total rate of heat input to the boiler, and thermal efficiency of the cycle have to be determined.

Condenser pressure is given 10 kpa, boiler pressure is given 15 Mpa, intermediate reheating pressure is 2.15 Mpa. Steam temperature at the exit of the boiler T_3 is given 500°C.

So, let us first draw the schematic you know this is boiler. So, we will be having one pump and then as it is reheat Rankine cycle, steam will be reheated at an intermediate pressure. So, it will be again reheated inside the boiler and steam will be allowed to expand and then, it will come out from the turbines.

So, this is q_{in}, this is w_{in}, I am writing in specific form of these quantities, this is q_{out}, this is w_{out}. So, I have shown here in a simple form that after doing some amount of work, steam is taken inside the boiler and again, it is reheated before it expands finally up to the condenser pressure.

So, after doing certain amount of work, steam is extracted and taken inside the boiler and again taken into the turbine for its further expansion. Now, if we draw the T-s diagram, say this is the condenser pressure and we will be having another one that is boiler pressure.

So, this is an intermediate pressure. So, steam is heated inside the boiler. It is allowed to expand in first stage of turbine. After doing certain amount of work, it is taken in the boiler wherein it is heated at an intermediate pressure up to the point 5. So, T_3 equal to T_5. And then steam is allowed to expand further isentropically up to point 6. So, boiler pressure is 15 Mpa that is $p_3 = p_2 = 15$ Mpa; $p_6 = p_1 = 10$ kpa.

So, $h_1 = h_f\big|_{10kpa} = 191.81\text{kJ/kg}; v_1 = v_f\big|_{10kpa} = 0.00101\text{m}^3/\text{kg}$.

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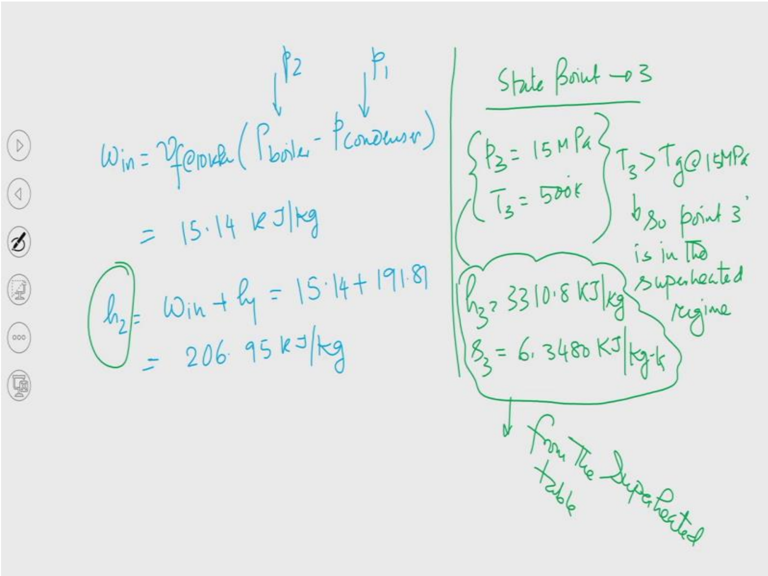

Now, $w_{in} = v_f\big|_{20kpa}\left(p_{boiler} - p_{condensor}\right) = 15.14\text{kJ/kg}$. So, if I apply steady flow energy equation applied to the flow process which is occurring inside the pump; so, $h_2 = w_{in} + h_{f1} = 15.14 + 191.81 = 206.95\text{kJ/kg}$. So, now it is given that p_3 is 15 Mpa and T_3 = 500°C. And if you look at steam table, T_3 is greater than T_g corresponding to 15 Mpa. So, point 3 is in the superheated regime.

Now, from superheated steam table, h_3 will be equal to 3310.8 kJ/kg and s_3 will be equal to 6.3480 kJ/kg-K. Now, if we look at the process 3 to 4 that is isentropic process; so, $s_3 = s_4$.

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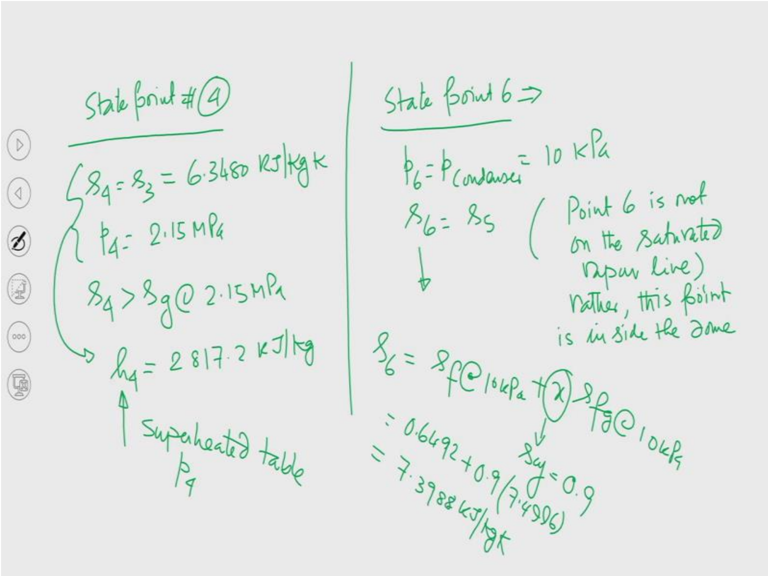

So, it is given intermediate reheat pressure $p_4 = p_5 = 2.15$ Mpa. Now, as $s_3 = s_4 = 6.3480$ kJ/kg-K is greater than s_g at 2.15 Mpa, So, it is in superheated regime. From there you can calculate h_4 and that is coming as 2817.2 kJ/kg from superheated steam table. Maybe, it is very difficult to get exactly 2.15 Mpa from the steam chart, but you need to go for linear interpolation.

Now, I will be going to state point 6. So, pressure is given is same as condenser pressure that is 10 kPa and entropy will be equal to s_5. Now, if we look at the diagram, this point 6 is not on the saturated vapour line. This is little away from the saturated vapour line. Though, maybe from the drawing, it may be apparent that the point 6 is lying on this saturated vapour line, but this is not the case, because the point 6 is in the two-phase mixture that is in the vapour dome. So that means, $s_6 = s_f\big|_{10kpa} + x\, s_{fg}\big|_{10kpa}$.

From the problem statement, it is not given what is the quality of the steam. In fact, for the time being if we this is 0.9. So that means, quality of the steam at the exit of the turbines is 90 percent.

So,
$$s_5 = s_6 = s_f\big|_{10kpa} + x\, s_{fg}\big|_{10kpa} = 0.6492 + 0.9 \times 7.4886 = 7.3988 \text{kJ/kg-K}$$
$$h_6 = h_f\big|_{10kpa} + x\, h_{fg}\big|_{10kpa} = 191.81 + 0.9 \times 2392.1 = 2344.7 \text{kJ/kg}$$

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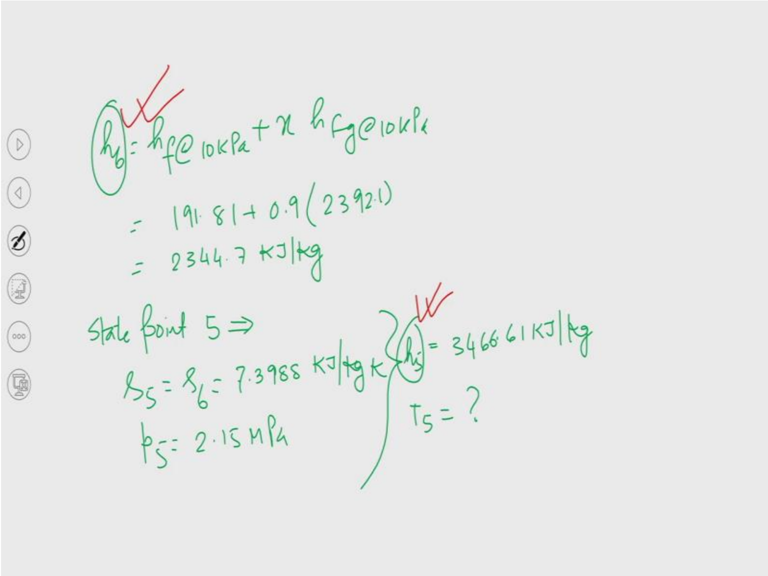

Now, $\left.\begin{aligned} s_5 = s_6 &= 7.3988\text{kJ/kg-K} \\ p_5 &= 2.15\text{Mpa} \end{aligned}\right\} h_5 = 3466.61\text{kJ/kg}$

I would like to discuss one important point. See, in this problem it is said that steam is reheated at an intermediate pressure that pressure is given, but it is not mentioned that it is reheated up to the initial temperature of steam. If it is given then perhaps, intermediate pressure may not be required.

Now, though initially I had written that T_3 equal to T_5 that we can say from our understanding. When we had discussion about the reheat Rankine cycle, we have discussed that reheated steam is allowed to expand in the first stage up to an intermediate pressure and then again, it is reheated inside the boiler up to the temperature and that temperature is equal to the initial steam temperature.

From that understanding, I had written over here that is T_3 is equal to T_5, but nothing is said about this in this problem. What you can do it now? You know p_5 that is intermediate pressure that is 2.15 Mpa, you know s_5. So, you know two properties. From the steam table you can calculate h_5 and you also can check what is T_5.

If it is 500°C, then what we had initially assumed that will be justified.

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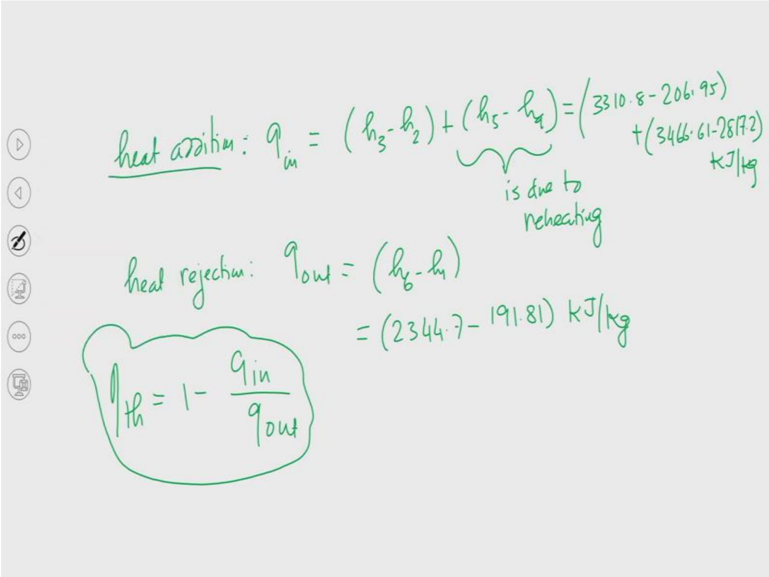

So, the total amount of heat added to the system is nothing but $(h_3 - h_2) + (h_5 - h_4)$ that is when the steam is again taken inside the boiler to heat that steam up to the desired temperature, at that temperature, we need to have additional supply of fuel inside the boiler. So, q_{in} = (3310.8 – 206.95) + (3466.21 – 2817.2) kJ/kg. Now, what is heat rejection? Heat rejection is $q_{out} = h_6 - h_1$ = (2344.7 – 191.81) kJ/kg. Thermal efficiency will be equal to $1 - \frac{q_{out}}{q_{in}}$.

So, if we try to summarize, we have solved two different problems. One is from ideal Rankine cycle, which is straight forward, only to map the processes in T s plane. And from there if we try to apply, whatever you have learnt from this particular module of this course, we can easily calculate the amount of heat is supplied and amount of heat getting rejected. If we note these two quantities, we can easily calculate the efficiency.

For the second problem we have solved today. This is the concept initially I had written that T_3 is equal to T_5. Later, I have given this task to you to check whether the temperature after reheating is getting equal or not.

So, the intermediate pressure is 2.15 Mpa is given. From there, systematically, again by representing all the processes in this T s plane and by applying the steady flow in equation for all the processes, we have different thermodynamic properties. Finally, we have seen here that since at state point 5, we know that entropy will be equal to the entropy at point 6. We also know the intermediate pressure we can easily calculate h_5 and also T_5.

See here, you could have easily calculated h_5 without knowing p_5 provided if, something was given here initially that T_3 equal to T_5. But at least, this intermediate pressure at state point 4 is essential to know. Otherwise, but up to what pressure steam will be allowed to expand in the first stage is very important.

So, this is all about this particular these two problems we have solved today. Before going to you know conclude, I would like to tell you that for this particular module that is the steam power cycle. We have discussed about different cycles. We have seen the problems associated with any particular cycle. Then of course, modifications and those modifications are basically considered in modern steam power plant.

Then, we have briefly discuss about 3 different components; that is turbine, boiler and condenser. And then finally, you have solved two different problems from the power cycles.

I hope, I have discussed to the extent possible without going into the deeper analysis but I hope you have enjoyed this course. And if you have any questions from the topics that I have discussed in this forum, you can raise question in the discussion session and, I will try to address all those questions.

Thank you very much.