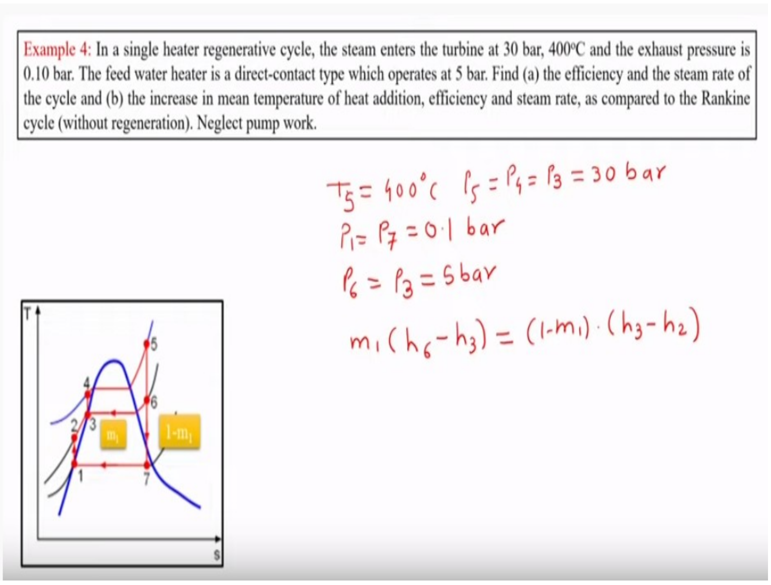
Steam Power Engineering
Prof. Vinayak N. Kulkarni
Department of Mechanical Engineering
Indian Institute of Technology-Guwahati

Lecture - 16
Examples of Binary Cycles

Welcome to the class. Last time we had seen some examples on Rankine cycle with reheat or maybe regeneration and also the example for the back pressure turbine or cogeneration plant. Today we will continue with similar example, but we will also see the example for binary cycles. So let us see our first example.

(Refer Slide Time: 00:52)



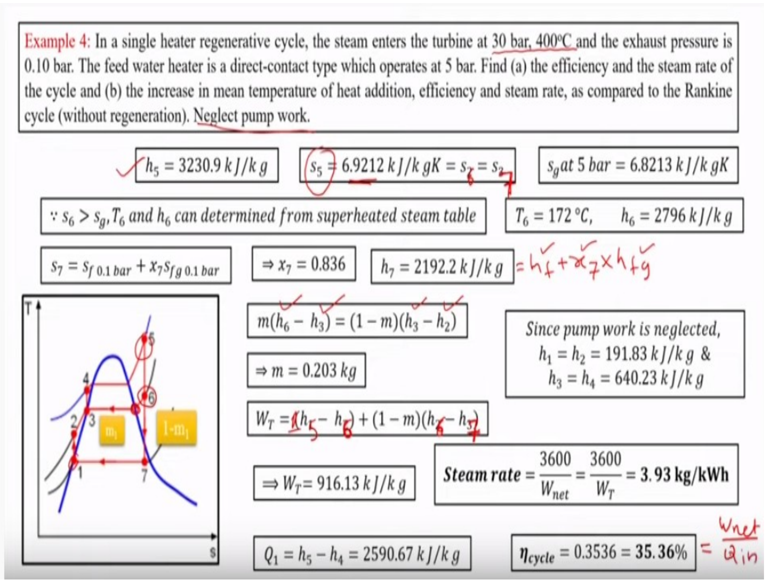
Our first example reads that there is a single reheat regenerative cycle of steam where steam enter the turbine at 30 bar and 400°C. And the exhaust pressure is 0.1 bar. The feed water heater is a direct contact type feed water heater which operates at 5 bar pressure.

Find out efficiency and steam rate of the cycle. We know steam rate means specific steam consumption SSC and increase in mean temperature of heat addition efficiency and steam rate as compared to the Rankine cycle without generation. We are supposed to neglect the pump work. Let us feel this would be our possible T-s diagram. So in this T-s diagram what we are given with?

We are here given with the fact that T_5, so here we will see whatever it is given to us, as per this diagram we are given with T_5 and that is equal to 400°C. Were also given with $P_5=P_4=P_3$ and that is 30 bar. And then we are given with $P_1=P_7=0.1$¿. So these things are given to us. We are said that $P_6=P_3=5$¿. And we are said that it is a direct contact type feed water heater.

Since it is direct we are knowing that point 3 will be a saturation point and then we know that m_1 mass which is bled from the turbine is losing its enthalpy from h_6 to h_3 and that is giving rise to the enthalpy for $(1-m_1)$ steam which is pumped to pressure h_2 but it is rising its enthalpy from h_3 to h_2. So these things are given to us. So now let us work with this example and find out whatever it is told to us.

(Refer Slide Time: 03:04)



So first, we know now $h_{p5}$is known to us. We know T_5, we will go to the steam table. We go to the saturation part of the steam table and then we will know the enthalpy which is $h_5=3230.9$. Then, we have to find out 0.6 which is at 5 bar. So for that we will take entropy's help from 0.5.

So we know at the same part in the steam table, which is saturation, super saturated part or superheated part of the steam table corresponding to 30 bar and 400 °C we found out entropy as 5. But this s_5 is equal to basically s_6 and s_7. This s_5 is equal to s_6 and s_7. Knowing this, we can find out what is the in s_g corresponding to 5 bar. That means we are trying to see what is the entropy here.

And so this entropy is 6.821. But we know s_5 is 6.9. So basically s_6 is greater than s_g. That means T_6 and h_6 are to be found out from the superheated part of the steam table corresponding to 5 bar. And that turns out to be T_6 is equal to 172 °C and h_6 is equal to 2796 kJ/kg. Then we can also take use of $s_7 = s_5$.

So $s_7 = s_f$ at 0.1 bar, which is this basically s_1 and x_7 that is dryness fraction at 7 into s_{fg}. The total change in enthalpy due to feed change at 0.1 bar. Then we know x_7 is equal 0.836. This would be helpful to find out at h_7 since h_7 is equal to $h_f$at 0.1 bar plus x_7 plus h_{fg} sorry, into x_7 into h_{fg} at 0.1 bar. So this is our h_7. This h_f is known at 0.1 bar, h_{fg} is known at 0.1 bar, x_7 is known from the previous day.

So, this is how we evaluated our h_7. Now we can know what is h_1; h_1 is 0.1bar saturation liquid enthalpy and then that is equal to h_2 since we are supposed to neglect the pump work. So $h_1 = h_2 = 191$. We are also taking help to neglect the pump work where $h_3 = h_4$ and then h_3 is also known to us. Then as what since direct feed water heater is given to us.

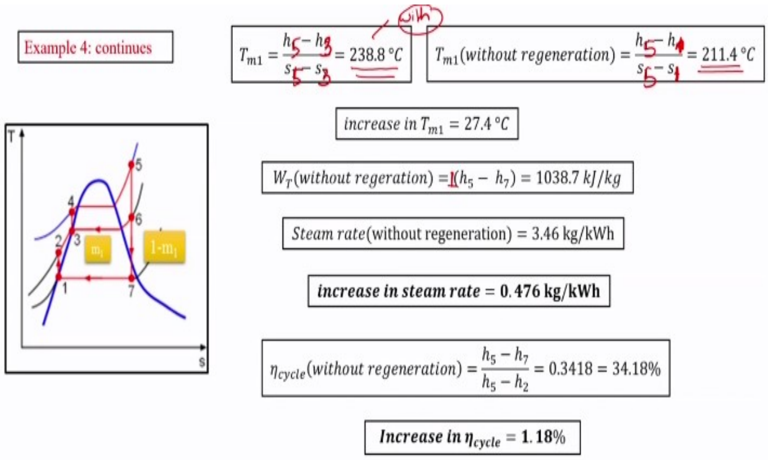
So this is the formula which we were knowing. From that we can find out m. Since h_6 is known from previous step, h_3 is known as a liquid saturation enthalpy h_3 is known and we know h_2 So knowing all these things we can find out m. Then we can find out turbine work. So for turbine work, we know that 1 kg of steam is expanding from h_5 to h_6 and $1 - m$ kg of steam is expanding from h_6 to h_7.

So we have formula which is $1(h_5 - h_6) + (1 - m)(h_6 - h_7)$. So turbine work turns out to be 916.13 kJ/kg. Then we know formula for specific steam consumption or steam rate which is 3600 divided by W_{net}. But W_{net} does not have pump work. So W_t and that turns out to be 3.93 kg/kWh. Then we can find out Q_1 which is heat addition from the external source that is $h_5 - h_4$. This is 2590.67.

So this helps us to find out cycle efficiency and this is 0.3536 which is basically $\frac{W_{net}}{Q_{¿}}$

And W_{net} is equal to W_t and $Q_{¿}$ is equal to Q_1.

(Refer Slide Time: 07:53)

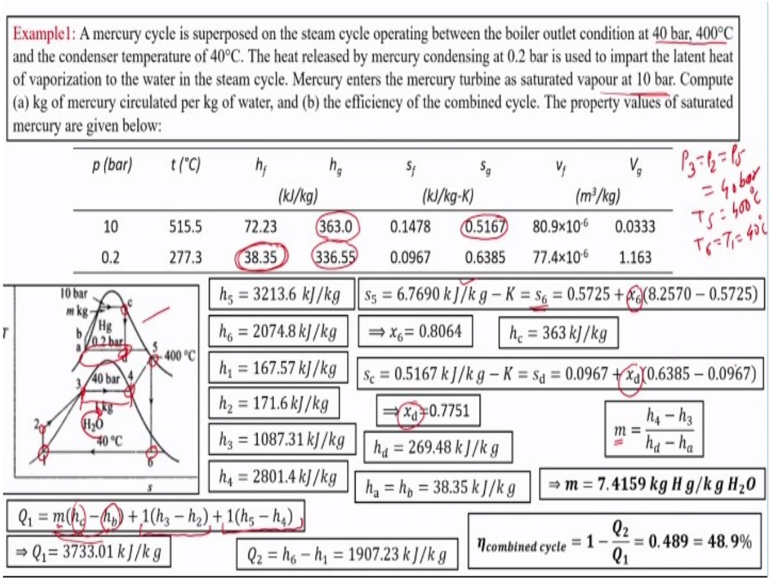


Then this example is continued. We can find out mean temperature of heat addition. Mean temperature of heat addition for the cycle without heat addition and for cycle with heat addition. So mean temperature of heat addition is basically, with regeneration is here $\frac{h_3 - h_5}{s_3 - s_5}$. This is mean temperature of heat addition with regeneration and without regeneration is basically h_1 h_5 sorry we have basically mean temperature of heat addition as $\frac{h_5 - h_3}{s_5 - s_3}$

This is with regeneration and without regeneration we have $\frac{h_5 - h_1}{s_5 - s_1}$. So this gives us the mean temperature of heat addition to be 238.8 with regeneration and 211.4 without regeneration. So this is giving us that mean temperature of heat addition has increased by 27.4°C due to regeneration.

So turbine work without regeneration is 1 kg of steam has completely expanded from state 5 to state 7. So it is 1038.7. So steam rate is 3600 divided by turbine work and that is without regeneration it is $3.46\,kg/kWh$. So increase in steam rate is $0.476\,kg/kWh$ and efficiency of cycle is basically without regeneration, it is $h_5 - h_7$ that is turbine work divided by heat addition which is $h_5 - h_2$. And this is 34.18. But efficiency with regeneration has increased by 1.18%.

(Refer Slide Time: 10:38)



So, this is how we would have solved this example for the regeneration case. Now we will move on to the next example. And next example says that mercury cycle is superposed on the, there is mercury cycle which is superposed on the steam cycle. So mercury cycle is given as a topping cycle and water cycle or steam cycle is given as a bottoming cycle where there is heat exchange between boiler outlet condition at 40 bar and 400 °C and the condenser as 40°C.

So the boiler for the steam is given as 40 bar and 400 °C and condenser for steam is given as $40°C$. The heat released by mercury condensing at 0.2 bar is used to impart the latent heat of vaporization to the water in the cycle. So it is told that only latent heat of vaporization is given by the topping cycle the water and that is mercury is doing condensation as at 0.2 bar.

Mercury enters the turbine, mercury turbine, as saturated vapor at 10 bar. Compute kg of mercury circulated per kg of water, efficiency of combined cycle. Property of mercury is given to us. Knowing this, this is our diagram, which states that one, we have water as the bottoming cycle and mercury as the topping cycle. We are given with the fact that $P_3 = P_2 = P_5 = 40$.

We are also given that $T_5 = 400°C$ And we are told that the pressure is such that the temperature which is $T_6 = T_1 = 40°C$. So these things are given to us. So knowing these and also the conditions for the steam and the conditions for mercury, we can solve this example. So initially, we can say that h_5, we will go to the steam table, which is a superheated part of the steam table.

We will go to 40 bar and 400 °C and find out h_5. Soh_5 is known to us. For h_5, from h_5 we will also see in the steam table what is s_5. So $s_5$is known to us. But $s_5 = s_6$. But $s_6 = s_f + x_6 s_{fg}$. So from that we can find out x_6. So x_6 = 0.8064. Then we know x_6 so we can find out h_6. So enthalpy at the exit of the turbine. Then we also know h_1; h_1 = 167.57. We also know h_2.

So here we are doing the addition of turbine work sorry pump work in h_1. So h_1, h_2 basically is equal to h_1 plus the pump work. So this is h_1 plus pump work and pump work is $v \Delta P$ So ΔP is the pressure difference between $P_2$and P_1. P_2 pressure is 40 bar. P_1 pressure is the pressure corresponding to saturation pressure at 40 $°C$

So this turns out to be 171.6 kJ/kg. Further we wanted to know h_3 since heat exchange is given, which is latent. So h_3 is equal to the saturation liquid enthalpy corresponding to 40 bar. This is known. Further h_4 is known, that is saturation enthalpy of vapor corresponding to 40 bar. So we know h_c; h_c is given as the data corresponding to 10 bar. So mercury at the higher pressure is 10 bar.

So for 10 bar, we know what is h_g. So this is given to us, that is 363. So s_c is entropy at c is given to us. This is entropy is given to us as this and this entropy is equal to the s_d and s_d's entropy can be found out as $s_a + x_d s_{fg}$. So s_{fg} is given to us which is $s_g - s_f$. So $s_g - s_f$.. So these all things are given. So we can find out $x_d$and this turns out that x_d = 0.7751.

So h_d can be find out by adding h_g plus x sorry $h_f + x h_{fg}$where h_{fg} is $h_g - h_f$ So into x_d. So this is our h_d. So then we know $h_a = h_b$ since we can neglect pump work. This gives us the formula for mass flow rate of mercury or fraction of mercury required per kg of steam flow rate is equal to $h_4 - h_3$ which is latent enthalpy rise for the steam divided by the heat rejected by the mercury which is h_d by h_a.

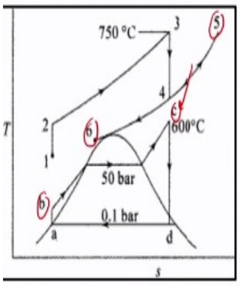
So knowing all the enthalpies we can find out m and that is 7.4159 kg of mercury per kg of water. Further heat released in the heat added in the boiler is total amount of heat where we have m amount of mercury is rising its enthalpy from h_c from h_b to h_c. So here in the mercury's boiler we are adding heat. Then we are also adding heat in the economizer of the steam and super heater of the steam.

So economizer of steam we will have enthalpy rise from h_2 to $h_3$and economizer will have, sorry super heater will have enthalpy rise from h_4 to h_5. So we have total heat addition 3733.1. We have total heat rejection which is $h_6 - h_1$. So we have combined cycle efficiency as $1-\frac{Q_2}{Q_1}$ which is 48.9%. So we found out all the things whatever required for us in this example.

(Refer Slide Time: 18:18)

Example2: In a combined gas turbine-steam turbine power plant, the exhaust gas from the open cycle gas turbine is the supply gas to the steam generator of the steam cycle at which additional fuel is burned in the gas. The pressure ratio for the gas turbine is 7.5, the air inlet temperature is 15 °C and the maximum cycle temperature is 750°C.

Combustion of additional fuel raises the gas temperature to 750°C and the gas leaves the steam generator at 100°C. The steam is supplied to the turbine at 50 bar, 600°C and the condenser pressure is 0.1 bar. The total power output of the plant is 200 MW. The calorific value of the fuel burned is 43.3 MJ/kg. Neglecting the effect of mass flow rate of fuel on the air flow, determine (a) the flow rates of air and steam required, (b) the power outputs of the gas turbine and steam turbine, (c) the thermal efficiency of the combined plant, (d) the air fuel ratio. Take $c_p = 1.11$ kJ/kg-K and $\gamma = 1.4$ for air. Neglect pump work.



$$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{(\gamma-1)/\gamma}$$

$$T_2 = 512.165K$$

$$T_4 = T_3\left(\frac{p_4}{p_3}\right)^{(\gamma-1)/\gamma} = 620.52K$$

$$h_c = 3670\ kJ/kg$$

$$h_d = 2305\ kJ/kg$$

$$h_a = h_b = 192\ kJ/kg$$

$$\dot{m}_a c_{p_g}(T_5 - T_6) = \dot{m}_s(h_c - h_b)$$

$$\frac{\dot{m}_s}{\dot{m}_a} = 0.2056.......(2)$$

$$(W_{net})_{GT} = \dot{m}_a c_{p_g}(T_3 - T_4) - \dot{m}_a c_{p_a}(T_2 - T_1)$$

$$(W_{net})_{GT} = 221.47\dot{m}_a$$

$$(W_T)_{ST} = \dot{m}_s(h_c - h_d) = 1365\dot{m}_s$$

$$1365\dot{m}_s + 221.47\dot{m}_a = 200\times10^3......(1)$$

$$\dot{m}_a = 398.34 kg/s \qquad \dot{m}_s = 81.9 kg/s$$

$$(W_{net})_{GT} = 80.22MW \qquad (W_T)_{ST} = 111.78MW$$

So let us see our next example. And our next example says that, in the combined gas turbine steam turbine power plant, the exhaust gas from open cycle gas turbine is the supply gas to the steam generator of steam cycle at which additional fuel is burnt in the gas. So it is told that exhaust of the gas turbine is first heated by burning extra fuel and then supplied for the supplied as the flue gas in the boiler of the steam power plant.

The pressure ratio of the gas turbine is 7.5 and air at the inlet is having temperature 15°C and maximum temperature of the gas turbine is 750°C. Combustion of additional fuel rises the gas temperature to 750°C and the gas leaves the steam generator at 100°C. This data is also corresponding to gas turbine cycle. So we have given all these points.

The steam is supplied to the turbine which is steam turbine at 50 bar and 600° C and this steam condenses to the pressure of 0.1 bar. Total power output of the plant is 200 MW. Calorific value of the fuel burnt is 43.3 MJ/kg neglecting the effect of mass flow rate and fuel on the airflow. Determine the flow rate of air and steam required, the power output of the gas turbine and steam turbine plant, thermal efficiency of the combined plant, and air fuel ratio.

We are given that C_p of the fuel, C_p of the gas is 1.11 kJ/kg and γ of gas is 1.4.
So we are first going to find out what is the T-s diagram. Our T-s diagram would look like this, where we have bottoming cycle as water and topping cycle as gas. We are given with T_3 which is 750 °C and T_5 is also 750 °C. We are given with $\frac{P_2}{P_1}$ which is pressure ratio and that is told to be 7.5.

So knowing this information, we can work out with the gas turbine cycle. So $\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}}$ This is the isentropic relation since it is a compressor. So in the compressor we are having isentropic compression from the inlet condition. So knowing the pressure ratio and knowing the temperature T_1, we can find out T_2. So T_2 is 512.165 K.

Then similarly, from the same pressure ratio we can find out T_4. So $\frac{T_4}{T_3} = \left(\frac{p_4}{p_3}\right)^{\frac{\gamma-1}{\gamma}}$.

Here as read T_3 is 750 °C. $\frac{p_4}{p_1}$ is known to us as 7.5. So we found out T_4 as 620 K. Then we can find out h_c.; h_c is the enthalpy at the entry to the steam turbine and this enthalpy can be found out from the superheated part of the steam table corresponding to 50 bar and 600° C.

Then we know at h_d since h_6 sorry s_c is equal to s_d entropy at c is equal to entropy at d and entropy at c can be found out from steam table 50 bar and 600° C. Then we can go to the lower pressure which is 0.1 bar condenser pressure. And then from that $h_f + x_d h_{fd}$. From that we can find out enthalpy at d but for that we need what is the dryness fraction at d.

So for that we are going to equate the entropy at c and entropy at d and then find out dryness fraction. So knowing this we can as well equate $h_a = h_b$ We are supposed to neglect the pump work as given in the example. Then we can find out what is the net work in the gas turbine. Net work in the gas turbine is turbine work minus compressor work. We cannot neglect compressor work since as what we had discussed in one of the classes work ratio of the gas turbine cycle is low.

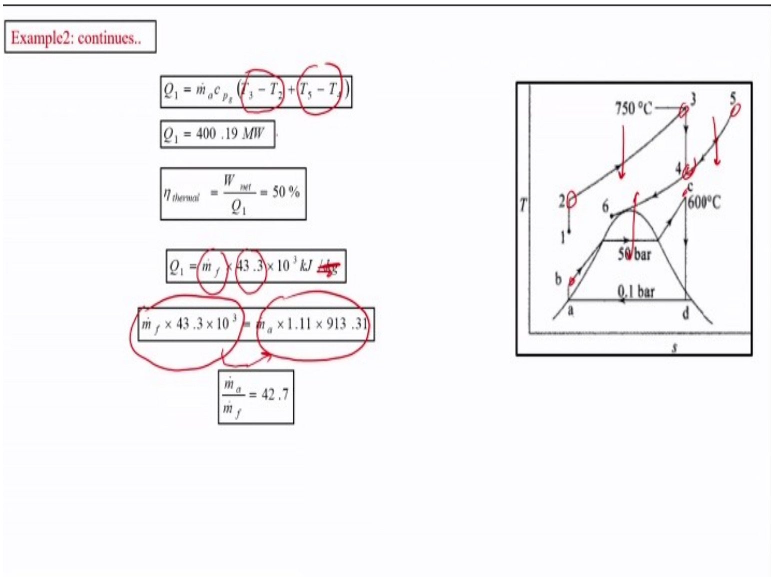
So compressor and turbine works are very high. So we cannot neglect compressor work. So for the net work in the gas turbine we have turbine work minus compressor work. So turbine work is $\dot{m}_a c_{p_g}(T ¿¿ 3 - T_4) - \dot{m}_a c_{p_a}(T ¿¿ 2 - T_1) ¿¿$ .So we actually know these quantities and then from that we can take the gas turbine work is equal to $221.47\, \dot{m}_a$ which is mass flow rate of air and that is not known to us.

Steam turbine work is equal to mass flow rate of steam into $h_c - h_d$. Basically, there is a mistake. So the work done by the steam turbine is $\dot{m}_s(h_c - h_d)$ So we know h_c, we know h_d. So we can find out it is as $1367\, \dot{m}_s$. But we know that this turbine, steam turbine work plus gas turbine work is equal to total work done. And that is given to us as 200×10^5

That is 200 MW. So we know also that $\dot{m}_a c_{p_g}(T ¿¿ 5 - T_6) ¿$, this is the heat lost by the gas turbine to the steam turbine where steam turbine is getting the heat from h_c to h_b. So basically it is rising its enthalpy from b to c. So this is the second equation. So this is equation number 2. So we know two equations and we know two unknowns, which is $\dot{m}_a$ and $\dot{m}_s$.

So we can find out first the ratio of $\frac{\dot{m}_a}{\dot{m}_s}$ from this equation, which is now equation 2 for us, renewed equation 2 for us. Then this we can put over here, then we can find out $\dot{m}_a=$¿398.34 and $\dot{m}_s=$¿81.9 kg/s. So we found out mass flow rate of steam and mass flow rate of air. Further, so we found out what is the steam gas turbine's net work and what is the steam turbine's net work. So these two also are found out.

(Refer Slide Time: 25:54)



Then we will continue with this example. So we know that now Q_1 is the heat received in the gas turbine and gas turbine is receiving heat twice basically. One is during its combustion chamber and one is before passing it to the boiler, it is also getting heated from 4 to 5. So first heat addition is T_3 to T_2. T_2, rise in temperature from T_2 to T_3 and second heat addition is rise in temperature from T_4 to T_5.

So these two heat additions are for the gas turbine. So knowing this all quantities we can find out Q_1 = 400.19 MW. Then efficiency of gas turbine power plant is net work upon turbine work and that turns out to be 50%. So this is we would have found out our net, this is the total net work of the cycle, combined cycle. This is not the efficiency for the gas turbine power plant. This is the efficiency of combined cycle.

So this is the net work of the combined cycle and this was given as 200 MW. But heat supply is basically only in the gas turbine. In the steam turbine we are not giving any heat. In last example, where steam cycle, steam cycle were coupled, there we were only having heat exchange in the latent part for between the topping and bottoming cycle. But now we are having gas turbine as our cycle where complete heat, which is h_b to h_c was given from the gas turbine.

So there is complete exchange between two cycles. There is no external heat added in the bottoming cycle. So we have only external heat addition in the topping cycle. So this turns out to be the efficiency for overall cycle. So $\frac{W_{net}}{Q_1}$ and that is 50%. But Q_1 is equal to mass of flow rate of fuel into calorific value of fuel. So that is $\dot{m}_f \times 43.3 \times 10^3 kJ/kg$ of fuel.

So this is $\dot{m}_f \times 43.3 \times 10^3$, this is kilo joule not per kg of fuel. This is kilo joule. So this is the heat supplied by combustion by the fuel and this is heat received by the air. We are not assuming any loss. So heat rejected due to combustion or heat released in combustion is heat supplied in the gas turbine.

So that equated would give us mass flow rate of air divided by mass flow rate of fuel as 42.7. So we need 42.7 times more air for the combustion of fuel in the gas turbine. So knowing this we know now how to solve example for the combined cycle which is gas turbine-gas turbine or also for the gas turbine and steam turbine cycle. We have also seen the examples corresponding to the reheat regeneration super heating.

So how the concepts which are known to us from the basic theory of steam turbine and combined cycle we are now eligible to solve the examples and we have illustrated how to solve the example. So we will see the next part which is now our steam turbine part from the next class Thank you.