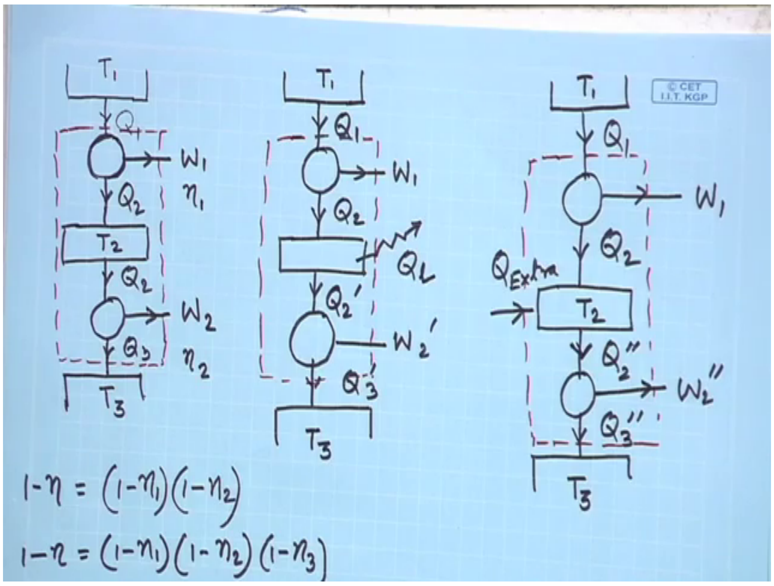
Energy Conservation and Waste Heat Recovery

Prof. Prasanta Kumar Das
Department of Mechanical Engineering
Indian Institute of Technology, Kharagpur

Lecture – 24
Combined cycle (Contd.)

Hello, everyone we were discussing combined cycle power plant and in a generalized way we wanted to derive the efficiency of a combined cycle power plant when the individual power plant efficiencies are known to us. So, I have done the derivation and just very quickly we will recapitulate and we will proceed from that point.

(Refer Slide Time: 00:48)

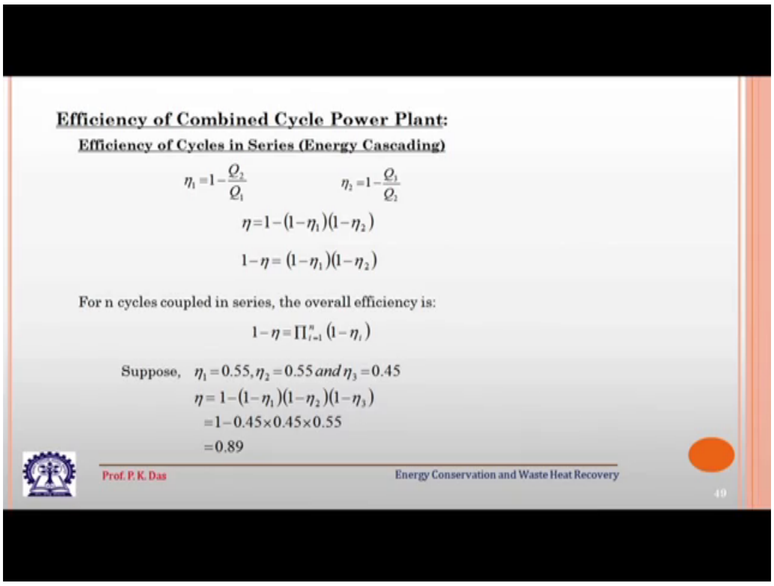


Let us say we have got a combined cycle power plant, where the highest temperature which is available that is T 1 and we are taking Q 1 amount of heat, then the topping cycle is rejecting Q 2 amount of heat to a reservoir of intermediate temperature which is at T 2 and the same heat from the same reservoir is picked up by another cycle which is a bottoming cycle and it is rejecting Q 3 amount of heat to the reservoir which the lowest temperature, that is T 3. And the first heat engine does a work of W 1 the second heat engine does a work of W 2.

So, in this case we have derived, that if we know the individual efficiencies of the cycles. Let us say the first cycle has got an efficiency eta 1, the second cycle has got efficiency of eta 2 and then 1 can derive that eta the efficiency of the combined cycle, let us say this is the combined cycle. So, combined cycle you see now takes Q 1 amount of thermal energy from a temperature T 1 and rejects Q 3 amount of thermal energy from a to a reservoir at T 3 and while it does W 1 plus W 2 amount of work.

So, the efficiency of this combined cycle if it is eta then 1 can derive 1 minus eta is equal to 1 minus eta 1 multiplied by 1 minus eta 2.

(Refer Slide Time: 03:03)



Efficiency of Combined Cycle Power Plant:

Efficiency of Cycles in Series (Energy Cascading)

$$\eta_1 = 1 - \frac{Q_2}{Q_1} \qquad \eta_2 = 1 - \frac{Q_3}{Q_2}$$

$$\eta = 1 - (1-\eta_1)(1-\eta_2)$$

$$1-\eta = (1-\eta_1)(1-\eta_2)$$

For n cycles coupled in series, the overall efficiency is:

$$1-\eta = \prod_{i=1}^{n} (1-\eta_i)$$

Suppose, $\eta_1 = 0.55, \eta_2 = 0.55 \, and \, \eta_3 = 0.45$

$$\eta = 1-(1-\eta_1)(1-\eta_2)(1-\eta_3)$$
$$= 1 - 0.45 \times 0.45 \times 0.55$$
$$= 0.89$$

Prof. P. K. Das

Energy Conservation and Waste Heat Recovery

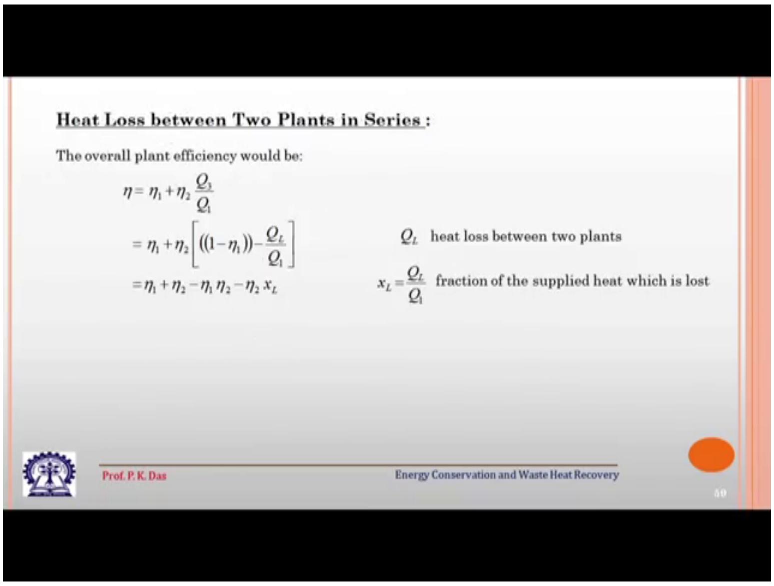
So, if we see the PPT, then we will find that this has been written over here, but the interesting thing is that; though we have derived it for 2 heat engine cycle it can be extended for n number of cycles coupled in series. Series coupling means that the thermal energy rejected by the cycle at the top the cycle which is operating at high temperature that thermal energy will be picked up by a cycle which is acting at the bottom that is which is operating at a lower temperature.

So, in that case we will get if there are n number of cycles coupled in series, then 1 minus eta is the efficiency of all the cycles combined together that will be a given by a multiplicative law and this is summation of all 1 minus eta i, i starting from 1 sorry; this will be given by the product of all 1 minus eta i where i starts from 1 and i is equal to up to i is equal to n.

So, for 3 cycles we will get let us say there are 3 cycles that is; we will get 1 minus eta 1 into 1 minus eta 2 into 1 minus eta 3 just like this we will get for different cycles we will get the expression for efficiency. So, it will be given by a product we can take an example how this increases the efficiency of the cycle. Let us say we are considering a 2 cycle case eta 1 is equal to 0.55 and eta 2 is equal to 0.55 eta 3 is equal to 0.45 there are 3 cycles. And if it is a acting as a combined cycle topping cycle, intermediate cycle and bottoming cycle, then we will have the combined efficiency is equal to 0.89 you see quite a large efficiency.

So, at least theoretically this can be achieved, if we have got different cycles and combine them in series. Now, we have to remember one thing, that we have considered a very idealized case, what we have considered? We have considered whatever thermal energy will be rejected by the topping cycle will be accepted or absorbed by the bottoming cycle, but that is never possible in practice in practice what happens.

(Refer Slide Time: 05:53)



Heat Loss between Two Plants in Series :

The overall plant efficiency would be:

$$\eta = \eta_1 + \eta_2 \frac{Q_2}{Q_1}$$

$$= \eta_1 + \eta_2 \left[((1-\eta_1)) - \frac{Q_L}{Q_1} \right]$$

$$= \eta_1 + \eta_2 - \eta_1 \eta_2 - \eta_2 x_L$$

Q_L heat loss between two plants

$x_L = \frac{Q_L}{Q_1}$ fraction of the supplied heat which is lost

Prof. P. K. Das

Energy Conservation and Waste Heat Recovery

59

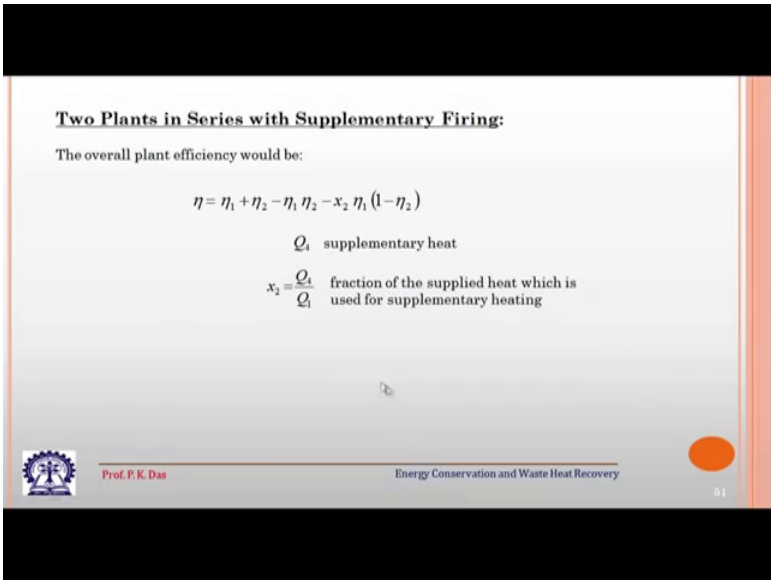
If I quickly, draw the situation in practice let us say we have got 3 cycles there are 2 cycles 1 is a topping cycle and another is a bottoming cycle .

So, in practice what happens there will be certain amount of heat loss, let us say I denote it by Q l capital L let us say I denote it by capital L. When there is heat transfer from the topping cycle to the bottoming cycle, through a heat exchanger let us say. So, you see the entire thermal energy left by the topping cycle which is Q 1 cannot be sorry the entire amount of thermal energy left by the topping cycle, that is Q 2 that will not be entirely accepted or it cannot be entirely supplied to the second cycle or the bottoming cycle.

So, you see now the combined cycle diagram will be something like this where the combined cycle is receiving Q amount Q 1 amount of thermal energy from a source at T 1 and it is ultimately rejecting Q 3 dashed amount of thermal energy to a reservoir at temperature T 3 while it is doing W 1 plus W 2 dash amount of work which is less than the previous case and from the cycle there is a heat loss which is Q L.

So, in this case the efficiency will be different and in this case if we go to this slide we will PPT, if we see that in the PPT I have shown the efficiency of this situation where there is heat loss between 2 plants in series. So, you see it will depend upon how much heat loss is there and; obviously, the efficiency will be less than the previous case.

(Refer Slide Time: 08:38)



Two Plants in Series with Supplementary Firing:

The overall plant efficiency would be:

$$\eta = \eta_1 + \eta_2 - \eta_1 \eta_2 - x_2 \eta_1 (1 - \eta_2)$$

Q_4 supplementary heat

$x_2 = \frac{Q_4}{Q_1}$ fraction of the supplied heat which is used for supplementary heating

Prof. P. K. Das

Energy Conservation and Waste Heat Recovery

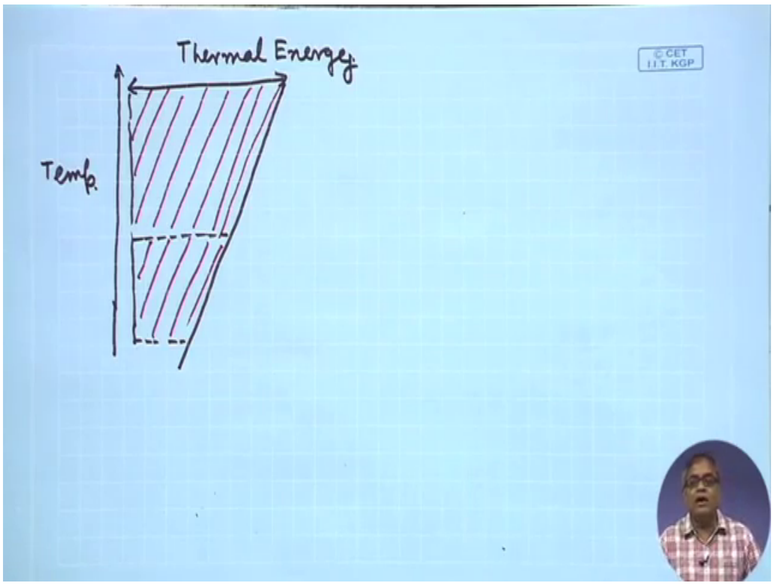
The third situation which we can consider that in many cases what happens to take care of the heat loss or to have more output from the combined cycle often some extra amount of energy is supplied to this combined cycle, but this is supplied to the bottoming cycle not to the topping cycle, but to the bottoming cycle. This situation I am depicting is like this, the topping cycle takes heat which is Q 1 and does W 1 amount of work rejects Q 2 amount of thermal energy to an intermediate reservoir at temperature T 2. At temperature T 2 this bottoming cycle has to pick up thermal energy, but what happens here some extra Q; Q extra that is supplied.

So, that the bottoming cycle get Q 2 double dash amount of heat, it rejects Q 3 double dashed amount of heat to the reservoir at the lowest temperature and does W 2 double dashed amount of work. So, this situation of the combined cycle is now like this. So, we have got some extra amount of fuel supplied to the supplied to this combined cycle and in this case also the efficiency expression will be different and if we go to the PPT we can see the efficiency expression.

These derivations I have not done in the previous case or in this case assuming that these are quite simple and following the logic of the first derivation which I have done any one of you can do this. There could be another situation where we have got both extra amount of energy supplied to the bottom cycle and some amount of heat loss when the heat is transferred from the topping cycle to the bottoming cycle. So, that also you can derive. Probably, that is the most general case which you can derive and get the efficiency expression for that kind of a combined cycle.

Now, with this word we have got more or less some general idea, how the efficiency of the combined cycle will change and how we can get a good amount of or rather a high enough efficiency for energy conversion for conversion of thermal energy into mechanical work. Now this is called energy cascading.

(Refer Slide Time: 11:53)

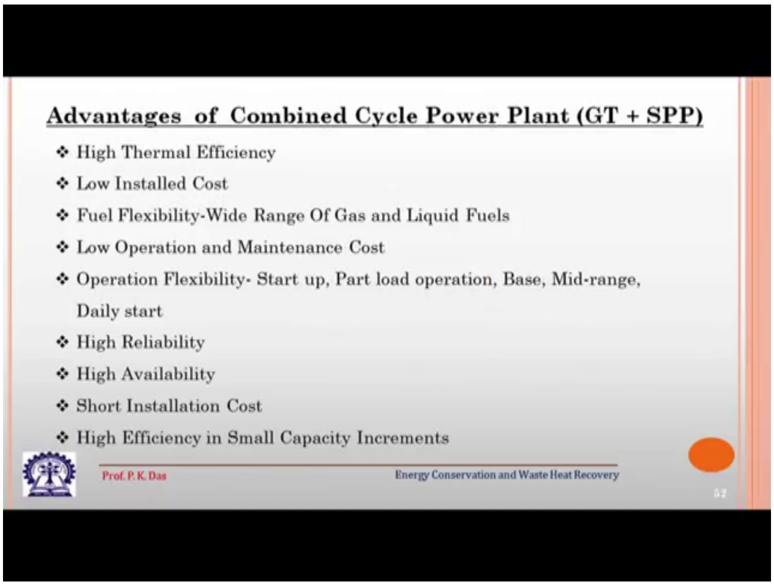


Now energy cascading means let us say we start from some amount of thermal energy this side it is shown thermal energy and let us say this side is temperature.

Now, as the energy flows thermal energy flow from high temperature to low temperature the amount of energy will reduce something like this. And the idea is that if we end somewhere over here, then we will get only this much of energy and we can convert it into useful work, but if we design the cycle. So, that we go towards the bottom then more and more energy is available to us for converting into useful work.

So, that is what we are doing by your combined cycle, if we combine it topping cycle then an intermediate cycle and then a bottoming cycle; obviously, we can convert more of the thermal energy into useful work.

(Refer Slide Time: 13:14)



Advantages of Combined Cycle Power Plant (GT + SPP)

- High Thermal Efficiency
- Low Installed Cost
- Fuel Flexibility-Wide Range Of Gas and Liquid Fuels
- Low Operation and Maintenance Cost
- Operation Flexibility- Start up, Part load operation, Base, Mid-range, Daily start
- High Reliability
- High Availability
- Short Installation Cost
- High Efficiency in Small Capacity Increments

Prof. P. K. Das

Energy Conservation and Waste Heat Recovery

52

So, in this message, let us see what are the advantage of combined cycle power plant? Our focus as I have told that one of the successful exploitation of the principle of combined cycle power plant is the combination of gas turbine and steam power plant.

So, keeping that into mind we have noted down what are the advantages of combined cycle power plant? High thermal efficiency already I have shown that how the thermal efficiency of a combined cycle power plant can increase low installed cost. So, because per unit output as the efficiency has increased so per unit output it is installed cost will be less. Another thing compared to steam power plant the gas turbine power plant installation costs are less.

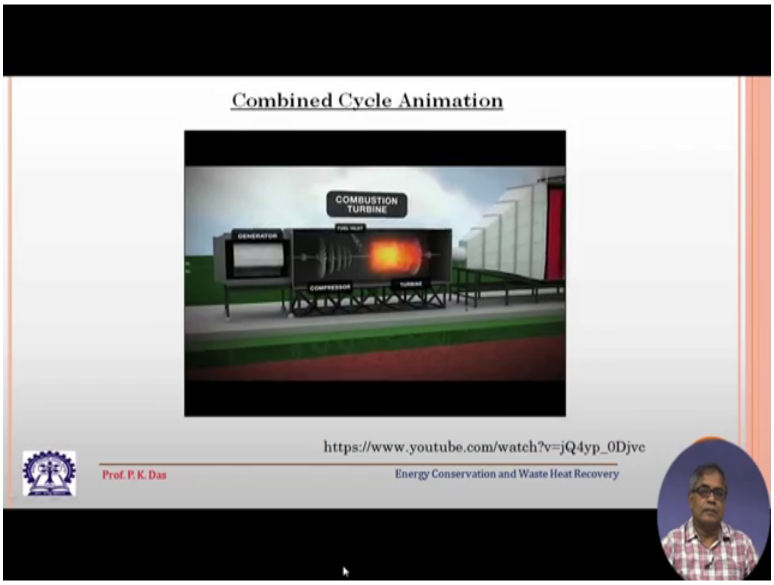
So, when it there is a combination that advantage also we will get. Then high fuel flexibility wide range of gas and liquid fuels, because for gas turbine if gas turbine is used then one can think of natural gas one can think of any kind of liquid fuel and in certain design in use of solid fuel is not is not impossible. So, one can use solid fuels.

Low operation and maintenance cost. So, compared to a steam power plant the maintenance cost will be low for a gas turbine plant and again well cost as we can use a fuel mix. So, there could be some sort of advantage. Operational flexibility start up part load operation base mid range daily start up problem. So, all these advantages are there this disadvantages are there because gas turbine can be started much more quickly compared to your steam turbine power plant.

So, the startup problems are much less and in part load only the gas turbine power plant can run. So, those kinds of flexibilities are there high reliability is there, then high availability why high availability, because it can work on different kind of fuels fuel mix etcetera. So, high availability short installation cost installation cost for gas turbine power plant is relatively low or relatively less. So, when we are having a combination of gas turbine and steam turbine power plant. So, we have got short installation cost then high efficiency in small capacity increments.

Suppose, I want to increase the capacity by small amount then we will not lose much of it is efficiency.

(Refer Slide Time: 16:36)



Combined Cycle Animation

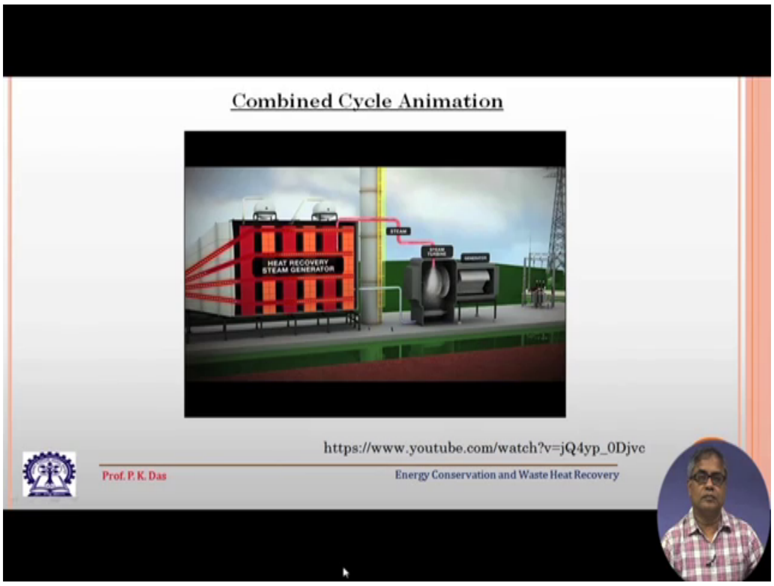
https://www.youtube.com/watch?v=jQ4yp_0Djvc

Prof. P. K. Das

Energy Conservation and Waste Heat Recovery

So, these kind of advantages are there when we are having combined cycle power plant particularly keeping in mind the combination of gas turbine and steam turbine power plant. Now, here I like to show you an animation well.

(Refer Slide Time: 17:22)



Combined Cycle Animation

https://www.youtube.com/watch?v=jQ4yp_0Djvc

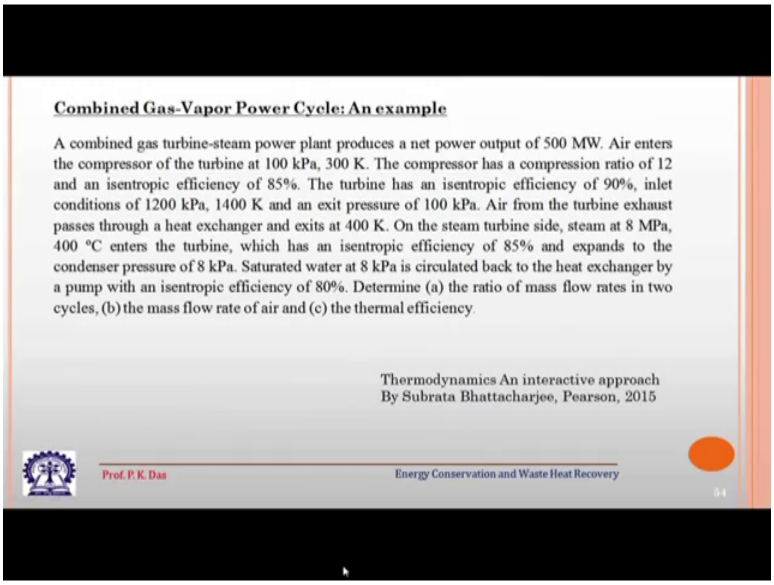
Prof. P. K. Das

Energy Conservation and Waste Heat Recovery

So, with this animation probably you have got the idea, how a combined cycle power plant based on the topping cycle gas turbine based topping cycle and a steam power as bottoming cycle work this is for the product of a particular company. So, they were talking about two such unit is and, but you have got the idea, how it operates from the starting up to the end of the process how does it operate. And probably you have noticed which is a very common feature of this kind of power plant is that, they will have power generation separately from the gas turbine power plant and steam turbine power plant; that means, there will be two separate generators and in the previous in the animation which I have shown. So, at the starting end I am sorry at the starting of the plant schematic there was one generator and at the end there was another generator. So, two generators are there.

So, this is a very common feature there could be; that means, the gas turbine and steam turbine are on separate shaft there could be sometimes there could be multiple shafts for gas turbine; that means, there could be two gas turbines or more than that running in random and there could be steam turbine also. So, there are different design variations.

(Refer Slide Time: 19:18)



Combined Gas-Vapor Power Cycle: An example

A combined gas turbine-steam power plant produces a net power output of 500 MW. Air enters the compressor of the turbine at 100 kPa, 300 K. The compressor has a compression ratio of 12 and an isentropic efficiency of 85%. The turbine has an isentropic efficiency of 90%, inlet conditions of 1200 kPa, 1400 K and an exit pressure of 100 kPa. Air from the turbine exhaust passes through a heat exchanger and exits at 400 K. On the steam turbine side, steam at 8 MPa, 400 °C enters the turbine, which has an isentropic efficiency of 85% and expands to the condenser pressure of 8 kPa. Saturated water at 8 kPa is circulated back to the heat exchanger by a pump with an isentropic efficiency of 80%. Determine (a) the ratio of mass flow rates in two cycles, (b) the mass flow rate of air and (c) the thermal efficiency.

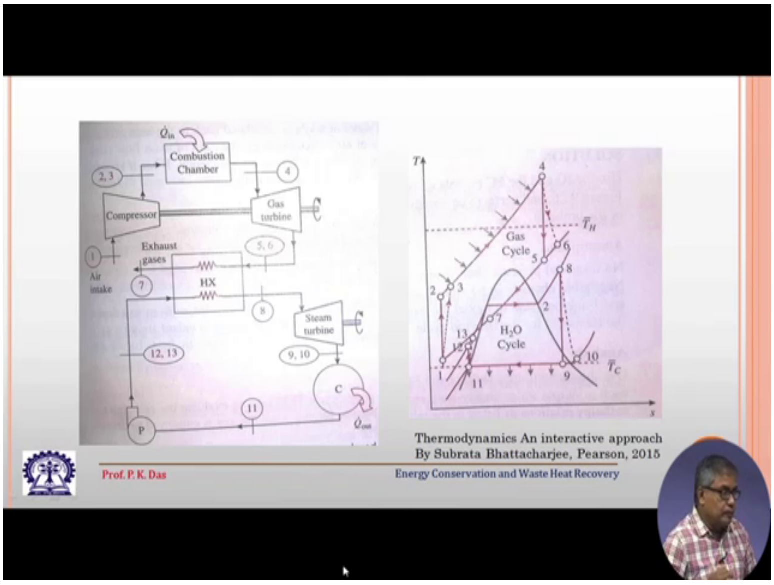
Thermodynamics An interactive approach
By Subrata Bhattacharjee, Pearson, 2015

Now, with this let us go to some example and very quickly let us see how the calculations can be done for a combined gas vapor power cycle. We have taken it from a book which has been acknowledged over here. Let me read out the problem. A combined gas turbine-steam turbine plant produces a net power output of 500 Mega Watt. Air enters the compressor of the turbine at 100 kPa, and 300 K. The compressor has a compression ratio of 12 and an isentropic efficiency of 85 percent. The turbine has an isentropic efficiency of 90 percent, inlet conditions of 12000 kilopascal, 14000 K and then exist pressure of 100 kPa. Air from the turbine exhaust passes through a heat exchanger and exists at 400 K.

In the steam turbine side, steam at 8 mega Pascal, 400 degree Celsius enters the turbine, which has an isentropic efficiency of 85 percent and expands to the condenser pressure of 8 kilopascal. Saturated water at 8 kilopascal is circulated back to the heat exchanger by a pump with an isentropic efficiency of 80 percent.

Now, we have to determine the ratio of mass flow rates in 2 cycles, in the topping cycle air flow is there we will consider it as an air standard cycle and in the bottoming cycle there is flow of steam. So, 2 fluids are there involved. So, we have to find out the ratio of mass flow rates in the 2 cycles, then mass flow rate of air absolute value of the mass flow rate of air and the thermal efficiency of the combined cycle.

(Refer Slide Time: 21:32)



Thermodynamics An interactive approach
By Subrata Bhattacharjee, Pearson, 2015

Prof. P. K. Das

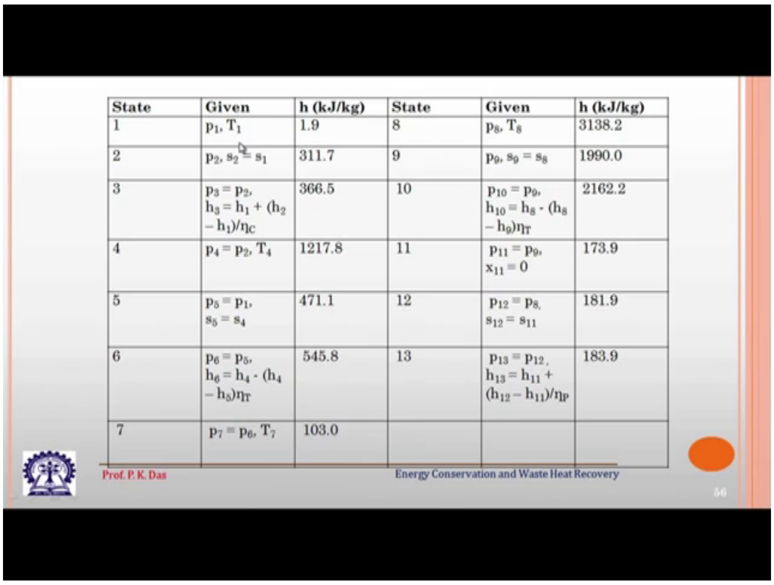
Energy Conservation and Waste Heat Recovery

So, let us proceed; the cycle diagram and the block diagram schematic diagram of the cycle; that means, thermodynamic representation of the cycle on T s plane and the schematic representation of the cycle showing different components of the gas turbine power plant and the steam turbine power plant are given in this particular. I will not go into explanation, because these are more or less self explanatory and separately we have dealt with both the cycles.

Now, here in the thermodynamic diagram of the cycle so at the top we can see the topping cycle; that means, the gas turbine cycle at the bottom we can see the bottoming cycle that is the steam turbine cycle when these 2 cycles are combined together heat input is only at this point; that means, at this process which is the process of heating air or supplying energy to the air and in practical case it is in the combustion chamber of the gas turbine cycle. Heat rejection is also by a process like this where heat is rejected to the ambient atmosphere in the condenser for condenser cooling or through condenser cooling this heat is rejected.

So, this is our heat addition process this is our heat rejection process; obviously, there will be some amount of heat rejected by the exhaust gas, but that probably will not enter into our calculation with this.

(Refer Slide Time: 23:14)



State	Given	h (kJ/kg)	State	Given	h (kJ/kg)
1	p_1, T_1	1.9	8	p_8, T_8	3138.2
2	$p_2, s_2 = s_1$	311.7	9	$p_9, s_9 = s_8$	1990.0
3	$p_3 = p_2,$ $h_3 = h_1 + (h_2 - h_1)/\eta_C$	366.5	10	$p_{10} = p_9,$ $h_{10} = h_8 - (h_8 - h_9)\eta_T$	2162.2
4	$p_4 = p_2, T_4$	1217.8	11	$p_{11} = p_9,$ $x_{11} = 0$	173.9
5	$p_5 = p_1,$ $s_5 = s_4$	471.1	12	$p_{12} = p_8,$ $s_{12} = s_{11}$	181.9
6	$p_6 = p_5,$ $h_6 = h_4 - (h_4 - h_5)\eta_T$	545.8	13	$p_{13} = p_{12},$ $h_{13} = h_{11} + (h_{12} - h_{11})/\eta_P$	183.9
7	$p_7 = p_6, T_7$	103.0			

Let us move to our solution. We will follow the same tabular method which is convenient to follow and if we go to the previous slide. So, here we have given points, but different important junctions of the cycle we have given the points, because these state points of the fluid are important 1, 2, 3, 4, like this.

So, for each of these point we will try to determine the property particularly enthalpy, because enthalpy will be needed for our calculation. So, first point you see this is the gas cycle P 1 and T 1 are known and then from there we can calculate the enthalpy and once again let me remind you that we are we are following an air standard cycle. So, we will assume the ideal gas law, we will assume constant specific heat for air and we will follow like this.

So, this is the your enthalpy of the enthalpy at the first point at the entry to the gas turbine cycle for air; that means, at the entry to the compressor. Second one if we see then we will find that it is after the compression process; after the compression process the compression ratio is given pressure at the entry of the compressor that is P 1 is given. So, P 2 we can calculate from there and if we assume that the compression process is isentropic then s 2 is equal to s 1. So, from there we will be able to calculate the enthalpy of the air at the end of the compression.

But the compression is not isentropic. So, what we will do these we have explained in connection with our steam power plant. So, considering the isentropic efficiency of the compressor which is given and considering h 2 enthalpy that is known h 3 can be calculated. So, this is the value of h 3 366.5 and h 3 is high so; that means, we due to this inefficiency of the compressor we have to spend more work for achieving same amount of pressure ratio alright. Then we will go to the fourth point here P 4 is equal to P 2, because we assume that the heat addition process is isobaric heat addition process and then T s this information T 4 is given. So, from there we can calculate the enthalpy.

So, this is P 4 then P 5; P 5 is equal to P 1 again if we assume that isentropic expansion has taken place in the gas turbine we will get what is the enthalpy at 0.5, but isentropic expansion has not taken place. So, assuming the isentropic efficiency of the turbine which is a supplied figure eta T is supplied. So, then we can calculate what is the entropy at the end of expansion that is P 6. So, this is what we will get and here again you can check that we will have this is again having a higher value. So, P 4 minus P 6 this difference will be small. So, you will get smaller I mean lesser amount of work, because there is some sort of inefficiency or irreversibility.

So, let me stop here, because we are we are running out of time. So, up to the gas turbine cycle I have described, we have calculated and got all the values of enthalpies at all the points all the important points of the gas turbine if necessary we can calculate it is efficiency also, but what is more important from here we can go for the calculation of this steam power plant steam power cycle which is the bottoming cycle.

Thank you.