Energy Conservation and Waste Heat Recovery
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Lecture – 21
Recapitulation of common power cycles (Contd.)

Welcome everyone to this lecture which we are continuing for energy conservation and waste heat recovery. If you recall, we were discussing steam power plant and we have seen different variations of steam power plant, but in all the cases, we have considered ideal processes; that means, ideal steam power cycle the variation of Rankine cycle, we have considered that also constitute only ideal processes.

Now let us try to understand if there is any kind of irreversibility which will be there in a practical cycle; what is the implication and then let us quickly look into some sort of energy balance of steam power plant.

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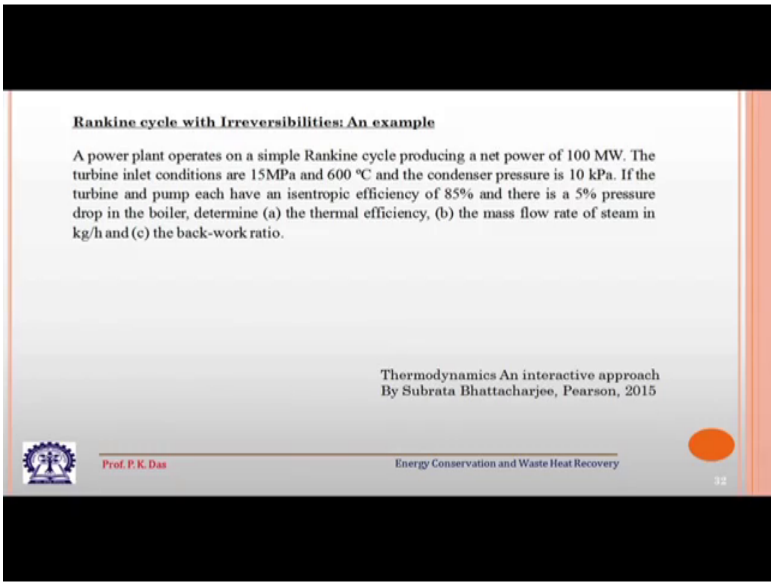

So, we like to discuss Rankine cycle with irreversibilities with the help of an example, it is taken from a book, I have acknowledged the book a power plant operates on a simple Rankine cycle producing a net power of hundred megawatt the turbine inlet conditions are 15 mega Pascal and 600 degree Celsius and the condenser pressure is 10 kilo Pascal if the turbine and pump each have an isentropic efficiency of 85 percent and there is a 5 percent pressure drop in boiler determine the thermal efficiency, the mass flow rate of steam in kg per hour and the back work ratio.

So, as we have done similar problem earlier, we will try to go through it quickly.

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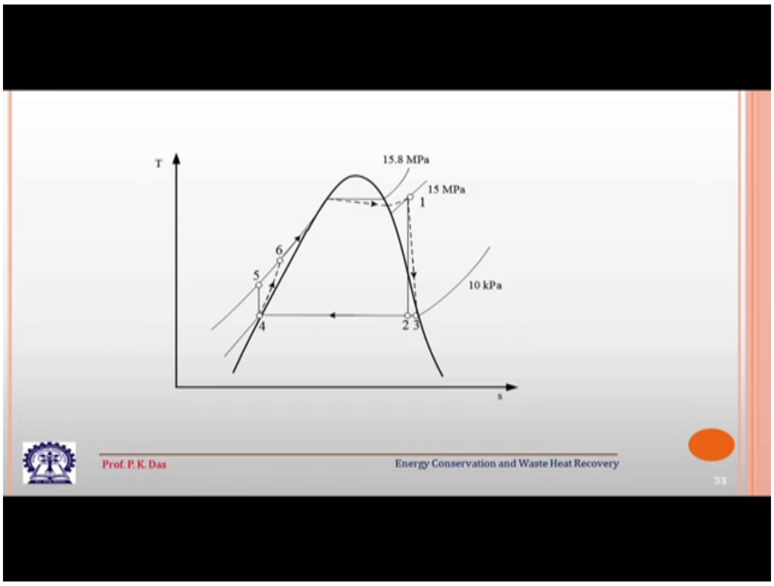

Now, this shows the cycle which is which is described by the statement of the problem, here you see the pressure rise in the pump in the feed pump that is from 4 to 5, but in between there will be a pressure drop. So, the same pressure dp, P 5 will not be there at the exit of steam from the boiler. So, it will be slightly lower and when this was 15.8 mega Pascal the feed pump raises the pressure to 15.8 mega Pascal, whereas, at the boiler exit, we will have steam with the pressure of 15 mega Pascal, then it goes to the turbine in the turbine, it should have undergone; it should have undergone some sort of sorry; it should have undergone an adiabatic reversible adiabatic or isentropic expansion if the process would have been ideal, but there will be certain amount of losses or and irreversibilities.

So, instead of isentropic expansion one 2 we will get one 3 where there is certain amount of irreversibility then 3 to 4 that is the process in the condenser in actual plant there could be some losses. So, that has been neglected in this problem, then 4 to 5 could have been ideal compression process of water in the in the in the pump pressurize process, but there will be again losses irreversibilities. So, the process will be 4 to 6 and then the cycle will get closed. So, the dotted lines, they show the actual line and the solid line they show the ideal line for this particular cycle.

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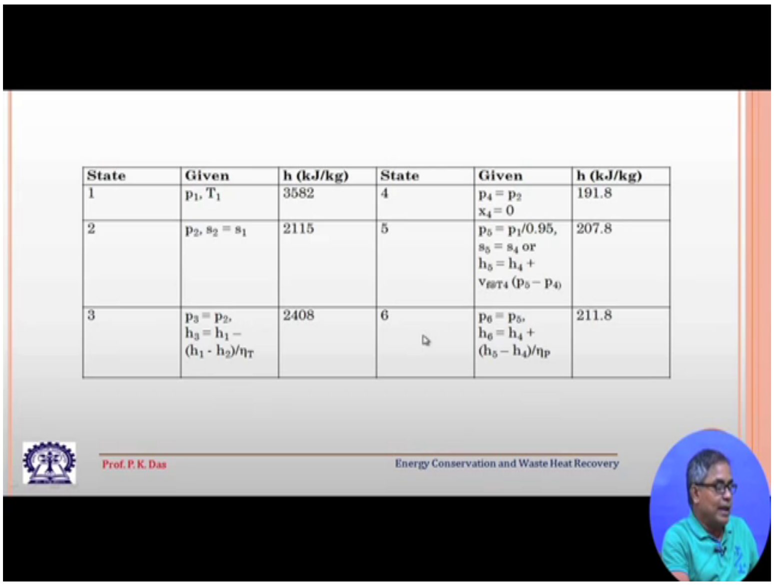

State	Given	h (kJ/kg)	State	Given	h (kJ/kg)
1	p_1, T_1	3582	4	$p_4 = p_2$ $x_4 = 0$	191.8
2	$p_2, s_2 = s_1$	2115	5	$p_5 = p_1/0.95$, $s_5 = s_4$ or $h_5 = h_4 +$ $v_{f@T4}(p_5 - p_4)$	207.8
3	$p_3 = p_2$, $h_3 = h_1 -$ $(h_1 - h_2)/\eta_T$	2408	6	$p_6 = p_5$, $h_6 = h_4 +$ $(h_5 - h_4)/\eta_P$	211.8

Now, again we will follow the same procedure for state one pressure and temperature is known. So, the enthalpy can be calculated or estimated from the steam table, then for 2 the that is the ideal expansion in the turbine. So, point 2; we can determine because pressure is known to us and from point 1 we know the entropy. So, the same entropy will be at point 2. So, point 2; we will find out the enthalpy this would have been the enthalpy if this steam would have expanded through the turbine isentropically, but isentropic expansion did not take place. So, point 3 we will go to the point 3 where the actual expansion due to a actually expander expansion which is the condition of this steam at the exit of the turbine.

So, pressure is same P 3 is equal to P 2, but h 3 is not equal to h 2 and h 3 and h 2 they are related by this relationship over here where eta turbine is the isentropic efficiency of the turbine. So, we know h 1, we know h 2 eta turbine is specified in the problem. So, from there we will get 2408 that is the value of enthalpy at point 3. So, you see initially the steam enthalpy was 3582 if it would have been expanded by isentropic expansion we could have got at the end enthalpy of the steam 2115, but it has not expanded along an isentropic path. So, this will be the final enthalpy at point 3. So, what you can see the difference of these 2; 3582 minus 3408 is the actual work done in the turbine whereas, the work done in the turbine could have been 3582 minus 2115 if the expansion would have been isentropic. So, in this example we can show that or I like to show that if there is irreversibility we will guess get lesser amount of work, all right.

So, we will move to now point 4; point 4 is the; is at the end of the condensation process where the steam will be fully condensed and the condition will be condition will be saturated liquid. So, we will have P 4 is equal to P 2 pressure is not changing x 4 is equal to zero because it is saturated liquid from steam table readily we will get the enthalpy value P 5 this is after the process of pressurize after the process of pressurize in the pump if the process of pressurize would have been an isentropic compression process now P 5 that is P 1 divided by 0.95 and then that is how we will get the pressure and then we will get the as we have considered this process to be an isentropic process. So, s 5 is equal to is 4 and already we have discussed how to get the pump work. So, considering the pump work as vpp work, we can get this h 5; h 5 value is equal to 207.8, but this is not the actual point after compression of fluid in the pump. So, after pressurize in the pump due to the actual process the condition will be 6. So, now, P 6 is equal to P 5 and h 6; we will get by this considering the isentropic efficiency of the pump which is even in the problem and now it will be to 112; 211.8.

Again, if we see that what is the work given by the pump to the to the water. So, we will find one thing that if it could have been ideal pressurize process within the pump; that means, isentropic process we could have spend this much amount of work this is 207.8 minus 191.8, but now as there is irreversibility we will spend 211.8 minus 191.8 so; obviously, due to irreversibility we have to spend more work.

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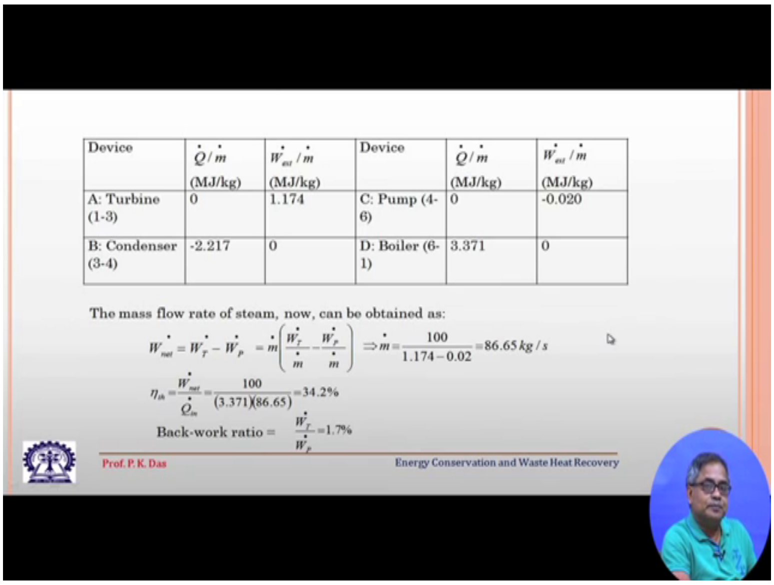

Let us go to the next slide here for the devices we will get these quantities A is turbine, we are considering this is this is there is no heat transfer. So, work done by the turbine per unit mass we will get from this equation mega joule per kg. Similarly for the condenser, we will get what is the heat loss per unit mass Q dot by in there is no work done for the pump; what is the work done per unit mass this is negative work; work has to be supplied and boiler; what is the energy supplied to the fluid per unit mass that is also a you will get.

Now, the mass flow rate of steam now one can obtain as the total work is known and then that is equal to W P dot minus W P dot and this is equal to the quantity which is given within the bracket and then by some sort of algebra, we will get that the mass flow rate is 86.65 kg per second; this is the mass flow rate then thermal efficiency, this is W dot net by Q dot and putting all the values etcetera this will be thirty 4 point 2 percent efficiency what is back work; back work is the or back work ratio back work actually, we will get from here back work ratio WP dot divided by WP dot. So, from here we will get the back work ratio.

So, with this we will come to the end of this example and here we can we have learnt that how different losses can be taken care of how different losses in the steam power plant can be taken care of and what is its implication how the work that we can particularly the work in the pump and the turbine that will change and; obviously, that will have effect on the efficiency how the efficiency will change.

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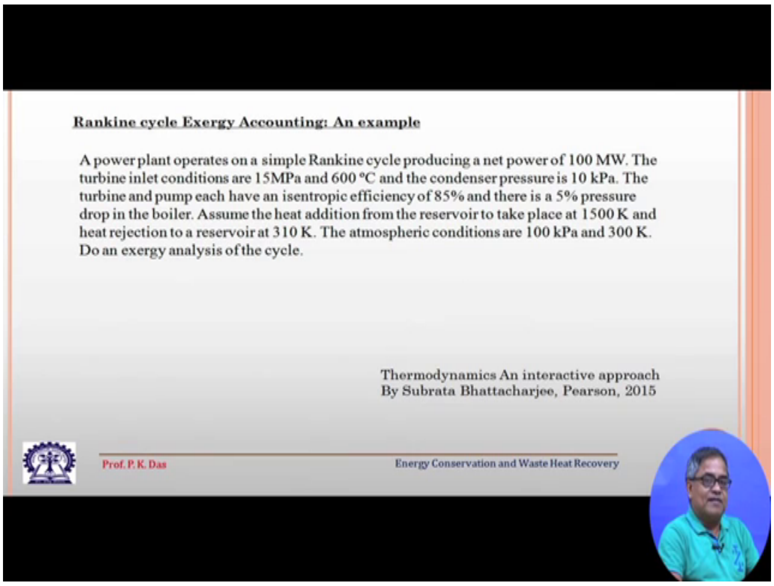

Next I like to take an example where we have done Exergy analysis in the in our thermodynamics whatever background you wanted to give regarding thermodynamics when we have discussed the thermodynamic principle. So, we like to apply those Exergy the analysis technique for a steam power plant that will give you some sort of practice of the Exergy, if in signal which probably you have learnt earlier and now we have recalculated and what is the implication of this Exergy on the power plant that also we will be able to find out how the Exergy is changes are taking place that also you will be able to able to find out from this example.

So, let me read out the problem a power plant operates on a simple Rankine cycle producing a net power of hundred megawatt the turbine inlet conditions are 15 mega Pascal and 600 degree Celsius actually the earlier problem which we have taken we have taken the same example for some sort of Exergy accounting and the condenser pressure is 10 kilo Pascal the turbine and the pump each have an isentropic efficiency of 85 person and there is a 5 percent pressure drop in the boiler assume the heat addition is from a reservoir to take place at 1500 K and heat rejection to a reservoir at 3 10 K the atmospheric conditions are 100 kilo Pascal, 300 K and we like to do and Exergy the analysis for the cycle.

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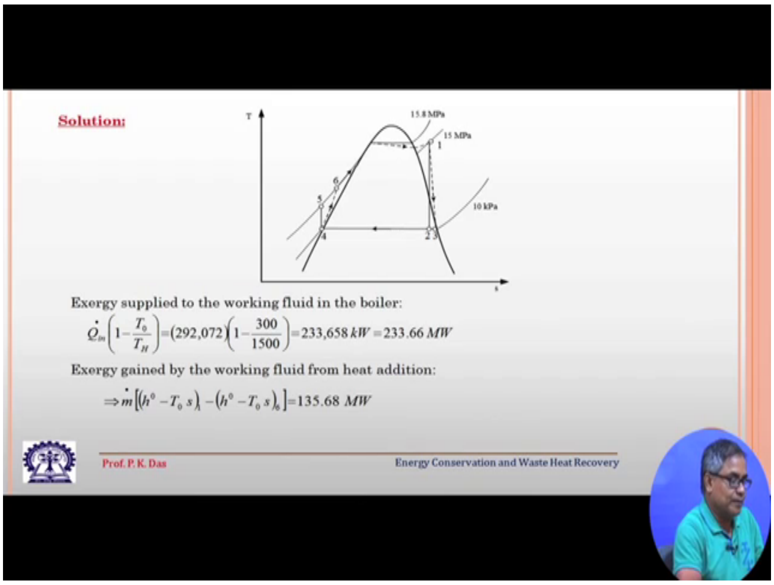

So, we will proceed like this for ready reference the same cycle diagram which we have used for the previous problem again it has been shown here. Now Exergy is supplied to the working fluid in the boiler. So, boiler basically we are heating and the heating process is from is from point 6 to point one. So, during this process we are transferring heat and we want to determine Exergy supplied to the working fluid in the boiler. So, the formula, if you see your earlier class note or the earlier lectures you will find that this is the Exergy the content of the heat transfer here this is the ambient temperature which has been stated in the problem and also in the problem.

It has been stated some approximate temperature which can be assumed as the temperature of the thermal reservoir from where heat is being transferred to the fluid. So, this is ph and Q dot in already we have calculated in the previous problem. So, this I am not doing again and Q dot in how did we get it from h 1 minus h 6 we got you Q dot in. So, putting in this formula we get 233.66 megawatt that is the excite a Exergy ion supplied to the working fluid in the boiler.

So, you see where as the heat supplied was this much 292.072 megawatt the Exergy supplied was much was less than that that is 233.66 megawatt. So, that gives the concept that makes the concept of Exergy bit more clear in terms of in the terms of this number scheme Exergy gained by the working fluid from heat addition now this is the heat given to the boiler, but what Exergy picked up by the fluid when it is passing through the boiler. So, that we will get from the Exergy changes of Exergy change of the fluid the fluid is leaving the boiler at point one and the fluid is entering at point six. So, from there and this is the formula h which is up with a superscript o that I have called methylpy and; obviously, in this case kinetic and potential energies are not to be counted change in kinetic and potential energies are small compared to enthalpy term. So, with all these thing if you put in values in from your steam table steam property values you will you have to put and then you will get this is nothing, but 135-168 mega megawatt.

So, whereas, heat supplied to the heat supplied to the boiler is 230; sorry; Exergy supplied to the boiler in 233.66 megawatt the Exergy picked up by the fluid is 135.68 megawatt. So, we can see that how in actual process there is the Exergy; if we think of that this is the available or energy this is the essential energy how gradually it reduces that we can find out from this particular example.

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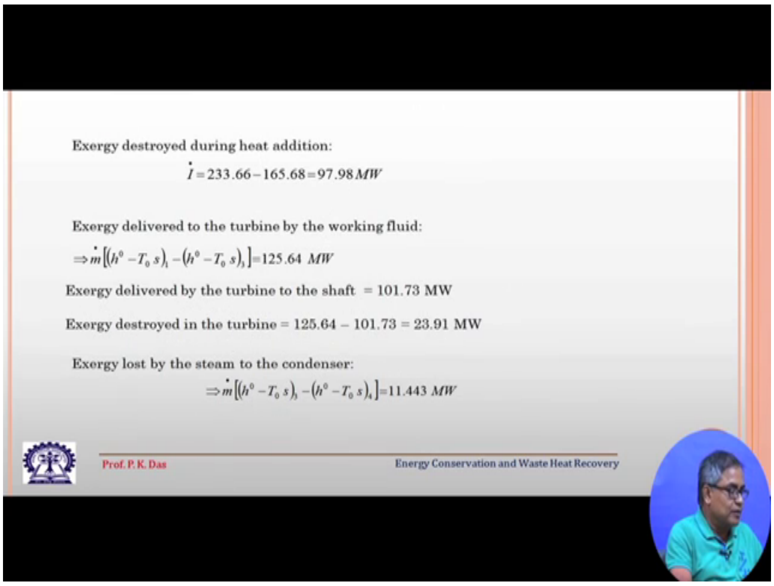

Next what we do; Exergy destroyed during heat addition the heat addition process; obviously, it is an irreversible process and again the numbers we have calculated from there we can find out the Exergy destroyed; Exergy destroyed is also the irreversibility. So, we have indicated it with I dot and this I dot Exergy destroyed during heat addition that is equal to 97.98 megawatt, then we are the fluid is coming out of the boiler and it is going to the it is delivered to the turbine it is going to the turbine. So, by the fluid Exergy will be delivered to the turbine and what is the Exergy delivered to the turbine by the working fluid that I will get the turbine expansion is from point one to point 3; point 3 is the actual working point or rather the actual point after expansion.

So, again by following the same we will get 125.64 megawatt, but Exergy delivered by the turbine to this shaft this we have calculated earlier and this is nothing, but 101.73 megawatt. So, Exergy destroyed in the turbine we will get 23.91 megawatt that is the Exergy destroyed in the turbine, then the steam will pass through the condenser after the expansion it will come to the condenser and it will pass through the condenser. So, Exergy lost by steam to the condenser again, we can use the same kind of formula which we have used earlier and then from there Exergy lost by steam to the condenser is equal to 11.443 megawatt.

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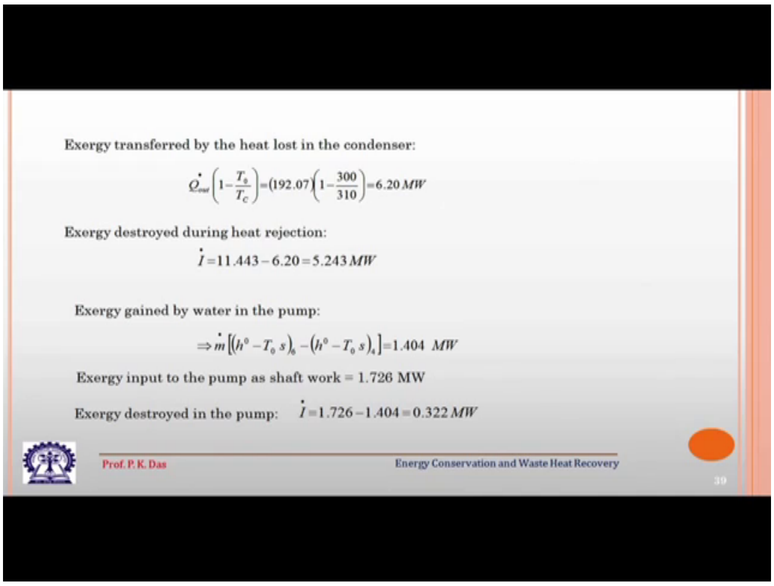

So, then we Exergy transferred by heat lost in the condenser that also we can calculate and this is 6.2 megawatt; so, Exergy destroyed during heat rejection that is 11.443 minus 6.2, this is 5.243 megawatt. Now we get the Exergy gained by water in the pump the pump that is pressurizing the condensate which is obtained from the condenser. So, the water will gain certain amount of Exergy and that Exergy using the similar formula, we will get that is 1.404 megawatt and Exergy input to the pump as shaft; shaft work that is 1.726 mega; what this we have got from our earlier calculation the earlier problem when we have warked out we have got this number. So, you see that Exergy destroyed in the pump that will be actual work done because it is some sort of work absorbing device. So, actual work done minus the Exergy gained by the fluid. So, this is 0.322 megawatt.

So, now we have done some sort of Exergy accounting more than that we can do certain thing which I have not included in the lecture or in this slide, but you can do it let us say, we have we have got what we can do this is this is very illustrative example which you can do off your own you can do; obviously, you can calculate the first law efficiency based on all the figures, etcetera and first low thermal efficiency we have already calculated in the previous example.

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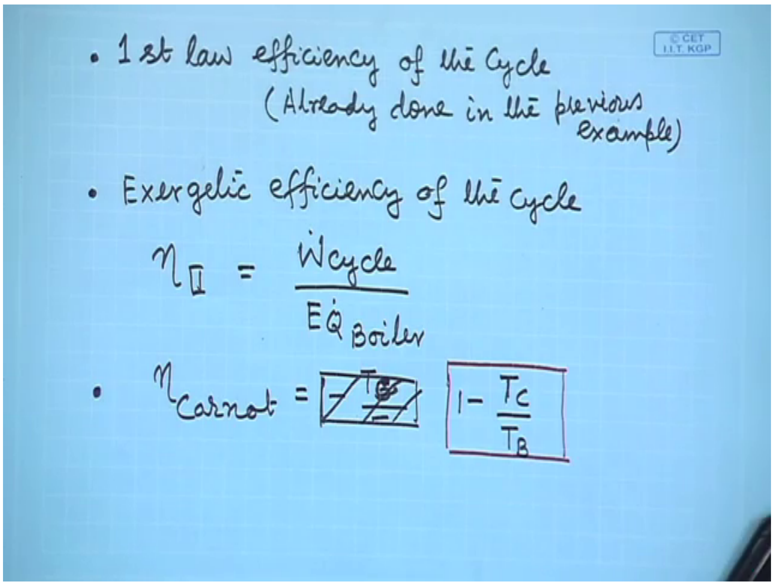

So, let me write first law efficiency of the cycle you have this is already done in the previous example. So, now, all the Exergy values are known. So, what you can do this is one thing you can do second thing what you can do exergitic efficiency of the cycle this also you can do how we can do that you know what is the work done by the cycle and also you know what is the Exergy supplied in the boiler. So, suppose I call it eta two. So, what we can do W cycle this is the net work done by the cycle and we can do EQ dot this is W dot cycle and EQ dot boiler this also we have calculated in this problem. So, EQ dot boiler that we can take AO; we are supplying EQ dot boiler, this is the Exergy and we are getting this amount of work what is equivalent to Exergy. So, we will get the second law efficiency or exergitic efficiency of the cycle.

Further we can do another exercise you see for this particular problem we have given the temperature at which heat is added. So, this is approximate, but one can estimate kind of a temperature at which heat is added in the boiler and then we have also given a temperature at which heat is rejected in the condenser. So, if we consider that then we can get eta Carnot of the of the cycle eta Carnot of the cycle means if the entire heat would have been added at that particular temperature and if the entire heat has been rejected at the temperature lowest temperature given. So, we can find out eta Carnot or equivalent eta Carnot for the example given. So, this will be T boiler you see we have given me mentioned a temperature which can be assumed that tempera it has been added to that temperature and then your TC sorry. So, this should be this should be 1 minus T condenser by T boiler these 2 temperature has been provided. So, with this we will be able to find out eta Carnot.

So, you see we can get 3 si; 3 efficiencies here first law efficiency already we have calculated with the value Exergy balance whatever we have done. So, with that we can calculate the W, sorry; eta 2 or exergitic efficiency and then the temperature which have been given with that we can get a Carnot efficiency of the equivalent cycle and then one can; obviously, make some sort of the comparison and one can also understand how the energy is lost and degraded that is why we are having these 3 values and these 3 values gives 3 different perspectives for the cycle.

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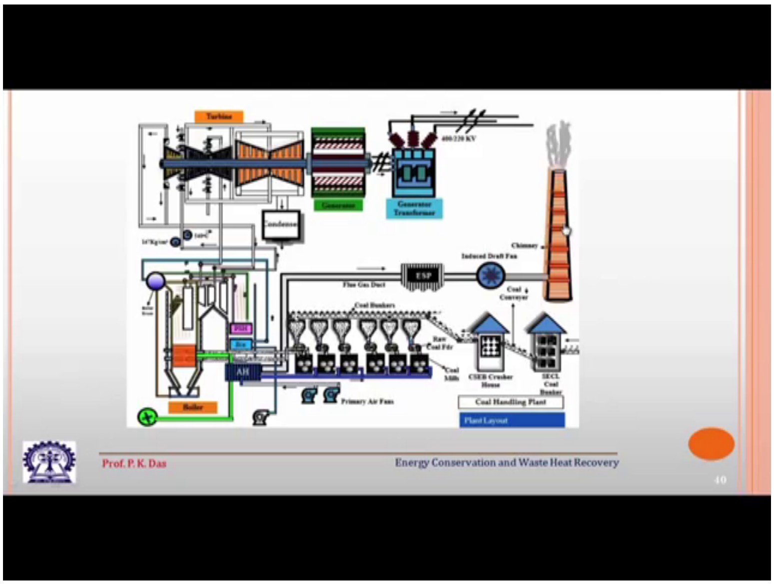

I like to end our discussion on steam power plant, but before doing show I like to show an animation of this steam power plant which will give you some idea how does a steam power plant operate and it is more or less self explanatory and one can see different activities the coal needs to be pulverized it will go to the coal bunker. So, that is the first thing then from the pulverizer, it will ultimately go to the boiler it is; it has been shown that it is some sort of a pulverized coal firing system and you see boiler heat pump has started because the water has to go to the boiler. So, this has started and then no sorry this is the boilers hand that has started and then of course, boiler feed pemp; pump that also you will find that it will start after some time.

So, now we can see the combustion has started within the boiler and then now you see that hot product of combustion after heat transfer it is going out of the chimney or scat. So, different sections of boilers are being operated one after another. So, there are primary super heater secondary super heater. So, they are being operated and then it will go to the turbine. So, you can see the operation of the turbine.

Now, you see the different stages of the turbine all the different stages of the turbine are in operation. So, ultimately steam comes to be condenser it condenses and again the cycle starts. So, starting from the starting from the coal pulverization and then its injection in the boiler flame the flame has been created in the boiler. So, from there the water circuit and different stages of the steam turbine how each of the stage is being operative and then ultimately drives a generator close to the condenser where it condenses. So, that brings it to an end and this end time you have seen that ultimately the flue gas that comes out of the chimney or scat so; obviously, in the path in the path of the flue gas we have got or we design it in such a way maximum utilization of thermal energy is possible out of the hot product of combustion.

So, this is just an demonstration in a very nutshell because in power plant actual steam power plant is very large, but when we are ending our discussion on steam power cycle. So, this example will give you some idea how different units are placed and how the thermal energy of the hot flue is being utilized in different heating sections how the steam from the high temperature to high temperature and high pressure condition is getting expanded to the lowest pressure at the LP stage or low pressure stage of the turbine. So, with this we come to an end to our discussion on steam power cycle we will see other power cycles which are important in our next lecture.

Thank you.