Energy Conservation and Waste Heat Recovery
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Lecture – 18
Recapitulation of common power cycles (Contd.)

Welcome everyone, if you recall we were discussing power cycles, I told that there are certain important power cycles which we like to have a recap and that will be important to know what is the potential of waste heat recovery from these power cycles, sometimes even what is the potential for energy conservation in these power cycles and at the same time whether these type of power cycles itself can be used for some sort of a bottoming cycle. So, that the waste heat from a high temperature cycle can be recovered either, once we had a good idea regarding the power cycle either we can modify them. So, that generation of waste heat is minimized or we can use them where there is available waste heat we can use them to recover that waste heat.

So, in that connection we have started with Rankine cycle. We have seen the basic Rankine cycle and then we have seen or we have discussed that there will be number of losses in the basic Rankine cycle. So, there should be some sort of an effort to modify the basic Rankine cycle. So, that maximum amount of energy we can utilize.

In fact, all the power generation units' utility power plants which use in power cycle. So, they do not have the basic Rankine cycle, but they have the Rankine cycle with the modifications we are going to discuss out of this one modification I have already discussed that is Rankine cycle with reheat option. And today we will continue with that and in connection with reheat cycle we will also try to see one example. So, that the calculations for Rankine cycle is again you can recall back from your course of thermodynamics and then we can also see that what advantages we are getting from this.

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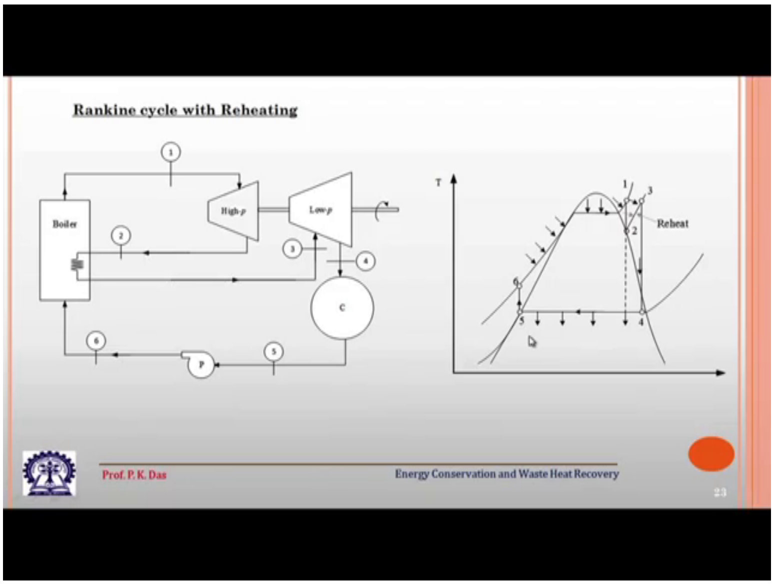

So, if we go to this slide here this diagram I have drawn in earlier in earlier lecture I have drawn this diagram, but here very quickly let us see this is the boiler from the boiler high pressure and high temperature steam is coming the condition is given by state one, it is entering into a turbine as the pressure is high we call it we differentiate this turbine as high pressure turbine and in the turbine the steam will expand and low pressure low temperature steam we will get out of the turbine, we are not sending it back to the condenser rather we are sending it back at state 2 to the boiler. And in the boiler again it is being heated this is called reheating process and in this section of the boiler where this will be done that is called a reheater.

And you see this is again one can think of as one energy conservation option or energy conservation technique, see if the boiler the flue gas could have gone with high temperature once we have reheat we can extract some more energy out of it. And then when the steam is reheated still it is pressure is low because we have not increased the pressure, only we have increased the temperature and it is going to the second boiler which is sorry second turbine which is called a low pressure turbine.

So, in the low pressure turbine it is expanded and then it is taken to the condenser, then as usual in the condenser we condense the steam the condensate or the water that goes to a feed pump. The feed pump raises the pressure raises the pressure to the boiler pressure and it again goes back to the boiler. So, this I have explained and with the help of a diagram which is in TS plane. So, this coordinate is s coordinate and the cycle is shown. So, from 1 to 2 now 1 to 2 is the expansion in the high pressure turbine, 2 to 3 this is heating in the reheater again in the boiler this reheating process takes place, 3 to 4 this is the expansion of steam in the low pressure turbine and then 4 to 5 this is heat rejection in the condenser in the condenser this 4 to 5 that process takes place.

And as usual we will assume that the condensate that comes out of the condenser at the saturated liquid condition and then it is taken to the pump at a low temperature, low pressure and then the pump raises it is pressure up to point 6 and then in the 6 it goes to the economizer this part is the economizer part and then this part is your this part is your evaporator part if you remember the schematic diagram of the boiler I have given at the beginning and then again it is the super heating part.

I have mentioned earlier, but let me again mention it generally these 2 temperatures are kept at the same level and this temperature this is the highest temperature of the cycle, this is the temperature at which steam will go to the turbine and pass through the blade passages of the turbine. So, this temperature is generally determined by the material property of the turbine and well so there are research activities going on, that the turbine blade can withstand higher temperature. So, that we can increase the cycle temperature even higher compared to what we use today in is steam power plant there are also some sort of scheme so that effectively transfer takes place from the blades.

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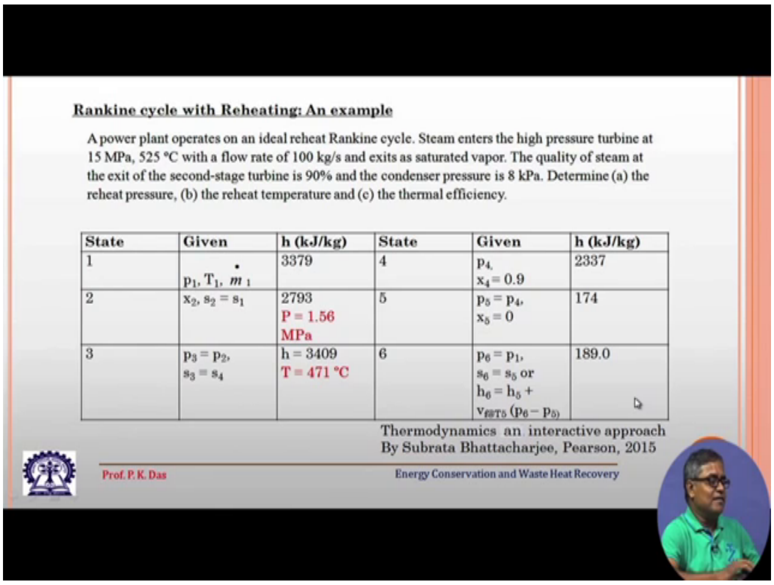

Now with this let us go to the next slide. So, next slide we have taken one problem, a power plant operates in an ideal reheat Rankine cycle, steam enters the high pressure turbine at 15 mega Pascal, 5 25 degree Celsius with a flow rate of 100 kg per second and exists at saturated Vapour. The quality of steam at the exit of this second stage turbine is 90 percent and the condenser pressure is 8 kilopascal, determine the reheat pressure the reheat temperature and thermal efficiency.

Now, if we have to work out this problem then; obviously, steam is the working substance and we have to take or we have to know this steam property at different important points of the cycle. Those important points have been marked by number 1 2 3 4 like that and these properties we get from steam table or nowadays one can use one engineering equation solver also for solving this problem. Assuming that you are familiar with steam table I am proceeding with this with the solution of this problem.

Now, we have to go back between this slide and the previous slide we have to switch to and fro between these 2 slides, you see if we go to the previous slide. So, this is your point 1. So, here the pressure and temperature of the steam is given. So, here we know the pressure and temperature of this steam and then if we know the pressure and temperature of this steam, then what we can calculate from the steam table we can calculate it is sorry enthalpy and also we can calculate it is entropy. So, both this point we can calculate.

So, if we go back to the next slide what we can find that the given quantities are P 1 T 1 and m dot 1, the mass flow rate that is given. So, from there we can calculate at state point 1 the enthalpy we can calculate. So, enthalpy with which steam is entering the entering the high pressure turbine that is known. Now we go to point 2, again let us go back to our previous slide. So, point 2 is this point; point 2 is this point means point 2 is the point where this steam comes out of the turbine and if we read this statement of the problem, then it is stated that steam entered the enters the high pressure turbine at 15 mega Pascal 5 25 degree Celsius with a flow rate of 100 kg per second and exists at saturated Vapour.

So, this is important it exists at saturated Vapour. So, what we have to do we go back to the previous slide. So, this process now let us concentrate so at this process we know the entropy and we are assuming that this is an ideal expansion through the turbine which may not be in the actual case, but we are assuming that it is an ideal expansion. So, if this is ideal expansion then it will be adiabatic reversible adiabatic or isentropic expansion.

So, if it is isentropic expansion then S 1 is equal to S 2 and S 2 there is another condition given in the statement of the problem. Statement of the problem it is given that it is in the saturated Vapour condition. So, it will be saturated Vapour line it will be on the saturated Vapour line. So, you see for determining state point 2 we have got 2 conditions, we know the entropy and we know the we know that it is in the saturated Vapour condition.

So, what we will do we have got S 2 is equal to S 1 and then x 2 is known means x 2 is equal to 1 that is known and then knowing S 2 at which condition the saturated Vapour will have the same enthalpy as sorry same entropy as S 1 that we have to determine from this steam table. If we are using a conventional steam table then probably some amount of searching and probably some interpolation may be needed depending on this steam table, but we will be able to find out the pressure at which S 2 is equal to S 1 and the condition is saturated Vapour. If we do that then we will get the pressure and the pressure is 1.5 6 mega Pascal.

So, let us go back let us spend some time on this problem. So, this point was known from the information taking that the expansion line is isentropic and end of expansion is on the saturated Vapour line we got 0.2 also now 0.2 is also known pressure is known and it is saturated Vapour condition. So, then very easily we can find out the enthalpy at this point. So, h 2 is known by this process. So, h 2 we have calculated step 2 the enthalpy is h 2, that is 2793 kilo joule per kg and then we go to state 3.

So, state 3 what is known, state 3 you see state 3 from 2 to 3 we follow this line, what is this line this is some sort of a constant pressure line. So, once we have known the pressure at 2. So, pressure at 3 is also known again we are dealing with ideal cycle so where we have neglected the pressure drop through the piping etcetera through the reheater. So, what we have assumed that at what pressure it comes out from the high pressure turbine the same pressure is maintained and at state 3; that means, at the inlet of the low pressure turbine we are having the identical pressure.

So, at state 3 what is known the pressure is known at state 3? Let us go back to the next slide. So, the it goes to this state 3 and what we assume that P 2 is equal to P 3 is equal to P 2 that we assume, then there is another information given in the problem the quality of steam at the exit of second stage turbine is 90 percent and the condenser pressure is 8 kilopascal.

So, this is regarding our state four. So, all the condition of state 3 we cannot calculate right now we have to go to state 4, but one thing we know regarding state 3 that it is pressure is given by 1.56 mega Pascal.

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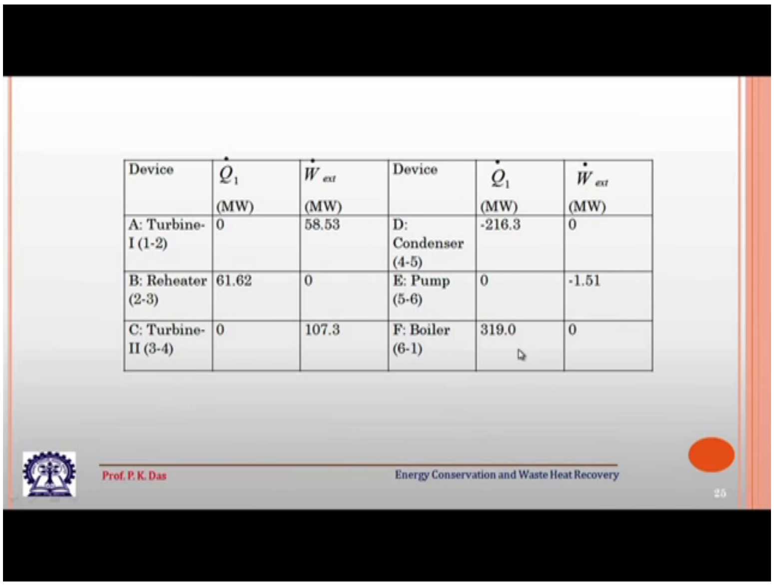

Device	$\dot{Q}_1$ (MW)	$\dot{W}_{ext}$ (MW)	Device	$\dot{Q}_1$ (MW)	$\dot{W}_{ext}$ (MW)
A: Turbine-I (1-2)	0	58.53	D: Condenser (4-5)	-216.3	0
B: Reheater (2-3)	61.62	0	E: Pump (5-6)	0	-1.51
C: Turbine-II (3-4)	0	107.3	F: Boiler (6-1)	319.0	0

Now, let us move to State 4. So, in state 4 the P 4 is given in the problem that is condenser pressure is 8 kilopascal and x is given. So, if these 2 things are given we can calculate the enthalpy following the laws what we or following the rules what we what we usually take for a calculation with steam table. So, we can calculate the enthalpy additionally what we can do we can calculate the entropy at state 4 also.

So, if we have calculated the entropy at state 4 if we go back then what we can see that this is an isentropic process. So, this and this entropy is 4 that will be equal to the entropy at state 3. So, state 3 now 2 conditions are known we know the pressure we know the entropy and; obviously, it will be in the superheated region. So, in the superheated region for the steam we know the pressure and we know the entropy so; obviously, we will be able to this point is now fixed on our thermodynamic plane and we can calculate any other thermodynamic property.

So, in 3 you see P 3 is equal to P 2 that is what I have already told and now the state is known S 3 is equal to S 4. So, we can calculate what is the temperature 471 degree Celsius? So, you see we have started with 525 degree Celsius that was the temperature of this steam initially and this temperature is lower than this 471 degree Celsius from material point of view we could have gone up to 525 degree Celsius, but rarely it is taken above 525 or rather the temperature at which steam enters at the first stage of the turbine.

So, our condition is fully known. So, with that we can calculate the enthalpy. So, enthalpy at state 3 that is 3409 kilo joule per kg that is known. Now we go to state 5 state 5 sorry state 5 is after the condenser and after the condenser means we know the condenser pressure and at this condition it is saturated liquid. So, we know we can easily and readily determine the enthalpy at this particular point from steam table.

So, that is what we have done at state 5 the pressure is known and the quality is equal to 0. So, we have calculated the enthalpy which is the enthalpy of the saturated liquid all right. Then we go to state 6 state 6 is the state point after the pump. So, after the pump what are what we are getting this I have already discussed after the pump, this will be in the liquid condition, but the pressure will be high.

So, this is an adiabatic process again or reversible adiabatic process again or it is an isentropic process and here we are getting the point in the sub cooled liquid region. Here generally properties are not available with conventional steam table, what we can do from the work done the enthalpy over here plus the work done that will give the enthalpy at 0.63. So, this is what I have explained in my earlier lecture and that is what we are going to do.

So, P 6 is equal to P 1 that is the boiler pressure that is known, S 6 is S 5 this is ah again I have told that it is reversible adiabatic process or isentropic process or h 6 is equal to h 5, that is the enthalpy of the saturated liquid at the end of the condenser at the exit of the condenser plus the pump work. So, for calculating the pump work we have taken the pressure difference between the boiler and the condenser and we have multiplied it with this specific volume at 0.5 specific volume of liquid, because it is at liquid condition a saturated liquid condition at 0.5 this is what I have explained earlier also and with this we will get the enthalpy at 189.0.

So, you see the in the pump the liquid entered with an enthalpy of 174 kilo joule per kg, it is going out of the pump with 189 kilo joule per kg. So, the difference between this 2 will give us the pump work or rather by adding the pump work we have got this change. So, with this if we proceeded towards the next page of calculation then we have written different kind of devices here device a turbine.

So, in the turbine the turbine 1 that is the high pressure turbine and the process is 1 to 2, there is no heat transfer assuming that it is insulated we have got this much of work. And then we have got reheater in the reheater we have got well there is heat addition and that also we can get it get from the enthalpy difference. So, in the reheater from the enthalpy difference from between 0.2 and 3, 61.6 2 megawatt is the enthalpy difference that is the amount of heat given work done is equal to 0.

Then we have given or we have gone to the second turbine or turbine low pressure turbine and here; obviously, again it is insulated no heat transfer, but there is 107.3 megawatt amount of work done. In the condenser there will be heat rejection. So, this is negative condenser is from 0.4 to 5. So, there will be a heat transfer if we do h 5 minus h 4 we will get some sort of a negative quantity. So, it is minus 216.3 heat is rejected to the cooling water in the condenser and; obviously, work done is equal to 0.

Then we go to the pump 5 to 6 again it is a reversible adiabatic device and heat transfer is equal to 0 and pump is consuming work for pressurizing the from the liquid and it is 1. 51 minus 1.51 because work is absorbed then we go to the boiler and in the boiler there is a transfer from 6 to 1. So, this is 319 megawatt amount of heat is added to the boiler .

But total amount of heat addition please pay your attention to this is this one in the boiler first when these steam is heated and taken to the superheated condition for supplying it to the high pressure turbine and again steam is heated in the reheater. So, total amount of heat addition will be 3 1 9 plus 61.6 2 this is the total amount of heat addition. Total amount of work that that will be the work done by turbine 1 and work done plus the work done by turbine 2 so 58.5 3 plus 107.3 (Refer Time: 24:57) with this let us go to next stage of calculation.

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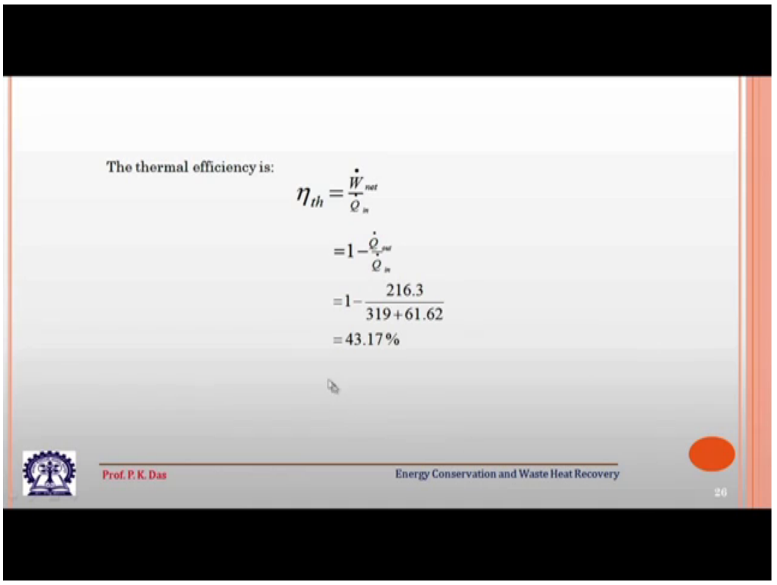

So, thermal efficiency will be W net W dot net divided, but divided by Q dot. So, here you see addition of both the turbine work that is given and here the addition of both the work sorry both the heat addition in the boiler and in the reheater. So, that is given and with that we get an efficiency of 43.17 percent. Now let us go back to the first cycle diagram I like to conclude this lecture, but before that I like to give you some messages which you can take back.

First thing is that we have the work output will increase, efficiency I have told that efficiency may increase because the simple reason is that part of the heat addition is at high temperature this temperature again we are adding heat at high temperature. So, efficiency may increase and if it is properly designed 1 may expect, 3 to 5 percent increase in efficiency. There could be lesser increase depending on the parameter of the ah parameter of the cycle, but one thing you can see suppose we did not have any reheating we could have followed this path and we could have come here at the end of at the end of our expansion in the turbine and then this steam would have been in relatively more wet condition which is detrimental to the turbine.

So, one additional benefit we get that when we are going for reheating. So, we get a steam with higher quality and that is better for the turbine. So, one may ask one question you may ask this question, that how many reheat we should have if we have more and more reheat that is possible, but what happens in that case. First thing is that ultimately we will the exit point will come out of this 2 phase dome. So, it will be in the superheated region of the vapor that is not good, because we have to then the condenser has to extract heat from the superheated vapor and that is not good.

Second thing this is this is one important point that if we have more and more reheater, then there are extra piping extra pressure loss and that may not that may eat away the benefit which we are getting from reheat. So, single reheat is quite common there are 2 reheats also particularly when the boiler pressure is high we can go for to reheat and in case of super critical boiler definitely one has to do reheat and one has to go for double reheat. With this we end our discussion on the modification of Rankine cycle with reheat we will see another modification of Rankine cycle in the next lecture.

Thank you.