Energy Conservation and Waste Heat Recovery
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Lecture - 25
Combined cycle (Contd.)

Welcome back if you recall we were solving one problem for combined cycle power plant and we were halfway through. A combined cycle power plant we have taken a combination of gas turbine and steam power plant and we were halfway through we have solved only the property values for the gas turbine power plant we have to do the rest of it. So, let us proceed.

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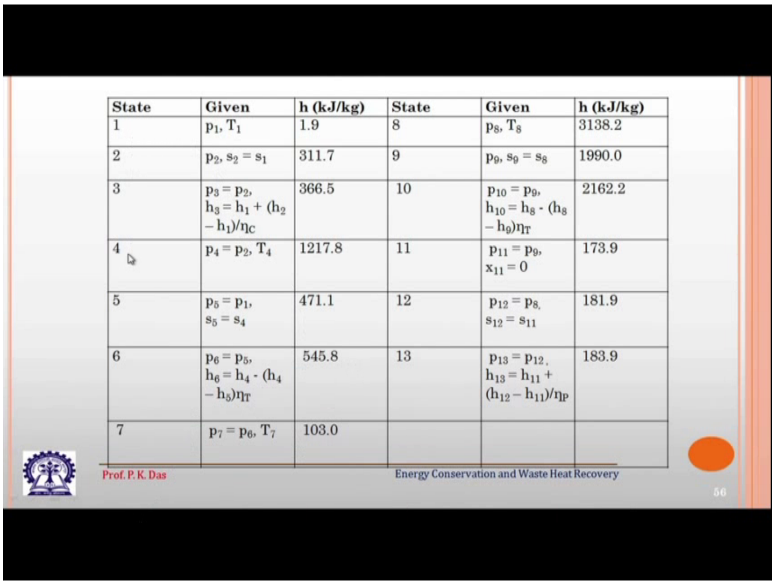

State	Given	h (kJ/kg)	State	Given	h (kJ/kg)
1	p_1, T_1	1.9	8	p_8, T_8	3138.2
2	p_2, $s_2 = s_1$	311.7	9	p_9, $s_9 = s_8$	1990.0
3	$p_3 = p_2$, $h_3 = h_1 + (h_2 - h_1)/\eta_C$	366.5	10	$p_{10} = p_9$, $h_{10} = h_8 - (h_8 - h_9)\eta_T$	2162.2
4	$p_4 = p_2$, T_4	1217.8	11	$p_{11} = p_9$, $x_{11} = 0$	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			

So, I draw your attention to the PPT; and if you recall from your earlier class that 1, 2, 3, 4, 5, 6 they represent the points over the gas turbine cycle.

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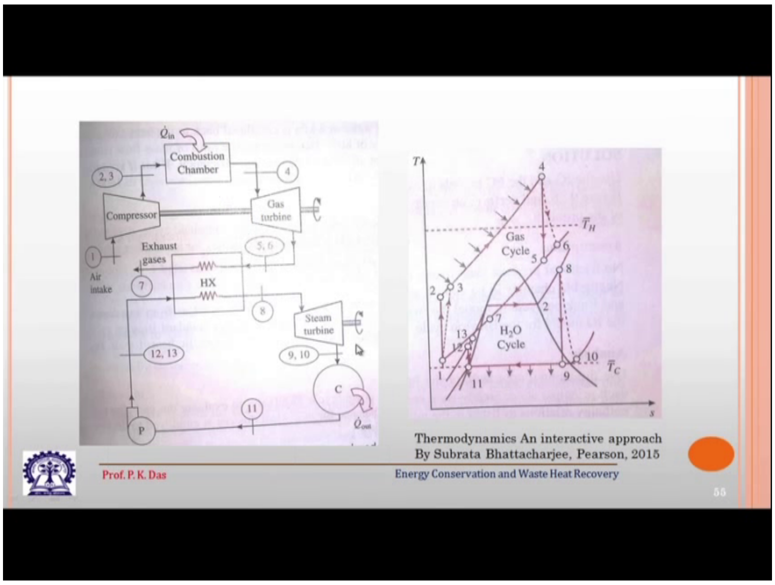

Let me go back to the cycle once again. So, you see 1, 2, 3, 4, 5, 6, these are the points on the gas turbine cycle and we have calculated these.

The property values particularly the enthalpy at these points following the usual procedure and we have come up to this. Then there is another point on the gas turbine cycle which is important, because 6 denotes the exit of the turbine. So, we know the condition of air at the exit of the turbine, that is, the enthalpy is h 45.8 kilojoules per kg, but after that it enters into another important component which is unique to combine cycle power plant, this is basically a heat exchanger and it is very extensively known as heat recovery steam generator on which we will spend some time later on. So, it enters in that heat exchanger and then exchanges heat with the bottoming cycle. So, that steam can be generated.

So, I am talking about this heat exchanger. So, you see after 0.6 it goes into that heat exchanger the gas stream and then the gas stream will be cooled to 0.7. So, at least up to 0.7 we have to do calculation to know the property particularly enthalpy and let us go back. So, at 7 P 6 and P 7 they are same in air standard cycle we are assume that there is no loss of pressure the this is isobaric heat rejection and T 7 is given. So, from there we can determine the enthalpy. \

So, we know the enthalpy with which the gas is entering, we know the enthalpy with which the gas is leaving. So, this is very important information. Then, let us go to your steam cycle. State 8 what is state 8? Let us go back little bit. So, state 8 is the point where the steam enters the turbine. And at this point the steam condition so it is superheated so pressure and temperature should be known to calculate the enthalpy.

So, exactly the same thing has been done P 8, T 8 it is known enthalpy from this steam table we can find out. Then if this steam could have expanded isentropically, then we could have got P 9 sorry; the 0. 9 which is at condenser pressure P 9 and assuming isentropic expansion we could got the could get that s 9 is equal to s 8. So, using all these information as we have used earlier, see the enthalpy at 0.9 can be calculated, but this is not the actually enthalpy of the actual state of the gas after expansion. So, the gas has expanded in not in an isentropic manner, they are if there is irreversibility to account for that we have been supplied with this quantity eta T which is the isentropic efficiency of the turbine.

Following the procedure which we have done earlier; we can calculate the enthalpy of the gas or of this steam at the point when it is coming out of the turbine. So, this point we can get 2162.0 kilojoule per kg that is the enthalpy of this steam. After that it passes through the condenser so it is condensed fully; that means, it comes out as saturated liquid considering that and knowing the condenser pressure we can calculate what is the heat transfer or heat rejected by the in the condenser. Then there is pump considering isentropic compression in the pump isentropic pressurize in the pump.

This is the enthalpy value at 0.12 which is at the end of isentropic pressurize, but that is not the case there will be certain amount of irreversibility to take care of that we have got the isentropic efficiency of the pump and then we can calculate at 0.13 which is the exit of the pump what is the enthalpy? So, enthalpy values at all the important points of the gas turbine cycle and this in turbine cycle are known. So, now, we can do the other cycle calculation we can find out the efficiency.

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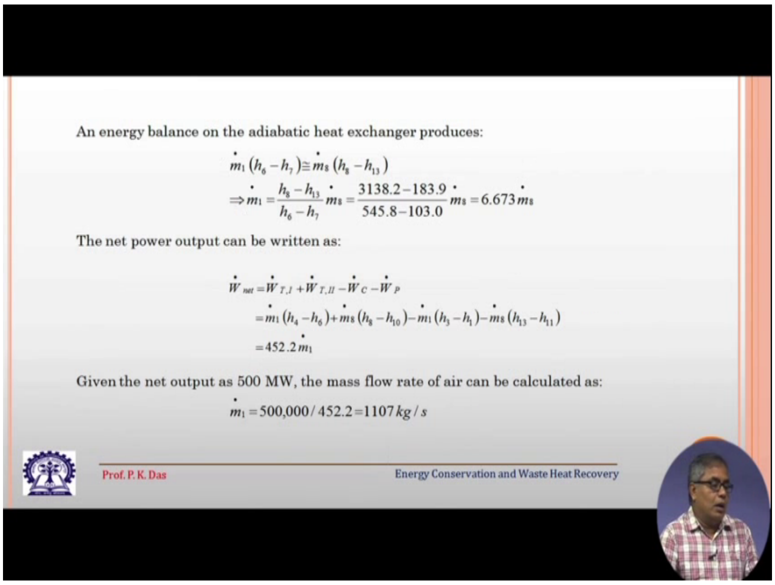

So, first what we like to do the heat exchanger which is there on between the gas turbine cycle and the steam turbine cycle which is also known as HRSG heat recovery steam generator we will do an energy balance for that. Neglecting losses from the HRSG we assume it is perfectly insulated.

So, whatever heat exchange is there heat exchange is there between the hot gas and the incoming water and steam afterwards it will form. So, there is no heat exchange to the ambient atmosphere. So, a simple thermal balance energy balance will give us this and then we can get m dot 1 which is nothing, but the mass flow rate of air and m dot 3 that is the mass m dot 8 that is the mass flow rate of steam or water. So, we will get some sort of a relationship between that; that means, 1 mass flow rate we can get in terms of other mass flow rate. The net power output can be written as once we have get this.

The net power output will come from 4 components 2 turbines are developing powers and 2 devices for compressing the fluid, one is the compressor and another is the pump they are absorbing power. So, the work done by 2 turbines are added and from there we work absorbed by the pump and compression they are subtracted; and with that we will get the work done in terms of m dot 1, that is, the mass flow rate of m. Now net output has been given as 500 Megawatt and then putting this information we can get, what is the mass flow rate of air? So, we have got the ratio of mass flow rates of the 2 fluids we have also got what is the mass flow rate of air needed for this combined cycle to produce 500 megawatt.

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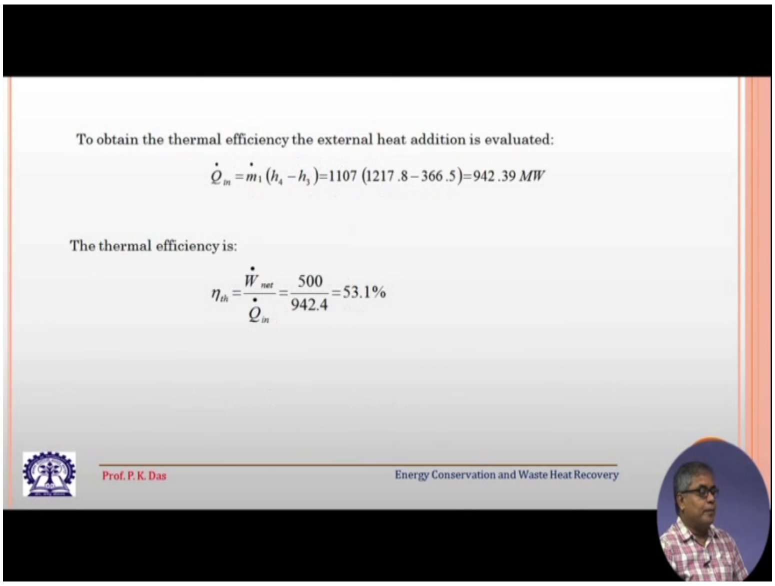

And then, what we can do? We can obtain the thermal efficiency. So, once we know the air mass flow rate we know per unit I mean sorry for per unit mass flow rate of air what is the enthalpy addition in the combustion chamber. So, now, we know what is the total amount of thermal energy supplied at in the comma in the combustion chamber that is 942.39 Megawatt? We know the; what is the work done that is 500 Megawatt and then with this we could get the efficiency of the combined cycle, that is, 53.1 percent. So, this is a substantial increase in the efficiency of a power plant which is operating on I mean which is basically a conversion device for thermal energy to mechanical work.

And this efficiency is much more you can do the calculation much more compared to the efficiency of the individual cycles. So, this shows that this shows the advantage we get by combined cycle power plant. So, that is why there is a common tendency of having the new power plant as combined cycle power plant apart from it is other if your other advantages the main advantage we can have such a good device for energy conversion and; obviously, along with it goes that the effect on the environment will be lesser.

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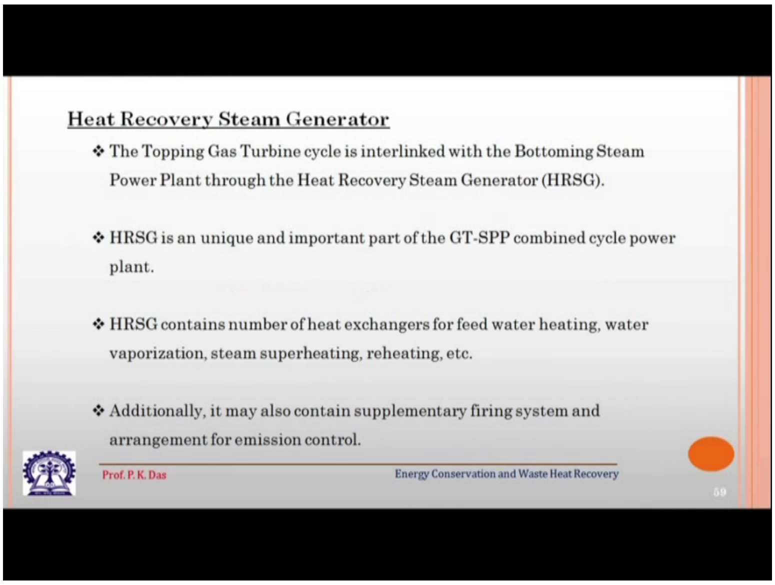

With this I go to a very important device which is part and parcel of a gas turbines steam power plant combination that is, called heat recovery steam generator.

Once or twice I have mentioned it, but let us study because this is some sort of waste heat recovery device which is very relevant for this course. So, we like to spend some times some time on this. So, heat recovery steam generator. The topping gas turbine cycle is interlinked with bottom bottoming steam power plant through a heat recovery steam generator, which is commonly known as HRSG. Let us come to this diagram. So, with this diagram I can explain what is HRSG? So, this is a heat exchanger where there is exchange of thermal energy between the exhaust gas and the steam or rather the water and then steam. So, this heat exchanger is called HRSG in case of combined cycle.

And here you see that this is the process which is taking place there are 2 streams. So, this is the process which is taking place in one HRSG. Now HRSG as the name suggests, so it is some sort of a device in which steam is generated, but primarily there is no combustion in certain cases there could be some additional fuel burning, but primarily there is no combustion. So, already combustion has taken place elsewhere hot gas is coming probably that hot gas has done certain amount of certain amount of work in a cycle and then that exhaust gas is coming and with this we are generating steam. So, this is the purpose of HRSG or heat recovery steam generator.

It could be there in connection with a combined cycle power plant where a gas turbine and the steam turbine is combined. It could be there where we get a source of I mean we have a source of hot gas, hot product of combustion and that hot product of combustion is being used for steam generation. So, it could be in that kind of application also; that means, it need not be is heat recovery steam generator need not be only in a gas turbines in turbine power plant combination, let us say from a furnace or incinerator we are having very high temperature gas at the outlet of the furnace which could have wasted in other ways it could have been wasted in usual process.

But, we are utilising it for generating steam then this will be called a heat recovery steam generator. There is a subtle difference between heat recovery steam generator and waste heat boiler heat recovery steam generator are generally units from which we get steam for using it for the purpose of power generation whereas, waste heat recovery boiler in most of the cases generates steam at low pressure and, that is used either for heating or process purposes. So, heat recovery steam generator whenever we are using this particular terminology, we refer to a component from which we get steam for the production of work or electricity. So, let us go back heat recovery steam generator; I have described it in connection with the gas turbine steam turbine plant.

But it could be more general the topping gas turbine cycle is interlinked with the bottoming steam power plant through the heat recovery steam generator. Heat recovery steam generator is an is a unique and important part of this combined cycle power plant unique, because it is not present either in the gas turbine power plant or in steam power plant when we combine them, then only it I mean; we need this kind of a component and it is very important because the energy cascading can be done with the help of our heat recovery steam generator. Heat recovery steam generator contains number of heat exchangers.

So, basically it is a device in which heat exchange takes place, but that exchange of thermal energy does not take place with a single heat exchanger, there are number of heat exchangers like feed water heat exchanger for feed water heating, vaporization of water and steam super heating then in some big HRSG there will be provision for reheating steam also. So, those kind of heat exchangers and each heat exchangers each of these heat exchangers are unique.

So, many of such heat exchangers will be there. Additionally, there could be supplementary firing system and there could be arrangement for emission control. And obviously, there could be some louvers connect connection which is basically adapt so there could be proper connections etcetera and control mechanisms. So, all these things are there; this additional firing that is one important feature and in many cases the HRSG will have additional firing we will elaborate on them.

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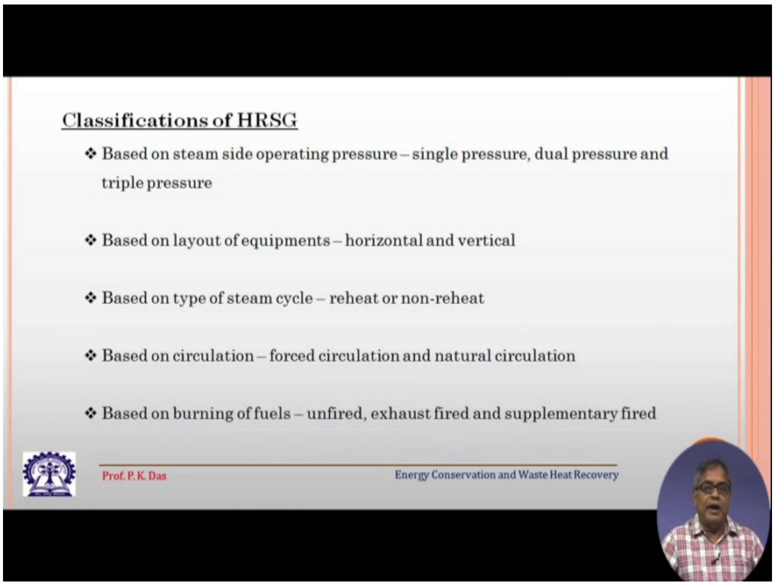

Now, HRSG is very commonly used in connection with your steam turbine, gas turbine; gas turbines, steam turbines, steam power plant combined cycle now. So, there are many variation of HRSG. So, based on this steam side operating pressure it can be described as single pressure, dual pressure and triple pressure; that means, there are 2 fluids in a HRSG. So, there is a gas which is passing over the surfaces different kind of surfaces heat transfer surfaces are there for an efficient exchange of thermal energy. And on the other side there is steam or steam water mixture, now this steam and steam water mixture they could be at different pressure. There are reasons why we go for different pressure the simplest case is singe pressure.

Then there could be 2 different pressures there could be even 3 different pressures more than 3 of course, is not right based on the layout of the equipments I told that there are number of heat exchangers and the hot gas passes through them. Now how they are arranged they can be arranged either horizontally or in vertical or in vertical direction and that will be the path of the gas. So, horizontal layout of the equipment one after another, that is, very common and we will we will try to show some figures for that based on type of steam cycle there could be reheat cycle or there could be non reheat cycle.

So, you can imagine you can well imagine that there could be many variation of the HRSG. Then based on the burning of fuel unfired, exhaust fired and supplementary fired. Let me spend some time on this. Unfired you can understand, because let us say there is a combination of a gas turbine and a steam power plant. So, we burn basically primarily we burn fuel in the combustion chamber of the gas turbine and the hot gas hot product of combustion does some work in the gas turbine, but when it comes out of the gas turbine it is temperature is quite high it could be 400, 400 degree in that range and then it has got enough kind of thermal energy to do additional work or that potential can be extracted the potential for doing work from this.

Potential for doing work from this hot gas can be extracted. So, what can we do we are sending it to a steam turbine power plant. And for steam turbine power plant we need to extract this energy in the form of a steam that is what we are doing. Now most of the cases we can do that and get this steam gets super heater steam and our steam power cycle can run, but in certain cases what happened? This arrangement is called unfired HRSG; that means whatever combustion has been taken place in the combustion chamber after that only we are extracting heat from the hot gas and no further combustion is taking place out of HRSG the hot gas is going and released to the atmosphere.

So, this is the first kind of HRSG what one can think of. The second one which one can think of is that combustion is not complete in the combustion chamber the gas, hot gas which is coming that might have some amount of fuel let in it. So, a second round of combustion without adding any additional fuel in the HRSG or after the gas has come out of gas turbine is possible and this is called exhaust fired this is not very common, but this is an option. The third one which is another option and which is again exploited in many of the applications is that supplementary fired. What is supplementary fired? Let me explain little bit. What is supplementary fired and what are its pros and cons?

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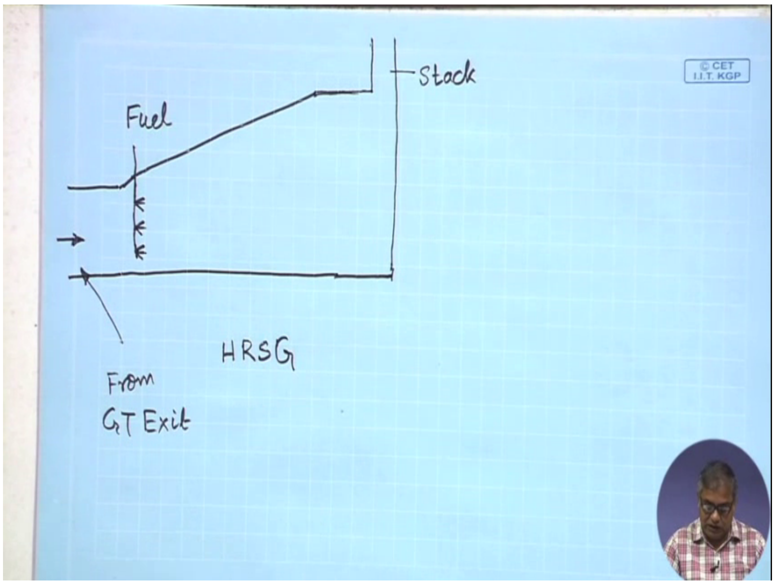

So, a horizontal layout of a HRSG looks like this.

So, from this side we have got from this side we have got gas from the gas turbine exit. So, this is from GT exit, and then it passes through this there are heat exchangers I am not drawing them and this is the stack. So, here what we can do we can have some amount of fuel injected; injected I am telling, because liquid fuels are quite common. So, that is why I am telling fuel injected, but in principle any kind of fuel can be burnt and some additional fuel is bunt.

So, what will happen rarely sometimes some additional air could be taken also it required. So, what is the effect of this so; obviously, this will increase the temperature of the gas and it will also increase the volume of the hot gas, because of this combustion.

So, we will have the advantage that, now we can generate more power from the bottoming cycle. We can have more variation of the steam power cycle which is our bottoming cycle and we can generate more power. Now let us say the exhaust exit point of the gas turbine that gives us a temperature of 420, 430 degree Celsius by this additional fuel by this burning of additional fuel we can go up to 600 degree or even higher than this. So, you see the steam cycle efficiency can be increased by burning this fuel, because we can go for higher temperature of the steam cycle higher degree of superheat for this applied steam we can go and more power we can generate.

Now, the point which we have to remember that by burning this additional fuel the combined cycle efficiency does not increase rather it decreases, but it gives more power, that is, why in many cases this additional fuel firing is there; and particularly, when we will have combined heat and power generation which we have not discussed so far, but we like to discuss in some of the coming lectures, there this additional fuel firing is really beneficial. So, depending on the cycle designs depending on the plan design and requirement of power, etcetera. So, we can have this additional firing and; obviously, it gives more flexibility in operation not only it increases the power generation, but also it gives more flexibility of operation.

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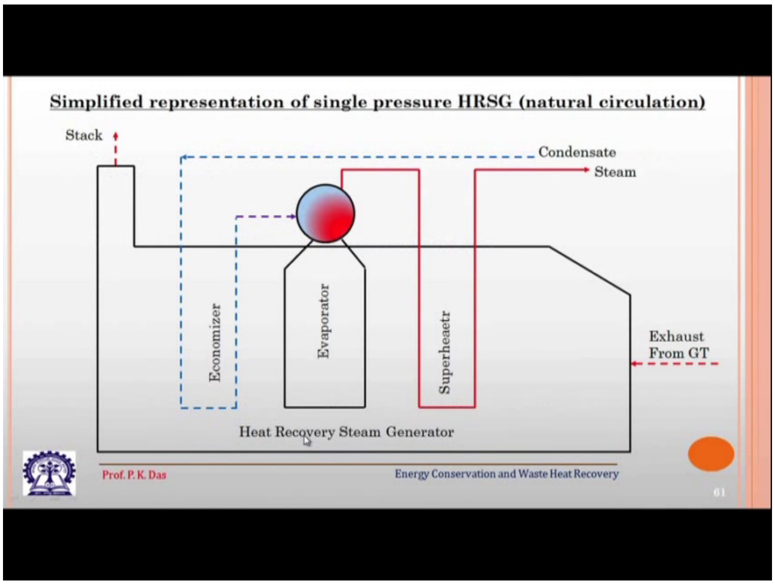

So, I think we will stop over here. And then we will go to these descriptions of description of different kind of HRSG in our next class.

Thank you.