IC Engines and Gas Turbines
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Lecture – 32
Closed Cycle, Multi-Spool Arrangement, Steam Power Plant

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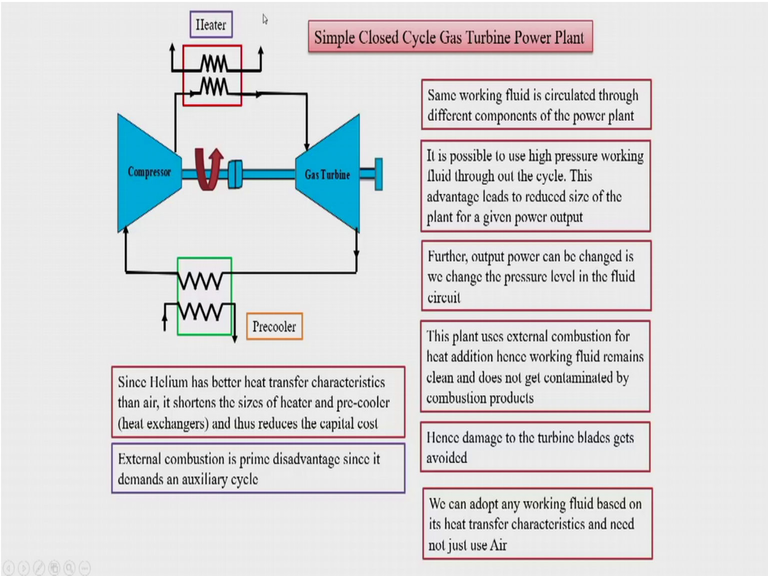

Welcome to the class. In last class, what we had seen was about the open cycle gas turbine power plant, what are the different possible arrangements for open cycle gas turbine power plant. In that case, we had seen that how conventional fuels like liquid and gaseous fuels are used in open cycle gas power plant, and if we want to have a solid fuel as a choice, then how arrangement would be changed. Before that we had also seen that why combustion chamber is necessary, and how we can integrate different components of gas turbine power plant to make it as a single entity.

And we had seen its difference with conventional IC engines which are petrol and diesel based, where we are having all the processes, thermodynamic processes of the power plant getting done in the same component, but in gas turbine we have separate components for separate processes.

We had majorly seen in last class about the twin shaft arrangement and which is helpful for taking care for the case, where we want variable operational requirements. In some case we want high load, in some case we want high speed, then the same power plant should take care. So, for that we have seen that there is a separate shaft which connects to the turbine and that complete entity is called as gas generator. And then there is a separate shaft which is coupled with a turbine is called as power turbine, and shaft is called as free shaft.

Then we had seen complex arrangements which are with intercooler, reheater and heat exchanger. We had also seen the limitation of heat exchanger. Now, having seen those things, we are now moving towards the simple closed cycle gas turbine power plant. In case of simple closed cycle gas turbine power plant, obviously, what components we would have are compressor and gas turbine. And then we have inlet of air to the compressor, and then it would go into the heat exchanger or which is called as a heater.

In this case for closed cycle gas turbine power plant and that heated air will go to the inlet to the gas turbine. And then it will come out from the outlet of the gas turbine and it would be passed to the compressor. But this air is hot, so we want to cool this air before passing to the compressor. Then there is a precooler which is coupled with a closed cycle gas turbine power plant. So, this arrangement which has compressor, heater, gas turbine and precooler is a simple closed cycle gas turbine power plant.

Here, what we can clearly see that the combustion chamber is bypassed. Now we have a heater. And in case of open cycle gas turbine power plant the exhaust was directly from the outlet of the gas turbine, but now here we are having air getting circulated into the complete circuit. So, this is a layout of simple open closed cycle gas turbine power plant. So, the circuit of air gets closed. So, it is a closed cycle gas turbine power plant.

Then there are many advantages of these closed cycle gas turbine power plant. One major advantage is that we have working fluid which is same which is passing through all components. In case of open cycle gas turbine power plant, we had air in the compressor which will get compressed then that air was supplied to the combustion chamber and in the combustion chamber fuel was burnt in the air. So, there onwards I used to say it has as a gas at the inlet to the gas turbine and gas at the outlet to the gas turbine.

So, there is air in the compressor, but there is a mixture of combustion products in the combustion chamber and in the gas turbine, but it is not true for the closed cycle gas turbine power plant. We have air in the compressor, we have air in the heater, we have air in the gas turbine and we have air in the precooler. So, same working fluid gets circulated throughout the complete power plant. One major advantage over here is that the working fluid here can be raised by its pressure in the complete circuit to the desired value of ours or to the requirements of ours.

In case of open cycle gas turbine power plant, we had air coming at the inlet to compressor that was from atmosphere. So, we had an atmospheric inlet or we generally have an atmospheric inlet for air to the compressor in case of open cycle gas turbine power plant. But in closed cycle gas turbine power plant, we can have air at any pressure of a or rather of the desired pressure of ours to the inlet of the compressor. And then it means that the pressure in the complete circuit can be different from that what we can think, in case of open cycle gas turbine power plant.

But since we can take any pressure, we can increase the pressure. Increase the pressure of the gas means we have to increase the density of the gas. Since, we are increasing the density of the gas, the size of the gas turbine power plant decreases. So, this is one advantage of open cycle gas turbine power plant, where we can use high pressure working medium, and it would ultimately lead to lower size of the power plant.

Here, if we want to change the work output, in case of gas turbine power plant of open kind, we had different settings to do with that or in if it is a single shaft arrangement then its fixed power kind of arrangement. But here, it is very simple to change the work output of the gas turbine power plant, we have to change the operating pressure of the circuit. So, if we can change the circuit pressure of the working medium, then we can have different work outputs from the same power plant. So, working pressure of the circuit becomes governing parameter for the power output of the closed cycle gas turbine power plant.

Here, we have one more advantages, what we had seen in earlier case in case of open cycle gas turbine power plant with solid fuels, in case of solid fuels, we had heat exchanger, in case of open cycle gas turbine power plant. Same concept is applicable over here. Here, we can have choice of our fuel. We can use any kind of fuel. There is no problem in choice of fuel, in case of closed cycle gas turbine power plant.

So, here what would happen is we are having external combustion in case of closed cycle power plant. Since, we are having an external combustion. External combustion leads to combustion products and those combustion products would be passed to the heater, and they will pass their heat to the air which is coming from the outlet of the compressor. So, there are heaters of such arrangements which are based upon the external combustion.

So, these closed cycle power plant is basically an external combustion engine and since we are having external combustion inbuilt advantage. What we can get is that we are not having mixing of the combustion products with the working medium of the power plant and since we do not have that problem. We are having higher life of the turbine blades and since we are having higher life we can use the power plant for longer duration. We have this problem due to lesser amount of erosion in the gas turbine blades.

There is one more thing which is coming into the advantage bucket of the gas turbine power plant and that is here we can choose the working medium. In case of open cycle power plant, we had fixed air as the working medium since air was getting compressed and air. Since it has oxygen as the natural oxidizer would get burn in the combustion chamber, we had air as the compulsory working medium for open cycle gas turbine power plant. But in closed cycle gas turbine power plant, we do not have problem. We can use any working medium. And since we have choice of working medium, we can opt for the working medium which has better heat transfer characteristics than our air.

So here, we have helium which has better heat transfer characteristics than air. And if we use helium for an operational fluid or as an operational fluid for the gas turbine power plant, it would also lead to lower sizes of the heaters, since it has higher heat transfer characteristics. So, it will get heated quickly or efficiently. So, we do not need big heater which would otherwise be required for air like gases. Thus it reduces the heater size and it would reduce the capital cost of the power plant.

One more point to be noted over here the combustion chamber in case of open cycle power plant is replaced by the heater. And since in open cycle power plant there was direct exhaust to the atmosphere, so there was no precooler. So, this entity precooler is also a heat exchanger, but here heat exchange is taking place between the exhaust of the turbine which is air high temperature low pressure air to the medium through which we are transferring heat in the precooler. So, precooler which was not there in open cycle power plant is getting introduced into the closed cycle power plant.

And having better heat transfer characteristic fluids we have efficient heater and precooler. So, we have lower sizes of theirs and we have lower cost. Heater and precooler, they are heat exchangers. Again I should repeat at this point, but there is one advantage, one disadvantage of this closed cycle gas turbine power plant. We are having external combustion over here. And since we are having external combustion over here we need to have a heat exchanger and that heat exchanger is associated with some cycle, here we mean cycle by the process in which heat transfer takes place in the heater.

Here, the heater will have working fluid which is passing its heat to the air, but it will go out of the heater, and it has to lose its heat to some agency, to some medium, and then again come back into the heater. So, this cycle is what we are referring as heater cycle. Similarly, in case of precooler the working medium of the precooler will take the heat from the air which is low pressure high temperature air from the gas turbine and then since it is heated, it is to get cooled. Again it will come into the precooler. So, these two precooler and heater auxiliary cycles are the requirements for closed cycle gas turbine power plant.

There is one more disadvantage that since heat is not transferred directly it through the process of combustion in air. We are having heat transfer which is taking place between two fluids through a medium, which are the surfaces of the heat exchanger, which is a precooler or heater. But, if we see for heater then there is maximum cycle temperature, maximum temperature in the cycle would attain in the heater. So, the upper limit of the cycle temperature would get set by the material used in the heater. So, if we get better materials, we can go for higher temperatures of the working cycle. So, this is about simple closed cycle gas turbine power plant.

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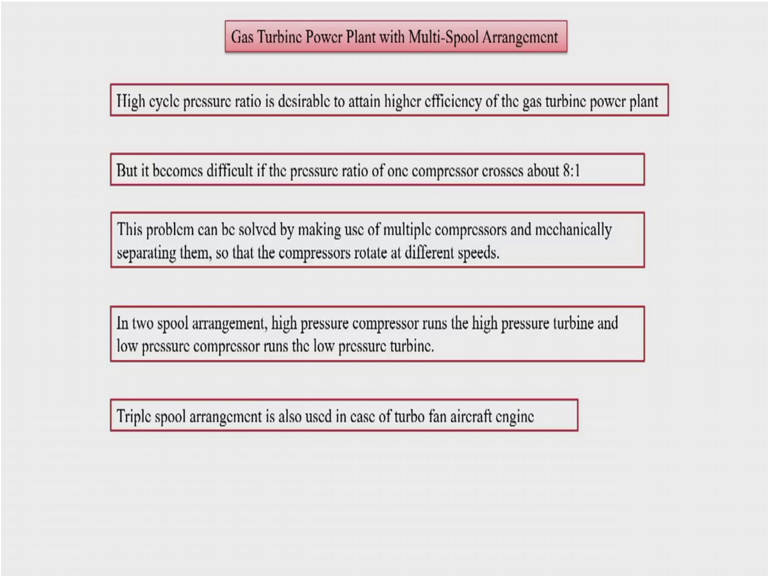

Then, we have one more arrangement of the gas turbine power plant, which is called as a multi-spool arrangement. In case of multi-spool arrangement, we see that we know that if we have higher pressure ratio of the cycle, in case of gas turbine power plant. Then higher pressure ratio leads to higher efficiency of the cycle. But higher pressure ratio demands that we need to go for higher compressions in the higher amount of compression in the compressor and if we decide to use only one compressor, which would let us go for the pressure ratio which is more than it.

Here, again I will recollect that pressure ratio of the cycle or compressor. We mean at this moment by the pressure at the outlet of the compressor to the pressure at the inlet of the compressor. So, this pressure ratio if it is increased about more than 8, then it is difficult to use or engage only one compressor to get the desired compression ratio, and hence the desired power output, and hence the desired efficiency.

So, if it is not possible, then what to do, but this problem can be solved if we use multiple compressors, and not just use of multiple compressors, but by use of mechanically decoupled multiple compressor. So, each compressor would run at different speed and would generate different pressure ratios, and all such compressors when we club together, then we get the desired pressure ratio of ours for the complete cycle. And then we expect higher efficiency and higher power output. In case of two spool arrangement, it is a multi-spool arrangement as what we see for the title of this slide.

So, in case of two spool arrangement, there will be two shafts. And we have seen that we have two compressors strength, one is higher pressure compressor and before that is low pressure compressor. So, there will be two shafts connected with two compressors, but in the case of low pressure compressor it will be run by low pressure turbine; and in case of high pressure compressor, it will be run by high pressure turbine. So, there will be two shafts.

But there is possibility of three spool arrangement also, and that possibility is, in case of aircraft engine, which is turbo fan engine. In case of turbo fan engine, if we have two compressors, then we have fan, two compressors and then we need three turbines, where in which fan will be run by one turbine, low pressure compressor will be run by one turbine, and high pressure compressor will be run by last turbine. So, this will be the arrangement in case of three spool arrangement.

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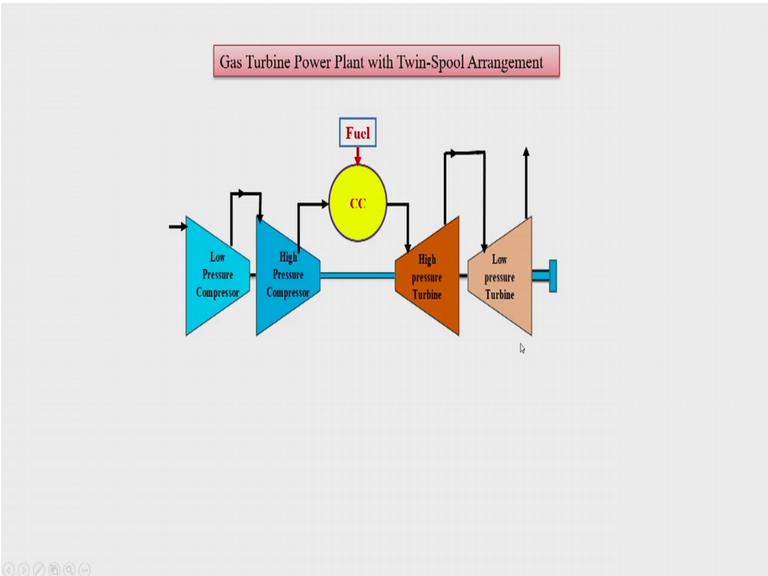

So, how would be the arrangement, in case of two spool arrangement, we have low pressure compressor, and we have low pressure turbine connected with a shaft. But then, we have high pressure compressor, we have high pressure turbine connected with some other shaft. So, these shaft will pass inside each other. So, this is an hollow shaft which is connecting high pressure compressor and high pressure turbine, which is again having a low pressure connection passing through it.

Then we have air which is coming inside in case of open cycle gas turbine power plant, we have air which is coming into the low pressure compressor. It will be passed through the high pressure compressor, then we will have combustion into the combustion chamber then that combustion product will go to the high pressure compressor, then it will go to the low pressure compressor and then it will go to the exhaust. So, such an arrangement is called as twin-spool arrangement ok. So, here we can get power output from the low pressure turbine, there is no problem.

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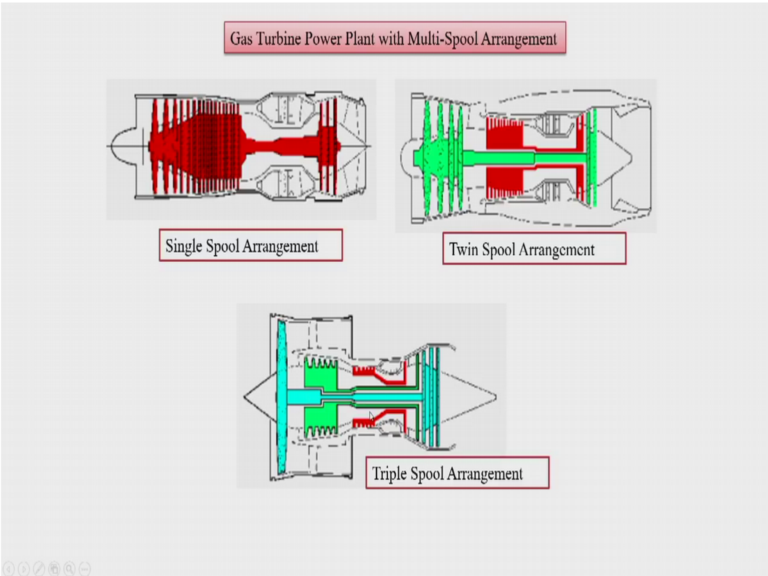

So, we have multi-spool arrangement as what we can see single spool arrangement. This is a single spool arrangement where there is a compressor. It is connected with a turbine using the single shaft. So, there is only one shaft. So, this is turbine, this is compressor, they are connected by single shaft. So, it is called as single spool arrangement.

But in case of twin-spool arrangement we have two compressors, we have initially low pressure compressor is green in color, it is connected to the low pressure turbine which is again green in color and their connection is a green shaft. But, we have different color for high pressure compressor, and then the shaft and the high pressure turbine. So, we have high pressure turbine is connected with high pressure compressor by a different shaft. So, this arrangement is called as a twin shaft arrangement, but there is a triple spool arrangement in case of this, this arrangement is called as twin-spool arrangement not twin shaft arrangement.

So, in triple spool arrangement, we have first as an example we have here fan, and this fan is connected with the low pressure turbine. Then we have compressor which is a low pressure compressor, which is connected with intermediate turbine, and we have high pressure compressor which is connected with high pressure turbine. So, each turbine is connected with each compressor, and they run each other. Their speeds are aerodynamically connected with each other, but their speed practically are different from each other. This could help us to raise the pressure ratio of the cycle, and hence to get more efficiency of the cycle.

Now, we have seen that there are some ways by which we can increase the efficiency of the cycle. What we had seen that we can increase the efficiency of the cycle by having example heat exchanger, then there is possibility of having increased efficiency by increasing the cycle pressure ratio. Similarly, we can again increase the efficiency of cycle if we use exhaust gas of the turbine to use it in other cycle. Then that gas which is coming out of the exhaust of the turbine would be used as a heat source for some other cycle, and that other cycle which we consider over here is a steam power cycle or it can be used in a steam power plants.

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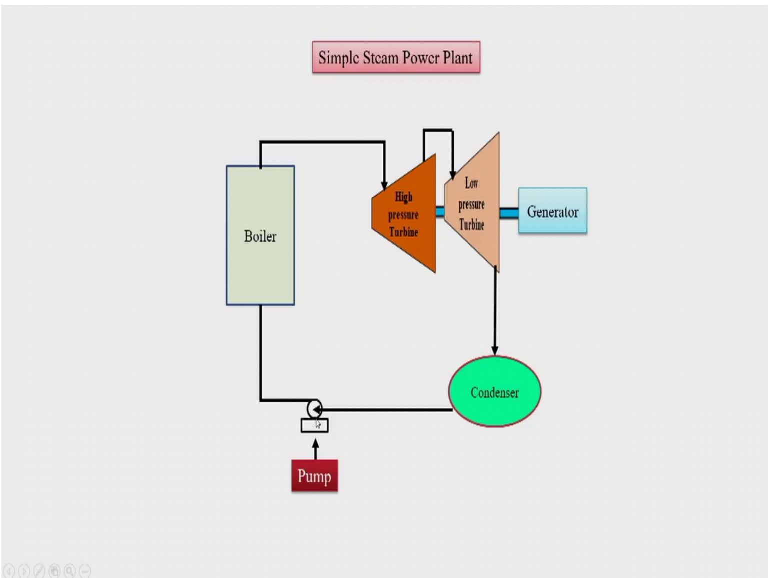

So, first we will see what do we mean by a steam power plant. In a steam power plant as we know we have high pressure and high temperature steam stored in the boiler, and this steam would go over the high pressure turbine. And then high pressure turbine exhaust is connected to the low pressure turbine, and then this low pressure turbine and high pressure turbine they are connected with a generator. Such that we can get required electricity output, but steam power cycle, they are generally closed power cycles. The outlet of the low pressure turbine is connected to a condenser. This is a difference between closed cycle gas turbine power plant, and closed cycle steam power plant.

In closed cycle gas turbine power plant, we said this entity as precooler, but it is named as condenser in case of steam cycle power plant. But then, the condenser outlet is connected to a pump which will pump the steam or which will pump the water to the boiler and by raising its pressure. So, this is a simple steam cycle in a steam power plant. Basically, here we are having steam into the turbine, but we are having phase change of the steam to water in condenser. So, we have only water into the pump. And we have both the phases as liquid and steam in the boiler.

So, we have both the phases vapour and liquid phase in the boiler, we have vapour phase in the turbine, we have both the phases vapour and liquid in the condenser, but we have again only one phase which is liquid in the pump. This is a schematic of simple steam power plant.

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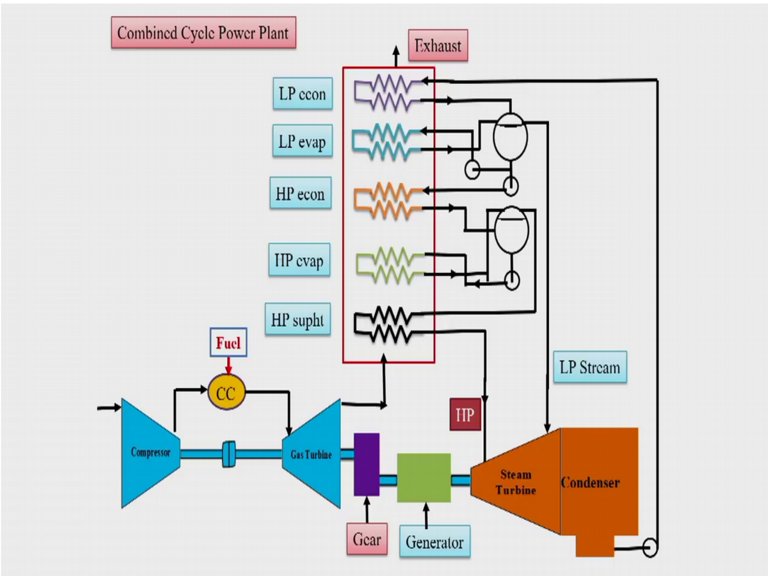

But then, when we see that we want to increase the efficiency of our gas turbine power plant. We can think of it to be coupled with a steam power plant. So, this is a little complicated diagram, but let us see how the passage is for the gas and how it helps us.

But practically what is happening over here is that there is an outlet to the turbine. And at that outlet there is a gas which is at high temperature. And if we can utilize that heat, we can use that heat for further work output of ours, then what would happen is power efficiency of the gross plant can increase.

So, for that now we are considering two separate cycles. One is gas turbine power cycle; another is steam power cycle. Now, we are combining both, so it is called as a combined power cycle. So, in case of a combined power cycle we are having first gas power cycle. So, in case of gas power cycle as we know air will come into the compressor, go after compression go to the combustion chamber interact with the fuel, get heated due to chemical reaction of the fuel, then it what would go to the gas turbine, and then it would run the gas turbine, and then it will come out as an exhaust. This exhaust here will not directly go to the atmosphere, it would pass through a heat exchanger and that heat exchanger is what we are talking as a part of steam power plant.

And in case of steam power plant, what would happen is this we have pump and this pump will raise the pressure of water and it would pass first the water into the low pressure economizer. Economizer is an entity or part of steam power plant where water gets heated before going to the boiler. As what we had seen in gas turbine power plant there we were using heat exchanger ok. So, economizer it will first go through from economizer it will come to this steam dome, and from steam dome it will go to the low pressure evaporator, such that the liquid water which has entered from the economizer would get heated and evaporated in the low pressure evaporator.

Then what would happen is it would come further and get pumped some steam. Some water rather from the drum would get pumped further to higher pressure, and it would enter into the high pressure economizer. So, this liquid water which has raised further its pressure is coming into the economizer which is a high pressure economizer, and that high pressure economizer is again connected to a separate steam drum. And then this drum is again connected to the high pressure evaporator. So, water will get evaporated which is a high pressure water which gets evaporated into the high pressure evaporator, and get settled in some portion into the steam drum which is a high pressure steam drum.

But further the steam which is present in the steam drum which is a high pressure steam drum will be passed further to heat and such heating is called as super heating. So, here the necessary steam which is required for the steam turbine as a complex path, before it is coming from the pump to the turbine. It does not just come from the boiler. It comes through a complex path into the steam turbine. And in this complex path it needs heat, and this heat is supplied by the gas turbine.

So, gas turbine exhaust would enter into the heat exchanger, it would first heat the high pressure super heater and it would heat the high pressure evaporator, then it would heat high pressure economizer then it would heat low pressure evaporator and then it would heat low pressure economizer. So, this is the path for the exhaust gas and this is the path for the steam.

Once steam comes out from this complete heat exchanger, it would get expanded into the steam turbine, and then it would go to the condenser. But, both the plants are connected with a generator. And this electricity generation would have higher efficiency which otherwise would have been generated only from the gas turbine power plant. Since, the exhaust energy which is coming from the exhaust of the turbine, we are using it to heat the water and make it to a high pressure steam.

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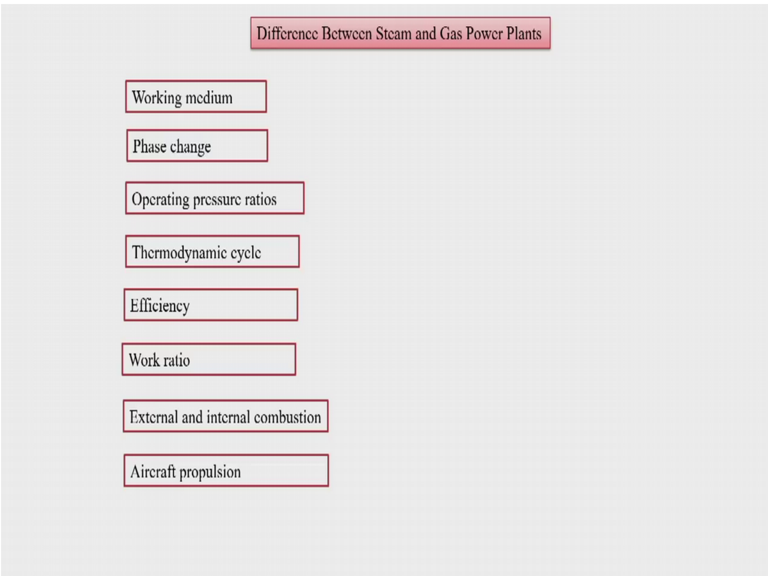

Then there is some difference between steam power plant and gas power plant. We have seen that we can use steam and we can use gas both for power generation. So, there will be some difference and that difference what we are discussing now. First difference, first difference is based upon working medium. In case of steam power plant, working medium is water. And water or we can have working medium any kind of liquid to start in the pump. But in case of gas power plant our working medium is gas or in general we have air.

So, working medium is different, but it is not just a working medium different. We had seen that in case of steam power plant there is a boiler and there is a condenser. Boiling and condensation are the process where phase transfer takes place. So, steam power plant believes upon the phase change of liquid water into the vapour in the high pressure section of the boiler.

But in case of condenser, it believes upon the condensation that is phase change from the vapour to the liquid in the condenser. So, this is the layout of the steam power plant. And with this layout pump handles only liquid, and turbine is expected to handle steam. But in case of gas turbine power plant we have compressor, which handles air, which have combustion chamber, which again handles gas, and then we have turbine which again handles gas. So, we are having only gas in the complete circuit. So, there is no phase change in case of gas turbine power plant.

Then gas turbine power plant as what we have seen they operate to the low pressure ratios. Their operational pressure ratios are something of the order 10, 20, 30, but the operating pressure ratio for the steam power plant is very high. Steam power plant boiler pressures can be 100 bar, 200 bar, 300 bar and condenses condenser pressure will be 0.1 bar 0.2 bar. So, pressure ratio is very high, in case of steam power plant. So, we are having high pressure cycle for the steam power plant, and comparatively low pressure cycle for gas turbine power plant.

So, these are the two separate power cycle power cycle. The power cycle for steam power plant is called as Rankine cycle. Power cycle for the gas turbine power plant is called as a Brayton cycle. As we are going to see later that these cycles are not having different processes, but interaction of energy is different in both the cycles. So, in case of Brayton cycle, we do not have phase change; but in case of Rankine cycle we have phase change.

Efficiency: if we start talking about efficiency then in general for the same work output, we have higher efficiency for the steam turbine power based power plant which is a steam power plant as compared with the gas turbine that has to do with the network output. In case of steam turbine power, we are having steam power plant, we are having pump and pump handles liquid. And since it is handling liquid, it needs lesser work input to raise the pressure of the water.

But in case of air we need larger work input, and that larger work input would get subtracted from the turbine work so as to get the network. By network we mean over here is the turbine work minus the compressor work or turbine work minus the pump work. So, pump work is negligible and turbine work is too large that makes the steam turbine power plant more efficient for having same for having more efficiency for same heat input.

Parallelly there is one more advantage of steam power plant which is called as work ratio. Steam power plants have higher work ratio and that work ratio by work ratio we mean over here is w net upon w t where we mean turbine work. So, network upon the turbine work this ratio is called as work ratio. In case of steam turbine power plant, since pump working is less, we are having work ratio very high; but in case of gas turbine power plant work, we have compressor work very large, so we are having work ratio lesser than much less than work 1, but in case of steam turbine power based power plant or steam power plant work ratio is closed to 1.

This gives us one indication. And what indication it gives us? That we are going to see down the line again, when we see thermodynamic cycle that if work ratio is higher, then what would happen is the cycle becomes less sensitive to the component efficiencies. Now, what do we mean by this statement? Here, we are having compressor and turbine as components and they are real components. So, they will have some efficiency which is not 100 percent. So, they are having efficiencies lower than 100 percent. So, now, turbine and compressors have efficiencies which are lower than 100 percent, and during the operation of theirs, their efficiency is decrease. If compressor and turbine efficiency decreases, then whole cycle efficiency would also decrease.

But what is the percentage alteration, what is the impact of change in efficiency of components on the cycle efficiency is what we are talking about. In case of steam power plant, if cycle efficiency we are trying to see, then it becomes less sensitive to the component efficiency means if components like pumps and turbines have reduced their efficiencies, but it does not alter much the efficiency of cycle. However, in case of gas turbine power plant, it is not the case. Since, its work ratio is lesser, lesser than 1, we have the efficiency of compressor and turbine having an impact on the cycle efficiency.

So, these are the some differences for the steam turbine and gas turbine based power plants. In case of gas turbine power plants as what we have seen if we are working with open cycle, then we can combustion chamber. And since we are having combustion chamber, we can adopt the internal combustion process in the open cycle gas turbine power plant. But in case of steam power plant, we are bound to have external combustion process, and then we have to have heat exchanger. But it is possible in gas turbine power plant that we can have basically external internal combustion as well as external combustion.

So, we have one more difference that, now, when we see the working medium difference as what we have steam or water, liquid water in present in the pump and gets circulated, it becomes steam in the boiler, and it remains steam in the turbine. So, there is water in steam power plant, and then there is gas in gas turbine power plant, and so water practically has very high density than the density of the gas. So, what would happen is the working medium which we are handling is very high density in case of steam power plant, so the plant becomes bulky.

Since, this plant is becoming bulky we generally avoid steam power plant for we cannot use rather steam power plant for air craft applications. However, gas turbine power plant is having major advantage that it has gas as working medium, and it has lower weight due to its not lower density, and we have it possibly to be connected with air craft for air craft operation. So, these are the differences between gas turbine power plant and steam turbine power plant and steam turbine power plant. So, here we end our class where we had seen that how are the arrangements of the open cycle based gas turbine power plant, and how we can have multistage compression achieved, rather multiple compressors connected with each other using multi-spool arrangement.

Further we had also seen that it is not just the pressure rise which is helped us to give the higher efficiency, but we can as well go with a combined cycle approach, and increase the efficiency of the gas turbine, and then overall gas turbine connected with steam turbine, the combined cycle efficiency will increases which otherwise would have been lower if we would have used only gas turbine power plant. And then since we have to use combined cycle for increasing the efficiency, we have seen how is the steam power cycle, what is its composition, and what are the basic differences between steam and gas turbine power plants.

Thank you.