Aircraft Propulsion

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Lecture 04
Gas Turbine Power Plant

Welcome to the class, in this class we are going to study about the components of a typical gas power plant and also what can be the proposed attachments for a gas power plant. Our aim over here is to study about a general gas power plant which might be used for aircraft applications or may be used for electricity generation. So, any of this today's class we are going to see about what would be the basic component which will constitute or comprise a gas power plant.

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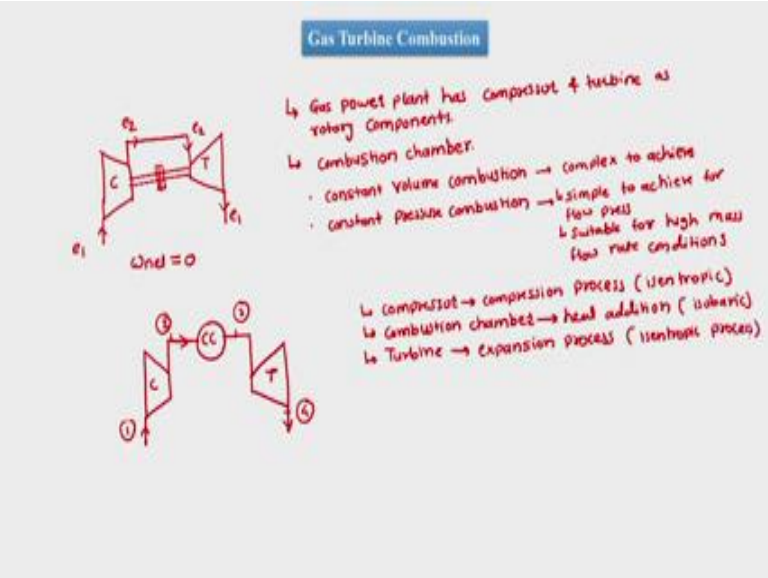

So, as we have seen that turbine and compressor two are the major components of a gas power plant. So, suppose we consider that there is a gas power plant in which there is a compressor and it has air which is entering with velocity certain velocity such that energy at the inlet to the compressor is e1. then the in energy and the outlet to the compressor is to such air is then passed directly in an ideal case to a turbine and then turbine receives energy E 2 and then it expands the air and then we have air at energy E 1 at the outlet and then these two practically as expected would be connected to each other.

In this case what we see this is the energy difference in case of compressor and energy difference in case of turbine with an ideal components of turbine and compressor leads to have zero value. Since energy difference is zero we do not have any net work output. So, in this particular case we have net work is equal to zero. So, this means we just do not have compressor and turbine as components of a gas power plant.

So, gas power plant has compressor and turbine as compressor and turbine as rotary components then there is also combustion chamber. So, in case of combustion chamber then there are multiple options one option is that as in case of our SI engines where we use petrol as fuel or gasoline as fuel we say that the combustion in such a SI engine which is based upon Otto cycle is constant volume. So, there is an option of constant volume combustion.

Constant volume combustion is very effective the constant volume combustion would lead to good efficiency if it is working with a given pressure ratio. So, initially it was expected that the gas turbine power plant would be built upon a concept of a combustion chamber which would lead to be constant volume combustion. But it needs a very specific arrangement where we need to have a closed volume in which combustion will be taking place. So, we need to have valves and associated arrangement for closing and opening of the valves such that we can have constant volume combustion.

But the problem of making such combustion chamber has led to development of gas turbine with constant volume combustion. Although in initial days of investigation of gas turbine power plant few engines were developed where there was constant volume combustion. But constant pressure combustion is normally used since constant pressure combustion has nice convenience in the flow process. So, we know that all the components of a gas turbine power plant are open systems.

So it is a flow process so constant pressure combustion is a good thing to get executed in a flow process. Further constant pressure combustion actually is helpful for higher mass flow rates. So, this constant volume combustion is complex to achieve constant pressure combustion is simple to achieve for flow process and then it is suitable for high mass flow rate conditions.

Hence constant pressure combustion is generally preferred in case of gas turbine power plants that is why we have a typical gas power plant comprised of a compressor and then we have a combustion chamber and then we have a turbine. So, this is what a general gas turbine power plant which is generally used for aircraft application. So, we have 1 to 2 as compression process 2 to 3 as combustion process and 3 to 4 as the expansion process in the turbine.

Hence here as what we can see we have compressor, for compression process here we have combustion chamber for heat addition process this is isentropic process. We have heat addition it is isobaric process and then we have turbine for expansion process and then this is also isentropic process. Here we are assuming that heat is rejected to the atmosphere by the mass transfer to the atmosphere and same mass is entering at lower temperature into the compressor.

So, practically here we are having three different components for three different processes which is unlike in case of a in case of a reciprocating compressor in case of a reciprocating engine. In case of a reciprocating engine we have only piston and cylinder arrangement and that piston and cylinder arrangement is going to give you all the processes.

Piston is going to compress the gas and then there will be fuel injection into the cylinder and then the high-pressure fluid will exert a force on the piston and then motion of the piston would lead to expansion of the gas and then opening of the valve will lead to the flow go out to the atmosphere. So, unlike reciprocating engines gas turbine engines have separate components for separate processes.

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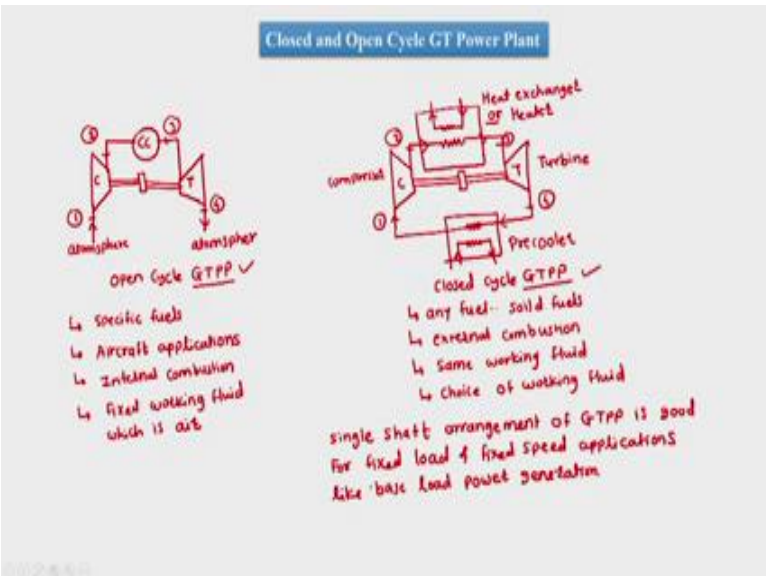

Now we will see what are the types of arrangement, basic arrangements for a gas turbine power plant, first arrangement is what we have seen is a open cycle gas turbine power plant in case of open cycle as what we mean this cycle is not closed where the exhaust from the turbine is not going to come into the combustion to the compressor again. So, this turbine is exhausting into the atmosphere and then this compressor is taking from the atmosphere.

So, this is state 1, this is state 2, this is state 3 and this is state 4. So, this is an schematic of open cycle gas turbine power plant. Now there would be some limitation of this open cycle power plant as this power plant we need to have specific fuels. We cannot use any fuel with this construction of the conventional open cycle gas power plant. We have specific fuels this is more applicable for aircraft applications.

Now we will see that what would be the arrangement for closed cycle gas turbine power plant. In case of a closed cycle gas turbine power plant we first will have air coming to the compressor and then we will not have combustion here but we will have heat transfer and then this heat transfer is basically heat addition at isobaric condition. And then we have turbine, this turbine is having an exhaust which is further passed into a heat exchanger and that will cool down the gas and then the same gas is transferred to the compressor.

So, there is separate arrangement which would give heating process and then there is a separate arrangement which would give a cooling process. So, this is a heater and this is a pre cooler this is called as pre cooler and this is state 1 this is state 2 this is state 3. So, 2 to 3 is called as heat exchanger or heater, 3 to 4 is turbine and 4 to 1 is pre cooler and 1 to 2 is compressor. So, this is an closed cycle gas turbine power plant and this closed type cycle gas turbine power plant can accommodate any fuel.

Mainly it can accommodate solid fuels which are not generally used for the applications of gas turbine power plants. So, here we can basically have external combustion means the gases which are combusting would not pass over the turbine and which are not directly involved in doing the net work. So, this is an external combustion while open cycle is practically an internal combustion engine.

So, here we can use any fuel, further same working fluid is passed in the circuit so we have choice of working fluid in case of closed cycle gas turbine power plant. However in case of open cycle gas turbine power plant we have fixed working fluid and then that is air which is air. Here we can choose the arrangement for the particular use of a fuel. Then we have these arrangements which are single shaft basically all both arrangements of open and closed cycle gas turbine power plant are shown over here a single shaft arrangement.

And then such arrangements are good for fixed load. So, single shaft arrangement of gas turbine power plant is good for fixed load and fixed speed applications like power generation, base load power generation. So, they are the two basic arrangements of a gas turbine power plant. Here we can have further thinking about a 2 cycle gas turbine power plant.

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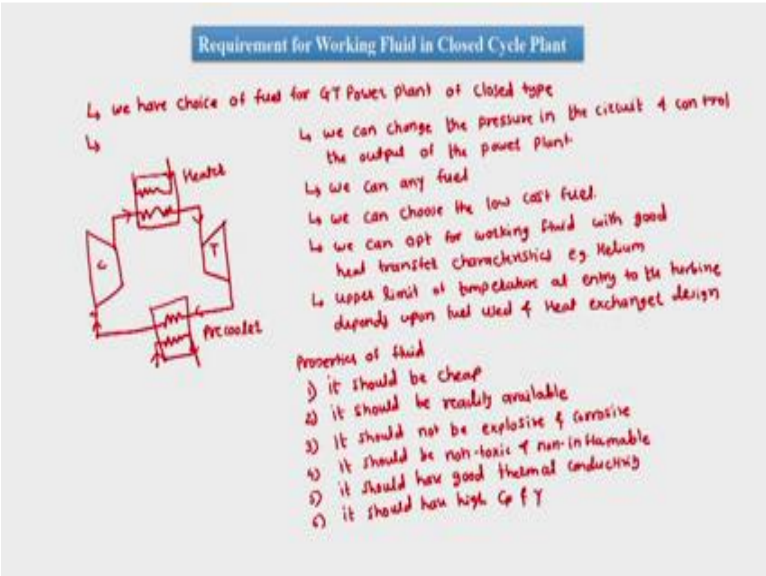

Now in case of a closed cycle gas turbine power plant as we have said we have choice of fuel for gas turbine power plant of closed type. Then in case of in such case we have seen that this arrangement of gas turbine power plant where we have turbine pre-cooler compressor and heater. So, this is heater this is turbine this is pre-cooler. Here this complete circuit has one working medium and then we can change the pressure in the circuit and control the output of the power plant.

This facility is not available for the open cycle gas power plant. We always get air at the inlet to the compressor at the atmospheric condition. So, here the air at the inlet to the compressor can have different pressure which we are going to set. And based upon that we can change the output of the power plant we can use any fuel. And then here we can choose the fuel, basically we can choose the fuel which is a low cost fuel also.

And this low cost fuel if we choose then that fuel upon getting combusted would generate the gases which are not going to get involved in expansion process of turbine and then hence what would happen is the turbine erosion is not going to happen. So, we can have this choice further we can opt for working fluid with good heat transfer characteristics. And such fluid is example helium, so if we use helium as the working medium for the gas turbine power plant then the gas turbine power plant can become compact and it can become more efficient.

However the upper limit of temperature at entry to the turbine depends upon the fuel used and the heat exchanger design along with the fact that there is certain limitation upon the material which is used for the gas turbine design. So, having said this we have specific requirement about the working fluid and then that working fluid what we are talking about in case of the open cycle gas turbine power plant is that such fluid which is used for the circuit of the open cycle gas turbine power plant should be properties of such fluid properties of fluid one it should be cheap.

Second it should be readily available, third it should should not be explosive and corrosive. It should be non toxic and non inflammable, fifth as I said earlier it should have good thermal conductivity for heat transfer. And it should have high Cp and gamma. Here we mean Cp a specific heat at constant pressure and here we mean gamma as the specific heat ratio. So, as we know helium is a mono atomic gas and it has highest gamma as 1.66.

So, helium is a good component good gas for universal cycle gas turbine power plant having said this we are going to see what are the other attachments for the gas turbine power plant.

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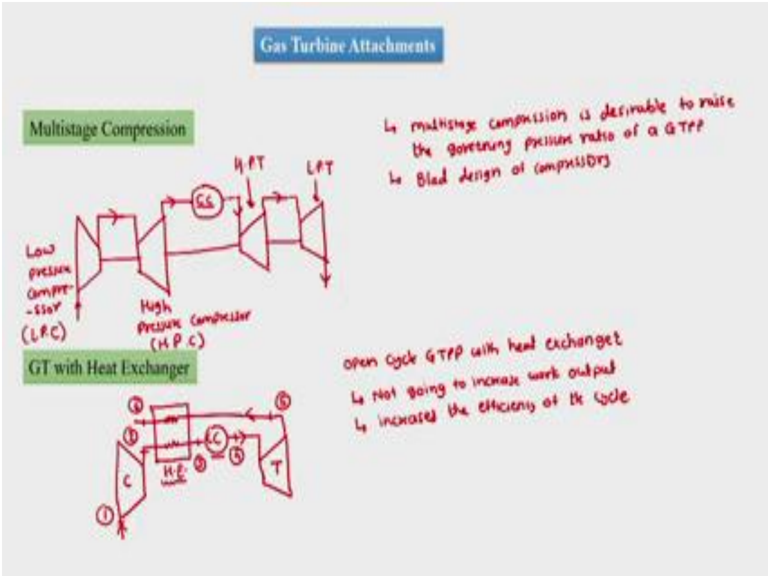

One such attachment is multistage compression here we know that output or efficiency of a gas turbine power plant depends upon the working pressure ratio but if pressure ratio is increased then there would be a problem in the flow for the flow into the compressor. Hence we cannot use single compressor for rising the desired pressure so instead of that further to have higher pressure ratio to achieve we can use the multi-stage compression.

And in multistage compression we are basically using multiple compressors and those compressors are at this moment called as low and high pressure compressors. So, this is a specific arrangement where we are having turbine connected with multiple compressors. So, this is called as low pressure compressor and then this is called as high pressure compressor so this is also named as HPT this is also named as LPHPC that we see this is LPC then it is LPT this is high pressure turbine.

And then this is low pressure turbine and then this is combustion chamber. So, we can use multiple compressors for achieving the high pressure ratio in a gas turbine power plant. However multistage compression is desirable to raise the governing pressure ratio of a gas turbine power plant. But Blade design of compressors become critical in the design of a multi-stage compressor and then if we can properly design the multi-stage compressor blades then we can achieve high compression ratio and then higher efficiency of the gas turbine power plant.

Then we have gas turbine power plant with heat exchanger this arrangement is very specific about the open cycle gas turbine power plant. In case of our open cycle gas turbine power plant we first have compressor and we let the gas go out we let the gas go out into the atmosphere from the turbine but here we will not let do that happen and the gas which is going to go to that atmosphere will be first used to heat the air which is to be passed to the combustion chamber.

So, the process is like this here first the air will get compressed from the station 1 to 2 in the compressor and in the process 2 to 3 air will get heated into the heat exchanger before it gets combusted in the process 3 to 4 into the combustion chamber. Then it gets expanded in the process 4 to 5 into the turbine and then the gas at state 5 which is at high temperature and low pressure would heat the air which is coming to the combustion chamber and which is at high pressure and low temperature the gas would lose its enthalpy from station 5 to station 6.

So, the such arrangement is called as open cycle gas turbine power plant with heat exchanger and obviously this is this is not going to increase the work output but this increases efficiency since we are actually losing the heat which ah otherwise we are actually losing the heat which is going from the outlet of the turbine. But in such case we are utilizing the heat so we are recovering the heat which is getting lost.

This is one way to see at it further way what we can see if heat exchanger would not have been there then there would have been combustion starting at the temperature which is the compressor outlet temperature. But we are now heating the air which is entering into the combustion chamber using a heat exchanger. So, combustion will happen at elevated temperature. So, heat addition would happen actually at elevated temperature.

So, from the basic thermodynamics since we are adding heat at higher temperature efficiency of the cycle will increases. So, this increases the efficiency of the cycle. So, we have seen that there are two possible arrangements but heat exchanger arrangement is generally used at low operating pressure ratios of the cycle since this has a lot of friction loss and it practically reduces the work output.

Although it does not reduce as what we see in case of ideal, but in case of actual there is reduction of work output with heat exchanger due to pressure loss in the process of heat exchange.

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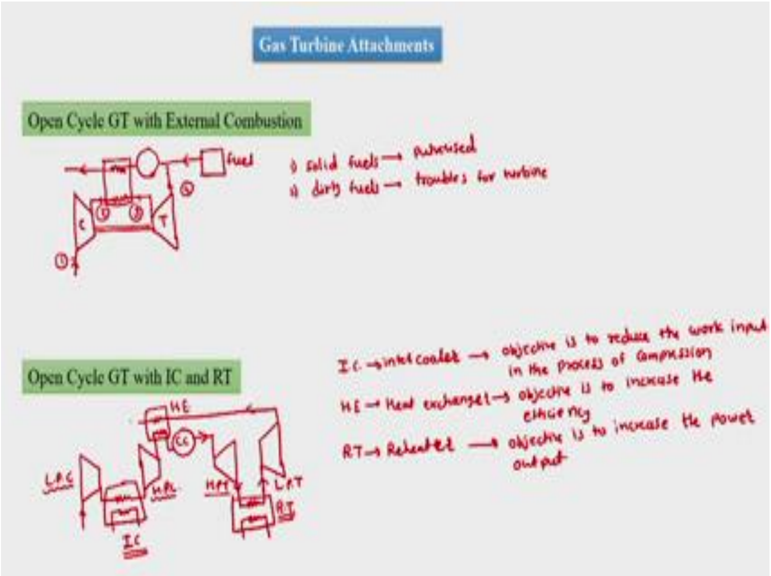

Then we have some else arrangement and then first arrangement is with external combustion. The same arrangement as what we have thought for the open cycle gas turbine, close cycle gas turbine power plant can also be thought in case of open cycle where we have compressor and then that compressor would not be having any internal combustion but it will have heat which is transferred and then that heat is transferred from some gas.

And so there is 1 to 2 process of compression 2 to 3 process of heat addition at constant pressure and 3 to 4 process is in the turbine but here indicated in different way that this 4 process and further this would get mixed with the fuel which is this hot gas from the combustion chamber would heat the fuel and then there will be combustion happening in the station and then such combustion would further generate the gases.

And those gases would be used to transfer the heat to the actual working medium into the open cycle gas turbine power plant. Here we can use solid fuels basically we practically mean that we can use the dirty fuels and then thus dirty fuels which would have products which are going to lead to erosion or corrosion which will lead to troubles for turbine. Here we mean that we can use pulverized coal in case of solid fuels or other solid fuels which are which are in different formats which we can use.

And then this type of arrangement is suitable mainly for electricity generation kind of applications or prime mover kind of applications for the gas turbine power plant. There is one more attachment for gas turbine power plant and then that is intercooler so we know that if we want to do compression multistage then we are providing some work input in the process of compression. But this work input should be reduced and reduced work input will practically increase the work output of the cycle.

Hence there is a method by which we can reduce the work output work input of the cycle and we can increase the work output of the total cycle that means we are here interested in increasing the net work of the cycle. And for that all sake we are trying to have low pressure compressor then we have high pressure compressor then we have high pressure turbine we have low pressure turbine here before going to that we are inserting certain heat.

So, this portion where air is getting compressed using the low pressure compressor and then further it is going to high pressure compressor. So, in between low and high pressure compressor we are going to reduce the temperature of air using an intercooler. So, here we mean IC as intercooler we know that a process of compression is achieved at the isothermal state then isothermal compression has minimum work input.

So, by this intercooler objective of the intercooler is to reduce the work input in the process of compression and then it will go to the combustion chamber but before that it will get heated into the heat exchanger. So, H E we mean that heat exchanger objective is to increase the efficiency of the cycle and then the air will go to the combustion chamber and from the combustion chamber it will get heat and then we will have air which is coming to high-pressure turbine after having high-pressure turbine expansion air will get heated either using an external heater or maybe using combustion and then that heater is called as RT so it is called as a Re-heater.

And an objective is to increase the power output of the cycle. So, once we have reheating done then air will go to the low pressure turbine and from low pressure turbine the gas will go to the heat exchanger and then it will get exhausted into the atmosphere. So, we are seeing that these two arrangements are extra these two attachments are extra for a gas turbine power plant.

So, simple gas turbine power plant has only compressor combustion chamber turbine in case of open cycle or adding to these three there will be a pre cooler for a closed cycle power plant. But we can have further attachments to the gas turbine power plant for our requirements either to increase the efficiency or to increase the work output and these attachments include intercooler, heat exchanger and re-heater. So, these are the some arrangements of gas turbine power plant.

Apart from these different arrangements of the gas turbine power plant we have different cases and one such case is called as Twin shaft arrangement of the gas turbine power plant.

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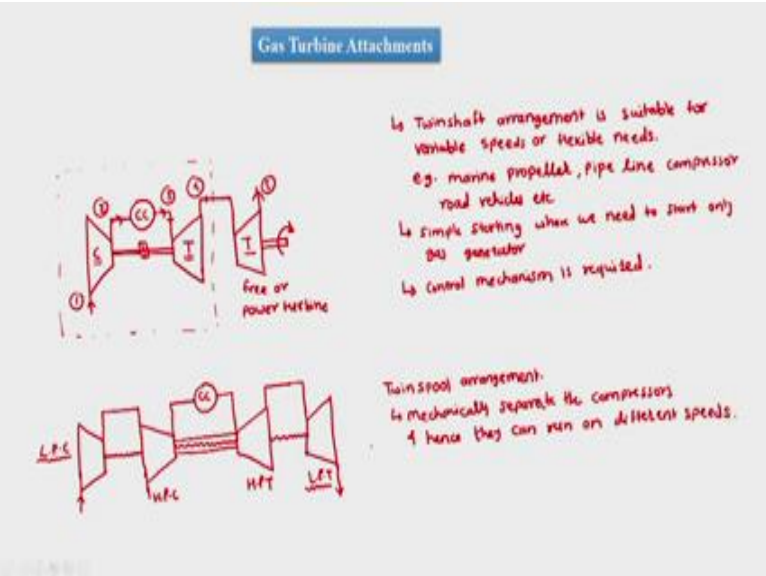

We have just now seen that there is a single shaft arrangement and that is very good for fixed load and fixed speed application but this is not always the case we might have a requirement where gas turbine would act as a prime mover and then flexible speed or flexible load would be the arrangement or will be the requirement and in such case we may need to design a gas turbine power plant which will suit for this application.

So, in such case we have an arrangement which is called as twin shaft arrangement and that twin shaft arrangement includes two shafts. So, this is compressor and then we will come into the compressor in the process 1 to 2 then it will go to the combustion chamber in the process 2 to 3. It will go to the turbine which is attached directly to the compressor and then it will get expanded in process 3 to 4 then it will pass over a next turbine which is called as free or power turbine which is mounted on a separate shaft.

And then air will go expand in that turbine in the process 4 to 5 and get exhausted into the atmosphere. So, such arrangement is called as twin shaft. Twin shaft arrangement is suitable for variable speed or flexible build our requirements are flexible variable speed or flexible needs examples of such arrangements are marine propeller. We have pipeline compressor.

Then road vehicles etc here we are thinking the gas turbine also as a prime mover that is where it is on to run the components or the machines which are based upon the input speed from the turbine. Such arrangement which is a twin shaft arrangement is specific in the applications which are variable speed or flexible speeds. We do not need any gearbox to be connected or here and further this unit where we are having a compressor, combustion chamber and turbine are connected together is called as gas generator.

So, there is a gas generator and in that gas generator provides gas to the power turbine and power turbine produces the necessary power output. So, this turbine produces the work which is just required to run the compressor and this turbine produces the necessary power output. So, the arrangement of open cycle gas turbine power plant over here is called as a gas generator. So, then we need to have simple starting process in case of twin shaft simple starting where we need to start only gas generator.

There we need to have only gas generator the problem associated with this is control. Control mechanism is required for the twin shaft arrangement since decrement of load increases the speed of the turbine and then that speed needs to be controlled. So, for that all sake this twin shaft arrangement needs a control mechanism. So, having said this we go for the next arrangement that is called as multi spool arrangement.

And in case of multi spool arrangement we are seeing that we need high compression ratio in case of gas turbine power plant and we said that multiple compressors can be used on multi stage compression can be done. But here we can have an arrangement something like this where we have different compressors run by the different turbines. So, this is low pressure compressor first, so this is low pressure compressor.

And then from low pressure compressor we will go to the high pressure compressor, this is high pressure compressor and then we have these two fixed on two different shafts. Air will then go to the combustion chamber and then it will go to the turbine this is low pressure compressor from the low pressure compressor air goes to again a high pressure compressor and then from high pressure compressor it will go to the combustion chamber from the combustion chamber it will go to the turbine.

And from the turbine which is high pressure turbine this is high pressure compressor air will go to the low pressure turbine and then it will get exhausted the basic thing which will happen over here, is that this compressor is connected to the low pressure turbine low pressure compressor is connected to the low pressure turbine and by separate shaft and high pressure compressor is connected to the high pressure turbine by a separate shaft.

So such an arrangement is called as twin spool twin arrangement and in twin spool arrangement we are having two compressors run by two separate turbines. This arrangement is useful to achieve higher pressure ratios which are required for the gas turbine power plant. Here we mechanically separate the compressors and hence they can run on different speed.

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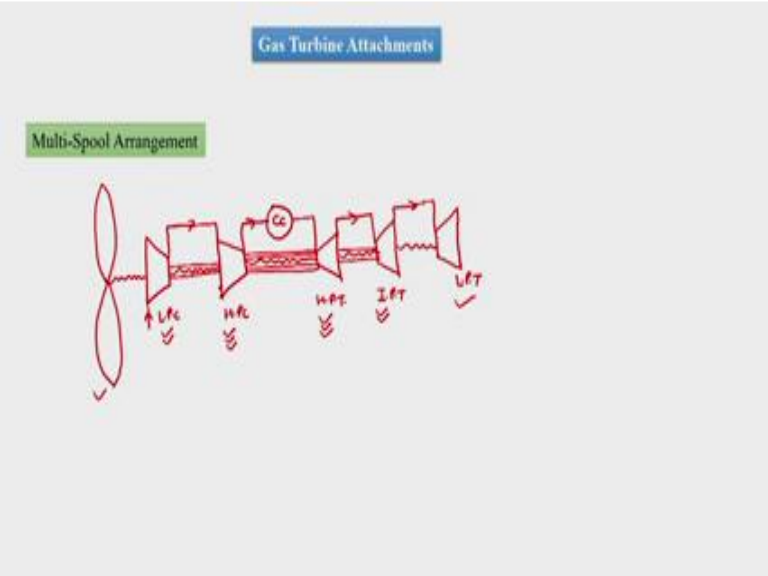

So, further after the twin spool arrangement there is an arrangement which is three spool arrangement and then three spool arrangement would again have the three compressors. Which are rather run by three turbines are in case of a turboprop engine the propeller would be run by the one turbine and two compressors will be run by the two turbines such an arrangement we can see over here.

Actually that we have first a low-pressure compressor and then air will go from low-pressure compressor to high-pressure compressor. And from high-pressure compressor it will go to the combustion chamber and from the combustion chamber it will go to first turbine which is high pressure turbine. From high pressure turbine it will go to the intermediate pressure turbine and from intermediate pressure turbine air will go or gas will go to the low pressure turbine.

Here as what depicted we would have a propeller running to be run and then this propeller would be run by the lowest pressure compressor which is LPT. And then we have low pressure compressor which will be run by the intermediate turbine and then we have high pressure compressor which will be run by high pressure turbine. So, this is a twin spool arrangement and this is a three spool arrangement which is necessary to decouple different speeds.

So propeller would run at a speed which will be catered by the low-pressure turbine low pressure compressor would run at a different speed which will be catered by intermediate pressure turbine and then high pressure compressor would be getting catered by the high pressure turbine. So, these are the arrangements for the these are some arrangements for the gas turbine power plant which are efficient and required to get the desired output or desired efficiency.

The next arrangement which can be thought for the gas turbine power plant is its combination with steam power plant.

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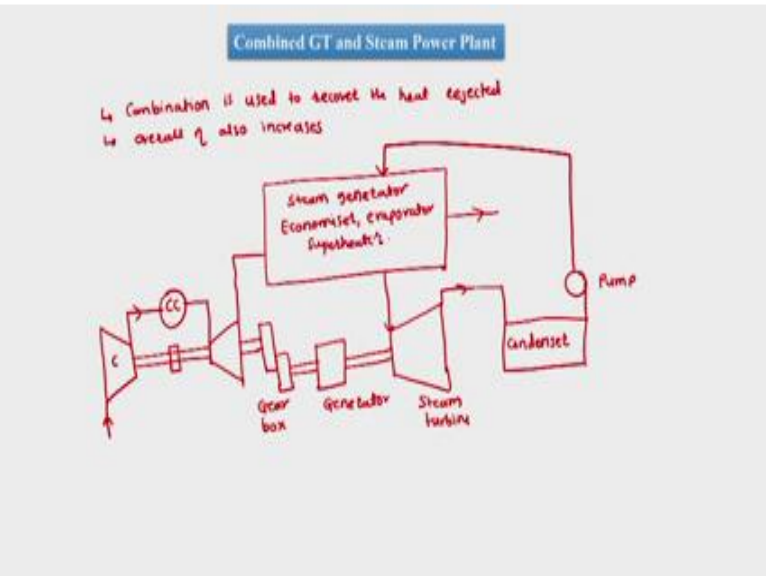

Here we actually are trying to use the exhaust heat from the gas turbine which should be used for heating the water which is used for the steam power plant. So, such combination is used is used to recover the heat rejected further it also improves the overall efficiency also increases. Such combination is thought like this where we will first have compressor where will first have compressor which will take the air.

Then it will go to the combustion chamber after the combustion chamber air will go to the turbine and then this is attached by a shaft this turbine exhaust is given to the boiler of the steam power plant and then it is exhausted from there. This shaft is connected by a gearbox to the shaft of the generator. So, this is gearbox this is generator further generator is also connected to the steam turbine to the steam turbine which receives the steam from the boiler and then it sends this steam to the condenser.

Then it goes from a pump to the steam generator this is steam generator which has everything as economizer, evaporator and maybe a super heater. So, this is a general arrangement in case of a combined steam power and gas power plant.

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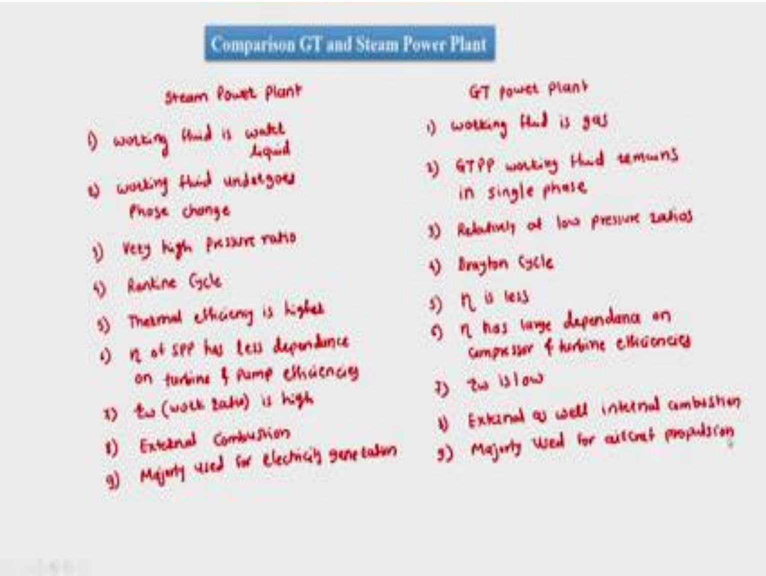

Having said this now we will compare the two power plants which is steam power plant and gas power plant in case of steam power plant we know that first difference between steam and gas power plant would be based upon the working medium. So, here we will write about steam power plant and here we will write about gas turbine power plant. So, first difference is working fluid here working fluid is water or in general other cases like refrigerants.

Here working fluid is gas it is liquid in the pump side it is working fluid is gas. Then in case of steam power plant working fluid undergoes phase change but in case of gas turbine plant working fluid remains in single phase, here we mean that the complete circuit of the plant which comprises of different components only one phase of the working fluid is available. Steam power plant works at very high pressure ratio and this gas turbine power plant works relatively at low pressure ratios.

Low pressure ratio practically speaking the thermodynamic cycle which is between steam power plant and gas turbine power plant they are similar by the processes. In case of steam power plant it is based upon the Rankine cycle. And in Rankine cycle is comprised of four processes which include isentropic compression, constant pressure heat addition, isentropic expansion and constant pressure heat rejection.

And gas turbine power plant is based upon Brayton cycle and Brayton cycle also has two isentropic processes for work interaction and two isobaric processes for heat interaction. But the major difference remains the fact that in case of steam power plant the working fluid undergoes phase change. In case of steam power plant thermal efficiency is higher since the net work output actually includes pump work and which is negligible.

So Wnet is high in case of steam power plant so it would have higher efficiency and thermal efficiency is less in case of gas power plant. The efficiency of steam power plant has less dependence on turbine and from efficiencies this has to do with the fact that the working medium undergoes phase changes ends. The difference between the separation between the turbine process and the pump process has the working dome in between or the phase change dome in between them.

So, pump work is very less and the turbine work is very high which has relevance with the work ratio which we will be seeing later on. So, work ratio is very high for steam power plant and due to which the efficiency of steam power plant has less dependence on turbine and pump efficiencies but this efficiency has large dependence on compressor and turbine efficiencies.

As said earlier this is work ratio work ratio is high and work ratio is looked for gas turbine power plant. It, steam power plant is mainly having external combustion, while in case of gas turbine power plant it can have external as well as internal combustion as what we have seen based upon the arrangement. If it is open cycle power plant then it will be external combustion open cycle with extra attachment can be open cycle with extra attachment can be external combustion in general classical open cycle will be the internal combustion further the arrangement with closed cycle is external combustion.

So, these are the major differences between steam and gas turbine power cycles now we will see the comparison hence there is one more point to be noted that this power plant which is steam power plant is majorly used for electricity generation. While gas turbine power plant is majorly used for aircraft propulsion. However gas turbine power plant is also used for electricity generation.

But steam power plant which was used earlier for locomotives is not that much economical to be used for the locomotives or transportation applications. Now moving on to the last point for this class which is the comparison between gas turbine engine and reciprocating engine. In case of aircraft propulsion we might use reciprocating engine also instead of gas turbine engines.

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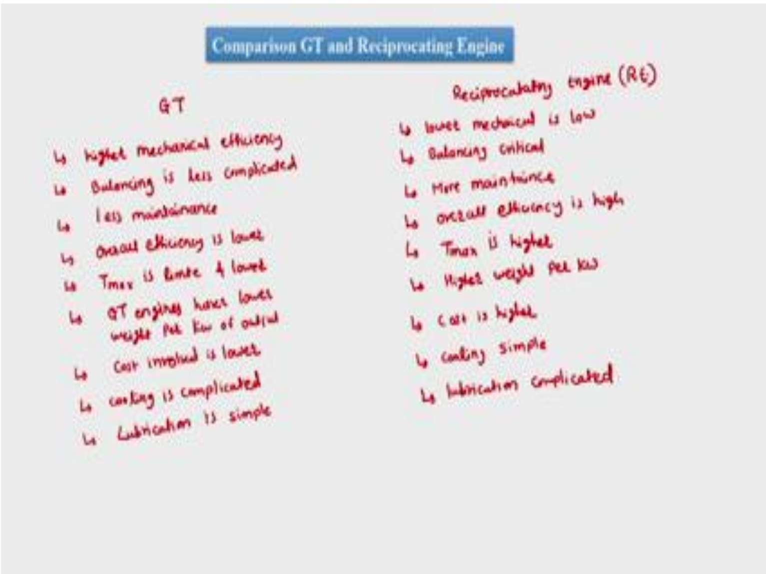

The difference between gas turbine and reciprocating engine is this here we will write about gas turbine engine and reciprocating engine which we will say as RE. So, gas turbine engine has higher mechanical efficiency basically in case of gas turbine engines we have lesser frictional loss than the reciprocating engines. And in reciprocating engines we have higher frictional loss so the mechanical efficiency is low.

Then in case of gas turbine balancing of the engine is less complicated since we directly get the rotational power however here we have to convert this the reciprocating motion into a rotary motion and balancing is critical or at least an involved job in case of reciprocating engine this engine needs gas turbine engine needs less maintenance as compared with the reciprocating engine.

As said more maintenance for reciprocating engines overall efficiency of gas turbine power plant is lower than the overall efficiency of reciprocating engine. This is due to the fact that gas turbine engines cannot operate on higher temperatures. Overall efficiency is high gas turbine engines maximum temperature of the cycle is limited and lower the fact that the strength of the material which is getting exposed for higher temperature decreases.

And hence the rotary components like turbine when get exposed to very high temperature they would have lower strength. Therefore we cannot expose the gas turbines to very high temperature as we can expose them ah we can expose the reciprocating engine in case of the power generation. Hence reciprocating engines have higher T max than the gas turbine engines and due to this fact since T max is higher in case of reciprocating engines they have a higher overall efficiency in case of operation than gas turbine engines.

But gas turbine engines have GT engines have lower weight lower weight per per kilowatt of power output than the reciprocating engines and then they have higher weight per kilowatt. The cost involved is lower and it is its installation is faster than here cost involved is higher in case of reciprocating engine cost is higher cooling of gas turbine is complicated which we are going to see in complicated next one of the classes that we need to have special arrangement for turbine blade cooling here cooling is simple.

Further lubrication is simple for a gas turbine power plant since we have no reciprocating part here lubrication is complicated in case of reciprocating engines. So, these are the relative merits and demerits of the gas turbine and reciprocating engines. So, this is how we can compare different engines and different cycles which are the complimentary cycles to each other. And we have seen also, what are the different arrangements possible for a gas turbine power plant, thank you.