Power Plant Engineering

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Lecture - 19
Gas Turbines

Hello I welcome you all in this course of Power Plant Engineering. Today we will discuss about the Gas Turbines gas, gas turbines another machine which can produce power in a thermal power plant. The gas turbine in gas turbines as it is clear from the name itself only gas is used for the generation of power.

So, there is no phase change in gas turbines and the entire power is generated by heating the gas. Now, gas can be heated either in a constant volume process or constant pressure process right. So, there are two different cycles Joule cycle where we are doing heating at a constant pressure, there is an Atkinson cycle where heating is being done at a constant volume. In gas turbines if you look if you compare the cycles say steam turbine works on a Rankine cycle right.

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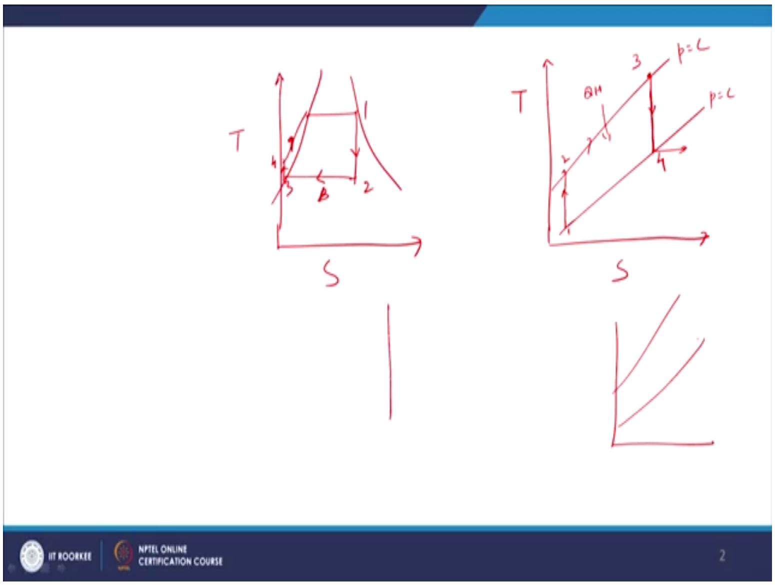

And we have amply discuss the Rankine cycle in previous lectures state 1 to 2 is expansion, 2 to 3 is condensation. Then 3 to 2 to 3 this is not 3, 4 is compression in the pump or pumping, and 4 to 1 the process takes place in the boiler. So, here all the processes they take place in a separate entities.

For example expansion in a turbine, 2 to 3 is condensation and the condenser, 3 to 4 there is the pumping house for pumping the water, and 4 to 1 there is separate boiler for generating a steam. So, this is a Rankine cycle and in gas turbine cycle if you draw the temperature entropy diagram. So, there are two types of cycles, one is a Joule cycle where heat is added at high pressure and high temperature right.

So, first of all the gas is pressurized, so I will draw two constant pressure lines, so first of all the gas is heated from the state 1 to state 2 right. I am just drawing the ideal cycle right, when we attain the gas out of the state to let us take here let us discuss about the air standard cycle air standard gas turbine cycle.

So, 1 to 2 and then 2 to 3 is constant this is a pressure is equal to constant this is have constant pressure lines. So, 2 to 3 process takes place where at high pressure heat is added, so there is addition of heat. Now, after reaching the state 3 the expansion takes place in a gas turbines, so this is gas turbines we have the expansion of the high hot gases takes place. And we get 3 to 4 at the and this goes to the air if it is open cycle, if it is a closed cycle, in a cooler it is cool to one and then again this process continues.

Now, this is known as a Joule cycle Joules and Brayton cycles joules Brayton cycle. Now, if in spite of adding heat as constant pressure if we add heat as constant temperature sorry the constant volume. So, the constant pressure and if we add the heat at the constant volume we will draw it will lot to be clear here if you draw on PV diagram.

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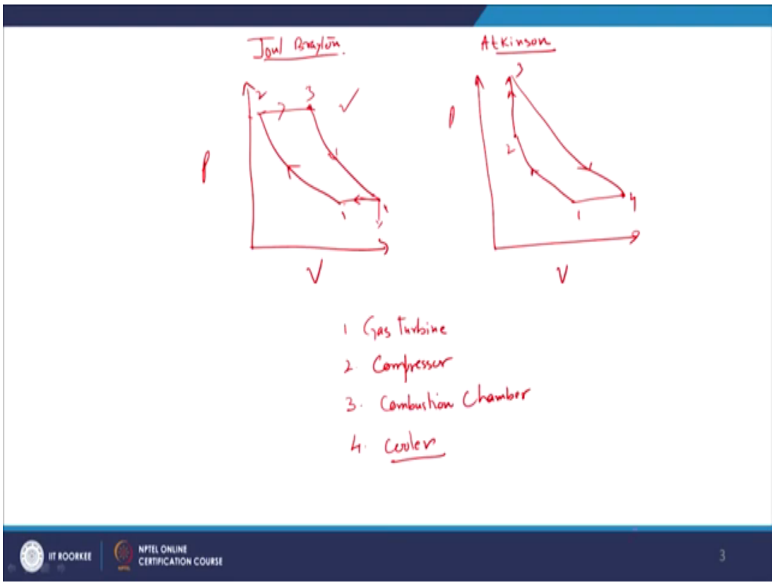

Now, if you draw PV diagram Joule cycle it will be more clear here, so Joule cycle will be something like this. This is the compression 1 to 2, process 2 to 3 is constant pressure heat addition, 3 to 4 is isentropic process where we gain the power output. And 4 to 1 when sub cooler is required otherwise this will go to the air.

But, if you look at the Atkinson cycle on PV diagram Atkinson's cycle on PV diagram the compression process will remain same 1 to 2. Now, heat addition will be at constant volume and after heat addition the rest of the process is remaining same this is 3 and this is 4. But, most of the gas turbines power plants they work on Joules Brayton cycle right.

So, Joules Brayton cycle has four components, 1 is gas turbine, number 2 it has a compressor, number 3 it has combustion chamber. So, it is an external combustion engine also combustion chamber, we have combustion of fuel takes place. And if there is a close cycle then it can be a cooler also cooler provided here to cool the gas, we do not got it condenser because there is no phase change. So, instead of calling condenser it is called cooler right.

So, this is Joule Brayton Brayton cycle this is Atkinson cycle; this is Atkinson this is Joule Brayton cycle. Now, we can classify the gas turbines there are number of different different gas turbines with different arrangements right. So, on the basis of combustion process we have already classified one is Joules working on the Joules cycle another is working on the Atkinson cycle.

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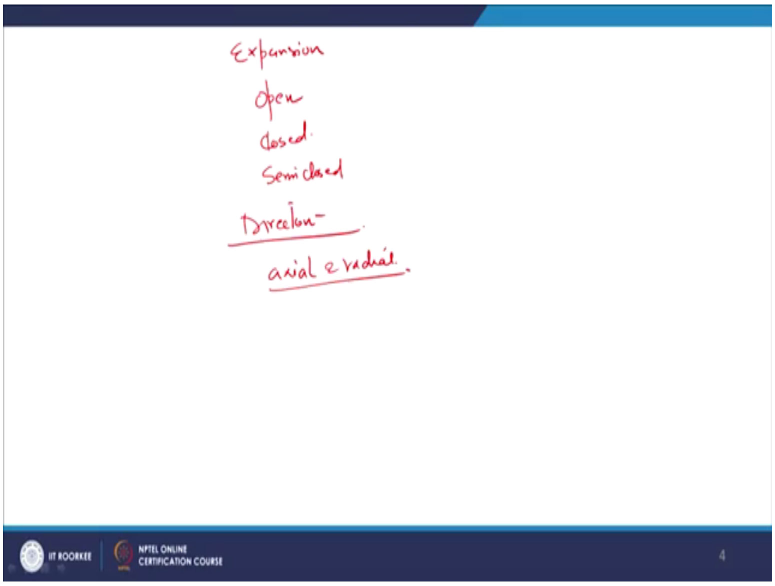

On the basis of expansion also impulse and impulse reaction the turbine you cannot always be classified the power is generated by impulse section only and power is generated by impulse section only. And power is generated by a impulse reaction type of turbine. Now, next one we can have classification like open turbine, close turbine, and there is a c v close turbine also.

So, if there are number of expansion turbines, so one turbine is closed and another turbine is open, so we call it semi close turbine semi close type of cycle right. Direction of flow, in direction of flow is the radial and axial; axial direction and radial direction. Normally, we have gas turbines which have a movement of the fluid in axial direction. Now, simple cycle of gas turbine I have already explained you, now we will go for the efficiency of the turbine.

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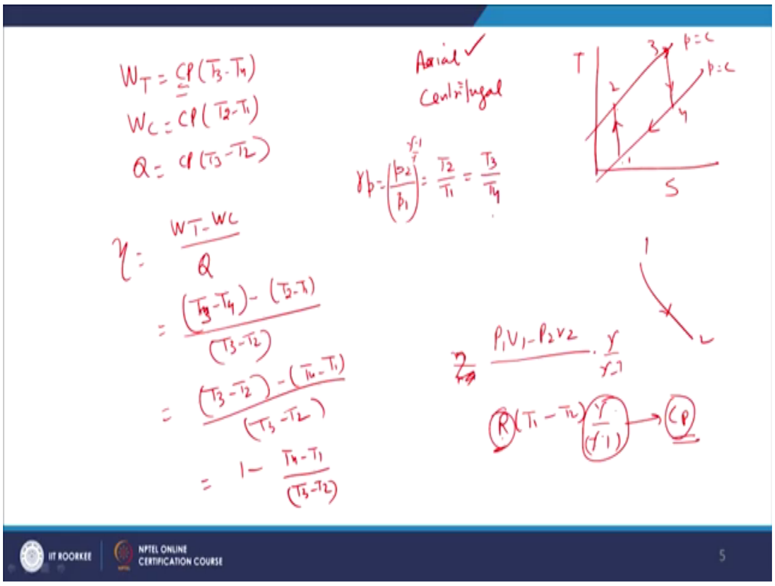

Now, if suppose we draw on temperature entropy diagram 1, 2, 3 and 4 right. So, work output work of the turbine is CP T 3 minus T 4; pressure is not constant it can always be asked, when pressure is not constant where you are taking CP. The reason being if you look at the work done in a adiabatic process suppose process is 1 to 2 right.

So, work done in the adiabatic process is going to be P 1 V 1 minus P 2 V 2 n upon n minus 1 or gamma if it is a adiabatic process then it is going to be the gamma 1 or gamma minus 1 right. Now, P 1 V 1 can always write R T 1 minus T 2 gamma over gamma minus 1, this R gamma over gamma minus 1 will constant CP it is not a constant pressure process.

But while driving the final expression we happy to get the value of CP. Now, the CP should not change in expansion process it is assumption, but CP also changes with the temperature. But, here will assume that CP does not change within in expansion process. So, work of the turbine is process 3 to 4, work of the compressor because part of this work would be consumed by the compressors. Because in gas turbines the mass flow rate for maintaining the same mass flow rate high bulk of fluid will be required because it is gas.

In a steam turbine we are dealing with the water, we are simply pumping the power water right here we are dealing with the gas. So, if we condense 1 cubic meter of this water vapor the volume will be reduced by 1500 times or 1200 times. So, a small pump can handle sufficient amount of water, but here we are dealing with the gas. So, that is why compressors ready this centrifugal and axial two types of compressors are used in the gas turbine, one is axial compressor, another is centrifugal compressor.

When bulk of the fluid has to be handled which is high quantity is high, then we go for axial type of compressors and these compressors they consume sufficient amount of energy. So, it cannot be neglected in Rankine cycle some of the times we neglect the pump work as consumed by the pumps because it is a few claw watts right. But, here substation amount of output is consumed by the for is consumed for pumping the gas.

So, or in other words we can say that the work ratio of gas turbine cycle is less than the steam turbine cycle. So, here we can say CP again T 2 minus T 1 right heat supplied is CP T 3 minus T 2 this is constant pressure process T 3 minus T 2 right. So, efficiency is going to be work turbine minus work all the compressor divided by Q and then it is going to be equal to a CP will cancel out in denominator and numerator.

So, this is T 4 minus sorry T 3 minus T 4 minus T 2 minus T 1 divided by T 3 minus T 2. We can rearrange this T 3 minus T 2 minus T 4 minus T 1 divided by T 3 minus T 2 or it is 1 minus T 4 minus T 1 divided by T 3 minus T 2.

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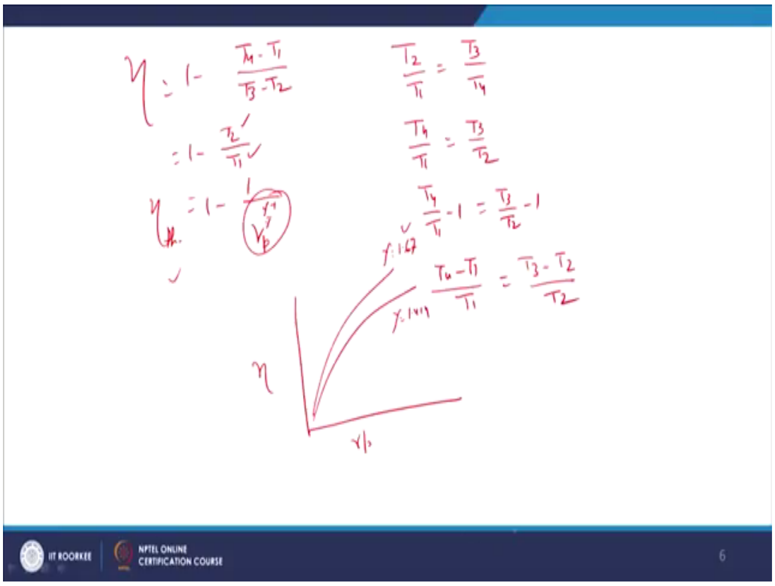

Now, here again I will write efficiency is equal to 1 minus T 4 minus T 1 divided by T 3 minus T 2. Now, here if you look at this is pressure ratio rp, rp is p 2 by p 1 is equal to T 2 by T 1 or we can say is raised to the power gamma over minus 1 over gamma is equal to T 2 by T 1. And in the same way it is T 3 by T 4, so here what we can do T 2 minus T 1 T 2 by T 1 is equal to T 3 by T 4.

So, or T 4 by T 1 is equal to T 3 by T 2 T 4 by T 1 minus 1 is equal to T 3 by T 2 minus 1 or T 4 minus T 1 divided by T 1 is equal to T 3 minus T 2 by T 2. So, T 4 minus T 1 divide by T

3 minus 3 2 is going to be 1 minus T 2 by a T 1 or if 1 minus 1 over r pressure ratio gamma minus 1 over gamma right.

Now, here if you increase the pressure ratio efficiency will increase thermal efficiency will increase. In ideal cycle thermal efficiency is not dependent upon the highest temperature it is dependent only T 2 and T 1 only. So, pressure at the inlet and outlet of the compressor if it is an ideal cycle, second thing is it is dependent on the gamma also.

So, if he increase the pressure ratio and if you compare the f with the efficiency the curve is going to be like this for gamma is equal to 1 point 4 1 4 that is for a diatomic gas. Instead of diatomic gas you have fill that cycle and make it a close cycle and if I use argon the efficiency will increase because here we are getting gamma is equal to 1.67. And if we increase the value of gamma the thermal efficiency will increase.

So, this is done in I am in close cycle gas turbine where we can fill the gas like krypton, mercury, or monatomic gases like mercury vapor can also be used, argon can also be used. So, monatomic gases if you are using here then we will get higher value of gamma and efficient we will get higher value of efficiency.

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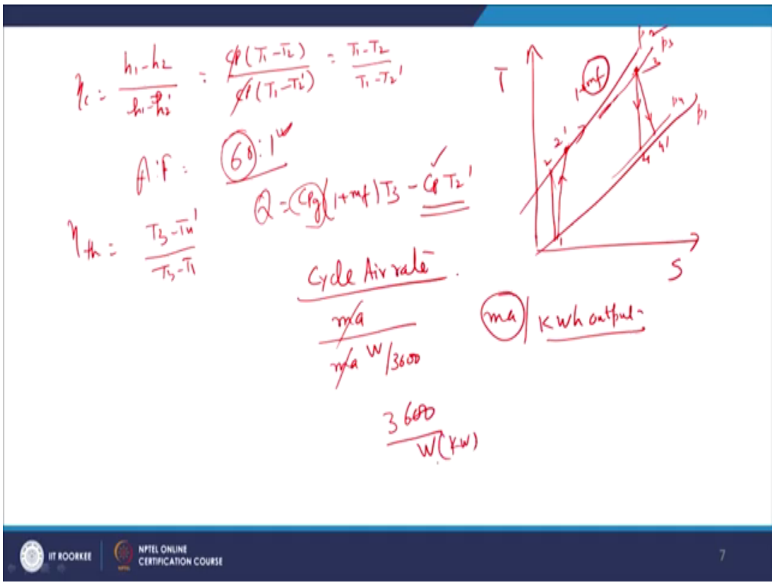

Now, we will come to the actual cycle because no power plant works on an ideal cycle if we look at here the actual cycle first of all compression right. So, what do the compression is not an ideal process because there are several losses in rotor dynamic machines like breed friction losses, entry losses. So, due to this and losses in the diffusers there is a increase in entropy, entropy does not remain constant right.

And we get the state 2 dash and efficiency of the compression is expressed by a ideal h 1 h 1 minus h 2 divided by h 1 minus h 2 dash. Now, h 1 minus h 2 is a changing enthalpy right. Again it will be CP T 1 minus T 2 divided by CP T 1 minus T 2 dash the CP CP will canceled out, it will be T 1 minus T 2 divided by T 1 minus T 2 dash.

Now, after this it goes to the combustion chamber where burning of fuel takes place. In ideal cycle we say if the air standard cycle we assume that the air is being used during the entire cycle, but in the actual cycle fuel is added. So, suppose air fuel resistor there is some of the air fuel ratio air fuel ratio. And let us say 60 into is to 1 for 1 kg of air, 60 kg air, 1 kg fuel will be used. And we are assuming that the mass flow rate of the fuel in the cycle is 1 kg per cycle right for the sake of calculations.

Now, here mass of the fuel is also added, so we will write 1 plus mf mass of the fuel. Second thing is in the combustion chamber also there is going to be a pressure drop, because movement of fluid will not take place to the combustion chamber. So, the there is a pressure drop in the combustion chamber; in fact, if you look at the microscopic level at the exit of the compressor there is valve. So, across the valve also there is a pressure drop.

So, we are just considering only major pressure drops in the cycle, so in the combustion chamber once the pressure drop takes place inside the combustion chamber. So, we get state 3 here lower than p 1 p 2 right. Now after this expansion of gas takes place inside the turbine. Now, for expansion because n after the expansion gases have to be exhausted to the atmosphere this is the atmospheric air.

So, exhaust pressure should be a little higher than the exhaust pressure otherwise the gases will not come out to the turbine not go to the atmosphere. So, this is again this is p 1 and p 2 let us say this is p 3 this is p 4, expansion in a gas turbine and again this expansion is not ideal that is certain change in the entropy, so we get 4 4 dash.

Now, here efficiency of the turbine is going to be T 3 minus T 4 dash divide by T 3 minus T 4 ideal output and actual output right. Then other minor losses also which we have not taken into the account, now here heat addition q is going to be CP g. Now, here specific heat of gas will be considered while taking the total enthalpy and 1 plus mf mass of the fuel T 3 minus specific heat of air T 2 dash.

Now, here you can see though we are consuming more energy in the compression and we are getting T 2 dash. But, heat addition has reduced by irreversibility of in compressor right. So, this pressure drop in a combustion chamber is a small, but because it is mass of the fuel is also added into the air. So, we cannot simply take this specific heat of the air, we have to take the specific heat of the gases right.

Now there is a term which is known as cycle air rate, cycle air rate is it is a mass of the air divided by mass of the air w divided by 3600. It means mass of the air per kilo Watt hour output how much air is required for 1 kilo Watt of output that is knows as air rate and it is 3600 divided by W, W is in kilo Watt right.

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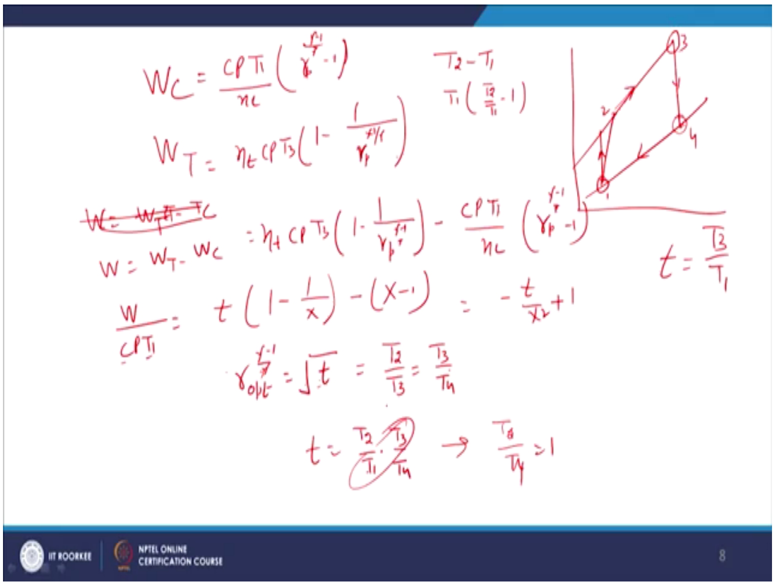

Now, if we look at the work of the compressor in a irreversible cycle right. Now, the work of the compressor is CP T 1 r raised to power gamma minus 1 or gamma minus 1 divided by efficiency of the compressor. I would just modify this we have taken T 2 minus T 1, we have taken T 1 outside it is T 2 by T minus 1 and T 2 by T 1 is compression ratio, the pressure ratio gamma minus 1 over gamma minus 1 ok.

And work of the turbine; work of the turbine is efficiency of the turbine CP T 3 1 minus 1 over r raised power gamma r p gamma minus 1 over gamma we are taking a efficiencies into the consideration. Now, we will have take difference of these 2 we will get the output.

Now, if you take W net W is equal to W T minus the W C sorry W T, W is equal to turbine work minus compressor work right. And this is going to equal to efficiency of the turbines CP T 3 1 minus 1 over r p gamma minus 1 over gamma minus CP T 1 efficiency of the compressor gamma minus 1 over gamma minus 1.

Now, what we want to do we want to take W by a CP T 1 and let us assume efficiency is equal to 1. For ideal case efficiency can always be introduced later on then it is going to be a T 3 by T 1. Now, T 3 by T 1 is maximum temperature in the cycle the ratio of maximum temperature in the cycle and minimum temperature in the cycle that is T 3 by T 1.

So, we can say it is denoted by T 1 minus r p gamma over gamma minus 1 we can always take x minus 1. Now, here w by CP to CP is constant in a cycle, T 1 is always call it the atmospheric temperature it is almost constant it does not vary much if you compare with T 3.

So, we want to have maximum work, in order to have maximum work we have to differentiate this with respect to X, for what value of X we are going to get the maximum work. And when we do this we get r p is equal to gamma over minus 1 over gamma is equal to under root T. Simply when we differentiate this is going to be minus T by X square plus 1 that is it if you differentiate this with respect to X.

And then we can find the X is equal to under root T that is r raised power gamma 1 minus 1 or gamma is equal to under root T. Now, r raised to power gamma over minus gamma is equal to T 2 by T 3 and is equal to T 3 by T 4 right. Now, we can say that T is equal T 2 by T 1 T 3 by T 4 right and this is T under root T is equal to this is equal to this if you multiply these two we will get T right.

And then we know that T 3 by T 1 is equal to T this is T, so we can say that T 2 by T 4 is equal to 1. T 2 by T 4 is equal to 1 means T 2 is equal to T 4 in that case we are going to get maximum output what does it mean? It means exhaust of the turbine exhaust temperature of the turbine should be inlet temperature of combustion chamber.

In that case the efficiency will be maximum and in regeneration we tried to do that what will in regeneration what we try to do? We just simply try to heat the exhaust of the compressor with the exhaust for the turbine; so that energy can be saved we will discuss it later on. And now the issue is how to improve specific output of the turbine right.

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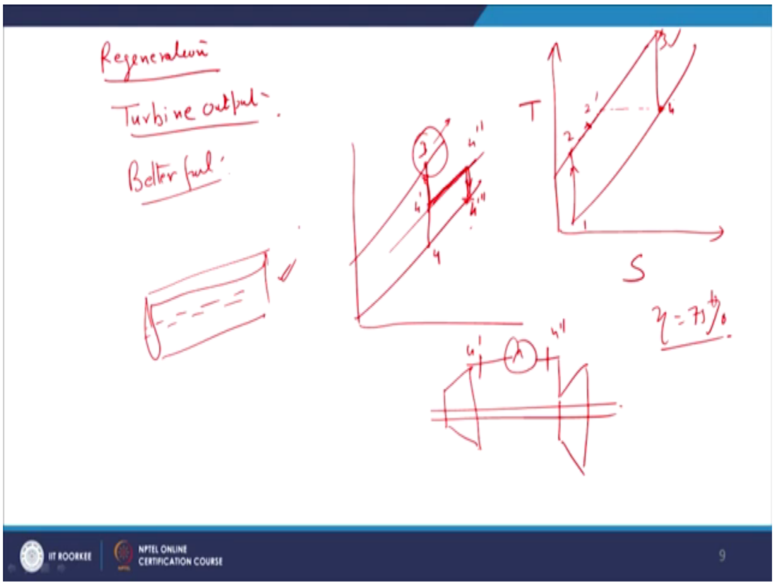

So, specific output of the turbine as i mentioned earlier it can be done by a regeneration, if the process of regeneration this is 1 to 2 right and 3 to 4. Now, exhaust is quite higher than the outlet of the compressor right, so with this exhaust this heated this is heated in a heat exchanger or a heater. And ideally this temperature should be equal to this 2 dash should be equal to 4 T 4. But, actually it does not happen the efficiency of this type of heated air to air heat exchanger is normally 75 percent 70 to 75 percent.

So, instead of getting here, so we learned up somewhere here right. So, this is the process of regeneration it improves the output of the not all output it improves the efficiency of the turbine, because less amount of heat will be required for heating the system. Now, by improving turbine output by simply improving the turbine output we can improve the a specific output.

Now, for improving the turbine output one process is reheating, when expansion is taking place it does not take place in one stage. Instead of that in between if the expansion takes place in two turbines, there is one turbine there is a heater. And then this turbine the exhaust of this turbine goes to another turbine and both are housed on the same shaft right.

So, process 3 and this is process 4 and this is state 4 and this is state let us say 4 dash at 4 dash this is 4 dash. Now, the hot gases are taken to the heater where heating takes place and then we get 4 double dash this is 4 double dash. And after 4 double dash again the expansion takes place in another turbine. So, the process is like this 3 to 4 dash, and 4 dash to 4 double dash, 4 double dash to 4 triple dash here. So, exhaust is a little higher temperature, but we get more output from the turbine. Another way of increasing the maximum temperature of the cycle add more heat; if you increasing the maximum temperature of the cycle definitely more output will be getting from the turbine.

In addition to that better fuel should be used, so that calorific value of the fuel is high right that is how we can increase the specific. Now, for increasing the temperature we have to go for improved material right, because this temperature T 3 is decided by the metallurgical limit of the turbine material. If we can any how we can enhance this metallurgical limit we can increase the T 3 as well, so it is related with the metallurgy.

Another thing is we can go for higher temperature if the cooling of plate there is a new technique of providing the cooling to the blades. So, inside of the blades channels are made;

inside the blades channels are made and these channels. And air is circulated in these channels that is how because gas temperature we have increased right.

But, in any how have if you can keep the blade school in that case we can increase the efficiency of the turbine. So, blade cooling where a lot of research is going on in this area of cooling of gas turbine blade, so that we can enhance the efficiency of the gas turbine cycle.

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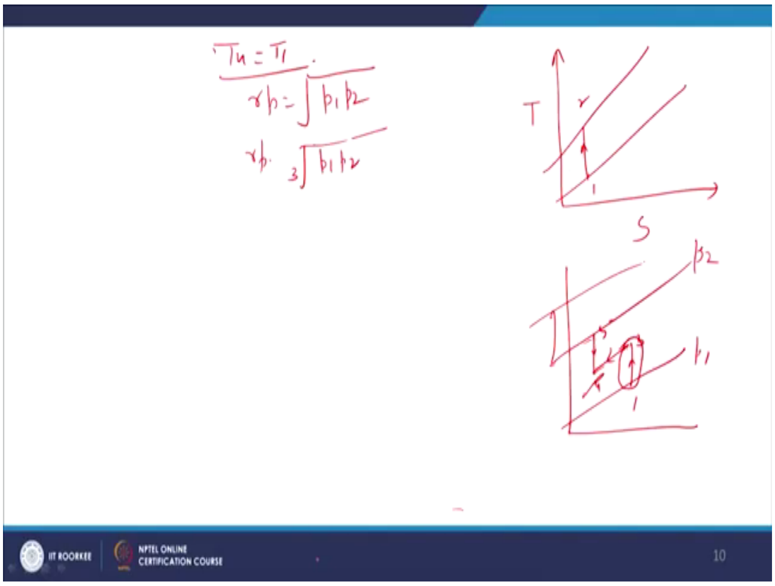

Now, efficiency can also be improved by reducing the compressor input, so this is state 1 to state 2. Now, for compressor input reduction, because we are dealing with air or gas which has a very low density in that case we can go for multi state compression. So, instead of compressing gas in 1 stage after compression in 1 stage the gas is taken away is state 1 this is state let us say 3, it is cool to state 4 and then again it is compressed to state 5.

Now, this inter cooling reduces the power input and I will tell you if suppose there is a 2 stage inter cooling and there is a perfect inter cooling. Perfect inter cooling means T 4 T 4 is equal to T 1 that is perfectly inter cooling. So, in that case the pressure ratio is going to be under root this is let us say this is p 2 this is p 1 p p 1 p 2. If it is 3 stage inter cooling we can have a another stage also in that case pressure ratio is going to be the cubic root of p 1 and p 2, and in this case each state the work consumed is going to be the same.

So, if you are able to calculate work consumed in 1 stage has multiplied by 3 you will get work consumed in 3 stages. Sometimes water induction is also there are several methods of inter cooling it can be done through the jacketing, it can be done through a water induction. Now, the effect of various modification on the performance of a simple cycles.

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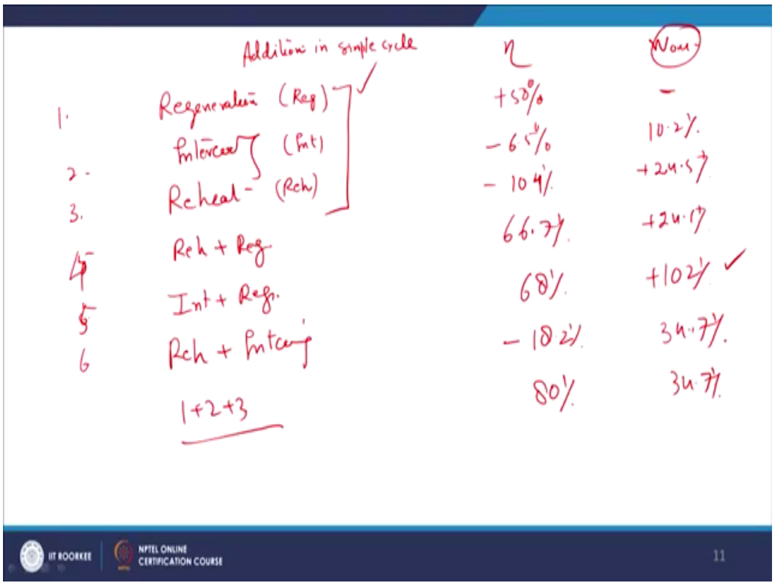

So, addition in simple cycle and efficiency and output; number 1 if we do the regeneration they are field data. So, efficiency is increased regeneration efficiency is it can be increased up to this is field data, increase up to 50 percent output improvement is not there right as I said earlier.

Now, inter cooling, now inter cooling efficiency may reduce 6.5, because we are taking away heat from the system. So, efficiency is reduced, but work output is increased by 10.2 percent, reheat in reheat also efficiency may not it is there is a misconception that if you do re heating in the turbine efficiency will increase.

Efficiency I mean may not increase efficiency does not increase often it mean in some of the cases, but often it does not increase right. But, definitely the output can be increased up to 224.5 percent. Now, 5 this is a regeneration this is inter cooling and this is a reheat. Now, we will take combination of reheat plus regeneration we will reheat the turbine in between an exhaust of the turbine will be used for heating the outlet of the compressor. In that case we will getting 66.7 percent of improve efficiency and this is 24.5 percent.

Now, inter cooling and regeneration inter cooling of compression during compression and regeneration. And inter cooling and regeneration it gives a approximately 68 percent and 1 0 2 output becomes quite high it is almost double this is 3, 4, 5, now 6 is the reheat plus inter cooling. Now, if you do reheating and inter cooling the efficiency goes down by 18. 2 percent, but the work output is 34.7 percent enhancement in our work output. And the last 1 is all these 3l 1 plus 2 plus 3 here efficiency can be increased by 80 percent and output is 34.7 percent.

So, we can say that regeneration is the best process if you are going to improve the efficiency of the turbine. Regeneration is the best process reheating the efficiency does not increase; in fact, the output you can increase by heating. And reheating can be done in a number of stages not only single stage it can be done in a number of stages.

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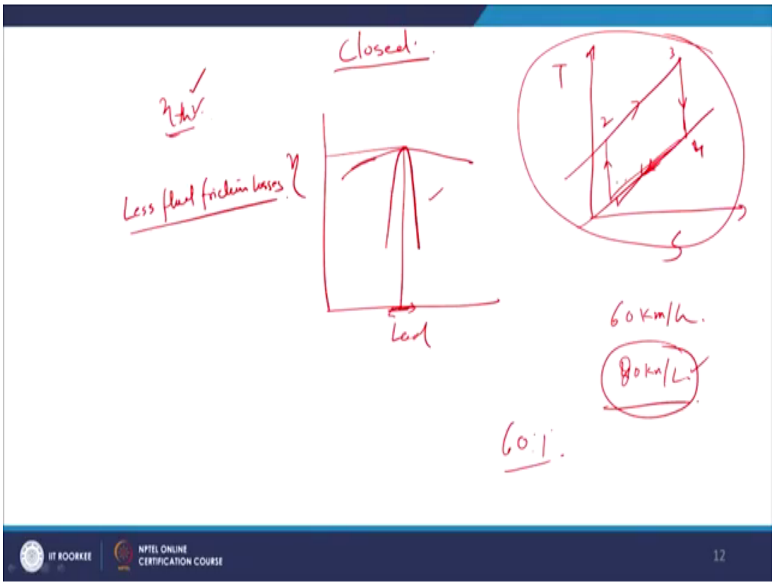

Now, we will discuss about the advantages of close cycles as I said earlier there are 2 types of gas turbine cycles; one is close cycle 1 is open cycle. So, if we compare the performance of a close cycle with an open cycle the close cycle has higher thermal efficiency, why? Because, if we again draw temperature entropy diagram T S state 1 to state 2, stare 3 to state 4 the entire this TS diagram can be shifted.

Then because it is a close cycle we can operate it on higher pressure right p 1 may not remain atmospheric it can be 2 times atmospheric pressure because it is a close loop right. So, for this reason we the enhancement in the thermal efficiency can be realized because it is working on the high pressure.

So, specific not a specific output, for the same output the size of the turbine can be reduced. Because, turbine efficiency is a high yes it is thermal efficiency is high it is implicit therefore, the same output we can reduce the size of the turbine it has better part load efficiency. Now, every machines including say for example, scooter, motor cycle, car or that is a reciprocating machine or rotary machine is designed for a particular load and that is known as design load.

Now, suppose this is the design load and at the design load it has certain efficiency right. Now, if you deviate from the design load right if you deviate from the design load means suppose let us talk about a motorcycle. Motorcycle is designed for let us say 60 kilometer per hour on ideal road condition when you do not apply brake the fuel consumption is 40 or I mean eighty kilometers per liter.

But, when you drive a motorcycle you never realize 80 kilometers per liter because you always drive the machine on off to the end condition. You are sometimes you are in a crowded area you are driving at 20 kilo meters per hour, you are on highway, you are driving with a 100 kilometers per hour. So, and you often on and off you are applying brakes, so this average is never realized. But, those machines have very good part load efficiency I mean if you look at the part load efficiency of a reciprocating machine it is something like this.

So, even if you are not operating on a design load efficiency much of these efficiency is not sacrificed. But, if you look at the gas turbine gas turbine air fuel ratio is 60 is to 1 fuel air fuel ratio yes, in reciprocating machine diesel engine or petrol engine it is of the order of 10 or 15 or 20 right.

But the off design performance of the gas turbine something like this it is almost vertical suppose. So, just you deviate from the a design condition there is a sharp fall these lives are almost vertical there is a sharp fall in the efficiency of the engine right. And this is one of the reason this is one of the reason why these gas turbine engines are not used in automobiles this is one of the reason yeah there are several other reason is also, but this is one of the reason right.

And in this close cycle gas turbine there is a good heat transmission we are using here fluid fiction loss are less, fluid friction losses right. No contamination is here contamination is not there, so longer life of the gas turbine and then the compressor blades. High output in expensive and there is no loss of work media.

These are the advantages of the close cycle there are certain disadvantage is also it is a dependent system. It is dependent system because cooling has to be done a cooler has to be provided right. So, it is not fit for say airnotic purpose, I mean you cannot apply this close cycle gas turbine in an airplane. However, for bearing application this can be very good because it is compact in size and for bearing applicants you know in the sea a lot of plenty of water is available, so cooling of gas is not a problem.

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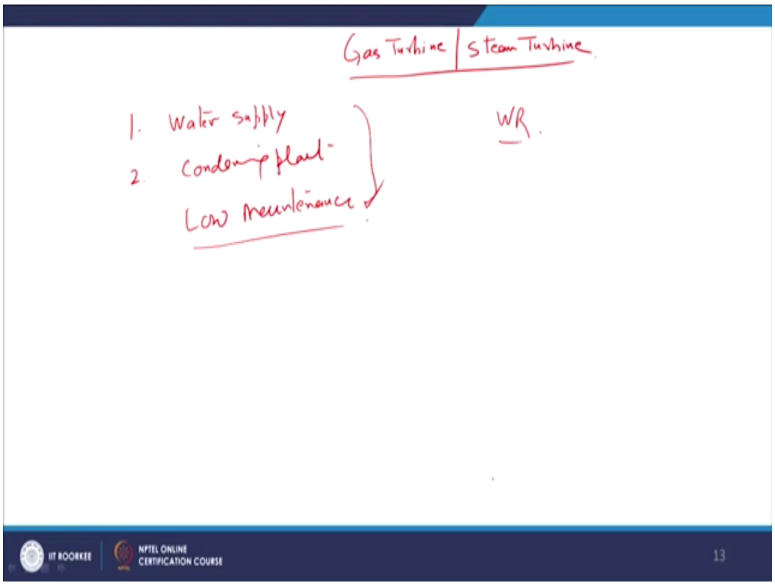

Now, if you compare the gas turbine and steam turbine power plant, we have in India we have gas turbine power plants also. So, first of all no water supply is not required for steam power plant what much water is required? Water is required for generating steam, water make up water is required, water is required for the condensers for gas turbines much water is not required.

In fact, there is no water requirement nil, if you look at the cycle water requirement is nil in gas turbine. So, it does not have condensing plant normally if it is a open cycle condensing plant is not require, in steam turbine it condenser is required, in a steam turbine is separate boiler house is required right here.

And boiler and its accessories are required, in gas turbines boilers are not required only combustion chambers are required and where combustion takes place at the atmospheric pressure. If it is indirect type of thing even is the pressure, pressure is also not very high in gas turbine if you compare the pressure in the steam turbine. So, in a gas turbine less components have to be designed, in a stream turbine more components more safety walls have to be provided more components have to be designed. So, the maintenance is low maintenance is low they are all connected with each other.

So, when less components have to be designed maintenance part, so there is low maintenance low maintenance in the turbine. The best part is it starts very quickly, I mean if you have to start the steam turbine and you will have to inject water in the boiler and the boiler will light up and then this turbine will start. But, here in the gas turbine the start is very quick right.

So, as see emergency power plant also gas turbine power plants are used, because immediately you can start the gas power plant cost is because they are less number of components cost is less. But, there are certain disadvantages also, like work ratio is less for said earlier have equally compared the Rankine cycle with the gas turbine cycle the Joule cycle work ratio is less for a gas turbine power plant.

And air rate is quite high right and as I said earlier part load efficiency is very poor for the gas turbine. So, it limits the application of the gas turbine that is all for today.

Thank you very much.