

## Applied Thermodynamics for Marine Systems

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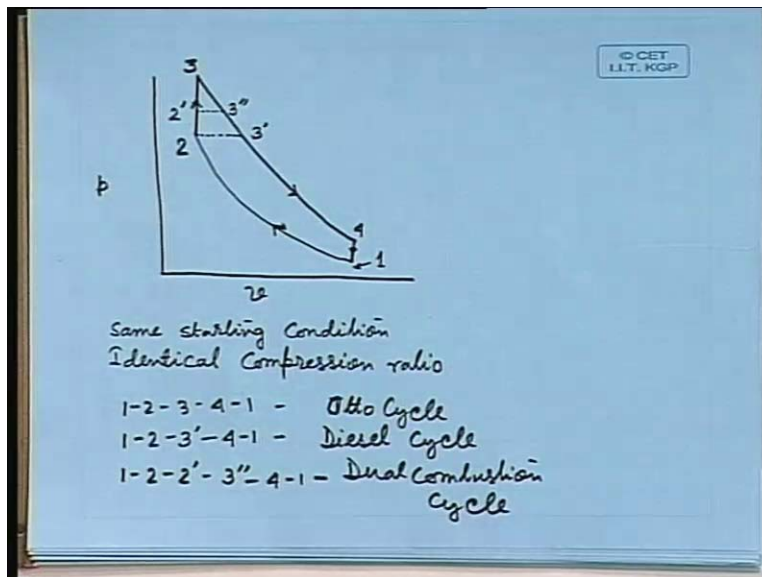
Indian Institute of Technology Kharagpur

### Lecture - 25

#### Gas Turbine Cycles

Good morning. We were discussing regarding the cycles of internal combustion engines and we have given the expression for the efficiency of three very important cycles, which are used in internal combustion engine. One is Otto cycle, one is diesel cycle and another is dual combustion cycle. Sometimes it is also called mixed combustion cycle or limited pressure cycle. We have got the expression for all the cycles. We can make some sort of a comparison between the cycles; I think that is bit interesting to see. If we want to make some comparison there should be a basis. The basis of comparison in the first case, we can think that let us take air because these are all air-standard cycles. Let us take air at the same condition. Let us have same compression ratio. If we do that let us say this is our PV diagram. We have got 1 – 2. Let us say this is our point 2 then let me try to draw it once again.

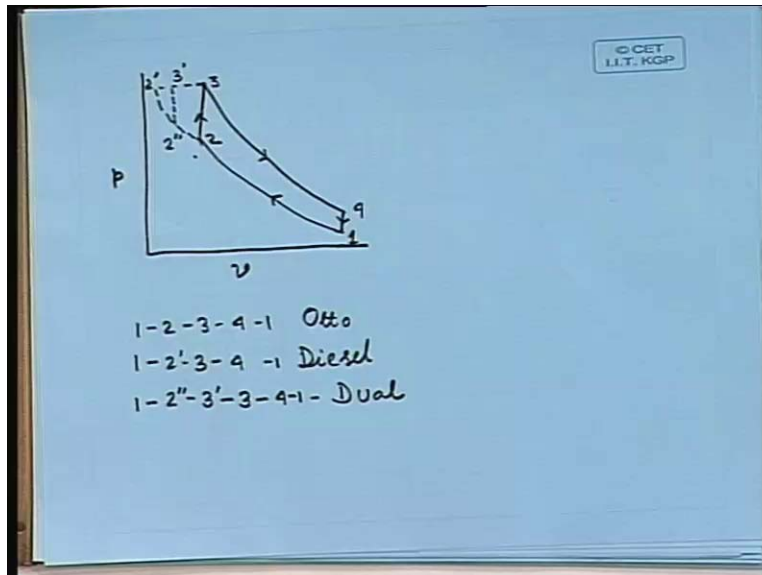
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This is our PV plane. We are having the compression from point 1. Then we are having the combustion in Otto cycle and then we are having expansion and heat rejection. This is your point 1, then point 2, point 3 and point 4. This is your Otto cycle. If we select the criteria for comparison between different cycles, we will have the same starting point 1 and same compression ratio. In that case our diesel cycle will be something like this. 1 to 2 that will be common point for all the cycles; then let us say this is 3 dash, 4 and 1. Let me write the same starting point or starting state condition, whatever you may call it and identical compression ratio. So this is the condition for comparison and we have 1-2-3-4-1, this is your Otto cycle. Then, 1-2, this will be common, then 3 dash 4-1 this will be your diesel cycle. Then if we have got a dual combustion cycle we have to go up to certain point along the constant volume line and then there will be a constant pressure heat addition also, so we will come somewhere here.

You will have 2 prime 3 double prime and then 4-1 like this. 1-2-2 prime 3 double prime 4-1, this is dual combustion cycle. What we can see is that we are having the area of different cycles that will be different and the maximum area we will get, in case of Otto cycle, then we will have dual combustion cycle and then we will have diesel cycle. The maximum output we will get from the Otto cycle, then our dual combustion cycle and then our diesel cycle, if we have the same compression ratio for all the three cycles. We know that we do not have the same compression ratio for all the three cycles. If all the three cycles are having the same compression ratio then this happens or then this compression is valid, but generally we do not have same compression ratio for all the three cycles. We have less compression ratio for Otto cycle. But the diesel cycle and dual combustion cycles are suitable for CI engines, compression ignition engine where we can go for a higher compression ratio. Another way of comparing the cycles is the maximum temperature in the cycle that you can allow, because the material has to withstand the maximum temperature. From that point of view one can again make some comparison and what could be the maximum temperature of the cycle; keeping that constant, whether we can do some analysis or not.

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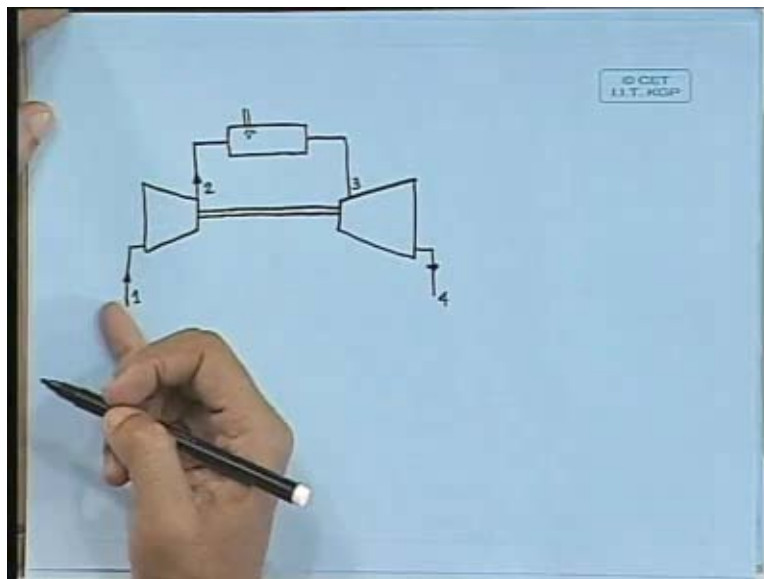
We will have PV and then this is your Otto cycle. This is 1, this is 2, this is 3 and this is 4. If this point where the maximum temperature will occur in Otto cycle, if we want to keep it fixed for other two cycles also, that means Diesel cycle and dual combustion cycle, then our diesel cycle will be something like this. That means 1-2 dashed 3-4. This will be our diesel cycle. Let me write this; 1-2-3-4 is Otto. 1-2 dashed 3-4 diesel, and then we will have dual combustion cycle. In dual combustion cycles, what we will do? We will go up to certain point and let us put it by some other colour; we will have this one. In all the cases we will have point 3 as the common point. 1-2 double prime, then let us have 3 prime, another 3 I am bringing here, 3-4 and 1; in all these cases, 1 will be there for completion of cycle. This is your dual combustion cycle.

You can see in this case diesel cycle gives maximum output, then dual combustion cycle and then Otto cycle. What we can see is that the Otto cycle and diesel cycle are two extreme cases of cycles. Dual combustion is having mixed features or combined features of both the cycles, so it will have somewhere in between. These are the different thermodynamic cycles used for internal combustion engine. In actual case the cycles will be much different as we have discussed earlier. I have shown that actual cycle diagram will be much different compared to this thermodynamic cycle diagram. The actual cycle diagram - suppose with an engine you have got indicator mechanism and from there you can get the actual cycle diagram pv diagram of the cycle that will be much different. From there, using the indicator diagram and the fuel consumption one can get

indicated efficiency; that will be much lower compared to the thermodynamic cycle efficiency. Our cycle efficiency will be lower in case of internal combustion engine what we calculate from air-standard cycle. That is why there are different techniques by which one can overcome some of the short comings and have a higher cycle efficiency like super charging, turbo charging etc., one can do. We will not go into those practical aspects considering the background; you have already done the components, different systems of the engines, so probably short discussion regarding those will not be much helpful to you.

We will go to another type of cycle, which is also air-standard cycle. But that is not used for internal combustion engine but that is used for your gas turbines. Sometimes people want to call gas turbines also internal combustion engine or internal combustion cycle. Because here the combustion takes place within a very compact arrangement and it is not like that we have got some sort of a separate and elaborate arrangement like a boiler as it is used in steam power plant.

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A gas turbine power plant basically will have a compressor, which will take air from the ambient and then it will compress it to the required pressure. This high pressure and high temperature gas or air will be sent to some combustion chamber where liquid fuel will be injected, so combustion will take place. A further rise will be there in the temperature of the gas and then this high temperature gas will be sent to a turbine where it will expand while passing through the blade

passage. Then at the end of the turbine the gas has done its work and it is not suitable also for further combustion because it is full of carbon dioxide; oxygen quantity has deteriorated or has become less so it has to be sent to the ambient atmosphere again. This is the cycle. Let us say, this is 1, this is 2, this is 3 and this is 4. What I have shown the turbine and compressor - they are mounted on the same shaft and that means whatever power is developed by the turbine part of it will be utilised for running the compressor.

Generally all these things, turbine, compressor and the combustion chambers are axially located and within a compact geometry they are located, particularly for power plants which are attached to mobile systems like aircrafts or maybe sea-going vessels; so all these things are in a compact structure. There are land units and land power plants, which are stationary power plant - there one can have slightly elaborate arrangement. Let us see the difference between this cycle and the other cycles. In both the cases like what we have discussed for internal combustion engine and what we are discussing for this gas turbine, in both the cases we have got gas as the working fluid. The gas basically is air in which some combustion has taken place. The product of combustion is what is going through the turbine and through the compressor only air is passing. Air and the product of combustion becomes the working fluid. In case of internal combustion also it is so and in case of gas turbine is also it is so. That is why there is some similarity because working fluids in both the cases are same.

But there is a great difference. In internal combustion engine within the same chamber, the piston cylinder chamber, the entire cycle takes place; all the different processes of the cycle takes place inside the same chamber. Here for a particular process we have a particular component. Compression will take place in the compressor and then combustion - if we think it to be a heat addition process - that will take place in another place and then the expansion will take place in another component. What happens in case of internal combustion engine is that the pressure and temperature continuously varies in the chamber where the cycle takes place. If we take any component there at a particular point the pressure, temperature remains constant; so these are steady flow devices. If we do not consider the transients during the operation, transients may occur during start-up and during the shutdown of the engine, during some sort of disturbance in the operating condition, if we forget that for the time being then this is a steady flow device. Everywhere at any point we will have same properties throughout the running of the device.

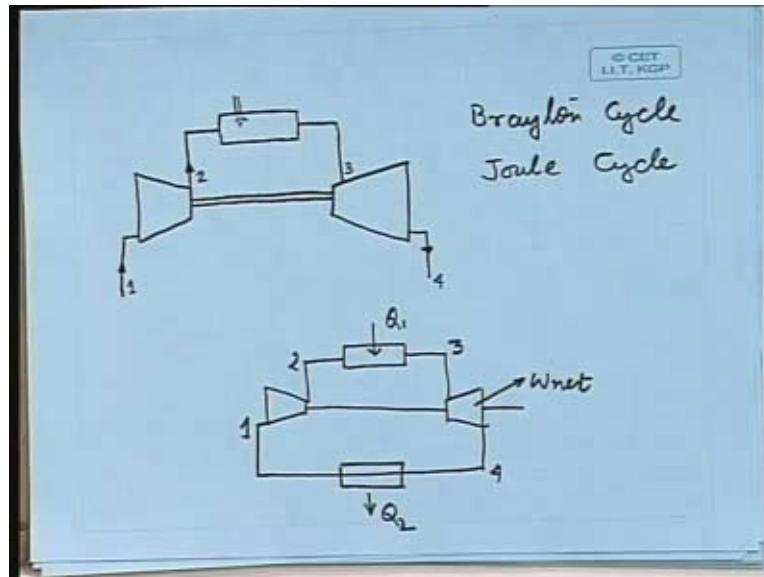
What does it mean? The highest temperature will occur at a particular point only. The lowest temperature again will occur at a particular point.

In case of IC engine, reciprocating internal combustion engine it is not like that. There, we will have a fluctuation of temperature. Is it good or bad? It is good in one way because suppose we are attaining a maximum temperature quite high but after sometime again the temperature is low so it will have time to cool down. Here a particular component in case of gas turbine will be subjected continuously to a very high temperature. From the material point of view the maximum temperature, which we can achieve in internal combustion engine cannot be achieved in our gas turbine power plant, simply from material point of view. But we know that higher the maximum temperature of the cycle, higher is the cycle efficiency. We will lose in cycle efficiency. This is one very important aspect one has to keep in mind. Then it has got a number of differences with other steady flow cycle like Rankine cycle; we will discuss it later on.

Let us look into this. The way I have shown the cycle, it is an open cycle, it is not a closed cycle. We are taking certain air and at condition 1 or state 1, we are compressing, then changing its composition and combustion is taking place, then it is expanding and the air at the end of the cycle we are getting at a condition 4, which is different from 1. So the cycle is not a closed cycle it is an open cycle. This is another factor which decreases the efficiency of the cycle. We have to remember that reciprocating internal combustion engines are also open cycles. The open cycle efficiency will be lower compared to the efficiency of an equivalent closed cycle. But when we want to discuss or analyse the air-standard cycle, we have to convert it into a closed cycle.

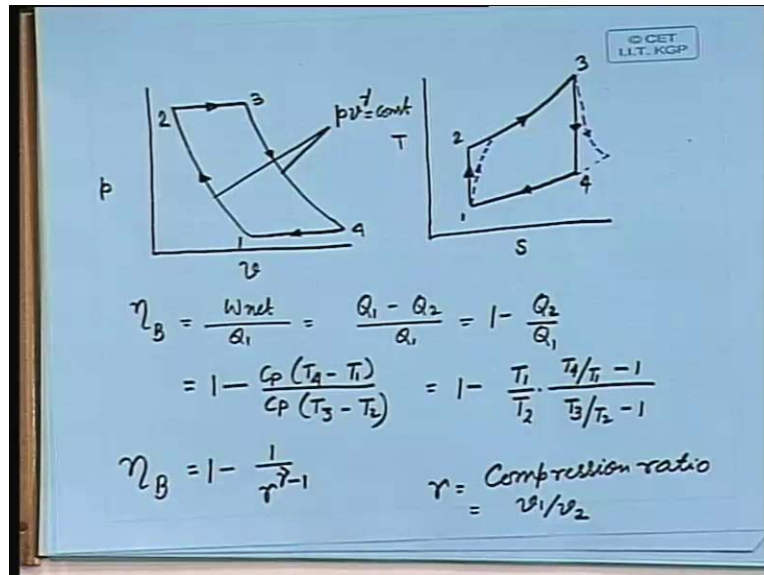
If we want to convert it or want to have the equivalent closed cycle, then, we are assuming some sort of imaginary heat exchange process, which is a cooling process and then we are connecting 4 and 1. This combustion process also we are replacing by a heat addition process.

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We will have basically  $Q_1$ , this is  $W_{net}$ , some network we are getting and then we will have 1 and 2-3-4 and here again we will have another device, which will allow the gas to reject heat.  $Q_1$  is the heat addition from a high temperature body and  $Q_2$  is the heat rejection to a low temperature body. So this is the air-standard equivalent of the actual gas turbine cycle. Let me tell you the gas turbine cycle is known as Brayton Cycle. It has got another name also - it is called Joule cycle. Either we call it Brayton cycle or we call it Joule cycle. We will have this type of arrangement for the basic Brayton cycle and then we can have the PV diagram.

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Basically what we are doing in this case is we are taking air at a low pressure and temperature and then we are compressing it. We are doing it like this; 1 then 2 and then we are adding heat. We are adding heat when the gas is flowing through this heat exchanger. Through the pipe there will be some pressure drop generally which is neglected. So this is a constant pressure heat addition. We will have a constant pressure heat addition. Then we are having expansion in the turbine. This is the expansion in the turbine and then last process again there is heat rejection through a heat exchanger; we are idealizing this as constant pressure heat rejection. We are having constant pressure heat rejection. 1-2-3-4 isentropic compression, constant pressure heat addition, isentropic expansion and constant pressure heat rejection. This is what we will get. If we want to have the TS diagram, this is T and this is S. So 1 to 2 is like this isentropic compression, then constant pressure heat addition, then isentropic expansion and then constant pressure heat rejection so 1-2-3-4, we will have these four processes.

Let us think a little bit. I have shown all ideal processes. If I think of non-ideal situations, what will happen? 1 to 2 isentropic compressions will not remain isentropic. What will happen? Due to irreversibility what will happen? Entropy will increase or decrease? Increase. In this direction the process will go. Only thing is that we have assumed the pressure will remain constant, but the pressure will not remain constant. Instead of this constant pressure line we will get a different



line. As there is a change in temperature there will be change in pressure. Due to friction there will be a drop in pressure.

There is a heat addition process - that is if it increases temperature, it can increase also pressure. Now it is like this. The gas which is there is not in confined condition. It is moving. But when it is moving it has to go through pipes or conduits, where there will be frictional loss. What is the essence of this? I have shown a constant pressure heat addition that will not remain. Let us say 3 is our end point. We are mainly concerned with these two isentropic processes, so, here also there will be increase in entropy. The expansion process will also be something like this and here, there will be pressure drop. Something like that we will get in the actual cycle, whereas the ideal cycle ignores all these losses. The calculation of efficiency is very easy. We can write  $\eta_{\text{Brayton}}$  is equal to  $\frac{W_{\text{net}}}{Q_1}$ . So this is  $\frac{Q_1 - Q_2}{Q_1}$  and that is equal to  $1 - \frac{Q_2}{Q_1}$ . We can have this as  $1 - \frac{T_3 - T_2}{T_4 - T_1}$ . It is constant pressure heat addition, so we will have  $C_p T_4 - T_1$  divided by  $C_p T_3 - T_2$ . Just like our previous case we will do the analysis. We will have  $1 - \frac{T_1}{T_2}$ . Then here we will have  $\frac{T_4}{T_1} - 1$  and  $\frac{T_3}{T_2} - 1$ .

We can do the analysis so that  $\frac{T_4}{T_1}$  and  $\frac{T_3}{T_2}$  one can calculate. Starting from the point 1 and assuming these two processes are isentropic process  $p v^\gamma = \text{constant}$ . Assuming these two processes to be isentropic processes, one can do the analysis. If we do the analysis then we will have  $\eta_{\text{Brayton}}$  is equal to  $1 - \frac{1}{r^{\frac{\gamma-1}{\gamma}}}$  where  $r$  is compression ratio. We will have the same expression as the Otto cycle. How are we defining the compression ratio?  $v_1$  upon  $v_2$ .

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$$\eta_B = 1 - \frac{1}{r^{\gamma-1}}$$
$$\eta_B = 1 - \frac{1}{r_p^{(\gamma-1)/\gamma}}$$
$$r_p = \frac{P_2}{P_1}$$

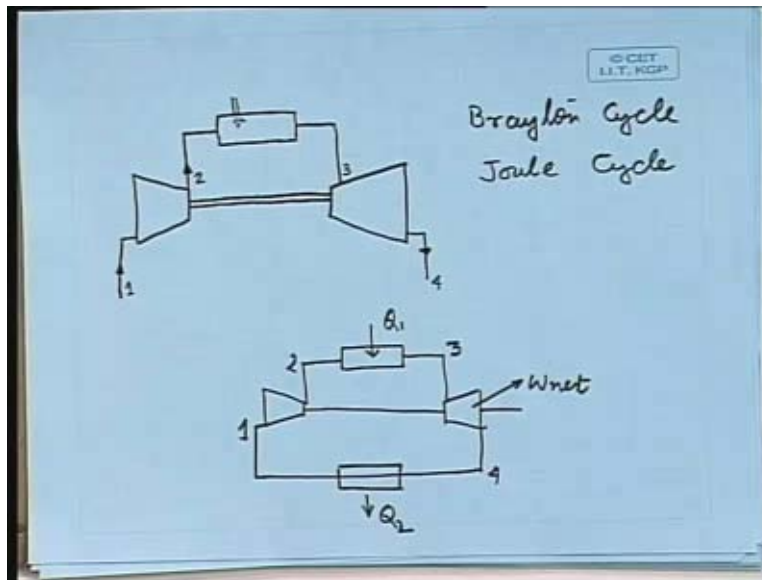
$r_p =$  Pressure ratio

Let me write it. eta Brayton is equal to 1 minus 1 by r to the power gamma minus 1. When we are dealing with internal combustion engine, a piston is moving. We know different volumes. What is the total volume, what is the clearance volume? In terms of volume we are talking. In case of gas turbine cycle, gas is moving in the compressor. There, generally we do not talk about the volume. We talk about initial pressure, final pressure or in terms of the pressure ratio of the compressor. Whereas, in case of internal combustion engine we talk in terms of volume and in that case we will talk in terms of pressure or pressure ratio. Instead of compression ratio we would like to use the pressure ratio. The compression ratio is basically a ratio of two volumes, and there we will like to use ratio of two pressures. If we do that then eta Brayton will be 1 minus 1 by  $r_p$  pressure ratio and then gamma minus 1 by gamma.  $r_p$  pressure ratio is the highest pressure by the lowest pressure  $P_2$  by  $P_1$ . The cycle operates between two pressures, so,  $r_p$  is equal to  $p_2$  by  $p_1$ .

Let me write,  $r_p$  is pressure ratio. The pressure ratio is very crucial in case of Brayton cycle because the cycle efficiency depends on the pressure ratio. What will happen? What will we get if we increase the pressure ratio or if we decrease the pressure ratio? We will get more efficiency; at least thermodynamically, we will get more efficiency. But what happens in actual practice that is one of the differences between the gas turbine cycle and the Rankine cycle. Gas

turbine cycle is also a steady-flow cycle and Rankine cycle is also a similar type of a cycle. If we compare between gas turbine cycle and Rankine cycle there are some sort of similarities.

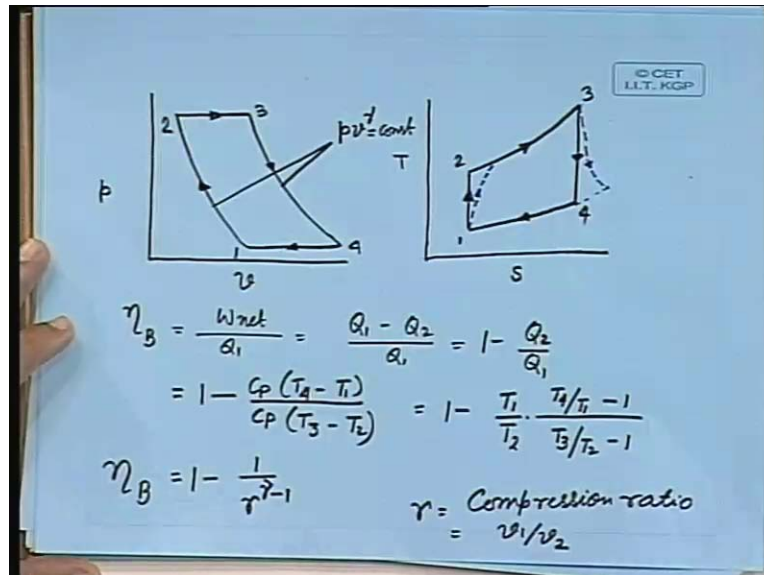
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We have instead of a boiler some device which is supplying thermal energy and then we are having turbine, then just like a condenser we are having some device where we are exchanging heat or rejecting heat. Then just like pump we have got a compressor. But the main problem is that a pump handles the incompressible liquid. So, only very small amount of power is needed to run the pump. But compressor handles a compressible fluid. As it compresses the fluid more and more, the temperature of the fluid increases and the effort needed for further compression also increases. So, the compressor takes away a very large chunk of work produced by the turbine.

We have seen in case of calculation of Rankine cycle, I have told you that in a number of situations we can neglect the pump work. When the boiler pressure is moderate, we can neglect the pump work. It is a small percentage of the turbine work, but here we can see, if we do some calculation the compressor work is almost 30-40% of the turbine work. We have to be very careful regarding the compressor. We know that if we increase the pressure ratio then we will have more work drawn by the compressor and ultimately we will suffer as far as the output is concerned, the output will get reduced. Also the irreversibility that I have drawn here increases with the compression ratio.

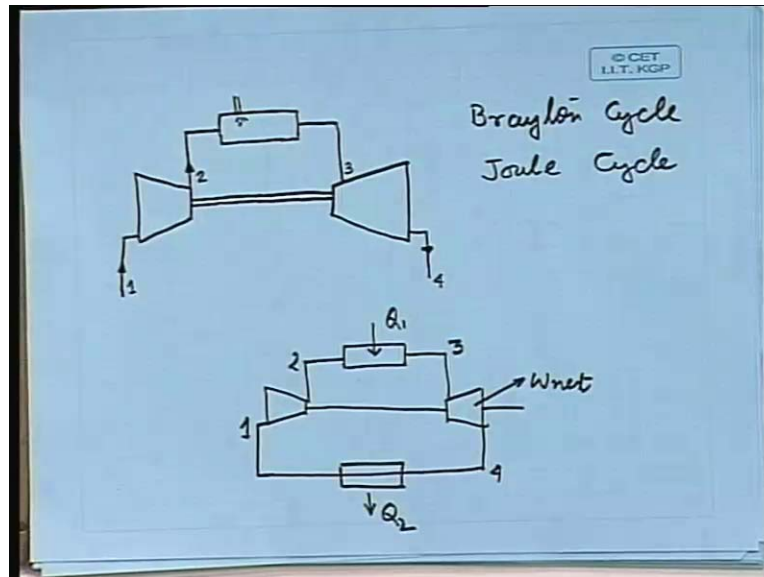
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Keeping all this in mind there is a restriction that we cannot increase the pressure ratio to a very great extent. But gas turbine cycles are very important cycles. In certain cases it is a must - it has got so many leverages over the other cycles. What are those things? It is very compact. Volume to power ratio could be quite high rather, power to volume ratio. That means power developed to the volume of the power plant that will be quite high. It could be made light weight and within a very short period of time it can produce peak power. In a boiler from starting, to having the peak generation it takes some time, whereas in case of gas turbine power plant we will have the peak power within a very short period of time. With load fluctuation this power plant will adjust itself very well so that is why for mobile systems like aircraft etc., gas turbine power plant is a very good choice. We have to do something so that we will not also lose in the efficiency or in the output. The basic Brayton cycle, which I have shown is rarely used. We have different modifications of Brayton cycle.

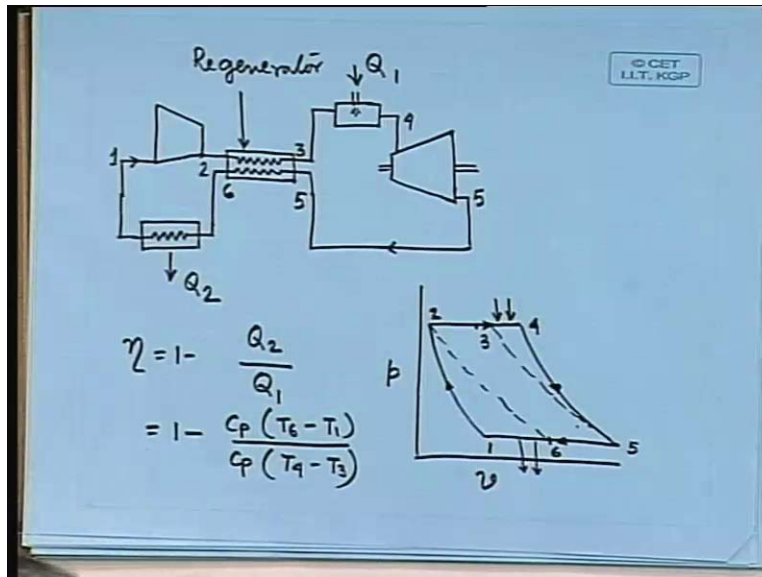
Now we will see the different modifications of Brayton cycle that is possible. I think that is one of the reasons why we also try to select sometimes gas turbine cycle for marine systems. It is compact and peak power generated could be quite fast and the fluctuation of load it can accommodate well. Probably a mixture of gas turbine and steam turbine combined together can give lot of desirable features what we want from a power plant.

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If we consider this basic Brayton cycle, here the gas is coming out of the turbine product of combustion, but the temperature is still higher compared to the ambient air. It will have some energy along with it, which we can tap instead of leaving it to the ambient atmosphere or to the sink so we can tap certain amount of energy. That can be done by some heat exchanger and we can recover a certain amount of heat from the exhaust gas. That is what we can do and that heat will be utilized for heating the air before it goes for combustion. We will need a lesser amount of fuel to be burnt in the combustion chamber. We will show this process. From the exhaust gas, we can generate steam and do things. That is some sort of a mixed cycle where we are having both steam generation and gas turbine. So there could be different type of designs. But I like to discuss when I am discussing air-standard cycle that is different variation only in the Brayton cycle not bringing any other cycle.

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What we can do is like this. We have got the compressor. Then this is the air, which is coming out of the compressor and that will be heated by the exhaust gas. Let us say this is one stream, this is another stream and here again there will be heat rejection. Ultimately this is the heat rejection. Then this gas will go to the combustion chamber where combustion will take place. Then it will go to the turbine; expansion and useful work one can get. This is the turbine. What are the different important points 1, then this is 2, this is 3, this is 4, then this is 5, then this 6 and 1. We can have the cycle diagram in the p-v plane. It is like this, not much different from the other cases. Basically 1,2; then 2 to up to 4 is a constant pressure process, heat addition at constant pressure. Then 4 to 5, this is expansion process and one can take it as isentropic expansion. Then 5 to 1 is again constant pressure heat rejection process.

The only thing is that between processes 2 to 4, 2 to 3 this is heat addition by exhaust gas and 3 to 4, we have put external heating. Here also we can have 5 to 6 this is by the heat loss to the incoming air and this is heat rejection. This means this process is internal. One can write efficiency  $\eta$  is equal to 1 minus  $Q_2$  by  $Q_1$  and in this case 1 minus  $Q_2$ . What is  $Q_2$ ?  $C_p$  into  $T_6 - T_1$  by  $C_p T_4$  minus  $T_3$ . This is your  $Q_1$  and this is your  $Q_2$ . 2-3-5-6, these are the points. This is how we can save a certain amount of fuel and this is done because gas turbine exhausts are at high temperature so that waste heat we can recover or we can utilize. This is called a regenerator. This heat exchanger is called a regenerator because it is internally heating. Just like we had

regenerative feed heating in case of steam turbine or steam power cycle so here also it is called regenerator. Let me give the name regenerator. This is one way of increasing the efficiency.

Regenerator may be of some interest. Sometimes it serves number of other purposes. One is day by day the environmental norms are becoming stringent and stringent. When you are putting a very hot exhaust to the ambient atmosphere, you are creating thermal pollution. This is to some extent better as far as thermal pollution is concerned; at least at a lower temperature it is being exhausted. Then from a strategic point of view if a very hot exhaust gas comes out then it is very easier for the enemy to detect. Thermal detection is possible when you are having a very hot exhaust. That is why also sometimes it is convenient particularly these are not for civil applications, but for military application that we should have the exhaust at a lower temperature.

$\text{NO}_x$  and  $\text{SO}_x$  we cannot actually discuss in this small period of time. Actually that depends at what temperature the combustion is taking place, particularly  $\text{NO}_x$  generation, combustion temperature. But when you are having a mixed cycle, one can have lot of options to take care of those things. Actually the pollution problem is a bit complex because if we go for high temperature then it is one way good that we are creating lesser amount of carbon monoxide. All the carbons are totally oxidised to produce carbon dioxide which is a safer gas. In case of internal combustion engine if we have to control the pollution there are different techniques. One of them is re-burning the product of combustions or recycling part of it. That could be one method but not a very good method because it gives partial solution so what one wants to do nowadays it is by catalytic converter. A catalytic converter till date is the better solution. Why, I will tell you. There are different strategies - one strategy is that you spray water. If we increase the temperature of combustion that is good because it is giving me lesser carbon monoxide, but that is bad again because it is more prone to  $\text{NO}_x$  formation. Whereas catalytic converter the way we select the catalytic converter it can take care of mainly three types of pollutants. One is HC that means whatever remaining hydrocarbons are there, carbon monoxide and  $\text{NO}_x$ .

The way it does the reaction, it takes care of these three things. So, that is why though the water injection or the recycling of the burnt product are some partial solutions of pollution problem but they are not the complete solution. At today's point of view catalytic converter is the best solution. Pollution definitely is a very important issue and in gas turbine cycle also it is important

issue. What one of you have pointed out is that we burn low sulphur fuel. That is true. But nowadays people are talking in terms of fuel mix and using some sort of fuel, which are not very conventional one and particularly when we are going for stationary power plants. Gas turbines nowadays are used for stationary power plants also to a large extent. In that case it will be combined with a steam turbine power plant. Along with it we will have two cycles; one is a topping cycle, one is a bottoming cycle; we will have two types of cycles. In those cases we will have different type of fuels and definitely we will try to have low cost fuels. In those cases different type of techniques we have to take. If it is a stationary power plant we can afford having separate units for the pollution control; means exhaust gas we can treat and then the gaseous effluent can be put to the atmosphere.

Those are not within the scope of our discussion but those are possible. In case of mobile power plant, we do not have very high sulphur content in the fuel. Here you see that one needs to know  $T_6$  and we need to know  $T_3$ . The regenerator, some details are to be known otherwise we cannot do this analysis - that is taking a standard heat exchanger and what type of effectiveness we can allow; what type of temperature difference? The terminal temperature difference is very important.  $T_2$  and  $T_6$  are the two temperatures at which the gases are coming close together. There should be some difference. If it is only 2 degree Celsius then there will not be any effective heat transfer. The terminal temperature difference and effectiveness - considering all those details one can work out this temperature and then efficiency can be determined.

I think I will stop here. Not much is left as far as gas turbine cycles are concerned. We will complete that and then we will start heat transfer. Thank you.