Applied Thermodynamics for Marine Systems
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Lecture - 24
Gas Power Cycles, Cycles for IC Engines

Now, we will have a brief discussion on internal combustion engine - particularly the thermodynamic aspects of the internal combustion engine. The internal combustion engine basically is a heat engine where the thermal energy is converted into mechanical work. It will work continuously, so it will work in a cycle. We know that, as engineers, we want to have the maximum efficiency; if there is any working cycle we have to follow. First, we will try to see why we cannot follow an ideal cycle like the Carnot cycle.

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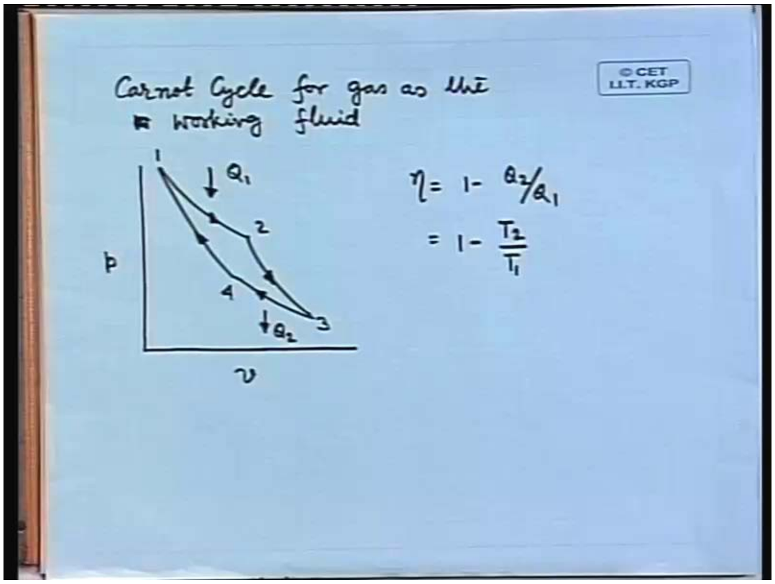

Carnot Cycle for gas as the working fluid

$$\eta = 1 - Q_2/Q_1$$
$$= 1 - \frac{T_2}{T_1}$$

Carnot cycle for gas as the working fluid; we have seen the limitation of the Carnot cycle for vapor as the working fluid. Now, we will try to examine the limitations of the Carnot cycle with gas as the working fluid. This is the PV diagram of a Carnot cycle – 1, 2, 3, 4 - a cycle like this, isothermal, adiabatic, isothermal, adiabatic. Here we have got Q in, here we have got Q out and out of the cycle we will have efficiency eta is equal to 1 minus Q_2 by Q_1. This will be 1 minus T_2 by T_1; that is the maximum possible when these two temperatures T_2 and T_1 are specified. But the problem is that for gas as a working fluid, the isothermal heat addition and isothermal heat rejection are almost impossible, unless we have a very large engine with a very large surface area and with infinitesimally slow process. One may try to approach isothermal heating and isothermal cooling; one will not get exactly, but one may approach. Again, if you have to have these adiabatic processes, then we have to have fast processes. What are we having? For a part of the cycle we have a very slow process; we need a very slow process, a higher surface area for better heat transfer. For part of the process, we need to have very low surface area and high speed. It is difficult to design such a cycle, it is not practical.

Another thing that happens is that we see that the total change in volume for the cycle is v_3 minus $v_{1.}$ This is v_3 and this is $v_{1.}$ That is the total change in volume. If we think of in terms of the engine then this is nothing but the swept volume. This is called the swept volume. The swept volume becomes very large compared to the total work done. What does it mean? It means that the mean effective pressure, MEP is very low for Carnot cycle. The swept volume is large means a very large engine, a very large volume, but we are having a very small amount of work output, so our MEP becomes very small. This is only representative of the ideal process. In actual case what will happen? In actual case, there will be friction. So we are having a low MEP without considering friction. When we will consider friction, we will get very minimum output out of the cycle. Cycle design is not possible, not practicable, even if somebody designs the cycle, friction etc. cannot be eliminated and we will get very low output from the cycle. Though thermodynamically the efficiency is very high, practically the efficiency will be low and practically this cycle we cannot develop also. That is why with gas as the working fluid one cannot have a Carnot cycle designed. One has to look for other type of thermodynamic cycles. We know that internal combustion engines are very versatile equipment and are very useful equipments. In those equipments, the combustion takes place inside the engine itself and the hot product of combustion pushes the piston and we can get work output out of it.

Internal combustion engine - let us have some small idea regarding the working of internal combustion engine.

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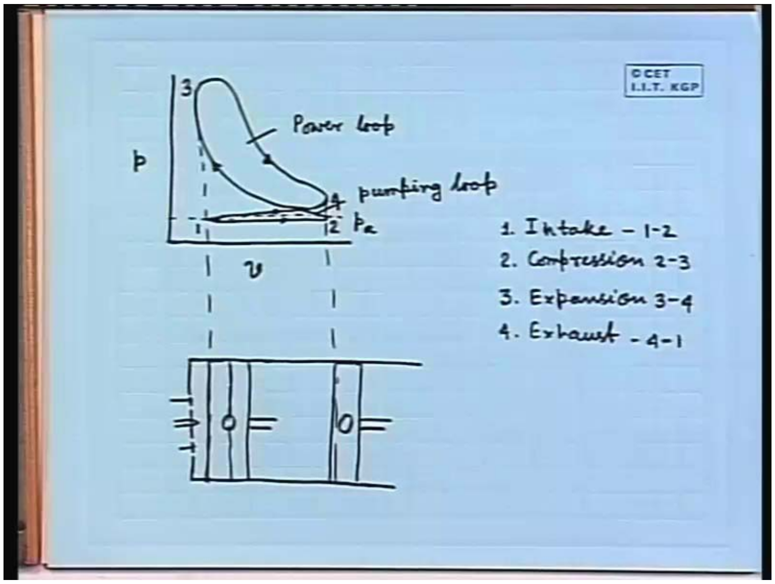

1. Intake - 1-2
2. Compression 2-3
3. Expansion 3-4
4. Exhaust - 4-1

If we see the PV process of the internal combustion engine, the actual internal combustion engine will be something like this. This is p_a or atmospheric pressure. There are basically two loops - one is called power loop and another is called pumping loop. What I have shown is the piston cylinder arrangement. This is the cylinder, this is the piston and these two are the two extreme positions of the piston. This is called one dead center of the piston, this is the outer dead center of the piston and this is the inner dead center of the piston. The piston has a reciprocating motion between these two dead centers, inner dead center and outer dead center.

There are four processes; there are two types of machines. If we consider the general working process then there are four processes. The four processes will be: intake, compression, expansion and exhaust. These are the four processes which we will have. Basically, if we see the four processes in these two loop or in this PV diagram, one can have intake is 1 to 2 - so we call them 1 - 2; then compression is 2 to 3, so 2 - 3; then expansion is 3 to 4, 3 - 4 and exhaust is 4 to 1. In this piston cylinder arrangement, there are two valves - one of them is inlet valve and another is exhaust valve. In the intake process what happens is the piston moves from the outer dead center towards the inner dead center reducing the pressure inside; pressure inside falls below the atmospheric pressure. I have shown the atmospheric pressure somewhere here. During the process 1 to 2, the pressure falls below the atmospheric pressure, so air is sucked in; either air or air fuel mixture is sucked in inside the engine cylinder. Then, both the inlet valve and exhaust valves are closed. The piston has an outward movement from the inner dead center to the outer dead center. At that time, either the sucked air or the sucked air fuel mixture is compressed and that is the compression process. Towards the end of the compression process if we have sucked air-fuel-vapour mixture then an ignition is created with the help of a spark plug, which is symbolically shown here or towards the end of the compression of air, we inject liquid fuel in the form of fine spray. So, the fuel-air mixture then gets further compressed and evaporated, and ignition takes place.

In both the cases, in case of air-fuel mixture or in case of compressed air with fuel injected in it, we have an ignition and combustion of the fuel. Due to the compression process, pressure and temperature increases and that pushes the piston towards the inner dead center. So far, we have seen in the suction process, in the compression process, that some external agency is needed to move the piston. Now due to the combustion, the gas inside the engine has enough motive power to push the piston from the outer dead center to the inner dead center; so now we get some useful work. The hot and high-pressure gas pushes the piston and by that process it also goes to a low pressure, its temperature falls and it does the amount of work it was supposed to do. The piston is at one end, the entire engine cylinder is now filled up with spent gas, which has done the work. This gas has to be expelled out of the engine, so that again fresh charge can be taken and again the cycle can start. Again the piston has to move from inner dead center to the outer dead center while the exhaust valve is open, so the gas pressure will rise above atmospheric pressure and the spent gas will go out of the engine. This is what we have in a nutshell in an internal combustion engine. The process is complex.

Generally, when we do the thermodynamic analysis we do certain amount of idealization. The idealized cycle is called the air standard cycle.

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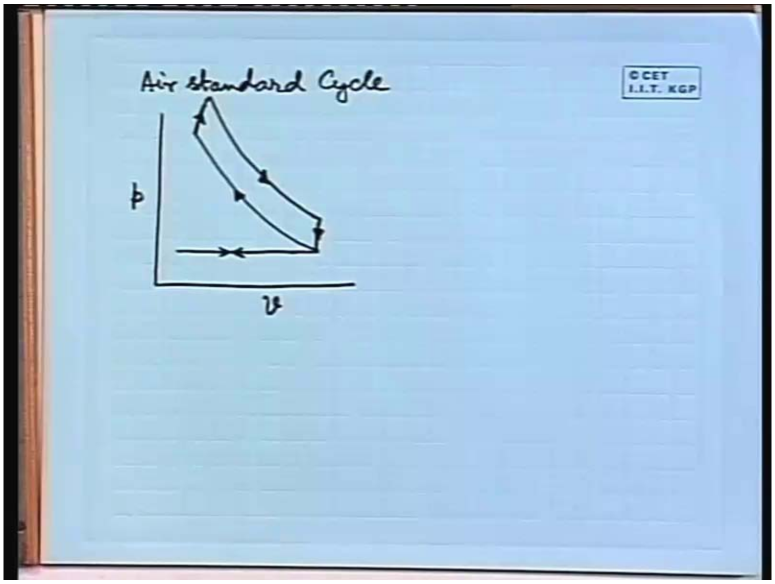

I can represent any air standard cycle here. It is assumed that both the suction and the exhaust, these two processes of intake and exhaust, either we call it suction or intake and exhaust, take place at atmospheric pressure. So, instead of this loop, we will have a straight line. It is pointless to carry this thing along with this cycle diagram; so we can do away with this straight line also. Let us say this is one representation of an ideal cycle. So, abolition of the suction and exhaust process, that is one of the attributes of the air standard cycle. Then we assume that air and only air is the working substance inside. That means air is the working substance and it does not change its chemical property during the process; it does not change its chemical composition during the process.

The combustion process which takes place inside the engine is replaced by a reversible process, in which heat is added from some external agency. Again, we have got some sort of a reversible heat rejection process. Moreover, one assumes that the specific heat remains a constant during the process; there is no change of specific heat. Actually though there will be a large amount of change of pressure and temperature, we assume that the specific heat does not change. This is what the air standard cycle is. Because, we want to first idealize the cycle, then we can see what the performance of the idealized cycle is vis a vis the actual cycle. One can have the air standard cycle instead of the actual cycle for the thermodynamic analysis. We know that basically internal combustion engines are of two types - SI engine and CI engine. For SI engines, for a petrol engine, the idealized cycle is known as the air standard Otto cycle.

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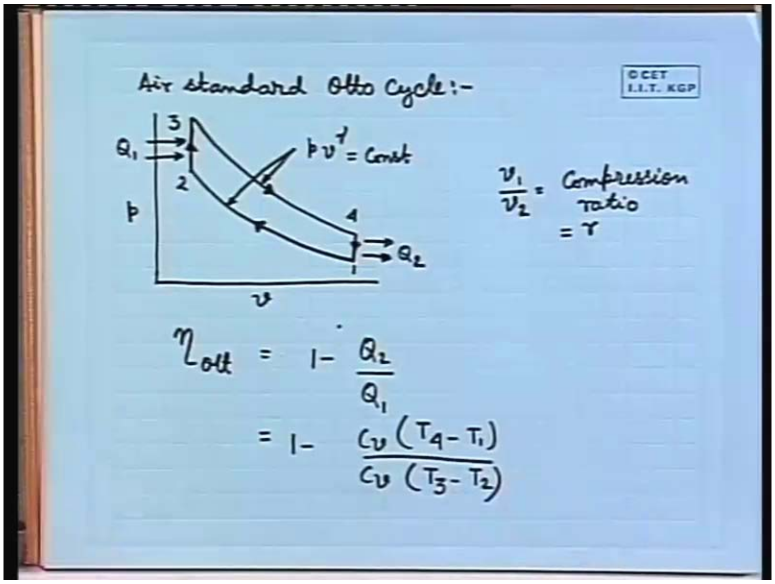

Air standard Otto Cycle:-

$\frac{v_1}{v_2}$ = Compression ratio = r

$$\eta_{ott} = 1 - \frac{Q_2}{Q_1}$$

$$= 1 - \frac{C_v(T_4 - T_1)}{C_v(T_3 - T_2)}$$

In the air standard Otto cycle, we will have an adiabatic compression of air from 1 to 2. This is actually v and this p; constant volume heat addition from 2 to 3, then adiabatic compression from 3 to 4 and then constant volume heat rejection from 4 to 1. These two are adiabatic processes; pv to the power gamma is equal to constant. This we will have and there is one important parameter – the compression ratio. We will have v_1 by v_2 and that is the compression ratio. One can relate this thing to the engine parameters. v_1 is the volume inside the cylinder and v_2 is the clearance volume. By this one will get compression ratio and I like to represent it with r. r is the compression ratio and then the efficiency Otto is equal to 1 minus Q_2 by $Q_{1.}$ One can write 1 minus C_v T_4 minus T_1 divided by C_v T_3 minus $T_{2.}$ This is what we can write.

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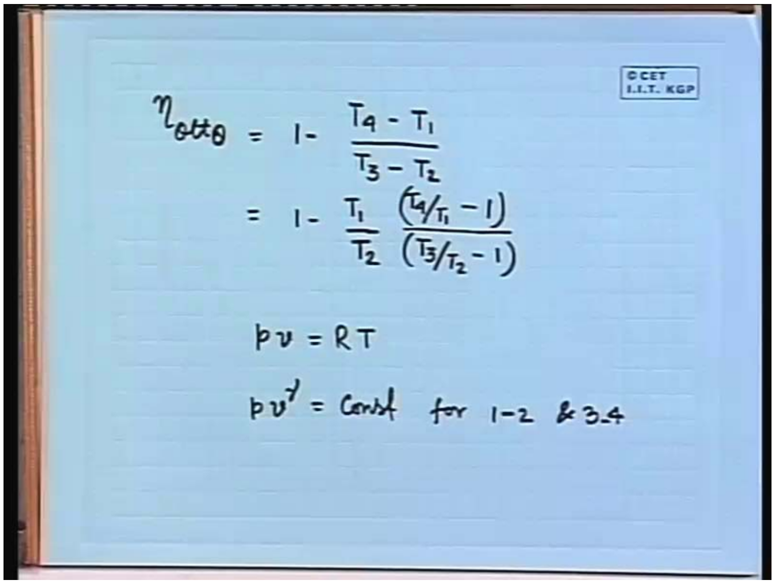

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$$\eta_{otto} = 1 - \frac{T_4 - T_1}{T_3 - T_2}$$

$$= 1 - \frac{T_1}{T_2} \frac{\left(T_4/T_1 - 1\right)}{\left(T_3/T_2 - 1\right)}$$

$$pv = RT$$

$$pv^{\gamma} = \text{Const} \quad \text{for } 1\text{-}2 \ \& \ 3\text{-}4$$

Basically eta$_{otto}$ is equal is equal to 1 minus T_4 minus T_1 divided by T_3 minus T_2. One can write 1 minus T_1 by T_2. Here one can write T_4 by T_1 minus 1 and T_3 by T_2 minus 1. This is what we can write. One has to find out the relationship between different temperatures. If we look into the cycle there are four nodes – 1, 2, 3, 4 and the relationship between the four strategic points is important and that one can find out very easily. One can use the ideal gas law because we are analyzing the air standard cycle where air is assumed to be an ideal gas. One can use pv is equal to RT, so that relationship is there; pv is equal to RT and then for two paths that means pv to the power gamma is equal to constant for 1-2 and 3-4. These two paths, pv to the power gamma is equal to constant. These two conditions we can use and we can determine the relationship between different temperatures.

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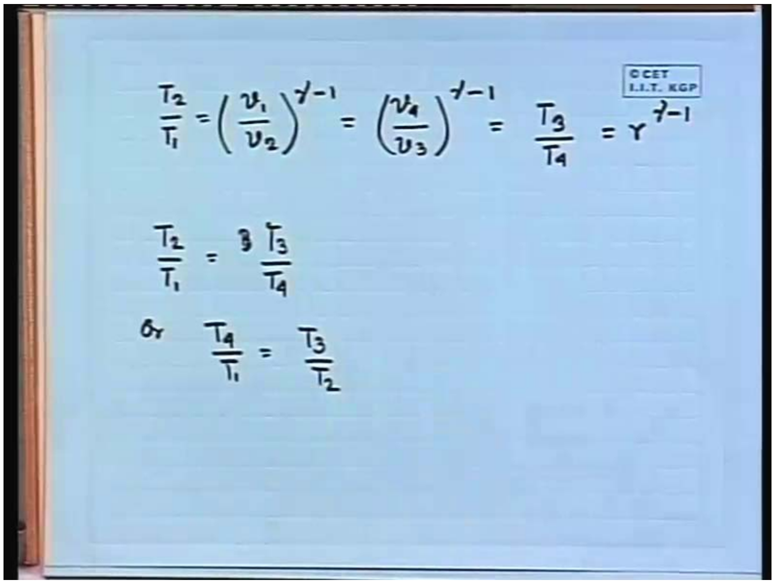

$$\frac{T_2}{T_1} = \left(\frac{v_1}{v_2}\right)^{\gamma-1} = \left(\frac{v_4}{v_3}\right)^{\gamma-1} = \frac{T_3}{T_4} = r^{\gamma-1}$$

$$\frac{T_2}{T_1} = \frac{T_3}{T_4}$$

$$\text{or} \quad \frac{T_4}{T_1} = \frac{T_3}{T_2}$$

Basically one can start from this point, point 1 because here, this is the intake point and generally this point is taken equal to the atmospheric condition. One can start from here and one can move along the cycle. So T_2 by T_1 is equal to v_1 by v_2 to the power gamma minus 1. So this is equal to v_4 by v_3 to the power gamma minus 1. This is equal to T_3 by T_4 which is equal to r to the power gamma minus 1. v_1 by v_2, I have defined as compression ratio, r. What we get is like this - T_2 by T_1 is equal to T_3 by T_4 or T_4 by T_1 is equal to T_3 by T_2. Now, I will write down, I will start from this point.

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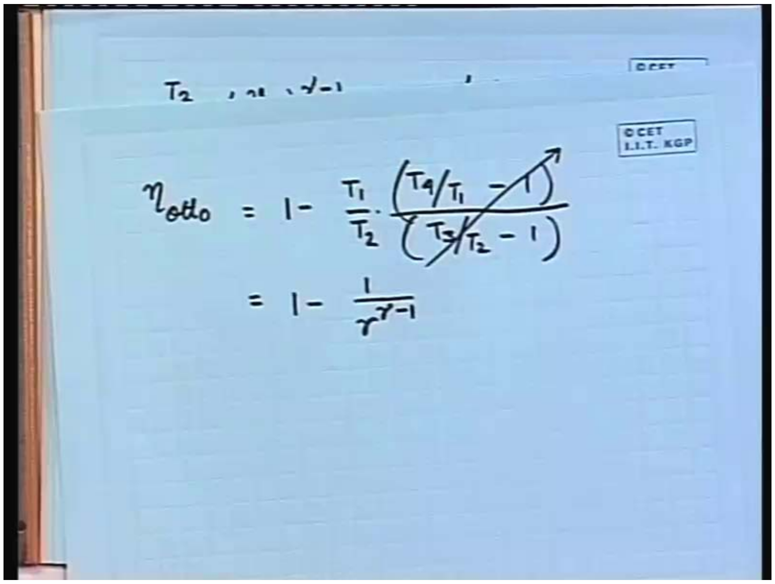

$$\eta_{otto} = 1 - \frac{T_1}{T_2} \cdot \cancel{\frac{(T_4/T_1 - 1)}{(T_3/T_2 - 1)}}$$

$$= 1 - \frac{1}{r^{\gamma-1}}$$

Let us say eta_{otto} is equal to 1 minus T_1 by T_2 into T_4 by T_1 minus 1 divided by T_3 by T_2 minus 1. These two quantities are same. It can be cancelled and then one can write it as 1 minus 1 by r to the power gamma minus 1. This is what we can get from our thermodynamic analysis of the cycle and r is the compression ratio. For analysis of the ideal cycle, one can take gamma to be 1.4. In other cases, one can take different values of gamma but for ideal cycle one can take gamma is equal to 1.4. What one can see is that the efficiency of the Otto cycle can be increased by increasing r. Gamma, we do not have much control - it is a property of the gas or the working fluid. For the working fluid we do not have infinite amount of independence, for selecting working fluid; but r probably we can do something, we can select higher values of compression ratio.

The problem with selecting higher values of compression ratio with the conventional design and conventional fuel of the internal combustion engine is that, that before you produce the spark auto ignition will take place. So it will ignite automatically or of its own before you produce the spark; that will give uncontrolled combustion which is not desirable. That is why we have got a limitation on the value of r; that is why for petrol engine or for SI engine the compression ratio is generally small compared to its counterpart that is diesel engine, so you will have a lower value of compression ratio. Now, we go for the other type of arrangement.

In this case, the Otto cycle is suitable for SI engine, spark ignition engine, where what we do is that when the air is being sucked in the air stream itself, the fuel is sprayed; that means before the air comes into the engine, with the help of a corborator we do it, the fuel evaporates in the air steam. So a fuel-vapor mixture is formed and that mixture then enters the engine. That is one way of having the internal combustion engine. Another thing what I have said is that if we have air only then we can compress it to a very high value. There is no chance of having any combustion because there is no combustible vapor in the air. So, we can compress the air to a very high value and then only we can inject fuel in it. That type of engine is known as diesel engine and the cycle that is also known as diesel cycle.

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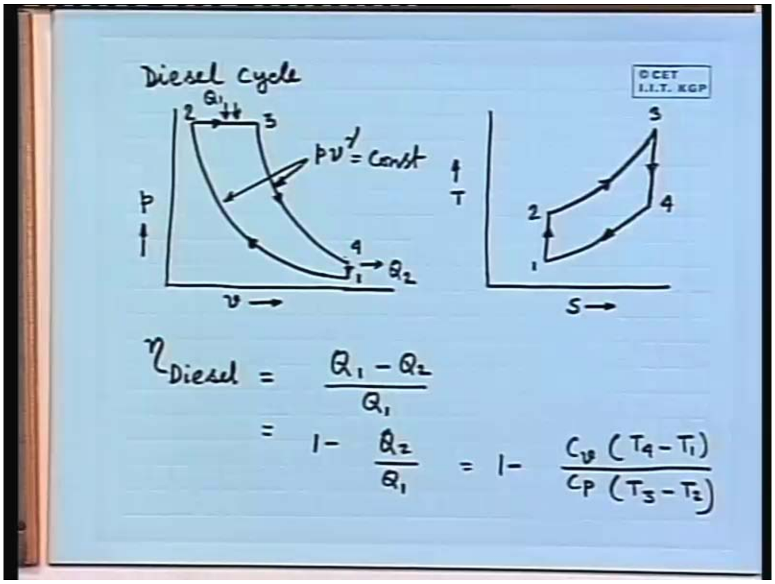

Diesel cycle

$$\eta_{Diesel} = \frac{Q_1 - Q_2}{Q_1}$$

$$= 1 - \frac{Q_2}{Q_1} = 1 - \frac{C_v (T_4 - T_1)}{C_P (T_3 - T_2)}$$

That type of engine is known as the CI engine that is compression-ignition engine. The PV diagram of the diesel cycle will be something like this. This is the PV diagram of the diesel cycle. We can have side by side the TS diagram also. 1 to 2 is the adiabatic process; 2 to 3 there will be rise in temperature; 3 is the highest point and like this 1, 2, 3, 4 - something like this. This is Q_1, this is Q_2 and these two are pv to the power gamma is equal to constant. Efficiency of the diesel cycle will be Q_1 minus Q_2 divided by Q_1; work done divided by the energy supplied. This will be 1 minus Q_2 by Q_1. So, this is 1 minus, Q_2 that is the constant volume heat rejection process, C_v T_4 minus T_1 divided by C_p, constant pressure heat addition, T_3 minus T_2. At this point, we want to define a few quantities.

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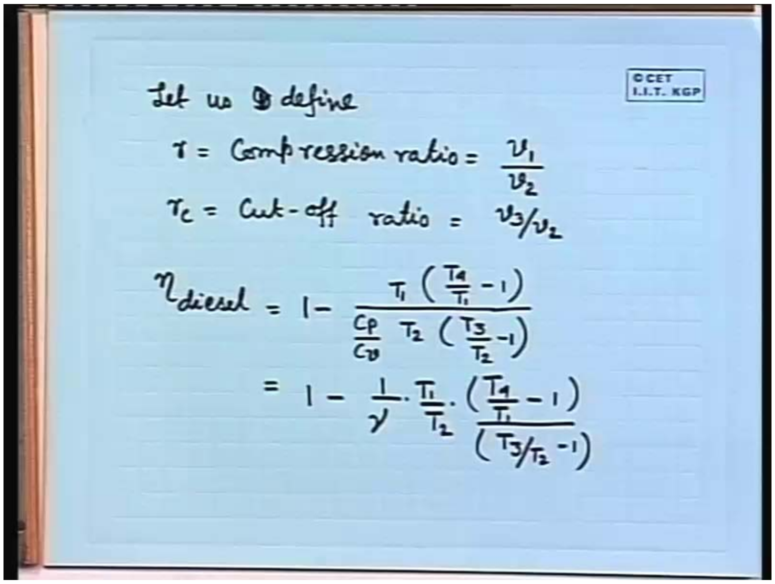

Let us define

r = Compression ratio = $\frac{v_1}{v_2}$

r_c = Cut-off ratio = v_3/v_2

$$\eta_{diesel} = 1 - \frac{T_1\left(\frac{T_4}{T_1} - 1\right)}{\frac{C_p}{C_v} T_2 \left(\frac{T_3}{T_2} - 1\right)}$$

$$= 1 - \frac{1}{\gamma} \cdot \frac{T_1}{T_2} \cdot \frac{\left(\frac{T_4}{T_1} - 1\right)}{\left(T_3/T_2 - 1\right)}$$

Let us define r is equal compression ratio is equal to v_1 by v_2, that is the compression ratio, where v_1 is the total volume of the engine and v_2 is the clearance volume. Already we have seen it in the Otto cycle, it is the same quantity. Then we have got cut-off ratio r_c; we call it v_3 by v_2. Physically it means that at point v_3 the fuel supply is cut-off. We start supplying the fuel at point 2 and at point 3 the fuel supply is cut-off. So, this is your cut-off ratio. I will not go into the detailed derivation. What one has to do is here again, one has to get the relationship between different temperatures. I can do slightly ahead and then I can leave it to you. eta_{diesel} that is 1 minus C_p by C_V and then one can have T_1 here then T_4 by T_1 minus 1 and one can have T_2 here then T_3 by T_2 minus 1. We have 1 minus 1 by gamma into T_1 by T_2 into T_4 by T_1 minus 1 and T_3 by T_2 minus 1. Now the method we have followed earlier one can do the analysis; if we do the analysis, we will have a much cleaner expression.

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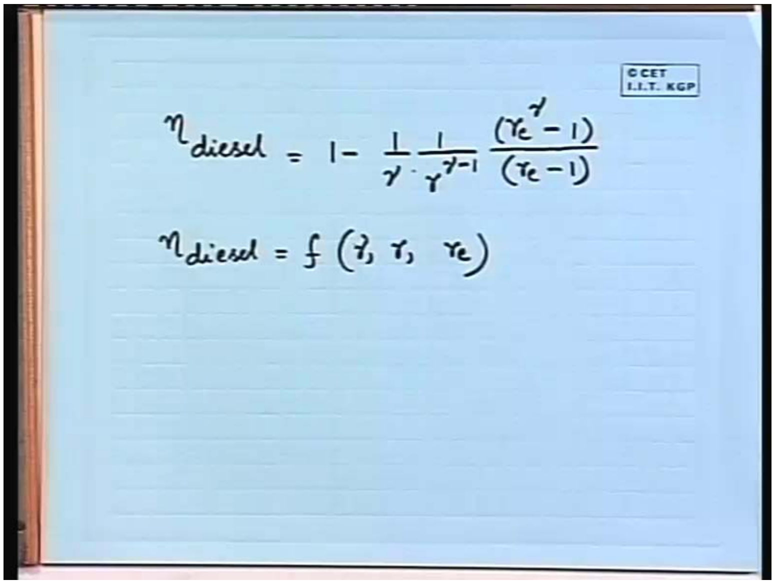

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$$\eta_{diesel} = 1 - \frac{1}{\gamma} \cdot \frac{1}{r^{\gamma-1}} \frac{(r_c^{\gamma} - 1)}{(r_c - 1)}$$

$$\eta_{diesel} = f(\gamma, r, r_c)$$

Tta$_{\text{diesel}}$ is equal to 1 minus 1 by gamma into 1 by r to the power gamma minus 1, then at the top r_c to the power gamma minus 1. This you will get and here you will have r_c minus 1; so this will be the formula. Again, eta$_{\text{diesel}}$ will be a function of gamma, then r and r_c. Here, we do not have much restriction on r. We can increase r. In fact in CI engine, we have got CI engines, we have got high compression ratio. The only problem is more the compression ratio more bulky will be the engine. The engine weight will become larger and larger to withstand the pressure fluctuation; one side we are having low pressure almost near to atmospheric and other side we have got a much higher pressure; so engine will be bulkier.

Again, there are practical limits. So, we cannot go beyond certain value of r; r_c also one should restrict it. This is the engine cycle diagram (Refer Slide Time: 43:15). If we have got lower r_c, then fuel cannot be injected. If you have got higher r_c then what we can see is that we are not getting large amount of work due to the expansion. So, one has to compromise between these two. In the diesel cycle we will have the efficiency in terms of these quantities. In fact, we have idealized the combustion process by two different techniques or by two different ideal processes, reversible processes. First, we have thought that the combustion process can be represented by a constant volume heat addition process. Next, we have idealized that the combustion process can be idealized as a constant pressure heat addition process. In fact, the combustion process is so complex, that it cannot be idealized either by constant volume process or by constant pressure process. But what has been seen is that at the initial stage of the combustion there is very quick increase in pressure, the volume remains almost constant. After that, pressure remains more or less constant but there is increase in volume. People thought that probably a better representation of the process will be, if we have both constant volume and constant pressure process. This cycle is known as a mixed pressure cycle or dual cycle. The dual combustion cycle or mixed combustion cycle or mixed pressure cycle - there are different names for the cycle which I am going to describe.

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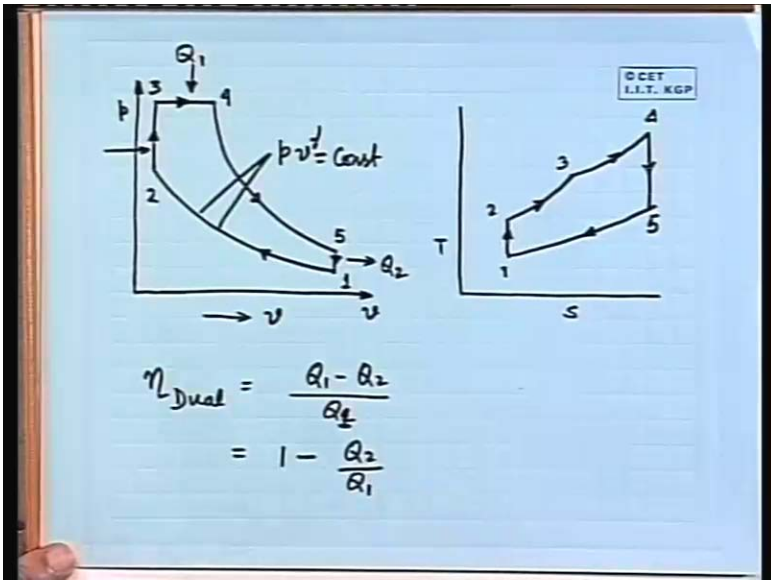

$$\eta_{Dual} = \frac{Q_1 - Q_2}{Q_1}$$
$$= 1 - \frac{Q_2}{Q_1}$$

Ideally, the cycle is something like this. Pressure, volume and we start form one point 1. 1 to 2 is the compression process, 2 to 3 is the constant volume heat addition, 3 to 4 is the constant pressure heat addition, 4 to 5 is the adiabatic expansion and 5 to 1 is the heat rejection process which takes place at constant volume. What we can have is through both these two, we can have heat addition. So, we have Q_1 then you have Q_2. These two are adiabatic processes, this is constant volume and we can have a TS representation also. This is constant entropy process that means reversible adiabatic process. This is 1 to 2, then, this is a constant volume process - 2 to 3, constant pressure process - 3 to 4, 4 to 5 adiabatic process and 5 to 1 constant volume heat rejection process. This is how we will get the cycle. The efficiency of dual combustion cycle or mixed combustion cycle will be Q_1 minus Q_2 divided by Q_1 is equal to, this is the heat addition, so it will be 1 minus Q_2 by Q_1.

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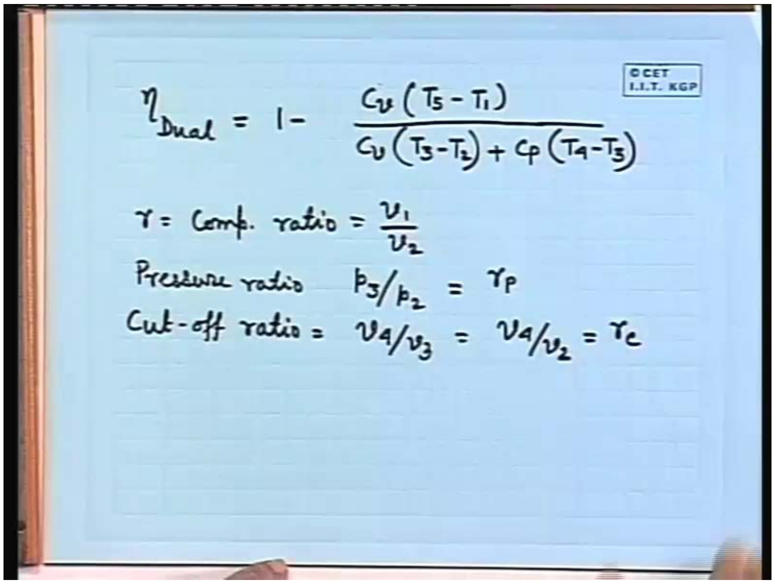

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$$\eta_{Dual} = 1 - \frac{C_v (T_5 - T_1)}{C_v (T_3 - T_2) + C_p (T_4 - T_3)}$$

r = Comp. ratio = $\frac{v_1}{v_2}$

Pressure ratio $p_3/p_2 = r_p$

Cut-off ratio = $v_4/v_3 = v_4/v_2 = r_c$

Let us start from η_{dual} is equal to 1 minus C_v, constant volume heat rejection process, T_5 minus T_1; there are two heat addition processes, so this will be first C_v T_3 minus T_2 and plus C_p T_4 minus T_3. At this point let us define r that is compression ratio that will be v_1 by v_2. Then we have got pressure ratio that is p_3 by p_2 and we have got cut-off ratio that will be equal to v_4 by v_3 that is equal to v_4 by v_2. The pressure ratio we call it r_p and we call it r_c, cut-off ratio.

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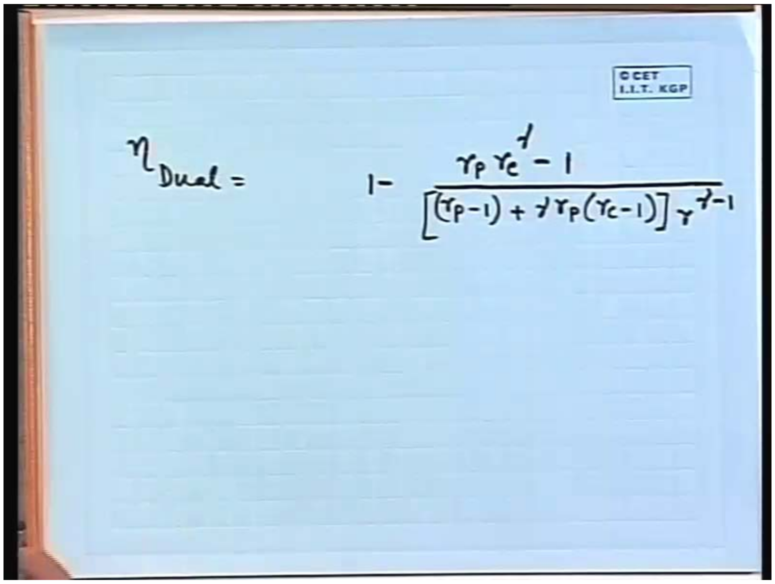

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$$\eta_{Dual} = 1 - \frac{r_p r_c^{\gamma} - 1}{\left[(r_p - 1) + \gamma r_p (r_c - 1)\right] r^{\gamma - 1}}$$

If you introduce all these things then you will get eta$_{dual}$ is equal to 1 minus r_p r_c to the power gamma minus 1 by r_p minus 1 plus gamma r_p r_c minus 1 and this whole will be r to the power gamma minus 1. This can be taken as the general expression and if we put let us say r_p is equal to 0, we will get the expression for diesel engine. That we can check also. r_p is equal to 1 not 0. You can try those things you can first thing you can try the derivation of this equation and then you can try all these things.

I think we will stop here and we will continue from this point in our next class.