**Thermal Engineering Basic and Applied**
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**Lecture - 56**
**Thermodynamic Analysis of CI Engine**

I welcome you all to the session of Thermal Engineering Basic and Applied. Today, we shall discuss about the thermal analysis of CI engine. If we recall in the last class we have discussed about the performance of Otto cycle and to do that we had to consider several processes those constitute together to form the Otto cycle. So, today we need to discuss about the thermodynamic performance of CI engine.

And you all know that the processes of CI engine are analyzed by comparing with an air standard cycle that means the processes which are there in a CI engine those processes together constitute a cycle and if you would like to analyze the cycle performance we need to compare that cycle with an air standard cycle and the air standard cycle which is used to analyze the performance of CI in is known as diesel cycle.

So, before going to discuss about rather before going to derive the efficiency or the thermal efficiency of the diesel cycle. Let us briefly look into the processes which are there in a CI engine.

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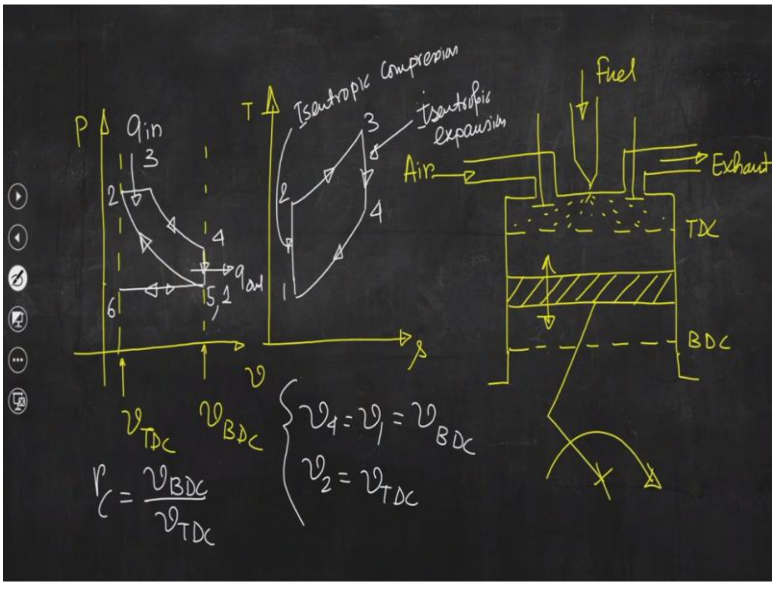

So, if we draw the schematic of a CI engine. So, this is intake valve and this is exhaust valve. The first stroke is the intake stroke and during the stroke piston travels from top dead center to the bottom dead center while the exhaust valve is remaining closed but intake is open and fresh air is drawn into the engine cylinder. So, that is the intake stroke.

Next stroke is the compression stroke so when piston is at BDC at the end of the intake stroke exhaust valve is already closed, intake valve is now closed and piston travels from BDC to TDC and the air which is drawn into the cylinder during intake stroke is now getting compressed so that is the compression stroke. When piston is about to reach at TDC during the end of the compression stroke both valves are closed.

What is done fuel is supplied or fuel is injected into the cylinder in the form of spray and that is what I had tried my best to show the spray pattern and when piston is at TDC or little away from TDC in the next stroke, entire combustion is completed and when the combustion is completed as we know what we have discussed in the Otto cycle in the context of Otto cycle that it is because of the rise in pressure and temperature of the working substance the thrust which is being applied on the piston face is the responsible force for the movement of piston from TDC to BDC that is the power stroke. So, this is basically power and sometimes it is known as expansion. So, basically what is happening that when piston is at TDC or piston is again traveling back from TDC to BDC after the compression stroke, combustion would be completed.

And it is because of this combustion the rise in temperature and pressure of the working substance which is there inside the cylinder will create a thrust on the piston face and that is the driving force for the movement of piston from TDC to BDC again and that is the power stroke. So, it is getting the combustion gases which are there inside the cylinder is now expanded.

So, combustion gases which are there inside the cylinder are now getting expanded because of the movement of piston from TDC to BDC and when again piston is coming towards BDC, before it reaches at BDC exhaust valve is allowed to open essentially to take blow down. So, the purpose is to reduce the gas pressure inside the engine cylinder. So, when piston is about to reach at BDC during end of the power stroke exhaust valve is allowed to open.

The sole purpose is to reduce the gas pressure inside the combustion chamber. So, that when piston is again coming back from BDC to TDC in the next stroke it will experience relatively lesser resistance. So, when exhaust valve is allowed to open certain amount of, combustion gases will leave out from the combustion chamber or cylinder and while the combustion gases are leaving from the engine cylinder, those gases will carry certain amount of energy.

So, it is called blow down or heat rejection and finally when piston is again traveling back from BDC to TDC intake valve is remaining close, but exhaust is now fully open and that it is called exhaust stroke. So, the combustion gases, those are there inside the combustion chamber or cylinder will now leave from the combustion chamber.

So, combustion gases will go out from the combustion chamber or engine cylinder during the exhaust stroke. So, we have understood all these strokes and if we try to map all these processes in P-v and T-s plane because we have discussed in the last class to establish the mathematical expression of thermal efficiency we need to map all these processes in different thermodynamic planes.

What are those different planes? One is P-v another is T-s and we have discussed that the T-s plane is very important because the area under the process line in T-s plane will give us the heat interaction. So, from there directly without going for any mathematical calculation, just by knowing the process line and if we can draw the area under the process line from that plane we can calculate the amount of heat being supplied to the system.

And the amount of heat being rejected from the system, from there we can quantify the thermal efficiency. One important part is that in the context of Otto cycle we have discussed that the combustion process which is very important and this process as if is providing certain amount of heat to the system. So, when we had tried to represent that particular process in particularly in P-v plane that is a kind of constant volume heat addition that is what we have discussed in the context of Otto cycle.

But can we again represent that particular process that is combustion process by a constant volume heat addition in P-v plane pertaining to this cycle that is diesel cycle or not that is what I would like to discuss briefly over here. You know that what we have discussed in the context of Otto cycle is that when piston is reaching at TDC for the Otto cycle SI engines that it is not a pure air rather it is charge air fuel mixture.

So, air fuel mixture is getting compressed when piston is traveling from BDC to TDC both valves are closed and when piston is reaching at TDC or about to reach at TDC we need to switch on this spark plug and the moment when spark plug switch is on then it ignites the total charge that is remaining inside the cylinder as a compressed state. So, that particular situation ensure that the entire combustion should be completed when piston is remaining close at TDC.

Though it is very unlikely that the moment of the piston is spontaneous so it is not possible that we can keep the piston there for a while when it is reaching a TDC an entire combustion should be completed, but the assumption of constant volume combustion that is when piston is reaching closer to TDC and we need to switch on the spark plug and the moment when spark plug switch is on the entire charge will be combusted.

And as if momentarily when piston is reaching TDC entire combustion would be completed and as if the volume is remaining constant so it is a constant volume combustion, but for the CI engines or the diesel cycle that is what we are going to discuss today is that it is not possible to represent that combustion process by constant volume heat addition.

Piston will be reaching at TDC, in fact even if we start spraying fuel when piston is about to reach at TDC then also it is not possible to mimic the process of combustion by a constant volume because we have discussed about the ignition delay.

And it has two components one is physical delay another one is the chemical delay. So, these two different delays constitute together the ignition delay. So, because nozzle is a mechanical device. So, this particular device needs finite amount of time to spray certain amount of fuel per cycle into the engine cylinder. So, during that particular time it is very unlikely that the piston will remain exactly a TDC and the volume will remain constant.

Instead of considering the constant volume combustion I mean combustion by constant volume heat addition process for the CI engines what is, consider is that when piston is about to reach at TDC fuel supply to the engine cylinder is started and the fuel being supplied during first phase will be combusted and it is because of this combustion there will be certain amount of rise in pressure inside the cylinder.

And when piston is again traveling back from TDC to BDC towards BDC entire combustion would be completed and the cumulative effect of this should be such that the pressure inside the cylinder is remaining more or less constant instead of volume. So, as I said movement of the piston is very spontaneous and you know it is very difficult to assume that the piston will be there at TDC.

And during that time entire combustion will be completed and this is not possible accounting for this ignition delay because the supply of total amount of fuel that is needed for cycle requires certain amount of time also the if we can ensure that the fuel is supplied in proper time accounting for the chemical delay that we have discussed, it will take certain amount of time for the total combustion.

And at that time piston again will come back from TDC to BDC. If it is the case, we can see that piston is reaching towards TDC and again coming back from TDC. So, volume will not remain constant so it is very difficult to assume the process by constant volume heat addition process instead what we can do we can assume that the pressure which is being developed during the supply of first phase of fuel.

That will take part in the combustion and it is because of this first phase of combustion a rise in pressure will be there. So, that pressure is such that when piston is again coming back from TDC to BDC you can argue with me that the pressure will fall, but at that time again second phase of combustion has already started. So, as if the pressure is remaining constant more or less during the entire process.

And that is why the combustion process of a CI engine is represented by a constant pressure heat addition process in P-v plane. So, that is what is very important to remember. So, now if we draw the P-v and T-s plane that is very important to analyze. So, if we assume this is so this is $V_{BDC}$ this is $V_{TDC}$ and say this is intake process constant pressure air intake.

And if we say this is point 1 when piston is again coming back from BDC to TDC that is the compression process and that process as I said that we are trying to analyze all the processes using an air standard cycle and that is the diesel cycle and we are assuming that the working substance is behaving just like an ideal gas and we can use ideal gas equation to know the pressure and temperature at the end of different processes.

So, this is the compression process and we have discussed in the last class that this is represented by an isentropic compression process. So, 2 to 3, when piston is at TDC as I said that combustion will start, but combustion will last till piston has started traveling from TDC to BDC and as if the pressure is remaining constant accounting for the rise in pressure during both first phase of combustion and last phase of combustion.

And this is the point 3 and the you can see that it is not a constant volume combustion, the combustion is not represented or mimicked by constant volume heat addition process because volume is getting changed instead, but pressure is remaining constant and finally 3 to 4 so this is the expansion or power stroke and 4 to 1 that when piston is about to reach at BDC, volume is remaining more or less constant.

What we need to do? We need to open the exhaust valve to take certain blow down; blow down of the combustion gases only to reduce pressure inside the cylinder and this blow down process as if is the representative measure of heat rejection from the system. So, basically that is 4 to 1 that is q out. So, the points 5 and 1, these two points coincide each other.

And again when piston is coming back from BDC to TDC exhaust valve is now fully open the 5 to 6. So, 6 to 1 was the constant pressure intake that we have just mentioned and finally 5 to 6 is constant pressure blow down. So, these two processes are thermodynamically same. So, we no need to consider these two processes while analyzing the thermal performance of this cycle.

And this 2 to 3, q in, so constant pressure heat addition and 1 to 2 is isentropic process. So, 1 to 2 isentropic compression and 3 to 4 isentropic expansion. So, we can just go for the calculation of pressure and temperature at the beginning and at the end of each process and from there we can quantify.

One thing I would like to tell you so you can see that this v4 equal to v1 equal to $V_{BDC}$ and v2 equal to $V_{TDC}$ and V BDC by V TDC that is the compression ratio. So, compression ratio $r_c =$

$v_{BDC}/v_{TDC}$ that is what we have discussed in one of the previous classes. So, we can now go for the calculation of the thermal efficiency. One thing I would like to tell you that that here process 2 to 3 is basically the combustion process.

And as if this process is represented in this P-v plane by a constant pressure heat addition process and in this process we can see from this P-v plane is that there is a change in volume. So, in this process of combustion, volume of the working substance is getting changed from v2 to v3. So, the ratio of this change in volumes is known as cut off ratio pertaining to the combustion of CI engines.

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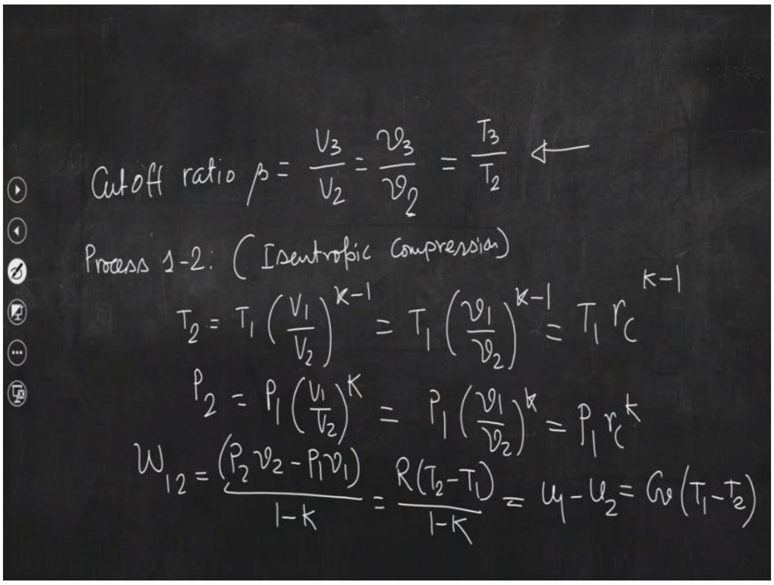


So, $Cut-off\ ratio\ \beta = \frac{V_3}{V_2} = \frac{v_3}{v_2} = \frac{T_3}{T_2}$ (from Ideal gas equation). So, there is a change in volume of the working substance during the combustion process and that is what we have discussed that it is very unlikely to expect that the piston will be there at TDC and momentarily all the entire combustion would be completed. It is not a case for this particular type of engine because the supply of fuel into the combustion chamber which is an essential element for the combustion would require a finite amount of time accounting for the ignition delay.

And it is because of this delay volume is going to change during the combustion process, but we can represent this process by constant pressure heat addition process and this is a very good assumptions that I can tell you because there will be rise in pressure during first phase of combustion and that pressure perhaps will be reduced as the piston is traveling from TDC to BDC.

But the rise in pressure due to second phase of combustion we will compensate that rise in pressure and as if the pressure is remaining constant during the entire process of combustion and that is represented by this. So, what we can see from here is that the T3 equal to T max. So, when the combustion process is completed the rise in temperature will lead to the maximum temperature and that is T3. Similarly, $p_3 = p_2 = p_{max}$ because momentarily that pressure is remaining constant and the pressure is almost the maximum pressure of this cycle.

Process 1-2 (Isentropic Compression)

$$T_2 = T_1 \left(\frac{V_1}{V_2}\right)^{k-1} = T_1 \left(\frac{v_1}{v_2}\right)^{k-1} = T_1 r_c^{k-1}$$

$$P_2 = P_1 \left(\frac{V_1}{V_2}\right)^{k} = P_1 \left(\frac{v_1}{v_2}\right)^{k} = P_1 r_c^{k}$$

Because this is the compression process so we need to supply work into the system.

$$W_{12} = \frac{p_2 v_2 - p_1 v_1}{1-k} = \frac{R(T_2 - T_1)}{1-k}$$

Just applying first flow applied to the non flow process with no heat interaction between the system and surroundings. So, basically the rise in temperature that is there due to compression process, but there is no heat interaction from the system into the surroundings.

$$W_{12} = u_1 - u_2 = C_v(T_1 - T_2); q_{12} = 0$$

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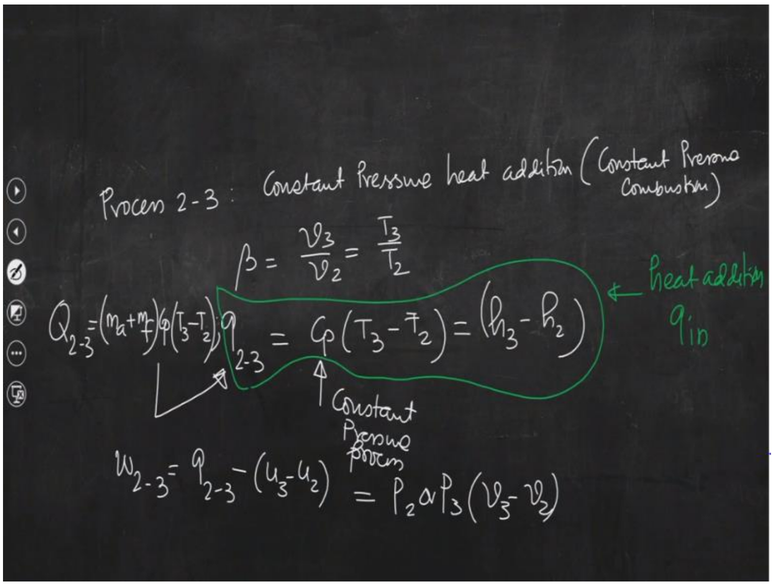

Process 2 - 3 (Constant pressure heat addition or constant pressure combustion)

So, we are we are interested in the addition of heat into the system that is I can write in specific form that is $C_p(T_3 - T_2)$, why it is Cp because the process is constant pressure process.

$$\beta = \frac{v_3}{v_2} = \frac{T_3}{T_2}$$

$$Q_{23} = (m_a + m_f)C_p(T_3 - T_2); q_{23} = C_p(T_3 - T_2) = h_3 - h_2$$

So, if we try to recall the combustion process for the Otto cycle, no work done as constant volume process but this is a constant pressure process. So, what will be the work done? Again if I write first law for the system that is for the non flow process.

$$w_{23} = q_{23} - (u_3 - u_2) = p_2 \; or \; p_3(v_3 - v_2)$$

So, what I can write over here it is very important to mention that. So, this is the heat addition in the cycle.

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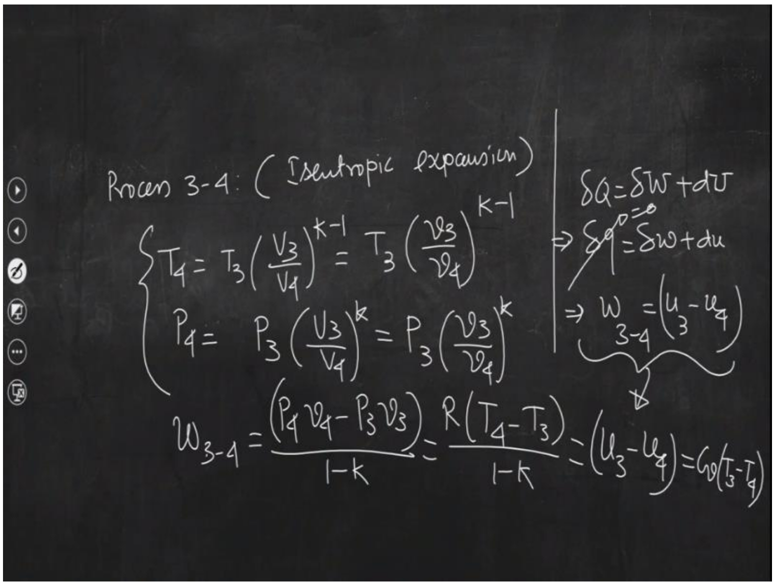


Next is process 3 to 4 and this is again isentropic expansion.

$$T_4 = T_3\left(\frac{V_3}{V_4}\right)^{k-1} = T_3\left(\frac{v_3}{v_4}\right)^{k-1}$$

$$P_4 = P_3\left(\frac{V_3}{V_4}\right)^{k} = P_3\left(\frac{v_3}{v_4}\right)^{k}$$

So, we can write the pressure and temperature at the end of the expansions process because we know the pressure and temperature at the beginning of the expansion process that is T3 and P3 and those are T max and P max.

So, there is no heat interaction between system and the surroundings, but what is the work interaction

$$\delta Q = \delta W + du; \delta Q = 0 \rightarrow W_{34} = u_3 - u_4$$

$$W_{34} = \frac{p_4 v_4 - p_3 v_3}{1-k} = \frac{R(T_4 - T_3)}{1-k} = u_3 - u_4 = C_v(T_3 - T_4)$$

If we go to the final process that is the process 4 to 5 or 4 to 1 because points 5 and 1 these two points you know coincide each other.

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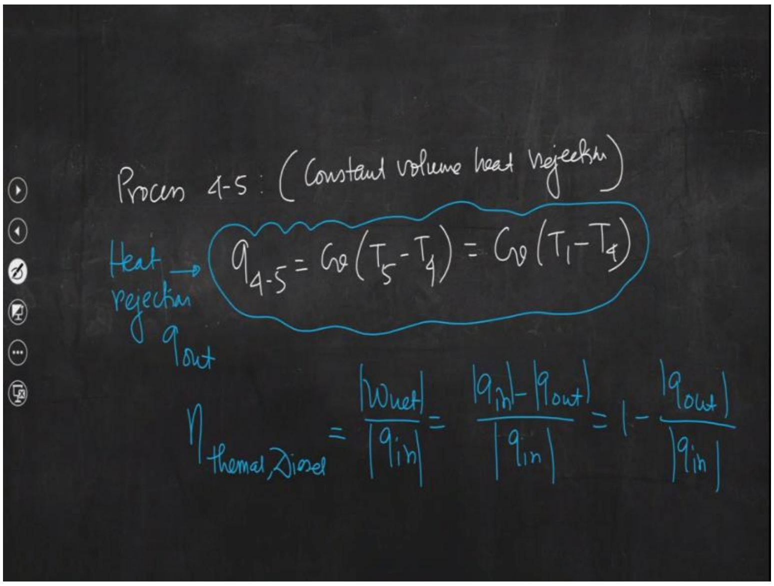


So, if we write process 4 to 5 that is constant volume heat rejection. Why it is heat rejection? Because as I said that blow down is taken at constant volume only to reduce pressure inside the cylinder and during this process when gases are leaving from the cylinder those gases are carrying certain amount of energy from the system so as if heat is getting rejected and it is very important you know that second law of thermodynamics puts a restriction that there must be a heat rejection, if we need to run all this process in a cyclic manner. So, what we can write that this is constant volume process so work done is equal to 0.

$$q_{45} = C_v(T_5 - T_4) = C_v(T_1 - T_4)$$

So, this is heat rejection q out and if we go to the previous slide, next process is 1 to 6 and as I said that process 6 to 1 and 1 to 6, these two processes are similar thermodynamically. So, rather it is not necessary that we should consider this two process in the cycle while calculating because they will cancel each other.

So, even if we consider these two process separately ultimate consequence should be 0. So, considering these two processes will be null.

$$\eta_{th,Diesel} = \frac{|W_{net}|}{|Q_{in}|} = \frac{|Q_{in}| - |Q_{out}|}{|Q_{in}|} = 1 - \frac{|Q_{out}|}{|Q_{in}|}$$

We are interested in the absolute value of this because heat and work these two in thermodynamics are also having certain direction. So, while we are calculating efficiency or thermal performance we are interested in the absolute value of these two quantities not the direction.

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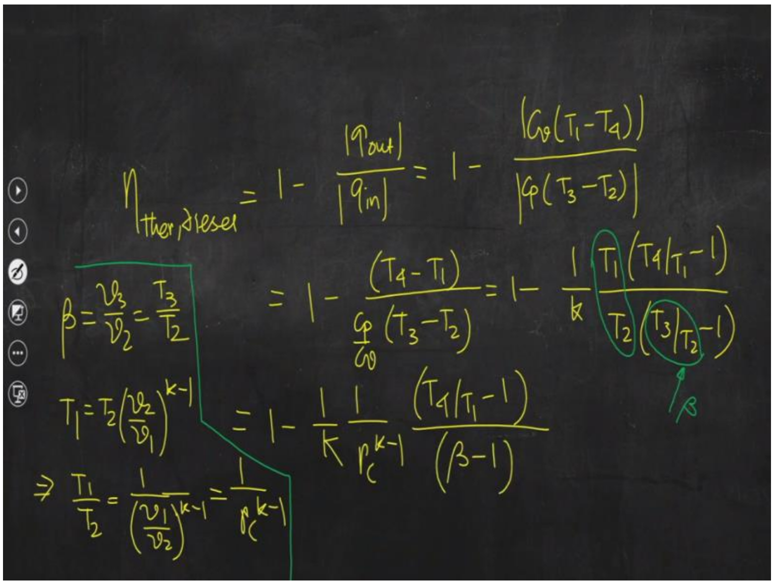

$$\eta_{th,Diesel} = 1 - \frac{|Q_{out}|}{|Q_{in}|} = 1 - \frac{|C_v(T_1 - T_4)|}{|C_p(T_3 - T_2)|} = 1 - \frac{T_4 - T_1}{\frac{C_p}{C_v} T_3 - T_2} = 1 - \frac{1}{k}\frac{T_1}{T_2}\frac{{T_4}/{T_1} - 1}{{T_3}/{T_2} - 1}$$

$$\beta = \frac{v_3}{v_2} = \frac{T_3}{T_2};\ T_2 = T_1\left(\frac{V_1}{V_2}\right)^{k-1} \rightarrow \frac{T_1}{T_2} = \frac{1}{\left(\frac{v_1}{v_2}\right)^{k-1}} = \frac{1}{r_c^{k-1}}$$

$$\eta_{th,Diesel} = 1 - \frac{1}{k}\frac{1}{r_c^{k-1}}\frac{{T_4}/{T_1} - 1}{\beta - 1}$$

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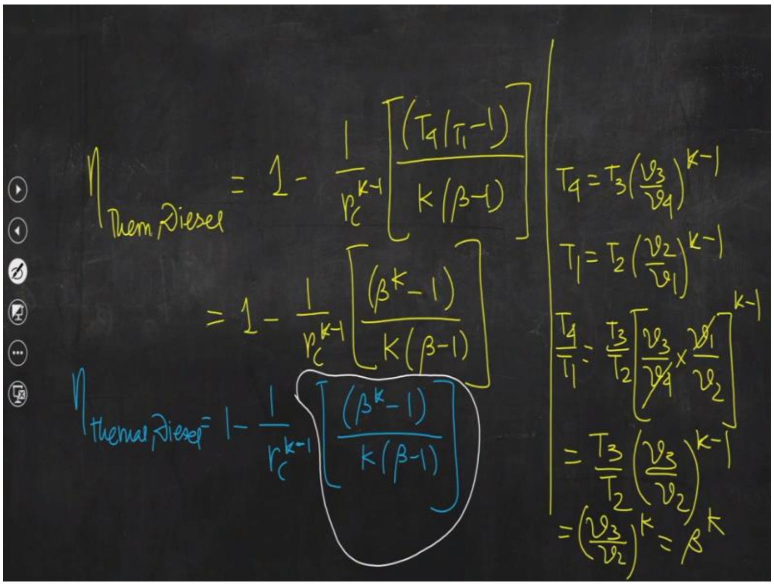

We know

$$T_4 = T_3\left(\frac{V_3}{V_4}\right)^{k-1};\ T_2 = T_1\left(\frac{V_1}{V_2}\right)^{k-1} \rightarrow \frac{T_4}{T_1} = \frac{T_3}{T_2}\left[\frac{V_3}{V_4}\times\frac{V_1}{V_2}\right]^{k-1} \ and\ v_4 = v_1$$

$$\frac{T_4}{T_1} = \frac{T_3}{T_2}\left[\frac{V_3}{V_2}\right]^{k-1} = \frac{V_3}{V_2}\left[\frac{V_3}{V_2}\right]^{k-1} = \left[\frac{V_3}{V_2}\right]^{k} = \beta^k$$

Now,

$$\eta_{th,Diesel} = 1 - \frac{1}{r_c^{k-1}}\frac{{T_4}/{T_1} - 1}{k(\beta-1)} = 1 - \frac{1}{r_c^{k-1}}\left[\frac{\beta^k - 1}{k(\beta-1)}\right]$$

So, this is the thermal efficiency of the diesel cycle and that we can see from this expression is the efficiency of diesel cycle is function of compression ratio as well as the cutoff ratio. Now $\left[\frac{\beta^k-1}{k(\beta-1)}\right]$ is extra term, in comparison to the thermal efficiency of Otto cycle.

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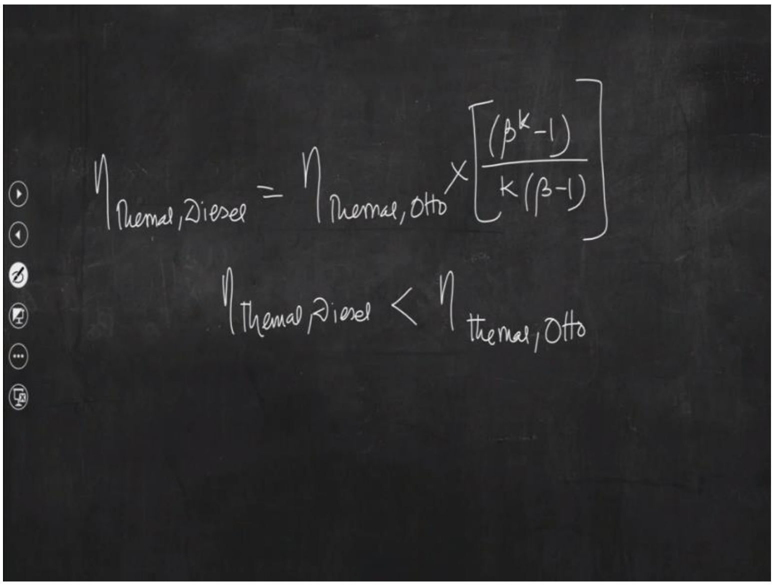


$$\eta_{th,Diesel} = \eta_{th,Otto}\left[\frac{\beta^k - 1}{k(\beta - 1)}\right]$$

k is always greater than 1 and cut off ratio if we know the definition $\frac{V_3}{V_2}$ which is always greater than 1. So, the, quantity that we have written inside the bracket is always greater than 1.

So, for a given compression ratio the thermal efficiency of diesel cycle is less than thermal efficiency of Otto cycle and it indicates that constant volume combustion is more efficient than the constant pressure combustion.

Because for the Otto cycles, we could represent the combustion process by constant volume heat addition process, but for the diesel cycle we had seen that we could represent the combustion process by constant pressure heat addition process, since efficiency for a given compression ratio, efficiency of Otto cycle is greater than efficiency of diesel cycle which indicates that the constant volume combustion is efficient than the constant pressure combustion.

But mind it diesel engines rather run with a higher compression ratio than the Otto cycle and hence efficiency of diesel cycles should be always greater than efficiency of the Otto cycle. So, to summarize today we have discuss about the combustion process in CI engines and we had seen that the combustion process of CI engine can be represented by a constant pressure heat addition process which is in contrast to the constant volume heat addition process that is there in the in SI engines.

And finally we could establish the thermal performance or thermodynamic efficiency of the diesel cycle and we had seen that the efficiency can be represented as a function of compression ratio as well as the cutoff ratio. So, with this I stop here today and we shall continue our discussion in the next class. Thank you.