Thermal Engineering Basic and Applied

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Lecture - 55
Thermodynamic Analysis of SI Engine

I welcome you all to this session of Thermal Engineering Basic and Applied and the topic of our today's discussion is the Thermodynamic Analysis of SI Engine. So, before going to have this analysis today, let us first review several processes those already we have discussed and then we can try to map those processes again in different thermodynamic planes essentially to estimate the efficiency because SI engine, spark ignition engine we had seen that we are supplying fuel and at the cost of that fuel we are trying to get some work output.

And we have discussed that the stored energy that is the chemical energy which is remaining stored within the fuel is converted to the internal energy of the gases inside the combustion chamber and that internal energy is eventually converted to the work which is available at the crankshaft. So, you can understand that again through several processes using this particular engine we are trying to have energy conversion.

And since it is nothing but the conversion of energy from its one form to another form, we need to calculate the efficiency or performance. So, why it is called thermodynamic analysis because if we just try to recall several processes and then we will find that, inside the combustion chamber pressure, volume and temperature of the working substance, these three properties are continuously changing. So, if we need to know what is the volume at the end of any particular process, then we need to know about several thermodynamic relations laws from there we can quantify what would be the work output finally in terms of several thermodynamic properties.

So, let us first review again several processes that constitute together to form this cycle of SI engine.

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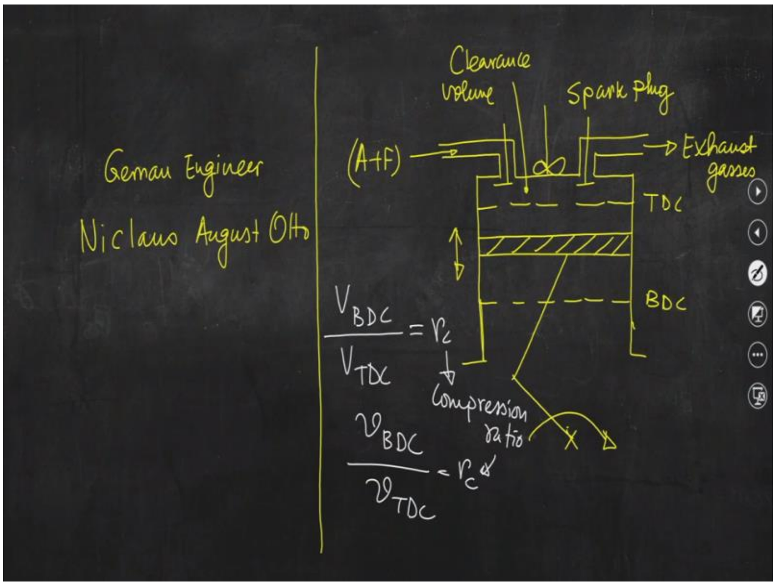

And to do that let us first draw the schematic. So, we can see this is a schematic depiction of a spark ignition engine, of course we did not show several components, but these are required only to understand several processes. We have discussed that engine cylinder is having to and fro moment between these two locations that is bottom dead center and top dead center.

And we had seen that there are two valves, intake valve and exhaust valve. So, when intake valve is open, exhaust valve is closed piston comes from TDC to BDC and that is the intake stroke and in this stroke we are taking fresh charge is drawn into the cylinder. So, this is the intake stroke, next stroke is exhaust is remaining closed, but when piston reaches at BDC at the end of the intake stroke, this intake valve is closed.

And then piston comes from BDC to TDC. So, the fresh charge which is they are inside the, engine cylinder then that gets compressed. So, the fresh charge gets compressed in the stroke and that is the compression stroke. So, when piston comes at TDC that is at the end of the compression stroke, both valves are closed.

So, basically this is the clearance volume. So, the compressed charge is remaining there in the clearance volume and spark plug switch is on, I mean spark is initiated and this is the combustion that we have discussed and it is because of this combustion, that the rise in pressure and temperature inside this cylinder will be excessively high.

That high pressure create a thrust on the piston face and the piston comes again back to BDC from TDC and that is the power stroke that we have discussed. Both valves are remaining even close during that stroke that is the power stroke and that is also known as expansion and finally when piston is at BDC that is at the end of the power stroke then exhaust valves is allowed to open piston again comes from BDC to TDC.

And inside the combustion chamber combustion gases expel out through the exhaust manifold to the ambience. So, we have discussed about all these four processes several times in previous classes. Now you have understood that one stock is power stroke that is the stroke in which we are getting power that means if you try to understand out of these four processes rather four strokes only one stroke is power stroke because you are getting power remaining other three strokes are ideal stroke.

And we need to supply power to the crankshaft. So, these all four processes occur in a cyclic manner rather these four processes constitute together to form the cycle of the SI engine because it is spark ignition engine so combustion will not be completed until and unless spark plus switch is on. So, now let us try to map all these processes in two different thermodynamic planes.

One is PV another is TS and why we are trying to map all these processes in thermodynamic planes because as I said we need to understand several thermodynamic properties both at the beginning and end of each stroke only to calculate the thermal performance or thermodynamic efficiency of this cycle which is very important. Now for this for the analysis of SI engine what we can do?

We have understood the cycle, though thermodynamic cycle, at the end of the cycle all the working substance which is nothing but several gases that will leave out from the engine cylinder. So, those gases are not cycled back into the process. So, it is a open cycle so it is better to say a mechanical cycle. So, for the analysis of SI engine this cycle should be approximated with an air standard cycle.

And the air standard cycle which is used for this particular analysis that is for the analysis of SI that is known as Otto cycle. So, German engineer Nikolaus August Otto who invented this cycle and that is why this cycle is named as Otto cycle.

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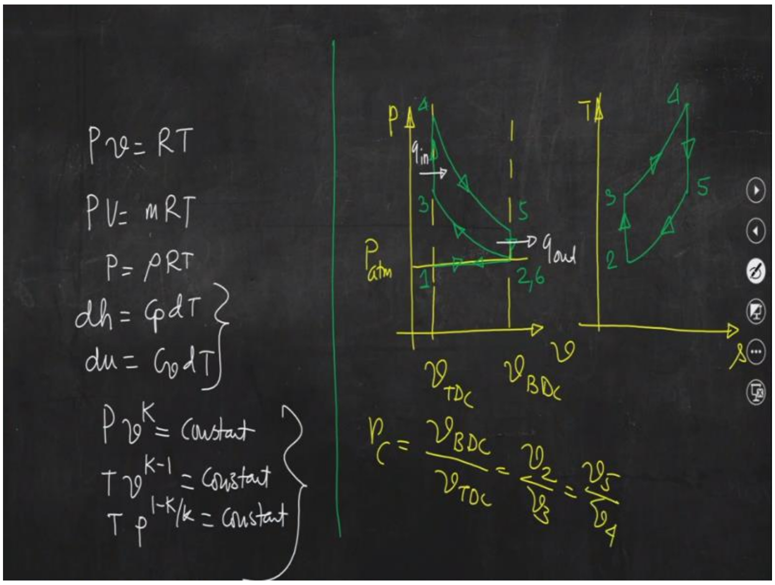

So, let us briefly map all the processes in thermodynamic planes. So, first is P-v another one is T-s why we are going to have T s because we are trying to understand what is the power output at the cost of some input energy. If we try to calculate the area under any process line in T-s plane that gives directly the heat transfer, heat exchange that we have studied in our thermodynamics and that is from second law.

So, basically if we can map all the processes in T-s plane and if we try to calculate the area under any process line in T-s plane that gives us the heat interaction. So, let us assume that the this is the pressure P atm and if we consider so this is let us say this is V_{BDC} and say this is V_{TDC}. So, piston is having moment between these two locations what we have seen in the last figure. So, when piston is at BDC the volume corresponds to V_{BDC}, when piston is at TDC the volume of the gas or volume inside the cylinder is the V_{TDC}. Now we can map the processes; so first process is intake. So, maybe piston is at TDC and is coming to BDC and this is the process. So, let us say this is process this is point one and then it is coming to two.

So, pressure is constant because volume is changing and what is the pressure? Pressure is the atmospheric pressure. So, basically though we can say because we should have some pressure difference between the atmospheric pressure and pressure inside the engine cylinder and that is the driving force but so it can be approximated as the constant pressure intake process.

And then when piston is at two the next process is compression process that is the compression stroke then you know this is coming to let us say point 3. So, piston is again coming back from

BDC to TDC. So, the fresh charge is getting compressed and this process can be approximated as an isentropic process. Now, say this is point 4.

So, spark plug switch will be on and combustion will be initiated and will be completed and it is because of this combustion, pressure and temperature inside the cylinder will be high. So, you can see that pressure increases, but the volume is remaining constant more or less. It is assumed that the entire conversion will be completed when piston is at TDC. So, it takes a very less time and it is approximated as a constant volume heat addition that is the combustion process.

And finally piston comes from TDC to BDC following this isentropic process we are assuming that the process is isentropic that is no heat interaction between the system and the surroundings and that to it is frictionless process. So, these are approximated processes 4 to 5 and finally when piston is at BDC basically exhaust valve is allowed to open.

And momentarily is certain amount of combustion gases which are there inside the cylinder at a high pressure will leave out and when the combustion gases are coming out from the engine cylinder they are carrying certain amount of enthalpy, certain amount of energy. So, that is basically exhaust. So, certain amount of combustion gases will leave out from the combustion chamber or engine cylinder and it is heat loss.

So that process is also known as constant volume heat rejection so say 2, 6. So, basically this is the constant volume exhaust. So, as if certain amount of heat is getting rejected from the system that is from the engine cylinder at constant volume. So, momentarily when piston is at BDC exhaust valve is allowed to open and certain amount of combustion gases will leave out.

So, this is the constant volume heat rejection process. So, when we open the exhaust valve momentarily certain amount of combustion gases will leave out that is true, but eventually you need to clear all the gases that those are there inside the cylinder and piston will come from BDC to TDC.

And that process is 6 to 1 to complete the cycle. Try to understand I would like to tell you one important point over here you know that process 1 to 2 and 6 to 1 these two processes are same and they are same thermodynamically, they cancel each other. So, while analyzing SI engine or the cycle we can analyze keeping the processes 1 to 2 and 6 to 1 left off from the figure.

It is not necessary that we have to analyze the cycle considering these two processes because these two processes are thermodynamically same so they cancel each other. So, if we can consider that, it is convenient to represent only the processes 2 to 3, 3 to 4, 4 to 5 and 5 to 6 or 5 to 2 because points 2 and 6 are same. 2 to 3 that we have approximated isentropic process and 3 to 4 you can see the temperature will increase, constant volume heat addition that is combustion process. So, pressure has increased from P3 to P4, temperature also will increase and that is reflected over here and finally 4 to 5 is the expansion and it is because of this expansion temperature of the working substance and pressure will reduce.

And that you can see from both this diagrams and finally 5 to 2 or 6 that is constant volume heat rejection that you can see that the temperature will reduce. So, T2 is less than T5. Now, if you try to analyze the performance of the SI engine. So, let us discuss certain issues.

We have discussed that to analyze this cycle, to analyze the performance of SI engine, these cycles which are having 4 different processes are compared with an air standard cycle and that cycle was invented first by Nikolaus August Otto and that is known as Otto cycle. So, basically we are trying to compare all the processes which constitute together to form the cycle of SI engine that can be approximated with an air standard cycle.

So, when you are trying to analyze all the processes by using an air standard cycle we can assume that the working substance what is there for the SI engine as an ideal gas. So, we are considering working substance to an ideal gas for the analysis and it is due to the fact that we are assuming that the cycle is approximated by an air standard cycle. So, if we assume that it is not purely air it is air fuel mixture that is during the compression stroke.

Again for the expansion stroke it is not only purely air and fuel rather it is several components of the combustion product. So, what we can write we are assuming that air standard cycle. So, for standard cycle will be using several ideal gas relationship. So, while we are trying to analyze it is better to analyze per unit mass of the working substance that is using the specific volume.

$$Pv = RT; PV = mRT; P = \rho RT; dh = C_p dT; du = C_v dT; Pv^k = C; Tv^{k-1} = C; TP^{\frac{1-k}{k}} = C$$

Now let me introduce here one term that is very important that piston is having essentially movement between these two location that is BDC and TDC. So, when piston is at BDC, this is V_{BDC}. When piston is at TDC volume of the working substance is V_{TDC}. Now the ratio of these two volumes V_{BDC} by V_{TDC} is known as the compression ratio of the engine.

$$r_c = v_{BDC}/v_{TDC}$$

So, let us first consider process 2 to 3 because we are not going to consider process 1 to 2 and 6 to 1 as I said these two processes are thermodynamically same. So, they cancel each other.

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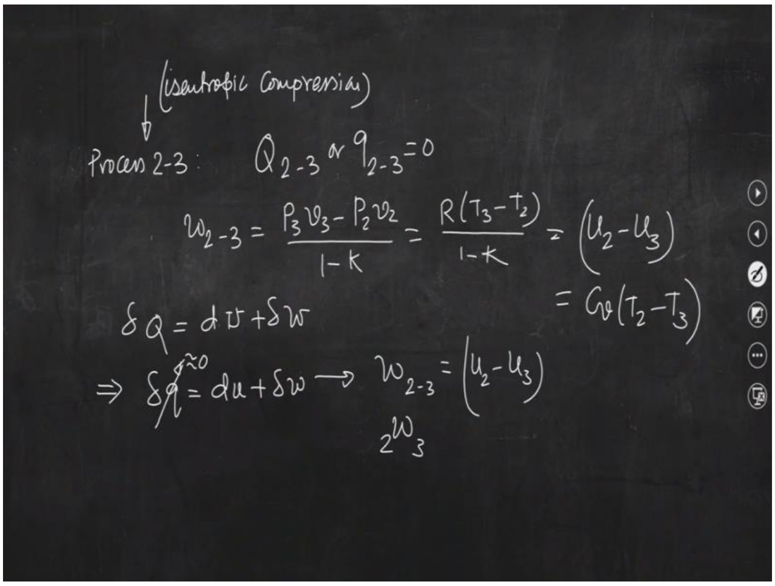

So, process 2 to 3, What is this process? Process is isentropic compression. So, there is no heat interaction, frictional effect is neglected because but we are trying to approximate essentially to quantify the thermal efficiency. In reality frictional effect will be there and also we cannot really prevent heat loss. But we can tell that these assumptions are not very bad assumption and as if the process is not violating severely from the isentropic process. So, now if we if we write it for the isentropic process.

$$W_{23} = \frac{p_3 v_3 - p_2 v_2}{1-k} = \frac{R(T_3 - T_2)}{1-k}; Q_{23} = 0$$

Now I would like to tell you one important thing, this is the expression of work done because this is work which is done on the compression on the mixture. So, basically if we try to write the first law of thermodynamics applied to a system, it is not for a flow system that is first law of thermodynamics for a non flow system, for the cyclic process then we can write

$$\delta Q = \delta W + du;\ \delta Q = 0 \rightarrow W_{23} = u_2 - u_3 = C_v(T_2 - T_3)$$

So, we can get it using this ideal gas equation and we have also seen that it can be written in terms of the internal energies. Next process is 3 to 4 that is the constant volume heat addition that mimics the combustion process in practical applications and in reality.

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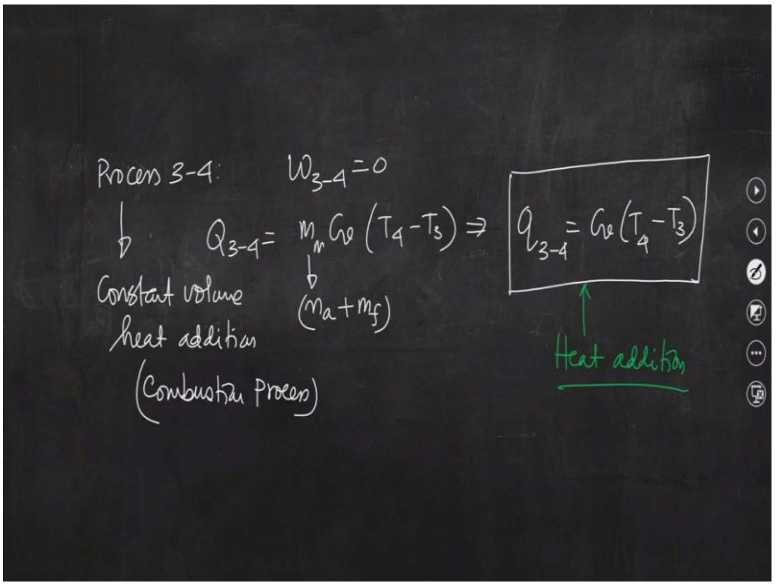

So, we can write process 3 to 4 constant volume process so work done is 0.

$$W_{34} = 0;\ Q_{34} = m_m C_v (T_4 - T_3) = \left(m_a + m_f\right) C_v (T_4 - T_3)$$

$$q_{34} = C_v (T_4 - T_3)$$

Next process is 4 to 5. This is again isentropic expansion that is the power stroke.

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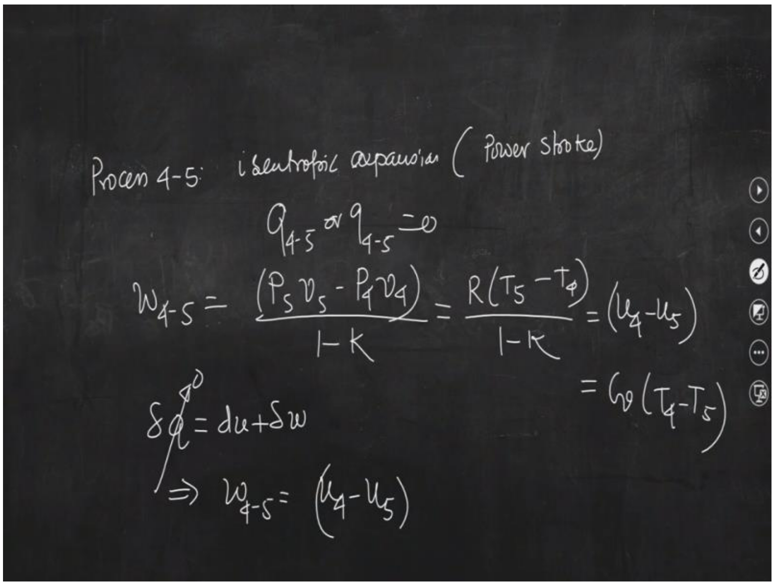

So, I am not going to write again whether the valves will remain closed or open because you know. So, this process is power stroke both valves are remaining closed. So, what about this isentropic process so no heat interaction.

$$Q_{45} = 0;\ W_{45} = \frac{p_5 v_5 - p_4 v_4}{1-k} = \frac{R(T_5 - T_4)}{1-k}$$

$$\delta Q = \delta W + du;\ \delta Q = 0 \rightarrow W_{45} = u_4 - u_5 = C_v(T_4 - T_5)$$

So, we are left to it the last process that is process 5 to 2 because this is the blow down so constant volume blow down. So, immediately after opening the exhaust valve though the piston is remaining at BDC certain amount of combustion gases will come out from the engine cylinder and those gases will carry certain amount of energy.

So, I mean as if you know heat is getting lost. So, this is the q out. So, as I told you that you can directly get it from the area under the process line in T s plane. So, what we can do we can next calculate the process 5 to 2.

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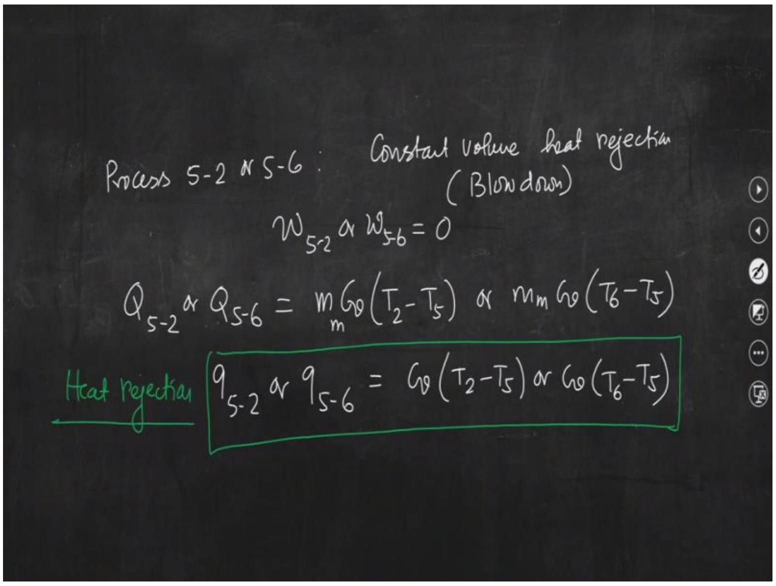

So process 5 to 2, I am not going to write 6 because it is these two points are same. So or 5 to 6. So, this is the process is constant volume heat rejection, some books it is written blow down.

$$W_{52} = 0;\ Q_{52} = m_m C_v(T_2 - T_5) = (m_a + m_f) C_v(T_2 - T_5)$$

$$q_{52} = C_v(T_2 - T_5)$$

I am writing so this is basically heat rejection if we go to the previous slide so that is basically heat addition. So, we are supplying this heat to the cycle through the combustion and we are supplying fuel while out of this heat being supplied to the cycle, you can understand this is the amount of heat is going to be rejected. So, this is not the useful heat. So, you can understand that we are not able to utilize the heat totally. So, certain amount of work that will be getting from this process is not equal to the input energy. So, definitely we can define thermal or thermodynamic efficiency of the cycle.

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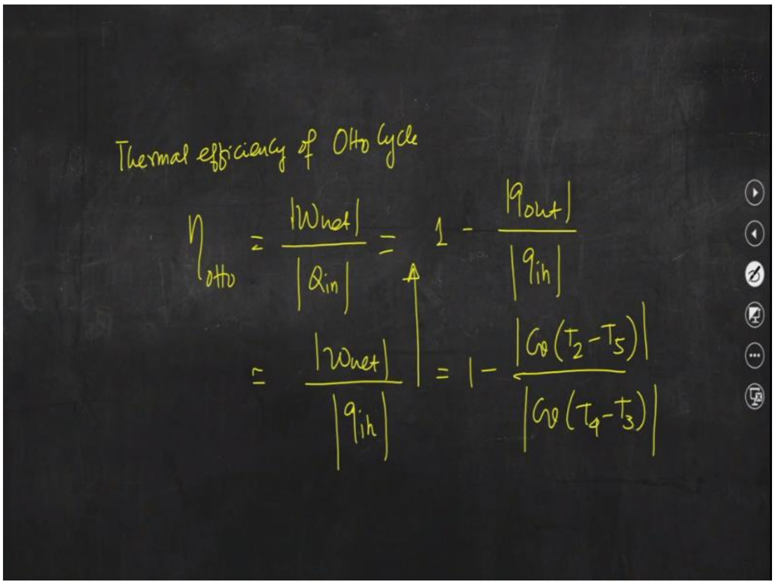

$$\eta_{th,Otto} = \frac{|W_{net}|}{|Q_{in}|} = \frac{|Q_{in}| - |Q_{out}|}{|Q_{in}|} = 1 - \frac{|Q_{out}|}{|Q_{in}|} = 1 - \frac{|C_v(T_2 - T_5)|}{|C_v(T_4 - T_3)|}$$

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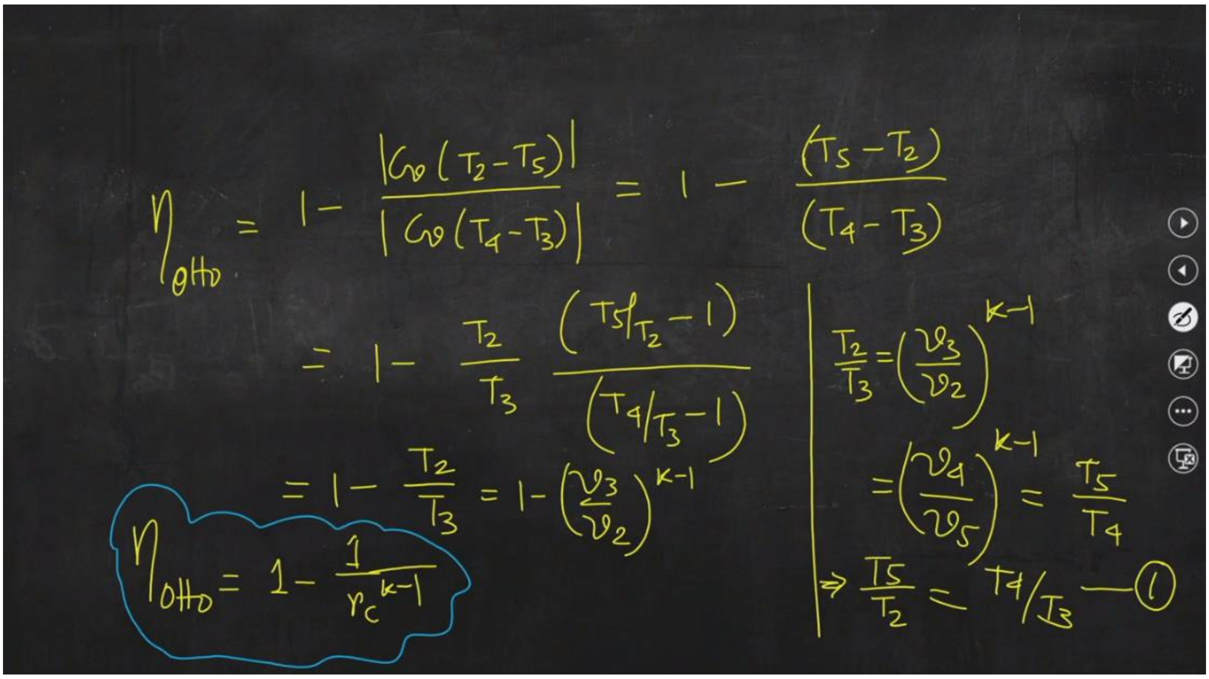

$$\eta_{th,Otto} = 1 - \frac{|C_v(T_2 - T_5)|}{|C_v(T_4 - T_3)|} = 1 - \frac{(T_5 - T_2)}{(T_4 - T_3)} = 1 - \frac{T_2}{T_3}\frac{{T_5}/{T_2} - 1}{{T_4}/{T_3} - 1}$$

We know,

$$V_3 = V_4; V_2 = V_5;\ T_2 = T_3\left(\frac{V_3}{V_2}\right)^{k-1} \rightarrow \frac{T_2}{T_3} = \left(\frac{V_4}{V_5}\right)^{k-1} = \frac{T_5}{T_4} \rightarrow {T_5}/{T_2} = {T_4}/{T_3}$$

$$\eta_{th,Otto} = 1 - \frac{T_2}{T_3} = 1 - \left(\frac{V_3}{V_2}\right)^{k-1} = 1 - \frac{1}{r_c^{k-1}}$$

So, this is the mathematical expression of the thermal efficiency of Otto cycle. So, thermal efficiency of the Otto cycle can be expressed in terms of the compression ratio.

So, try to understand higher the compression ratio, higher will be the efficiency, but that is within the range of a certain value. So, even for the SI engine compression ratio is fixed and working within this particular range if we increase the compression ratio efficiency of the Otto cycle will increase.

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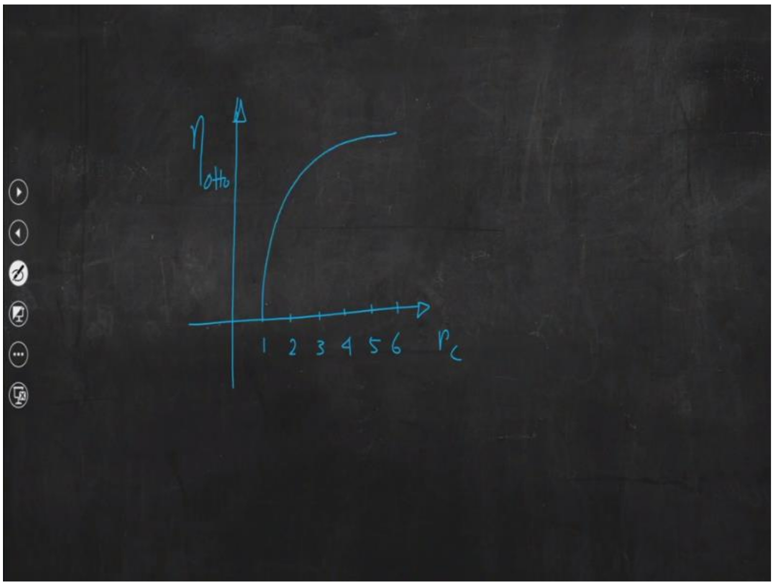

If we try to plot r_c vs η_{Otto}. So, when rc equal to 1 then thermal efficiencies is 0. So, you can understand that if we start from here it varies like this. So, this is the variation of thermal efficiency of Otto cycle versus the compression ratio plot. What we can understand if we increase the compression ratio efficiency increase.

So, if we summarize today, we have discussed about several processes which are important to analyze the SI engine and we have mapped all those processes in two different thermodynamic planes, we have compared all the processes those constitute together to form a cycle and that cycle we have compared by using an air standard cycle which is the Otto cycle, German engineer Nikolaus August Otto who first invented the cycle.

And from there using the air standard equation we have tried to quantify the thermal efficiency of Otto cycle and we have seen that the thermal efficiency of the Otto cycle can be written in terms of the compression ratio of the engine, higher the compression ratio efficiency will be higher within the working range or allowable range of the compression ratio of SI engine.

So, with this I stop here today and we shall continue our discussion in the next class. Thank you.