Course Name: Engine System and Performance
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Lec 4: Analysis of Basic Cycles

I welcome you all to the session on engine systems and performance. Today, we shall discuss the basic cycles used to analyze the performance of internal combustion engines, and thereafter, we shall try to analyze those cycles to estimate their thermal efficiencies. So, in the last class, we talked about engine classification. And we saw that engines can be classified based on several points or issues. The broad classification is based on the type of combustion and the number of strokes, which we have discussed. Now, given that both spark ignition engines and compression ignition engines.

Both engines have much in common, but there are still some fundamental differences between these two types of engines. So, an important difference is their analysis, and today we shall discuss that topic only. Considering several cycles, rather basic cycles, used to describe the processes or to represent those processes which are present in SI and CI engines. So, if we first discuss a four-stroke cycle SI engine. A four-stroke cycle SI engine, typically found in four-wheelers or two-wheelers.

Now, you have studied this in your undergraduate internal combustion engine course. Still, we shall discuss this just to recapitulate, in this course again. So, if we try to recall the schematic depiction we discussed in the last class, in a spark ignition engine, a spark plug is present, and that spark plug acts as an external agent to initiate combustion. So, briefly, if we try to recall, just drawing a schematic of an SI engine.

So, this is the schematic depiction of a spark ignition engine. So, this is the spark plug. This is the intake manifold. And this is the exhaust manifold through which combustion gases leave the engine cylinder or combustion chamber.

Now, in a four-stroke cycle, I am not going to discuss this because the piston reciprocates between these two locations: top dead center and bottom dead center, and there are four different strokes: intake So, the intake stroke is when the piston travels from top dead center to bottom dead center. There is a valve in these two locations: the exhaust valve remains closed, and the intake valve opens. Through this intake manifold, if it is an SI engine, certainly it is not only the air but the air-fuel mixture, which is also known as the charge. So, the air-fuel mixture will be drawn into the engine cylinder as the piston travels from top dead center to bottom dead center. That is the intake stroke. The next stroke is the compression stroke. The exhaust valve remains closed when the piston reaches bottom dead center, the intake valve is closed, and then the entire space is filled with the charge, which is drawn into the cylinder or combustion chamber during the intake stroke. It will now be compressed as the piston moves up. That is the compression stroke. When the piston is about to reach TDC, we need to switch on this power plug, assuming that it will take some finite amount of time to switch on this power plug, and by that time, the piston will be reaching TDC, and the entire charge will be combusted. So, the entire combustion will take place and that is why, as if the piston has reached TDC, the compressed charge, which is now here in this space, will be combusted.

So, the entire combustion will take place, and as if the volume is remaining constant. So, this is approximated as a constant volume combustion. And because of this combustion, that is, we will have a substantial amount of, energy in the form of heat, and pressure will also be there. So, that high pressure will create a thrust on the piston face, which will allow the piston to travel back from TDC to BDC again. And that is the power stroke.

And finally, when the piston reaches BDC, at the end of the power stroke, then the next stroke is the exhaust stroke, where the piston will again move up, the exhaust valve will open, and as the piston travels up, all the combustion gases will exit through the exhaust manifold into the atmosphere. So, this way, four different strokes will occur, and these four different strokes will be executed in a cyclic manner because the reciprocating motion will be converted into rotary motion using the crank and connecting rod mechanism, and we can drive a two-wheeler or four-wheeler. So, the question is, that is fine, but to analyze, essentially, we are supplying an air-fuel mixture through the intake manifold into the combustion chamber.

So, we are supplying a certain amount of energy, and that is the chemical energy. That energy remains stored within the fuel. So, when we try to burn the fuel, that is combustion, we again get some form of energy. That is energy in a different form, that is heat. But again, that energy is not available to the shaft of the engine.

So that means that heat energy will again be converted into work, and that work will be available to drive the four-wheeler or two-wheeler. So, the question is, at the cost of some input energy, that is the chemical energy which remains stored in the fuel, we are going to get some other form of energy. So, we need to know what fraction of energy recovery is there, and to know that, we need to quantify the thermal efficiency or mechanical efficiency of the engines. Forget about mechanical efficiency because you have studied all these things in your undergraduate course, but now what we can do is analyze the cycle and also calculate the thermal efficiency.

That is the indicated thermal efficiency, that is the energy which will be available inside or at the top of the piston phase. So now to analyze this, we need to know some cycle. Thermodynamic cycle, because we have studied in our thermodynamic course that Rankine cycle. Then Carnot cycle, the most important ideal cycle, but the cycle that we will discuss today, these cycles are not called as thermodynamic cycles because it is not the closed one. You can understand that the working substance that comes into the engine cylinder during the intake stroke, that working substance will not be recycled.

That working substance will take part in combustion, and because of this combustion, will be having several combustion gases, and those combustion gases will leave out from the engine cylinder through the exhaust manifold into the ambience. So, essentially. The working substance is not, getting recycled back. So, one of the most important, criterion for a cycle to be called as the thermodynamic cycle is the working substance has to be recycled back. So, this is not there.

Second thing is the composition of the working substance is getting changed when it took. Air-fuel mixture into the engine cylinder, it is enough air and also enough fuel, air-fuel mixture. But after the combustion, the composition will be different. So, composition is also going to be changed at the end of the cycle. So, this also contradicts that the cycles will be called as the thermodynamic cycle.

So, but we can call these cycles the mechanical cycles. So, what is the need? So, all these four strokes are there. Four strokes will occur or recur consecutively. And what we could see is that at the beginning and end of the stroke, the thermodynamic state of the working substance will be changed.

So, to know the thermal efficiency or indicated thermal efficiency, we need to know the pressure and temperature, the pressure and temperature of the working substance, at the beginning and end of each and every stroke. To know that, we need to compare these processes, we need to map these processes using several thermodynamic planes, and we need to adhere to any cycle, just to, compare or just estimate the efficiency. So, all these processes are approximated by, the air standard cycle for four-stroke cycle SI engines, and that air standard cycle is called the Otto cycle, which is named after one of the inventors of this type of engine, Nicholas Otto.

So, let us now briefly discuss these processes. Rather, if we can represent these processes in thermodynamic planes. So, if we try to represent these processes, one of the most common thermodynamic planes is the *P-v* plane. Similarly, we also need to map these processes in another thermodynamic plane, that is, the temperature-entropy plane. So, if we map the processes, let us start from TDC.

When the piston is at TDC, both valves are closed. As the piston travels from TDC towards BDC, the intake valve will open, and the exhaust valve remains closed. That is the intake stroke. So, this is, and there is basically, that naturally aspirated wide-open throttle. So, in this case, there is no system that can boost or that can be used as the pressure boost of the intake air.

Rather, the traveling or, movement of the piston from TDC to BDC will allow the air-fuel mixture to be drawn into the cylinder. So, assuming that this is the pressure. So, you can understand here that the pressure is atmospheric pressure. If we now bring the piston down from TDC to BDC inside, we are creating some sort of, vacuum, and that pressure difference will allow the pressure difference to be the driving force for the air-fuel mixture to be drawn into the engine cylinder.

So, if we assume that this is the first process and say this is point 1. So, when the piston reaches BDC at the end of the intake stroke, that is point 1. Then the next stroke is the compression stroke. So, basically, that it would be like this because, as I said, in SI and CI engines, we are trying to represent all the processes using an air standard cycle.

In particular, for a four-stroke cycle SI engine, we are trying to map all the processes using an air standard cycle that is named or called the Otto cycle. So, if we are trying to use an air standard cycle, we must assume that the working substance is air, and we can apply the ideal gas relationship. So, if that is the case, then process 1 to 2 is isentropic compression.

So, the process will be compression. So, as if both the valves are closed now, the piston is traveling back from BDC to TDC, and the entire charge is getting compressed. So, the process is a compression process, and we can approximate that process by an isentropic compression so that we can easily map it here. Next, 2 to 3, as I told you, when the piston is reaching TDC, the entire charge will be occupied in this place, and the spark plug switch will be on. The spark that will be developed here will initiate the combustion, and the entire charge will be combusted as if, during that time, the piston is remaining there at TDC, though the movement of the piston is spontaneous. So, this approximation allows us to consider that the combustion can be mimicked by a constant volume combustion.

So, constant volume means the volume is remaining constant. So, you can understand that it is because of this combustion, this pressure is P_3, and this P_3 is the maximum pressure in the cycle. And then, At the end of the combustion, as I said, the high pressure and high temperature will create a thrust on the piston face, which will allow the piston to go down again from TDC to BDC. And that is nothing but the expansion of the combustion gases inside the cylinder.

And that expansion can again be mimicked by an isentropic expansion. So, this is the process. And finally, So, this is 3 to 4, and then 4, when the piston is at BDC at the end of the power stroke, we need to open the exhaust valve immediately. So, that inside the cylinder, high-pressure gases will leave momentarily, when you open the exhaust valve.

So, when combustion gases are, leaving out of or leaving from the engine cylinder, those gases will carry certain enthalpy. So, we will be having energy loss, heat loss. So, that is 4 to 1, and as if when the piston is exactly at BDC, if we open the exhaust valve, that high pressure which is there inside the cylinder will allow the combustion gases to leave out, and while the combustion gases are leaving, mass loss is there, and that mass, the mass of combustion gases, will basically be having some enthalpy.

So, that is heat loss. So, this is q_{out}. I am writing, you know, in terms of specific quantities, and this combustion is q_{in}, heat addition. So, that you have studied. So now, if we try to represent all these processes in the T-s plane, then let us map all these processes.

So, what I said, that 1 to 2 process is an isentropic process. What does it mean? The process is isentropic, so entropy will remain constant. So, if we map the process 1 to 2, right, and then 2 to 3, this is constant volume combustion, what is combustion? Combustion is nothing but an exothermic reaction.

So, it is because of this process that we will have a substantial amount of heat generation. So, that heat is as if this process is adding heat to the system. So, constant volume heat addition. So, if it is constant volume heat addition, you can understand that pressure is becoming maximum, and that heat will also increase the temperature. So, temperature will also be maximum.

So, this is T_3. And this T_3 is T_{max}. T_3 is T_{max}. And then, 3 to 4, you can see that again, 3 to 4 is basically an expansion process. So, isentropic expansion, so this is the process, and 4 to 1, that I said, is heat rejection.

So, when the piston is at BDC, if we open the exhaust valve momentarily, a certain amount of combustion gases will leave out and While the combustion gases are leaving, we are also going to have a loss of enthalpy. So, that is basically heat rejection. So, q_{out}, and it is because of this heat rejection that the temperature of the working substance or the combustion gases will be less. So, eventually, it will come to 1.

So, this way, we can complete the cycles. So, now these two are the representations of all these processes in two different thermodynamic planes, one is the *P-v* plane, and another one is the *T-s* plane. So, from this, now we shall try to quantify what could be the thermal efficiency, or later on, we shall see that efficiency is basically indicated thermal efficiency. So, if we write now, so very well that thermal efficiency from the second law, we can write that:

$$\eta_{thermal} = \frac{|w_{net}|}{|q_{in}|}$$

It is better to always represent in terms of specific quantities, that is, per unit mass of the working substance. So, if we know q_{in} and if we know w_{net}, then we can quantify this. So, what is w_{net}? So,

$$w_{net} = q_{in} - q_{out}$$

So, we can derive from the first law of thermodynamics, which is the energy balance. So, that heat addition minus heat rejection is essentially the amount of energy we are going to get in terms of work. So, this is w_{net}. So, if we write this expression on the next page, then we can write:

$$\eta_{thermal} = \frac{|q_{in} - q_{out}|}{|q_{in}|}$$

So, basically, you will get:

$$\eta_{thermal} = 1 - \frac{|q_{out}|}{|q_{in}|}$$

We are writing, we will be taking only the magnitude, not the direction. So, what is q_{out} You can see q_{out} is this.

So, I am not going to discuss this in detail because you have already studied this, but just to have the mathematical expression of this quantity, which is thermal efficiency, we are trying to discuss these processes. So, q_{out} is this constant volume heat rejection. So,

$$q_{out} = C_v(T_4 - T_1)$$

So, if we write,

$$|q_{4-1} = C_v(T_1 - T_4)|$$

And what about q_{in}? That is q_{2-3}. If we go back to the previous slide, you can see q_{in}. This is the q_{in}, and this is the q_{out}.

So, q_{in} is constant volume heat addition. So,

$$q_{in} = C_v(T_3 - T_2)$$

That is what I have written on the next page. Now using these two quantities, if we try to write the expression,

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

So, if you write one step further,

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

So, this is the expression. Now, if we go back to the previous page, So, 2 to 3 is basically, 1 to 2 is basically what is the process? Isentropic compression.

2 to 3 is constant volume heat addition, and 3 to 4 is also isentropic expansion. So, can we write, Now, we have a relation between the temperatures T_1 and T_2. So, again, as I said, we have assumed that the working substance is air, though it is not purely air; it is an air-fuel mixture. But you have studied these issues, the consideration, or the validity of this approximation. It is mostly air, but it is not pure air. What we assumed is that we

have considered the working substance as air, and we have approximated all these processes by an air-standard cycle. Then, we can also use the ideal gas relationship.

So, from this, we can write T_2. and T_1. So,

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

So, $k = C_p/C_v$. So, now, it is very important that if we go back to the previous slide, see v_1 and v_4 are the same, and v_3 and v_2 are the same. So, instead of writing v_1, you can also write v_4. Instead of v_2, you can also write v_3. So, just if we change it, we can write

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

So, just if we write one step further, then we can write

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

So, this will allow to write, if we go to the next slide,

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

But we have seen that $T_4/T_1 \; and \; T_3/T_2$ are equal, so This will get cancelled because $T_4/T_1 = T_3/T_2$. So, we are left with

$$\eta_{thermal} = 1 - \left(\frac{1}{T_2/T_1}\right)$$

And what is T_2/T_1?

$$T_2/T_1 = (v_1/v_2)^{k-1}$$

So, that is equal to

$$\eta_{thermal} = 1 - \frac{1}{(v_1/v_2)^{k-1}}$$

So, this is known as,

$$\eta_{thermal} = 1 - \frac{1}{{r_c}^{k-1}}$$

because v_1 is when the piston is at TDC, that volume corresponds to the volume when the piston is at BDC, and v_1 corresponds to the volume when the piston is at TDC. So, as if we are trying to compress the volume, so this is basically v_{BDC}, and this is v_{TDC}. So, as if we are trying to compress the volume from v_{BDC} to v_{TDC}. So, the ratio of v_{BDC} to v_{TDC} is known as the compression ratio, r_c.

So, what we can write ${r_c}^{k-1}$, where r_c equal to v_{BDC}/v_{TDC}. So, what you can see from here is that if you try to write the indicated thermal efficiency versus compression ratio. Now, why is it indicated thermal efficiency? Because that we have estimated this efficiency considering the heat transfer to or from the air inside the engine cylinder. So, this is the efficiency which is indicated. So, this is not the efficiency which is available at the shaft of the engine. I mean, this efficiency is not calculated considering the energy which is available at the shaft of the engine.

Rather, this efficiency is calculated based on the fact that or based on the energy transfer or heat transfer to or from the air of the engine cylinder. So, this is the indicated thermal efficiency. Now, when r_c equals 1, efficiency equals 0. So, 1. Now, it will be like this.

So, this is the, curve $\eta_{thermal}$ versus r_c. So, if we increase the compression ratio, efficiency will increase. That you can see. So, if we increase r_c, efficiency will increase. So, this is all about the thermal efficiency of, 4-stroke cycle SI engine. So, let us quickly discuss the 4-stroke cycle CI engine.

So, again, if we just draw the schematic. So, this is only air. So, this is only fuel. So, instead of a spark plug, we are now having a fuel nozzle through which fuel is injected. So, the fundamental difference here is that since fuel is supplied, fuel is nothing but composed of several hydrocarbons.

And because of these hydrocarbons, if, and that too, there is a spark plug, what is done, is that when the piston is reaching towards TDC during the compression stroke, the compressed temperature which would develop due to the compression of the air, that temperature itself will allow the fuel to ignite when fuel is sprayed into the combustion chamber. Now, depending on the fuel composition, an ignition delay will be there. So, basically, physical delay plus chemical delay, that is the total ignition delay that you have studied in your undergraduate course. So, because of this ignition delay, what is done, is that when the piston is about to reach towards TDC, fuel is sprayed.

So, when fuel is sprayed, that fuel will initiate or that fuel will be combusted. So, that is known as the first phase of combustion. So, when the piston is yet to reach TDC, fuel will be sprayed, and the first phase of combustion will be there. And it is because of this first phase of combustion that some pressure will develop. And when the piston is reaching TDC, combustion will still be there.

And because of the chemical delay or ignition delay, when the piston will be, leaving from TDC towards BDC during the power stroke, still, certain, fuel will be there for combustion. So, the late phase of combustion. Considering all these, it is not possible to mimic the combustion by a constant volume process because combustion will start when the piston has not even reached TDC. Combustion will continue when the piston will be reaching TDC, and it will last even when the piston is leaving from TDC towards BDC. So, during this process, the volume is no longer constant; rather, because of this first phase of combustion, some pressure will be there, and then again, another combustion will be there though the piston is coming back from TDC towards BDC, as if the pressure is remaining constant because of several phases of combustion.

So, that is the fundamental difference. So, here the combustion process cannot be mimicked by a constant volume process; rather, it is mimicked by a constant pressure process. So, if we try to draw the pressure-volume diagram and *T-s* plane and processes in the *T-s* plane. So, if we try to draw the processes in both *P-v* and *T-s* planes, so the same process, so this is one, and then this is the compression process.

Now, it is not the constant volume but rather constant pressure combustion, and then finally, so this is 3, this is 4, this is 1. So, 1 to 2 is, isentropic compression, 2 to 3 is q_{in}. That is constant pressure combustion, 3 to 4 is again isentropic expansion, and 4 to 1 is heat rejection, that is blow down. So, when the piston will be at BDC, if we open the exhaust valve momentarily, a certain amount of gases will leave from the engine cylinder to the ambiance through the exhaust manifold, and those gases will carry a certain amount of heat, or that is why we are assuming that is called Constant volume heat rejection.

Similarly, if we try to draw the processes in the *T-s* plane, you can see that 1 to 2 is isentropic. So, this is an isentropic process, isentropic compression. Then 2 to 3, is constant pressure combustion. So, here the temperature will be maximum.

So, this is 3, and then 3 to 4. So, this is the blowdown. So, T_3 is T_{max}, and P_3 equals P_2 equals P_{max}. So, this is what we can see.

So, again, if we try to write the, kind of thermal efficiency of this particular cycle, just I am trying to write $\eta_{thermal,Indicated}$. Why it is indicated? Because we are trying to quantify the efficiency considering the heat transfer to and from the air of the engine cylinder. So, air or working substance that is air inside the engine cylinder from the air or to the air, we are trying to calculate the heat transfer to the air because of combustion and from the air because of this blowdown. So, this is again Following the previous step, we can write,

$$\eta_{thermal,Indicated} = 1 - \frac{|q_{out}|}{|q_{in}|}$$

One thing we will discuss here is that if you try to recall, during the combustion process, the volume has changed; the volume of the working substance has changed. So, we can define one ratio that is called the cutoff ratio. The cutoff ratio is β, equal to this, defined as v_3/v_2. So, the cutoff ratio β is defined as this change in volume that occurs during the combustion process. So, the volume has changed from v_2 to v_3, and this ratio of v_3 and v_2 is known as the cutoff ratio because the volume of the working substance has changed.

So, basically, if we try to express or if we try to quantify the thermal efficiency using w_{net}/q_{in}. So, w_{net}, while we will be calculating, you also need to take into account the work done during this process. So, the cutoff ratio is defined as the change in volume that occurs during the combustion process, v_3/v_2. So, if we now try to write this q_{out}, what is q_{out}?

$$|q_{out} = C_v(T_4 - T_1) = C_v(T_1 - T_4)|$$

$$\left|q_{in} = C_p(T_3 - T_2)\right|$$

It is this constant pressure, So, this is constant pressure heat addition. So, if we write one step further, we can write

$$\eta_{thermal,Indicated} = 1 - \frac{|C_v(T_1 - T_4)|}{\left|C_p(T_3 - T_2)\right|}$$

$$\eta_{thermal,Indicated} = 1 - \frac{1}{C_p/C_v}\left(\frac{1}{T_2/T_1}\right)\frac{(T_4/T_1 - 1)}{(T_3/T_2 - 1)}$$

So, we can write

$$\eta_{thermal,Indicated} = 1 - \frac{1}{k}\left(\frac{1}{T_2/T_1}\right)\frac{(T_4/T_1 - 1)}{(T_3/T_2 - 1)}$$

So, if we write T_2/T_1,

$$T_2/T_1 = (v_1/v_2)^{k-1}$$

What is v_1/v_2 again in terms of compression ratio? So, this is v_{BDC}, and this is v_{TDC}. So, what we can write, is nothing but

$$T_2/T_1 = (v_1/v_2)^{k-1} = (v_{BDC}/v_{TDC})^{k-1}$$

So, that is

$$T_2/T_1 = (v_1/v_2)^{k-1} = (v_{BDC}/v_{TDC})^{k-1} = r_c{}^{k-1}$$

So, this is the compression ratio of the engine. So, we can write

$$\eta_{thermal,Indicated} = 1 - \frac{1}{kr_c{}^{k-1}}\frac{(T_4/T_1 - 1)}{(T_3/T_2 - 1)}$$

So, what is T_3/T_2? So, v_3/v_2, that is a constant volume process. So, this is nothing but T_3/T_2. So, we can write that

$$v_3/v_2 = T_3/T_2$$

So, this is

$$\eta_{thermal,Indicated} = 1 - \frac{1}{kr_c{}^{k-1}}\frac{(T_4/T_1 - 1)}{(\beta - 1)}$$

Cutoff ratio. So, this process, is a constant pressure process. So, if we apply, the ideal gas relation, then

$$\beta = v_3/v_2 = T_3/T_2$$

So, that we have written. Now, if we just write these steps further, one step further, then we can write.

$$\eta_{thermal,Diesel} = 1 - \frac{1}{kr_c{}^{k-1}}\frac{(T_4/T_1 - 1)}{(\beta - 1)}$$

This is what we can write. Now, what about T_4/T_1? So, what is T_4? If we try to go back to the processes, we can write T_4 in terms of T_3 and T_1 in terms of T_2. And then you can also express that quantity in terms of β because β is already T_3/T_2. So, if we write here, T_4 is equal to how much?

$$T_4 = T_3(v_3/v_4)^{k-1}$$

divided by this is

$$T_1 = T_2(v_2/v_1)^{k-1}$$

that is nothing but

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

Since v_1 equals v_4, that you can see from this *P*-*v* diagram, v_4 equals v_1. So, then what we can write, this will get cancelled, and eventually v_3 by v_2 is equal to again T_3 by T_2.

So, we can write this expression equal to

$$\eta_{thermal,Diesel} = 1 - \frac{1}{k{r_c}^{k-1}}\frac{(\beta^k - 1)}{(\beta - 1)}$$

So, this is the mathematical expression of thermal efficiency of a four-stroke cycle CI engine. Now, one thing I forgot to tell you is that to compare the performance of a four-stroke cycle SI engine, we have discussed an air standard cycle, and that air standard cycle is called the Otto cycle. Similarly, the processes of a four-stroke cycle CI engine are approximated by an air standard cycle. Because we have applied ideal gas relations, assumed that the working substance is air, and that cycle is known as the Diesel cycle.

So, $\eta_{thermal,Diesel}$, Dr. Rudolf Diesel, who first invented this particular type of engine, and to honor the name of Dr. Rudolf Diesel, this cycle is called or named as the air standard Diesel cycle. So, now what we can tell from here is that k is always greater than 1, β is always greater than 1, because T_3 is always greater than T_2. Now, the quantity given in this bracket is always greater than 1.

So, for a given compression ratio, if we try to compare the thermal efficiency of the Diesel cycle or Diesel engine, which is always less than the thermal efficiency of a four-stroke cycle petrol engine or a four-stroke cycle SI engine. Now, since Diesel engines typically have higher compression ratios, hence four-stroke cycle CI engines will always have higher thermal efficiency than four-stroke cycle SI engines. So, to summarize today's discussion, we have discussed the basic cycles typically used to map several processes of both four-stroke cycle SI and CI engines, essentially to estimate their performance efficiencies, and then we have briefly discussed several processes in different thermodynamic planes.

And from there, we have tried to quantify the mathematical form we have tried to express is the mathematical form of thermal efficiency, that is, the indicated thermal efficiency of both four-stroke cycle SI and CI engines. So, with this, I stop here today, and we shall continue our discussion in the next class. Thank you.