Engineering Thermodynamics
Dr. Jayant Kumar Singh
Department of Chemical Engineering
Indian Institute of Technology Kanpur

Week-09
Lecture-40
Gas Power Cycle

Welcome to lecture 2 of Gas Power Cycle. In this lecture, we will discuss the reciprocating engine. Especially, we will solve some problems of the auto cycle. The engine is a piston cylinder, and it is used everywhere. It is used in many places in the automobile industry. That is why this invention is very important. Because you can see its use everywhere. That is why it is called a basic component in any engine. The sketch of this engine is in the form of a piston cylinder. And in this, the basic definition is written as that you have this cylinder, and this is your piston. And the piston also has two positions. One is called the top dead center, TDC. In which When this piston comes here, it cannot move much forward. And this particular volume has become dead space. And the second is the bottom dead center. Where it comes down from the top and then stops here. And this position is the largest volume that forms in the cylinder. Because when it is above, it will be the lowest volume. piston will be on this side and when piston will be here, cylinder will have maximum volume this distance between TDC and BDC we will call it stroke and the distance you can see in the valve which will be on the diameter that is your bore now normally piston will be back and forth and when it will go from TDC to BDC stroke, this will give you volume expansion and compression. You can also see that it has an inlet valve. From here normally you will have air-air fuel mixture, from where combustion will take place after burning, after combustion the piston will move. Finally, there is an exhaust valve from where your burned fuel will go. So, we will use it like this, we will understand it later. As I said, this stroke is the distance between it, and this is the largest distance that the piston can travel in one direction. Exhaust wall will be combustion because after it comes this combustion will burn so normally in internal ignition we burn it with spark and in compressed it will be so much compression that the ignition temperature will rise then it burns on its own and after the combustion project is done it will go through this wall and normally It is a process, a stage to get out. So, we will know more about this. But we will not understand much about the detailed engine. We will understand the process and its thermodynamics. Now, another definition that is useful is clearance volume. This volume is the minimum volume that forms in the cylinder. It will be when the piston will go up and stop in TDC. So, this volume will be your clearance volume. And the displacement volume will be from this position to this position. When it moves from here to here, it will displace this amount. So, what is the displacement volume? When it moves between TDC and BDC. So, you can see this amount. When it moves, it will displace the volume. It will take it out. So, this is the definition.

Now, it is important that when it goes back and forth, there will be compression because the volume is changing. The volume is changing from TDC to BDC, from bottom to top. When it goes up in BDC, the volume is seen. So, when it goes down, the overall volume of the cylinder is maximum. Air is in expansion form; the fluid will occupy the complete volume. When it goes to TDC, it will be compressed, so its volume will be the lowest. So that's why we use another definition, compression ratio R. R is the ratio that forms the maximum volume in the cylinder. divided by the minimum volume. So, ratio of maximum volume and minimum volume. This means R is your Vmax. and divided by Vmin. So, Vmax will be the volume of the cylinder when the piston is at the bottom. And the minimum will be when the piston is at the top. So, this is the R compression ratio. Another term we use in this is mean effective pressure. Now, you pay attention to this. This is your pressure and volume. If we show this piston cylinder horizontally, then this piston will move from one side to another. And when it will be here on BDC, then we will write this point as such. And when it reaches here on TDC, then this point will be minimum, and this is maximum. The volume of the cylinder on BDC is maximum. Now normally, you will get this process on back and forth. This is what you see. This will go like this. And then your curve will come back like this.

Now we will talk about this later. When it will be done in the form of a cycle. In the sense that when the back and forth will be done, then it will be done in this form. Ok. We will discuss how many strokes there will be. Means how many strokes there will be to complete a cycle. We will discuss that now. But when this cycle happens, then the area under the cycle, the curve you see now, black the area I have colored is W net. So, this area will be covered till inside. Now a term comes out that if W net is there then normally, we can say that this total, because the pressure is variable but if we take out that it has a fictitious pressure an imaginary pressure which we apply on the piston on the entire power stroke then how much will it be? The amount we are generating if we divide it by the total volume change Wnet is called as P∆V So this is P∆V and this is MEP∆V This is the kind of imaginary pressure that we apply to the stroke and if the volume changes this much, then this will be the total work net So we use this method Wnet is equal to MEP multiplied by piston area multiplied by stroke Area multiplied by stroke is the displacement volume So MEP multiplied by displacement volume is W net. So, this is your expression. And we can write it as well that MEP is W net divided by displacement volume. So, what will be the displacement volume? As much as V max minus V minimum, which we wrote here.

Now let’s talk about Spark Ignition Engines When we put the fuel mixture through the wall there will be two ways to burn the fuel First, the spark will spark and the fuel mixture will start burning This is the major reason for internal combustion engines gas based or petrol based engine which we drive, that is maximum but diesel based engine is different that is called compression ignition engine in this you compress so much that it increases its self-ignition temperature when the temperature itself is more than self-ignition temperature then it starts burning so this is called diesel engine This type of engine is called compression ignition engine. This is called spark ignition. Normally, cars are more on this. And of course, we have said that this is a diesel engine. This is in the form of compression ignition. Now we will talk about a normal internal combustion engine. Because the internal combustion engine is inside the engine, both your car, the petrol and diesel, will be called internal combustion engines. This is an example, which is called an auto cycle. This is a classic form of spark ignition engine. It has four strokes. We will do 4 strokes, 4 pistons from one end to the other end. But the crank shaft that rotates you will revolutionize your cycle twice. This 4 you can see is a complete thermodynamic cycle. you are covering the thermodynamic cycle and in this crank shaft which will be in your engine will rotate twice but there will be 4 strokes so first let's understand the stroke and understand the diagrams rest of the mechanical aspects we will not talk about in detail but you will have to understand what happens in this whole cycle And since it is a cycle, it means that it has to come back to the same position in PV form. Or if you take a thermodynamic phase diagram, it has to come to that point. So usually, the actual spark ignition engine form is seen like this, which is the left-hand side curve. If the gas is at this point, then there is P atmosphere. So, this is the intake. And this point here, the intake, comes from here from TDC to BDC. Which means it is taking the upper part. And this part, the intake part, is the stroke. After that, the compression starts. So, this is why it came to BDC. The compression started from BDC. It is compressed.

Here, at this point, the ignition starts. and the combustion is over after the burn this point is over but the temperature pressure will be high so that's why the expansion started here you can see that the pressure is high then the expansion started and when the expansion starts again at this point we open the exhaust valve after that when the expansion is done the exhaust comes out again and at that point the piston moves back which is on your TDC. So, we can see it like this. If we start from here, with compression stroke. In compression stroke, it means that already here, this is the compression stroke, which is basically A, which we are showing. At this point, this is your BDC, this piston is at the bottom, it moves here. Here compression happened, here ignition happened. and your piston starts burning from here and starts moving slowly. This is the power expansion stroke. So, this part that you can see, this power expansion stroke, basically, if this is your A, then This is your B. This is the entire B. And then comes your Exhaust stroke.

Now, after coming here, it will come back. In which the Exhaust stroke will come out. So, this part is seen. After opening the Exhaust, this is the C part. And finally, your Exhaust is full up to here. And then comes the Inlet stroke. So, this is your A, B, C, D. You can also see this in a simplified form. Because it is difficult to do a real analysis. Because you can see that naturally, you can see that both the changes are happening. Pressure is changing, volume is changing. So, this process becomes difficult. That's why we call it the ideal form. Ideal form means it will be in your internal reversible form. And the strokes you are seeing here, compression stroke, expansion stroke, exhaust stroke, inlet stroke, we can do it in different ways. So, first, this part, compression roller, we call it as an isentropic compression. We call it adiabatic and internal reversible. There is no heat transfer from the boundary. So, this one is isentropic. So, from 1 to 2 is isentropic. Initially, this part was here. This part, which I wrote. So, this is 1. From 1 to 2, which was more than the ignition. So, this is P part. So, we said from 1 to 2. I have simplified this part. We have said that this is isentropic from 1 to 2. This is the burn. Burn represents combustion. This is a heat supply. This is called idealization. Heat is supplied. We are not showing that combustion is happening inside. We are saying that heat is supplied from somewhere. When heat is supplied, it is happening at a constant volume. This is idealization. Here, the heat is supplied from 2 to 3. You can see, from 2 to 3. Here, I am simplifying this process completely. From 2 to 3. So, from 2 to 3, the heat is added to the constant volume. Then, your expansion. You can see the expansion here. You can see the compression here. Compression is also in the isentropic process. We are saying that the expansion is also in the isentropic process. So, this is your isentropic. So, both are in the isentropic. and then between 4 and 1, heat rejection. Here we are saying that it is rejecting. Now pay attention to this, we are not getting this from anywhere, that air fluid is coming from anywhere. Pay attention that this one is definitely open because it comes out continuously and gases come out, air fuel mixture enters, then burns, and then your... It is an open cycle, but we have closed the ideal auto cycle. The mass is exchanging from the external environment. The cable is getting heated. So, this is a simplification, a lot of idealization for your Spark Ignition engine. So, this is the last one, constant volume, heat rejection. So, this is your heat rejection constant volume. Total processes are done in this auto cycle which is in the form of ideal. You have 2 isentropic processes, 1 to 2. 1 to 2 is your isentropic process. This is your isentropic compression. After that, heat addition, constant volume, isentropic expansion, then heat rejection. So, I am saying that in this, 1 to 2 isentropic compression, constant volume heat addition, isentropic expansion, constant volume heat rejection.

Now, the important thing is that this is an auto cycle, named after the name of Nicholas Otto. We have simplified this very much. We will put an A standard assumption, which we discussed in the previous lecture. This cycle should be noted that it is an ideal, internal reversible process. we can write it like this because it has an isentropic process involved so we can present it in the TS diagram as well so for example 1 and 2 are isentropic so 1 and 2 will come in constant S this is S so it becomes constant S and then 2 and 3 are constant volume heat addition then 3 and 4 are constant entropy isentropic expansion and then 4 and 1 are constant volume heat rejection so it is like this your four processors in this cycle. Now, we can analyze this thermodynamic data if we want. I have left some things to see how we can fill up the science here. For the thermodynamic analysis, you have to understand that the auto cycle is a closed system, not open. We will assume that kinetic potential energy. We will disregard the changes that are negligible. We will consider it negligible. We will consider it as zero. Right? Now we can apply this closed system to the energy balance. We will apply it to unit mass. So, pay attention to this. Here you have Q in and Q out. In minus net Q out, like this, Q net in minus W net out will be delta E, which will be delta U because we have assumed that kinetic energy is not a potential change. So, this is your basic definition. If you consider this cycle, then you will get this total effective energy balance. In which Q net in is Q in which you can see Q in minus Q out and what will be connected with this because it is expansion and isentropic is compression so energy is working here and in this case it is working means it is working in the surrounding so that is what W out will come from here and W in will come from here Now you have to take out the total work is important for us because it will be important for us. What does the cycle do? It will convert heat into total work. So for this you have to do that because we have taken the air standard assumption so we can convert these cues into internal energy differences because in this process 2 to 3 which is a constant volume heat addition Qin there is no additional work in this is it not? so in this Qin will be your U3 minus U2 which will be Cv multiplied by T3 minus T2. because this is an A standard assumption and similarly your Qout will be U4 minus U1 which is Cv multiplied by T4 minus T1 Now, this is Qin Now, you can remove eta from this Now, eta is equal to Wnet equal to Qin This will be 1 minus Qout divided by Qin Now, pay attention to this which is of an otto cycle. By definition, if we take out Wnrt, it comes out from here. If you look at the Q Wnet in the balance, then Wnet is equal to So, in this, Wnet will give you Qin minus Qout in this system. So you can write 1 minus Qout is T4 minus T1 Cv Since it is delta U, so delta U will be written in the form of Cv Now, if you replace Cv T4 minus T1 with CvT3 minus T2 then Cv will be cancelled and eta TH auto will be 1 minus T4 minus T1 minus T3 minus T2 and we can replace it later if we want or you can write it in the form of T1 and T2 now you can think that process 1 to 2 and 3 to 4 is isentropic and it means that your volume this volume is V1 is equal to V4 and V3 equal to V2. So, if there is an isentropic process and we assume that this is the ideal gas form, which is our standard assumption, cold standard assumption, then due to this, in the isentropic process, you clearly consider PV to the power k constant, the expression of the ideal gas. For that, when we discussed the ideal gas, we had taken out many expressions in it. The ratio of the temperature at the end of the two processes and the other relations that we get from it we can use them here as well. And in this case, the ratio T1 by T2 comes out as V2 by V2 and K-1. K is the ratio of heat capacities, Cp by Cv. And this comes out as This is equal to V3 by V4. K-1 because v4 is equal to v1, so you can replace it also and v3 by v4 will naturally come out from this relation t4 by t3. So, this is important. If you want, you can simplify it more in relation. Now notice that if this relation is there, which we have taken out from here, then this relation, this term, if I replace it with this, if I use it, then its value comes to 1. This means that you have eta auto 1 minus T1 by T2 which is 1 minus look here V2 by V1 to the power k minus 1 We can also write it as 1 minus V1 by V2 k minus 1 and V1 by V2 is your compression ratio because the maximum volume is this and the minimum is this so the ratio of this is called R this means that eta is 1-R 1 by R is k-1 which is R Vmax by V1 Vmax by Vmin equal to V1 by V2 so here basically First, you used the air standard assumption. Then, you used the basic definition to draw these relations for this condition, which is for the ideal motorcycle. Then, you used the ratio of the volume. The ratio of the volume is the compression ratio of V1 by V2. So, if you pay attention, the thermal efficiency of the brick depends on R, which is the compression ratio. and compression ratio and you have to see that k is not constant so kp also depends on the specific hit ratio.

$$\eta_{th,otto} = \frac{w_{net}}{q_{in}} = 1 - \frac{q_{out}}{q_{in}}$$

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

$$\eta_{th,otto} = 1 - \frac{T_1(\frac{T_4}{T_1} - 1)}{T_2(\frac{T_3}{T_2} - 1)}$$

Process 1 →2 and 3 → 4are isentropic and v2=v3 and v4 =v1

$$\frac{T_1}{T_2} = (\frac{V_2}{V_1})^{k-1} = (\frac{V_3}{V_4})^{k-1} = \frac{T_3}{T_4}$$

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

$$\eta_{th,otto} = 1 - \frac{1}{r^{k-1}}$$

Where r is compression ratio

$$r = \frac{v_{max}}{v_{min}} = \frac{v_1}{v_2}$$

Now, if you want to control it or increase its efficiency, you have to see in which range you operate. If you plot the graph, you will see that the ETA auto comes out in compression ratio.

Now, it is clearly visible that as you increase the R, the eta will increase. In this range, you normally operate, but if K is also increased, then also your eta will increase. So, normally, if we do it in high compression, then it is prematurely called ignition. This is called auto-ignition. In practice, we will not do high compression in this case because engine knocking sound comes out. So, a specific range is operated and normally it will depend on the working fluid. You can change the working fluid or increase it for efficiency. But all these things are an engineering way of optimization. Let's apply what we have understood and solve a question. This is your ideal auto cycle. It has already given the compression ratio. It is said that the value of compression ratio is 8. It means that your V1 by V2 is given 8. It is said that the condition of the beginning of the compression process is 8. 100 kPa and 17 degrees Celsius. So, you have been given the condition of 1. And 800 kJ per kg of heat has been transferred in constant volume addition. Counting for very specific heat. We have to find out. You have to take specific heat with temperature variation. And we have to find out how much maximum temperature comes out and the pressure in this whole cycle. and how much is the network, how much is the thermal efficiency, how much is the mean effective pressure of this whole cycle. So we will draw this in the PV diagram. So in the PV diagram, isentropic compression is done, 2 heat addition Then your isentropic expansion and then your constant volume heat rejection so 1, 2, 3, 4 and here your Q in and Q out 1 is the data of the pressure 1 is the pressure of 100 kPa this is the information now the maximum temperature where will it be? at which particular point? so naturally it will be at state 3 because at this time after adding heat your major temperature will come out there first we will assume to do this question that first air standard assumption is applicable kinetic energy and potential energy is negligible And we have been told that the heat capacity and the specific heat will have to be taken into account.

So now let's talk about T3. How do we get T3 out? For this, we have to take the air table. So, if you look at the air table carefully So I have taken out A17 from the test book So temperature is given, enthalpy is given and there is a PR is actually called PR ratio, it is a reference It is done with a reference ratio And U is given and then there is VR Again that is also a reference and this is your S which is your entropy under condition Zero pressure as it is called Now what is normally done is that when PR If we divide 2PR, it will be equal to P1 by P2. So, let's see how to solve this problem. Because you have to use this table. So, from this table, you have to use PR and VR. Let's start and understand how to solve this problem. First of all, the information given to you is 17 degrees. T1 is 290 K. So, you will get U1 from the air table. So U1 is 290 K. And U1 has the value of 206.91 KJ per kg. So this will be your 676.1 Now let's talk about the 1 to 2 which is called isentropic process In isentropic process the compression is 1 to 2 Now in this if you take in this reference Vr1 by Vr2 So this ratio that I have written here You can write this easily in the form of an ideal gas V2 by V1 is the corresponding value So this is normally to simplify This is the property of the ideal And you can directly use this So this is reduced But because the constant in reduced will be cancelled If you take the form of the ratio That's why Vr1 by Vr2 Will come out 1 by Vr2 will be V1 by V2 So now you have this ratio So you know Vr1 And V1 by V2 is R Which is given as 8 So from here you will get VR2 Which is 1 by 8 times VR1 And from here you will get 84.51 Now we will see 84.51 VR2 here somewhere between 84.5 and 84.4 so if you interpolate the temperature you will get the value of T2 which is 652.4 Kelvin and then you can essentially take out T2 from 652.4 Kelvin by taking out U from corresponding value So U2 will be 475.11 kJ per Kelvin So U2 and T2 are also available Now you have to check the Qin address for the 2-3 operation You need to know the Qin address for the constant volume operation To get Q3 you need Q2, so you have got U2 To see the process, you have to check the Qin value of Q2 and Q3 Qin value is 800 kJ per kg Q3 is 475.11 kJ per kg and from here your U3 will come out which is your 1275.11 kJ per kg Now from this table you will see the corresponding temperature and from here comes your 1575.1 k and its corresponding VR3 will come out to be 6.108. So, one thing is also written in the question that We have to remove pressure, temperature, T3 and P3. So, we have to remove both. So the important thing is that for this we have to... we have to use the equation of P3V3 by T3 is equal to P2V2 by T2 and from here P3 is equal to P2T3 by T2V2 by V3 and V2 by V3 is 1 because this is your 2 and 3, your 1 is constant volume So T3 by T2 is T3 which we have just taken out T2 is taken out so you know this expression T3 we just took out 1575 So P3 will come out And P2 will have to be taken out So P2 you know or not So you have to take it out from here T2 is given to you 652 point So P2 also has to be taken out For P2 you will take out P2V2 by T2 is equal to P1 V1 by T1 P2 is equal to P1 T2 by T1 V1 by V2 which is 8 T2 and T1 are already taken out P1 is 100 kPa P2 is 1799.7 kPa Plug in P3 is equal to which is 4.345 Mpa So this is how you have obtained maximum temperature and maximum pressure. Now the second question is what will be the network output of this? So, for network output you will have to find the energy balance. So your W net will be your simple Q net. Because this is a cycle, delta U will effectively become zero. The area under the curve of the whole cycle will only be your Q net or W net. In minus Qout You have to remove this Qout You know Qin, you have to remove Qout You have to remove this U4 minus U1 You have to remove Qout U4 minus U1 We know U1 because we have to find the condition for U4 which you can find from the table. To find this you have to use the ideal gas concept that you already know VR3, and you also know that VR3 by 3 by 4 3 by 4 is the same compression ratio, 8 because you will change the same amount of volume. So VR3 by VR4 which is V4 by V3 which is R this will give you VR4 which is R times VR3 and we know VR3 we have taken it out now and it is 8 so it is 48.86V you will see this in the table and from the table you will take out the corresponding temperature which is 795.6K Internet energy is 588.74 kJ per kg Now you have all the information Apply Qout in this expression Now you will do U4-U1 which is 588.74 minus the original U1 206.91 which we wrote earlier enter the value of u1 and you will get 381.83 kJ per kg so this is the key out this means that wnet is 800 minus 381.83 kJ per kg which is 418.17 kJ per kg So this is your problem, we just did part B, now we will do part C. Part C is straightforward, to remove C eta, you have W net divided by Q in. If you plug in, you will get 5.523, this is your 52.3%. This is your eta, which is the eta of the motorcycle. And then you will remove the meaning. Effective pressure for the cycle. Now the meaning of an effective definition was written earlier. Mean effective definition was MEP W net delta V which is basically V max minus V minimum which is V1 minus V2. You can write it like this V1 1 minus 1 by R If you plug all these things you can extract the information but most importantly, we have written everything in V1R we have not extracted V1 but we can extract it because you have the I.G.E. so V1 is equal to RT1 by P1 is known, R is known, T1 is known so this is 0.8 323 m3 and here you can plug in the WP minus 5754 kPa because you know the V1 and the WP minus 8 so this is the total WP-5754 kPa one more thing to notice is that when we wrote ETA we defined ETA for the motorcycle so we defined this also Now, pay attention to the K heat capacity. If we take air, we apply it as we did in the case of normal oil, then we consider the table. By considering the table, you get variations of things. Because U is changing, and other things are changing. But if you take CP, if you take R and You write eta as 1 minus rk minus 1 This is basically a cold air assumption where the values of a specific heat are at 25 degrees Celsius and will remain at room temperature so there are no variations in temperature In such cases, what is your efficiency? minus 1 by 4 equal to 56.5 percent. So, this basically tells us that this variation has reached 52 to 56. Assuming that the specific hit is constant. So, pay attention if you are applying, pay attention to this because we were told that to take specific hit variable, it also means that we had to remove all the conditions and then Wnet by Qin was to be removed. Otherwise, we could have removed ETA in any way. But in this, it is called cold air standard assumption. If we put it in, it means that it is constant. This is a constant specific heat value. So, in such assumptions, it can be easily applied. But otherwise, your definition is Wnet by Qin. But the things we cancelled in it, we assumed that it is a core layer standard assumption. I hope you understood this. What is the principle of the reciprocating engine? What are the assumptions of open and gas power cycles? How did we represent the open spark engine in the closed cycle by the auto? And by using an example, we solved some problems. I hope you have come to this point. Then we will continue this discussion in the next lecture, but we will use diesel and the Brayton cycle. Till then I take your leave, see you next time.