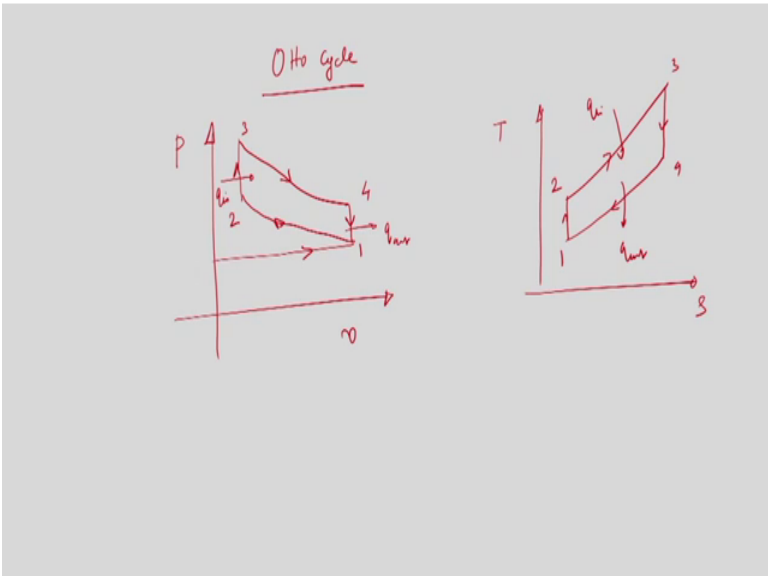
IC Engines and Gas Turbines

Prof. Pranab K. Mondal
Department of Mechanical Engineering
Indian Institute of Technology Guwahati

Lecture – 07
Otto, Diesel and Dual Cycles (Contd.)

So, we will continue our discussion on IC engine. And today we will discuss about diesel cycle. In the last lecture, we have discussed about the mathematical relation of Otto cycle, we have quantified the thermodynamic efficiency of Otto cycle. So, just today before I go to discuss about the Diesel cycle, I will recapitulate the Otto cycle once again. If you can recall that Otto cycle basically you know four stoke engine, SI engine is approximated by an air standard cycle, and this ideal cycle is known as Otto cycle.

(Refer Slide Time: 01:01)



While you are talking about Otto cycle and if you can recall the Pv and Ts diagram. And just I will try to recapitulate Otto cycle. And if we try to recall you know recall the Pv and Ts diagram, so this is p and this is v diagram, pressure versus v diagram, and then corresponding Ts diagram. So, we have seen that we have taken a few approximations like that whenever air is introduced, not air the air fuel mixture is introduced in the new cylinder during intake stroke, we are assumed that the entire process is occurring at a constant pressure.

So, we have approximated this is a constant pressure intake, air fuel mixture that is charge is being introduced into the cylinder at constant pressure. These assumptions is not very bad assumptions rather this is a good approximation because pressure inside the cylinders should be slightly less than atmospheric pressure, otherwise there will be a frictional loss to the intake manifold, while air fuel mixture is showing full intake manifold to the cylinder.

Similarly, we have assumed that whenever after the end of the intake stroke that is air fuel mixture is being introduced, then all the valves should be closed, exhaust valve is remaining closed from during intake stroke as well. And during the compression stroke it will remain closed. And what we are doing? We are doing we are closing the intake wall as well at the beginning of the compression stroke. So, we have approximated compression stroke by an isentropic process.

So, if this is intake stroke, then we are approximate we are approximated that the compression stroke is represented by an isentropic process. Then what will happen? At the end of the compression stroke we should ignite that we should switch on the spark plug. So, the combustion will take place. And the combustion is represented by constant volume heat addition process. So, in case of Otto cycle, the combustion process is represented by a constant volume heat addition process.

Then after the end of the combustion, we will have you know high temperature since, it is a constant volume process, so pressure will increase. As a result of the increasing result of the increment of the temperature inside the combustion chamber inside the cylinder, so we will have a rise in pressure. And that will create a thrust on the piston first, and it will allow piston to go back from TDC to BDC. And we will have a power stroke that is expansion stroke.

Again we have approximated that power stroke by an isentropic process. And then finally, you are having you know constant volume heat rejection that is exhaust blow down, I mean whenever piston is reaching towards the BDC at the end of the power stroke, we open exhaust valve. We have discussed about the reason behind opening the exhaust valve slightly below BDC or at the end of the power stroke, that means, we should close the exhaust valve whenever piston is far away from BDC towards the end of the power stroke.

We have discussed the reason because while you are doing so, because we need to expel out combustion product before piston reaches at BDC at the end of the power stroke. This will allow some enthalpy to go out that is fine, but what it will do it will you know weaken the pressure inside the cylinder, that in the next stroke when piston is coming from the BDC to TDC that is exhaust I mean stroke then piston will create less resistance while it is traversing from BDC to TDC.

Since, I told you that out of this first stroke we are having only one power stroke and there are three ideal strokes. So, it is quite you know good to good practice that we should open exhaust valve before piston reaching at BDC to at the end of the power stroke so that the piston will rest if a piston will face less resistance and we require less power which you, I mean our for the movement of the piston from BDC to TDC.

So, these four processes are the intake, compression, power stroke and blow down. So, the combustion product combustion processes represented by constant volume heat addition q in; and then it just blow down higher because whenever we are opening exhaust valves, some amount of you know combustion product will go away. We will spill out from a cylinder, and it will carry enthalpy or from the cylinder. So, I mean it is exhaust blow down. So, it is q out. So, these processes you know constant volume.

My this question today is whatever approximation we have taken that isentropic process, compression process is represented by isentropic process, expansion process is represented by isentropic process while constant, heat addition that is combustion process and exhaust blow down heat output. So, heat rejection so heat addition and heat rejection both these process are approximated by a constant volume process, constant volume heat addition, constant volume heat rejection.

As I said you that intake process is constant pressure process, this is not a very bad assumptions, because pressure is remaining fairly constant while we are introducing air fuel mixture into the cylinder and pressure should be slightly less than specific atmospheric pressure only to account the fictional losses in the intake manifold.

Similarly, when you are having compression process the isentropic process we are approximating by isentropic process, this is also not a very bad assumptions, because see rather this is a good approximation except at the beginning of the compression stroke our intake valve is still open; I mean I have discussed it again that exhaust valve is remaining open even at the end of the, even at the beginning of the compression stroke.

Because during intake stroke we cannot completely remove all the residue from the cylinder during (Refer Time: 07:07) stroke. So, some amount of air fuel mixture will be, you know we will mix with the residue of the combustion product and for that we need to keep open the intake valve or even when piston start traveling for BDC to BDC towards TDC at the beginning of the compression stroke only to have a better efficiency; so only to have efficient mixing, efficient combustion.

So, at the beginning of the compression stroke since exhaust intake valve is remaining open. So, and at the end of the compression stroke we are switching on the spark plug. So, except these two cases I mean at the beginning and at the end of the compression stroke, our process is the isentropic that whatever we have assumed this is a good approximation.

Similarly, when we are approximating the combustion process by a constant volume heat addition, this is also not a very bad assumptions; this is also good approximation, because which normally what is done when piston is below TDC. I mean at the end of the compression stroke, spark plug switch is on.

And whenever piston is received at the TDC, at the end of the compression stroke, because switching on the spark plug you require a finite amount of time, although it is of the order of microsecond, but still we require finite amount of time and by that time if you start switching on the spark plug versus piston is slightly away from the TDC that are slightly below TDC.

And if we switch on the spark plug by the time when piston reaches at TDC, the spark plug switch is on intake combustion is completed and as if the volume is remaining constant. So, constant volume heat addition is not again a bad approximation not a bad assumption. So, it is also good approximation.

Second thing third; thing is expansion the power stroke, it is again represented by an isentropic process, but again this is not a very this also good approximation except two cases. One is see at the end of the compression; at the end of the power stroke, when we open the exhaust valve only to have a blow down. So, and at the end of the you know power stroke rather expansion stroke we will open the exhaust valve, only to have a blow down, only to reduce the resistance, only to reduce the pressure inside the cylinder so that the piston will face less resistance while coming from BDC to TDC, again during the exhaust stroke.

And second thing is that you know that beginning of the power stroke is; beginning of the power stroke is also affected by the last part of the combustion product. You know, beginning of the power stroke is affected by the last part of the combustion process. So, except end of the power stroke, rather end of the you know expansion process expansion stroke or power stroke is affected by the opening of the exhaust valve, while beginning of the power stroke is affected by the last part of the combustion process. So, except these two things the processes you know isentropic that whatever we have assumed this is also a good approximation.

Last one is again exhaust blow down. So, whatever we have assumed that I mean before piston reaches at BDC, during the power stroke we open exhaust valve only to have a blow down, only to spill out some combustion product from the cylinder. And this is whenever you know piston is reaching at BDC, whenever piston is reaching at BDC, then we start you know intake valve is remaining closed or exhaust valve is remaining open.

Whenever piston is reaching at BDC as if and piston is traversing from you know BDC to TDC and that is you know constant pressure. So, whatever I am telling that you know blow down in the railing therefore, must not be constant volume not quite rather constant volume process, because there is no high percent cylinder to resist piston in the flying exhaust stroke.

So, why what you are doing? Only to reduce the pressure inside the cylinder, so that the piston while traversing from BDC to TDC at the exhaust during exhaust stroke should not experience huge resistance, and to for or to take into account that what we are doing we are opening the exhaust valve, when piston is slightly away from BDC during the end of the power stroke. And we are approximating it is the volume is remaining almost constant, because the piston is slightly away from BDC, so volume is remaining almost constant.

So, the heat rejection that is exhaust blow down, it is also a constant volume process and this approximation is not a very bad approximations. So, we have discussed about the four different process, because we have taken approximation while doing some mathematical analysis, only to have a quantification of the thermodynamic efficiency of the Otto cycle.

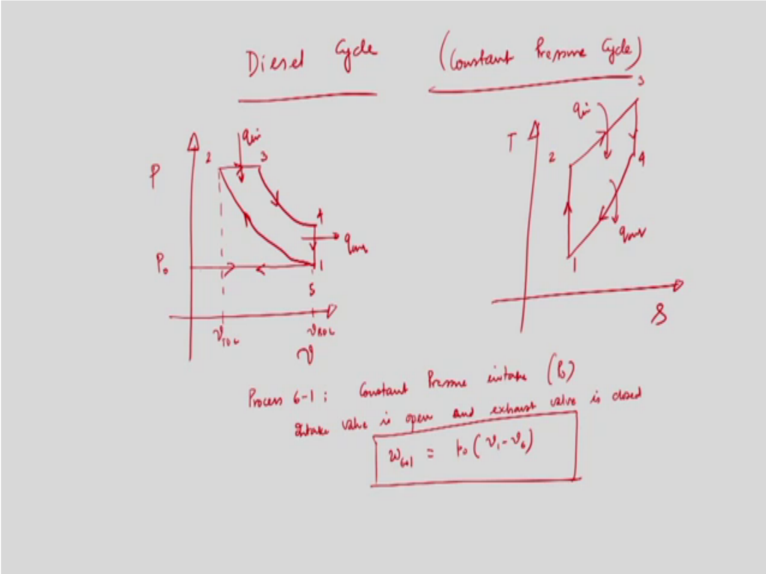
And today we have to discuss about that the whatever assumptions, whatever approximations we have taken those approximations are not bad approximation these are good approximations; except a few cases that we have discussed that at the beginning of the compression stroke, at the end of the compression stroke, at the beginning of the power stroke, and at the end of the power stroke I have discussed.

And you know that if I draw the Ts diagram, so these process is you know isentropic process. So, if I give the name, say this is 1, 2, 3, 4. So, 1-2 is isentropic compression, then 2-3 is basically combustion process that is heat addition process. So, peak pressure and peak temperature will go high, because the constant volume process temperature will go high because of the combustion; since, processes is volume is remaining constant, so pressure will go high. So, 2-3 to 3, 3 is a peak temperature T 3 and P 3 are the you know P 3 is the peak pressure and T 3 is a peak temperature.

Similarly, 3-4 is again isentropic process, isentropic expansions. And 4-1 is the blow down that is heat, this is the heat rejection q out and this is q in. So, we have discussed that we have last class we have discussed about the, we have discussed about the thermodynamic analysis of the Otto cycle. We have calculated the thermodynamic efficiency of the Otto cycle, considering air to be an ideal gas and we have used ideal gas relationship.

And we have taken a few approximations. Today, we have discussed that the approximation that we have considered only to drive the mathematical thermodynamic efficiency or thermal efficiency of Otto cycle. Those approximations are not very bad approximation rather, those are good approximations except a few things and that is what we have discussed. So, today we will discuss about with this I complete the discussion about the Otto cycle. And we will again discuss about the, we will work out a few example based on Otto cycle, but now we will discuss about the diesel cycle, this is very important.

(Refer Slide Time: 13:55)



So, today I will discuss about Diesel cycle, and we will try to quantify the thermodynamic efficiency. Before, let me discuss you that since the constant combustion process is represented by a constant volume process, also the exhaust blow down that is a heat rejection is represented by constant volume process, Otto cycle is sometimes known as constant volume cycle.

So, Otto cycle is sometimes known as the constant volume cycle, because we have approximated that and this is not a very bad approximation that the combustion that the heat addition process is a constant volume process. So, today now we will discuss the diesel cycle that you know four stroke in CI engine, four stroke cycles CI engine. Again we are approximating by a air standard cycle and the ideal cycle is known as the diesel cycle, while we are trying to analyze the thermodynamic you know a change of the thermodynamic state at the end of each and every strokes during the you know of a four stroke cycle CI engine.

We are approximating by air standard cycle and the ideal cycle is known as Diesel cycle. Instead of having constant volume constant volume combustion in a Diesel cycle we are approximating a constant pressure, because why we are doing so, let me discuss you let me discuss first this and then we will go to drive the mathematical analysis rather towards the quantification of thermodynamic efficiency, rather thermal efficiency of the diesel cycle.

In a CI engine, if we try to recall that the while we have discussed about the difference between SI and CI engine. We have discussed that CI in a CI engine, combustion process is not a similar to what is there in the SI engine, because in the SI engine we normally introduce during the intake stroke air fuel mixture is charged.

But in case of a CI engine, we introduced air to the intake manifold during the intake stroke, we compressed air to a temperature and pressure and that at the end of the compression stroke when the temperature are temperature and pressure of the air is high; then we inject rather we stay fuel through a fuel injector, and we utilize the high pressure temperature condition to ignite that to initiate the combustion itself.

Now, question is whenever we are introducing fuel or when you are spraying fuel into the cylinder at the end of the compression stroke through fuel injector, we require finite time and we will discuss why we were discussing about the combustion process that it is known as ignition delay that means, we require finite time to inject rather to supply fuel into the cylinder.

Whenever you are supplying fuel in a whereas, spraying fuel in to the cylinder in a form of a, in a spray pattern in a nice spray pattern, because it is required that again we will discuss. We require finite time and only to supply fuel, only to spray fuel through fuel injector, because fuel injector is also a mechanical device it requires a finite time to you know to create a spray pattern to supply fuel into the cylinder also, this is known as physical delay.

And also the moment at which we supply fuel, because fine we should try to fragment the fuel particle into more finer and finer droplet, but still we require some chemical delay, because the moment at which we supply fuel it would not take part in the combustion and it requires a certain amount of time, although it is of the order of millisecond, but we require finite time. So, this two you know and it depends upon the chemical characteristics of the fuel.

So, you know this physical delay together with the chemical delay is known as ignition delay. Considering this ignition delay, we are approximating that the pressure inside the cylinder will remain constant while entire combustion is completed. So, why because we cannot represent the combustion process by constant volume process, as I said you that the moment of the piston is very you know instantaneous. So, is very you know it is very rather spontaneous, moment of the piston is spontaneous.

So, whenever piston is reaching you know at the where a piston is racing at TDC at the end of the you know compression stroke, it is not possible to keep piston hold for a while over there, so that the volume will remain constant and inter combustion will be completed.

Instead what is done normally rather to explain this, we can explain it in this way that whenever is piston is slightly below TDC at the end of the compression stroke, we try to supply fuel through fuel injector. And as I said you that we require some amount of time accounting the ignition delay which is nothing but the you know physical delay plus chemical delay, so that delay period I mean we will considering the delay period whenever piston is slightly below TDC, and we start spraying fuel and maybe combustion might start.

And then again when is when piston is coming after distinct TDC and when is again piston is traveling back from TDC towards BDC during the next stroke that is expansion stroke, combustion may last combustion maybe lasted. So, and during that we cannot assume that the volume will remain constant that means, we have started spraying fuel when piston is slightly away from TDC, during the end of the compression stroke.

And combustion maybe initiated over there, but combustion will last again when piston is returning back from TDC towards BDC, during the beginning of the power stroke. So, while it is happening we cannot assume that the volume will remain constant rather we can assume the pressure inside the cylinder will remain constant. That means, to take into account the effect of ignition delay and we are approximating that the combustion will start when piston is slightly away from BDC TDC, and it will last when piston is slightly when piston is returning back again from TDC.

And I mean rather while slightly away from TDC, during the beginning of the power stroke, and during that process volume will no longer remains constant rather pressure will remain constant that we are approximating it, and that is why combustion process in a diesel engine is approximated by a constant pressure process. And sometimes diesel cycle is known as constant pressure cycle. So, diesel cycle is known as sometimes constant pressure cycle.

So, today we will discuss about the you know, again we will discuss about the thermodynamic, we will do the thermodynamic analysis of the diesel cycle. And we will discuss, we will try to quantify the thermodynamic efficiency of the diesel cycle fine. So, again we have to draw Pv and Ts diagram. So, if we draw the P v and Ts diagram, so this is P, this is v and this is temperature entropy diagram T s.

So, intake process only air is being introduced intake stroke and again were approximating that the pressure will remain constant. Again I am telling that the pressure inside the cylinder will be slightly below the atmospheric pressure, and this approximation is not a very bad approximation rather this is a good approximation, and we are approximating these the process will be like this.

So, maybe and P naught, this P naught will be slightly lesser atmospheric pressure only to take into account the fictional losses in that of the you know rather fictional losses in the intake manifold. Then what is done? Then while the cylinder is filled up with the air fresh air, then we are having compression strokes. So, compression stroke again is represented by an isentropic process, and that is what you have discussed this is also not a very bad approximation, this is also good approximations.

The intake valve will remain closed or remain open at the beginning of the compression stroke, and at the end of the compression stroke again we have to ignite you know some amount of, we have to spray some amount of fuel or required amount of fuel to initiate combustion. So, during these two things, I mean during these two I mean cases, I mean at the beginning of the compression stroke at the end of the compression strokes the process is an isentropic process and this approximation is a good approximation.

So, here we are having isentropic process, maybe these process is you know so fine isentropic compressions stroke; so, maybe 1 and 2, 1 and 2. And then you know SI engine you have approximated this is a constant volume process, but here it is a constant pressure process, that is combustion process is a constant pressure process that is what we have discussed a little ago that instead of considering of volume will remain constant, we can assume the pressure will remain constant, because it will start when slightly below when piston is slightly below TDC, and it will last even when slightly you know coming from TDC towards this BDC.

So, we are approximating instead of volume to be constant pressure will be constant, constant pressure. And then again, power stroke is approximated by a constant by an isentropic process again by an isentropic process.

And finally, exhaust blow down is again approximated. So, this is 3, this is 4, this is 5 and let us say this is 6, this is 6. So, 4-1 is exhaust blow down that means, this is similar to what we have discussed in the context of discussion of SI engine. So, we have seen that the only difference is that here combustion process is represented by a constant pressure, and that is why the cycle is sometimes known as constant pressure cycle.

So, this is the heat addition q in, and this is exhaust blow down q out. And this is not a very this also good approximation, because I mean we should open exhaust valve when piston is little away from BDC during end of the power stroke. And we will need to spill certain amount of combustion product only to reduce the pressure inside the cylinder, so that the piston will face less resistance while traversing back from BDC to TDC in the next stroke that is exhaust stroke.

So, this is the PV diagram. Now, if we draw the Ts diagram, then again we will go get that 1-2 here pressure at the pressure at the at the end of the compression, temperature at the end of the compression should be high enough as compared to the SI engine, because when we are utilizing the high pressure and temperature of the you know air to ignite the fuel itself, because we are utilizing the self ignition properties for itself without having an external is not like spark plug, in case of a CI engine.

So, the temperature and pressure P 2 or P 3 are even same peak pressure, because we have approximated this process the combustion process by constant pressure process, rather T 2 you know T 2 and then of course, so T 2 will be high that is at the end of the tempera at the end of the compression process temperature will be high.

Then we are having combustion product for combustion process. So, 3 will be again higher than the temperature 2, T 3 will be higher than temperature T 2. And then we are having 3-4 that is exhaust blow down, and then we are having 3-4, 4-1 and 2-3, and 4-1 is the exhaust blow down.

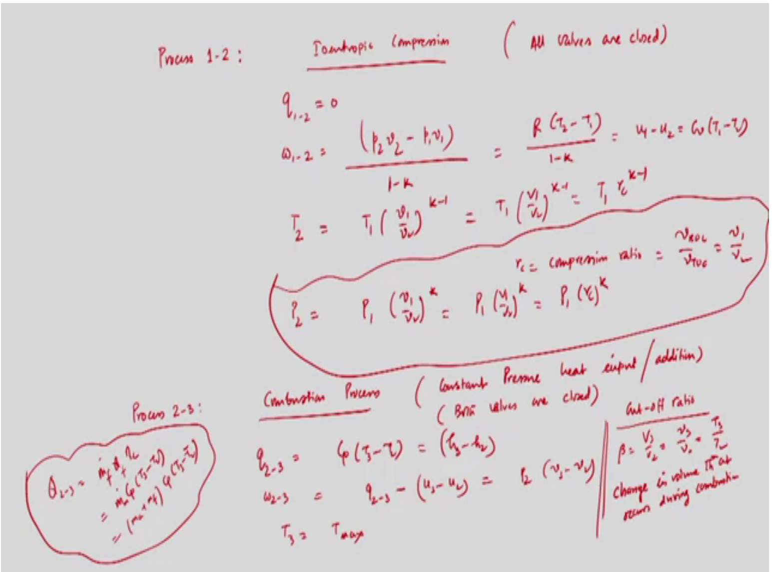
So, this is Q in heat addition, this is Q out flow rejection. So, 1-2 and 4 3 to 4 these process are approximate approximated by an isentropic process, and these are not very bad assumptions that we have discussed fine. Again while you are trying to do the analysis thermodynamic analysis, we have to because as I said you that the four stroke cycle CI engine is approximated by air standard cycle and the ideal cycle is known as Diesel cycle.

While combustion process is represented by constant pressure process and sometimes is known as constant pressure cycle. So, again we will be using will treating air to be an ideal gas and we will be using ideal gas relationship to drive the thermodynamic efficiency or thermal efficiency of Diesel cycle.

So, now we will write different processes. So, process 1-2 it is very important process that a process 6-1, this is very important. So, I will write process 6-1 that is known as constant pressure intake. So, this is known as constant pressure intake, pressure is remaining constant that is P naught. And here what is done? Intake valve is open and exhaust valve is closed.

So, what will be work done, because it is a constant pressure intake volume is changing. So, work done w work done by w 6 6-1 will be equal to P naught into v 1 minus v 6, v 1 is BDC and v 6 is v TDC rather you know that is this is not point 6. So, this is v TDC and this is v BDC. So, v 1 minus v 6, so work done during the intake stroke is like this.

(Refer Slide Time: 27:49)



Next we will move to another process. So, process 1 to 2, so if I write process 1 to 2, so process 1 to 2, what is this process? Compression - isentropic compression. Again we are telling that we have I have written the ideal gas relationship in my last lecture will be utilizing those while again we had to try to drive thermodynamic efficiency or thermal efficiency of the Diesel cycle. So, isentropic compression strokes we will write that all valves are closed all valves are closed that is intake and exhaust valves are closed.

So, although at the beginning of the compression stroke is affected by the opening of the inlet valve and at towards the end because of the spraying of the fuel so but we are we are assuming that all valves are closed. So, if that is the case so isentropic process, there should not be any heat interaction right. So, q 1 to 2, q 1 to 2 will be equal to 0; w 1 to 2 we have to calculate, w 1 to 2 will be if we go back to the diagram p 2 v 2 minus p 1 v 1 divided by 1 minus k that equal to R into T 2 minus T 1 divided by 1 minus k that equal to u 1 minus u 2 that equal to C v into T 1 minus T 2 C v into T 1 minus T 2. These are all these are we can obtain from ideal gas relationship very straight forward.

So, what will the temperature at the end of the compression stroke, T 2 will be equal to T 1 into v 1 by v 2 to the power k minus 1 is equal to p 2 by v 2 by v 1 to the power sorry v 1 by v 1 by v 2 to the power k that equal to P into r c to the power k, where r c is equal to compression ratio is equal to be v BDC by v TDC is equal to v 1 by v 2. If you go back to my previous slide, v 1 and v 2 are nothing but the v BDC and v TDC fine.

So, this is the compression ratio. So, we have obtained no heat interaction, this is isentropic process. Work done we have calculated during the process within the compression process, because you need to do some work and that is for energy we are getting from the flywheel. Temperature at the end of the compression process is T 2 like this. And similarly pressure at the end of the compression process is P 2 that equal to P 1 into v 1 by v 2 to the power k sorry that equal to P 1 into v 1 by v 2 to the power k is equal to P 1 into r c to the power k, where r c is equal to compression ratio that is what we have discussed.

And T 2 is equal to T 1 into v 1 by v 2 to the power k minus 1 is equal to T 1 into v 1 by v 2 to the power k minus 1 is equal to T 1 into r c to the power k minus 1, where rc is equal to compression ratio fine. So, process 1 to 2, we have identified the change of pressure and temperature at the end of the compression stroke that we have calculated using an ideal gas relationship.

So, now we go to process 2 to 3, this is very important process 2 to 3 is the combustion process. This is combustion process rather we have assumed that this is represented by constant pressure heat input or heat addition process, both valves are closed both valves are closed. Process 2 to 3 is the combustion process constant process heat input or addition both valves are closed. So, here pressure is remaining constant.

So, what will be work done and you know q 2-3. So, q 2 to 3 specific addition is equal to what pressure C p into T 3 minus T 2, C p into T 3 minus T 2 that equal to h 3 minus h 2, change, change in enthalpy between point 3 and 2. And w 2 to 3, this is very important that is q 2 to 3 minus u 3 minus u 2 that equal to P 2 into v 3 minus v 2 pressure is remaining constant change in volume v 3 minus v 2 v 3, v 2.

Again if we go back to my previous slide v 3 and v change in volume; there is change in volume during the combustion process that is volume is no longer remaining constant that is what we have discussed that it is combustion will restart when piston is slightly below TDC. It will last even when piston is coming back from TDC, so that the volume will change. Volume will no longer remain constant rather we are approximating pressure and constant and this is a very good approximation.

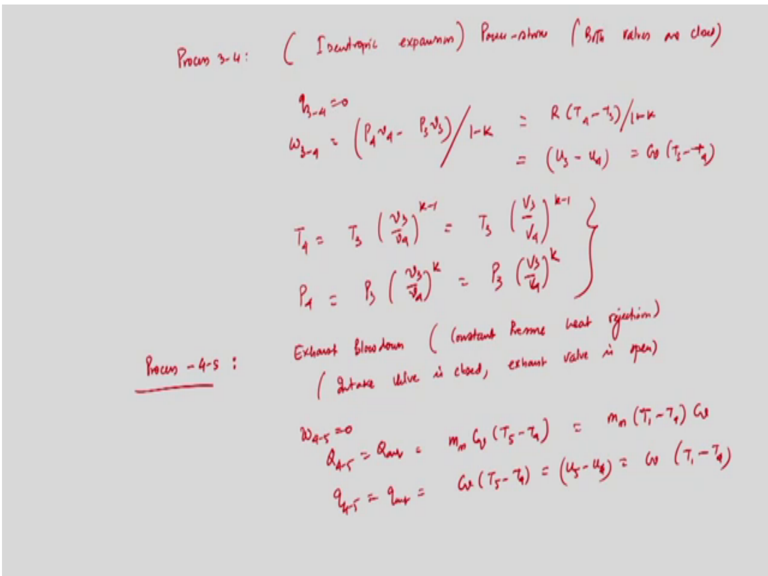
So, from this expression of work done we can see that we can have work done and the w 2 3 will be q 2 3 minus u 3 minus u 2 is equal to P 2 into v 2 and v 3. And T 3 is equal to T max and this is the maximum temperature, so that is very important. Now, this is what we need to this is what we will be required while we are while we try to obtain the thermodynamic efficiency or thermal efficiency fine.

Here see during the end of during the combustion process is rather q 2 to 3. And I can write that q 2 to 3 will be equal to you know how much mass flow rate of fuel, calorific value of the fuel and combustion efficiency that equal to m dot m mass flow rate of mixture C p into T 3 minus T 2. So, this in the mass flow rate of mixture that is mass flow rate of air plus mass flow rate of fuel into C p into T 3 minus T 2. So, this is the heat addition in the combustion process. This is heat addition in the combustion product mass flow rate of you know what is the amount of heat is being added during the combustion process.

So, mass flow rate of air plus mass flow rate of flow of fuel into C p into C p into T 3 minus T 2, and that will be equal to mass flow rate of fuel into calorific value of the fuel itself is equal to combustion efficiency fine. What you have seen that, at the during the combustion process volume is changing from v 2 to v 3 right. So, since volume is changing one ratio was defined which is known as cut off ratio. So, cut off ratio which is very important and is defined, cut off ratio it is beta is equal to v 3 minus v 3 by v 2 that is sorry that is V 3 by V 2 that is small v 3 by v 2 is equal to T 3 by T 2.

So, this is defined as the change ratio of change in volume, it is defined as the change in volume that occurs during combustions; that occurs during combustions. So, during the combustion process, volume is changed from v 3 to v 2. This ratio of v 3 by v 2 is known as cut off ratio and I mean as defined and indicated you know defined by beta. So, next process is 2 to 3 are identified. And next process is what that is 3 to 4 that is again isentropic process, 3 to 4 this is very important that is known as isentropic expansion process and that we need to know.

(Refer Slide Time: 36:07)



So, process 3 to 4, so this is again isentropic expansion or sometimes it is known as power stroke. All valves are closed, rather both valves are closed, both valves are closed. We are considering, but again I will say that whenever piston is reaching at BDC rather before reaching piston BDC, we need to open the exhaust valve we need to have excess blow down to reduce the pressure at the cylinder, so that the piston will face less resistance during you know while coming from BDC to TDC at the end of the compression stroke. So, this is very important.

So, again while we are writing that the process 3 to 4 is isentropic expansion or power stroke, both valves are closed. We have to know the pressure and temperature at the end of the compression stroke because while we are trying to quantify the thermodynamic efficiency we find, we are having heat addition. So, we need to know what is the amount of heat being rejected during exhaust blow down and for that we need to know the pressure and temperature at the end of the power stroke fine.

All valves are closed, since this is an isentropic process there is no hint heat interaction. So, q 3 to 4 will be equal to 0, but w 3 to 4 will be there that will be equal to how much? P 4 from the you know Pv diagram that will be equal to w 3 to 4 is equal to P 4 v 4 minus P 3 v 3 divided by 1 minus k right. So, is equal to if we use that T 4 minus T 3 by 1 minus 1 minus k that equal to u 3 minus u 4 that equal to C v in to T 3 minus T 4. These we will get from the ideal gas relationship straightforward, fine, no heat interaction, no heat transfer, q 3 4 0, w 3 4 we have obtained.

So, what will be T 4, because T 4 will be equal to T 3 into v 3 by v 4 to the power k minus 1 that equal to T 3 into capital V 3 by capital V 2 the power k minus 1. Similarly P 4 is equal to P 3 into v 3 by v 4 to the power k is equal to p 3 into V 3 by V 4 to the power k. So, this is what is the pressure and temperature at the end of the power stroke.

We have seen that P 2 and P 3 are the, if you go back to my previous slide where you know Pv and Ts diagram T 3 is the maximum T max. And P 2, P 3 are the P max from the Pv diagram and we have obtained. And from Ts diagram, we have obtained that T 3 is the max. Of course, because T 3 is the state at the end of the combustion, so temperature will go high definitely no problem.

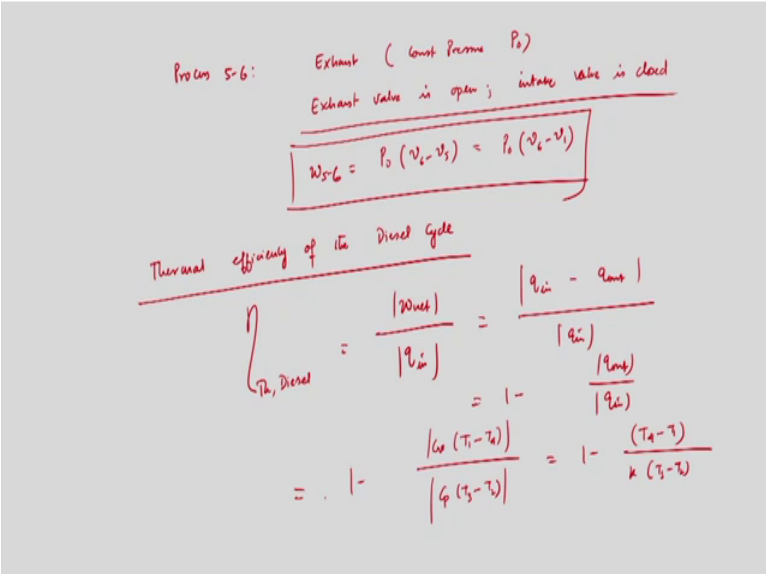
Then we will discuss about process 4 to 5, that is exhaust blow down or we can see this exhaust blow down or this is constant pressure heat rejection right. In this process, of course, intake valve is closed, intake valve is closed, exhaust valve is open, intake is closed, but exhaust is open we have to have open exhaust valve otherwise how we have blow down.

So, in this process, constant volume process, there should not be no, so w 4 to 5 will be equal to 0 q 4 to 5 that is very important that is q out that will be equal to m into you know C v into T 5 minus T 4 right; this is very important. So, T 5 is as good as T 1, so mass flow rate of mixture into T 1 minus T 4 into C v. This is we are getting, this is sorry this is of course, Q out capital Q out Q 4 5 is equal to Q out is equal to while you know specific task heat rejection is equal to q 4 5 equal to q out will be equal to definitely C v into T 5 minus T 4 that equal to u 5 minus u 4 that equal to C v into T 1 minus T 4 because T 5 is as good as T 4 fine.

So, we have obtained the heat transfer the heat rejection at the during blow down process we have seen that no work done is because constant volume process. Now, finally, this is very important that we have to discuss, this is exhaust blow down, and final process is what that is the constant pressure exhaust.

So, this is blow down means constant pressure constant volume heat rejection that means we should open exhaust valve whenever piston is slightly away from BDC at the end of the power stroke and we will require we need to spill out certain amount of combustion product only to reduce the pressure inside the cylinder that is what I told many a times. So, and we should expel out certain amount of combustion certain amount of combustion product from the cylinder and by that time piston will reach at the VDC, so that the volume is remaining almost constant. And this is also good approximation, so the constant will be the heat rejection.

(Refer Slide Time: 42:52)



And next process is you know 5 to 6, process 5 to 6 is the exhaust. This exhaust process rather and constant pressure, let us say a P naught constant pressure P naught exhaust you know here what is happened what is happening, exhaust valve is open intake valve is closed. And while we are having exhaust process, so we will have only constant pressure process and w 5 to 6 will be equal to P naught into v 5 v 6 minus v 5 equal to P naught into v 6 minus v 1 because v 5 is equal to v 1. If we go back to my previous slide where you have drawn the P v and Ts diagram, v 5 is as good as v 1.

And this point is 6. So, v 6 is as good as again v 2, this point is 6. So, this point is again v 2. So, we have obtained from this analysis considering air to be an ideal gas and following the ideal gas relationship we have obtained pressure and temperature at the end of the compression and combustion as well as the power stroke. We have obtained the heat input and heat output rather heat rejection, heat addition in the combustion process and heat rejection in the exhaust blow down. And we also obtained the work done required during the exhaust and the intake and as well as the combustion process.

So, we have obtained work done during intake combustion as well as the exhaust constant pressure exhaust process. So, from there you have to quantify the thermal efficiency of the Diesel cycle, because we have seen we know the heat input to the system, we know the heat output from a system that is heat addition heat rejection and you know that what is the amount of work is done into the system because work done is we have seen that work is done during intake stroke, you know during combustion process as well as during the exhaust process.

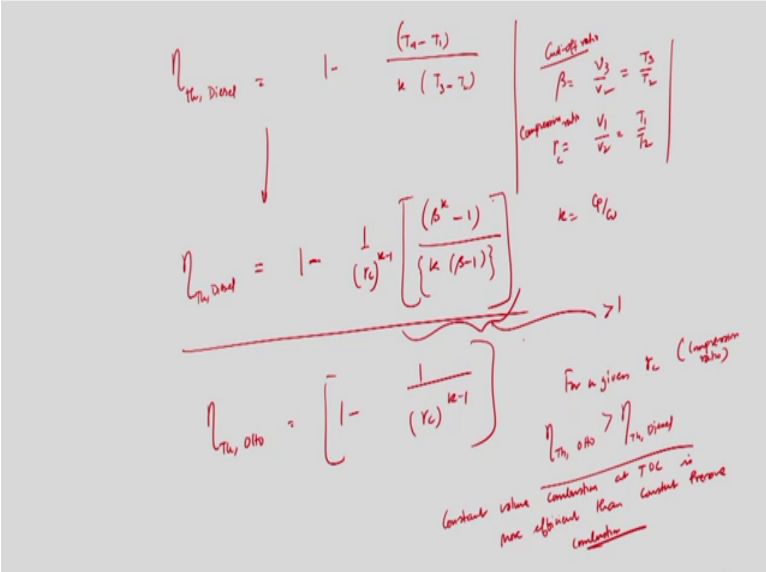
So, if you try to now calculate thermal efficiency, so thermal efficiency of the Diesel cycle, eta, eta Diesel, eta thermal, Diesel that will be equal to; so why? So we have heat input to the system and what is the net work. So, we have what is the net work output that is we need to know need to know because power stroke will be getting work, we are supplying work to the engineering during intake as well as during the exhaust stroke, and also the sorry during intake stroke and during exhaust blow down and also during the combustion process. So, and we are getting work output from the engine during the power stroke.

So, we know what is a net work output. So, what is it net work output from the engine? w net divided by what is the you know heat input to the system. So, what is a work output from the system and heat into the system and that is the thermal, thermal efficiency of Diesel engine. So, we have seen that during intake stroke we have to supply some amount of energy and that they need air from flywheel during the combustion process again work is done. And we are getting more output from the engine during the power stroke and also need to supply some amount of work, we need to supply energy during the constant pressure exhaust.

So, what is the w net? That equal to q in minus q out divided by q in so that will be equal to 1 minus q out by q in. So, heat q out is a heat reject rejected from the system and q in the heat input to the system. So, what is the heat rejected from the system? That is C v into T 1 minus T 4, so 1 minus C v into T 1 minus T 4. What is a heat input? Heat input only in the combustion process that is q 2 to 3 that is C p into T 3 minus T 2. So, this is C p into T 3 minus T 2, so that is the heat input so C p by C v that will be get (Refer Time: 47:49).

So, what I can write that equal to 1 minus T 4 minus T 1 divided by C p by C v that equal to k into T 3 minus T 2. And we have to rearrange because here T 4, T 1, T 3 minus T 2, and we will ultimately get efficiency in terms of compression ratio and the cut off ratio. So, the cut off ratio is basically beta and then you know compression ratio is.

(Refer Slide Time: 48:26)



So, if I rearrange this term so eta thermal Diesel, eta thermal, Diesel equal to 1 minus T 4 minus T 1 divided by k into T 3 minus T 2 right. Beta is equal to cut off ratio is equal to v 3 by v 2 that is what we know, beta is equal to cut off ratio v 3 by v 2 is equal to T 3 by T 2 is equal to T 3 by T 2. Our compression ratio that is very important that is v 1 by v 2 compression ratio is going to be v 1 by v 2 r c, so that is equal to r c is equal to v 1 by v 2 is equal to T 1 by T 2.

So, if I rearrange all this term, and then I can write that this efficiency of the Diesel cycle can be represented written 1 minus if I rearrange these term, we have to do a little a few more steps. And we can it can be written that the efficiency of the Diesel engine can be written 1 by r c to the power k minus 1 beta to the power k minus beta to the power k minus 1 divided by k into beta minus 1. So, this is very important. So, this is beta to the power k minus 1. And so this is the eta thermal of Diesel cycle, this is very important that eta k is equal to C p by C v k is equal to C p by C v, beta is the cut off ratio these beta is the cut off ratio and this is compression ratio.

So, if I rearrange the terms, and if we do a little a few more steps, it can be shown that the efficiency of the Diesel cycle can be written 1 minus 1 by r c to the power k minus 1 into beta to the power k minus 1 divided by k into beta minus 1. So, this is the efficiency of the Diesel cycle. So, from that it is the value in terms of in term in the value of the terms in the bracket is greater than 1, when this equation is compared I mean. So, if we compare the efficiency of this is efficiency of the Diesel cycle, and if we compared this with the efficiency of a thermal efficiency of Otto cycle, then what can I write? So, thermal efficiency of Otto cycle that is we have derived in the last lectures, and that we have obtained 1 minus 1 upon r c to the power k minus 1. So, this is the thermal efficiency of the Otto cycle right.

So, thermal efficiency of the Diesel cycle and thermal efficiency of the Otto cycle we have written of efficiency of the Otto cycle we have derived in my last lecture. Today I have derived the thermal efficiency of the Diesel cycle and we need to do a few more steps only to arrive at the final expression where I have written that clear we have written the definition of beta r c and k.

So, what is seen if I compare this these two you know efficiencies, Diesel engine efficiency that the extra term that is there in the efficiency of the Diesel cycle that is the within the bracket, within the you know bracket and this is greater than 1 that. So, when the situation is compared to the Otto cycle that for a given compression ratio thermal efficiency of Otto cycle, we get up then the compression of Diesel cycle.

So, for a given value of compression ratio these value, the quantity within the bracket because beta cut off ratio k is always greater than 1 beta is always greater than 1. So, now, because v 3 by v 2, v 3 by v 2 if I see the Pv diagram, v 3 by v 2 is greater than 1. So, beta is greater than 1, k is where the greater than 1, so the term within the bracket is always greater than 1. See if I compare the efficiency of Diesel cycle and Otto cycle, so here is what is seen that for a given compression ratio efficiency of the Otto cycle will be always higher than the Diesel cycle.

So, efficiency of the, so for a given compression ratio this term is always greater than 1. So, for a given r c or compression ratio efficiency, thermal efficiency of Otto cycle is always greater than thermal efficiency of diesel cycle for a given compression ratio right, because this content is always greater than 1. If that is the case, I mean then we can conclude that constant volume you know combustion, constant volume combustion at TDC is more efficient than constant pressure combustion.

So, what I can conclude? If we compare the efficiencies of diesel cycle and Otto cycle, since the quantity is within the bracket is always greater than 1, since beta is always greater than 1, k is always greater than 1. Then for a given compression ratio, it can be shown that the efficiency of the Otto cycle is always greater than the efficiency of the diesel cycle, so that means the constant volume combustion at TDC is always is more efficient than the constant pressure combustion right.

But since the diesel cycle the CI engines are having higher compression ratio, always you know are having high compression ratio rather operated, CI engine operate with a higher compression ratio than SI engine. So, of course efficiency of the CI engine will be always higher. So, for a given compression ratio it can be shown that the efficiency of the diesel cycle will be less than the Otto cycle, that means the constant volume combustion at TDC is a efficient than more efficient than the constant pressure combustion.

But question is CI engines are having normally higher compression ratio whereas, CI engines occurs with the higher compression ratio and that is why efficiency of the diesel cycle will be always be higher than the Otto cycle. So, with this I stop here today and I will continue our discussion on the in the next lecture.

Thank you very much.