Thermal Engineering Basic and Applied

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Lecture - 58
Pressure Crank Angle Diagram, Engine Efficiencies

I welcome you all to the session of Thermal Engineering Basic and Applied. Today, we shall discuss about the pressure crank angle diagram and then we shall define several efficiencies in the context of internal combustion engine operation. So, if we recall the operation of 4 stroke cycle engines for both SI and CI engines we had seen that the rise in pressure essentially due to combustion is very important.

And the rise in pressure inside the cylinder because of the combustion is of prime interest to both designer as well as operator. Now you can understand that the rise in pressure is very important to the designer because the work output will essentially, a function of the rise of pressure that will be developed inside the cylinder on the other hand the rise in pressure due to combustion inside the cylinder is again a concern to the operator why it is so?

We shall discuss today that if the rise in pressure inside the cylinder is very high then it is again not desirable from the perspective of this smooth operation of engine. So, in one side the rise in pressure is important because the work output from the engine is dependent on the rise in pressure. So, definitely it is an important parameter to the designer, on the other hand it is also equally important to the operator because the pressure rise inside the cylinder should not be excessively high otherwise it will create several issues from the perspective of the smooth engine operation.

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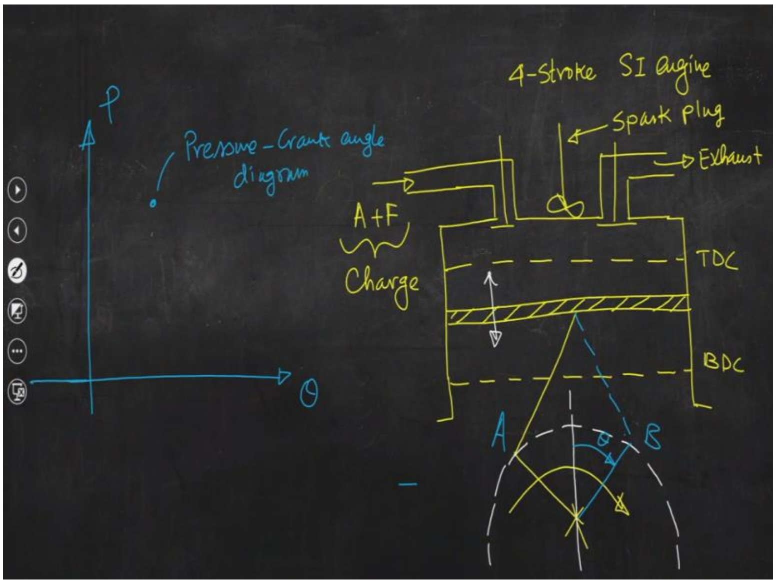

So, now let us briefly review what we have learned from the basic cycle you know that we have discussed in the context of 4 stroke cycle engines. So, we have one spark plug, we are talking about 4 stroke SI engine, this is exhaust, and this is intake manifold through which charge that is air plus fuel mixture that charge is drawn into the cylinder.

So, the charge is drawn into the cylinder during intake stroke. So, now if we try to draw crank is rotating in this manner. So, the sole objective is to get converted the reciprocating motion of the piston into the rotary one and that is why this crank and connecting rod mechanism is here. Now, if we assume another position wherein piston will be shifted towards right because it is rotating in the clockwise direction.

And if it is the revised position of the piston and it has displaced say by angle theta. So, if we give name, so this is B and this is A. So, so piston has a linear displacement inside the cylinder which is equal to the angular displacement of the crank by an angle theta. Now, it is having continuous movement between these two positions.

Why we are interested to draw the rise in pressure with a change in crank angle in p theta plane that is pressure crank angle diagram. We shall map the rise in pressure vis-a-vis the angular displacement of the crank and that will give us an information about the rise in pressure during the combustion process and which is very important to the designer.

As I said this is not only an important parameter to the designer, but also important to the operator. So, now let us discuss about the basic cycle and several strokes. So, intake stroke, exhaust valve will remain closed intake valve is open and piston is traversing from TDC to BDC and air fuel mixture is drawn into the cylinder and that is the intake stroke.

When piston is at BDC that is at the end of the intake stroke, intake valve will be closed that means both valves are closed now and piston will travel back from BDC to TDC that is the compression stroke that we have discussed so many times. At the end of the compression stroke you know we have discussed that we are discussing today in the context of SI engine, but if it is CI engine instead of air fuel mixture only fresh air should be drawn into the cylinder.

And towards the end of the compression stroke fuel would be supplied into the cylinder by a fuel nozzle, in the form of spray. Now since we are discussing today about the 4 stroke cycle SI engine that means we have taken air fuel mixture inside the cylinder during intake stroke and that is getting compressed during compression stroke.

So, when piston is reaching towards TDC at the end of the compression stroke, we need to switch on the spark plug and that is the initiation of combustion. So, we are igniting the compressed charge which is there in the vicinity of the spark plug and that initiation that is the ignition. So, that initiation of ignition will eventually ignite the entire compressed charge and entire combustion would be completed.

And by the time we have assumed that the piston is almost instantaneously there at the TDC so as if the volume is remaining constant and it is because of this assumptions we could now represent the combustion process that is heat addition process by a constant volume process in P v plane that we have discussed in one of the previous classes.
And we have seen that the sole purpose of having this combustion is to increase the pressure and temperature of the substance inside the cylinder and that high pressure eventually create a thrust on the piston face and that will allow piston to go back from TDC to BDC and that is what we have termed as power stroke. So, if we consider four different strokes that is intake, compression, power and exhaust out of these four strokes we are getting power from only this stroke.

So, the rise in pressure inside the cylinder due to combustion is very, very important to understand the thrust that will be acting on the piston face and eventually what would be the work output from the engine and it is because of this reason we need to know what would be the rise in pressure during the revolution of crank that is essentially due to the instantaneous movement of the piston between these two locations during the entire process.

So, let us now draw the, you know, p-theta diagram that is pressure crank angle diagram. So, sole purpose of understanding about the rise in pressure during the, entire one cycle subsequently the work output from the cycle and that information we can get if we try to draw pressure of the working substance inside the cylinder as the piston is moving between these two locations. And as if that linear motion is equivalent to the rotary motion of the crank that is in the p theta plane.

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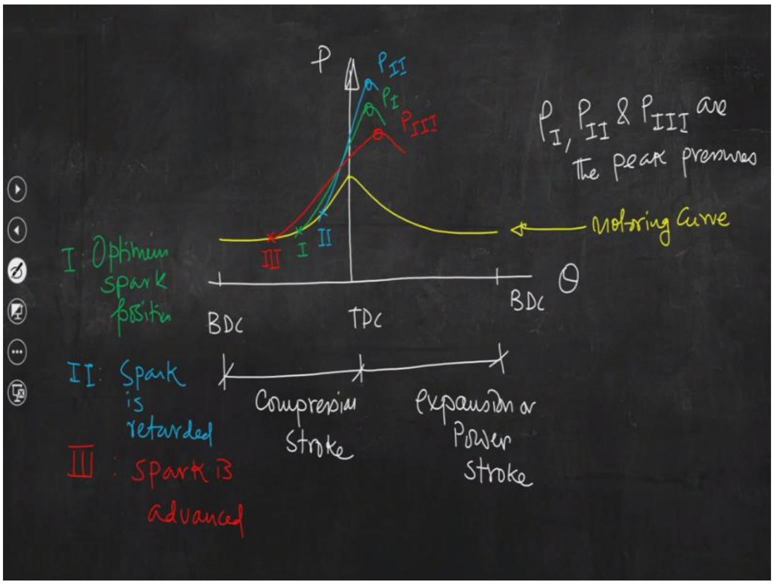

So, if we try to draw, this is BDC, this is TDC and this is again BDC and this is theta plane. Now we are interested in the quantity pressure that is developed during the, process so what we can draw is $p - \theta$ plane. So, you can understand that the rise in pressure during the reciprocating moment of the piston we are trying to get that information in this $p - \theta$ plane.

That means as if the piston is moving between BDC to TDC and TDC to BDC. So, that reciprocating motion is now mapped in this plane that is angular rotation of the crank. So, the reciprocating movement of the piston is equivalent to the angular moment of the crank and that is why you are trying to draw it in this p theta plane.

So, this stroke is compression stroke and the piston is again coming from TDC to BDC that is the expansion or power stroke. So, first of all if we go back to the previous slide, piston will be having movement between these two locations say the first case is there is no spark plug we have taken charge inside the cylinder and we are compressing it and there is no initiation of the combustion by switching on the spark plug.

As if charge is there, we are bringing piston from BDC to TDC and again we are allowing piston to go back from TDC to BDC. So, if we do this by a virtual external motor then this curve will be like this. So, this is called motoring curve. You can see that if we bring piston from BDC to TDC that is intake stroke.

So, intake stroke entire space is filled in with the fresh charge and both valves are now closed. We are bringing piston from BDC to TDC as I told you that this curve is generated as if an external motor is rotating this crank. So, that is why it is called motoring curve virtually as if an external motor is running this crank.

So, what will happen, both valves are closed, piston is coming from BDC to TDC that is compression stroke pressure will rise and that is what we can see that the pressure is rise and further when piston is coming back from TDC to BDC that is expansion stroke and pressure will fall. So, this is the motoring curve, now what will happen we will consider three different cases.

Now we have the real case that is spark plug, so when piston is coming from BDC to TDC we can switch on this spark plug. So, it is quite common that spark plug switch is on when piston is about to reach a TDC because switching on spark plug and the initiation of combustion needs some finite amount of time.

And at that time piston will be reaching at TDC and it is ensured that entire combustion would be completed. So, the volume is remaining constant. Now, I will discuss three different cases. First case is say this is the spark position say case 1. So, I am writing optimum spark position and if we switch on spark plug here then you know that the curve will not be like this.

Instead it is because of the combustion there will be a rise in pressure inside the cylinder. So, the rise in pressure will be a function of rate of combustion. So, what is the rate of combustion that is if the rate of combustion is very high then the total combustion time will be less and rise in pressure will be high. So, you can correlate the rise in pressure to the rate of combustion.

So, if the spark plug position is here at 1, that is optimum spark position then that would be this pressure rise. So, see this is peak pressure P_I. Now you can see that the rise in peak pressure is little away from TDC.

It is again important that designers should not allow that the pressure rise would be maximum before piston reaches at TDC. If it is the case then to reach a TDC extra resistance that will be faced by the piston is again not desirable. So, the rise in pressure should be either at TDC or closer to TDC, but not before TDC. Next, we are considering one another point that is say point 2 say here.

So, spark is retarded, so that means position 1 is optimum position, but if we retired at the sparking position that as if you delayed the sparking position. So, as if when piston is almost closer to TDC we are allowing spark to occur and then instantaneous pressure rise due to combustion will be like this, that is P_{II}.

I will consider that is case 3 we can take another point here that is spark is advanced. So, as if we have advance this spark in its position and so this would be the say peak pressure P_{III}. So, what we can see from this P theta diagram is that in all these 3 cases it is because of this sparking, there is an instantaneous rise in pressure inside the cylinder.

And it is because of this rise in pressure we are getting maximum work output. If the sparking is optimum then we can see that the rise in pressure is there, but it is little away from TDC. In all these cases the maximum pressure or peak pressure is occurring when piston is little away from TDC that is when piston is coming back from TDC. As I said you if the designer is designing the system in such a way that the peak pressure will be there when piston is yet to reach at TDC, It is not a desirable case because the rise in pressure even before reaching piston as TDC we will create external resistance to the movement of the piston. So, now we can see that if you consider case 2; case 2 would be even more, I can say desirable in terms of the maximum power output because the rise in pressure is high and also peak pressure is high. So, if rise in pressure is high then the average pressure would be high and that is why the work output would be high.

On the other hand if we consider sparking position that is point 3 then you can see that the rise in pressure is not very high and also the rise in pressure is shifting little away from TDC. So, the location of P_{III} is greater than location of P_I is greater than P_{II}. So, if we advance this sparking position the rise in pressure is low not only that the location of peak pressure is shifting little away from TDC.

On the other hand if we retired this sparking position and consider the sparking position is 2. So, what we can see that the rise in pressure is excessively high and that is again important because we may get maximum work output, but this excessive rise in pressure though that may help to get maximum work output it is not also desirable. So, I had written already the one is the optimum spark position why?

So, if it is 3 maximum pressure rise is less, work output would be less, but since the rise in pressure is not very high. So, the operator will not feel the jerky operation. On the other hand if we consider 2 maybe the maximum pressure rise you know very high, work output will be very high, but also the peak pressure is very high and the sudden rise in pressure is also very high, curve is very stiff.

And it is because of this sudden rise in pressure the operator can fill a jerky motion. So, though case 2 would be desirable if we consider the work output, but it may not be desirable to the operator because the operator will fill a jerky motion. On the other hand, case 3 though operator should not fill a jerking motion because it is you can see the rise in pressure is not very high, sudden rise of pressure is not there.

But the maximum pressure rise is also less. So, the work output will be less. Considering these two, as I said you the rise in pressure during the entire process pertaining to 4 stroke cycle engines is important to both designer and the operator. So, to designer, point 2 would be good because he or she is designing the engine in such a way that the maximum pressure rise and consequently the work output would be high.

But the operator will feel a jerky motion. So, considering these two aspects it is recommended that pressure rise should be optimum so that the work output would be optimum, but the rise in pressure should not be very sudden so that the operator can feel a smooth motion. So, basically considering these two it is recommended that optimum spark position should be one that means rise in pressure is also optimum.

Work output would be optimum also the peak pressure rise and sudden rise in pressure is not there and operator will not fill the jerky motion. So, as I said why this diagram is important only to understand the rise in pressure and also whether the pressure rise is sudden or not to understand the stiffness of the curve in p theta plane. These two are very important from the perspective of efficient as well as smooth operation of the engine. If we consider point 2 or case 2, the sudden rise in pressure is very high and also the rise in pressure is high. Now question is if there is a sudden rise in pressure, there is the detonation.

Detonation is something which is related to the pre ignition or auto ignition. So, if we consider the 4 stroke cycle SI engine we have understood that when the charge is getting compressed as the piston is moving from BDC to TDC, the charge which is there closer to or in the vicinity of spark plug will be ignited first because this is the initiation of the combustion or ignition.

Now, if the rise in pressure is very high then that pressure rise will now create just like a force is acting on the farthest compressed charge that is the charge which is there in the vicinity of the piston face and after a few cycles of operation already the piston face, cylinder walls are having high temperature. So, these spots will create just like an artificial spark plug.

And as the main flame front will be coming from the spark plug area, secondary flame fronts will also appear from these hotspots and the appearance or onset of secondary flames will be triggered if the rise in pressure is very high. So, if the rise in pressure is very high and if it is sudden then not only it will create a jerking motion, but also it will try to you know strengthen or onset of secondary flames.

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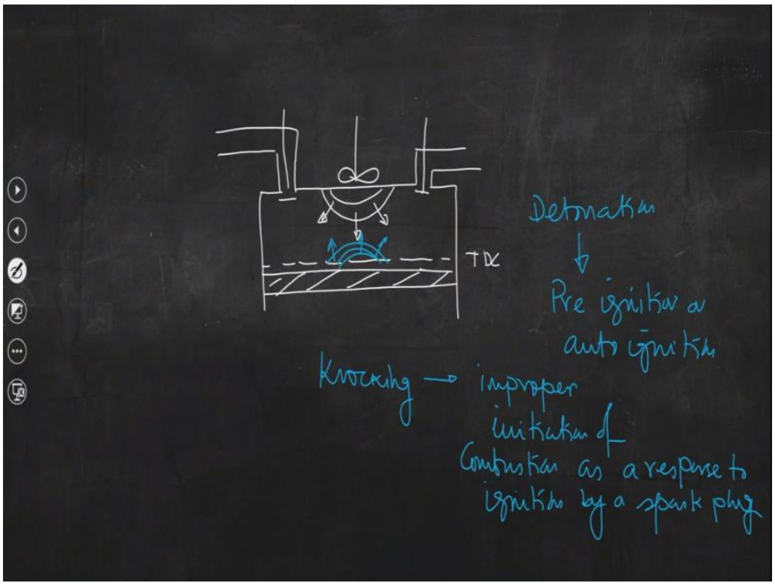

So, basically you can understand that a secondary flame will produce like this. So, when can you understand that combustion has started, it is basically the appearance of a visible flame. So, when combustion has started from this particular location that is the location close to the spark plug. So, this is the piston face. So, this is TDC. So, piston has already reached at TDC so total charge is now compressed. Both valves are closed and the main flame front is traveling from sparking area towards the entire part of the combustion chamber. Now as I said you if the rise in pressure is very high that this flame front as if creating more pressure on the charge which is there on the piston face.

And in the farthest area of the combustion chamber. What will happen that the secondary flames will be there because of the rise in temperature of the cylinder walls, also the rise in temperature of the piston face surface. Now that further rise in pressure will trigger easily or easy onset of the secondary flames.

So, secondary flame has initiated here and that secondary flame will travel like this. So, always chance is there that the secondary flame will generate. Now if the rise in pressure is excessive and it is sudden that sudden rise in pressure will also help to initiate all these secondary flames.

So, a time will come the secondary flame will collide with the primary flame and that is again not a desirable phenomenon and that is known as detonation. So, basically this is auto ignition or pre ignition.

Pre ignition you know as I said you that it is not necessary that only ignition will start due to the spark which is created by spark plug. Secondary flames also will produce due to the temperature of this hotspots, but as I said you the excessive rise in pressure and also sudden rise in pressure will trigger easy onset of the secondary flames due to pre ignition and if that is there these two flames will collide each other and will lead to an undesirable phenomenon which is known as detonation. Now let me tell you so this is not a desirable phenomenon at all and sometimes you should not be confused with detonation and knocking. So, detonation is solely due to pre ignition or auto ignition and it is not a desirable phenomenon because it may lead to damage of mechanical components, overheating also with kind of abrasion of the material.

But knocking is something which should not be confused with detonation. Knocking is basically improper initiation of the combustion as a consequence to the ignition and that means the fuel air mixture does not initiate the combustion properly and the knocking is something where sharp noise is produced.

And that is solely due to the improper initiation of the combustion and of course of the fuel air mixture and it should not be confused with the detonation. So, these two things are not same. Detonation is due to the pre ignition, auto ignition as we have discussed today that these two flames will collide each other and the secondary flame will be produced due to the auto ignition or pre ignition.

And if these two flames collide each other there will be an audible noise and together with that erratic pressure rise will lead to mechanical damage and also overheating, but the knocking is solely due to improper initiation of the combustion due to the ignition of course by a spark plug and it is because of this the fuel air does not initiate the combustion properly within the combustion chamber and these two things are completely different.

The phenomenon knocking is also not desirable sharp noise is produced and also the consequence of this phenomenon is that overeating also kind of erosion of the material from the piston face due to knocking. So, these two events are not desirable in the context of internal combustion engine. So, we have talked about detonation and knocking.

Detonation this is due to pre ignition or auto ignition on the other hand we have discussed about knocking. So, this is due to improper initiation of combustion as a response to ignition by a spark plug. So, these two things we have discussed these two events are not desirable and these two should not be confused. Finally, we will discuss about the efficiencies.

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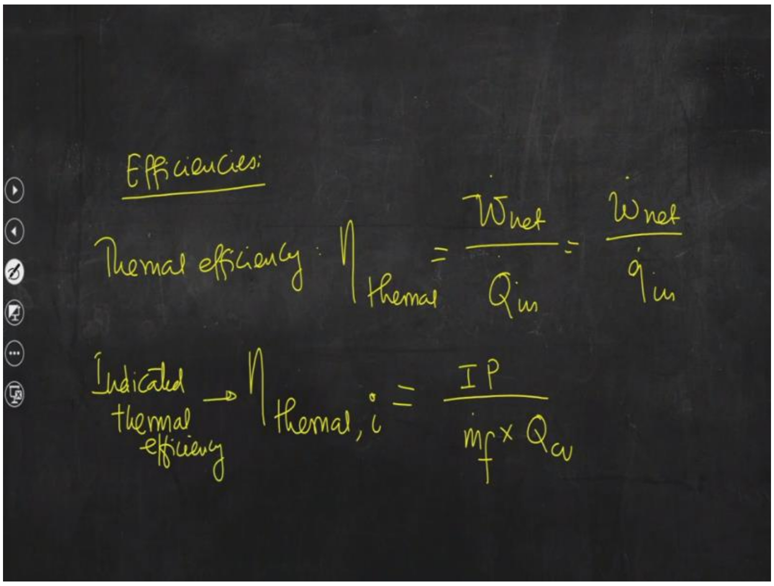

So, efficiencies of internal combustion engine. First of all we have already discussed about thermal efficiencies because we could derive the mathematical expression of thermal efficiency of both otto and diesel cycles that we have discussed in the previous classes. So,

$$\eta_{th} = \frac{W_{net}}{Q_{in}} = \frac{\dot{W}_{net}}{\dot{Q}_{in}}$$

So, this is the thermal efficiency that we have studied in second law of thermodynamics. So, you can understand we can write in the rate form. So, this is rate of network that is the work done. So, now we have discussed that the work available inside the combustion chamber or cylinder is not equal to the work which is available at the shaft.

Work available inside the cylinder is the indicated work while the work available at the shaft is the brake work. So, accordingly thermal efficiency also can be defined in terms of the rate of work done whether the work is indicated work or the brake work.

$$\eta_{th,i} = \frac{IP}{\dot{Q}_{in}} = \frac{IP}{\dot{m}_f \times Q_{CV}}$$

So, if it is indicated so rate of work done is the power. So, if we calculate that power inside the cylinder that is indicated power and if we use that power to define this thermal efficiency that would be the indicated thermal efficiency.

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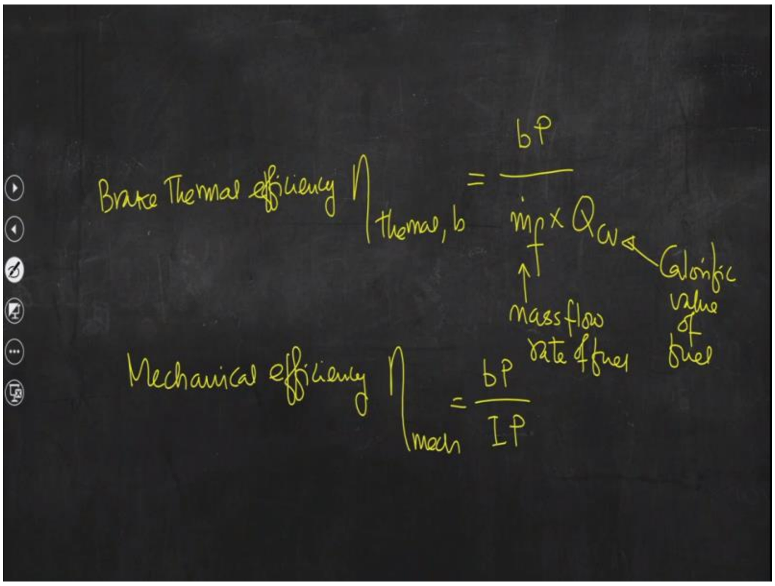

Similarly, we also can write brake thermal efficiency, we will consider the which is available at the shaft.

$$\eta_{th,b} = \frac{BP}{\dot{Q}_{in}} = \frac{BP}{\dot{m}_f \times Q_{CV}}$$

And this thermal efficiency can be defined in terms of the brake work or indicated work and finally we can write mechanical efficiency. So, available work at the shaft is less than the work which is produced inside the cylinder because some part of that work is utilized to overcome the frictional losses. So, this can be defined as brake power divided by indicated power.

$$\eta_{mech} = \frac{BP}{IP}$$

So, indicated power is always greater than brake power. So, it depends on the designer that is why this is called mechanical efficiency.

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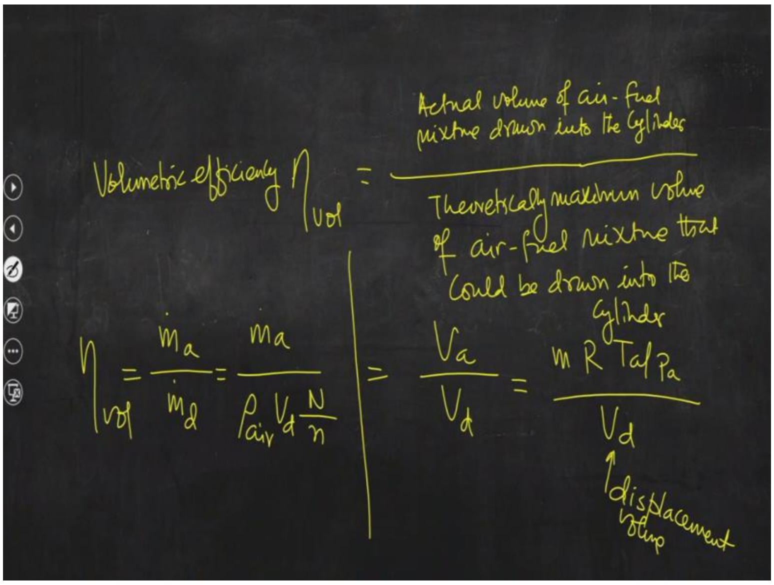

Finally, I will write one most important term that is volumetric efficiency. So, if we go back to the previous slide, you can see that we are taking charge into the engine cylinder during intake stroke and this charge is nothing, but air fuel mixture or we can ignite the fuel by a spark plug, but we need to have proper or efficient combustion and fuel here we are using spark plug to ignite.

But this combustion as I said is nothing, but the appearance of visible flame and that combustion needs presence of air that is oxygen and that oxygen will come from the air. So, we need to supply sufficient amount of air for burning this fuel and we have discussed in one of the previous classes that stoichiometric air fuel ratio. So, to burn per kg of fuel how much oxygen is required.

And if we need to get this amount of oxygen so what would be the amount of air that should be supplied and of course to the engine cylinder. So, for efficient combustion we need to supply sufficient amount of air, issue is if the combustion is improper then though we are supplying certain amount of energy, but the efficiency when you are trying to calculate will not be correct.

We need to ensure that the combustion should be efficient only then we can calculate the remaining other efficiencies. So, that means the input energy that we are intending to supply by burning fuel should be correct one so that the combustion would be efficient. So, volumetric efficiency from the name itself you understand it can be defined by both volume of air and mass of air.

So, actual volume of air fuel mixture drawn into the cylinder then if we allow piston to come from TDC to BDC as if we are creating a space to have that air fuel mixture into the engine cylinder. So, theoretically that is maximum volume of air fuel mixture that could be drawn into the cylinder. So, if we allow piston to come from TDC to BDC we are creating a space to get theoretically maximum volume of air fuel mixture. So, what would be the theoretically maximum volume of air fuel mixture that could be drawn into the cylinder is not equal to the actual volume.

And the ratio of these two quantities is the volumetric efficiency. So, this is actual volume of air fuel mixture drawn into the cylinder divided by theoretically maximum volume of air fuel mixture that could be drawn into the cylinder. So, this can be written actual volume by theoretical volume. Theoretical volume is the displacement volume because we are trying to get piston from TDC to BDC.

$$\eta_{vol} = \frac{V_a}{V_d} = mRT_aP_a/V_d$$

The actual volume of air that depends on the ambient temperature and pressure. So, basically that is the function of local temperature and pressure. So, this is the definition of volumetric efficiency, but we also can write this volumetric efficiency in terms of mass. $\eta_{vol} = \frac{\dot{m}_a}{\dot{m}_d}$

Now mass of air fuel mixture or mass of charge getting into the cylinder to the theoretically mass of air that should fill the displaced volume. So, this is mass of air fuel mixture if it is SI engine, if it is CI engine mass of air getting into the cylinder to the mass of air fuel mixture that is filling the displaced volume.

The displaced volume is when piston is coming from TDC to BDC. So, we also can write this quantity like

$$\eta_{vol} = \frac{\dot{m}_a}{\dot{m}_d} = \frac{\dot{m}_a}{\frac{\rho_{air} V_d\, N}{n}}$$

N is RPM, n is number of strokes. So, if it is 2 stroke or 4 stroke cycle engine that will accordingly depend. Now issue is the mass of air that should fill the displaced volume that depends on the number of stroke and the revolution. So, this is also used to define the volumetric efficiency. So, to summarize, today's discussion we have discussed about the need of p theta curve in the context of internal combustion engine operation. We have seen that the rise in pressure which is developed due to combustion inside the cylinder is very important to the designer.

But also it is equally important to the operator and then we have defined several efficiencies those are important to measure the, performance of internal combustion engines and we have seen that mechanical efficiency, thermal efficiency and volumetric efficiency, these three efficiencies are sufficient to you know measure the performance of the internal combustion engine. With this I stop here today and we shall continue our discussion in the next class. Thank you