Applied Thermodynamics
Prof. Niranjan Sahoo
Department of Mechanical Engineering
Indian Institute of Technology, Guwahati

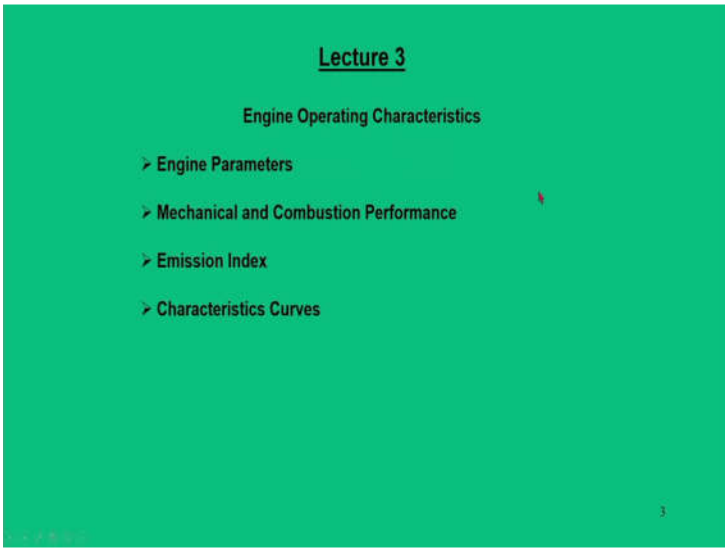
Module - 03
Internal Combustion Engines
Lecture - 24
Engine Operating Characteristics

Welcome to this course Applied Thermodynamics. We are in module 3, Internal Combustion Engine.

(Refer Slide Time: 00:47)

In this we have the following list of topics. Out of this topic number 1 and 2 has been covered and now we are in the topic number 3 that is engine operating characteristics. So, this particular topic we are going to discuss today.

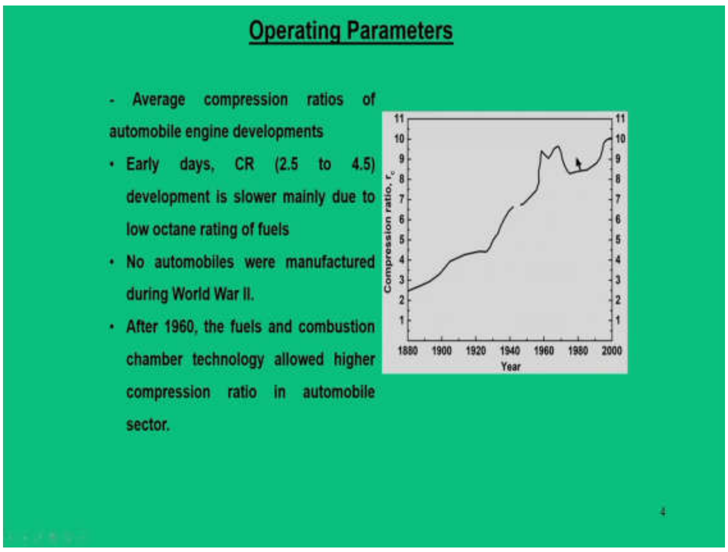
(Refer Slide Time: 01:08)



In the engine operating characteristics the following segments we are going to cover. First we will introduce some important engine parameters. Then we will discuss about mechanical and combustion performance of the engine and then we have to discuss about the emission index because that is the emission norms that every engine has to follow.

And finally, we will end of in discussing the few characteristic curves and that characteristics curves we try to see the particular trend that the performance combustion and emission parameter should behave with respect to SI engine and CI engine.

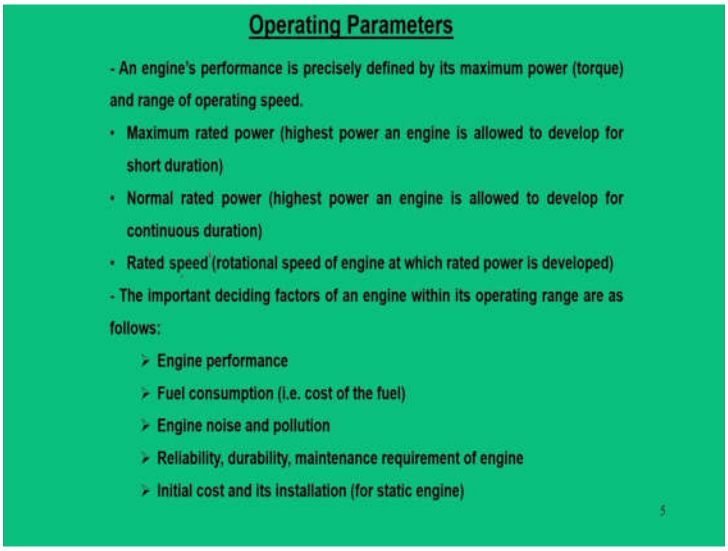
(Refer Slide Time: 02:00)



So, let me start with the first topic that is engine operating parameters. So, when you discuss about the operating parameter the first parameter that comes in is the compression ratio and in fact, the compression ratio mostly decides the size of the engines. So, in the earlier developments that means, if you look at this particular plot in the earlier development the engine starts with a compression ratio something in the 18th and 19th century with compression ratio in the range of 2 to 3.

Then subsequently with time the compression ratio people try to increase. So, when you are trying to increase the compression ratio, then effectively we are looking into bigger size engines and towards the end of 19th century, we have the typical compression ratio in the range of 8 to 10. So, this is the plot that shows the a typical trend that how engine development has occurred from last two centuries.

(Refer Slide Time: 03:32)



Now, if you look at the compression ratio, then what other things that is most important is the fact that we need to characterize the engine performance. First is compression ratio, second apart from this we have to define certain user parameters in terms of range of power or torque on range of operating speeds.

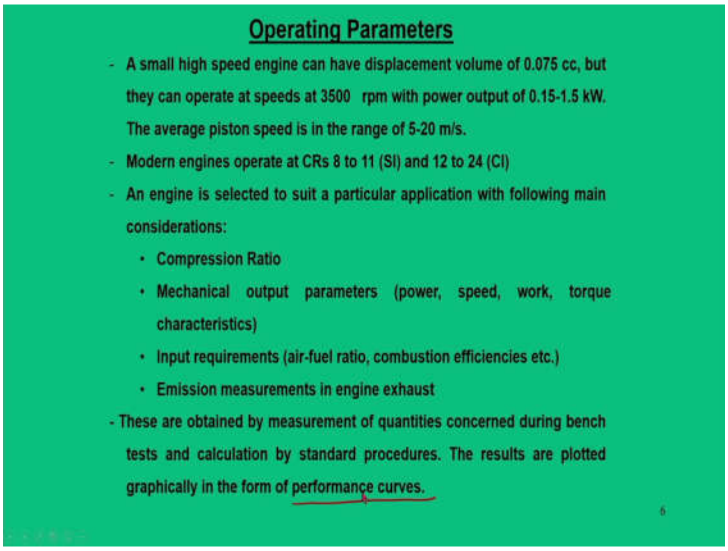
So, based on that we defined three important parameters that is maximum rated power which is nothing but the highest power and engine is allowed to develop for a short durations that means, the highest power usually obtained for a very short duration by the engine. The normal rated power this is the highest power that engine is allowed to develop for continuous durations.

So, engine is run for 1 hour, 2 hour, 5 power, 8 hours likewise how much highest power it can develops if we run for 8 hours or 10 hours a day. So, that is called as a normal rated power. The third point is to be rated speed. So, the rotational speed of the engine at which the rated power is developed. So, maximum rated power, normal rated power and rated speed.

Now, to look into this particular parameters we need to have some deciding factors. So, these deciding factors are the engine performance. Now for example, if we want to run the engine at this maximum rated power or rated speed then what should be my engine performance? Whether the engine has any issues while running at that rated speed or rated power and that point of time what is the fuel consumption because this fuel consumption leads to the cost of the fuel.

Now, while doing so, whether there is any engine noise or pollutions? Now, by catering all of them we also need to look into the reliability, durability, maintenance requirement for the engine. And apart from this four parameters, the other vital segment is the initial cost and its installation. So, that is mainly for static engine and for transport sector we also require what is with the cost of the engines. So, these are the deciding factors that a user is expected to know.

(Refer Slide Time: 06:24)



Now, just to give a glimpses that what are the different types of engines we look into or we see in the market. So, the engine can have a very small displacement volume in the order of 0.075 cc or centimeter cube and this engine also can operate at maybe at close to 35000 RPM with a rated power output of 0.15 to 1.5 kilo watt.

So, a small engine can also run at very high speed, but the power output may be less, but in that case also the average piston speed in the range of 5 to 20 m/s. Other extreme could be we can run the engine at low RPM, but high displacement volume.

So, these two things actually tells us that what should be our engine side and what are the its rated operation. By doing so, we will be able to characterize the engine performance. So, as I mentioned in the beginning apart from this we have compression ratio that is typically 8 to 11 for SI engines and 12 to 24 it is per CI engines that is mostly used for modern engines.

Now, having said so, then we need to look the matter that let us say that we have certain engine with some desired compression ratio. It has certain displacement volume and it is operated at certain rated RPM. Now, for this engine we need to use it for a particular application.

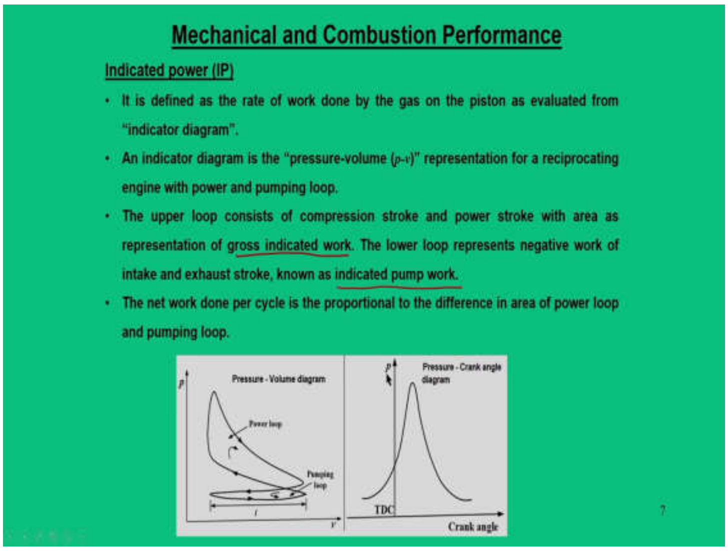
So, now when we run the engines, we expect there are there are some input entries sorry or input parameters, there are out some output parameters. The output parameters could be power, speed, work, torque all these things. And input requirement could be the air fuel ratio, combustion efficiency; that means, if the fuel is introduced in the engine not necessarily that 100 percent of the fuel will be burnt. So, there is a combustion efficiency comes into picture.

So, these are some input requirement and these are some output parameters. So, basically what the performance characteristics means? By using these operating parameters we need to find out a correlation between the output parameters and input requirements. So, that is the main philosophy of discussion today.

Apart from this we also try to emphasize on the certain aspect of emission measurements. That means, if the combustion is not proper then what else we are going to get in the engine exhaust, whether those exhaust are desirable or undesirable for environmental point of view.

So, all these things can be possible only when we do some bench test and with some standard calculation procedures. And we are trying to map the results in the form of graphical nature and we call them as perform engine performance curves. So, this will be towards last part of the lecture where to going to emphasize on this particular performance curves.

(Refer Slide Time: 10:26)



So, let me start with the first one that is mechanical and combustion performance of the engines. So, the first parameter what we are going to look at is the indicated power. So, as you know that in thermodynamics we have been told that the pressure-volume characteristics can be plotted graphically based on certain thermodynamic processes like constant pressure, constant volume, isentropic process.

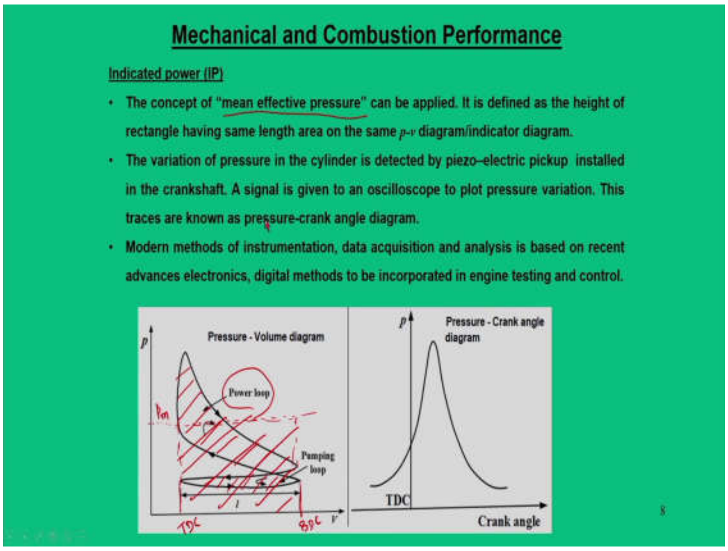
So, we will now touch upon similar plots and in this philosophy of IC engine we call it as a indicator diagram. So, it is nothing but as the rate of work done by the gas on the piston and as evaluated from indicator diagram. This indicator diagram is nothing but a pressure-volume diagram and this pressure-volume diagram is characterized in this fashion and are shown in this figure that is where we have a power loop and we have a pumping loop.

The upper loop that is the power loop consists of the compression stroke and power stroke with area representation as gross indicated work. So, that means, the area under PV diagram in the upper loop or power loop is known as the gross indicated work and the lower loop is known as pumping loop and it is the negative work and we call it as a indicated pump work.

So, the net work per cycle would be the proportional to the difference in the area of power loop and pumping loop. This is one way representation of pressure volume diagram in thermodynamic sense, but with engine terminology we normally represent the volume as a mapping with the rotation in the crankshaft. So, that particular method we call this as a pressure crank angle diagram and a typical curve of a pressure crank angle diagram is shown in this figures.

So, in this particular two plots what we have try to show is that one PV plot that will give you the thermodynamic estimates and that can be correlated with the rotational motion of the crankshaft. So, that is in terms of pressure crank angle diagram and typically we have a concept of mean effective pressure.

(Refer Slide Time: 13:16)



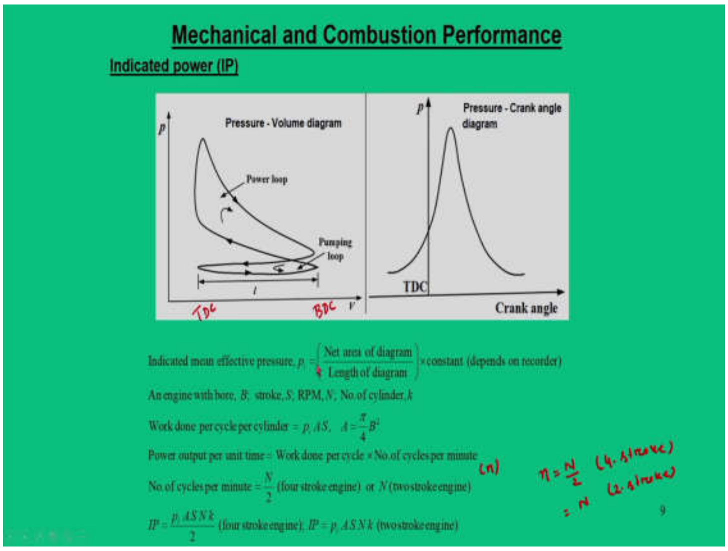
So, this mean effective pressure is nothing but a constant pressure line which can be represented in this PV diagram. What it says is that over a set of engine displacement or piston movement from TDC to BDC, this is the area under the curve and we call this as a gross indicated work and that is the power loop. And the other side is that is negative work that is in the pumping loop. So, we can calculate the net area.

Now, imagine a situation that we want to evaluate an equivalent area which is same as this net area. So, for that case I will imagine a rectangle with a displacement volume from TDC to BDC and put a mean line and I call it as a mean effective pressure line. So, the net area which can be drawn with this mean effective pressure line and this happens to be a rectangle. Then that particular pressure is known as mean effective pressure.

So, actually the engine does not have a mean effective pressure, but we can represent them in our mathematical estimates. So, there are standard methods in which these pressure-volume diagram can be drawn through by a mechanism what we call as piezo electric set up which is installed in the crankshaft. And from this crankshaft we will get a signal that can be recorded in an oscilloscope to plot the pressure variations and this is known as pressure crank angle diagram.

So, basically from the pressure crank angle diagram we can get back this indicator diagram and with our modern instrumentation and data acquisition systems and advanced electronics, we can incorporate to get the estimates of the work output from this indicated diagram and from there also we can calculate the mean effective pressure. And from this mean effective pressure we can come back to the indicated power. How? We will it will be followed in the next section.

(Refer Slide Time: 16:01)



So, whatever I have explained. So, we are going to represent in the mathematical form. So, the indicated mean effective pressure is defined as p_i that is equal to net area of the diagram which means, net area between the power loop and pumping loop.

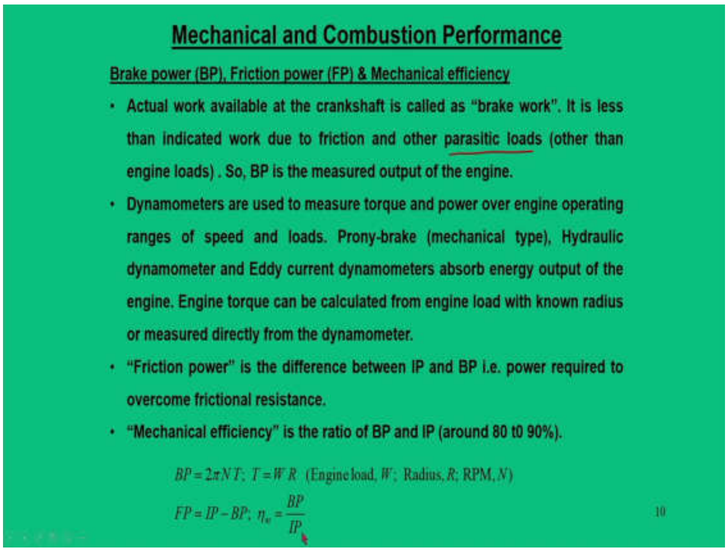
That means, from the power loop if you subtract the area of the pumping loop then we will get the net area and length of the diagram is nothing but the piston motion from TDC to BDC and that is known as L into constant. This is a typical constant which represents parameter that depends on the recorder. So, this constant is a fixed constant with respect to instrument point of view. $p_i = \left(\frac{\text{Net area of diagram}}{\text{Length of diagram}} \right) \times \text{constant}$.

Now, from this indicated mean effective pressure then we are going to calculate indicated power. How? Now, let us consider an engine with bore B, stroke S which has an engine RPM N and this engine has a number of cylinders k. So, we can write is that work done per cycle per cylinder is nothing but the $p_i\, A\, S, \quad A = \frac{\pi}{4} B^2$.

So, once we know the work done per cycle per cylinder then we can calculate the power output that means that is work done per cycle into number of cycles per minute. Now, here we have to take the catch that what is this number of cycles per minute. So, number of cycles per minute is normally represented as n and this n = N/2 that is for 4 stroke or n = N that is for 2 stroke, because this n is the number of revolutions based on the number of revolutions of the crankshaft.

So, accordingly by putting the respective expressions we can get back the indicated power $IP = \frac{p_i\, A\, S\, N\, k}{2}$, where k is the number of cylinders if it is a four stroke engine. There is no division of 2 if it is a two stroke engines. So, based on this indicated diagram we are able to estimate the indicated power in terms of indicated mean effective pressure.

(Refer Slide Time: 19:21)



Then, next thing what we are going to discuss about, brake power, friction power and mechanical efficiency. When we see the indicated power, it is at the engine input side, now from the engine output side. Engine output side that means, engine can be run with no load or with load. So, when we actually apply a load onto the engines then basically we are braking the engine and we interpret that as a brake power.

And in the process of engine running, there are other losses that is taken into account as a friction power. So, these two terms go side by side because as you increase the speed of the engine, this friction power comes down and when we engine speed is less friction power is more. So, these two terms go side by side. And last term is the mechanical efficiency which is nothing but the correlation between the brake power and the indicated power.

Now, let us see that in what way we are going to get the estimates of brake power and friction power. So, just to explain this fact I can say that the actual work available at the crankshaft we call this as a brake work and it is less than the indicated work, because it is mainly due to the friction and other parasitic load. Parasitic load means other than the engine loads.

For example, in an car we have AC, we have lights, we have other auxiliaries that takes the power in the engine even we have fuel pump. So, all these instruments take the power from the shaft of the engine. So, these are treated as a parasitic load which is nothing but the other than engine load. Other than engine load in our term means other than the shaft power.

So, this brake power is nothing but the measured output of an engine. Now, how do we measure this brake power? So, for that purpose dynamometers are used. So, what does the dynamometer do? They measure the torque because engine is run at certain RPM then they measure the torque, maybe we can run the engine at different speeds and the loads that is our input end and these dynamometers try to measure the torque and then from the torque and engine RPM, we can calculate the power.

So, what are the typical dynamometers? These dynamometers are called Prony-brake which is a mechanical type. It can be a hydraulic dynamometer. Another kind of could be eddy current dynamometer that is electrical, it is mostly used ones and they absorb energy output of the engines.

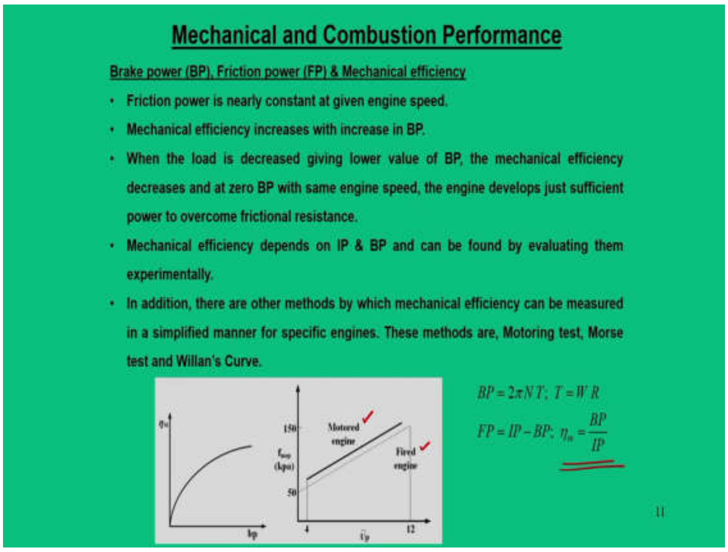
So, all these I am not going to into details because these are a different segment or topics as far as IC engine mainly is concerned, but in our philosophy we will just look into the fact that how we measure the torque and power output from the dynamometer and try to correlate our engine operating parameters.

So, for brake power we require dynamometer and then there is no method in which we can directly get the friction power, but friction power is nothing but the difference between the indicated power and brake power. So, that is the power required to overcome the frictional resistance.

So, once we know the indicated power, brake power then we can calculate the mechanical efficiency. So, how we can write in this manner? So, first thing is that brake power that is nothing but $BP = 2\pi N T$ and T is the torque. And the torque is nothing but $T = W R$, W is the engine load and R is the radius.

That means, the location at which we are going to measure the torque or in this case it is the radius of the shaft. Then difference between these two will give you the friction power that is $FP = IP - BP$. Then we can calculate mechanical efficiency which is nothing but the ratio of brake power to indicated power $\eta_m = \frac{BP}{IP}$.

(Refer Slide Time: 23:59)



So, here moving further we need to give another insight to the fact as I mentioned that the brake power and friction power should be looked into simultaneously. So, this particular plot shows the variation of mechanical efficiency with brake power. That means, if you increase the brake power, the mechanical efficiency goes up. Normally, mechanical efficiency is ratio of brake power to IP indicated power. Of course, indicated power is a fixed number. So, brake power has to change with the mechanical efficiency.

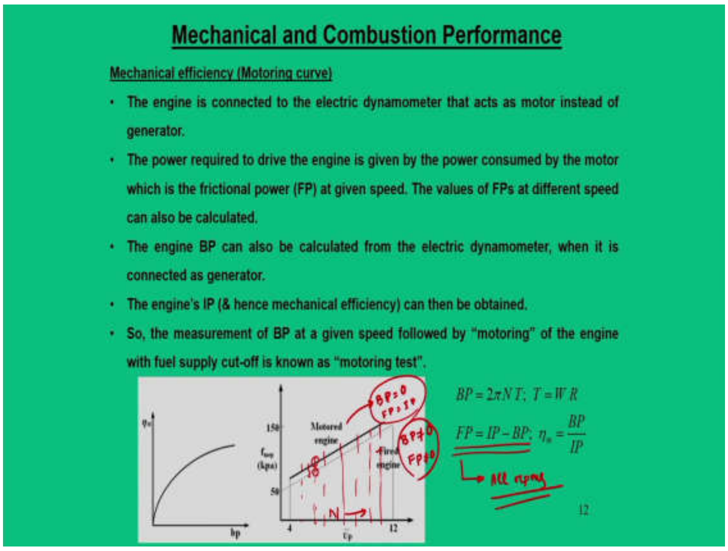
And typically this is not a straight line because the friction power is also playing another culprit. So, that is what it is not a linear trend. So, it is a kind of a trend that is observed here. Now, another concept we are going to discuss is that how to calculate the fiction power. So, when the engine is run without any brake load, then we call this as a motored engine.

So, the word motored engine comes and we also has another word we call as fired engine. So, in a motored engine we can say that the engine is running without any load, but in a fired engine intentionally dynamometer applies a load onto the engine. So, all these things we are going to calculate because we need to find out the brake power, indicated power and mechanical efficiency.

Another important points that I need to emphasize here is that when the load is decreased giving lower value of brake power, the mechanical efficiency decreases under zero BP that is zero brake power with same engine speed, the engine develops just sufficient power to overcome the frictional resistance. That means, when there is no brake load, but still engine is running. So, it develops a power and that power is consumed through this fictional resistance and we call this as a friction power.

To calculate all these things there are some experimental methods what we call as Motoring test, Morse test and Wilson curve. So, these are the typical standard methods in which we were going to calculate brake, power friction power and indicated power in the laboratory.

(Refer Slide Time: 26:44)



So, first method what we are going to say is the motoring curve. So, the motoring curve as I mentioned the engine is run with a dynamometer, but that dynamometer does not provide the brake power. Means, that dynamometer is not used to apply load, but rather it is connected to a motor that consumes that power. That means, the entire power that is developed by the engine it goes as a friction power.

So, in other words in a motored engine your brake power is 0, but friction power would be nothing but the indicated power. But, in a fired engine where the dynamometer actually applies load to the engine your brake power is not equal to 0. Of course, friction power is also not equal to 0. So, this is a real sense and this is a ideal sense to estimate the friction power and this is how the concept of motoring test is all about.

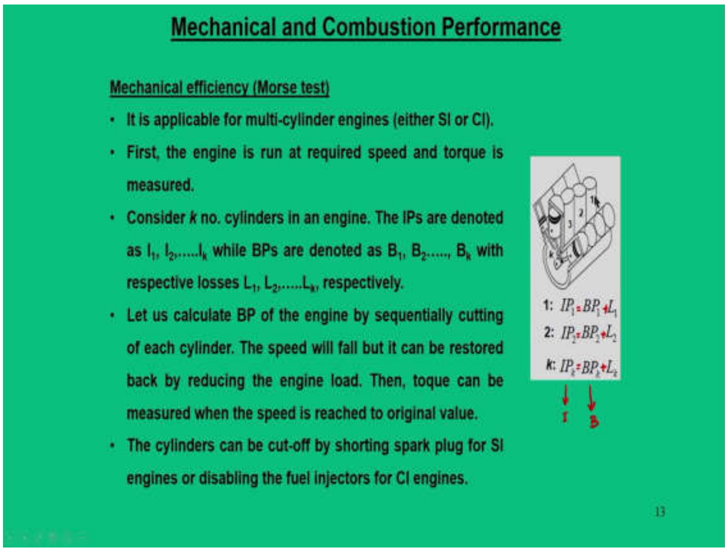
So, in one case we have to run the engine in a motored conditions and the other way we can run the engine in a fired conditions. So, based on that we can calculate the friction power. So, first thing how do you do the motoring test? So, during motoring test you connect the engine with a dynamometer, but that dynamometer will act as a motor so that the brake power is 0 and friction power is nothing but the indicated power.

And that means, in this way we can calculate the friction power of the engine. And that can be done at different speeds, different speeds means, here this is plotted with average piston speed and we can correlate it as N. So, at every N, one can find out what is the value of friction power that is nothing but the indicated power because the brake power is 0.

Another curve can be drawn which is a plot between this friction power and RPM or frictional mean effective pressure versus RPM. So, at that every point one can calculate there are two points; that means, at any N we will have two values one for the fired engine other for the motored engines and difference between these two is nothing but the friction power and this expression can be used for all RPMs.

When you do all the RPMs and then we can estimate the curve mechanical efficiency verses brake power which comes in this fashion. So, it is not exactly a linear fashion that is the parabolic nature. So, this is all about motoring curve that talks about how you are going to calculate the mechanical efficiency of the engine. Another test that we are going to do is a Morse test.

(Refer Slide Time: 30:13)



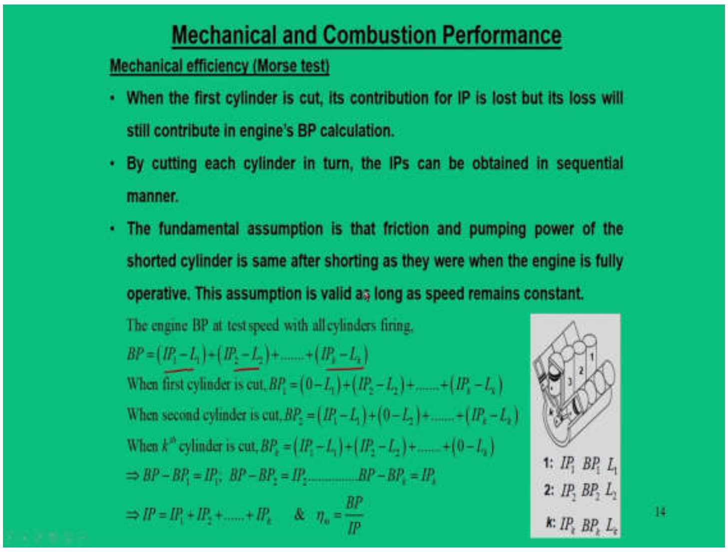
So, this particular Morse test is referred for either SI or CI, but with a condition that it should be multi cylinder engines. So, that means, this particular test is only applied for multi cylinder engines. So, as you can see there are number of cylinders 1, 2, 3 and we have k number of cylinders. And each cylinder is assigned as some indicated power IP_1, BP_1 and L_1; L_1 is nothing what the frictional losses.

So, we can write $IP_1 = BP_1 + L_1$, and $IP_k = BP_k + L_k$. So, how we were going to estimate? So, first let us consider there are k number of cylinders in an engine. The indicated powers are defined as either I_1, I_2, I_3, I_k and this is nothing B_1, B_2, B_k, L_1, L_2, L_k.

Now to calculate the brake power of the engines what we are going to do? We are subsequently cut each cylinders. So, for example, engine is first run with all the cylinders and you cut the cylinder 1.

That means you disconnect the cylinder 1 from this, but what happens is that since engine is running with all the cylinders still although it will not contribute to the brake power, but it can contribute the friction to the entire running operations. So, the friction power remains there. So, this cut off can be done either for SI or CI. For SI engines we can cut off the spark plug, for CI engine we can stop the fuel injection. So, thereby we can do this fuel cut off.

(Refer Slide Time: 32:32)



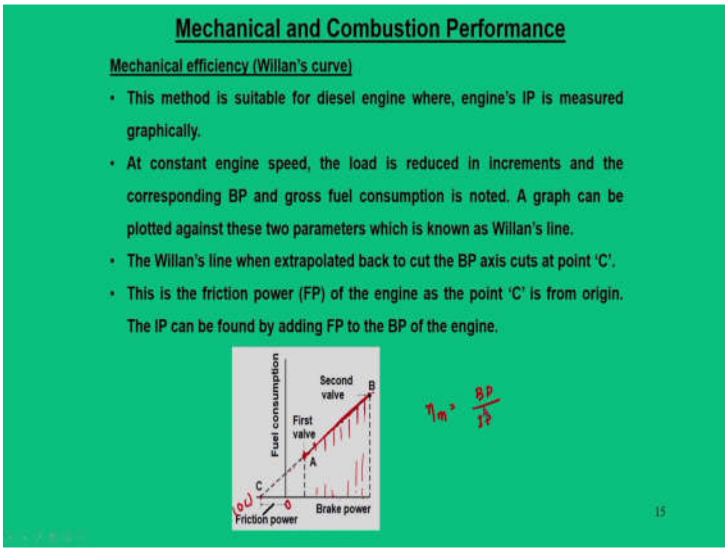
Now, once you do that what we are going to get in our estimate is that when the engine is run with all the cylinders firing we can calculate the brake power as $BP = (IP_1 - L_1) + (IP_2 - L_2) + ... + (IP_k - L_k)$.

From this when the first cylinder gets cut off, its indicated power becomes 0. So, that same expression can be written as $BP_1 = (0 - L_1) + (IP_2 - L_2) + ... + (IP_k - L_k)$. Similarly, when the second cylinder is cut off the 0 term appears for IP_2, likewise when the k cylinder is cut off 0 term appears per last k cylinder.

So, we can find a relation $BP - BP_1 = IP_1;\ BP - BP_2 = IP_2 .... BP - BP_k = IP_k$. So, in this ways if you sequentially add all these terms we will end up getting a term that is $IP = IP_1 + IP_2 + ... + IP_k$ means total indicated power of all the cylinders.

So, ultimately from the first expression we already know BP, we now we get the indicated power from this method and we get the mechanical efficiency. So, this is how the Morse test is conducted to calculate the mechanical efficiency of the engine.

(Refer Slide Time: 34:17)



The last one is known as Wilson's curve and this is mostly applied for a diesel engines because in the diesel engine we have provisions of cutting off the fuel through fuel injector and in fact, it is only applied for that concept. So, if you look at this particular plot, it is a plot between fuel consumption and brake power.

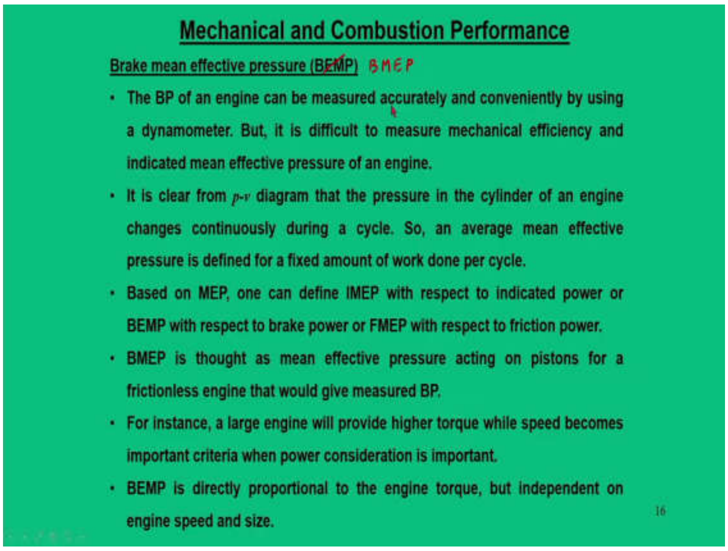
So, normally what happens? When we want to increase the brake power we should increase the fuel consumptions. So, basically when the fuel gets injected, for every fuel consumption rate we can estimate the brake power experimentally.

So, that means, this first point end defines the point at which the fuel is injected first and for different fuel injection value, we can get different brake power. So, we can generate this data experimentally. So, these are basically experimental observation in which we keep on increasing the fuel consumption, we get the brake power.

So, basically we get the curve AB from this experimentally observed data and it will be treated as a straight line. Now, this is with respect to a particular engine. Now, what you do is extrapolate this data from point A and try to see that where it cuts at the negative axis of this brake power. So, this cuts are the point C.

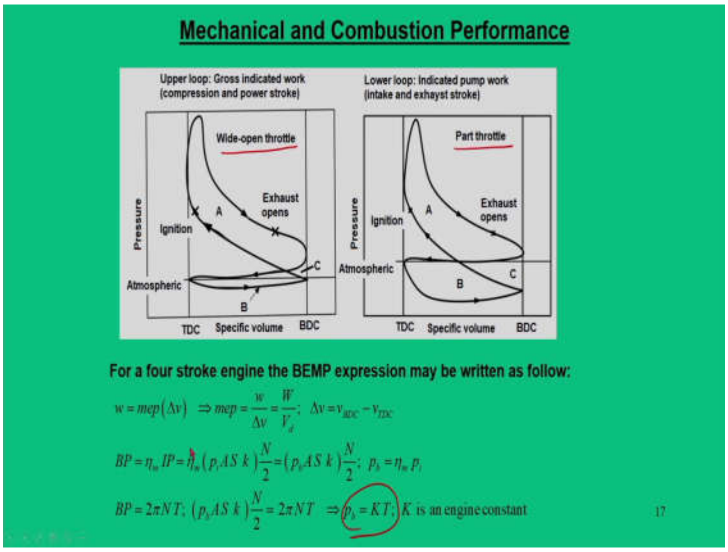
So, if you take the origin as O then OC can be considered as the friction power and because it is negative to the power axis. So, in this fashion we get the friction power and we also know the brake power. So, one can find out the mechanical efficiency that is brake power by indicated power.

(Refer Slide Time: 36:47)



So, now we are going to introduce another concept which is called as brake mean effective pressure. It should be BMEP. So, the concept goes in a similar manner in which we defined the indicated pressure. So, I do not want to give more emphasis on this. So, we want to go into the same relation the way we did it for indicated power calculations. What we have seen in that diagram for calculations as the plot between pressure and volume diagram.

(Refer Slide Time: 37:30)



But, here we are going to plot the pressure and volume diagram at the output conditions. So, the output condition could be of two possibilities one is wide open throttle other is part throttle. So, wide open throttle condition means that your throttle valve is fully open. So, when the throttle valve is fully open, engine is allowed to run with full fuel capacity; that means fuel can go to into the engine to a maximum. Now, when there is a part throttle; that means, engine is allowed to run with some partial amount of fuel.

So, these are the typical concept that you use in the engines. Why you use wide open or part throttle? Because the valve has certain finite amount of space which it is going to allow for the fuel to enter into the engines. So, if I say 100 percent open, I cannot ensure that 100 percent fuel is going because the valve occupy a certain space within that region. So, that is the word where you are using the wide open and part throttle condition.

Now, with the same concept of work calculations we have introduced $w = mep(\Delta v)$ and here Δv is nothing but the piston displacement from TDC to the BDC or BDC to TDC. So, that way we call this as a displacement volume. This mean effective pressure, you are now going to use as a brake mean effective pressure. So, how you are going to do?

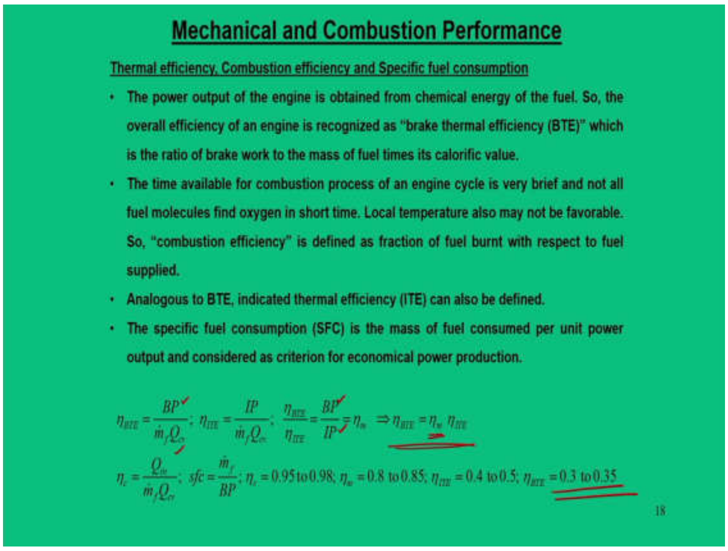
First we can calculate the brake power as mechanical efficiency of the engine into indicated power. Since we know the indicated power in our already calculations, so, we can write that expression using in terms of indicated pressure.

$BP = \eta_m \, IP = \eta_m \left(p_i A S \; k \right) \dfrac{N}{2}$. Now, here we are going to introduce the term which is brake mean effective pressure p_b . So, that is nothing but $\eta_m \, p_i$.

So, this is how we are going to calculate the brake power from this indicated power, but other way is that we can also get the brake power by using the dynamometer that expression goes as $BP = 2\pi N T$. Now, if you equate these two term what we are going to find that this brake mean effective pressure is nothing but $p_b = K T$; that means, brake mean effective pressure is a direct indication of the torque developed by the engines.

So, if you do that, so, we can find that most of the term will get cancelled other term like A and S becomes a constant. So, that is what the constant K appears here. So, in this way we can interpret the brake mean effective pressure for the engines and this is written for four stroke, but for two stroke this N/2 will be replaced as only N. However, in our situations we always use four stroke. So, we go ahead with this expression.

(Refer Slide Time: 40:57)



Apart from this we are now going to discuss something about the thermal efficiency, combustion efficiency and specific fuel consumption. So, this is all about the mechanical aspects, now we are bringing fuel into picture. So, when we are bringing fuel into picture, so, that way we define three terms like brake thermal efficiency of the engine which is nothing but the ratio of brake power to the total fuel heating value.

So, this is the output that we get from the engine and this is the input we are providing in terms of the fuel. So, that is nothing but $\dot{m}_f Q_{cv}$. Q_{cv} is your calorific value. In similar sense we can also define the indicated thermal efficiency that is $\eta_{ITE} = \frac{IP}{\dot{m}_f Q_{cv}}$. So, the ratio of these two again turns out to be the fact that ratio of brake thermal efficiency to the indicated thermal efficiency becomes the mechanical efficiency.

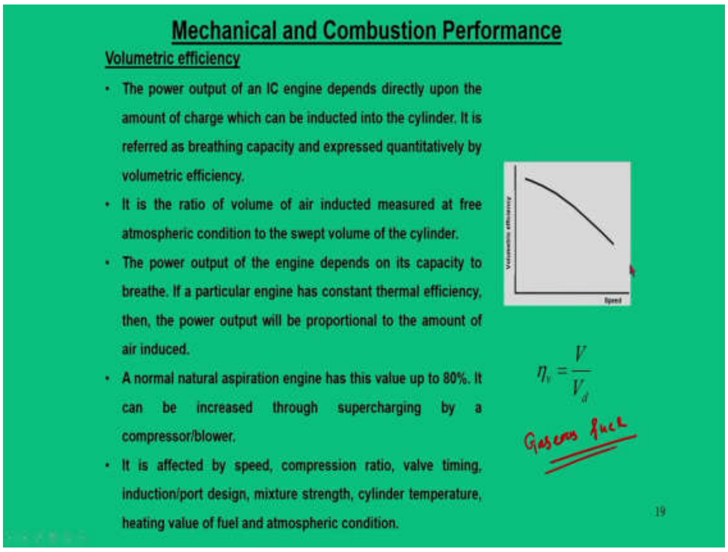
So, this is one aspect, we should not get confused that between thermal efficiency and mechanical efficiency. The mechanical efficiency it is between brake power and indicated power, thermal efficiency is between brake power and the fuel heating value. So, these two terms should not be confused.

So, apart from this, total fuel heating value can be correlated in terms of combustion efficiency that is $\eta_c = \frac{Q_{in}}{\dot{m}_f Q_{cv}}$. So, that is nothing but actual heat that is going into the engine from the fuel divided by total heating value of the fuel. So, this is how we define this combustion efficiency and there is another term which is called as specific fuel consumption.

This is of more interest for the user and it is mostly interpreted in the term of mass of the fuel consumed divided by the brake power $sfc = \frac{\dot{m}_f}{BP}$. Many of the books also represent as BSFC that is also true, but in most of time we normally not interested with indicated specific fuel consumption. So, mostly we interpret in terms of brake power. So, either you write sfc or bsfc it has same meaning.

So, just to give a number that for an engine to have, one should think that the fuel should have a combustion efficiency between 95 to 98 percents and typically mechanical efficiency falls in the range of 80 to 85 percent. Indicated thermal efficiency is typically 40 to 50 percent and finally, we get the indicated brake thermal efficiency for an IC engine is in the range of 0.3 to 0.35. So, in other words we say we are actually consuming the total thirty percent of the fuel energy.

(Refer Slide Time: 44:08)

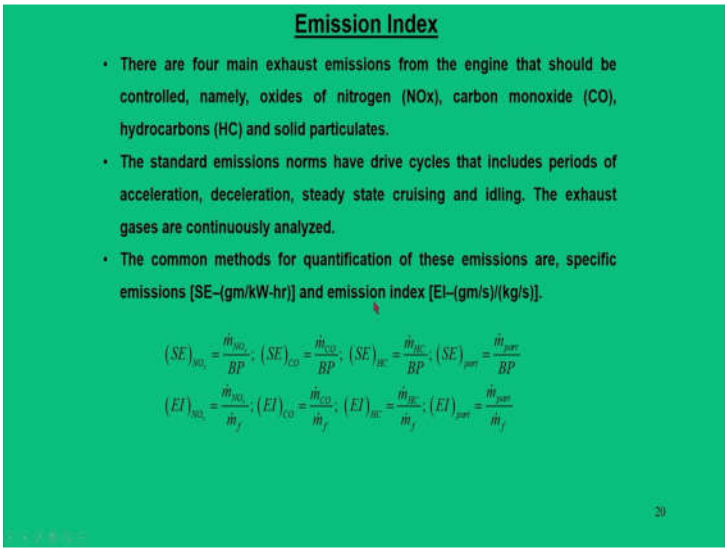


And in another terminology we are going to talk about something on volumetric efficiency. And this volumetric efficiency is defined as the ratio of total volume to the displacement volume and this is volume of the air which is inducted to the swept volume of the engine.

So, normally this volumetric efficiency word comes for gaseous fuel and this term is not so significant for liquid fuels and this is very significant term for gaseous fuel. Most of the engines that use bio gas or LPG or natural gas, that term volumetric efficiency plays a role because they have to mixed with air.

So, accordingly how much air you require for a given fuel that depends on the size of the engine and this is affected by the speed of the engine, compression ratio of the engine, valve timing, mixture strength, cylinder temperatures; all these things are very vital part of this engine. As you can see from this plot, a typical trend will tell you that volumetric efficiency drops when engine speed increases.

(Refer Slide Time: 45:51)



And then we have the emission index. This emission index means when the engine is run, there are some unwanted products that comes out of the engines and they are treated as an oxides of nitrogen oxides of carbon monoxide and hydrocarbons and other solid particulates.

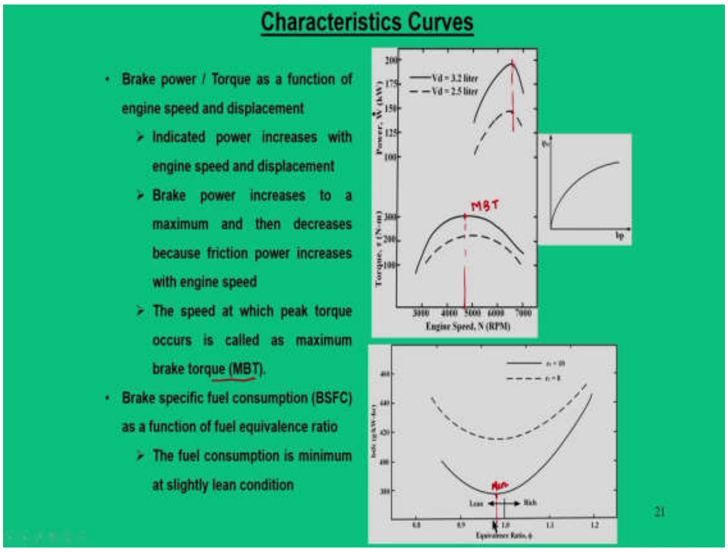
So, the common method of quantification is by two means, one is in terms of specific emissions that is how much grams of that particular gas comes out per kilo watt hour, this one way of representation. Other way is that in terms of fuel consumption; that means, in the denominator instead of brake power if you represent in terms of fuel consumption that is $\dot{m}_f$

So, these expressions are listed here and from the engine data one can calculate all these numbers and take appropriate way to calculate this emission index. And either you can represent in the form of specific emissions or in the form of emission index.

$$(SE)_{NO_x} = \frac{\dot{m}_{NO_x}}{BP};\ (SE)_{CO} = \frac{\dot{m}_{CO}}{BP};\ (SE)_{HC} = \frac{\dot{m}_{HC}}{BP};\ (SE)_{part} = \frac{\dot{m}_{part}}{BP}$$

$$(EI)_{NO_x} = \frac{\dot{m}_{NO_x}}{\dot{m}_f};\ (EI)_{CO} = \frac{\dot{m}_{CO}}{\dot{m}_f};\ (EI)_{HC} = \frac{\dot{m}_{HC}}{\dot{m}_f};\ (EI)_{part} = \frac{\dot{m}_{part}}{\dot{m}_f}$$

(Refer Slide Time: 46:55)

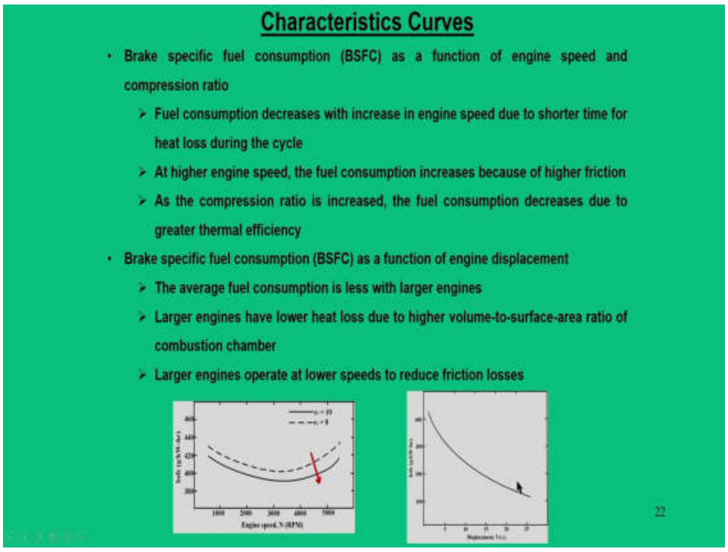


Now, here I am going to talk about some characteristics curves or trends and first characteristics curve is the brake power or brake torque which is a function of engine speed and displacement. So, as you see in this particular plot, it says that when the speed of the engine increases, the torque or power also increases, but with a particular time it further drops that is because when engine speed increases your friction power also increases.

So, the net loss is that it will drop the brake power that is what brake torque also comes down. And there is a particular location where the torque is maximum and it is termed as MBT that is maximum brake torque and it also appears the point at which the brake power is maximum.

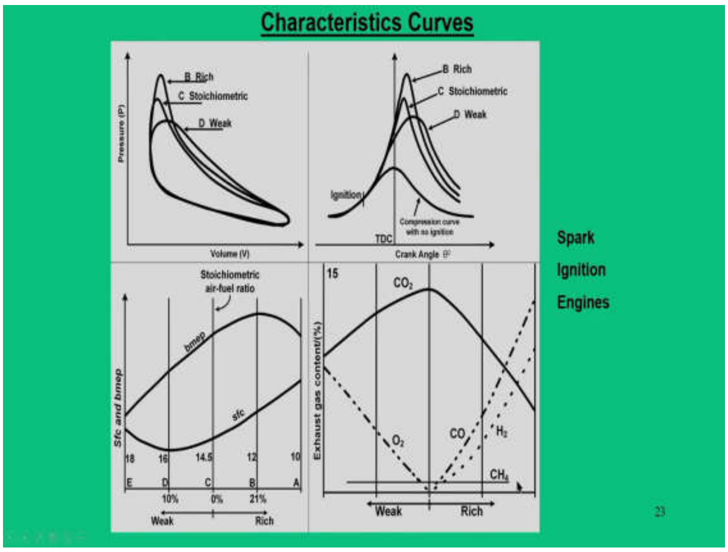
So, the trend of brake power curve is changing because you because your friction power is also changing with speed. Another term could be brake specific fuel consumption as a fuel equivalence ratio. So, the fuel consumption is minimum, when it is a slightly lean mixer. So, if you took a particular trend, and the fuel consumption is minimum; so, we can say the BSFC that is brake specific fuel consumption is minimum at lean equivalence ratio.

(Refer Slide Time: 48:41)



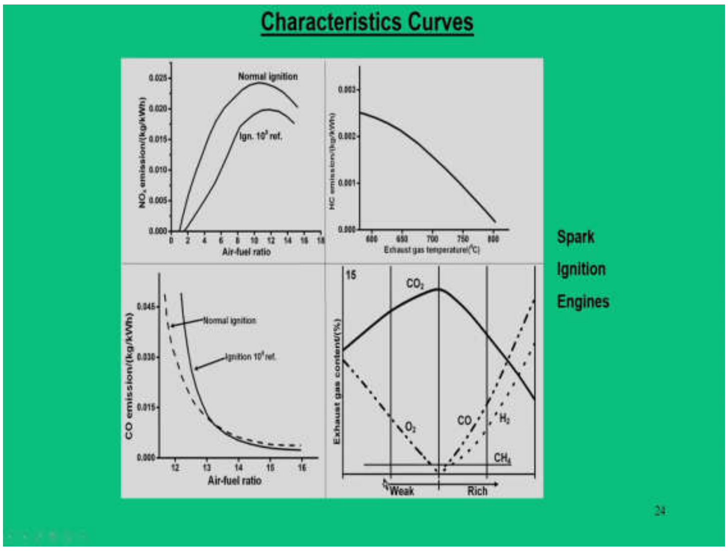
Another kind of plot that can be plotted is in the form of brake specific fuel consumptions as a function of engine speed and compression ratio. So, with increase in the engine speed the brake specific fuel consumption drops as I have already mentioned, but what happens when you are increasing the compression ratio in this order; the brake specific fuel consumption drops. And the brake specific fuel consumption as a function of engine displacement; so, when engine displacement increases, the specific fuel consumption also comes down. But it may not go at a higher speed, but with the displacement, the brake specific fuel consumption drops.

(Refer Slide Time: 49:28) .



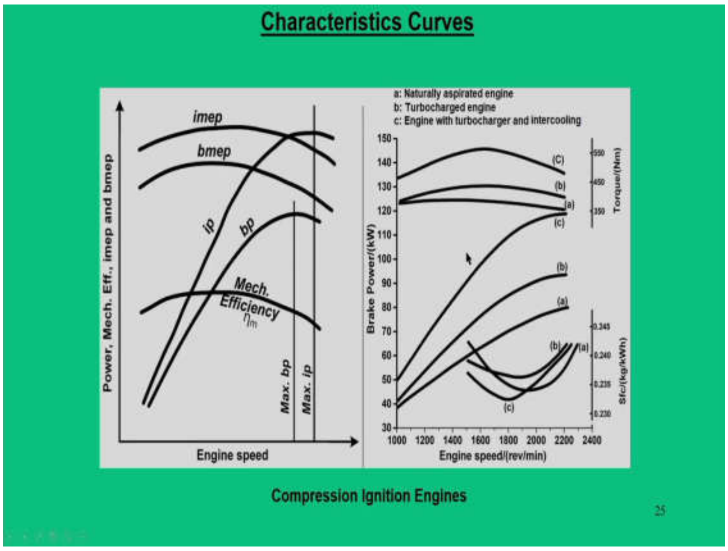
Other specific characteristics curves that can be drawn for spark ignition that is pressure-volume diagram, we can also think about specific fuel consumption for fuel rich, exhaust gas content.

(Refer Slide Time: 49:41)



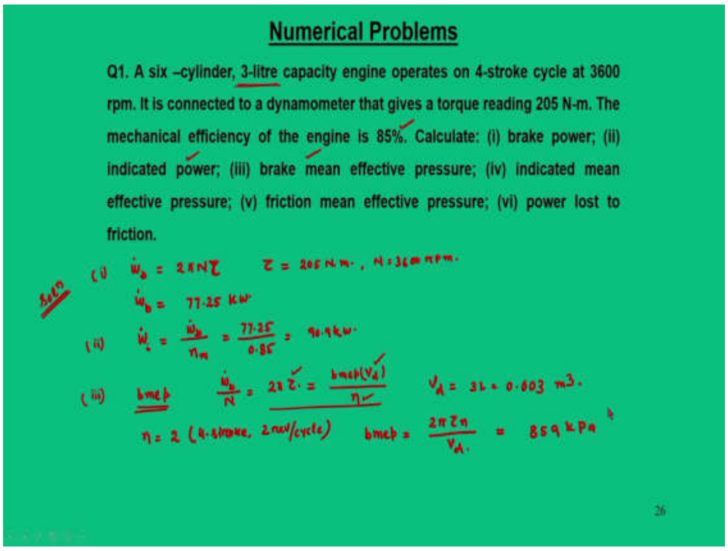
Then in terms of emission norms with respect to air fuel ratio, we can think of carbon emissions with air fuel ratios. All these things are also very specific for characteristics curve and they are in particular for SI engines.

(Refer Slide Time: 49:56)



And for compression ignition engines, by running the engines by the method what I have explained, one can superimpose different curves to get the general trends for CI engines. So, when you define the characteristics curves, it has to define two ways: one for CI engine other is for SI engines.

(Refer Slide Time: 50:19)



So, this is all about the lectures that I have delivered today. Now, we are going to solve some numerical problems based on this particular lecture. So, the first problem that we are going to solve is as follows. We are going to discuss this problem in a step by step manner. So, we consider a six cylinder 3-liter capacity engines it operates on a 4-stroke cycle and it operates with 3600 rpm and it is connected to a dynamometer that gives a torque reading 205 N-m.

We are also given with the mechanical efficiency of 85 percent and we are supposed to calculate the brake power, indicated power, brake mean effective pressure, indicated mean effective pressure, friction mean effective pressure and power lost due to frictions. So, let me start the solution step by step.

So, we need brake power that is $w_b = 2\pi N\tau = 2\times\pi\times205\times3600 = 77.25\text{kW}$.

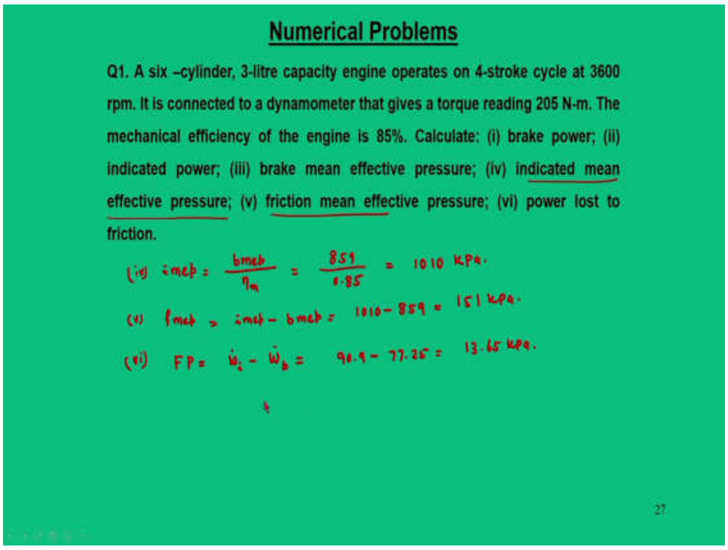
The second problem is we have to calculate the indicated power. So, for indicated power

$$\dot{w}_i = \frac{\dot{w}_b}{\eta_m} = \frac{77.25}{0.85} = 90.9\text{kW}$$

Third term we are going to calculate as brake mean effective pressure bmep. So, for bmep calculations, $\frac{\dot{w}_b}{N} = 2\pi\tau = \frac{\text{bmep}(V_d)}{n}$, this n is equal to 2 that is for 4-stroke and 2 revolution per cycle.

So to calculate V_d, what we are going to see that this a 3 liter capacity. So, this V_d = 0.003 m^3. So, we can calculate from this expression that $\text{bmep} = \frac{2\pi\tau n}{(V_d)} = 859\text{kPa}$.

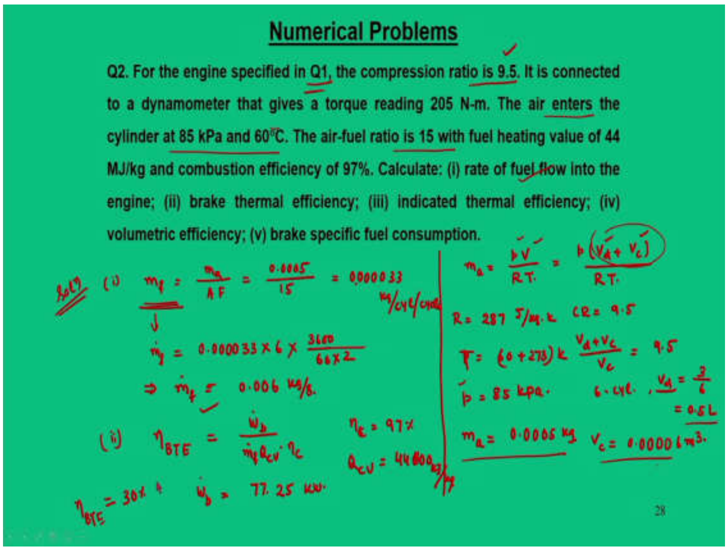
(Refer Slide Time: 55:00)



Then we are going to calculate the indicated mean effective pressure. So, this indicated mean effective pressure can be calculated from brake mean effective pressure and this is expressed in this manner that $\text{imep} = \frac{\text{bmep}}{\eta_m} = \frac{859}{0.85} = 1010\text{kPa}$

Then we are going to calculate the friction mean effective pressure $\text{fmep} = \text{imep} - \text{bmep} = 1010 - 859 = 151\text{kPa}$. Then power lost to the friction, so, it is nothing but $\text{FP} = \dot{w}_i - \dot{w}_b = 90.9 - 77.25 = 13.65\text{kPa}$

(Refer Slide Time: 56:54)



The next problem that goes is that for the same engine specified in question 1, here the other data that is given as compression ratio and this compression is ratio is required because we need to calculate certain terms. And also other data is that here we are talking about the air fuel ratio that is 15 and here air enters to the engine at certain condition 85 kPa and 60 °C.

So, our main intention is to calculate the fuel flow rate into the engine, brake thermal efficiency, indicated thermal efficiency, volumetric efficiency and brake specific fuel consumption. Now, let us start one by one the first term that we are going to calculate rate of fuel flow.

We have $\text{CR} = 9.5 \Rightarrow \dfrac{V_d + V_c}{V_c} = 9.5$ & for 6 cylinder, $V_d = 3/6 = 0.5\text{L}$

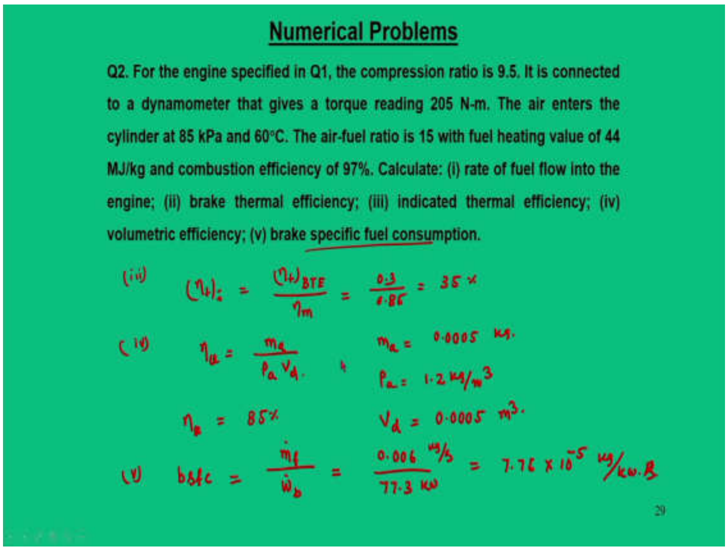
So, $V_c = 0.00006\text{m}^3$; Now, $\text{m}_a = \dfrac{pV}{RT} = \dfrac{p\left(V_d + V_c\right)}{RT} = 0.0005\text{kg}$

So, $\text{m}_f = \dfrac{\text{m}_a}{AF} = \dfrac{0.0005}{15} = 0.000033 \; {kg}/{cyl}/{cycle}$

So, this mass flow can be correlated to mass flow rate $\dot{m}_f = 0.000033 \times 6 \times \dfrac{3600}{60 \times 2} = 0.006\text{kg/s}$. So, we are able to estimate the first term that is fuel flow rate.

Now, $\eta_{BTE} = \frac{\dot{w}_b}{\dot{m}_f Q_{CV} \eta_c} = \frac{77.25}{0.006 \times 44000 \times 0.97} = 0.3$

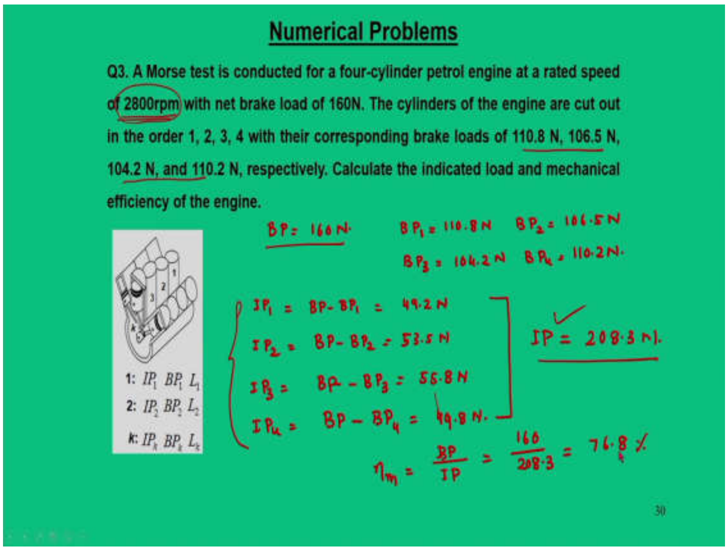
(Refer Slide Time: 63:36)



Then once you have brake thermal efficiency then we can calculate indicated thermal efficiency $(\eta_t)_i = \frac{(\eta_t)_{BTE}}{\eta_m} = \frac{0.3}{0.85} = 0.35$. Then we need to know volumetric efficiency. So, $\eta_v = \frac{m_a}{\rho_a V_d} = \frac{0.0005}{1.2 \times 0.0005} = 85\%$.

The last part is brake specific fuel consumption $\text{bsfc} = \frac{\dot{m}_f}{\dot{w}_b} = \frac{0.006}{77.25} = 7.76 \times 10^{-5}$ kg/kW-s

(Refer Slide Time: 65:48)



And the last problem is on Morse test. So, this particular derivation I have already indicated in the lecture class. So, here I just want to emphasize that the engine is a four cylinder engines 1, 2, 3, 4. For each engine, the brake load is measured as 110.8, 106.5, 104.2 and 110.2 N. Total brake load is already given as 160 N.

$$IP_1 = BP - BP_1 = 160 - 110.8 = 49.2N$$
$$IP_2 = BP - BP_2 = 53.5N$$
$$IP_3 = BP - BP_3 = 55.8N$$
$$IP_4 = BP - BP_4 = 49.8N$$
$$IP = IP_1 + IP_2 + IP_3 + IP_4 = 208.3N$$

So, we already know BP, we know indicated power, since the our engine is running at same RPM at all the cases, so, we can directly say that mechanical efficiency is nothing but BP/ IP that is 160/208.3. So, this is 76.8%. So, we have given with the load, but our analysis was done in IP_1, IP_2, IP_3 because intentionally 2800 rpm is common for all the loads. So, N will get cancelled.

So, in this way we can calculate the indicated load IP as 208.3 N or the mechanical efficiency 76.8% So, with this I will conclude this lecture.

Thank you for your attention.