Course Name: Engine System and Performance
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Lec 30: Measurement of indicated work, Numerical problem

I welcome you all to the session on engine system and performance. Today, we shall discuss the measurement of indicated work, and then we shall solve one numerical problem on this particular topic. Until now, we have discussed the measurement of fuel and air flow rate, as well as the measurement of engine speed. We have also discussed the measurement of needle lift, which is important to determine the amount of fuel to be discharged or drawn into the manifold or engine cylinder. So, indicated work, this particular quantity, which is the work done by the gases inside the cylinder— is one of the important quantities to be measured, essentially for the estimation of engine performance.

So, if we would like to measure or quantify engine performance, indicated work is one of the important quantities. Now, the work done by the gases on the piston is essentially the indicated work. But certainly, the work available at the output shaft of the engine is not the indicated work because there are some frictional losses. So, let us discuss today the measurement of this important quantity, and then we shall solve one numerical problem.

We all know that as the piston moves between top dead center and bottom dead center, the piston's location changes inside the engine cylinder, and certainly, the pressure inside the cylinder will also change. If we put it, in another way, the gas pressure inside the engine cylinder changes, which in turn affects the work done or even the piston movement. So, the work done by the gases within the cylinder of the engine are W,

$$W = \oint F dx = \oint P A_p dx$$

F is the force. So, typically, if we try to write it in a more accurate form, it should be the area of the piston (A_p). So, the work done by the gases on the piston face.

So, this P is the pressure of the gases within the cylinder, which is continuously changing as the stroke of the piston changes, that is from intake to compression stroke, compression to power stroke, etc. This A_p is the piston face area, and dx is the distance traversed or moved by the piston. So, the cyclic integral stands for the work done per cycle. Essentially, if we talk about four-stroke engines or two-stroke engines, all these engines, four-stroke, two-stroke engines are operated, following two different mechanical cycles that we have discussed, depending on the type of combustion.

So, maybe a two-stroke petrol engine or a four-stroke petrol engine is there. So, essentially, depending on the type of engine, we can have two numbers of strokes, or we can have that engine can be classified based on the types of combustion as well. So, now, whether it is a four-stroke engine or a two-stroke engine, all these engines to execute several processes. All these several processes of these engines, are executed by a cycle. So, this work, the cyclic integral, indicates the work done per cycle.

The question is, the pressure of the gases inside the cylinder changes continuously, and it is not very easy to measure pressure variation. So, the target should be to measure the instantaneous variation of pressure in the engine cylinder. Nowadays, there are sophisticated measuring devices available with the help of electronics or digital technologies, but still, the concept that was introduced is to use mean effective pressure.

So, that means if we go to the next slide, W, which is the work done.

$$W = (mep) \times \left(A_p \times L_s\right)$$

So, this is mean effective pressure, or the average pressure, as the gas inside the cylinder changes continuously. Instead of calculating or determining instantaneous pressure, it is convenient to write the work done in terms of mean effective pressure. So, mean effective pressure multiplied by the area of the piston and the length.

So, essentially, this should not be dx because the moment we try to write in terms of mean effective pressure, we can write that as the stroke length (L_s). So, essentially, we can write this as V_s, which is the stroke volume. So, the question is, this is a very convenient means of measuring the work done by the gases within the cylinder.

We could have calculated instantaneous pressure using state of the art devices, but instead the introduction of the concept of mean effective pressure is also equally good to determine the work done by the engine. Now, if we try to know, essentially the pressure mean effective pressure. So, the pressure inside the engine cylinder is continuously changing and work done that will be calculated using the pressure variation and its average value inside the engine cylinder that is typically known as indicated mean effective pressure and essentially work that we will be calculating is indicated work done.

Indicated work done per cylinder per cycle that equal can be obtained this indicated mean effective pressure which is multiplied with area of the piston into stroke length that is V_s. So, question is as determination of work done or indicated work done is very important to predict the performance of the engine.

Next, we shall discuss one method to calculate or to have some information or to have some quantification of indicated mean effective pressure as the piston changes its location continuously inside the engine cylinder. So, this IMEP (indicated mean effective pressure), is obtained from the indicator diagram with the help of indicator device devices.

Now, let us discuss one method which is consistent with the measurement of indicated mean effective pressure using this indicator diagram. So, just for the sake of completeness, this is indicated mean effective pressure.

So, if you go to the next slide wherein we can see a schematic defection or a schematic in this particular slide schematic is depicted just to make you understand about the device or mechanical system which is used to know or which is used to measure indicated mean effective pressure through indicated diagram. So, essentially this device is an indicator device. The working principle of this device relies on the accurate measurement of indicated diagram which in turn will be used to measure indicated mean effective pressure. So, what are the components if we can see though all components are not leveled in the schematic. you can see that this is essentially a spring.

So, this is spring, this is a small drum, this I will tell exactly the functionality of all these components or parts later on, but let us now first level all these components. So, this is known as stylus, this is mechanical linkage and essentially this is engine cylinder. So, let me write a few steps first then that will help you to understand what are the steps used or to describe the functionality of this particular mechanical device or indicator device.

So, essentially this device, earlier indicated diagrams where produced by mechanical device or mechanical plotters linked to the engine cylinder. So, indicator device which will give us an information about indicator diagram. So, essentially in this engine cylinder you can see on the top of the engine cylinder there is an arrangement and that arrangement is again essentially a mechanical arrangement.

So, few steps, A) is a small cylinder inside which there is a small piston. So, a small cylinder housing a small piston. And the small piston inside the small cylinder will have some true motion against the spring. That spring you can see, so the piston is connected to the spring, you can see. And so, the cylinder inside the small piston will have reciprocating motion, a to-and-fro motion between—or I can't say between—two locations. So, the piston will reciprocate inside the small cylinder, which is connected to the spring against or some against the forces. So, what—you can see that small cylinder. and piston.

The piston is also small. These two are attached to the engine cylinder such that the pressures in the cylinder will develop because of the combustion force, causing the small piston to move or to have a to-and-fro movement against the force of a calibrated spring. So, this piston is a spring-loaded piston.

So, this is engine cylinder. So, on the top of this engine cylinder this mechanical housing is there, that is, housing is composed of one small cylinder, a small piston. The small piston arrangement is such that small piston can have to-and-fro movement between. I mean inside the small piston, not between. The small piston can have to-and-fro movement inside the small cylinder, which is mainly due to the pressure that will develop inside the engine cylinder.

So, when pressure develops inside the engine cylinder, that pressure will force the small piston to move up against the force of a calibrated spring. So, then if we write number 2), the movement of the small piston, is proportional to the pressure inside the engine cylinder. So, it is engine cylinder. That means if the pressure inside the engine cylinder is low, movement will be low, if pressure is high, movement will be large, movement will be there.

So, that is what it is. Now, question is, second problem is, if you look at the schematic depiction carefully, you will find that this piston is somehow connected to a mechanical linkage that I have already marked or leveled in the schematic. So, if I go to right, in the next slide that the movement of the piston is transmitted. So, number 3, the movement of this small piston is transmitted through a mechanical linkage. It is a large mechanical linkage to a stylus. If we go back to the previous slide, let us describe it. So, the piston is getting movement inside the small cylinder, but the piston movement is proportional to the gas pressure that we have discussed. Now, the piston is connected to this mechanical linkage, which is relatively large.

So, the movement of the piston is transmitted to this stylus that you can see here through this mechanical linkage. And you can see on the right-hand side of the schematic, there is a small drum, and a paper sheet is wrapped over the small drum. So, this small drum, which is wrapped with a paper sheet outside. So, if we go to write in the next slide for that, a paper sheet is wrapped around a small drum. Which is caused to oscillate in accordance with the stroke of the piston of the engine. This is not the small piston. So, if we go back to the previous slide again, the small drum which is there, a sheet of paper is wrapped around the small drum, and the small drum is designed to oscillate in tune with the strokes of the engine.

So essentially when it is an intake stroke, compression stroke, power stroke, and exhaust stroke, in tune with all these strokes, the small drum will oscillate. That is how it is designed. Now, if we go to the next slide again, so what will happen, is the stylus that you can see, which is connected to the mechanical linkage, which is connected to the small piston through this mechanical linkage. The stylus will be having or it will move up and down. Because the small piston will move up and down, experiencing a change in pressure in the engine cylinder, which in turn will allow the stylus to move up and down, which is parallel to the axis of the drum. But the drum itself is oscillating in tune with the engine stroke. So, if you go to the next slide, point number 5, that the stylus moves up and down parallel to the axis of the oscillating drum and while the stylus is moving up and down which is parallel to the oscillating drum. In the course of this movement of the stylus it will or it will produce a record of engine cylinder pressure against the engine piston position. So, the record thus produced is termed or is called as an indicated diagram.

So, essentially, we wanted to have this indicated diagram, because knowing this indicated diagram we will now take an effort to have some quantification of the indicated work. So, from the indicated diagram next task should be to have some information about the indicator or the area of the diagram from there, from that area should be, we shall try to quantify work done. So, area should be converted to work and for that we need some constant. So, idea is, try to understand drum, a small drum which is wrapped or, with one sheet paper.

Drum is designed to oscillate in tune with the engine strokes so certainly and drum will not be stationary, it will oscillate on the other hand that small piston will again move inside this small cylinder in tune with the pressure inside the cylinder and since that movement is transmitted to this stylus through the mechanical linkage so we'll be having one record of inside or cylinder pressure at different strokes. Because small drum is also oscillating with the engine stroke. So now we have this indicator diagram. Now the question is this indicator diagram is used to produce or used to measure indicator work, indicated work by measuring area of that indicator diagram, but this method has some limitations.

What are those limitations? This method is not suitable for small engine and high-speed engine. So, if we need to quantify or we need to measure work done by an engine, if the engine volume is very small and engine is having high speed. If the engine volume is small then you can see that on the head of the engine that mechanical assembly is integrated.

So, essentially this small piston, small cylinder, mechanical linkage, stylus all these particular mechanical assembly is placed on the head of the engine. Now, if the engine is very small, positioning of this mechanical assembly will alter or will affect the compression ratio, number one. Number two is certainly to obtain this indicated diagram that we have discussed so far is dependent on the efficacy of the mechanical linkage because movement of small piston is transmitted to this stylus through this mechanical linkage. If the engine is having very high-speed mechanical linkage will be having some inertia, any mechanical device is having some inertia.

To obtain information for an engine with operating at high-speed, mechanical linkage may not be suitable or even if we try to have some information using this mechanical linkage, performance or measurement will not be satisfactory. So that way, the limitation of this particular method that we have discussed is, or limitations are, it cannot be used for small engine and it also cannot be used for engines operating with high speed. So, limitation of this method are as follows.

So, this method cannot be used for small engines or a small engine. Number two, for high-speed engines, this method is also not suitable. So, we have listed down that this method can be used for speeds up to 600 rpm. So, this is what it is. Now, let us discuss the limitations. Then, what are the advantages of this particular method? Inside the cylinder, engine pressure or engine pressure changes continuously.

And, the measurement of instantaneous pressure inside the engine cylinder is not a very easy task. Though it may be possible using state-of-the-art sophisticated instruments, those are really possible with the advent of digital technologies. But still, what will happen? That engine pressure will be changing continuously as the stroke length changes. Over and above, there are several unexpected situations. And those situations are: if there is a delay in ignition time, if there is a delay in fuel injection time. Also, if there is a failure of the nozzle to deliver atomized fuel or fuel with fine droplets, or even when there is damage to the piston ring. So, all these unexpected scenarios may alter engine pressure. So, what I said: first of all, if there is a delay in ignition timing, if there is a delay in fuel injection timing, if there is a failure of the fuel injector to supply atomized fuel, and if a piston ring is, or the piston ring becomes non-functional.

So, in all these scenarios, if we need to know about the engine condition or engine performance, this particular method is very suitable because it will give some information at each and every stroke about the pressure that will be there inside the engine cylinder. So, that way, it is suitable. Now, the question is, let us discuss the most important part. We have discussed that a fine indicator card is obtained with the mechanical indicator diagram, which is obtained using that particular device, the indicator device.

Now, what we need to get is the indicator card. So, essentially, using that indicator diagram, we need to measure the area, and that area should be converted to work using some constant. So, let us discuss the indicator diagram that we have discussed in the previous slide. The indicator diagram can be obtained using the mechanical system or indicator device.

Now, using this indicator diagram, what do we need to know? We need to know the area or indicator area. So, the area of the diagram (indicator area). The area of the diagram is obtained using a mechanical planimeter that you have studied in your undergraduate course.

So, mechanical planimeter is used to obtain this area. So, what does this device do? Mechanical planimeter is a device that computes area by tracing its periphery. So, if we know one diagram and if we use this mechanical device planimeter that device can help us to compute area by tracing its periphery.

This planimeter computes the area of the diagram by tracing periphery, but Let me add here an important point, if we use this mechanical device to obtain or to compute area, someone needs to do it carefully, so you have to trace the diagram or trace the periphery quite accurately to obtain the area. So, someone who will be doing this task should be very careful and the person should do practice quite frequently to obtain reliable and accurate results ok. So, now as I said you that once we got the area then that area should be converted into work. So, this area should be converted into work and a calibration constant is needed. So, then area converted to work using a calibration constant.

So essentially, that indicated mean effective pressure. That can be found more directly. So, we need to convert area into work, that is mechanical. That is work. So, this, IMEP is essentially.

We know the area. So, the area that is obtained by this mechanical planimeter, if I divide this area of the indicator diagram using the length of the indicator card, that is L_d. So, this L_d is the length of the card. This A_p is the area of the indicator diagram. So, I should write A_d. Now, because we have used suffix p in the context of piston area. So, in the context of writing or in the context of piston phase area, we should now write A_d.

So, this A_d is, so this is the indicator area of the indicator diagram. So, this indicated mean effective pressure is obtained by knowing the area. If we divide it with the length of the indicator card, that will give you the ordinate length in mm. So, this is multiplied with constant K, that is the calibration constant.

Thus, we can write that the indicated mean effective pressure, which is obtained using this indicator diagram, is

$$imep = K\left(\frac{A_d}{L_d}\right)$$

So, you can see that particular method is helpful not only to measure the indicated mean effective pressure, but if there is any change in pressure inside the engine cylinder because of delay in ignition, delay in injection, fuel injection time, delay in or failure of the valve or fuel injectors. Fuel injector to supply atomized fuel, or if there are some issues or there is some issue with the piston ring, in all these scenarios, the inside pressure will change, and this method is suitable. So, with this, let us now solve this numerical problem quickly.

Problem 1: The following data are obtained for the calculation of indicated horsepower (IHP) from experiments on a single cylinder four stroke CI engine: area of indicated diagram is 4.8 cm^2, length of indicated diagram is 6.8 cm, spring constant is 7.8 bar/cm, cylinder diameter is 200 mm, stoke length is 550 mm, speed of the engine is 400 rpm. Calculate IMEP and IHP.

Solution:

So, indicated mean effective pressure that can be obtained using the indicator area of the indicator diagram A_d divided by length of the indicator diagram or length of the indicator card L_d. So, this will give ordinate length multiplied with this constant will give the indicated mean effective pressure. So, let us first calculate this indicated mean effective pressure in the next slide.

So, if we calculate indicated mean effective pressure for this particular problem:

$$imep = 7.8\left(\frac{4.8}{6.8}\right) = 0.551 \text{ MPa} = 5.51 \text{ bar}$$

So, if we do this then essentially what will be getting is 5.51 bar that equal to 0.551 MPa. So, that is the indicator mean effective pressure. Now, from the diameter of the cylinder, we can calculate area of the piston face essentially, this is the pressure which is acting on the cylinder face which will force the piston to move from the top dead center to the bottom dead center. Now, in your area of the cylinder is essentially the area of the piston face, though there is a clearance, but we can approximate that the inner area of the cylinder cross-sectional, area is equal to the area of the piston face.

So, that is

$$A_p = \frac{\pi}{4}\left(D_{cyl}\right)^2 = \frac{\pi}{4}(0.2)^2 = 0.03 \text{ m}^2$$

So, we can calculate the average gas force on the piston face or on the piston,

$$= 0.551 \text{ MPa} \times 0.03 \text{ m}^2 = 0.02 \text{ MN}$$

So, this is the unit. Now, if we go to the next slide, then indicated based on the data we have, we can calculate indicated work done per cycle. So, we have calculated so far, the force due to pressure, that is indicated mean effective pressure acting on the piston cylinder. So, from the force, we can now calculate the indicated work done per cycle is. So, force that we have calculated is 0.02 MN into. If we go back to the previous slide, you can see that the stroke length is 550 mm.

So, essentially piston has to move between these two centers and that is the stroke length. So, if we go here, then that is 0.55 meter. Indicated work done per cycle,

$$= 0.02 \text{ MN} \times 0.55 \text{ m} = 0.01 \text{ MJ}$$

Newton meter is joule. So, that is the unit.

You have to write unit carefully because otherwise you will come up with wrong answer. So, this is the indicated work done per cycle. Now, for a four-stroke cycle engine, number of cycles per second. So, four-stroke engine, so there are two revolutions per cycle. So, if we calculate this

$$= \frac{400}{60 \times 2} = 3.33\ \frac{1}{\mathrm{s}}$$

So, finally, if we try to calculate indicated horsepower, that is IHP,

$$= 3.33\ \frac{1}{\mathrm{s}} \times 0.01\ \mathrm{MJ} = 0.03\ \mathrm{MW} = 30\ \mathrm{kW}$$

So, if we calculate it, it comes out as 0.03 MW (joule per second). So, essentially, this is 30 kW. So, this is the final answer to this problem.

So, we have discussed this numerical problem essentially to illustrate the concept that we have learned today.

So, to summarize today's discussion, we can say that we have discussed a method used to measure the indicated work, and thereafter, we have solved this numerical problem to illustrate the concept discussed in today's class.

So, with this, I stop here today, and we shall continue our discussion in the next class.

Thank you.