Course Name: Engine System and Performance
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Lec 29: Measurement of fuel flow rate, air flow rate and needle lift in a CI engine

I welcome you all to this session on engine system and performance. Today, we shall discuss the measurement of both air and fuel flow rates, and then we shall discuss the measurement of another important parameter, which is the lift of the needle, essentially related to the measurement of fuel injection in a CI engine. In the last class, we talked about engine performance and then discussed the measurement of an important parameter, which is engine speed. Let us discuss the measurement of fuel flow rate and air flow rate today. Because these two important parameters are crucial to predict or quantify engine performance. We have studied in our undergraduate internal combustion engine course that the air-fuel ratio or fuel-air ratio is very important. Care should be taken to provide a stoichiometric air-fuel ratio to the engine to ensure efficient combustion. If combustion is efficient, not only will engine efficiency increase, but also emission levels can be reduced.

So, let us discuss today the technique of fuel flow measurement using a particular method. Before discussing this, let us recall that there are many measuring devices we have studied in our undergraduate fluid mechanics course, and those devices are used essentially to measure the volume flow rate of fluid or liquid, to be precise. Today, we shall discuss measurement techniques typically used to measure fuel and air, which are similar to what we learned in our undergraduate fluid mechanics course.

For example, if we would like to measure the flow rate of fuel or fuel flow rate to the engine, that means the amount of fuel to be injected into an engine. The simplest technique is to place a fuel tank. If we consider a fuel tank, and if we place this fuel tank on a weighing balance, then we can record, the fuel tank on a weighing balance and then record the time required to consume certain mass of fuel by an engine. So, this is very simple method. A stopwatch can be used for this. So, this method is very old and simple. Now, just if we have one stopwatch and also pipette to measure the mass of fuel for certain amount of time that would be consumed by an engine. This method can be used to measure for both liquid and gaseous fuel.

A pipette and stopwatch can be used or may be used. Stopwatch can be used to measure the duration and pipette can be used to measure the amount of fuel that would be consumed by the engine. Now, what is important to mention in this context here that when the fuel is going to the engine, here a turbine pump can be placed.

So, if I erase this, so one turbine pump can be placed in the line just to control the flow rate and the rotational speed of the turbine pump is a measure of the flow rate of fuel. So, this is a turbine pump, that can also be placed in the line which is connecting this fuel tank to engine and the speed of this pump can be used or can be taken as a measure of the fuel flow rate. Note that using this device we can measure the volume flow rate of fuel instead of mass flow rate of fuel. So, this is very simple and old method that I have already mentioned.

If we discuss the technique, which is also used to measure fuel and is schematically shown in this slide. You can see that. This is the calibrated volume. Now, fuel is coming from the fuel tank. So, here we have one fuel tank and a valve for normal operation. If we observe this or when there is a need for normal operation of an engine. So, during normal operation, valve 1 is kept open. If we keep valve 1 open, then certainly fuel flows directly from the tank to the engine.

So, this is the case. Now, you may ask me a question: if this is the case, why do we need this particular calibrated volume in this setup? You can see this particular volume, which is placed between valve 1 and the line supplying or connected to the engine cylinder or in the engine intake manifold.

Essentially, it will go to the engine, but this fuel will be supplied to the engine through fuel injectors. Now, this calibrated volume is essentially used to measure the amount of fuel to be supplied during measurement. We need to measure the amount of fuel that should be or is to be supplied to the engine. So, what is done is that the vane pipe essentially should end.

If the vane pipe, this vane pipe ends below the level of—so if I erase this—so here we have fuel. So, this is the fuel tank— If the vane pipe ends below the level of fuel in the fuel tank, then care must be taken in filling the calibrated volume. If the vane pipe ends below the level of fuel in the fuel tank, then care must be taken to fill up this calibrated volume.

So, you can ask this question yourself and try to get the answer on your own. So, this calibrated volume—what is done? When this is to measure the fuel flow.

So, essentially what we need to do. We need to measure fuel flow rate using this setup or device. So, if we need to measure the fuel flow rate using this device, then valve 1 is kept closed. Number 2) is, fuel is taken from the calibrated volume, calibrated volume to the engine. So, this is the step. So, fuel is taken from calibrated volume to the engine valve 1 is remaining closed.

Now, essentially, these 2 steps are followed during measurement of fuel and if we need to have or if you need to draw fuel from the calibrated volume to the engine during its measurement. Certainly valve 2 has to remain open. Valve 2 should remain open. So, question is, if we go back to this previous slide, so during normal operation, this valve 2 will remain closed, valve one should be kept open and fuel flows directly from fuel tank to the engine. So, that is normal operation or normal period of engine operation. Now, if we need to measure the amount of fuel should be taken by the engine per 1 hour or per 2 hour or per 1 minute. So, valve 1 is kept closed, valve 2 is kept open, valve 2 is allowed to open and then calibrated volume will be filled by the fuel and then engine will take fuel from the calibrated volume and since the calibrated volume from the calibration itself, we can measure exactly the amount of fuel will be consumed by the engine certain per one hour.

So, this is the method by which fuel flow is measured. Now, the question is, for the measurement of fuel for SI engines, but if we need to measure fuel flow rate using the method that we have discussed for a CI engine, the problem is associated with the return flow. So, what is return flow? So, let me discuss here that problem associated with the measurement of fuel flow in a CI engine. The answer is, this is related to the return flow of fuel. Let me draw the schematic definition that will help you to understand this problem in a better way. If we go back to the previous slide, you can see that this line is now connected to the injector of an engine because essentially, fuel should be supplied to the engine by an injector.

So, essentially, for CI engines, we use fuel injectors. So, this line is not directly going to the engine; certainly, it is going to the engine, but the fuel will now go to the fuel injector, and from there, fuel will be sprayed into the engine cylinder. So, in the injector, there is a needle, and unit injectors or fuel injectors. So, I will draw here a schematic depiction of the needle of an injector. So, this is the intake manifold and this is the fuel in

to the injector, fuel from the tank. So, this fuel is coming from fuel tank and if I draw now the needle, the needle is having one stem. So, this is the fuel needle. So, this is injector needle.

Now you have studied this and here fuel is sprayed. So, this is the intake manifold. Now, what happens, the fuel that comes from fuel tank that hits the needle and then needle is lifted off and as the needle is lifted off, it is unseated. The normal tendency of the needle will be to remain seated here and this is spring loaded needle. So, when the high-pressure fuel is coming through this line that high pressure fuel is trying to lift the needle and the gap that we will create through that gap fuel will be discharged into this intake manifold.

So, this is the manifold. Now, so what happens, the movement of the needle that we will discuss today. So, essentially to measure the amount of fuel to be discharged into this manifold depends on the measurement of needle lift. So, that we will discuss later in today's class. So, what we can understand that the fuel that comes from fuel tank that high pressure fuel will try to lift the needle.

And as the needle is lifted, the gap that will be created, which is responsible for the pathway of fuel to be discharged into the manifold. Now, this is spring-loaded needle. So, the natural tendency of the needle is to remain seated over here. So, it will again come down. So, when needle is again coming here and it is sitting on the guideways, then the fuel that will return from the fuel tank that must be taken into account. So, basically pipeline would high pressure line, if the gap is closed because of the normal or natural tendency of the needle, because needle will remain seated. Then what will happen that high-pressure fuel should be again returned. So, the return flow must be taken into account to measure the fuel flow rate for or using this technique for the CI engines. So, this is one problematic issues.

Typically, fuel which is coming up to here, that will have little high temperature because this part is also having high temperature. So, liquid fuel when it is coming in contact with surfaces having high temperature. Liquid fuel will gain some temperature and that temperature will be higher. So, if we need to take that amount of fuel for the calculation of fuel flow rate. So, care must be taken to reduce the temperature of the fuel to the supply fuel and that fuel should be connected to the supply fuel line downstream the injector essentially to calculate the exact amount of fuel flow rate. So, this is what is the problematic issue that I have discussed. And another problem is, while measuring this fuel flow rate, using this technique, this surfaces are having relatively higher temperature.

So, liquid fuel might get evaporated and that vapor block also create some problematic issues to measure the fuel flow rate.

So, let us move to discuss about the measurement of air flow. We have discussed about fuel flow rate, then we have seen that a very simple and old method is to place the fuel tank on weighing balance and then to measure or to record the time which is required to consume certain amount of fuel by the engine. Then we have discussed about this particular measurement that is fuel flow measurement using calibrated volume. We have also discussed one problematic issue that is related to the flow of fuel in a CI engine.

So, now let us discuss about air flow measurement. Measurement of air flow is not so easy in the sense because it is very difficult to ensure that the amount of air that would be measured by any measuring device will be equal to the amount of air reaching the engine. Actual measurement of air flow which is very important essentially to calculate air fuel ratio but actual measurement of air flow is not so easy in a sense that the amount of air that we will predict, this engine will take this much amount of air during certain amount or for a certain period of time that amount of air will reach the engine.

So, the amount of air measured by any measuring device is not equal to the amount of air reaching the engine because air leaks into the cylinder or air leaks out from the cylinder. So, air leaks into the engine cylinder, and air can also leak out of the engine cylinder through valve glands. So, though we should make an effort to measure the amount of air that should reach the engine using some device, that quantity, may not be equal—or rather, will not be equal—to the air that would be in the engine cylinder. So, but let us discuss another problem.

The issue is measurement of air flow rate. So, the first problem is, it is not easy to ensure that the air, or the amount of air that passes through the air flow meter, reaches the engine. It actually reaches the engine. So, this is one problem. The second problem is, air flow is highly periodic. If it is a single-cylinder engine, perhaps this aspect you have studied in your undergraduate internal combustion engine course, because we need to supply air through the intake manifold to the engine during the intake stroke only.

If it is a 4-stroke engine, the remaining three strokes are not associated with air movement or air flow. Point 2—that air flow is unsteady and periodic. So, the measurement of air flow, which is unsteady and periodic, is very common for any engine. Air is drawn into the engine cylinder during the intake stroke, while the remaining strokes are not associated with air flow.

So, this is highly periodic and also unsteady. So, the unsteadiness and periodic nature of airflow, which is common for all engines, and if the measurement of airflow is unsteady. So, then, because any measuring device we use is suitable for steady flow measurement. So, knowing a priority that the airflow is unsteady and periodic, using any measuring device or devices.

Measurement of airflow is not very easy. So, that is very common. So, it is not as easy as measurement meters or devices are suitable for steady flow analysis. So, these two problems we have discussed.

Now, let us discuss the set of devices that are shown here schematically. So, you can see that this is a manometer, this is an orifice plate. So, typically, what is done is that this is called a large plenum chamber. So, this plenum chamber is connected to the supply line with an orifice plate at the inlet. So, this plenum chamber is connected to the supply line of air or air supply line which is going to engine with an orifice plate at the inlet. At the inlet of this plenum chamber we have one orifice plate and see this manometer is connected across this orifice plate. So, probably you have studied in your fluid mechanics course this orifice meter is used.

So, now for the measurement of flow, so what you can see, when the air is coming in and the problem associated to this unsteadiness or periodic nature of flow can be elevated if it is a multi-cylinder engine, but even then, some degree of unsteadiness should be there and also air is having less viscosity. So, the amount of air that will be drawn into the engine cylinder will be having some frequency or it will resonate with the engine frequency. So, if that is the case then actual measurement will be affected. So, what is done this big or large plenum chamber is connected to the supply line and this plenum chamber is having one orifice plate at the inlet.

Now, when air is coming through this certainly using this orifice plate or orifice meter, we can measure the flow rate, we can measure the drop of pressure across the orifice plate then, we can measure the flow rate, but the positioning of this plenum chamber will help to ventilate all the unsteadiness that will be there due to air flow. So, air will be drawn into the engine cylinder during intake stroke only while there are three other different strokes. So, unsteadiness will be or unsteadiness can be dampened out together with due to natural frequency of the engine that air mass also will try to resonate.

So, all these things can be dampened out using this large plenum chamber. So, this is what is important. Now, this is a water tube manometer. So, now, the measurement of air

flow rate is not very easy, but on the other hand, the actual measurement of air flow rate is necessary.

So, try to understand: on one hand, the actual measurement of air flow rate is difficult, primarily attributed to the unsteadiness associated with the flow, together with the periodic nature of the flow. But on the other hand, we should measure the air flow rate correctly because only then can we ensure whether the air-fuel ratio should be stoichiometric or not. So, the practice should be to measure the fuel flow rate correctly. If we go to the next slide, to measure the fuel flow rate correctly, let me tell you first, and then if we can calculate the— air-fuel ratio from the exhaust gas analysis, from the fuel flow rate we have already calculated.

If we know the air-fuel ratio from the exhaust gas analysis, then from there, we can quantify what the amount of air should be or what the air flow rate should be. So, if I write here that the most accurate method or means— of evaluating the air flow rate is to measure the fuel flow rate first and determine— the air flow rate by calculating the air-fuel ratio from the exhaust gas analysis. So, this is, what is important—that is why I have mentioned it here.

So finally, we shall discuss the measurement of needle lift. So, if we go back to our previous slide, where we have shown this injector needle. So, try to understand that the measurement or accurate measurement of fuel flow rate is necessary for the accurate measurement of air flow rate that we have just discussed. Also, if we need to measure fuel flow rate accurately, what we need to do is measure the lift of this needle. Today, we shall discuss one technique or one method used to measure the needle lift. The measurement of needle lift.

So, let us discuss the measurement of needle lift. So, the lift of the needle in the injector must be measured accurately to measure the fuel flow rate, which in turn will be used to measure the air flow rate accurately. So, the measurement of needle lift. So, if we redraw this. If this is the needle, Then, these are the guideways. So, fuel flows through this. Also, fuel will flow from the fuel tank. Ideally, fuel is supplied from both sides so that the lift movement should be symmetric and uniform. So, this is the needle. And so, this needle lift is very important. The natural tendency of this needle will be to remain seated on these guideways. So, this is a spring-loaded needle. And high-pressure fuel that comes from the fuel supply line, forces this needle to lift off, and then only this liquid fuel

comes, or is discharged into this manipulative or if it is the engine cylinder. Now, this lift, or needle lift, should be measured accurately to measure the fuel flow rate.

So, number 1) moment at which the needle is lifted from these guideways is the beginning of fuel injection. Number 2) is when the needle again seats on the guideways or lift hits zero, fuel injection stops. So, this is the method. So, essentially, we have to measure the movement of this. So, these are the guideways. So, this is also a guideway.

So, this is what is done. Now, question to measure the needle lift, a frequency modulated system is used. and this frequency modulated system is based on or utilizes the fact that changes in inductance of a coil should be recorded.

That means this frequency modulated system that changes the inductance of a coil. So, essentially this particular system is reliant on the fact that the inductance of a coil should be changed and that should be measured or recorded. So, what is done? To do this, one is an armature is connected to the injector needle. To have this, so basically our objective is to measure this lift of the needle and to do that we will be using frequency modulated system which record the changes of inductance in a coil. What is done essentially an armature is connected to the injection needle then number 2) is the armature extends halfway into the coil of the induction of that particular coil should be recorded. So, at the arbiter extends half way into the coil and number 3) the coil forms part of a tuned circuit that resonates at close to 2 MHz. Point 4), as the needle moves up or is lifted up, what will happen as the needle moves up or is lifted up? Due to the motion of the needle stem, inductance of the coil changes with a consequent change in resonant frequency.

So essentially, you are trying to measure the change in resonant frequency or change in inductance in the coil. As the conduction changes, it will change the resonant frequency also. That is why it is a frequency-modulated system. So, this frequency modulation—so essentially, what will happen, is that we can see the frequency will be changed. If we go back to the previous slide, so this is number 5) the frequency modulation is converted to an analog voltage which is, or that is proportional to needle lift in a uniformly wound coil. So, the coil is uniformly wound, and from there we can measure the needle lift.

So, let me go back to the previous slide. This is essentially the stem. What are the steps? We are using a frequency-modulated system, which essentially relies on the change in inductance of a coil, and that should be recorded. So, what is done? The armature is connected to the injection needle through the stem and and that armature extends halfway into the coil. So, there is a coil which is uniformly wound and halfway of the coil.

So, as the needle is lifting up, so the coil forms part of the tuned circuit that resonates at close to 2 MHz. The coil will resonate. Now as the needle moves up or lifted up, that essentially due to the motion of the needle. So, when high pressure fuel will try to force the needle to move up, that will help the armature to also move and the inductance of the coil will change because armature is halfway into the coil.

And when the induction will change, it will result in a change in resonant frequency and this resonant frequency or frequency modulation is converted to analog. Voltage that is proportional to needle lift, we are trying to understand the amount of needle is lifted by the forcing due to fuel or high pressure or pressurized fuel. So, this lift in essence will try to help us to understand the amount of fuel should be supplied, how much the needle is getting lifted, and what would be the duration. Following this we can calculate the amount of fuel should be injected or supplied to that line.

So, to summarize our today's discussion, we have discussed about several methods of fuel flow measurement. Then we have discussed about air flow measurement method and also, we have discussed about the measurement of needle lift which is very important to measure the accurate fuel flow rate which in turn will help to measure accurate air flow rate. Also, we have discussed several problems associated with the measurement of both fuel and air into the engine cylinder.

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

Thank you.