Course Name: Engine System and Performance
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Lecture – 32

Lec 32: Measurement of volumetric efficiency

I welcome you all to the session on engine system and performance. Today, we shall discuss the measurement of volumetric efficiency. We have studied in our undergraduate internal combustion engine course that the parameter which governs the power output from the engine is essentially the mass flow rate of air, or rather, the amount of air. This is one of the most important parameters. We know very well that if we can supply a large amount of air to the engine cylinder, certainly a large amount of fuel can be burnt, and the power output by the engine would be greater. But we can certainly calculate theoretically the amount or mass flow rate of air to be supplied to the engine based on the displacement volume of the cylinder. Or rather, cylinder design, number of cylinders, speed, and also ambient air temperature and pressure, etc.

But though we can theoretically calculate the mass of air to be drawn into the cylinder per cycle, the actual amount of air that will be drawn into the cylinder will always be less than the theoretically calculated value. The reason is there are several parts that offer resistance to the flow of air. Those parts are the air cleaner, the intake valve, and certainly the design of the intake manifold. Certainly, the design of the intake manifold. So, all these issues should be taken into account when considering the amount of air that will take part in the combustion.

Considering this aspect, one term is defined: the volumetric efficiency, which we have studied in our undergraduate internal combustion engine course. Now, what is the definition of this particular efficiency, the volumetric efficiency?

$$Volumetric\ efficiency = \frac{\text{Actual mass of air drawn into the engine cylinder}}{\text{Theoretically calculated mass of air drawn into the cylinder}}$$

The volumetric efficiency is the ratio of the actual amount of air, or actual mass of air, drawn into the engine cylinder to the theoretically calculated mass of air that should have been drawn into the cylinder during a given period of time. This is essentially based on the displacement volume of the cylinder and the ambient air temperature.

So, the ratio of these two quantities is the volumetric efficiency. Certainly, from the definition of volumetric efficiency, you can understand the actual mass of air or actual mass flow rate of air that will take part in the combustion is always less than the theoretically calculated value. That is why this efficiency is defined. Now, this efficiency, is based on cylinder displacement volume, pressure, and temperature of the ambient air. So, this is what is important to know. Now, again, this efficiency is defined here as valid for unsupercharged engines. What does it mean? If we try to know this quantity for the supercharged engines, then we need to know what we had written over here: pressure and temperature of the ambient air. But for the supercharged engines,—supercharging involves a small compressor. Integrated into the system, and the purpose of that small compressor is to raise the pressure as well as increase the temperature—so, the compression process itself. Now, if we somehow integrate a supercharging unit to any engine, then that engine is called a supercharged engine. For a supercharged engine, we need to know the pressure and temperature of the air in the intake manifold. It is not the pressure and temperature of the ambient air, but certainly the pressure and temperature of the air in the intake manifold. So, that is the difference.

So, now the question is: volumetric efficiency should always be less than 1. Efficiency cannot be 100%—that we have studied in our basic thermodynamics course. So, mathematically, the displacement volume of a particular engine—is V_s, then, the mass of air to be drawn into the cylinder per cycle—is very important. So, this displacement volume is V_s, and if the density of air is ρ_s, then, theoretically, the calculated mass of air,

$$m = \rho_s V_s$$

But then, the actual mass of air should be

$$m_{actual} = \eta_v \rho_s V_s$$

Certainly, η_v is less than 1. So, you can understand: the actual mass of air drawn into the engine cylinder is less than the theoretically calculated value.

So, now, let us look at this particular term, which is volumetric efficiency. So, this is the volumetric efficiency of the engine. We are considering for this mathematical derivation or mathematical form of the volumetric efficiency. So now, the question is if we need to know or quantify volumetric efficiency because we are talking about engine performance.

There are many things we have discussed until now, and those important quantities are directly related to the engine performance. Similar to those quantities, this quantity is also very important to know about the performance of the engine. So, if we need to know about this, what we need to know is the actual mass of air, the actual amount of air, or the actual mass flow rate of air to be drawn into the engine cylinder during a particular cycle. This is very important to know. So now, there are several methods available to measure this quantity, which is the actual mass of air. So, we shall discuss in today's class two different methods used to calculate the actual mass of air, essentially to calculate the volumetric efficiency of the engine. So, let us now discuss these two different methods sequentially. So, if we look at this schematic depiction, then we can see, this particular device which you have studied even in your undergraduate fluid mechanics course, is an orifice meter that you have studied.

So, this is a thin plate orifice used to measure the actual mass flow rate of air to be drawn into the engine cylinder. Theoretically, we can calculate this, and it is a function of cylinder design, displacement volume of the cylinder, speed, ambient air temperature, and pressure. All these things are important. Now, if we look at this schematic depiction, you can see that this thin plate orifice is integrated into the intake manifold. So, this is incoming air.

So, this is incoming air. Now, this air is coming through this tube or pipe or manifold, and going to the engine cylinder. In between, we have this thin plate orifice, and you can see this is a square-edged orifice plate. If I draw here, probably in fluid mechanics, you have studied orifice meters. So, an orifice meter—these are the streamlines. So, the streamlines first, then—so this is the orifice plate, and this is upstream of the orifice meter and this is the downstream side of the orifice meter. Now, if we draw the streamlines, when flow is approaching this small orifice, so in the flow pathway, there is a constricted passage. And the diameter of this orifice, the shape of the orifice is determined based on some reason, because there are some issues, there are some criteria based on which the diameter of the orifice and also the shape of the orifice is determined. Now, when the steam or the flow is approaching this orifice, then streamlines will try to converge with each other, and these streamlines are converging, and again, the trend of converging will continue until this location, if we make it *c*-*c*, after that, again, streamline will diffuse.

So, essentially, to adjust to this change in flow cross-sectional area, streamlines will, converge. And they will keep on converging until this location that is section *c*-*c*, which is known as vena contracta. After that, again, streamlines will diverge. So, say for example, if we take one section 1-1 here, and this is *c*-*c*, and if we apply the mechanical energy balance equation,

$$P_1 + \frac{1}{2}\rho v_1^2 = P_c + \frac{1}{2}\rho v_c^2$$

So, that is the mechanical energy balance equation that you have studied. We are assuming that we are taking the same datum. Now, I will come to this point later on. So, I have drawn this schematic essentially to make you understand that an orifice meter is essentially a flow measuring device, rather a steady flow measuring device, in which there is a sudden contraction in the flow area, and when streamlines are approaching this area or this orifice, they converge, and, convergence continues until this particular location where the minimum area is formed and that minimum area, is known as vena contracta. So, if we look at the schematic depiction that is here in this slide. So, this diameter of the orifice, diameter of the tube, and also there are two pressure taps here.

So, all these are information. The diameter of the orifice is *d*. The diameter of the upstream tube is *D*. And the positions of these two pressure taps are provided in the ASME handbook. So, this is a thin plate orifice meter. And you can understand two pressure taps are there.

And from these two pressure taps, we can measure the pressure drop as the flow passes through the orifice meter. Now, if we apply the mechanical energy balance equation, you can understand. So, that is the very simple expression and I will tell you how it is possible to measure the actual flow rate of air, which will be drawn into the engine cylinder, using this thin plate orifice.

$$v_c^2\left(1 - \frac{v_1^2}{v_c^2}\right) = \frac{2(P_1 - P_c)}{\rho}$$

So, I am taking what you have already learned in your fluid mechanics course. Pressure drop across the orifice plate or orifice meter. Now, while writing this, we are assuming that v_1 is much, much less than v_c, and that is quite obvious also.

Because we know that from the conservation of mass or continuity, as the flow approaches the small gap, then certainly to satisfy mass conservation, velocity will increase. Because assuming that the density remains the same and incompressible fluid flow. So, velocity will increase. And velocity in this particular section, you see where the distance between streamlines is very small, that is the minimum cross-sectional area, so velocity is very high.

And if we consider then, flow velocity at section *c-c*, that is in vena contracta, is much, much higher than upstream flow velocity. If that is the case, then we can write

$$\frac{v_1}{v_c} \ll 1$$

And that is why we have ignored this term and simply we are writing

$$v_c = \sqrt{2\Delta P/\rho}$$

Now, this is the velocity that we have calculated based on the measurement of pressure between these two sections, that is using these two pressure terms.

We have written this equation, but we did not take into account the losses due to fluid friction. So, if we take into account the fluid friction, and if we go to the next slide, then if we know the velocity, the mass flow rate should be the velocity of the fluid multiplied by the area at this location, which is the orifice meter. So, this is the mass flow rate multiplied by density. So, velocity multiplied by area gives the volume flow rate, and multiplying by density gives the mass flow rate. So, that is again based on the pressure drop that we have measured using pressure taps.

But let me tell you one thing: we are calculating this using this equation, and this equation does not take into account the loss due to fluid friction. So, if we need to get the actual mass flow rate, which is our target, we have to multiply this quantity by some coefficient, C_d.

$$\dot{m} = C_d(\rho v_c A_c)$$

And certainly, this quantity should be less than 1, so that we can obtain the actual mass flow rate. Had we not multiplied this quantity by C_d, which is the coefficient of discharge, we would have obtained the ideal mass flow rate, which is not correct.

So, if we go back to the previous slide. So, what we have done today, we have just recapitulated what we have learned in our undergraduate fluid mechanics course, essentially to know the velocity of here in the orifice because the location *c-c* is very close to orifice so you can approximate that, the velocity vc is the velocity of the fluid or flow velocity here in orifice plate itself. So, coming back to the schematic depiction, one important point that i should mention if we try to have the information of actual mass flow rate of air, this device can be used, if we provided a steady flow is ensured. This device that is orifice plate or orifice meter, can be used to measure actual mass flow rate of air with some mathematical calculation that we have discussed, now only.

But, this device can be used provided a steady flow is ensured because this device is, a steady flow measuring device. Now, if we talk about internal combustion engine, you can understand if we talk about four-stroke cycle engine, so out of four different strokes, air is drawn into the engine cylinder during intake stroke only. While remaining are the three strokes, no air is drawn into the engine cylinder.

So, the air flow through the orifice meter or air flow through this intake manifold is highly unsteady, periodic. So, if we need to eliminate or if we need to minimize unsteadiness associated with the air flow, which will be there, which is very much pertinent to this engine system, we have to have a large tank upstream. So that is one of the important issues that you should keep in mind that before using this device, a large tank should be integrated to this device in the upstream side essentially to minimize or essentially to remove unsteadiness associated with the air flow which is very much true for flow of air during intake stroke of an internal combustion engine. So, now question is the size of the tanks should be very large so that unsteadiness can be minimized; it cannot be made zero, but it can be minimized. Typically, a large tank is attached to this device on the upstream side, and the size of the tank should be at least 50 times the displacement volume of the engine.

So, this is what is important to know at this point in time. And as I said, information about '*d*,' which is the diameter of the orifice plate, and '*D*,' the diameter of the tube, and the positions of these two pressure taps are provided in the ASME handbook.

So, a designer should consult the ASME handbook to design this orifice—this thin-plate orifice meter—which will be used or can be used to measure the actual mass flow rate of air. So now, let us solve a numerical problem to illustrate the technique or method we have discussed in today's class. If we solve one numerical problem, that will make you more clear about this particular method. Let me first read the problem statement.

Problem: A four-cylinder, four-stroke engine runs at 1400 rpm. The bore and stroke are 8 cm and 14 cm, respectively. Inlet conditions are 1 bar, 305 K. Calculate the ideal air-breathing capacity of the engine. If the pressure differential across the orifice is 12 cm of water and the density of water is 1000 kg/m^3, Calculate the air velocity through the orifice. The diameter of the orifice is 3.5 cm and the coefficient of discharge 0.65. Calculate the volumetric efficiency.

Solution: So, there are three different parts. Essentially, we need to calculate volumetric efficiency. But to calculate volumetric efficiency, we need to know the actual velocity of air through the orifice and also the air-breathing capacity of the engine. So, let us solve this problem, and it will help us to understand the method in an even clearer way.

If we write here from the data given, we can calculate the total displacement volume. So, if we write total displacement volume equal to 4 cylinders. So, if we calculate the displacement volume per cylinder, then multiply that quantity by 4, it will give you the total displacement volume. So, that equals

$$= 4 \times \frac{\pi}{4}(0.08)^2 \times 0.14 \text{ m}^3$$

$$= 0.002813 \text{ m}^3$$

So, this is for one cylinder, and if we multiply, so this is meter cube. So, if we multiply with 4, then it would be the total displacement volume. So, if you calculate it, the quantity that we will get is 0.002813 m^3. So, this is the total displacement volume.

Now, see this total displacement volume. Theoretically, we can have mass flow rate into the engine cylinder. If it is a single-cylinder engine, it is the displacement volume into the density of the air. So, this quantity, total displacement volume, is the ideal volume offered by the engine.

So, now, displacement volume is in meter cube. So, we can have volume flow rate. So, this is a four-stroke engine. So, a four-stroke engine means in one cycle, there are two revolutions.

So, if we calculate number of cycles per second equal to rpm divided by 60 that is rps into there are two revolution.

$$= \frac{1400}{60 \times 2} = 11.66 \frac{1}{\text{s}}$$

$$= 0.002813 \times 11.66 \text{ m}^3/\text{s} = 0.0328 \text{ m}^3/\text{s}$$

So, that is the capacity of ideal air breathing. So, that is the ideal air breathing capacity of the engine that is the answer of this first part, that of this question.

Now, if you go to the next slide, but this is the ideal or theoretically calculated, but actual should be always less than the theoretical one and that is why we are trying to calculate. So, inlet air density, we have to know from the given thermodynamic state. That is, pressure is given, Temperature is given.

$$\rho_i = \frac{P_i}{RT_i} = \frac{1 \times 10^5}{287 \times 305} = 1.1424 \text{ kg/ m}^3$$

The unit is very important. So, we have calculated the density of incoming air based on the thermodynamic state given in the problem statement—inlet conditions are 1 bar and 305 K. So, if we go to the next slide, what can we do next? As we discussed in today's class, if we need to calculate the actual mass flow rate of air—if we go back to the previous slide—we need to understand the pressure drop across the orifice plate.

$$\Delta P = \frac{12}{100} \times 1000 \times 9.81 \text{ Pa} = 1177.2 \text{ Pa}$$

So, it is coming as 1177.2 Pa. So, this is the pressure drop. Knowing this, we can calculate the air velocity through the orifice,

$$V_a = \sqrt{2\Delta P/\rho_i} = \sqrt{2 \times 1177.2/1.1424} = 45.39 \text{ m/s}$$

So, we have calculated it. So, the answer to the second part of this question is 45.39 m/s.

Now, knowing the air velocity through the orifice, we can calculate the actual mass flow rate of air. So, let us make an effort to calculate this. First, let us calculate the actual volume flow rate of air, which equals the,

$$= C_d \times V_a \times A = 0.65 \times 45.39 \times \frac{\pi}{4}(0.035)^2 = 0.0283 \text{ m}^3/s$$

So, if we calculate this, it is coming as 0.0283 m^3/s, so this is the actual volume flow rate of air. Now, if we go back to the problem statement or in fact we have already calculated the ideal air breathing capacity that is ideal volume flow rate of air so theoretically volume flow rate of air per second was 0.0328 meter per second that we can see from here. So, this is the theoretically calculated volume flow rate of air and we have actual volume flow rate of air. So, now, we can have the volumetric efficiency,

$$\eta_v = \frac{0.0283}{0.0328} = 86.49\%$$

It is 0.8649 or 86.49% that is the volumetric efficiency. So, this is what we wanted to calculate through this numerical problem, volumetric efficiency.

Try to understand we have discussed about the method consistent with thin plate orifice meter to calculate actual volume flow rate of air and we have solved one numerical problem essentially to illustrate that method and we had seen it is possible to calculate actual volume flow rate of air through the orifice which in turn will give us the volumetric efficiency.

So, now let us discuss the second method, which is also used to measure volumetric efficiency, and that method is essentially based on the analysis of dry flue gas or hot flue gas. So, using this method, we can also calculate volumetric efficiency. Again, to illustrate one problem before solving it, let me briefly describe this method. So, in this method, we can measure volumetric efficiency provided we know the mass flow rate of fuel and also the composition of the fuel. So, this is the typical layout that you can see from the schematic depiction, and this method is used to measure fuel flow rate and also the analysis of dry flue gas. So, in this schematic depiction, you can see that in this engine, fuel is supplied from this fuel tank, and there is a burette which is used to measure the fuel flow rate.

Air is coming from this air box, and we can also measure the air flow rate. Now, the exhaust gases that come out from the engine can be taken through this smoke meter and finally through the exhaust gas analyzer to analyze the composition of the fuel and the composition of the exhaust gases. And from that composition, we can estimate the volumetric efficiency. Let me solve one numerical problem to illustrate this method first.

So, as I told you, this method is based on the analysis of dry flue gas or hot flue gas, but for this particular method, we need to know two important quantities. One is, the mass flow rate of fuel, and number two is the composition of the fuel. So, these two are important to know the volumetric efficiency using this method, is dry flue gas analysis or hot flue gas analysis. Now, let me solve one. Essentially, we have to analyze hot flue gas or dry flue gas or the combustion gases or exhaust gases that come out from the engine. Based on this analysis, we can quantify volumetric efficiency, provided we know the mass rate of fuel and composition of fuel. So, let me solve one numerical problem. So, let us first read this problem statement.

Problem: A single-cylinder, four-stroke engine runs at 500 rpm. Its displacement volume is 6500 cm^3, and it produces 22 BHP with a specific fuel consumption of 0.24 kg/BHP hr. Calculate the rate of fuel consumption by the engine. If the inlet charge density is 1.2 kg/m^3, calculate the ideal mass of charge that can be swallowed by the engine per second. The fuel has a composition (on a mass basis) of 86% carbon and 14% hydrogen. The percentage composition (on volume basis) of dry exhaust/flue gas (*dfg*) is 10.3% CO_2, 12.4% O_2, and the rest is nitrogen. Calculate the volumetric efficiency of the engine.

Solution: So, let me solve this problem because solving this problem will help you understand how this particular method works to calculate or predict volumetric efficiency. So, if I solve this problem, what is given is, the engine produces 22 BHP (brake horsepower) with a specific fuel consumption of 0.24 kg/BHP hr. So, let us define what BSFC is,

$$BSFC = \frac{mass\ flow\ rate\ of\ fuel\ \text{(kg/hr)}}{BHP\ \text{(kW)}}$$

$$0.24 = \frac{mass\ flow\ rate\ of\ fuel\ \text{(kg/hr)}}{22}$$

So, from there, we can calculate the mass flow rate of fuel. So, from there, we can write the rate of fuel per cycle consumption by the engine equals

$$= 0.24 \times \frac{0.24}{3600} = 0.001466\ \text{kg/s}$$

So, this is what we can write. So now, next, we should calculate. It is written that or it is given, if the inlet charge—now, the question is—you have studied about charge essentially in the context of SI engine. Air-fuel mixture is drawn into the engine cylinder, which is known as charge. Otherwise, typically, it is air. But nowadays, even for modern engines, that it is not only pure air that is drawn into the engine cylinder. For multi-port fuel injection systems, it is this charge—that is, air-fuel mixture—that is drawn into the engine cylinder. So, charge is nothing but air-fuel mixture or sometimes it is pure air as well. So now, we have to calculate the ideal mass of charge that can be swallowed by the engine per second, given the density or charge density is 1.2 kg per meter cube. So, if we go to the next slide, then we can write the ideal mass of air or charge that can be swallowed by the engine equal

$$= 6500 \times 10^{-6} \times 1.2\ \text{kg}$$

$$= 6500 \times 10^{-6} \times 1.2 \times \frac{500}{60 \times 2} \text{ kg/s}$$

$$= 0.0325 \text{ kg}/s$$

So, this should be kg per second. So, if we calculate it, it is coming as 0.0325 kg per second. So, this is basically, the ideal mass of air that can be drawn into the cylinder by the engine.

So now, if we talk about dry flue gas (*dfg*), we consider 1 k mole, of it. So, we consider 1 k mole of dry flue gas, and then in the problem statement, it is given on the volume basis: 10.3% CO_2, 12.4% O_2, and the rest is nitrogen. So that means if we go to the next slide, then we can have 0.103 k mole of CO_2, 0.124 k mole of O_2, then,

$$(1 - 0.103 - 0.124) = 0.773 \text{ k mole of } \mathrm{N_2}$$

So, this is the analysis of dry flue gas. So now, if we calculate

$$\frac{\text{kg of } dfg}{\text{k mole of } dfg} = (0.103 \times 44 + 0.124 \times 32 + 0.773 \times 28) = 30.14$$

So, this is coming as 30.14. So, one k mole of dfg contains 30.14 kg of dfg. So that information we got it. Now, what we can see, if we go to the problem statement in the dry flue gas, carbon is present in the form of carbon dioxide that is given.

Mind it, nitrogen is given, but assuming that no NOx formation is there. So, nitrogen is there only in the, N_2 form itself. No NOx is formed. So, if we go to the next slide, then, in the dfg, carbon is present in the form of CO_2 and reaction is C + O_2 then CO_2.

So, you can understand from this that

$$\frac{\text{kg of Carbon}}{\text{k mole of } dfg} = 12 \times 0.103 = 1.236$$

So, now let us write some chain kind of rule that is

$$\frac{\text{kg of } dfg}{\text{kg of fuel}} = \frac{\text{kg of } dfg}{\text{k mole of } dfg} \times \frac{\text{k mole of } dfg}{\text{kg of Carbon}} \times \frac{\text{kg of Carbon}}{\text{kg of fuel}}$$

Try to understand. We said that following this method, we can calculate volumetric efficiency if we know about two things: one is mass flow rate of fuel and composition of fuel. So, from the composition of fuel, we will see, but we know the kg of fuel. That is very important to know. So, we can write straight away. The fuel composition has given. So, fuel composition is 86 percent carbon and 14 percent hydrogen. So, that means if we talk about 1 kg of fuel, it contains 0.86 kg of carbon; that is the fuel composition. So, try to understand: we wanted to have two things. One is the mass flow rate of fuel, and the other is the composition of fuel. So, the composition of fuel is given.

$$\frac{\text{kg of } dfg}{\text{kg of fuel}} = \frac{30.14 \times 0.86}{1.236} = 20.971$$

So, knowing this, let us now consider the nitrogen mass balance. Now, consider the nitrogen mass balance, and if we consider, the nitrogen mass balance and assume no NOx formation. So, we can write kg of nitrogen that is from air—only nitrogen will come from air—by kg of fuel. Essentially, whatever nitrogen we are getting from the air, if that nitrogen is not taking part in NOx formation, then that nitrogen will be there in the *dfg* also.

$$\frac{\text{kg of } \mathrm{N_2} \text{ (from air)}}{\text{kg of fuel}} = \frac{\text{kg of } \mathrm{N_2} \text{ (in } dfg)}{\text{kg of fuel}}$$

$$= \frac{\text{kg of } \mathrm{N_2} \text{ (in } dfg)}{\text{k mole of } dfg} \times \frac{\text{k mole of } dfg}{\text{kg of } dfg} \times \frac{\text{kg of } dfg}{\text{kg of fuel}}$$

$$= (0.773 \times 28) \times \frac{1}{30.14} \times 20.971 = 15.059$$

So, if we do it, then essentially, we are getting that. kg of nitrogen that is coming from air by kg of fuel equals 15.059. So, from assuming that, now we have to assume that dry air contains 76.8% nitrogen. So, that is there in the atmospheric air nitrogen. So, there we can write,

$$\frac{\text{kg of dry air}}{\text{kg of } \mathrm{N_2}} \times \frac{\text{kg of } \mathrm{N_2}}{\text{kg of fuel}} = \frac{\text{kg of dry air}}{\text{kg of fuel}}$$

$$\frac{1}{0.768} \times 15.059 \approx 19.60$$

$$\frac{\text{kg of dry air}}{\text{kg of fuel}} = 19.60$$

So, the fuel flow rate into the cylinder, if we go back to the previous slide, the fuel flow rate to the cylinder is this, based on the BHP power developed by the engine. So, if we know the fuel flow rate is 0.001466, now we have this ratio.

So, we can write that the air flow rate equals

$$actual\ air\ flow\ rate = 19.60 \times 0.001466 = 0.0287$$

Now, this is basically the actual air flow rate. So, this is the actual air flow rate which is needed to burn the quantity of fuel that will produce 22 BHP.

So, then from there we can calculate volumetric efficiency

$$\eta_v = \frac{0.0287}{0.0325} = 0.8845 = 88.45\%$$

So, this is the volumetric efficiency.

So, we have discussed the measurement of volumetric efficiency, which is very important to know because if we supply more air to the engine, more fuel can be burnt, and the power output will be higher. But there are some restrictions provided by the air cleaner, the intake manifold, inlet valve, all these parts, accounting for resistances from all these parts, the actual airflow rate to the engine cylinder should always be less than the theoretically calculated value, and hence volumetric efficiency is defined. Now, before, concluding today's lecture, let me tell you one thing: the factors which really, affect the volumetric efficiency. So, for the sake of completeness, the factors affecting the volumetric efficiency. So, number one is that you can readily understand the density of the fresh charge or air. After arrival in the cylinder, because when the charge arrives in the cylinder, the hot wall of the cylinder will have some heat transfer from the wall into the fresh charge. It will reduce the density and essentially it will reduce the amount of air drawn into the engine cylinder. And volumetric efficiency will drop. Number two is the pressure and temperature. The pressure and temperature of the exhaust product in the clearance volume. So essentially, if the clearance volume pressure is higher, then when the intake stroke occurs, the pressure inside the combustion gases, which will be in the clearance volume, will create some resistance to the incoming fresh air charge. So essentially, if this is the case, then volumetric efficiency should be reduced. So that is also very important. So, ideally, the pressure and temperature in the clearance volume should be such that they do not create too much hindrance for the incoming air to enter the cylinder. There is, the design of the intake and exhaust manifolds, and the final point is the timing of the intake and exhaust valves. So, the design of the intake and exhaust manifolds is very important. The intake manifolds should be designed so that they do not create huge resistance to the flow of incoming air. The second thing is the exhaust manifold design should allow easy escape of combustion gases from the engine cylinders.

So those are the design criteria. Now, the timing of the intake and exhaust valves is also very important. If the intake valve opening and closing are done properly, certainly the actual mass needed to burn the fuel can be drawn in. Similarly, exhaust valves should open and close in time to allow combustion gases to escape from the engine cylinder. Otherwise, it will try to dilute the fresh charge, which will be drawn into the engine cylinder during the intake stroke, and this in turn will reduce the volumetric efficiency.

So, if we summarize today's discussion, we can say that we have discussed the measurement of an important quantity: volumetric efficiency. We have discussed two different methods. We have solved two numerical problems to illustrate the methods we discussed in today's class. Thereafter, we have listed a few factors that affect volumetric efficiency.

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

Thank you.