Course Name: Engine System and Performance
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Lec 12: Components Involved and Numerical Problems: Energy Transfer

I welcome you all to the session of engine system and performance. And before coming to our discussion on today's topic, let me discuss one important thing that we have been discussing for the last two lectures. That is the transport of energy from the engine cylinder. And we have seen that energy should be transferred from the engine cylinder knowing fully that we are giving or we are supplying some energy which is chemical energy. And even after supplying certain amount of energy, we are converting that energy into useful work.

Though the direct conversion is not possible still we are trying to remove certain amount of energy from the engine cylinder essentially to save engine components from excessive heating from their melting and other mechanical failures. We had discussed out of total energy that we are going to supply to the engine, only a part of that engine is utilized or available at the shaft. Remaining energy needs to be transferred from the engine cylinder to the ambience or we need to supply coolant as well to remove substantial amount of energy because transfer of energy from engine cylinder into the ambience.

I mean the amount of energy that we need to transfer that we need to remove from engine if we need to rely on the convective transport from the engine or cylinder wall into the ambience. Then we need to have several other complex arrangements like extended surfaces and we really do not know what should be the length, what should be the area of those extended surfaces to have adequate or required amount of energy transfer. So, if we recall total energy that $\dot{Q}_{loss}$ that we need to transfer from the engine that is, say loss is

$$\dot{Q}_{loss} = \dot{Q}_{coolant} + \dot{Q}_{loss,exhaust} + \dot{Q}_{oil}$$

That is what we have discussed. We had seen this is 2 to 10 percent, that is even 5 to 15 percent and that is 10 to 30 percent. We have discussed that transfer of energy by oil that is lubricating oil.

There are a few places or spots in the engine block where integration of the cooling system is not so easy, like the piston face. The piston face is exposed to the maximum temperature of the engine cycle. During the combustion process, the maximum temperature develops, and the piston face is exposed to that maximum temperature. So, what is done essentially is that lubricant is splashed over the piston face, which in turn removes a certain amount of heat from the piston face. That part is there. We have discussed this part in the previous class.

Transport of energy by coolant, which is circulated through the cooling water jacket. Essentially, heat transfer in the combustion chamber is something we have discussed. When we discussed heat transfer in the combustion chamber, we saw the transfer of energy from the engine wall or cylinder wall into the coolant. There, we also discussed that the entire or total length of the engine cylinder is not surrounded by the cooling water jacket. Some parts or portions are not covered by the cooling water jacket, so heat is transferred directly from the outer wall of the cylinder to the ambience. That is convective heat transfer, which we have discussed. Now, what is important to know again is the loss of energy through the exhaust manifold or exhaust gases.

If you try to recall, we have mentioned the exhaust valve, intake manifold, spark plug, and piston face. All these spots, all these places, have high temperatures. But, as I mentioned today, due to the lack of integration of the cooling system, it becomes very difficult to remove heat from these areas. Today, we shall discuss that when exhaust gases leave the combustion chamber, they take away a certain amount of enthalpy from the system. Also, when gases leave, chemical energy is also lost. So, some amount of energy in terms of enthalpy and chemical energy is lost.

Through the exhaust system, that is when exhaust gases are leaving. Now, the question is: when exhaust gases are leaving through the exhaust manifold. The exhaust manifold, is essentially a pipe or tube—so the tube wall or pipe wall will be heated up. So, is there any way to remove a certain amount of heat from the exhaust manifold wall so as to increase its life and also to prevent that particular part from excessive heating? Together with, what we have discussed briefly—that the intake manifold or intake system also facilitates the removal of a certain amount of heat that develops or is generated due to combustion. So, whether heat removal by the intake manifold is adequate or not—even if it is adequate—then how, or in what capacity, heat transfer or heat removal by the intake manifold is important for an engine.

So, we will discuss these two parts today, and then we will solve a numerical problem. So, let us first discuss heat transfer in the intake system. So, two questions we should—or rather, we would like to address today: whether or not the intake system facilitates in removing heat that develops due to combustion, and even if the intake system is able to remove or transfer a certain amount of heat, then in what capacity.

Let me draw the schematic diagram. So, if we draw the engine, So, this is the exhaust valve. This is the intake valve. This is TDC, and this is BDC.

So, the piston between these two locations, that is what we have discussed so many times. As such, you have studied this in your internal combustion engine course. So, this is the intake manifold, and this is the exhaust port or manifold. Now, you can readily understand that this is the combustion chamber, the combustion space. So, because of the combustion, the rise in temperature is of the order of 3000 K, which is what we have discussed. So, you can easily understand that the spark plug will be heated up, and the exhaust manifold will be heated up because eventually, combustion gases will leave through the exhaust valve and then the exhaust port. Also, because of this location, the intake system will be heated up due to the rise in temperature during the combustion process. So now, as I told you, due to the lack of integration of a cooling system, we really cannot transfer heat from this part, using coolant.

So, the question is, because of this combustion, the intake system will be heated up. And if we really do not remove heat from the intake system, then the intake system is basically the intake manifold. So, the intake manifold, intake valve, together with—or also, though carburetion is obsolete—the throttle valve will be there, and the carburetor will be there. So, considering all these parts or all these parts together, they form the intake system.

Now, because of the location, the heat rise due to the combustion process will also heat up the intake system. Then, the pipe temperature will increase—the pipe of the intake system, the intake manifold, and the intake valve temperature will increase. If we do not have a provision for cooling supply, then certainly, the rise in temperature of the wall of the intake system will lead to overheating of that part, melting of that part, and several other mechanical issues. So, when we are supplying air or when air is drawn into the engine cylinder during the intake stroke for a CI engine, or when it is air plus fuel, that is called the charge for an SI engine. Incoming air or incoming airflow—air-fuel mixture.

So, flow of incoming air or flow of charge will facilitate some sort of heat transfer from wall of the intake manifold. to the incipient stream by virtue of forced convection. Because when piston comes down from TDC to BDC pressure force inside the engine cylinder will allow certain amount of air if it is CI engine air fuel mixture. If it is SI engine to be drawn into the engine cylinder. So, flow will be there. That incipient flow or flow of air or flow of charge will facilitate to have or to transfer or to remove certain amount of heat from the heated wall of intake system to the stream itself.

Now question is the incipient stream will take away certain amount of heat from the heated wall that way. We can have certain amount of energy transport or energy transfer from the combustion chamber itself. So, because of combustion, the system will be heated up, wall temperature will increase and that temperature will be taken away by the incipient flow or incipient stream of air or air fuel mixture. So, indirectly, we can have transfer of energy which will develop inside the combustion chamber because of the combustion. By the air stream, now question is when incoming air or incoming charge temperature will increase, this is again sometime or this become favorable for the combustion. Because if we can increase preheating of air or preheating of charge, not sometime, if we have proper design, to some extent preheating is necessary, preheating of incoming air or preheating of charge.

Question is if transfer of energy or transfer of heat from the wall of the intake system to the incipient stream is maximum, then in the intake system itself, fuel will try or fuel will evaporate. The moment fuel evaporates. Again, evaporative cooling will be there. So, essentially transfer of energy from the wall into the incipient stream will be there due to normal forced convection. Receiving heat, some fuel will evaporate in the intake system itself and then evaporative cooling will be there.

The question is this: evaporative cooling of fuel, evaporation of fuel droplets, or some fuel. In the intake system itself, there are some merits and demerits. If we go to the next slide, heat flows from the hot wall by convection. That will be there, that is

$$Q = hA(T_{wall} - T_{gas})$$

So, this is the convective heat transfer coefficient of the incipient stream air/charge, this is the surface area, the area which will be involved for the removal of heat. So, this is basically the expression of that very easy. Now, the question is, the consequence of convective heating. The incipient air stream or incipient airflow mixture by the heated wall of the intake system. So, it has, some advantages and some disadvantages.

The advantages are that preheating is necessary, that is, if we can increase the temperature of air, that will increase. It will facilitate efficient combustion inside the combustion chamber. On the other hand, disadvantages are there because, some fuel droplets will evaporate in the intake system itself. Now, if fuel droplets evaporate, evaporative cooling will be there, which is also some sort of advantage. But the disadvantage is there because, first of all, increasing the temperature of air will reduce the density of air. And then, if we basically increase the temperature of the air-fuel mixture or air by this convective transport of heat from the heated wall of the intake system, then fuel will evaporate, and then fuel droplets will. I mean, occupy or fuel droplets will displace air. So, basically, when fuel evaporates, that will displace air. So, essentially, the reduction of air density or density of air due to high temperature, together with the displacing of air by fuel evaporation, will reduce air intake. That is the disadvantage.

So, maybe instead of getting the required amount of air for efficient combustion in the combustion chamber, the air that will reach is less. So, it has a sort of disadvantage. So, that we have discussed. Now, this is all about the transfer of energy, transfer of heat, or removal of heat by the intake system.

That means, if you have understood properly, what we can say is that because of this combustion process, rather high temperature will develop, which will heat up the intake system. And since the intake system or the intake wall of the intake manifold will be heated up, when air flows, convective transport of heat will occur from the heated wall into the incoming stream, which will in a way, that will increase the temperature of the incoming air. It will promote or facilitate efficient combustion, though it will have some disadvantages that we have discussed. But in a way, indirectly, the intake manifold is also helping to remove a certain amount of heat that will develop due to the combustion process. So, now let us discuss the kind of heat transfer in the exhaust system.

So, if we go back to the previous slide, we can see this is the exhaust system. So, we have discussed that part is, a very critical part. That system is a very critical system because that part will always be in contact with hot gases. Though, combustion will be there, combustion is just, a cyclic process because in a cycle, combustion will occur in one stroke, and the remaining strokes are idle strokes. But still, during combustion, an excessive rise in temperature will occur, and that temperature will heat up the system.

In the next stroke, when combustion gases leave through this path, the hot gases will again try to increase the temperature of combustion, that system. So that part is, a very critical part, but again, I am repeating, we really do not have the provision of having a cooling system there. So, the lack of integration of a cooling system in this area, makes the scenario even more difficult, and that way, we have to have some arrangement so as to remove a certain amount of heat from that part, and the melting or possible mechanical failure of this part can be prevented or attenuated. So, let us discuss now. What you can see, is that through this pipe or system, essentially, that is the intake manifold.

So, this is the exhaust manifold, and this is the exhaust valve. So, gas flow will be there. So, can't we apply a normal forced convection model to estimate the qualitative amount of heat that will be taken away by these gases?

So, basically, this wall will be heated up because of the combustion process. Now, when combustion gases are leaving, maybe those combustion gases can take away a certain amount of heat from the exhaust valve as well as from the wall of the exhaust system. A normal forced convection flow model, but we can apply a normal forced convection model with some modification. The modification is there because the flow of combustion gases is not steady. The flow is cyclic rather than pulsatile. So, that means we can apply a normal forced convection model with some modification, that is, the flow is pulsatile because, the flow will only be there during the exhaust stroke, and during the remaining three strokes, no flow will be there.

So, that means we can apply and that too when piston will be coming back from BDC to TDC, we can assume the flow will remain more or less steady, but in a cyclic over an engine cycle. This flow is pulsatile. Over an engine cycle, we have to consider. So, we can modify normal force convection model, as to take into account the pulsatile nature of the flow to estimate the heat transfer from the heated valve to the outgoing gas flow.

Now, one modification is there, as it is not possible to have a cooling system in this part. One, arrangement which is typically considered for automobile engines and also for large stationary engines. What is done, this exhaust valve is, having or exhaust valve typically in automobile engines and large stationary engines, exhaust valve is used. Exhaust valve has hollow stem and that stem contains liquid sodium. So that is the modification.

So, for automobile engines and large stationary engines, exhaust valve has hollow stem containing liquid sodium. So, let me discuss why do we need to keep liquid sodium and keeping liquid sodium does it help to remove more heat. So, that I will discuss.

So, basically exhaust system is having 400 to 600°C temperature for SI engine large, but it is having 200 to 500°C for the CI engine. That is when there is a steady state flow of exhaust gases, combustion gases, rise in temperature of this part for SI engine is 400 to 600°C. Whereas temperature rise of this part for a SI engine during steady state flow of exhaust gases is in this range 200 to 500 °C. So essentially you have to remove temperature so as to the system can run for a longer time.

And we can prevent mechanical failure of these parts. There are many parts, exhaust valve, valve stem, exhaust manifold wall, all this. So now question is, this is very important. I have written over here that for automobile engine and large stationary engines, exhaust valve has hollow stem containing liquid sodium.

Now, in which capacity liquid sodium will help to remove better heat. So, if we have hollow stem that is essentially you are trying to increase the area. So, it will hollow stem help to have more conductive transport of it. Now, we are supplying liquid or you are keeping liquid sodium in the hollow stream and that liquid sodium employs phase chain heat transfer.

So, basically, about heat pipes. The concept of a heat pipe is employed over here since the hollow stream contains liquid sodium. So, liquid sodium means we are trying to have or employ, a heat pipe in the system. Liquid sodium, when in contact with the heated part, will evaporate and then condense back to liquid at the low-temperature part of the exhaust manifold. And since, phase-change heat transfer is more effective than normal conduction, phase-change heat transfer is so effective that it can remove heat of the order of 4000 watt per meter square surface area. Keeping liquid sodium in the hollow stem will also, follow phase-change heat transfer. And if we had not considered the liquid sodium in this hollow stem, only conductive transport of heat would occur through the hollow stem.

But by keeping this liquid sodium, we are, in a way, trying to employ phase-change heat transfer, which is more effective in removing heat, which is of the order of 4000 watt per meter square. The effective conduction of this component, that is, the hollow stem, will be greater, and that way, we can remove a certain amount of heat from this system, that is, the exhaust system. So, now let us solve a numerical problem to illustrate the concept that we learned in the previous class, that is, heat transfer in the combustion chamber. So, let me read out the problem statement here first. So, the problem statement is like this.

Problem: A 2-liter, four-stroke SI engine operating at 2400 rpm using gasoline has 4 cylinders and volumetric efficiency of 80%. The engine's bore (b) and stroke length (s) are related as

$$b = \frac{s}{1.05}.$$

At a given temporal instant of the engine cycle, the gas temperature in the combustion chamber is $T_g = 1900$°C, while the cylinder inner wall temperature is 180°C.

Calculate the convective heat transfer rate to the cylinder inner wall at the temporal instant. Dynamic viscosity and thermal conductivity of gas at 1900°C are 5×10^{-5} Pa-s and 0.085 W/mK, respectively. C_1 = 0.085, C_2 = 0.80.

Essentially, if you try to recall, these two constants are needed to calculate the Nusselt number knowing the value of Reynolds number. So, we have to solve this problem. Try to understand; we have discussed that the temperature of the inner wall of the cylinder will be within this range: 180 to 200°C. And the rise in temperature in the combustion chamber is of the order of 3000 K. What we can see from the statement is also in that range.

Essentially, what do we need to do? We need to know a qualitative estimate of convective heat transfer or heat transport from the gas to the inner wall of the cylinder. So, let us solve the problem.

Solution:

So, first of all, we have to calculate the displacement volume,

$$V_d = \frac{2 \times 1000}{4} = \frac{\pi}{4} b^2 s = \frac{\pi}{4} \left(\frac{1}{1.05}\right)^2 s^3$$

$$s = 8.886 \text{ cm}$$

So, displacement volume per cylinder because the engine we are discussing today is a multi-cylinder engine because it has 4 cylinders. So, the displacement volume per cylinder is V_d. Now, what is V_d? It is given as 2 liters.

So, if we compare these two, then we will get from here, what about *s*? So, *s* is, 8.886 cm.

Once we calculate the stroke length, if we go to the next slide, we can calculate the bore diameter.

$$b = \frac{8.886}{1.05} = 8.463 \text{ cm}$$

So, if we draw the schematic definition, if this is the engine cylinder, the piston is like this.

So, though there is a small clearance or small gap between the inner wall of the cylinder and the piston's outer wall, but still, we can assume that the piston diameter is as good as the bore. So, this is the engine bore. So, this is bore b, and this is the piston diameter. So, this is d_p. b is bore, d_p is piston diameter. So, the bore is this. We can calculate next the area of the piston face. So, this is the piston face.

Though, there will be a small gap between the cylinder inner wall and the piston outer wall. Rings are provided with the piston to remove friction, rather to increase the life of the piston, as we have discussed. We can approximate d_p as almost equal to b. So, the area of the piston face

$$A_p = \frac{\pi}{4}\left(d_p\right)^2 = 56.26 \text{ cm}^2$$

That equals to 8.463. So, this is the area of the piston face.

Now, why is the area of the piston face needed? That is needed because, we tried to calculate the Reynolds number because to establish the flow characteristics inside the engine cylinder and the underlying heat transfer, we must establish the expression of the Reynolds number and the Nusselt number. And that we could do in the previous class. Inside the engine cylinder.

That is to estimate the convective transport of feed from gas to the inner wall of the cylinder. Now, when we could define the Reynolds number, knowing the area of the piston face. That is why this is important. So, this is A_p. So, now what about the mass flow rate of air into the cylinder?

Because the Reynolds number, if you try to recall, is the mass flow rate of air plus the mass flow rate of fuel divided by A_p. So, that will give the velocity scale into bore divided by μg. So, this is the dynamic viscosity of the gas. In the cylinder. So now we can calculate the mass flow rate of fuel and the mass flow rate of air.

$$\dot{m}_a = \eta_{vol} \times \rho_a \times (V_d)\frac{N}{n}$$

And then if we calculate, if we use the value of volumetric efficiency,

$$\dot{m}_a = 0.8 \times 1.181 \times 5 \times 10^{-4} \times \frac{2400}{2 \times 60} = 9.448 \times 10^{-3} \text{ kg/s}$$

Just you check unit. So, this is kg per meter cube. This is meter cube. Meter cube will get cancelled. And this is revolution per minute. So, you have to convert per second. So, that would be into 60 kg. If you, because this is rpm, revolution per minute, so divided by 60 per second and 2 revolutions, so revolution will get cancelled. So, this is kg per second.

Now, the actual air-fuel ratio is given as 13.05. You can consider air-fuel. The air-fuel ratio is actually equal to 13.05. So, if we know the air-fuel ratio is actually equal to 13.05, we have calculated $\dot{m}_a$. So, $\dot{m}_f$, which is the mass flow rate of fuel per cylinder, will be equal to

$$\dot{m}_f = \frac{\dot{m}_a}{(A/F)_{actual}} = 7.239 \times 10^{-4} \text{ kg/s}$$

If we plug in the value, we will get 7.239×10^{-4} kg/s. So, now knowing the mass flow rate—let me box this. So, the mass flow rate of fuel has been calculated, the mass flow rate of air has been calculated, we know the area of the piston face, we know b, we know the dynamic viscosity, then we can calculate the Reynolds number. So, if we plug in all these values into the Reynolds number formula, that is, Reynolds number equals

$$Re = \frac{\left(\dot{m}_a + \dot{m}_f\right)}{A_p} \frac{b}{\mu g} = 3060.5$$

So, if we plug in the value of the mass flow rate of fuel, which is this, and the mass flow rate of air, which is this. So, it is one order less, as it should be. So, that means our calculation is in the right direction, and we have already calculated the area of the piston as this. So, if you plug in all these values, then we will get this Reynolds number.

Now, had we calculated Reynolds number try to recall Nusselt number that will give us an estimate about the qualitative rate of convective heat transfer from the gas to the inner wall of the cylinder so that equal to

$$Nu = \frac{h_g b}{K_g} = C_1 (Re)^{C_2} = 0.085(3060.5)^{0.8} = 52.245$$

We really do not know about h_g that we have to calculate but we know b and then it would be coming as 52.245.

$$\frac{h_g b}{K_g} = 52.245$$

So, that means h_g into b divided by $K_g = 0.085\ \text{W/mK}$, equal to 52.245. So, we will be getting

$$h_g = 52.47\ \text{W/m}^2\text{K}$$

So, this is watt per meter Kelvin by meter. So, this is watt per meter square Kelvin, So, this is watt per meter Kelvin by meter is coming down. So, watt per meter square Kelvin.

So, now, have we calculated h_g. Next, we calculate the convective heat transfer rate, that is, the convective heat transfer rate. From the gas to the inner wall of the cylinder, that is, per unit area if we try to express because we do not have any idea about the area,

$$\dot{q} = \frac{\dot{Q}}{A} = h_g\left(T_g - T_w\right) = 52.47\ (1900 - 180)$$

$$\dot{q} = 90.25\ \text{kW/m}^2$$

So, if you would like to summarize, you can understand this is the amount of basically qualitative. This is not, again, quantification of convective heat transfer that I have already mentioned in the previous class. If we need to quantify convective heat transfer rate, even in the inside the engine cylinder, outside the engine cylinder, we need to go for computation. So, qualitatively, we could calculate convective heat transfer from gas to the inner wall of the cylinder using some correlation based on the Reynolds number and Nusselt number.

And this is coming as 90.25 kW/m^2. So, to summarize today's discussion, we have discussed the role of both intake and exhaust systems to remove a certain amount of heat which develops due to combustion. Thereafter, we have solved a numerical problem just to illustrate the conceptual part that we have learned on heat transfer in the combustion chamber. So, with this, I stop here today, and we shall continue our discussion in the next class.

Thank you.