Course Name: Engine System and Performance
Professor Name: Pranab Kumar Mondal
Department Name: Mechanical engineering
Institute Name: Indian Institute of Technology, Guwahati
Week - 04
Lecture – 11

Lec 11: Components Involved: Energy Transfer

I welcome you all to this session on engine systems and performance. The topic of our discussion today is the energy transfer mechanism from the engine cylinder or combustion chamber and the components involved. If we recall, in the last class we discussed the need for transferring energy from the engine cylinder, and we saw that energy is supplied into the engine through fuel. Fuel contains stored energy within it, and that chemical energy essentially gets transferred or transformed into another form of energy—mechanical energy—which is or will be available at the shaft.

Now, that conversion from chemical energy into mechanical energy is not possible directly. So, what we saw is that combustion occurs, and through that process—which is indeed complex— several thermodynamic processes are involved. To understand combustion better, you need to know two fundamental subjects: thermodynamics and fluid mechanics, as well as heat transfer. So, the energy that remains stored in the fuel—the chemical energy—must be converted into a useful form of energy, which is mechanical energy. As I said, this conversion is not possible directly.

So, essentially, what happens is that chemical energy is converted into heat energy through combustion, and then that heat energy is transformed into mechanical energy, which will be available at the shaft through some mechanical arrangement. As, heat energy is a low-grade energy, and work is a high-grade energy. Essentially, it is not possible to convert heat into an equal amount of work. So, what I mean is, the energy supplied—the chemical energy into the engine—will first be converted into heat, and then again, it is not possible to have an equal conversion. Finally, heat would be converted into work.

So again, there will be some sort of reduction. So, what we discussed in the last class was that the total power generated,

$$\dot{W}_{power} = \dot{W}_{shaft} + \dot{Q}_{loss} + \dot{Q}_{loss,exhaust} + \dot{W}_{parasitic}.$$

That is what we had seen in the last class. This is the useful energy or work available at the shaft.

This is also, to some extent, I should say useful because this is also needed. So, this part is used to run several auxiliary systems like the air conditioning unit, several lights, to run a small pump, all these things.

So, if we look at that, the energy supplied to the engine is

$$= \dot{m}_f Q_{hv}.$$

Mass flow rate of fuel and multiplied by the heating value of the fuel.

So, this is the heating value of the fuel being supplied, and this is the mass flow rate of the fuel. So, out of this energy, which is nothing but the chemical energy remaining stored in the fuel, we are essentially getting this much useful energy. Certainly, this is also used, but that means this part is totally lost. These two parts are lost—loss of energy.

So, this is loss of energy. And what is this? The shaft work is essentially

$$= \dot{m}_f Q_{hv} \eta_b \eta_c$$

So, this is the expression of the useful work available at the shaft. So, that means essentially this minus this. So, this

$$= \dot{m}_f Q_{hv} (1 - \eta_b \eta_c).$$

This is brake thermal efficiency. This is combustion efficiency. We have discussed this aspect in the last class, and that is brake thermal efficiency. So, this amount is of no use. So, that is essentially, if we remove this parasitic load, that is essentially

$$\dot{m}_f Q_{hv} (1 - \eta_b \eta_c) = \dot{Q}_{loss} + \dot{Q}_{loss,exhaust}.$$

Now, this fellow has three subcomponents. So, that means this part is the loss of energy through exhaust gases. That means when combustion gases are leaving from the engine cylinder during the exhaust stroke, those gases carry a certain amount of energy in the form of enthalpy and also chemical energy, and those gases are also removing some energy from the combustion chamber.

But this is $\dot{Q}_{loss}$, that is the part, is significant. It has three subcomponents: it has

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

$\dot{Q}_{coolant}$, that is, we need to supply coolant. If it is a water-cooled engine, we need to supply water through the cooling outer jacket, and that circulation of water carries or removes a substantial part of energy from the combustion chamber or engine cylinder through the wall of the cylinder. And that part is, basically 10 to 30 percent, that is what we have discussed, plus we have $\dot{Q}_{oil}$ and plus we have $\dot{Q}_{ambient}$. $\dot{Q}_{oil}$ is not very high, that is 5 to 15 percent, and this is 2 to 10 percent, and this is 5 to 15 percent.

So, you can understand that Substantial amount of energy will be removed by the coolant from the engine cylinder. What this part is all about? $\dot{Q}_{oil}$. If you try to recall we have discussed that we need to supply lubricants to have in fact we have lubricating system. and that lubricants are splashed over the piston in fact lubricant. I should say lubricant is splashed over the piston face so as to remove certain amount of heat from the piston face itself.

Try to recall in the last class we have mentioned that there are a few surfaces or spots which are having high temperature and those surfaces and spots are piston face, spark plug area, exhaust valve and to some extent intake manifold. So that means the engine should have an arrangement to remove certain amount of heat from the piston face so as to increase the life of the piston. And that is why the lubricant oil is splashed over the piston face. As I said you that combustion is the process through which rise in temperature inside the cylinder is of the order of 3000 K.

If we really do not have, in fact, we should have, proper design and engines should have some arrangement so as to remove substantial amount of heat from the engine cylinder to prevent several components from overheating, to prevent several mechanical components from their possible failure. In fact, to prevent mechanical components from melting in. Over and above, if we really do not transfer adequate amount of heat from the engine cylinder, lubricating system or lubricants will, lost their ability to lubricant or, provides enough lubrication to the system.

Now, what about this ambient? I will be discussing. So, you can understand that we need to transfer this much amount of energy from the combustion chamber. So, let us now discuss heat transfer in the combustion chamber. So, this is very important: heat transfer in the combustion chamber.

Now, the combustion chamber is the place where the rise in temperature is of the order of 3000 K, which is what we have discussed. So, we need to remove a substantial amount of heat to reduce the temperature inside the cylinder. Now, there are three principal modes of heat transfer.

What are those? So, the modes of heat transfer are convection, conduction, and radiation. So, these are the three principal modes of heat transfer. Now, when fuel evaporates inside the combustion chamber as part of the combustion process, that process of evaporation also is involved to some extent with the heat transfer, evaporative heat transfer.

So, this convection, conduction, and radiation—now these three are the three principal modes of heat transfer. Now, let us look into this. It is not that significant, but still, we cannot trivially ignore the radiative transport of heat. So, we have to now look at these two different, or these two principal modes of heat transfer inside the combustion chamber.

So, let us now consider that when we need to—or rather, when the engine is started. During the first few cycles of engine operation, whether it is an automobile engine, a large stationary engine, or a small stationary engine, fresh air is inducted, or if it is an SI engine, a fresh charge is inducted into the combustion chamber. During that time, it may be the case that the temperature of the inducted air or fuel-air mixture is even less than the wall temperature. So, in that case, heat will be transferred from the wall into the inducted air-fuel mixture or air.

But when combustion starts, the temperature increases immediately and becomes so high that convective transport of heat initiates, resulting in the transport of heat from the gases inside the cylinder into the inner wall of the cylinder. And the cylinder wall will have a certain thickness, so from the inner wall to the outer wall of the cylinder, conduction will play an important role. Finally, in the outer wall of the cylinder, a cooling water jacket is incorporated, installed, or integrated. Now, the part of the cylinder which is in contact with coolant will be circulated continuously.

Again, convective heat transport will be there. And finally, the entire length of the cylinder wall won't be under the influence of the coolant. So, a few portions will be directly exposed to the ambient. So, from there, the outer surface of the cylinder wall, heat would be removed again by virtue of convection, but directly into the ambience.

So now, let us discuss this convective transport of heat, or let us identify where convection plays an important role and where conduction plays an important role. So, let us draw the schematic. So, just if we draw the schematic depiction of the engine cylinder. First, that is the intake manifold, so we'll have a spark plug, and this is the piston. Say, this is bottom dead center; this is top dead center. This is the exhaust. This is the intake valve.

So now, if we zoom in on the cylinder wall, so basically, this is the cylinder wall—it has finite thickness, say this is Δx. So, if we take this as the x-direction, now this is the cylinder wall. And a cooling water jacket is provided to take away heat from the cylinder or combustion chamber. So, this is coolant in, coolant out. This is the cooling water jacket, if it is a water-cooled engine.

And now again we will be having, this is the inner wall of the cylinder. So, temperature is T_{w1} and this is outer wall of the cylinder and temperature is T_{w2}. And this is temperature of the gas T_g. We have taken this part only to show the cylinder wall arrangement.

This is the combustion space. So, when combustion occurs, the stage is of the order of 3000 K. Certainly, it is not needed that 3000 K should be transferred, I mean, we need break thermal work.

So, the moment when combustion occurs, the rise in temperature initiates convective transport of heat from the combustion gases to the inner wall of the cylinder.

So, T_{w1} should be within 180 to 200 K. So, that means T_g is of the order of say 1000 K. So, immediately convective transport of heat will initiate or occur from the combustion gas space to the inner wall of the cylinder.

Now, certainly we need to maintain this much temperature at the inner wall of the cylinder, essentially to, keep the cylinder material or other different parts from overheating. So then, from the inner wall of the cylinder to the outer wall, heat conduction will occur because this is made of any material that we have discussed in one of the previous classes. And then finally, can see that these two parts are not in contact with the coolant. So, through which, from these two surfaces, again, heat transfer will occur to the ambient.

And from the outer wall, which is in contact—the outer wall portion that is in contact with the coolant—there again, some convective transport of heat will occur. And that convective transport of heat will be solely dictated or guided by the flow of coolant. So, from the outer wall of the cylinder, convective transport of heat—or convective transport of heat takes place from the, outer wall to the coolant and from the outer wall to the ambient directly. And the convective transport of heat from the outer wall to the coolant will depend on the coolant circulation, flow velocity of the coolant, convective heat transfer coefficient of the coolant, and also the convective transport of heat from the portion which is—or from the portions which are—not in contact with the coolant will depend on the ambient air temperature and also the convective heat transfer coefficient of the ambient air.

So, these are different modes of heat transfer inside the combustion chamber. Again, since the temperature of the gas is too high, we really cannot trivially ignore the radiative transport of heat, which is solely due to the very high temperature difference. So, this is all about a water-cooled engine.

Now, if we try to draw an air-cooled engine. So, if it is an air-cooled engine, you can see. If it is Δx, this extended surface—the fins—these fins are provided to enhance the transport of heat. Because air would flow over these fin surfaces, and that air circulation will allow more convective transport from the outer wall of the cylinder to the air—exactly the same here. So, here again, this is T_{w1}, and this is T_g, and finally, from T_w. So, this is T_w to T_{air}. So, these are basically the two different types of cooling systems we have discussed already. Now, let me discuss the mathematical expression of heat transfer—or, if we really would like to calculate the amount of heat transferred by all these processes, we need to go for computation. Essentially, if we need quantification.

But qualitatively, we can express the amount of heat transferred by all these processes from the engine cylinder into the ambience. So, what have we discussed? First of all, the convective transport of heat would be there from the gas to the inner wall of the cylinder. So, from the gas to the inner wall.

So, if it is $\dot{Q}_1$,

$$\dot{Q}_1 = h_g A(T_g - T_{w1})$$

Heat transfer across the wall. So, this is again $\dot{Q}_2$. If we write,

$$\dot{Q}_2 = KA\frac{\Delta T}{\Delta x}$$

where this

$$\Delta T = (T_{w1} - T_{w2})$$

So, this K is the thermal conductivity of wall material. And this is the convective heat transfer coefficient of gas. And then finally, from the outer wall to to the coolant. So, this is

$$\dot{Q}_3 = h_c A(T_{w2} - T_c)$$

and heat transfer from the outer wall to the ambience, that is

$$\dot{Q}_4 = h_a A(T_{w2} - T_a)$$

So, this surface area, A is not in contact with coolant flow. So, these are the expressions. If we sum up all these expressions, then we can have as such. This is not very significant because if we look at the schematic depiction, only a very small portion or portions are exposed to, ambience. So, basically, if we do not consider even this, but theoretically, we should consider this part as well.

Heat transfer through the cylinder wall per unit area,

$$\dot{q} = \frac{\dot{Q}}{A} = \frac{(T_g - T_c)}{\left[\frac{1}{h_g} + \frac{\Delta x}{K} + \frac{1}{h_c}\right]}$$

So, try to understand: in this expression, we did not consider this quantity. Theoretically, this quantity should also be taken into account when someone is designing the engine block or engine heat transfer—heat management in the engine. But, from the schematic depiction, it was clear that portions which are not in contact with the coolant flow are, rather insignificant, and also convective transport of heat because there is no airflow. So, as compared to the transport of heat by the coolant, that part is trivially or insignificantly small.

So that is why, in this expression, we did not consider that part. So here, all the terms because T_g and T_c. T_c is the coolant temperature.

Now this is the expression. Now the specialty of this transport of heat is this is basically cyclic heat transfer. So, I am writing the word cyclic. Cyclic heat transfer. Why cyclic heat transfer? Because combustion will occur in each and every cycle, and that is also whenever combustion will be there, then only the maximum amount of heat will be transferred. For the remaining other strokes, this much transport of heat may not be needed, so that is why this is cyclic heat transfer. Now I would like to discuss a few important things that here T_g.

Would we like to consider T_g constant? No. T_g will vary across the space of the combustion chamber. So, this T_g is not constant.

It will vary over an engine cycle and across the breadth and width of the combustion space that is within the cylinder. This is very important to know within the cylinder. What about h_g?

This hg is also not constant because it will also vary over an engine cycle. And it will depend on the formation of swirl, turbulence, and also gas motion. Because, the convective heat transfer coefficient, even if we consider coolant flow, the convective heat transfer coefficient of coolant will also depend on the velocity of the coolant flow. Similarly, this convective heat transfer coefficient of gas is not constant; it will vary. Rather, it will greatly vary, largely vary—over an engine cycle.

Quite obvious, that during combustion, convective transport of heat will be there, but when combustion is completed, convective transport of heat would still be there. However, during that time, the convective heat transfer coefficient will not be the same as we should consider when combustion initiates, and it depends on swirl, turbulence, and gas motion. When combustion occurs, the piston reciprocates between these two locations quite spontaneously, and the gas motion inside the cylinder is highly erratic and chaotic. If we could define the Reynolds number, then certainly the Reynolds number would indicate that the flow inside is highly turbulent. So, depending on the even swirl will form, as we have seen—probably you have studied in the internal combustion engine course—that when the main flame front develops, to, increase the speed of the main flame front. We need to, have some sort of, circulatory or swirl motion inside the cylinder. So, depending on all these swirl structures, the, kind of extent of turbulence inside the combustion chamber and gas motion, this convective heat transfer coefficient will vary.

What about thermal conductivity? Thermal conductivity is function of temperature. But this is thermal conductivity of cylinder wall material. So, we can assume this is fairly constant because cylinder wall is having finite thickness and continuously coolant would be circulated to remove heat. So, we can assume that that temperature fluctuation across the length or across the width of the cylinder wall is not that much high as to consider temperature dependent thermal conductivity.

So, this is K, is a function of temperature, but fairly constant, will be fairly constant. What about hc, convective heat transfer coefficient of the coolant? Again, it will depend on the flow velocity of coolant, but we can assume that typically coolant flow is fixed, we can assume that convective heat transfer coefficient of coolant will remain fairly constant.

So, we can assume h_c will remain fairly constant. So, this is very important. Now, why it will remain fairly constant because coolant velocity will remain almost constant. Now, let me tell you one thing because we need to solve a few numerical problems. So, we need to understand the transport of heat not even if we go for quantification.

At least qualitatively, if we need to know the transport of heat due to convection, we should characterize or we should know flow characteristics. So, even for a qualitative estimate of the transport of heat, we need to characterize the flow, the underlying flow, and also the heat transfer. So, to know or to understand flow characteristics and also the associated heat transfer, we must define the Reynolds number and the Nusselt number. To understand flow characteristics and associated heat transfer, we must define Re and the Nusselt number.

What is Re? Because if we define Re, then we can establish flow characteristics and associated heat transfer for different sizes of engines, for different speeds of engines, and all these things. So, why is it important to characterize the flow and heat transfer?

For different sizes of engine geometries and different speeds of engines, that is, piston speed. So, Re is defined as

$$Re = \frac{(\dot{m}_f + \dot{m}_a)B}{A_p \mu_g}$$

So, this is the mass flow rate of fuel plus the mass flow rate of air, that is, the mass flow rate of charge, divided by the piston area. This is the area of the piston face. And this is the dynamic viscosity of the gas inside the cylinder. And this is the bore. So, this is the Reynolds number, and then, knowing the Reynolds number, we can define the Nusselt number.

$$Nu = \frac{h_g B}{K_g} = C_1 (Re)^{C_2}$$

So, this is thermal conductivity of gas inside the cylinder. So, this is thermal conductivity of gas inside the cylinder that can be correlated like C_1 Reynolds number to the C_2, C_1 and C_2 are constants. So, that means defining Reynolds number properly which is very important to characterize flow for different sizes, different geometries and different speed of engine. We also can define Nusselt number which will allow us to characterize underlying heat transfer even for different sizes, different geometries and different speeds of engine.

Until now whatever we could discuss that is convective transport of heat inside the cylinder that is from the gases into the inner or from the gases to the inner wall of the cylinder. Convective transport of heat So basically, the Reynolds number and Nusselt number that we could define that these two numbers are basically for the convective transport of heat inside the cylinder. Similarly, convective transport of heat outside the cylinder can be just a model using normal internal flow convection and from there we also can define a Reynolds number and a Nusselt number.

This convective transport of heat outside the cylinder can be modeled by conventional methods of forced convection, for convective heat transfer. So, and from there we can define Reynolds number, Nusselt number.

Now, finally, I would write that radiative transport of heat inside the combustion chamber. This is also, though it is not very significant, but as I told you, we really cannot trivially ignore it because of the significant change or significant difference in temperature.

$$\dot{q} = \frac{\dot{Q}}{A} = \frac{\sigma\left({T_g}^4 - {T_w}^4\right)}{\left[\frac{1-\epsilon_g}{\epsilon_g} + \frac{1}{F_{g-w}} + \frac{1-\epsilon_w}{\epsilon_w}\right]}$$

So, this is the expression.

As I said, though this amount is not very substantial or very high, but still, because of the significant temperature difference between combustion gas and wall, we have this amount through this mathematical expression. What is this? σ is Stefan-Boltzmann's constant, T_g is gas temperature, T_w is wall temperature. Here, ϵ_g is emissivity of gas, ϵ_w is emissivity of wall. F_{1-2} is the view factor that you have studied in undergraduate heat transfer course between gas and wall. Between gas and wall, let me write instead of writing F_{1-2}, it would be F_{g-w}. So, this is F_{g-w}. So, this is the radiative transport of heat.

So, if we try to summarize our today's discussion, we have just, discussed about the transport or heat transfer in combustion chamber, knowing the amount of heat to be transferred by the coolant, and then we have depicted schematically the arrangement of the components, that is, the wall and also the cooling water jacket and then we have identified several modes of heat transfer for both water cooled and air cooled engine, then we have estimated all components that is heat transfer that is convective transport of heat from gas to the inner wall. Across the width of the wall that is conductive transport of heat then convective transport of heat from outer wall to the coolant and convective transport of heat from outer wall to the ambience directly. And then we have tried to summed up all this, then we got this expression which is cyclic heat transfer. We have identified that convective heat transfer coefficient of gas, conductivity of wall material, convective heat transfer coefficient of coolant, whether they are constant or they will vary. and then we could define Reynolds number based on this convective transport of heat inside the cylinder from there we could define Nusselt number just correlation these two numbers are defined just to characterize the flow and associated or underlying heat transfer for different sizes different geometries and different speeds of engine.

Finally, we could see that if we need to define Reynolds number and also Nusselt number to characterize the convective transport of heat that is flow and convective transport of heat outside the cylinder, we can simply use force convective heat transfer model outside the cylinder and though radiation or radiative transport of heat is not significant as the convective heat transfer is still we could mathematically quantify the expression of this quantity. Expression of this transport of heat and we had seen that due to significant temperature difference between gas and wall sometimes this quantity that is radiative transport of heat may become significant. Now what we could not discuss today is if we look at that the amount of energy which is getting lost or which need to be transferred is through the coolant, through the oil, through ambient, I mean directly to the ambient also. Another significant part is loss of energy or loss of heat through the exhaust gases which we need to know and though intake manifold is integrated to the engine block and rise in temperature because of the combustion is also getting transferred through intake manifold that part we didn't discuss today. So, in the next class we shall be discussing about the loss of energy through the exhaust gases into the ambience and the transport of heat or transfer of heat or removal of heat due to combustion process through the intake manifold.

Whether that heat is directly exposed or directly transferred to the ambience or that heat is again somehow is taken back to the inflow of air or inflow of fuel, that part we'll discuss in the next class. And we have discussed about the transport of energy by the oil that oil is lubricating oil and this heat transferred directly to the ambient that we have discussed today this fellow that q dot 4 because this quantity is not taken into account in this expression but still this is an important quantity and we have quantified. So, with this I stop here today and we shall continue our discussion in the next class.

Thank you.