Course Name: Engine System and Performance
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Lec 41: Engine heat balance

I welcome you all to the session of engine system and performance and today we shall discuss about engine heat balance. But before we go to discuss about this important topic, let us first recapitulate again a few factors those affect the performance of CI engine. If we can recall in our previous module wherein we have discussed about SI and CI engine performance. In that module we have identified a few factors those affect the performance of SI engine and today we shall see that many of these factors also affect the performance of CI engine in the same manner. And let us first identify what are those common factors.

There are two important factors those are very important to be precise, these two factors should be considered by the designer when a designer is designing CI engine for the better performance of the engine as well as smooth operation. So, if we try to write a few common factors, these factors affect the performance of SI mean, these common factors are speed, air consumption, number 3 is compression ratio. So, these three factors, if we can recall we have discussed in details, these three factors affect the performance of SI engine. Now if we know, so these factors also affect the performance of CI engines and we will see in which capacity these factors trigger engine performance. So, we know that if we increase the speed, certainly power output of the engine will increase. That we have discussed in the context of SI engine. Here also, increasing the speed of CI engine will ensure higher power output. So that means these factors is also very important to be considered for the design of CI engine.

Then what about air consumption? We all have understood by this time that certainly, if a greater mass of air is consumed by the engine, a greater amount of fuel can be burned, and engine efficiency will increase and this is true for both SI and CI engines. But in the context of a CI engine, proper use or utilization of air is very important.

And designers should design in such a way that the consumed air, or the amount of air drawn into the engine cylinder, should be used by the engine so as to make it effective for the operation of the engine. Essentially effective use of the consumed air should be ensured. Then, the last one is the compression ratio. So, higher the compression ratio, certainly, the peak pressure or the pressure rise at the end of the compression stroke will be greater. A higher rise in pressure is accompanied by a rise in temperature as well. And that too, when that high-temperature air or charge is combusted, upon supplying fuel or spraying fuel, the temperature rise will be even greater. So, if the compression ratio is high, the power output of the engine will be high, and if you can recall the thermal efficiency expressions for both SI and CI engines, thermal efficiency is a function of r_c, that is, the compression ratio.

So, but the compression ratio cannot be increased beyond certain limit for the SI engine because it will lead to another detrimental phenomenon that is knock. But for the CI engine though knock is not there but constructional issues will be there because engine will be bulky because to withstand that high-pressure cylinder valve should be thicker and that too some constructional problem will be there. All these factors affect the performance of CI engine and designer will select all these factors judicially for the better operation of engine as well as to have maximum performance. So, in addition to these three factors, here two another important aspect and those aspects are really important for the operation of CI engine.

Two important factors those affect the performance of CI engines. So, number 1) is, this is known as injection timing. Injection timing means in particular for the CI engines what is done? Air is compressed during compression stroke and towards the end of the compression stroke fuel is spread into the combustion chamber or in the cylinder. So, the injection time over which fuel is spread into the cylinder is very important essentially for the peak pressure to be developed and also total power output certainly. So, this injection time essentially refers the time duration over which the required amount of fuel must be injected or sprayed into the engine cylinder. Now this injection time has to be adjusted so that rise in peak pressure should not be compromised and at times, engine operations should not be jerky or rough.

So, these two important points you should remember. Here, injection time should be adjusted such that the engine produces maximum power without causing rough engine operation and producing undesirable smoke in the exhaust. The development of peak pressure. This is called the valve timing diagram. So, in the valve timing diagram, what is done. Say for example, this is TDC, this is BDC and this is again BDC. So, as the piston is traveling from BDC towards TDC during the compression stroke, then the suction volume of air or the consumed amount of air will be compressed and towards the end of the compression stroke, so essentially the air pressure will increase and towards the end of the compression stroke, rather before TDC, actually for the CI engines, fuel injection is started.

Because you can recall that in a CI engine, the combustion process is mimicked by a constant pressure heat addition, not a constant volume heat addition. So, in a constant pressure heat addition, it is assumed that the first part of combustion, so basically fuel injection will start before the piston reaches TDC and will continue when the piston travels back from TDC towards BDC during the power stroke. So, this is essentially the compression stroke and this is the power stroke or expansion stroke. Now, what will happen, if we have the peak pressure, so if it is the case that when the piston is coming back from TDC toward BDC, by that time the second phase of combustion will be completed. So, the piston is coming down from TDC to BDC, and the rise in pressure because of this combustion will try to create some jerky motion of the piston, and that is shown here. So essentially, you try to understand that the fuel injection period at the time of or injection time, which is the duration over which fuel should be injected, is very crucial for the smooth operation of a CI engine as well as better performance. Why better performance? If it is the case that a substantial amount of combustion is taking place when the piston is coming back or traveling back from TDC towards BDC, then, because the piston has already traveled back from TDC to BDC—the power produced because of the combustion will not be utilized.

So hence, we need to compromise with the efficiency or power output of the engine, and the operation will be jerky. So, this point is very crucial: the injection time should be adjusted, typically 20 degrees before TDC to 0 degrees TDC. So, this is essentially the square injection duration, which is typically followed for the design of a CI engine. That means fuel injection will start when the piston is 20 degrees before TDC and will be completed when the piston is at TDC.

Now, if we go to the next point, you can understand from this that the pressure rise due to combustion has to negotiate with the expanding volume of the cylinder. As the piston is traveling back from TDC to BDC, as if the cylinder volume is becoming more and more, so expanding. The next point that I would like to discuss in this context is the port and valve timings, and that is point number 2. This is again important.

Why is this important? So, we have studied that the inlet valve is very important, that the closing and opening time of the inlet valve is crucial so as to ensure that an adequate amount of air or charge can be drawn into the cylinder. On the contrary, proper opening of the exhaust valve is again necessary so as to allow or so as to expel the combustion gases from the cylinder into the ambiance with very small pressure difference. If the exhaust valve is allowed to open even when the piston has not reached the BDC, as it—if we go back to the previous slide—you can see that this is the power stroke, and the piston is getting work output from the stroke only. Now, the piston will reach BDC, but before it does, if we try to open the exhaust valve, the pressure in the cylinder is relatively very high, and that pressure will allow exhaust gases to leave the cylinder into the ambient. But if that is the case, then at the moment we try to open the exhaust valve, the pressure inside the cylinder will fall, and instead of getting some work or output work, or the enthalpy or energy, will be lost with the exhaust gases.

The proper opening of both the inlet and exhaust valves is very important, essentially for the smooth operation of the CI engine. The timing of the valves—here, timing refers to the opening and closing of the valves. The timing of the valve for both, 4-stroke cycle SI and CI engines—are guided by the same logic. What is the logic? The logic is to induct the greatest amount of air—or the largest amount of air if it is a CI engine—or the greatest amount of charge for the SI engines, the greatest amount of air or charge. So, this is logic number 1, and if you go to the next slide, we can write here— logic 2 is to expel the combustion gases from the cylinder or combustion chamber to the—ambience, with the smallest possible pressure difference. Pressure difference—certainly, that pressure difference is the driving force to have or to make any flow occur. So, until and unless there is a pressure difference, no flow can take place. So, when combustion gases or exhaust gases are allowed to leave from the cylinder to the ambient, certainly there must be a pressure difference. If the pressure difference is really more, certainly the combustion gases can be readily moved or expelled from the engine cylinder.

But, as I have discussed a few minutes back, if the pressure difference is more because atmospheric—if the combustion gases are typically expelled to the ambient, so that is atmospheric pressure. So, if the pressure difference is more, it means the pressure inside the cylinder will be more. We open the exhaust valve a little before the piston reaches that BDC, then that higher pressure difference will allow quicker removal of exhaust gases, but we will not be able to utilize that pressure, which will otherwise produce a certain amount of work output. This ensures that the exhaust valve design and the timing should be such that the combustion gases can be expelled from the cylinder to the ambience with the smallest pressure difference between the cylinder and the atmosphere. So, this is the important point.

In this context of both two-stroke cycle CI and SI engines, typically one process is there that is known as scavenging. What is this process? So, incoming air—so ports are allowed to open, so that incoming air will automatically allow the exhaust gases to leave out from the engine cylinder. Rather, the incoming air stream will—or if it is a CI engine, only air stream; if it is an SI engine, then it is an air-fuel mixture that is charged. So, the incoming stream of charge or air is allowed to expel the combustion gases from the cylinder.

Now when the combustion gases are leaving from the cylinder, if it is a SI engine, then certain amount of charge or fresh charge also will go away with the combustion gases. So, this is essentially a loss. because that charge otherwise can be used to produce some energy. So that part is very important. On the contrary if it is a CI engine, it is not the charge, rather certain amount of fresh air will be living with the exhaust gases.

So, if the amount of air is not adequate inside the cylinder, so the amount of fuel which will be supplied to the engine based on the design condition. will not be able to burn properly so that smoke or some knock emission will be there and output will be compromised. So, these things are very important to be considered for the operation rather for the design of both CI and SI engines. So, with this now let us move to discuss about engine heat balance. So, if I go to the next slide then what is engine heat balance and why do we need to consider this aspect in the context of engine performance and operation? So, we all know that essentially, we supply certain amount of energy in the form of fuel to the engine and that energy is chemical energy that is stored in the fuel itself. Now the fuel is burnt inside the engine cylinder in the presence of adequate oxygen that is air and then that chemical reaction or combustion reaction is exothermic. So, this reaction itself generates extensive amount of heat and it is because of this combustion that pressure rises and also temperature rises because of this heat liberation or generation. So, what you can understand the energy that is remaining stored within the swell in the form of chemical energy, that energy will be converted into mechanical energy or in the form of heat.

And that energy again will be converted to another form that is the work. So, we are supplying energy to the engine in the form of chemical energy. That energy will be converted to another form of energy, that is heat, and eventually we will be getting some energy at the output side, and that is the work. So, heat would be converted to work. So, you have studied thermodynamics; heat is regarded as the low-grade energy, and work is regarded as the high-grade energy.

So certainly, it is not possible to have equivalent conversion of heat into work because heat is low-grade energy and work is high-grade energy. So, some energy will be lost. So, we are supplying a certain amount of energy to the cylinder. Then we are producing energy in a different form.

Then some part of the energy being produced will be lost, and we will be getting some part of it at the shaft or output shaft. So, if we can really take an effort for the accounting of energy that is supplied to the engine, plus the energy that will be lost, plus the energy that is available at the shaft, and that accounting can be described using heat balance. Engine heat balance is nothing but the accounting of the energy that is supplied to the engine plus the losses, plus the energy that is available at the output shaft. It may be expressed by carrying out a heat balance. It is similar to the balance that is typically done by people in a bank. That means the amount that is deposited, the amount that is withdrawn, and the balance amount. So essentially, it is an engine heat balance.

So, heat is the energy. We have studied this in our basic thermodynamics course. Energy produced because of burning the fuel is heat, and energy available at the output source is the work. Now, as I said, the energy in the fuel—chemical energy—is stored. The fuel is burned in the presence of oxygen, and then we get energy.

Which is heat—heat is generated because of combustion. Now, that is the energy available inside the engine cylinder. Now, from here, we are getting work—that is also energy available at the shaft. So, energy is conserved. So, the amount of energy remaining stored in the fuel will be converted to another form of energy—that is heat.

And again, a certain amount of heat will be utilized to get work at this output shaft, while a certain amount of energy will be lost. That we have studied. So, the total energy will remain constant. So that means the amount of energy supplied to the engine is not equal to the energy available at the shaft. And that is why we had to define overall efficiency of the engine, thermal efficiency of the engine, mechanical efficiency of the engine, and volumetric efficiency of the engine.

So that means if we can make an effort to account for the energy supplied to the engine, plus the losses, plus the energy available at the shaft. So, the entire process can be expressed by carrying out a heat balance, and that is known as engine heat balance. So, the designer will design the engine so that maximum energy can be obtained at the output shaft. Our objective is to supply a certain amount of energy to get energy in a different form at the shaft.

So, the designer of the engine should be very careful to design each and every component. Having a very good design, the output available at the shaft can be maximized. And if we need to know all this information, or rather, if the designer needs to know exactly what would be the power output or output energy at the cost of the input energy, the designer needs to know the locations or identify these places wherein a certain amount of energy is utilized to overcome several auxiliary loads; a certain amount of energy is lost through coolant; and a certain amount of energy is utilized to overcome friction. In an engine, output power is obtained, or output energy is obtained, at the cost of some input energy.

Whenever a designer is trying to design an engine, the designer must be careful in designing several components to ensure that the output energy can be maximized. If that is the case, then the designer must know or must identify places, locations, or sources where a certain amount of energy will be lost or a certain amount of energy will be used to overcome other parasitic loads. So that the output power or output energy can be maximized at the cost of the input energy.

So, the heat balance is therefore a determination of the disposition of the energy that is provided to the engine in the form of fuel. That is the chemical energy and so, this is essentially the heat balance.

And this particular analysis or accounting of all these energy budgets rather helps—it helps to determine the areas which must be focused on for obtaining better performance. That means we know the amount of energy that is supplied to the engine at the cost of that input energy, if we can identify the areas where a certain portion of energy is used or utilized to overcome several parasitic loads or a certain amount of energy is lost through those areas, then it will help the designer to focus more on those areas to ensure that the performance of the engine can be maximized.

That means the output power or power available at this output can be maximized. So, this is the heat balance. If we look at the typical heat balance of an SI engine, it looks like this. So, what you can see from this heat balance, this is basically a typical heat balance for a typical SI engine.

What we can see from this diagram is that the percentage of the fuel energy—if we look at the Y-axis—you can see the percentage of the fuel energy is 100%. So, energy cannot be created or destroyed. So, the energy that is available with the fuel, say, if it is 100 percent, out of this 100, If we look at this diagram, we can see only roughly 40 percent is the indicated work, or a certain amount of energy or heat is supplied to the coolant. A certain amount of energy is carried away by the exhaust gases.

That means exhaust gases carry enthalpy. So, energy is getting lost. A certain amount of energy is transferred to the coolant. We all have studied that we need to supply fuel to get some work output. Knowing fully that we need to supply a certain amount of energy to obtain a certain amount of work, we are trying to take off or take away a certain amount of energy from the engine itself by supplying coolant.

That is where the second law of thermodynamics is very important. So that means any device cannot operate with 100 percent efficiency. So, we know very well that we are going to supply a certain amount of energy. Out of this 100 percent energy, you can see only one-third is the indicated work, that is, the work available inside the cylinder. The remaining 60 percent or even more than 60 percent of energy is used to overcome several parasitic loads, and almost out of the 60%, almost 30% is used, and 30% is lost with the exhaust gases. So, if we look at this indicated work, that is only one-third of the total energy being supplied to the engine. This indicated work has again some components. If we look at the block diagram which is placed in the right panel of this diagram. We can see out of this total one-third of the total energy or total fuel energy is the indicated work, and out of this indicated work, there are many components.

The most important component is the brake work, and that is the work available at the start. Then we have pumping work. So, what is pumping work? This has two components. Engines have one small pump and that pump is used to supply water to the radiator or to the cooling water jacket, etc. Over and above that small pump, which is driven by taking a certain amount of energy from the output energy, we all know that out of four different strokes, only one stroke is a power stroke. So, the remaining three strokes are idle strokes. So out of four different strokes, one stroke is a power stroke. And the remaining three strokes are idle strokes, so, to execute these three strokes, we need to borrow energy from the output power.

So that is known as pumping. So, pumping, basically, we need to pump the exhaust gases, so the exhaust gases should be expelled from the engine cylinder to the ambiance through the exhaust valve, and that is the exhaust stroke. So, the exhaust stroke, pushes all the gases from the cylinder to leave there and go to the atmosphere, and at the same time when the piston is coming back from TDC to BDC during the intake stroke, as if we are trying to pump a certain amount of fresh air or charge into the engine cylinder.

So, the energy needed to execute these two strokes is known as pumping energy. And then we have rubbing or frictional work, meaning the cylinder will move or reciprocate between these two locations continuously. So, when two mechanical components are in contact with each other, we really cannot ignore or make the frictional losses zero. Certainly, efforts have been taken to minimize the frictional losses, but still, the rubbing effect of frictional loss will be there. This is the rubbing or frictional effect, and also there is one small component known as accessory work, or this amount of energy is needed to run several auxiliary systems for the parasitic load. Say, for example, in a passenger vehicle, if we have an air conditioning unit to run, this air conditioning unit needs some amount of energy, and that energy is borrowed from the output work. Similarly, for a passenger vehicle, during the daytime, there is no need for any lighting system or requirement of light, but we may need to turn on the light, and the energy used to turn on the light will again come from the output energy. So, all these are parasitic loads, and these parasitic loads consume a small fraction of the indicated work, and all these components are given.

So, that means we can understand the designer needs to know exactly the areas where a certain amount of energy will be lost or will be used, and that information will help the designer to focus more on those areas to improve them so as to maximize the brake work, and it will essentially maximize or improve the engine performance. Qualitatively, energy balance can be better understood from this diagram. So, if we look at this diagram, we can get some qualitative information about this energy balance.

So, qualitatively, energy balance can be better understood from this diagram, but if we need to quantify, then exactly what portion of output work is needed? What portion of output work is needed to run this pumping work? What portion of output work is needed to overcome the frictional losses? What portion of output work is required to run the parasitic system? So, if we go for quantification, examination of the quantitative aspects of the typical energy balance diagram as shown in the previous slide.

Having a look at this diagram, we can estimate qualitatively. What portion of work is available at the shaft, and what portion of input energy is available inside the engine cylinder. What portion of that output energy is needed to overcome the frictional losses, to run the parasitic system, and for the pumping work. So, this is qualitative, but here we are trying to write some quantitative aspects.

First, approximately one-third of the fuel energy is lost as exhaust enthalpy. Second, another one-third is lost as heat rejected to coolant. Frictional losses are generally manifested as additional heat transfer to coolant or oil. Brake work is nearly 40% lower than the indicated work. If we go to the previous slide, out of the total 100% energy supplied to the engine in the form of fuel, one-third is getting lost through the exhaust gases because they carry enthalpy, one-third is lost to coolant, and the remaining one-third is indicated work. Out of this indicated work, the brake work is even 40% lower than the indicated work.

So, whatever amount of power that is produce inside the engine cylinder, 40% lesser of that work is available at the shaft that is break work is utilized to overcome this parasitic load and also to overcome the frictional losses. Pumping losses comprise approximately 5% of the total fuel energy. This 40% work which is not available at the shaft is used to overcome. So, break work is 40% less than the indicated work. This 40% includes pumping losses, frictional losses, and parasitic loads.

So, if summarize our today discussion, then it can be said that we had started our discussion on identifying factors those affect CI engine performance and to this end we have again recapitulate all those factors that affects both SI and CI engine, there after we had discussed engine heat balance, why do we need to have this heat balance and what is heat balance in the context of engine operation and then we have discussed about a typical heat balance for the SI engine and there after we had seen from the heat balance it self, it is possible to have qualitative estimation of several areas wherein energy is lost and then we have quantitative aspects of that particular heat balance diagram and we had seen exactly out of the total energy , which is supplied to the engine in the form of fuel, how much energy is available at that shaft as useful work.

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

Thank you.