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## Lec 33: SI engine performance curves and Performance characteristics

I welcome you all to the session on engine system and performance. Today, we shall discuss SI engine performance curves and performance characteristics. We have discussed engine performance parameters and their measurement methods. So today, we shall see performance curves and and also the performance characteristics, first for the SI engine. Subsequently, in this module, we shall discuss performance curves and performance characteristics of CI engines as well. So before discussing engine performance, essentially to discuss several curves, those used to present engine performance, let us first discuss air consumption in an SI engine.

because our objective in today's class is to discuss the performance of an SI engine. So, if we look at the schematic or if we look at this figure—rather not a schematic depiction, but a figure—what we can see is that it shows the variation of air consumption rate, IHP (Indicated Horsepower), torque, and air charge with the variation of engine speed. Now, first, if we look at air consumption—the variation of air consumption with engine speed, we can see that with increasing engine speed, air consumption increases. I am not going to discuss this part in greater detail.

But what you can see from this particular curve is, in an SI engine, if we consider this as the operating range of engine speed, there is a particular speed at which the charge—that is, the air-fuel mixture, to be precise—the charge which can be drawn into the engine cylinder, will have a maximum value. So, if we point here, this is having the maximum value here. That means the amount of charge drawn into the engine cylinder will be the greatest, and hence the power output by the engine would be the greatest corresponding to this point. So, there is a particular engine speed within this range of speed for which the charge that can be drawn into the engine cylinder will be the greatest. And if the charge drawn into the engine cylinder is the maximum, the power output will be maximum. And that is very important.

Now, the question is, before discussing the variation of air charge with engine speed beyond this maximum value. So, this is the engine speed. Corresponding to this maximum air charge, if we try to increase the engine speed further, we can see that the air charge drops from the variation plotted in this figure. Before discussing this, let us first discuss the air consumption rate. If we look, we can see that the air consumption rate continuously increases with increasing engine speed until this point, beyond which further increase in engine speed leads to a reduction in air consumption. That part we are not going to discuss because it is beyond the normal speed range of the engine. So, as we increase the engine speed, so if we increase the engine speed, the number of strokes per minute will increase.

So, that means if we increase the RPM, the number of strokes per minute will increase, and if that is the case, you can understand that the duration of air intake, or the duration over which charge or fresh air can be inducted into the engine cylinder, will be more, and hence, continuously, this air consumption will increase, as we can see. Now, if the amount of air drawn into the engine cylinder increases with increasing speed—that is, increasing RPM— so higher RPM means the number of strokes per minute will be more or will be higher, and then more air can be drawn into the engine cylinder.

If that is the case or that is the situation, then in the presence of more air, more fuel can be burned, and then the power output will be greater, and that is the indicated horsepower. So, the power which is available inside the engine cylinder is the indicated horsepower or the indicated power. So, you can see from the variation of indicated horsepower, that is IHP, which also increases with increasing engine speed. As such, from the curve presented in this figure, we can tell that indicated horsepower—that is, the power developed inside the engine—is proportional to the air consumption rate until this point.

Because we are not going to discuss beyond this point. You can see this because it is beyond the normal range of speed or operating speed of the engine. So, we have discussed these two. Now, let us focus on the variation of air charge with increasing engine speed. Now, the question is if we increase engine speed, certainly the amount of air drawn into the engine cylinder will increase. We have discussed this. Because essentially, we are increasing the number of strokes. If we increase the number of strokes, the number of intake strokes will be more, and more air can be drawn into the engine cylinder. Now, the question is: if the amount or mass of air drawn into the engine cylinder increases, and charge is nothing but the air-fuel mixture.

So, fuel will be distributed by the fuel injector or fuel nozzle. So, in the presence of more fuel, that means you can see that beyond this point, if we go beyond this particular point, air consumption still increases. But the amount of fuel supplied by the fuel injector will remain the same unless the electronic control unit instructs. Hence, the air charge—the fuel-air mixture—will drop, and that is what we can observe. So, with this discussion, let us move on to discuss the SI engine performance curves. So, this is very important.

Perhaps you have seen all these curves or studied them in your undergraduate IC engine course. We will try to recapitulate our understanding of this part. So, we can see that there are many curves representing IHP and BHP. So, this is—if I mark—indicated horsepower. This is brake horsepower.

This is brake mean effective pressure. This is brake torque. This is brake-specific fuel consumption. And this is frictional horsepower or FHP. Now, let us talk about the performance curves first.

Essentially, these curves are typically used to present the performance of an engine. By representing, plotting, or detecting these curves, the performance of an engine is predicted or represented. These curves are very important for comparing the performance of one engine with another. First of all, these curves are obtained from tests conducted on an engine. Once we plot these curves, they are plotted by varying the speed under full throttle or full load conditions.

Certainly, once we have generated all these curves by varying the speed, that is, by performing a test on an engine, under full throttle condition, that is, full load condition at a given load—rather, I should say. So, these curves are generated by varying the speed of an engine for a particular load. Now, if you would like to predict the nature of these curves for different loads, it is also possible to extrapolate using these curves.

That means, having generated a set of these curves for a given load by varying speed, curves for another load can be predicted. Now, what we can see is that, these curves are very important to compare the performance of an engine with another one. And typically, in these curves, indicated horsepower, brake horsepower, and frictional horsepower are plotted together with, in these curves, brake torque, brake mean effective pressure, and BSFC are also plotted in the same plane. So, you can understand, essentially, when a test is conducted on an engine by varying load, power output is measured. And also, in the same plane, if you would like to superimpose the curves for brake mean effective pressure and brake specific fuel consumption and also for the brake torque, we can have torque and BSFC. So, let us first discuss one by one. As I said, this is IHP, indicated horsepower; similarly, BHP, that is, brake horsepower; and FHP, that is, frictional horsepower.

So now, this is the power which is realized or which is available inside the engine. IHP, indicated one, that is the power developed inside the engine on the piston face. So that power is not realized at the shaft of the engine. While the power which is realized at the shaft of an engine is the brake horsepower. And frictional horsepower is nothing but indicated horsepower minus brake horsepower. The indicated horsepower equals brake horsepower plus frictional horsepower.

So, the total power developed inside the engine now has these two components. That is, one power which is available at the shaft. Another one is used to overcome the frictional losses inside the engine cylinder. So, what we can see from this curve, a few salient points that I'd like to discuss in the context of this curve, is when speed is low. So typically, that speed varies from 1000 rpm to 6000 rpm. But that even 6000 rpm is too high. But if we look at the variation, when the speed is low, then the frictional horsepower is very low. So, the frictional loss is low. That is true.

And at low speed, you can see that since the frictional horsepower horsepower is low. So, the indicated horsepower and brake horsepower are almost coinciding with each other. So, almost they are equal, which is quite obvious. So, when the frictional horsepower is low, from this equation, we can see IHP will be almost equal to BHP, which is what is reflected in this curve.

Now, if we increase the speed, certainly the frictional horsepower increases, which is quite obvious because, with increasing speed, the number of strokes per minute will increase. So, that means the frictional effect will be more, and that is what is seen here. Not only that, with increasing speed, certainly, the amount of charge that will be drawn into the engine cylinder will increase. So, certainly, this IHP will keep on increasing until this point, where it will reach the maximum. So, if I make it this point, this would be the maximum.

And since IHP is increasing with engine speed, as seen from this figure, and FHP also increases, so certainly IHP minus FHP, which is BHP, will also increase. So, the BHP, the curve representing brake horsepower, shows almost a similar trend to that of the IHP. We can see a maximum point. And what we can see is that if the speed increases, another important salient point is that if speed increases further, you can see this curve representing frictional horsepower will increase in this way. So frictional horsepower will increase while the IHP will decrease.

So, these two curves will meet at a point at a speed which is beyond 6000 RPM. We are not interested in this speed range because typically that is beyond the operating speed range of an engine. So, what you can see is that at low speed, FHP is minimum, and BHP and IHP are almost comparable. With increasing speed, IHP increases.

That is very important because the amount of charge drawn into the engine cylinder will increase, which in turn will help burn more fuel, so power output will be greater. Since frictional horsepower is increasing, despite having higher indicated horsepower, this will reduce maximum power, and hence the BHP will increase but will be less than IHP. But if we look at brake torque, even at low speed, it is low, but brake torque reaches its maximum even when IHP has not reached the maximum. That is another important salient point. So, at low speed, brake torque is minimum; it increases and reaches a maximum here. So, brake torque reaches maximum even when IHP has not reached the maximum value. So, these are the points I wanted to discuss in the context of this figure.

So, I told you that all these curves are very important. All these curves are obtained from a test conducted on an engine. And these curves are obtained by varying engine speed. At a given load, but the nature of these curves can be extrapolated or predicted for another load from this data set. And these curves are very useful to compare the performance of one engine with another.

So, with this, now let us discuss these two important parameters that we could not discuss in this context. So, we have discussed a few salient points. That is in the context of the variation of IHP, BHP, and FHP. We have also discussed brake torque, that it has a minimum value or low value when speed is low. Then with increasing speed, brake torque increases.

That is quite obvious. But the brake torque reaches maximum even when the IHP has not reached the maximum value. But we really didn't discuss BMP and BSFC. So, to discuss all these points, let us look at this particular figure. So, in this figure you can see what is shown here again with increasing engine speed from 600 to 3400, the variation of fuel consumption rate and BSFC, these two variations are depicted in this figure.

So, this particular curve is obtained under full throttle operation that is full load condition. When throttle valve is fully open, that means load is full or maximum load. So, now let us discuss about a few points again. So, what we can see? So, we can see that fuel consumption. So, that is very important. If we increase the engine speed, fuel consumption will be more. That is quite obvious, by this time from your understanding, of internal combustion engine course. So, let me go back to previous slide.

Fuel consumption will increase and that is why, with increasing speed power output will be more, so that means if speed increases, fuel consumption will be more because the more amount of air will be drawn into the engine cylinder and to burn in the presence of large amount of air, large quantity of fuel can be burnt and power output will be more. So, here we can see that with increasing engine speed, fuel consumption increases. We will come to this particular point BSFC that is break specific fuel consumption but the variation of this particular parameter that is fuel consumption with increasing speed, let us try to have a complete understanding using this mathematical description. So, fuel consumption that is mass flow rate of fuel $\left(\dot{m}_f\right)$. So, essentially it is

$$\frac{\text{kg}}{\text{s}} = \frac{\text{kg}}{\text{cycle}} \times \frac{\text{cycle}}{\text{s}}$$

Very easy to understand. So, fuel consumption is, that is mass flow rate of fuel, that is kg per second. We can decompose this with kg per second using this relation. Now, what is essential is cycle per second. So, if we increase the engine speed, so increasing engine speed what does it mean number of strokes per unit time will be more. So, that is very important as I had mentioned, number of strokes per minute will be more.

That means when RPM is higher, the number of strokes per unit time will be greater. That is a four-stroke cycle engine. So, in one cycle, there are two revolutions. So, essentially, this quantity will increase. So, if we increase the RPM, cycles per second will be greater.

That means, per unit time, we can have a greater number of cycles. And then, if that is the case, then this is kg per cycle—that is, the amount of fuel that would be consumed. So, you can understand. So, fuel quantity increases.

So, that means this curve is obtained at a fixed load—that is, when full throttle operation. So, it is fixed load that is the maximum load. If the load is fixed, so that is kg per cycle is also fixed. This is fixed for given load.

So, this is A and this is B. So, A is fixed for a given load. Now, B will increase with rpm. So that means if we increase rpm, though this fellow is remaining constant, kg per second that is fuel consumption will increase and that is what we can see from this curve, kg per cycle that is the amount of the load. So that is if the load is fixed per cycle, the amount of fuel will be used to produce load that is fixed. But the cycle per second is, though this fellow is increasing with increasing the value of rpm. Hence, the fuel consumption rate will increase with increasing speed at a fixed load.

Now, what about BSFC? So, if we go to the next slide, BSFC, perhaps the definition of BSFC, that is brake-specific fuel consumption. What is this? BSFC is the mass flow rate of fuel, that is kg per hour, per unit BHP kilowatt per unit.

BHP in kilowatt developed, so the amount of fuel that we need to supply for one kilowatt, that is BHP developed. So, if you would like to have one kilowatt brake horsepower, the amount of fuel that we need to supply is essentially BSFC. So, the variation of BSFC with load will now depend on the BHP that we would like to have. So, if we go back to the previous slide, we can explain what is happening. So now, do not try to look at the variation of this curve from low speed to high speed. So, let us start our discussion from this particular point. What we can see from this curve is that, with increasing speed initially, BSFC drops, then remains almost constant for a certain range of engine speed.

If the engine speed increases beyond that certain range, again BSFC increases. So that is the nature of this curve. Now, that is essentially the range where BSFC is remaining more or less constant. So, if we try to traverse from this particular point, so if it is 0.1 and if it is 0.2. so, if you would like to traverse from 0.1 towards left, that is if we reduce engine speed, So, then again you can see BSFC is becoming more or brake-specific fuel consumption, increases. What is the reason for this particular variation?

Reason is that when we reduce engine speed, then cycle per second will be less, is not it? So, engine will get that more time to cool off. So, the heat transfer from the combustion chamber to the coolant will be more. And if the heat transfer is becoming more, so this, combustion efficiency will reduce. To adjust to that drop-in combustion efficiency, more amount of fuels to be supplied and hence BSFC increases. Let me repeat once again.

When we reduce engine speed from 0.1, that means we are trying to decrease the engine speed. What will happen? Engine will get more time and during this time because cycle per second will be less. So, if it is this case means number of strokes per unit per minute or per second will be less. And then engine will get enough time to reduce or to transfer heat from combustion chamber to the surrounding or to the coolant.

And it is because of this reduction of large heat transfer, what will happen, that combustion efficiency will be poorer. And if the combustion efficiency becomes poorer because the load is fixed, so then what will happen, we need to enrich the fuel and that is why BSFC will increase, number one. Now, if we go from point 2 towards right, that is, if we increase the speed, then what will happen? So, if we increase the speed, again, you can understand that two things will be there. If we go to the next slide, then it will help. So, you can understand that either BSFC will be higher if mass flow rate of fuel becomes higher or BHP becomes lesser. Either way, we can have higher BSFC. So, what we had seen in the beginning that, is in the low speed range that for a given BHP that is brake horsepower to be developed by the engine, since engine is transferring heat getting larger amount of time to remove heat, combustion efficiency will be poorer. And to have the same power developed for a given load, we need to supply more amount of fuel to that is to enrich the mixture. And that is why BSFC will increase. Now, what will happen if we try to have the nature of the curve in that range where speed is becoming more, that is beyond 0.2 in this zone.

So, you can see that speed is becoming more. So, at higher speed, mass flow rate of fuel also will increase. Because at higher speed, number of strokes per minute will increase. So, the more amount of charge will be drawn into the engine cylinder and BHP also will increase. But the question is, as engine speed increases, frictional power also will increase, FHP. So, what will happen? That BHP will increase. $\dot{m}_f$ also, will increase.

So, if we increase the speed certainly more amount of charge will be drawn into the engine cylinder, more amount of fuel will can be burnt. So, BHP will increase. So, BHP will increase, $\dot{m}_f$ will increase, but between these two factors the rate of increase of BHP is less compared to $\dot{m}_f$. In other words, though BHP is increasing and $\dot{m}_f$ is increasing, but the rate at which $\dot{m}_f$ is increasing is more compared to BHP. Hence, the BHP will be more. And that is the explanation. So, what we can see from this particular curve? We can see that this is, if we fix the speed and these two curves are obtained for a fixed load, for a given load.

And essentially, if we fix the engine speed, then at that engine speed at a given load, we can have some information about the BSFC. Now, the question is, can we have this curve under varied load condition? keeping speed fixed. So, let me tell you once again these two curves are obtained rather BSFC that we have discussed. So, the variation of BSFC with engine speed is having quite decreasing then remain constant then again increases we have explained.

Now, this curve is obtained by varying engine speed at a given load. Can we have the variation of BSFC at a given speed but varying load? And that is also very important to know for the engine to predict the engine performance or to prescribe the engine performance. So, if we go to the next slide, then we can see this engine performance characteristics wherein the variation of BSFC is shown here. for a constant speed and constant air fuel ratio, but by changing the load.

And that is very important. So, what is the reason behind the variation of this? I mean, we already had seen the variation of BSFC with engine speed at a given load. Then, why do we need to have this variation again?

Then, we will explain. So, what we can see that, if the throttle opening is changed, that is full throttle opening to partial throttle opening, that is if we control the throttle opening area at that load is adjusted to yield the same speed.

So, the BSFC can be recorded. So, in the last figure we had seen the variation of BSFC with engine speed keeping load constant. Objective is to have the same variation for changing load keeping speed constant and constant air fuel ratio. If you would like to have this curve what we need to do? The earlier curve that we had seen that is essentially, if we go back to the previous slide, we can see that at a given engine speed say for example if the engine speed is something like this at this engine speed we can have this is the BSFC for a given load. So, we similarly what we can do, we can perform the test so it was full throttle operation that is full throttle opening that is fixed load or maximum load. Now what we need to do is here, we need to throttle opening area that means we are changing load. If we change the load at the changed load condition, we have to adjust the load in such a way to yield the same speed because speed has to remain constant and then the BSFC value can be recorded. If we repeat this then we can have the BSFC data for a wide range of load, but keeping the speed constant.

And if we get the curve, if we plot all these data points, we will be getting the curve like this. So now let us explain the variation of this curve and the underlying physical reasoning behind this variation. So, we should not start our discussion from small load to the maximum load. So, now let us discuss the variation or we shall start our discussion from extreme right to extreme left one. So, what we can see when full throttle open that is full load.

So, you can see that the BSFC has, So, let me use this color. So, BSFC corresponds to full load is this. Now, if we reduce the load that is by controlling the throttle opening area then, we can see BSFC increases. That means from full throttle opening to partial throttle opening if we need to have then the load will be changed at each and every change load condition. We need to adjust to obtain the speed constant. Then if we record the BSFC data and then the curve will look like this. What you can see when load is getting reduced or if we reduce the load, the BSFC is becoming more or higher. So, what we had mathematically described a few minutes back, BSFC (brake-specific fuel consumption) is nothing but $\dot{m}_f$ (kg per hour) per unit kilowatt power developed—per unit kilowatt power, that is, brake horsepower developed. So, here we had seen that brake horsepower or BHP equals indicated horsepower minus frictional horsepower. So, this is frictional horsepower. Either you can write it in small letters or capital letters.

So, if the speed remains constant, certainly frictional horsepower will remain the same. Now, if we reduce the load, certainly, IHP will be less. Frictional horsepower remains constant for a given speed. And if IHP reduces, then BHP will reduce.

So, if BHP reduces, certainly, you can understand that BSFC will increase. So, BSFC can increase either because of a reduction in BHP or because of an increase in $\dot{m}_f$. So, what we can see for this particular case is that if we reduce the load, then certainly, what will happen is that indicated horsepower will be less because the load is reducing. So, if the engine is not encountering the maximum load or the highest load, IHP will be less. But the speed remaining constant means frictional horsepower will be the same.

So, for a given value of FHP, if IHP reduces, that means BHP will reduce. If BHP reduces, then we can see from this mathematical description that for a given $\dot{m}_f$, BFSC will be more, and that is what we can see because, with a constant air-fuel ratio, that means $\dot{m}_f$ will remain the same, so the BSFC will increase, and that is what is reflected in this figure. So now, what we would like to draw is one important conclusion. We have seen the variation of BSFC with a change in load for a given speed and given air-fuel ratio.

So, if you would like to have a family of such curves—curves meaning, at various speeds—BSFC versus load at various speeds can be obtained, each showing the effect of varying load on BSFC at constant speed. That means the curve we have discussed here is obtained at a given constant speed. We can generate a family of such curves by changing the speed at various speeds, and each curve will show the effect of varying load on BSFC at a constant speed. So, now let us discuss one important point.

Until now, we have seen the variation of IHP, variation of brake horsepower—that is, power output—and then BSFC (brake specific fuel consumption). Then we have seen brake mean effective pressure, and all these we have seen. All these curves are used to compare the performance of one engine with another of a similar type. Now, the issue is, what is very important is if the engine design changes or if the engine design is different from one to another, then is it possible to use all these curves to predict the performance of two dissimilar engines? So, the big question is: whatever we have discussed until now—that is, the variation of BSFC, brake mean effective pressure, power output for different speeds and engine load and we have seen that all these curves are very important, to predict the engine performance and to compare a particular engine with another engine. But we can compare two similar engines by predicting or by generating a set of curves from experiments. It may be at different loads and different speeds, but if you would like to compare the performance of two different engines, then these curves, whatever you have discussed until now, are not suitable.

So, to summarize, we have discussed the air consumption of SI engines, then we have discussed SI engine performance curves, and then performance characteristics. And as I said, the performance comparison of one engine with that of another engine of different cylinders and different shapes is not so easy. In fact, the curves that we have discussed in today's class are not suitable to compare the performance of two dissimilar engines. We shall take up this issue in the next class.

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

Thank you.