Introduction to Aerospace Propulsion
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Module No. # 01
Lecture No. # 25
Performance parameters of IC engines

Today, we will discuss in this lecture, various ways in which the piston engine supplies power to aircraft propulsion unit. As we have been discussing in the last one or two lectures, piston engine has been used as a power supplier for aircraft engine, for last more than 100 years. We have been discussing various basis of these piston engines or IC engines, as they are often called and how they have been configured based on certain thermodynamic principles and certain thermodynamic cycles. We had looked at some of these thermodynamic cycles which actually govern the fundamental concept behind functioning of these engines.

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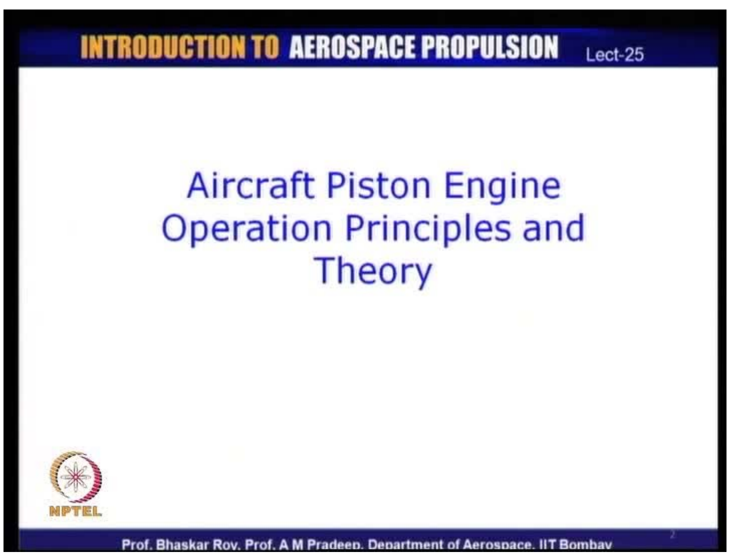

Today, we will look at some of the mechanical aspects of how these engines actually work, how they actually create power and how this power is finally harnessed for flying of the aircraft. So this are the basic principles under which, the piston engine works and that is what, we will discuss in this particular lecture. The mechanical theories we had looked at, the various thermodynamic cycles and the thermodynamic theories, the cycle theories and how they work, the ideal cycles and the real cycles. Today, we will try to look at the theory of the mechanical engineering that makes these engines work and exactly how do you go about designing them, how you go about predicting their performance or calculating their performance. We need to do that to make sure that the engine is working.

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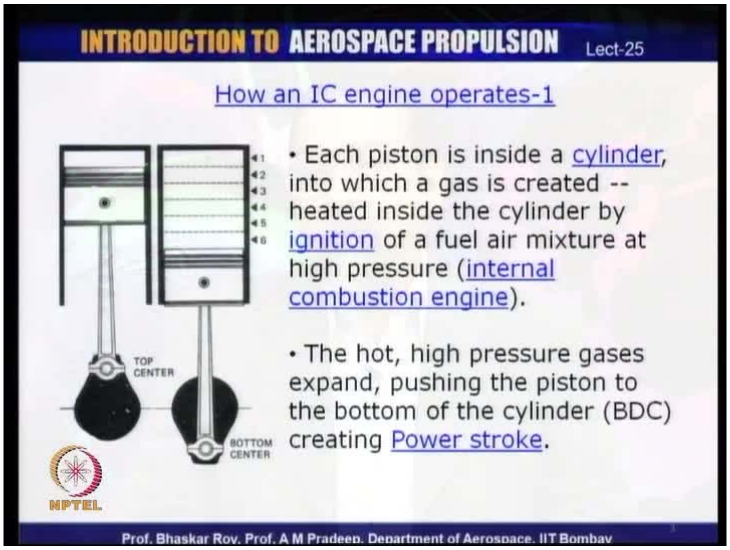

If you look at an engine and the first thing that you would see is the power that is created within a restricted volume which we call a cylinder. Now, within the cylinder, everything that you have seen in a thermodynamic cycle happens. The thermodynamic cycle basically is the metrics on which this piston and cylinder combination functions. So, inside the cylinder, you have a piston and as the movement of the piston allows certain amount of air, which we often call charge that comes in and then the fuel is burnt and what is created is a gas, which is a mixture of air and burnt fuel and when this hot gas starts operating, the cylinder moves. That is how, the movement of the piston is created inside the cylinder and this creates the power or work. That is what, we are mostly interested in. The fact that we burnt fuel, the fact that the burning of the fuel creates hot gas is the reason for which these engines are all called heat engines.

Basically, what we are looking at is of course, a heat engine and it is also referred to as an internal combustion engine - IC engine as it is popularly known. This internal combustion obviously refers to the fact that we have the combustion or heating inside a restricted identified space. This space is the cylinder and the piston and the volume contained within the piston and the cylinder and this is the space within which the heating is first done. Then we see the mechanism by which this heat is converted to work. So, conversion of heat to work is what we are actually dealing with, at this moment and that is why this is called generally, in a very generic manner, a heat engine.

(Refer Slide Time: 04:31) Now, what we see here is a piston, which is enclosed within a cylinder and then as the ignition occurs, a fuel mixture is burnt and a high pressure is created somewhere at the top of the cylinder over here and that high pressure, then activates the piston. So, this movement of the piston is created by the hot gas and that creates what we have already called power stroke.

It moves the cylinder from the top of this station to the bottom over here, which we have called the top dead center and the bottom dead center. Once they reach this top and the bottom, the piston starts their journey backward. That means, from the bottom, it starts moving to the top and when it reaches the top, after the ignition and the heating, it starts moving to the bottom. So, that is a movement of the piston. It moves from bottom to top and top to bottom and it keeps doing that all the time and during which we have the execution of the thermodynamic processes which are contained within the thermodynamic cycle, which we have presented in the last lecture. So, that is a mechanism by which basically, the whole thing works.

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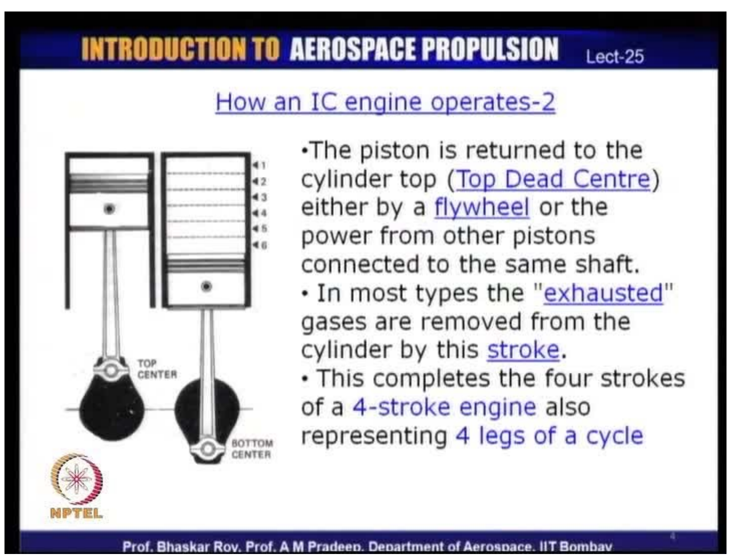

Now, you see the movement of the piston is created from the top dead center and as we know, when it moves from the top to the bottom, we call it a power stroke. As we know by now that only one leg or one process within the whole thermodynamic cycle actually is a power creating or work creating process; rest of the processes within the thermodynamic cycle are not power creating processes. So, same thing here; typically, these IC engines have 4 strokes and these are often called 4 stroke engines and only, one of the stroke is power creating.

How does the motion of the piston get sustained over other 3 strokes? This is normally done through what is known as a flywheel, which is in case of aircraft engine, it is a combination of the crank shaft, the propeller and rest of the things which means when once the power stroke is delivered and the power is delivered, this entire flywheel motion that is the propeller and crank shaft starts moving. That means, the rotary motion is initiated and once a rotary motion is initiated, that motion is sustained by itself for another 3 strokes. For, other 3 strokes are created by the continuous motion of these which we may now call flywheel for the time being let us say, and as the fly wheel moves the other 3 strokes are sustained till the next power stroke comes. So, out of the 4 strokes, one stroke is a power stroke and the other 3 are sustained by the flywheel so that till the next power stoke comes, the motion of the entire engine, motion of the pistons, motion of the shafts are sustained. This is important; if you do not do that obviously, the engine is going to come to a halt.

Once the power stroke is over, as we know, the next thing that needs to be done is the gases need to be exhausted. That means, the gases which were burnt, pressure were created and now the power stroke is over, which means the work that we wanted to get out of this high energy gas, has been taken out. Actually, we do not have any need for this gas anymore. So, we need to get rid of this gas and this is done by what is known as the exhaust stroke. In this exhaust stroke, this piston now starts moving upward and as it starts moving upward, the gas which contained the entire cylinder gets exhausted through one of the exhaust valves and as a result of which the used up gas is now sent out of the cylinder.

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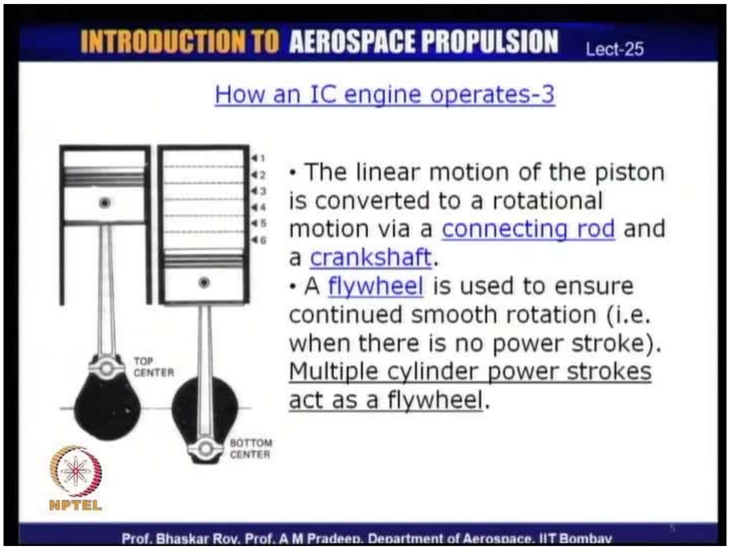

Cylinder is our working space and it is now sent out of the working space. As a result of which, once a cylinder is more or less exhausted, fresh charge or fresh air or fuel air mixture can now come in through the inlet valve and fill up the cylinders space all over again for the next 4 strokes - that means that the next cycle through which the work is performed. So, this is how the work is actually sustained from 1 cycle of 4 strokes to next cycle of 4 strokes. The linear motion of the piston, this is a bit of mechanical engineering which we need to know, is sustained through the connecting rod and is transferred to the crank shaft. the crank shaft You see what we have here, is a linear motion of the piston. It is just moving up and down, up and down or if it is positioned horizontally, it would be moving sideways.

So, what we have here essentially is a linear motion. The work is being done simply in the form of a linear motion and this linear motion now needs to be converted to a rotary motion and that is done through this crank shaft. As a result of which the crank shaft that supplies power to the propeller in case of an aircraft engine and that is how, the propeller rotates and creates thrust. So, we need to convert linear motion of the piston to a rotary motion and that is done through the system of connecting rods, cams and the crank shaft and then, we have the concept of flywheel, which then sustains the motion or continued smooth motion through the other strokes so that we have continuous motion.

When you have multiple cylinders, as we have seen that many of the aircraft engines actually have more than one cylinder, quite often up to 10, 12 or even 16, 18 cylinders. Now, what happens is the supply of power to the central crank shaft. Every engine has only 1 single engine crank shaft and all the cylinders supply power to that crank shaft. As a result of which, now that the cylinder power strokes are time staggered, the supply of power to the crank shaft is now, time staggered. As a result of which, when one particular cylinder is executing some other stroke, let us say, exhaust stroke or intake stroke, some other cylinder is probably providing the power stroke. As a result of which continuous power is being supplied to the crank shaft and the whole flywheel or the crank shaft propeller combine continues to rotate all the time because some cylinder or the other almost on a continuous basis is supplying power to the main crank shaft. This is how, typically in an aircraft engine, a multi cylinder arrangement continues to supply power to the main crank shaft.

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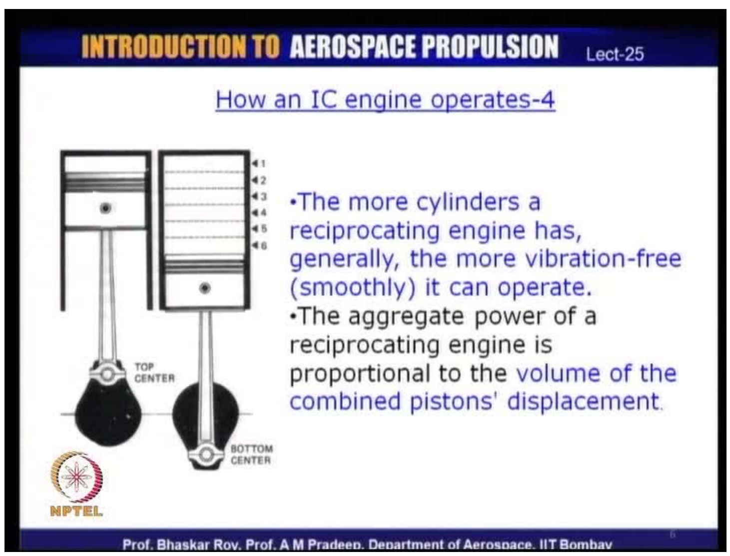

Now, it means that when you have more number of cylinders, there are certain mechanical advantages and today, we are discussing some of the mechanical issues involved with the engine. It actually creates a little more vibration free or smooth operation. This is very important in actual operation of an engine. If you can create engine that is vibration free - because what happens is as we have seen we have 4 strokes; one of them is a power stroke and during the other strokes the engine has to sustain itself in its motion. As a result of which, it is possible that there is an uneven application of force or movement on the crank shaft.

Now, this uneven application of force and movement on the engine can create certain amount of vibration. If you have more engine - more cylinders 6 or 8 or 10 even 12 as we have seen, up to 18 cylinders is possible and if you put them together, sometimes or the other, every spilt second, one of the cylinders is supplying power to the crank shaft; then that particular engine is likely to be more vibration free - it is likely to be more smooth because the crank shaft is almost getting supply of power, almost on a continuous basis. So, a multi cylinder arrangement quite often comes out to be a smoother operating engine compared to let us say, a single or a 2 cylinder engine.

The aggregate power of a reciprocating engine is then normally given in terms of the total volume of all the pistons together - that means the displaced volume. The amount of volume that is typically created between the top dead center and the bottom dead center - this motion is what the piston is executing every time as it moves from one end to another and this is what we call the displaced volume. This is the volume of displacement of the gas and this is the volume which is often quoted as a capacity of the engine. This, all the cylinders together, you can quote certain total amount of volume and that is often specified as the engine specification and is representative of the engine's capacity to produce power. So, total volume of all the pistons together is often quoted as the engines capacity and is indicative of the engine's capacity to produce power.

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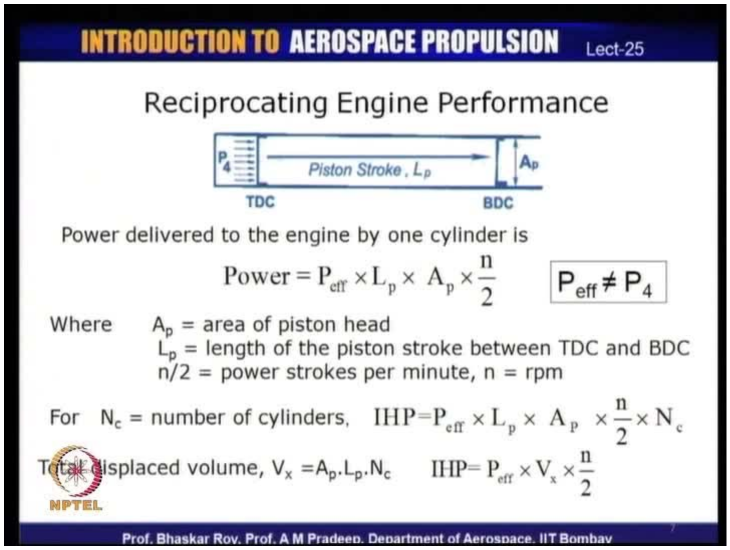

Let us see, how the particular cylinder actually creates power. We can put now numbers or simple relations to some of the concept that we have been talking about. You have a piston which we say that it has a piston stroke of length L p and it moves as we see, from BDC to TDC and then of course, back from TDC to BDC.

Now, when the piston is at TDC, from the cycle we have seen, it reaches a pressure of P 4; from the cycle diagram we have seen that. This pressure then is very high and it is also hot gas of course. As a result of which, it executes a lot of force on this head of the piston or often is called piston head and this has an area. Obviously more this area of the piston head more is likely to be the force, but as we have seen the aircraft engine have certain limitation of its size and weight and as a result the size and weight are often a little restricted.

The pressure created here, creates the force which then starts driving the piston to its power stroke - that means, its motion backwards from TDC, back from TDC to BDC and it executes the power stroke. The power delivered to the engine by 1 cylinder is often given by this simple relation which is power is equal to P effective into the power stroke into the area of the piston into n by 2, n by 2 being the power strokes per minute, where n is actually the rpm or the motion of the rotary motion of the crank shaft. So, it tells us very quickly that if it is rotating or if we are managing to rotate the crank shaft at high speed, we are able to get more power or vice versa, whichever way you look at it. As it is obvious, if you have more area of the piston then you get more power. You have a longer piston length which is the force into distance and that is your work done from your Newton's laws of motion and as a result of which, you get the power done. Now, P effective is something which we are yet to define actually and mind you, P effective is not same as P 4.

So, P effective is some kind of an average power - that is, average pressure that is applied on the head of the piston during its power stroke. We will define that little more formally in a couple of minutes. Just at this moment, remember P effective is not same as P 4, which is the maximum pressure that the piston or the cylinder actually experiences. The number of cylinders, if it is given by capital N c, the total amount of engine power that one can say, is created is given in terms of, as we know, in terms of IHP, which we call indicated horse power. Nowadays of course, they are all mentioned in terms of kilowatts and the N c comes in as the last parameter and hence you get the indicated horse power or what we can call a mechanical estimation of the ideal horse power. The total volume displaced which we are talking about just a while earlier, is now given in terms of area of the piston head, the length of the stroke into the number of cylinders. That is, the volume which I was talking about and that is a total displaced volume which is often quoted as the engine capacity. You might hear same things about the various automobile engines, where the total displaced volume is quoted as the engine capacity and hence we can write now IHP in terms of effective power, the total displaced volume into the power stroke per minute which is n by 2.

So, that gives us an idea about the mechanical estimation of the indicated horse power as we know, we have earlier defined indicated horse power from the thermodynamic cycle diagram. Now, we can see that we can have an estimation of that purely, from the piston and cylinder configuration point of view.

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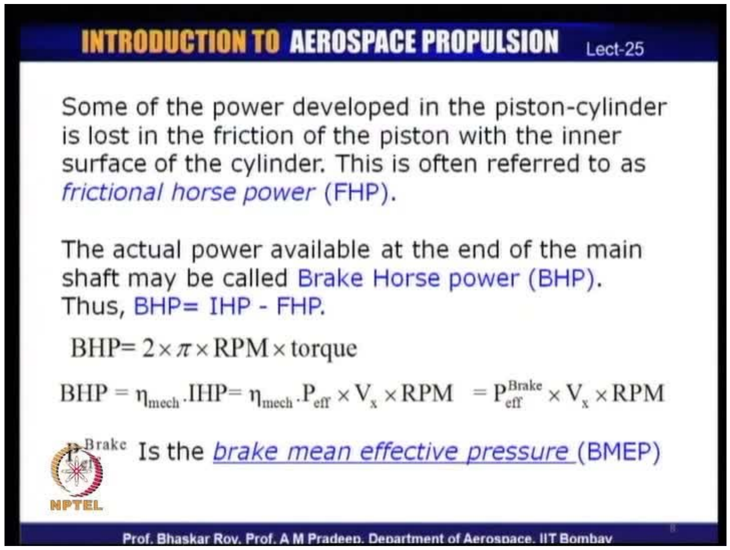

Now, some of the power that is developed in the piston cylinder is actually lost in friction of the piston and the inner surface of the cylinder. This is often referred to as frictional horse power and this is a continuous affair; this is going on during all the strokes of the piston. Mind you, one of the strokes is only the power stroke, others are not power stroke and even during the other power strokes, this friction is continuously happening and as a result of which, a lot of power is actually lost in the process of overcoming the friction between the piston and the inner surface of the cylinder. This needs to be, This not a small amount, this is a reasonably good amount and this needs to be factored into the actual power availability of the engine.

Actual power available at the end of the shaft may then be called the break horse power or BHP and this is of course, IHP minus FHP, which we call the frictional horse power. Now, the BHP can be written in terms of twice pi into RPM into the torque that is produced. We shall see as we go along that the torque produced by the engine is of great importance in running the propeller. The propeller has certain torque characteristics and we shall discuss that later on in this course. Unless you meet those torque characteristics, the thrust would not be created.

So, the torque created by the engine needs to match with that of the propeller and we know, from simple mechanical formulations that the horse power or the BHP can be actual looking down in terms of torque. Now this torque of course, can be also written down; the BHP can also be written down in terms of IHP into the mechanical efficiency of transmission of the crank shaft and that again into the various parameters here, the P effective, the total volume, the RPM and as a result of which, we get a parameter which we call P effective break. This is what we had mentioned earlier as P effective and now, we call this break mean effective pressure BMEP. Actually speaking, if you measure this whole thing with reference to IHP, you can actually come up with something which is indicated mean effective pressure IMEP; it is possible, but that will be an ideal mean effective pressure.

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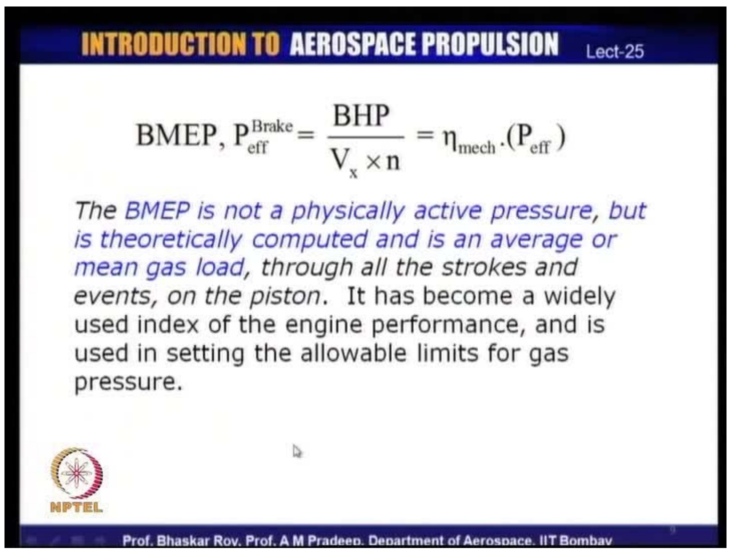

The more useful mean effective pressure is the break mean effective pressure, which is related to the final BHP that is being created and through the piston cylinder arrangement. This is why I said that this is some kind of an average pressure that is actually created by the theoreticians. It is not something that you can measure actually and it is not the physically active pressure which is active inside the cylinder. So, it is a kind of measure of the average mean gas load through which the piston actually operates and it has become a widely used index of the engine performance. As a result of which, we need to keep an eye on this break mean effective pressure for our various understanding of how the piston cylinder arrangement actually works.

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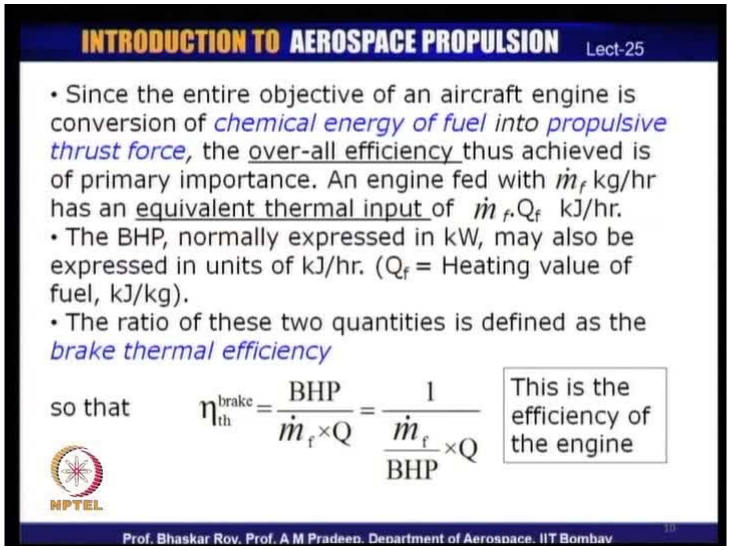

Since the entire objective of an aircraft engine, the IC engine or the piston engine that we are looking at is fundamentally to convert the chemical energy contained within the fuel into finally, propulsive thrust. What we have first to begin with the input to the engine is the fuel which has chemical energy contained within it. Once it is burnt, this energy manifests in the form of heat and then the heat is converted to the piston motion - linear motion, which is converted to the rotary motion; that rotary motion is transmitted through the crank shaft to the propeller and which then creates the propulsive thrust. So, it is a fairly a long drawn out procedure through which finally, thrust is created.

We have quite a few steps to contend with, before we get the thrust and thrust is what makes the aircraft fly. The overall efficiency of this entire process also needs to be understood and estimated, for us to know, what the energy efficiency of this entire power plant is. We have an engine which is fed with a mass flow let us say, m dot f and which let us say, has a thermal input of Q f and this mass flow has a thermal input of Q f and BHP is normally as I mentioned, expressed now in terms of kilowatts and it may also expressed in terms of kilo joules per hour and where Q f is the heating value of the fuel; this is a characteristic of the fuel; this is the chemical energy that is expected to be contained within the fuel. It will vary from one fuel to another quite often and quite substantially and hence you need to choose your fuel very carefully. You need to choose a fuel that has a good heating value and quite often many other characteristics of the fuel are also taken care of in choosing the fuel, but one of the main things or probably the first thing that makes for the choice of the fuel is the heating value of the fuel. You want to have a lot of heat generated by burning the fuel. As I said, the fuel is characterized by the heating value. It is a typical chemical energy content of the fuel that comes out through the heating value.

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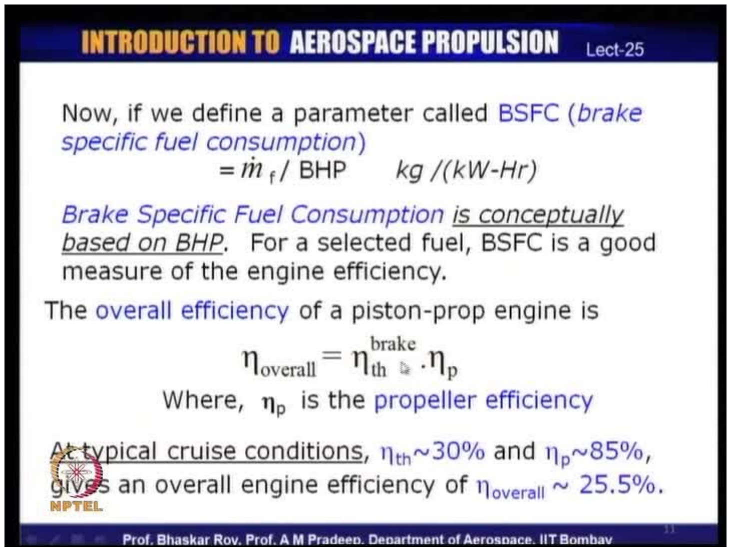

Now, ratio of these two quantities that means the chemical energy that we have, we can expect to be available in the form of heat and the final power that is created in terms of BHP. The ratio of the two is the break efficiency of the engine and this is a break thermal efficiency of the engine, which is the most important efficiency parameter that actually is quoted as efficiency of the engine. This can be written in terms of 1 by m dot f by BHP into Q and m dot f by BHP of course, is the parameter which is of importance and this is often referred to as break specific fuel consumption. This is given in terms of m dot f by BHP and is often expressed in terms of kgs per kilowatt-hour.

Now, break specific fuel consumption is conceptually based on the BHP. You can again Conceptually, you can have indicated specific fuel consumption, where instead of BHP you can use IHP and you can get that, but as I mentioned the more useful one is the break specific fuel consumption. When we say BSFC, we are talking about the utility of the fuel in terms of the break horse power, the final horse power that is available from the engine. In most of the modern engines, BSFC is quoted as the figure of engine efficiency or figure of merit for the engine efficiency. We have justifying the engine efficiency, a break thermal efficiency, but most engineers would like to prefer to use BSFC as a measure of the engine efficiency. So, quite often in the engine specifications you may not find the value of engine efficiency actually mentioned anywhere. It is more of a theoretical understanding by the designers, but the engineers and operators quite often would use BSFC as the measure of the engine efficiency. Now, we can also look at the overall efficiency of the piston and propeller combine. This is often given in terms of the overall efficiency which is equal to the break thermal efficiency into eta p which is the propeller efficiency and quite often the propeller efficiency comes out of the propeller understanding, which we will probably do later on in this course. Typically, when an aircraft is flying at cruise condition, the break thermal efficiency is likely to be of the order of 30 percent whereas, the propeller efficiency, aerodynamic efficiency and propeller functioning could be of the order of the 85 percent and in which case, the overall engine thrust producing efficiency could be of the order of 25.5 percent. Now, that is a kind of overall thrust production efficiency with which the aircraft power plant functions.

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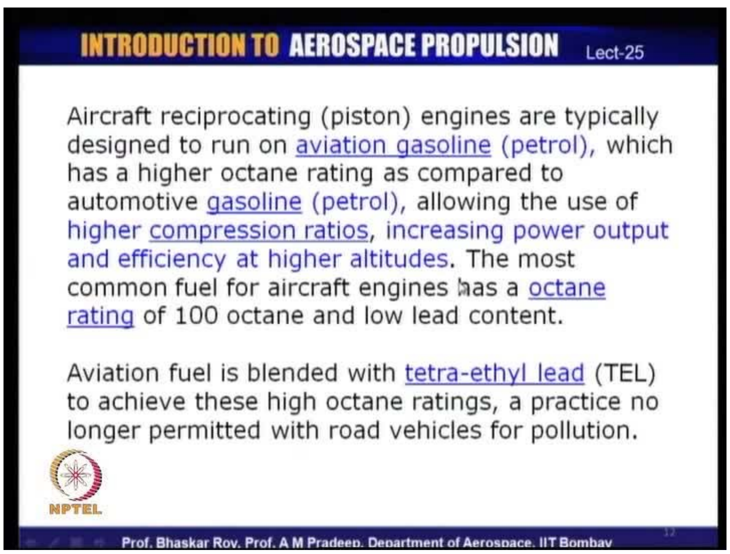

A word about the fuel: some of the fuels that are used in typical aircraft engines are basically the petrol based. In some parts of the world, they are also called gasoline. Now they have, as I mentioned a very high heating value; that is how they are chosen and quite often, they are to be used under high compression ratios. We need to have high power output and of course, as we have just seen the efficiency definition, good efficiency at various operating conditions of the aircraft and most specifically at high altitudes where the aircraft actually flies.

This kind of fuel is typified by what is known as high octane value and octane weighting is given in terms of 100 and the aircraft fuels are often of 100 octane. They often have what is known as a small amount of lead content. This lead is tetra-ethyl lead, which is often added to a basic fuel, blended with the basic fuel which is often as I mentioned some variety of petrol and provides high octane rating. We know that in the land based auto mobiles, this addition of tetra-ethyl is now banned because of the environmental issues, but in aircraft engine, it is still being practiced because aircraft mostly flies at very high altitudes and as a result of which, we require the high octane rating that is necessary to operate at very high compression ratios, at high speeds for producing high power, at reasonability good efficiencies.

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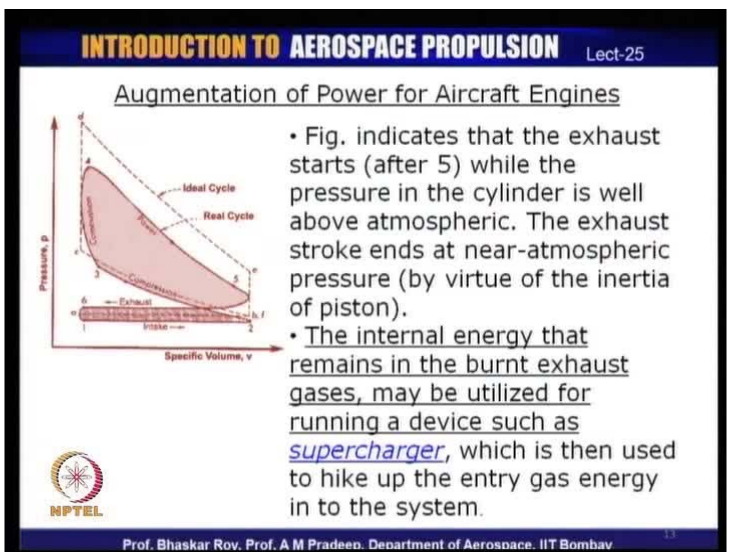

We now see that quite often an aircraft engine has to operate at high altitudes, where it has to produce good power at good efficiency and for power production at high altitudes, we have a few issues. If we go back to the cycle diagram which we are familiar with, we shall see that the exhaust that starts at the 0.5, well while in the cylinder, pressure is still quite high actually, high above the atmosphere. You realize the aircraft is gone to high altitude and the atmospheric pressure is rather low. The exhaust stroke which ends at near atmospheric, which as I mentioned by virtue of the inertia of the piston motion happens at a lower pressure. So, the difference between the exhaust pressure and the intake pressure starts going up and as a result of which, this loop which we see here, the intake exhaust loop starts consuming more and more, this area becomes higher and higher which is the non-productive or non-power creating loop of the cycle. As a result of which, a lot of power that is produced actually goes into this loop and it is not available at the end as BHP.

Now, this is a problem and as a result of which, the available BHP would go down. One of the ways of getting around this is by what is generally known as augmentation procedure and in this, an attempt is made to raise this intake pressure to higher level through a process which is known as super charging and a device that is called supercharger, which raises the intake pressure to higher value so that this intake exhaust loop again becomes a small one and does not take away a lot of power. As a result of which, the BHP available would again become a reasonable value for supplying power to the propeller. This super charging is a business which we will look into in some detail in the next class. For the moment, just remember that for aircraft engines you need to have this augmentation, which is normally not required in land based automobiles, but in aircraft without this augmentation procedure or without the supercharger, the aircraft would not be able to get sufficient power supply from the engine for executing its flight motions.

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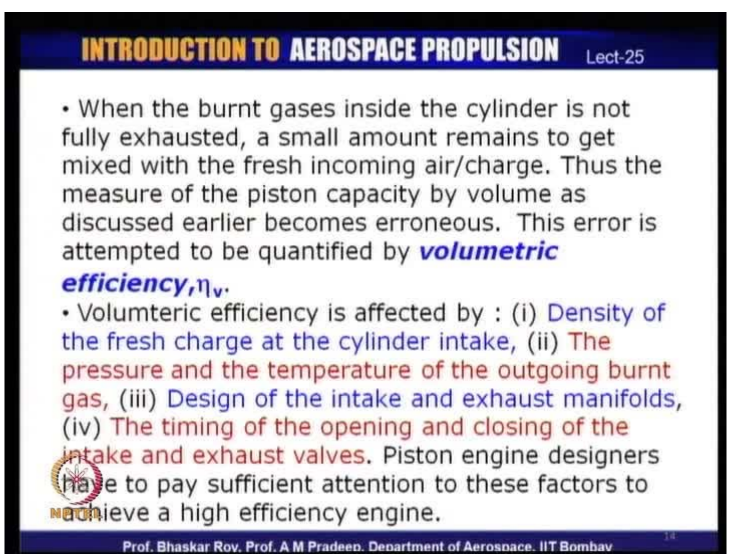

Now when the cylinder is operational, we have just seen that at the end of the exhaust stroke, the burnt gases are exhausted from the cylinder. However, we also know that at the end of the stroke, when the piston reaches the top dead center, there is a certain amount of volume which is still containing the burnt gases. All the burnt gases do not go out of the cylinder, a very small amount remains and when the intake valve opens and the fresh charge air comes in, it gets mixed with the fresh air and as a result of which, what you get finally, is a combination of fresh air charge and a certain amount of residual burnt gases that has remained after the exhaust stroke. As a result of which, effectively the piston capacity or the volume which we have been talking about effectively gets reduced.

This error is attempted to be now quantified through a term which we called volumetric efficiency. Volumetric efficiency, we shall define in a minute, but let us quickly understand what it is all about. What happens is, the density of the fresh charge effects a volumetric efficiency and we have seen in an aircraft engine, we need to hike this density through the process of supercharging and then the pressure and the temperature of the outgoing burnt gas which has remained or the residual amount and then of course, how quickly or how efficiently, the intake and the exhaust valves or manifolds as they are often called, open and close. So, the closing of the exhaust and the timing of the exhaust and the intake manifolds is of great importance and this is where the mechanical engineering comes in a big way. The engine needs to be designed to create a very efficient intake and exhaust manifolds otherwise, it will affect the volumetric efficiency and the timing of the opening and closing of these valves.

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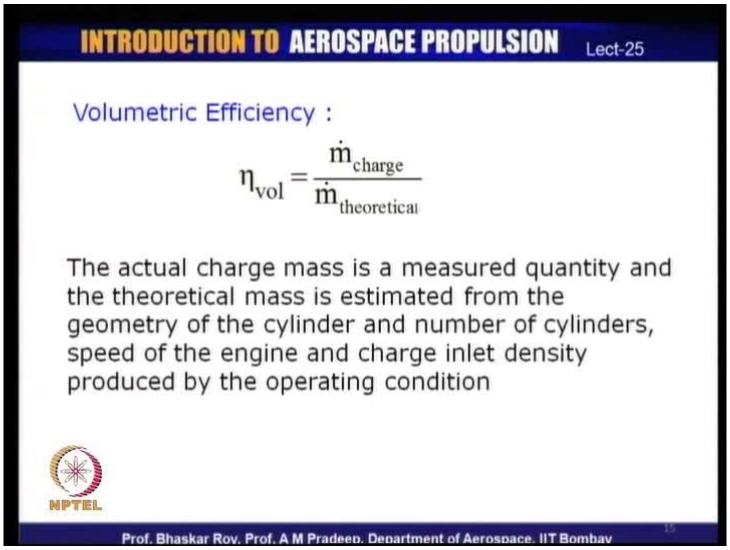

This is the engineering that needs to be engineered into this particular piston cylinder arrangement otherwise, it will affect the volumetric efficiency and this needs to be made with sufficient attention by the piston designers. Otherwise, the volumetric efficiency as it is defined would be coming into the picture and it is simply defined as the charge that is coming in or the charge that is now available by the theoretical charge, which we assume to be effective in the cylinder.

So, the ratio of the two is the volumetric efficiency: The actual charge is the mass that is theoretically estimated from the geometry of the cylinder and the total number of cylinders etcetera, which we often quoted as I mentioned earlier, as the engine capacity and as we see now quite often that theoretical capacity may not actually be effective or operational during the operation of the engine due to the various factors that we have just mentioned. So, the actual operation of the engine would get effected by the volumetric efficiency of the engine which is typically, less than 100 percent.

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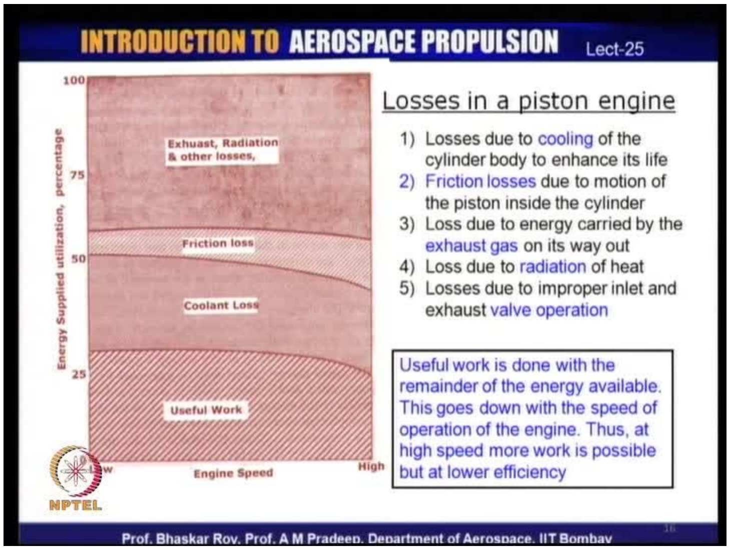

The various power that is created is affected by the various losses that occur. We mentioned one of the losses; that is the friction losses due to the motion of the piston. There are other losses which we need to contain with and they all affect the final power supply of the engine. One of the losses is due to the cooling of the cylinder body. You see the cylinder is getting heated; we are burning fuel. The cylinder is getting heated; the piston is getting heated and they get heated to very high temperature. In spite of the advancement of the material science and metallurgy, the heat bearing capacity of these metal bodies has certain limitations and if you have to provide them with certain amount of life span or working, which often is in terms of thousands of operational hours, then it is necessary that these bodies are cooled on a continuous basis to lend them a certain respectable amount of life.

As the result of which, a goodly amount of heat is actually lost through the cylinder body through the process of cooling. This process of cooling is absolutely essential for the life of the engine, but it affects a continuous operation of the engine in terms of its actual power supply efficiency. (Refer Slide Time: 40:13) So, a good amount of cooling losses actually take place and as we see in this particular simple graph, as the engine speed increases from the low to high, the cooling losses actually stay more or less of the same order. The friction losses keep on increasing as the motion of the piston becomes faster and faster, the friction losses are more and that is of course, easy to understand as this is a mechanical friction. The other important loss is due to the radiation of the various heat that is produced within the cylinder due to the exhaust, which the gas is going out and it takes away lot of heat with it.

So, the exhaust gas when it is exhausted or forced out of the cylinder goes away with a lot of heat. That loss of heat, the radiation losses and many other losses such heat related losses put together amount to a large amount of losses. Certain amount of losses is due to the improper inlet and exhaust valve operation. All of these are the mechanical functions of the engine and when you put all of them together, we find that the useful work actually is a small amount - little more than 25 percent of the energy that is produced through the burning of the fuel. So, only 25 percent of the energy is finally, probably available as useful work and it goes down a little with the speed of the operation of the engine.

Typically, one can say at high speed, you can get work done - total amount of work, but the efficiency of the work done is likely to be somewhat of the lower order. This is the penalty that you have to pay aircraft engine because you do want high work - high amount of work supply and as a result you are consigned to or you have to be content with the fact that you may have to be working at a slightly lower efficiency because the frictional losses and the other losses are somewhat on the higher side, at high speed operation.

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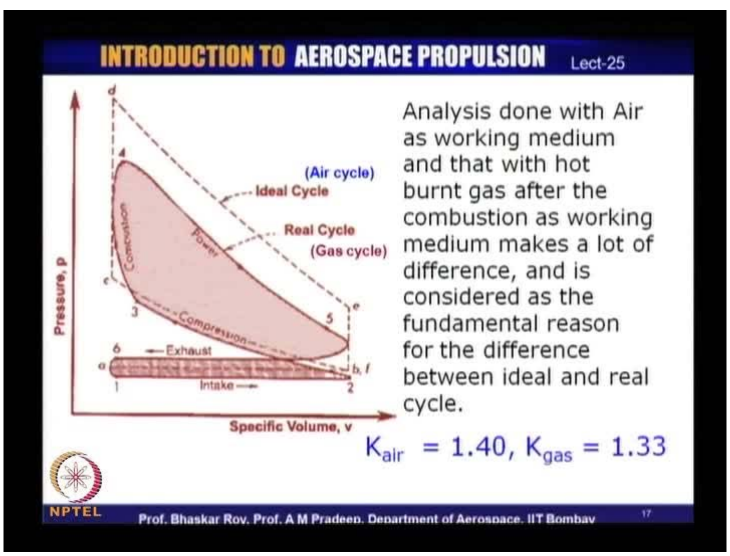

The other thing that we need to keep in mind is we have talked about ideal cycle and real cycle. One of the main differences between ideal cycle and real cycle is that the ideal cycle is actually operating on air cycle whereas; the real cycle is operating on a gas cycle. Inside the cylinder, fuel has been burnt, gas has been created and actual operation of the cycle is especially from point 4 to point 5 and through the exhaust, it is not air, it is gas combination of air and burnt fuel. What we have from 4 downwards - 4 to 5 and then on to 6, is actually gas. So, this part of the cycle is definitely gas cycle and that is why, that is one of the main reasons you see, there is a big difference between the ideal cycle which is given from d to e and the gas cycle - gas process from 4 to 5 and there on to 6. This difference is mainly due to the fact that you do not have air and as we know and we can count the numbers now, that for air, the specific heat ratio given by K - in some books is given as gamma, it is often of the order 1.4 whereas, for the gas it is 1.33 and when you factor them in your some rhymic cycle calculations, you will find there is a big difference between use of these two values in the power calculation or pressure ratio calculation. As a result of which, there is a big difference between these two areas and it is due to the simple fact that you do not have air here; what you have here is gas.

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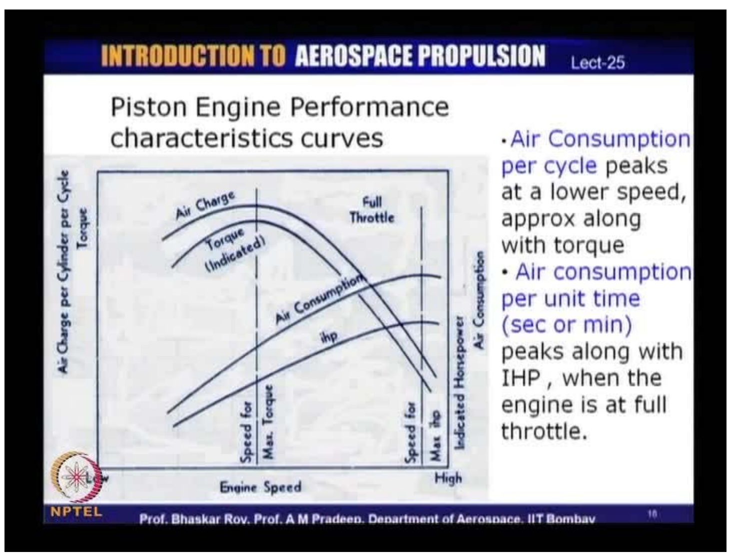

Let us look at some of the issues of the engine as a whole. What happens when an aircraft engine is a piston engine is performing for powering an aircraft? As we can see here, the air consumption per cycle - that is given over here as y axis and that goes up with the speed. On the other hand, air consumption per cycle goes up and it reaches a peak somewhere over here and it goes down whereas, the air consumption per unit time - per unit second or minute, actually continues to go up over here and it reaches a peak at a very high speed. So, there is a difference between the air consumption per cycle and the air consumption per unit time. The air consumption per cycle peaks at a somewhat lower speed, not at the high speed and then it actually starts going down with increase of speed of operation whereas, the air consumption per unit time actually goes up till the very high speed and then plateaus up. As a result of which, IHP, the indicated horse power actually, keeps going up and reaches the high value at high speed.

On the other hand, the torque created, peaks with the air consumption or charge consumption per cycle and it is approximately around and may not be exactly with the same engine speed, but somewhere around. As a result of which, the high torque is often created at somewhat lower speed not exactly at high speed, but high power is created at high speed. Now, this is a dichotomy which most engines have to live with, that high torque creation which is important for operation of the propeller and high power supply which is also important for creation of the thrust are at two different speeds, quite often two very different speeds. As a result of which, the engine operation needs to be properly configured or matched with propeller operation. We shall discuss about some of these later on again, in this course.

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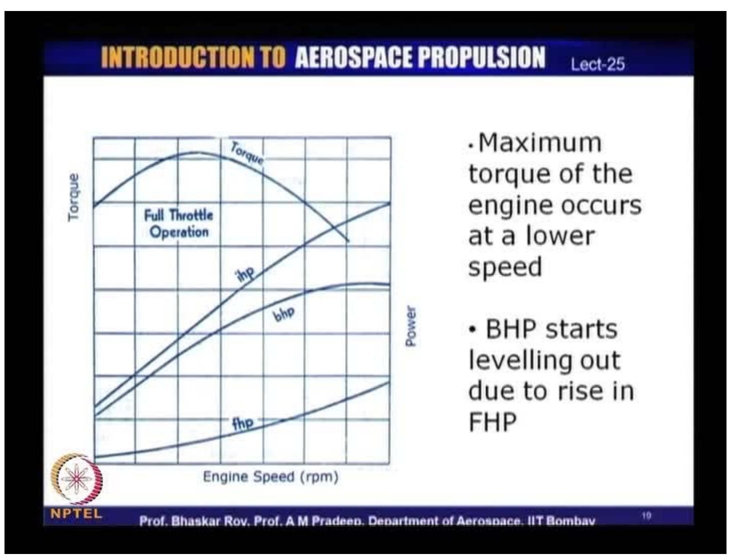

The maximum torque of the engine occurs, as we now see at a somewhat lower speed and the IHP keeps going up, as we have seen in the last graph. Whereas, the BHP which takes into account now, the FHP, actually keeps going up and then somewhere over here, the high FHP forces the BHP to level of and it sort of plateaus out and BHP may not increase any further, after certain engine speed.

So, every engine has high speed at which BHP reaches its peak and there is no point operating the engine above that. So, quite often, most engine speeds are cut of slightly about this high speed and it does not operate anywhere higher than those speeds and this is found out from this engine estimation, before the engine is actually installed.

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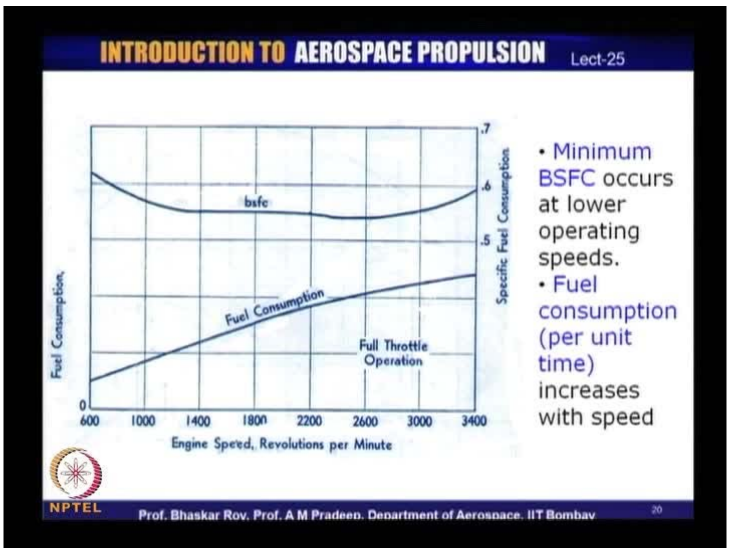

If we look at BSFC, we have seen it is one of the most important parameters of the engine operation; it is indicative of the efficiency of the engine. However, in this graph we see that BSFC and the total fuel consumption are two slightly different issues. BSFC is a unit fuel consumption per unit mass flow or unit power consumption, it is indicative efficiency and it reaches some kind of low plateau somewhere in the speed range over here, in this particular engine that is being shown. It reaches a low value over here at lower speeds; it actually has higher BSFC at high speeds and again, it starts going up and BSFC is no more the lowest.

So, the engine operation in this range of speed would probably give a low BSFC. That is true of most or almost all kinds of IC engines or piston engines and even automobile engines that run the cars or vehicles on the ground. Car manufactures or operators would tell you that car operation at certain a medium value of speed or rotation, often produces the best efficiency of fuel consumption. On the other hand, if you take the total fuel consumption and we are talking about full throttle operation, it continuous to increase with the speed. So, higher the speed of operation, higher is the fuel consumption. So, we have to balance between the We have also seen that higher the engine speed, higher the power production. So, there is always a balancing act that the operator has to find out between high power consumption, high power creation which reduces which obviously, has high fuel consumption. On the other hand, the BSFC also starts going up.

If you keep an eye on the efficiency of the engine, then you would probably like to operate somewhere at a slightly lower values of engine speed. We have seen that at one of these lower values, you also get high torque. So, high torque, BSFC, fuel consumption and power production are four different parameters and engine operators have to keep an eye of all of them, while operating the engine, to find the best balance during the various course of operation of the engine.

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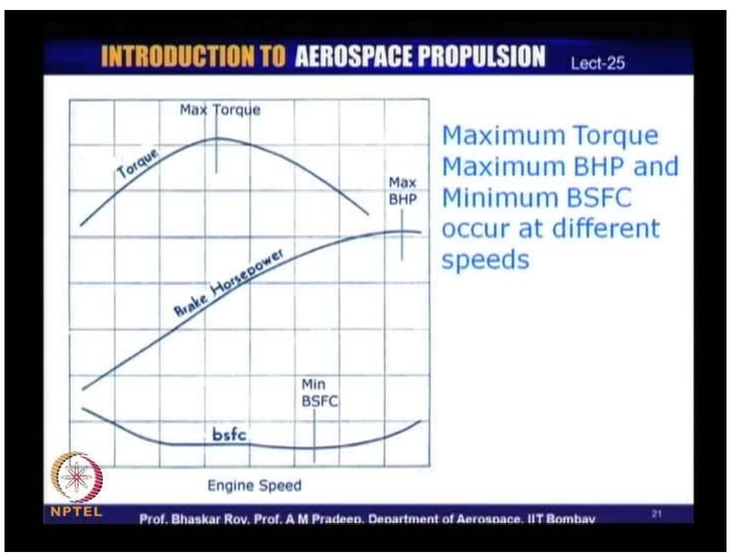

We see now that maximum torque operates at some speed, maximum power operates at another speed and minimum BSFC happens at third speed. So, we have three different speeds and this is true of most of the engines - all kinds of engines, IC engines that power the aircraft power plant. This is what an engine operator will have to quickly figure out and apply his engine control to operate. Typically, he would like to do it in such a manner that taken over the entire aircraft flight let us say, from takeoff to cruise to landing, finally, the total fuel consumption would be at a low value. This is something which requires a certain amount of control, which require a certain amount of engine control, propeller control, some of which a little bit of which we might discuss later on in this course and the two controls together we will have find a balance of using the engine for maximum torque or maximum BHP or minimum BSFC so that the total fuel efficiency of the engine is quite good, competitive and has an economic repercussion in the operation of the power plant. These are the issues that typically, an engine operator - an engineer would have to deal with, in the operation of the engine for flying an aircraft.

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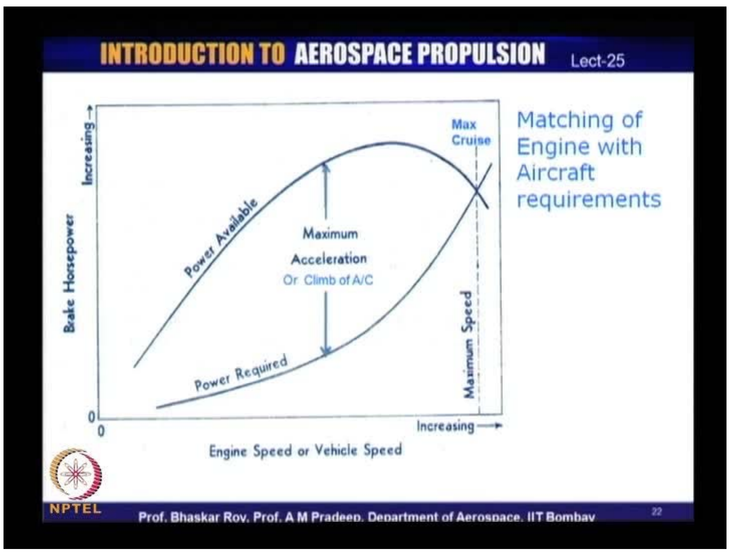

In flight flying of an aircraft engine, one of the things that is required is, once the engine takes off, it has to climb to a cruise and the engine typically needs to provide certain amount of extra power not only for cruising but also, for climbing and this is how the measure of the extra power needs to be quickly arrived at, so that when an aircraft takes off and then it finally, reaches a cruise where the power available and the power required are matched. Typically, cruise will be somewhere here, actually little before this and we shall talk about that again, later on how the matching of the aircraft and engine is done. This excess power availability from the engine is vitally important because this is what makes the aircraft climb; otherwise, aircraft would not be able to climb from low altitude to high altitude, to the cruise altitude.

So, this excess power requirement needs to be factored into the engine design and this is vitally important for aircraft engines.

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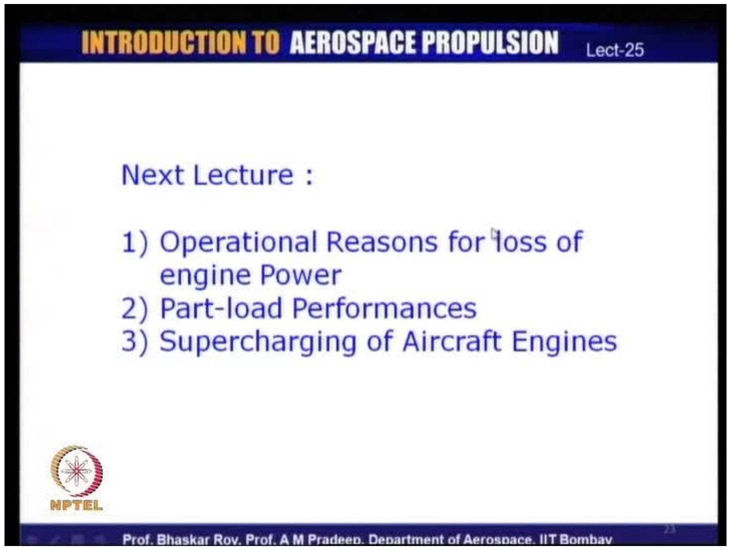

In this lecture, we have now looked at various aspects of engine that goes into the aircraft. In the next lecture, we shall see various issues that go into the operational reasons for loss of engine power. We shall see what happens, when the engine operates at part-load, which is when the engine is not at its full BHP, a full power creating capacity, but at some kind of part power creating capacity and what happens during those operations and we shall see that for an aircraft engine, for it to operate at high altitudes, it is necessary we have a supercharging which creates augmentation of power; without super charging, we cannot have an aircraft engine. So, these are important issues, specifically with reference to aircraft engines and these are the things, we shall discuss in the next class.