Jet Aircraft Propulsion
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Lecture No. # 26

Practical Combustion System; Stability, Fuel injection

We are talking about combustion chambers. In the last classes we talked about the combustion mechanism, and then we talked about some of the combustion parameters that help us quantify the overall combustion performances, in certain numbers that allow us to figure out whether the combustion is going on in a proper manner. In today's class, we will look at a few more issues related to the combustion. The first thing we will do is we look at the injection of fuel. Now the fuel that is be injected is liquid the working medium of the jet aircraft engine is air.

So, we have a fuel supply that is in the liquid form, which needs to be used to essentially put in energy into the aircraft engine. Now this liquid fuel supply that is made is of course, the aviation kerosene that we have talked about in the first class or the properties of the fuel, and its some kind of comparative values have been shown in the first class related to the combustion chamber. In today we will look at how the liquid fuel is injected into the combustion chamber to aid the process of combustion, which we have been discussing for last two classes.

And after the fuel injection phenomenon, we will look at some of the issues related to the holding of the flame, related to the stabilization of the flame, the immediately after the fuel is injected into the combustion chamber. A flame is created - flame is the process through which the heat is finally released into the engine. Fuel of course is the carrier of the chemical bonding, and flame is a process through which this energy is finally released into the working medium and that is air. So, we need to understand how this flame is stabilized, and what is the mechanism by which the flame stabilization can be carried out on a continuous basis throughout the operation of the engine under various operating conditions.

So, we will have a look at these mechanisms, and then we will have a look at or try to understand some of the vexing issues related to instability in combustion. Now the combustion instability is one of the problem that is been known for quite some time; however, it is become a focus of attention in the last few years. And we will discuss, why it is become a focus of attention in the last few years related to specially related to jet aircraft engine operations.

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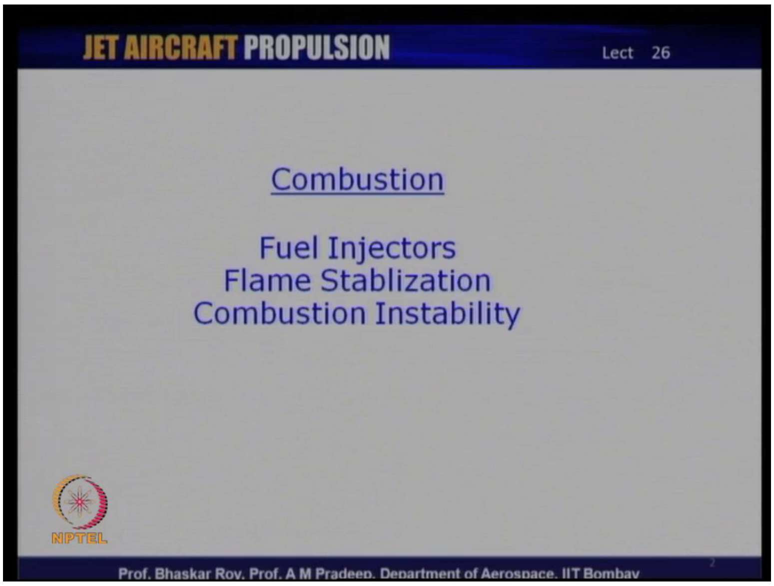

So, these are the issues we will discuss in todays lecture starting with the injection of fuel then going on to the flame stabilization and then talking about certain issues related to stability of the combustion phenomenon itself in the combustion chamber. So, let us take a look at these issues now one by one. Now fuel injectors are one of the issues that people have been designing injectors for more than 50 years now. However, various kinds of injectors have been designed over the years and we will look at one of the most commonly used fuel injector used in most of the aircraft engines these days and try to understand exactly how the fuel injection is carried out to aid the process of combustion.

So, it is it is a little more involve than any other kind of fuel injector that one may have seen in any other kind of engine and these fuel injectors are specifically design for jet aircraft engines. So, they are unique kind of fuel injectors. Let us take a look at some of these injector related issues and one such well good modern injector.

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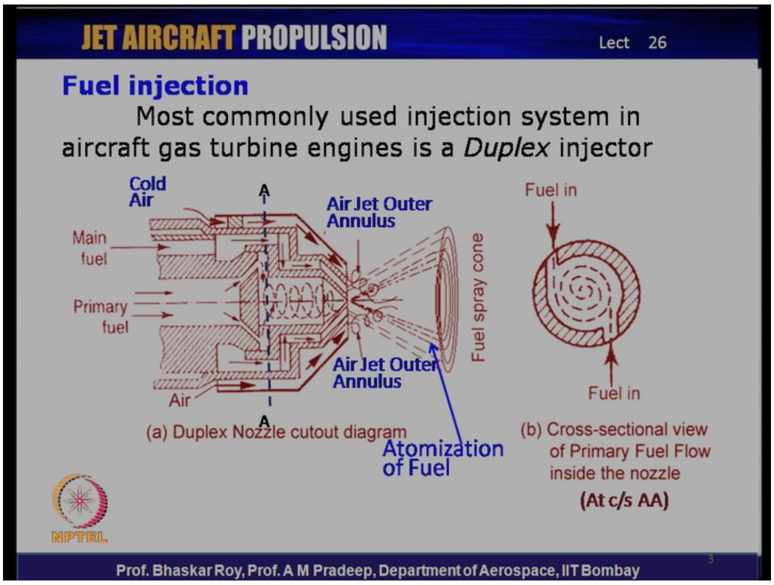

If we take a look at an injector one would see that there is lot of things happenings over here. One is you have fuel that is being injected and one of the issues that we have discussed before is that the injection process needs to be carried out in such a manner that the fuel when it comes out of the injector, actually creates a very large number of what is known as droplets of liquid fuel. So, that the processes of elaboration mixing with air and the process of creation of a gaseous mixture of air and fuel is done very fast and the fastness of the process of this mixing evaporation and mixing is extremely important.

So, the injector design and the injection process must be made in such a manner that it aids the process of atomization and mixing, before the combustion in a very small time that small time is often of the order of fraction of a second very small fraction of second really. So, let us see how the injection process is indeed done through an injector a typical injector in aircraft engine. Normally the fuel is sent through the injector in two parts, one is what is known as a primary fuel, which allows it go straight into the main fuel injector and this main fuel injector is shown over here.

It has a small baffle over here it goes around it and then gets injected into the main fuel injection chamber, which is circular which is shown on the right side here on B. So, the cross section A is kind of shown over here and it shows that the fuel is coming in into the main primary chamber injection chamber from two sides one from this side other from that side. And this geometry is designed in such a manner that the fuel input into this chamber immediately creates vertical fluid system rotating fluid system. So, this vertical fluid system then proceeds towards or push towards the nose of the injection, which is the convergent nozzle actually and this convergent nozzle then creates the jet or fuel that comes through.

But before the jet is created the jet has been given very strong vertical motion and then it comes out in a jet with the vertical motion. As a result of which it immediately creates a cone, which is as the result of the vertical motion inside and this cone essentially spreads out in a expanding manner. And as a result of which the surface of the fuel cone that is spread immediately expand substantially and the expansion of the sub the surface is essentially means that there is more surface area of the injection jet. As it proceeds away from the injection point and more surface area means more area through, which the evaporation and mixing can take place.

So, that is the intension that you create fuel spray cone that has an expanding surface area and that surface area essentially aids the process of evaporation and mixing in a very short period of time. Now to aid the process the modern aircraft nozzles engine nozzles have another fuel that is injected, which is in a concentric manner. So, there is another fuel supply that is coming in and that this comes through this concentric annular passage and it comes as a annular outer annuals jet impinging into the inner jet and also creates another outer annuals of the jet.

So, we have two jet systems that are coming out of the nozzle now. One is the inner annuals inner jet that is created by the primary fuel and the other is the outer annuals that are created by the so called main fuel supply. Now the important point here is the creation of this spray cone with an ever expanding surface area to aid the process of evaporation and mixing. To do that more efficiently the outer annuals now as an air jet. So, in addition to the fuel air is also pumped in through the nozzle injector nozzle and the outer most annuals is actual an air jet. This air jet creates an outer air jet annuals and an outer air jet cone.

So, we have a cone system fuel spray cone that is composed of inner fuel liquid fuel jet, the outer annuals of a fuel jet and the outer most annuals of air jet. The air jet of course, again aids a process of evaporation of a mixing and as I mentioned the evaporation mixing needs to be done in a very small fraction of a second. So, this outer annular jet essentially aids that process of evaporation and mixing very fast evaporation and mixing. Now because of the fact that the fuel is supplied in two different channels, one is the central channel the primary channel, another is the main fuel which comes out through the outer one outer annual. It allows the fuel supply to be control by two different means.

So fuel of course, is the primary control in aircraft engine and as a result of it the fuel control system now, as two control systems two elements to control, one is the primary fuel another is the main fuel. When aircraft is in takeoff or in high thrust creation mode both the fuel supplies are kept own. So, that more fuel is pumped into the combustion chamber. However, when the aircraft is in low thrust mode, which could be during the cruise the outer annuals or the main fuel supply could be actually switched off and only the primary fuel supply is kept on.

Because the amount a fuel supply required now is much lower and as a result of which two different fuel supply fuel flow control systems can be incorporated in the engine control. Now this control mechanism of course, is incorporate in the engine control algorithm. So, in addition to primary fuel now you have another fuel which is called main fuel. There is theoretically in fact, some people have made it which can be called a triplex nozzle system, in which you have third fuel supply and of course, a third fuel control supply.

However, since it adds to the control problems quite often most of the aircraft engines these days continue to use the duplex nozzle rather than the triplex nozzle and as the name suggest one could have simplex nozzle, which as only one single nozzle system very small aircraft and simple aircraft system often use the simple simplex nozzle, which as only the primary fuel supply. sometimes the simplex nozzle system has been slightly upgraded with primary fuel supply and a air jet outer annuals to aid the process of evaporation and mixing.

So, this is the process of fuel injection fuel fairly complex injector that needs to be created and this injectors are very small in size the diameter of this such an injector could be as you have seeing here could be of the order of just about two or three centimeters, just it will be more than an inch probably and as a result of which creating all this inside is of course, requires very fine fabrication and manufacturing techniques and some of these have been used for sometimes. So, these fuel injectors are indeed rather complicated manufacturing pieces and indeed quite costly.

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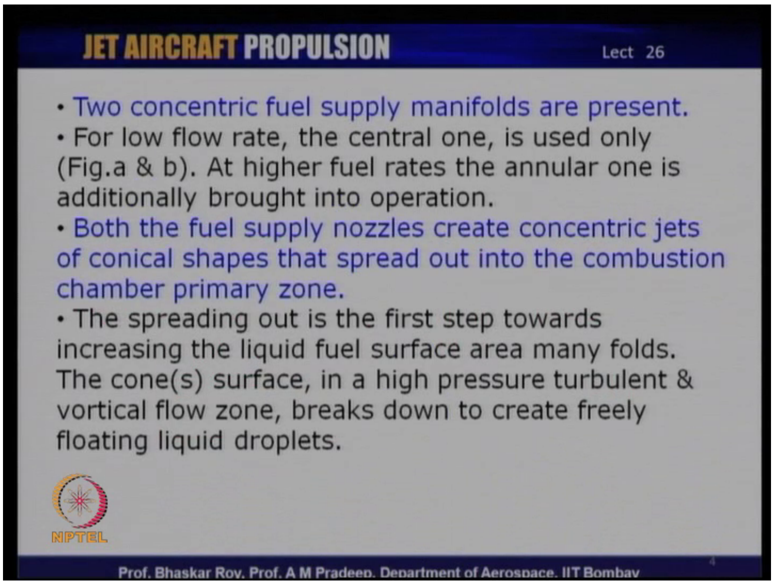

So, having look at the duplex injector we can just some up by saying that we have two concentric fuel supply manifolds, which as supplying fuels into the combustion chamber. The fuel flow rate the central one is used only when the low flow replies required. As I mentioned which could be during cruise and when high fuel flow rate is required during acceleration of the engine or that is of the aircraft and during takeoff and climb both the fuel flow rates fuel flows could be open and higher fuel flow rate is supplied into the combustion chamber. Both this fuel supply nozzles creates this participate in the process of creating this concentric jet that is the jet cone.

And that is spreads out into the combustion primary zone and so primary zone is where this jet of fuel is indeed infused into and that is where or the flame is created. This spreading out of the jet cone or the fuel jet is the first step towards increasing the liquid fuel surface area and this is what I was saying just now that the surface area increase is the intended purpose of creating this jet cone and once that is increased the jet actually breaks up in small droplets very small droplets of the size of fraction of millimeters of diameter and these droplets then evaporate very fast.

So, the cone surface in a high pressure turbulent and vertical flow zone that is created in the primary zone then breaks down this cone and creates freely floating liquid droplets and that is the mechanism that is needs to be created in the combustion chamber to aid the process of combustion without this mechanism and the there is a lot of engineering that goes into it.

Without this engineering the combustion inside the aircraft engine would not be possible to be done in the manner that needs to be done.

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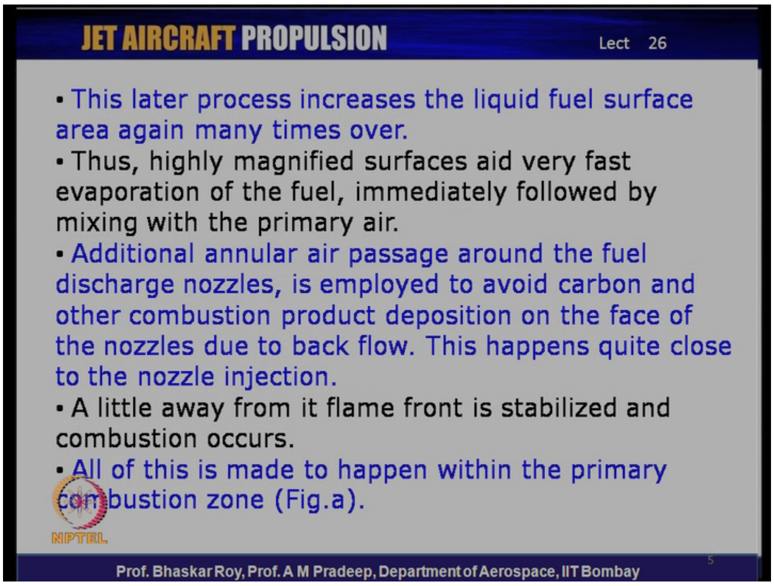

This later process increases the fuel liquid surface area many times over and as a result of which it aids the first of all evaporation, it aids the process of mixing and all these needs to be done in the primary zone with the air and remember this mixing as to be done in a correct fuel to air ratio. The additional annular air passages around the fuel, which is discharge through the nozzle outer annuals outer most annuals as we have just seen. It is also used one of the purpose main purpose is to avoid the carbon and other combustion product deposition on the phase of the nozzle.

Now this is important issue once the fuel comes out of the nozzle you have flame you have the combustion product that is created and remember that area the primary zone area is the very low velocity flow area. So, once the combustion products created there is an every possibility that some of the combustion product from the flame zone can get can float down and deposit on the phase of the nozzle. Now this is a problem this is simply known as carbon deposition in simple engine terminology it is it means that lot of combustion products are getting deposited on the phase of the nozzle.

Now, if that happens the nozzle exit the fuel exit would may get choked and the fuel would not come out of the opening that is created for the fuel jet. Now, this needs to be avoided and this air jet has this additional job of making sure that the combustion products do not come back on the nozzle phase and they get literally blown away from the nozzle. So, that the nozzle phase remains clean for entire operation of the engine and then we have the problem of a stabilizing the flame front, which is something we are going to talk about in this class and that, is a problem by itself and remember all this has to be done in the primary combustion zone.

You remember we had primary zone, we had secondary zone, we had tertiary zone and primary zone was actually the smallest space available in the combustion chamber actually more space is given to secondary and tertiary zone. So, within the primary zone all this has to be done a quite successfully to have complete evaporation, complete mixing, complete flame stabilization, complete completion of the flame front and then combustion products created all this to be done within the primary zone only.

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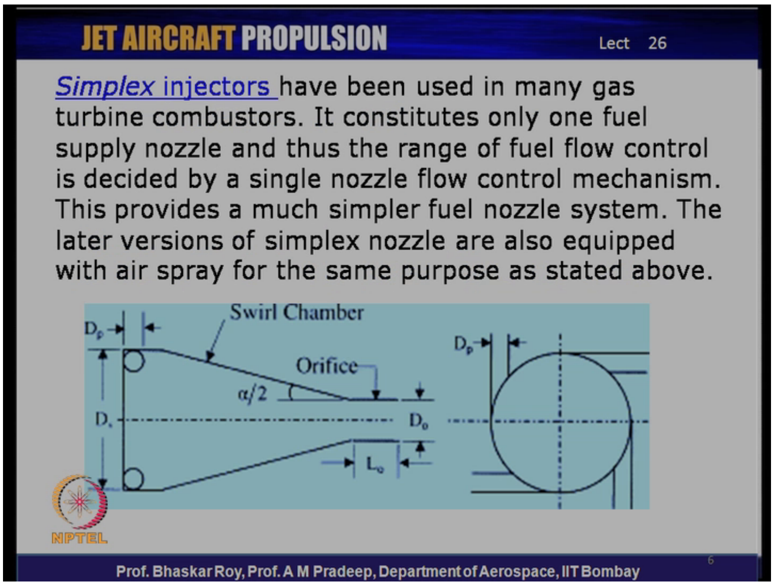

We are talking about simplex injector. So, we can have a quick look at what a simplex injector could be or his actually, it is actually used in many gas turbine engines which are comparatively simpler operation schedule and does not have too many a high fuel supply and low fuel supply requirements and a steady fuel supply would be sufficient and this is actually means that it provides very simple fuel nozzle system. Some of the later once as I mentioned is also equate with an outer annuals of air spray that means, outside this fuel supply there is an air spray that is coming which would aid the process of injection cone creation and also driving away the combustion products.

As we have seen in the duplex here again we have the main fuel supply chamber and the main fuel supply is made through these four supply tubes or channels and the fuel gets into this primary zone with a vertical motion and with this vertical motion only. It is channelized through this nozzle shaped injector an is injected out into the combustion chamber. So, this creation of the vertical flow inside the nozzle is extremely important because it creates it helps create the cone that comes out from the jet and that cone is extremely important in the process of evaporation and mixing.

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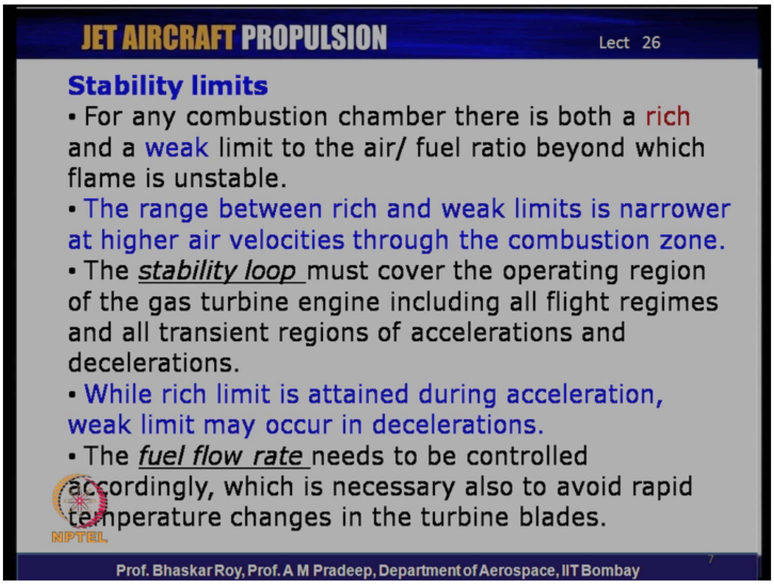

Now, we will look at some of the issues related to the combustion that is normally created by the combustion itself. Now during the process of an aircraft engine operation, we have seen an aircraft has we takeoff it has to climb, it has to cruise, it has to do all kinds of maneuvers, and then it has to descend and come back and land. During all these processes the fuel supply into the combustion chamber is most likely to vary, if you have a military aircraft which does all kinds of maneuvers, all kinds of accelerations, decelerations, all kinds of turning, and fast recoveries, during all these processes the fuel supply would need to be control very quickly.

So, the fuel the control of the fuel supply then also means that the injection processes and immediately thereafter the flame that is created that means, the entire combustion process would need to have a stability of its own. Now, this is easier say that done because we have seen that the fuel air ratio should obvious be somewhere near about the stoichiometric ratio. The correct chemically correct fuel air ratio if it goes if the fuel is too much it becomes a rich mixture and the combustion gets blown out. If the fuel is to less it becomes lean mixture and then again the combustion get extinguish.

So, in a very narrow range the fuel air mixture needs to be healed. So, the trick is to hold the fuel air mixture very close to the correct ratio. Now when the aircraft is doing all kinds of maneuvers engine is also expected to do all kinds of changes in its own schedule and during which above the fuel supply and the air supply into the combustion chamber is going to change. Now with the change of air supply you have to change a fuel supply because if the air supply is less you have to reduce the fuel supply otherwise you will have a rich blow out if the air supply is more you have to increase the fuel supply otherwise you will have a lean blow out.

So, during these changes in air supply you have to change the fuel supply and as a result of this transition the stability of the flame that is created needs to be ensure. So, we have a little problem here that the stability of the flame needs to be taken care of during the process of various kinds of transition or various kinds of changes in schedule of operation of the engine. Let us take a look at some of the issues related to the stability of the combustion and the stability of the flame as any combustion chamber there is about rich limit and a weak limit to the air fuel air ratio around the stoichiometric value that we have talked about.

Now, the range between rich and weak limits is narrower at high air velocities through the combustion chamber. So, the air velocity average air velocity through the combustion chamber is little on the higher side as it would be if the air mass flow is on the higher side. Then the limit is or the range available to you is actual narrower.

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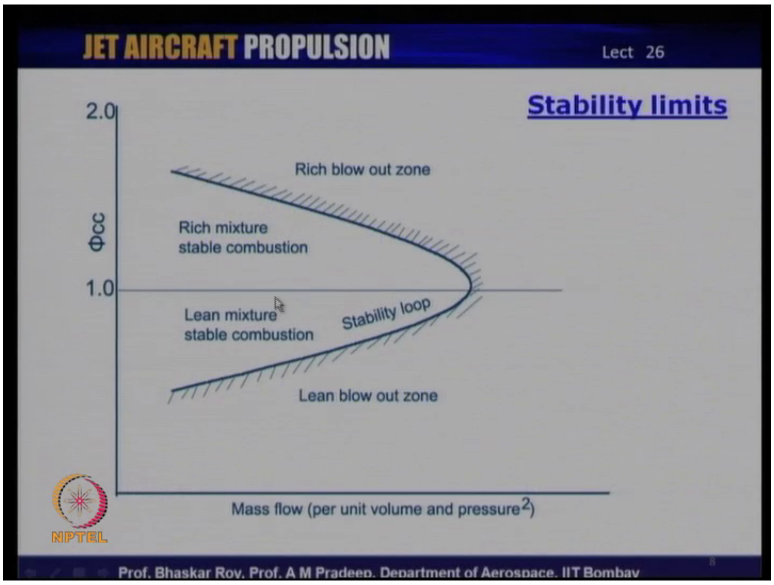

Then we have we will take quick look at what we are talking about this graph captures or tries to capture the problem that we are look at a typically a combustion would be carried out within this so called stability loop and outside the loop above this is what we call the rich blow out and the below is what we call the lean blow out zone and inside it we have the stable combustion possible. Now, the street line that we have here is the stoichiometric ratio about that the combustion is say to be a rich mixture and below that the combustion is said to lean mixture as long as it is within this stability loop we can say that its having stable combustion.

Now this line is shown here the y axis is shown here with value five of combustion chamber. Now let us define this five, this five is nothing but equivalence ratio and this equivalence ratio is what is shown over here plotted with the mass flow which is normalize per unit volume per unit pressure square. And as a result of which this plot is often called the stability plot and this curve given here is called the stability loop. So your combustion would have to be always within the stability loop outside the stability loop the combustion would simply get extinguished.

Now let us go back and an I will give out our issue over here the stability loop that is available must cover the operating region of the entire gas turbine engine including all flight regimes that we are talking about the takeoff the climb by the cruise and all maneuvers for military aircraft. All of it needs to be done within this stability loop; there is no possibility of the aircraft operation outside this stability loop of the combustion and hence the stability loop also defines the boundaries within which the whole engine can be operated and indeed the whole aircraft can be operated.

And this also means that the fuel flow rate needs to be control very accurately and as I mentioned the fuel flow control are the primary control of the aircraft engine. This needs to be done in a manner such that is matches with the air flow almost all the time during the operation of the engine and this is absolutely necessary to avoid rapid change in temperature in the combustion chamber delivery which is going to the turbine blades. You see if go into the stability loop to the higher side of rich mixture, if you allow the rich mixture to operate for long periods.

What happens is your delivering very high temperature to the turbine? Now if you deliver high temperature to the turbine it is most likely the turbine life will get substantially reduced. So, it is not a good idea to operate the engine with a rich mixture for long period of time. So, modern engine designers would try to make sure for most of the operation the engine actually operates with somewhat lower lean mixture for stable combustion. So, that the turbine life is also substantially enhanced in addition to the fact that you are consuming less fuel. So, the fuel consumption or the specific fuel consumption of the whole engine would be more economic for operational purposes.

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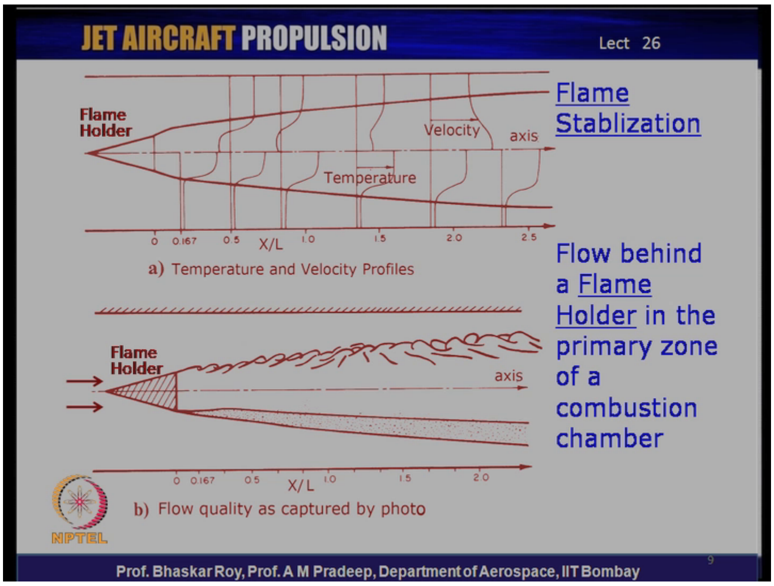

So, if you look at some of these issues we can look at how the flame is to be stabilized. You see many of the combustion chamber have a various kinds of flame stabilizers, they are called flame stabilizers. Now they are also called flame holders, which mean that you put some kind of element over here, which is a solid body. In the main primary zone of the of the combustion chamber and as the fuel air ratio of fuel air mixture flows over this behind this flame holder there is a zone, which is a dead zone as far as the aerodynamics of the air motion is concerned and behind this red zone it creates a low a forward velocity zone.

Now, this is done deliberately and as a result of this the flow around this actually aids across it is shown in the lower diagram. The process that is created here actually aids a process of mixing and uniformity of the temperature distribution over the combustion zone. So, the flame holder essentially does two things, it decelerates the fuel air mixture substantially and allows the flame to be stabilized and as a result of which this speed of motion of the air fuel mixture is matched with the motion of the flame.

Now, flame as we have seen before the flame moves from one point to another and the motion of the flame itself is often refer to as a flame speed and what we can say then is the flame speed matches with the air fuel air mixture ratio and as a result of which given the resident time within which the flame names to be yield in the primary zone. The air fuel mixture is completed the flame is healed the combustion is completed and then combustion products are allow to move away from the combustion zone.

So, flame holder essentially tries to aid this process of anchoring the flame in a small flame zone within which the flame can be burnt. So, that the flame does not move around too much in the primary zone and in which the combustion is then completed the upper picture here shows the velocity field of such flame holder and the upper half of that picture and the lower half shows the temperature variation in that zone, which fluid mechanically is often known as the base flow behind this triangular conical zone.

You have what is often known as base flow and the flow inside this base flow is undergoing a rapid mixing and evaporation and flame being stabilized and during this process there is a change in temperature from the access of this base flow to the outer periphery of the base flow, as you can see in terms of velocity and in terms of temperature and this is picked up from a particular test that is been carried out sometime back in NASA. So, the flame stabilization is a mechanism that needs to be deployed inside the combustion primary zone to ensure you have a flame that stays within anchored in a certain zone and it is stable and it is stabilized around that zone for completion of the combustion process.

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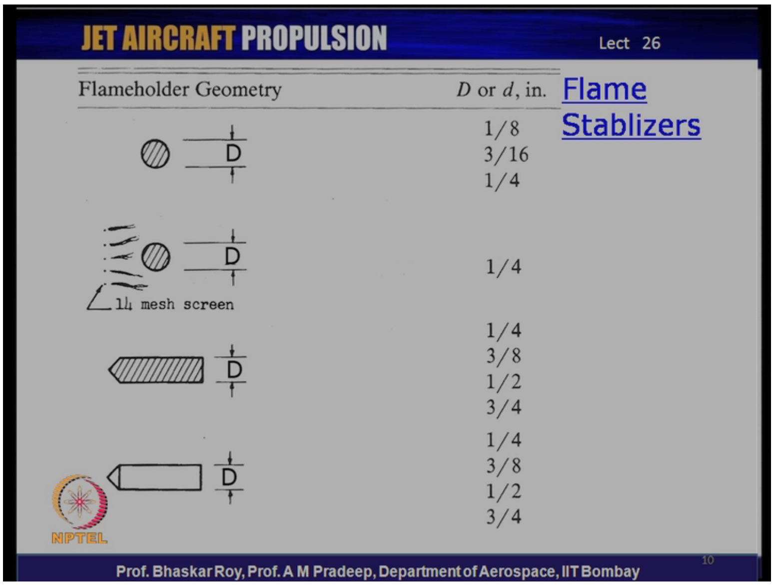

There are a number of flame stabilizers, we are seeing here only a few of them. You could have something as simple as just mesh screen, you can see here there dimension are indeed very small. They are less than one inch in diameter, and this mesh screen essentially is used as a flame stabilizer or often called flame holder. So, air fuel mixture passing through this mesh would get substantially decelerated, and that deceleration is the important issue that needs to be achieved, and once the deceleration is achieved the flame is stabilized. Very fast moving mixture of air and fuel would not give us stabilize flame it will pass through the flame unburned, and as a result of which will have a lot of unburned fuel air mixture right passing through the flame.

The lower to a diagrams here simply show the kind of flame stabilizer or flame holder that we were looking at you can have them and various sizes and essentially you could have it solid or you could have it as a some kind of hallow body around which the flow moves and the flow is behind that in the base flow region, the flow is substantially decelerated and that decelerated flow gives you the stable flame around that base flow zone. So, that is the mechanism by which the flame is stabilize and without stable flame it is not possible to have stable combustion phenomenon inside the combustion chamber.

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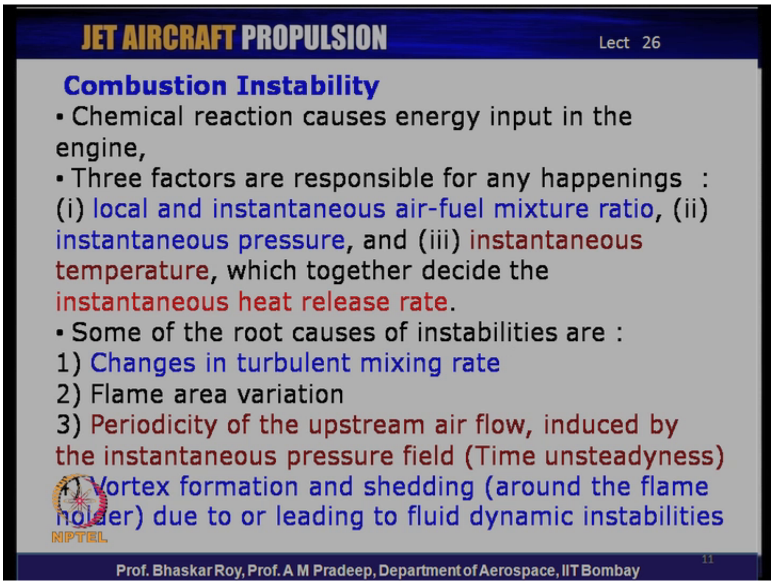

We can have some issues related to the combustion instability if you do not ensure or for some reason even after you have taken care to create a stabilizer to create a nice stabilization zone, even after that there are always possibilities of certain kind of flame instability or combustion instability somehow erupting in inside the combustion chamber. Now, this is a problem that is known for a long period lot of research as gone into it, lot of studies have gone into it and the combustion instability is continues to be a little bit of worry to many of the combustion designers.

Now let us have a look at what are the causes of combustion instability you see the main thing that is happening there is a chemical reaction. Now chemical reaction essentially gives you the energy input into the engine. Now without going into the chemical kinetics we can say that there are three physical factors responsible for combustion or whatever is happening inside the combustion chamber without referring to the chemical kinetics. One is the local and instantaneous air fuel mixture ratio. As I just was taking about the fuel air mixture ratio can change and sometimes it can change very fast depending on the operating schedule and the fuel flow control mechanism that is available and hence we need to know what the instantaneous air fuel mixture ratio is.

If it instantaneously goes above or below the lean or rich ratios it would extinguish the flame. The second factor that is responsible is the instantaneous pressure. Now you see the pressure is applied by the compressor and it is entirely possible that if the compressor is experiencing certain amount of instability. It may give certain pressure fluctuations carried into the combustion chamber and these pressure fluctuations would then impact on the combustion phenomenon itself. So, we have to keep an eye on the pressure modules that are coming in from the compressor and being carried into the combustion chamber.

And the third thing of course, is the instantaneous temperature that is created by the combustion itself. Now as we know that temperature can change with the combustion itself. So, we have three parameters here which to gather decide the instantaneous heat released rate. So, this instantaneous heat release rate can very quickly change from one value to another depending on any of the three parameters and all three parameters put together also decides the chemical kinetics that is taking place there. Now bone out of this knowledge we can say that some of the root causes of the instabilities can be a change in the turbulent mixing ratio.

We have seen that we have to have a good turbulent mixing going on in the primary zone. Later on a different kind of mixing in the secondary and tertiary zone and but the one in the primary zone is focus of attention right now. And this is highly turbulent mixing to aid the processor evaporation mixing and combustion and any change in this turbulent mixing rate could causes instability it would cause non uniformity in the fuel air mixture ratio, which could mean that in some pocket you have rich fuel air mixture in some other pocket within the combustion chamber itself in some other pocket you have a lean mixture.

So, if you have a rich mixture some where you have high heat release you have a lean mixture you have low heat release. So, this non uniformity within the combustion chamber itself could be one of the causes of instability. The other is the flame area variation we need to create as far as possible symmetric uniform flame that is generated through the process of injection and then mixing it is necessary that the flame is uniform and as a symmetric geometry of its own if it loses that then it could create instability within the combustion chamber by virtue of having a different kind of flame characteristics in different parts of the flame.

So, the flame must have uniform flame characteristics over the entire flame and third is the periodicity of the upstream air flow this is induces by the instantaneous pressure field coming from the compressor. Now this is unsteadiness that every engine design must necessarily deal with the flow inside an aircraft engine is always unsteady it is never steady. The degree of unsteadiness is what is important here; if it becomes really fluctuating it could cause a lot of instability in the combustion chamber.

The unsteadiness may be travelling from the compressor itself if combustion becomes unsteady it will create its own fluctuation, which could then travel on to the turbine and the entire engine would then experience a lot of fluctuating air flow fluctuating flow and whole lot of unsteadiness, which could be catastrophic to the working of the engine.

The fourth possibility is the vortex formation and the vortex shading around the flame holder we have seen the flame holder essentially some kind of a black body. It could be some shape conical shape or a mesh or something and that create a base flow behind itself low velocity flow. So, that comparatively slightly higher velocity flow goes about it and base flow a very low velocity flow is created just behind it. Now this creates a vortex. Now this vortex formation and the vortex shading that occurs around the flame holder this itself could lead to fluid dynamic instability.

So, there are number of reasons because of which the instability of the flame could be induced and then we could have combustion instability. Since the pressure inside the combustion chamber is very high the fuel has been injected in the combustion chamber at even higher pressure it has to be otherwise it will not be injected itself. And then at such a high pressure you are releasing very high temperature and a combination of high pressure and temperature, if those two parameters of fluctuating it could create lot of instability to the entire engine and that is most unwanted as far as the engine operation is concerned.

So, holding the air flow steady, holding the pressure steady, holding the temperature steady during the process of combustion is extremely important. Because any fluctuation in any of the three parameters these are the three primary parameters could lead to certain kind of fluctuations instability and that could be catastrophic because it could lead to complete blow up almost like an explosion. So, it is a kind of instability which is most avoidable. Now one of the reasons the modern aircraft engine designers a looking into this instability a little more closely today than probably ever before is the reason that most engines are now ask to operate at low fuel air mixture zone that is the lean mixture zone.

Now if you are operating at a lean mixture zone your operating at what we have called a low equivalence ratio zone. Now if your operating at a low equivalence ratio zone you remember your flow is now having lean mixture and during the lean mixture there is a possibility of instability more of instability than in the rich mixture and this instability than could be catastrophic. So, in the process of trying to achieve low specific fuel consumption of the engine, a low fuel consumption of the engine it could figure instability inside the combustion chamber which could be catastrophic.

So, more the engineers and the combustion chamber designers try to create combustion chambers for low fuel consumption lean mixture operation more it leads to possibility of instability in the combustion chamber. So and that is the reason why the combustion designers today are studying the combustion instability with more vigor than ever before.

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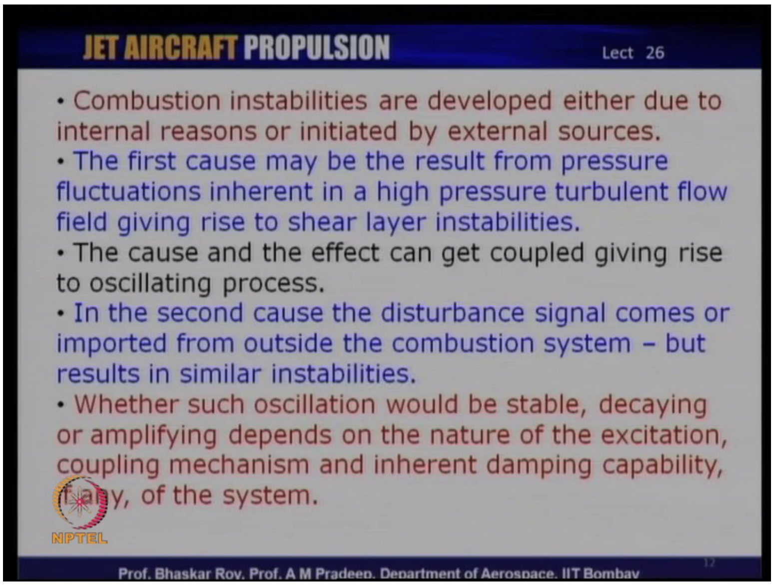

Let us try to summarize some of the issues that we have been discussing. The combustion instability as we now seen or more due to the internal reasons or it could be initiated by the external sources that is coming from the compressors for example, the first cause may be the result of the pressure fluctuation inherent in a high pressure turbulent flow field giving raise to shear layer instabilities and this is what we were seeing just a little while earlier in this picture that the base flow creates fluctuating flow over here behind the flame holder.

And this is to aid the mixing process; however, is this if you lose control over this mixing process and if this becomes violent it will read to not only it will not lead to flame stabilization. It will actually lead to flame these stabilization and it will lead to combustion instability. So, that is one of the issues that we need to be very careful about and then the cause and the effect together can get couple; that means, whatever is happening due to raise to instability by itself then flows backwards or acts backwards to produce more of the instability of the air flow or the turbulent, which again then builds up more of combustion instability.

So, they can get coupled and giving rise to an oscillating combustion process, which is most unwanted. The other cause is the disturbance signal, which comes from outside the combustion chamber which could be the compressor or it could be some fluctuation in the fuel supply process, which could result in similar instabilities. Now whether such oscillation would be stable or decaying or amplifying depends on the nature of the excitation that is experiencing the coupling mechanism, which we just talked about and the inherent damping capability of the combustion chamber and the combustion geometry that we have.

So, combustion chamber needs to be then given or endowed with certain amount of damping capability physically some of the instabilities that occur mean need to be immediately damped. So that they do not grow and this is what the combustion chamber designer would have to be careful about.

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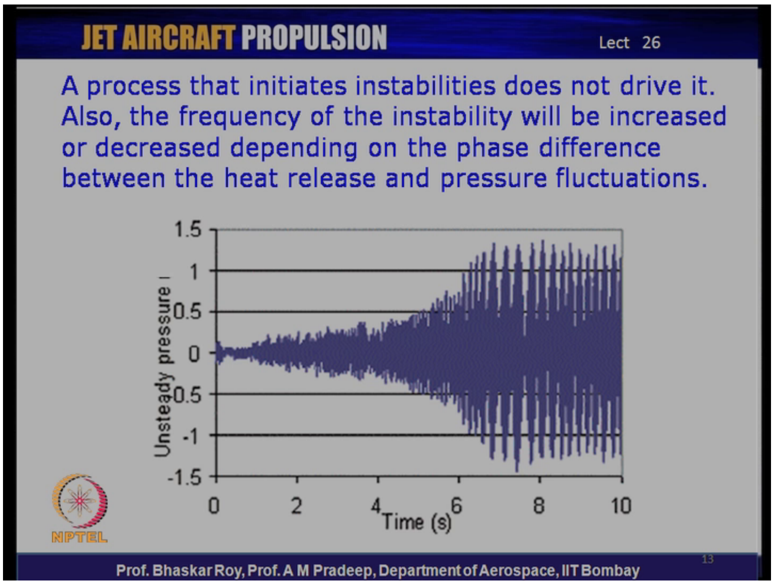

So, will look at some of the combustion instabilities that can occur the if you see here the combustion that is initiated from here and after very small amount of time, you can see it develops into instability and the frequency of the instability can get the decreased or increased depending on the phase difference between the heat released and the pressure fluctuation and then this phase difference between the heat release and the pressure fluctuation is an important issue because heat is released by the combustion phenomenon.

On the other hand the pressure fluctuation is getting imported from may be outside or it may be getting created by the combustion itself. So, the coupling of these two and a phase different between these two can actually lead to certain combustion instability and it can aid the process of instability and as a result of which it can go out control we see here a picture in which combustion instability has been captured in an actual test bed.

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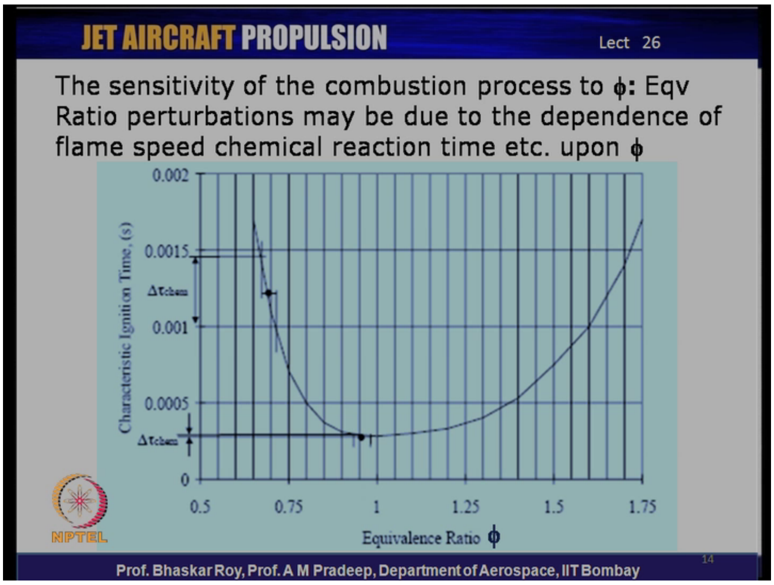

This is another picture where the combustion instability has been a tempted to be captured with reference to the equivalence ratio, which is the ratio of the instantaneous fuel air mixture to the ideal stoichiometric fuel air mixture has we have talked about before and then this equivalence ratio then tells us where we are. Now in this picture as we see the characteristic ignition time is given here, which as you can seen is in small fraction of a second and the equivalence ratio. Now, as you can see here as equivalence ratio goes too much it leads to very high time and again same thing happen. So, the combustion needs to be yield within this zone which is supposed to be the safe zone for combustion purpose.

So, we have to keep an eye on this equivalence ratio that trouble here is as equivalence ratio is decreased. As you can see here on the linear side the raise is fast the curve raise much faster than on the richer side. So, the instability sets in much earlier when the combustion becomes lean mixture. On the other hand the lean mixture is desired for low fuel consumption or low specific fuel consumption for the whole engine. So, if you want to design a combustion chamber for an engine with low fuel consumption. Then lean mixture needs to be studied in more detail because that is where you start getting more instability of the combustion phenomenon.

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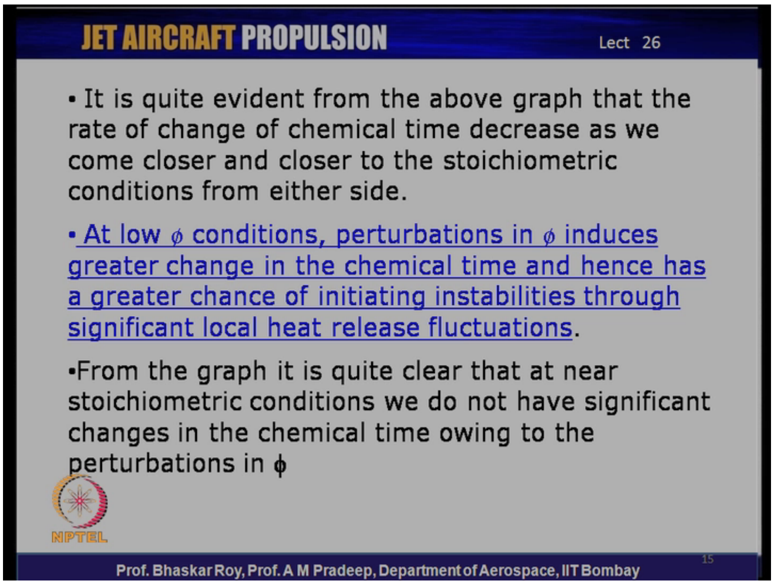

So, we have looked at a various possibilities of the combustion where you have various parameters, various physical phenomenons that impact the processor combustion and as we seen now the desired combustion chamber of the future in which it will operate very well at low fuel air mixture at low equivalence ratio also has a greater possibility of combustion instability. And this need to be studied and factor into the combustion chamber design otherwise the combustion would experience more of instability with catastrophic possibilities.

So, these are the things that put together needs to be factored into combustion chamber design. So, we have studied all kinds of combustion chambers we have seen the combustion problems; we have studied the various combustion parameters and the combustion mechanism and now we see that it has a number of issues, number of problems that need to be looked into very closely specially for the futuristic engines where it will operate smoothly without problem with comparatively lower fuel air mixtures that is lean mixtures.

So, that the engine has lower fuel consumption rate and to do that you need to have stable combustion and we see that the stable combustion needs to be very well studied and attended to so that you have a good combustion chamber, which produces stable combustion at low fuel combustion a fuel consumption weight. With the study of this combustion chamber we now come to the end of the combustion chamber, combustion chapter. We will move on to the other chapter of the aircraft engine.

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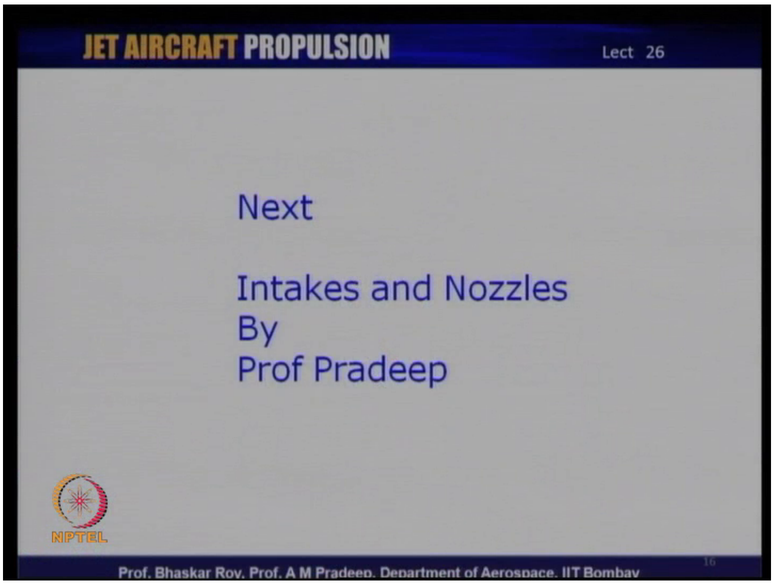

So the next chapter that will be taken up will be on intakes and nozzles, which are the two non working elements of an aircraft engine intake is in the beginning of the engine, and nozzle is at the end of the engine. And these two components would be now taken up, and they would be discussed in detail by professor Pradeep.