Jet Aircraft Propulsion
Prof. Bhaskar Roy
Prof. A. M. Pradeep
Department of Aerospace Engineering
Indian Institute of Technology, Bombay

Lecture No. # 25

Pr. Loss, Combustion efficiency; Combustion intensity

We are talking about combustion chambers. In the last class, we had a look at various kinds of fundamental combustion chambers, their geometries, and a look at how do they function. The mechanism of combustion as we know chemically it is basically a process of oxidation. In case of jet engines, the important issue at hand is how much of heat is released in the combustion chamber as an input to the engine in terms of energy input, and that energy input is to be honest for doing work in the form of thrust. Now, this energy input as we have discussed in the last class is essentially in the form of heat released by opening up of the chemical bonds, which of course means that there is a lot of chemical reaction that is going on, and invariably there are fields of chemical kinetics that do come in to the picture to decide how the combustion is actually going to be taking place, and how the heat release is actually going to be done.

However, as I mentioned the chemical kinetics, and the reaction kinetics or fields which are completely separate fields of expertise, and we will not get in to those areas which are pretty comprehensive by themselves. We will stick to the basic physics of combustion, and we will look at how the heat release is hardest in to a uniform heat supply in to the axial flow turbine, that normally is a position after the combustion chamber. Now, this heat release that is done involves a lot of steps. In the last class, we had a look at some of these steps.

Today, we will look at how these various steps, and the combustion mechanism that we talked about is put together in a certain number of parameters - combustion parameters that help us quantify what is going on inside the combustion chamber. This quantification is very important, because then step by step, we have an idea how the heat release or the energy release can be quantified, and what are the various penalties that one may need to pay to get this energy input in to the engine. So, in today's class, we will look at a few parameters which help us quantify some of the mechanism that are going on inside the combustion chamber, and some of the things that we discussed in the last class.

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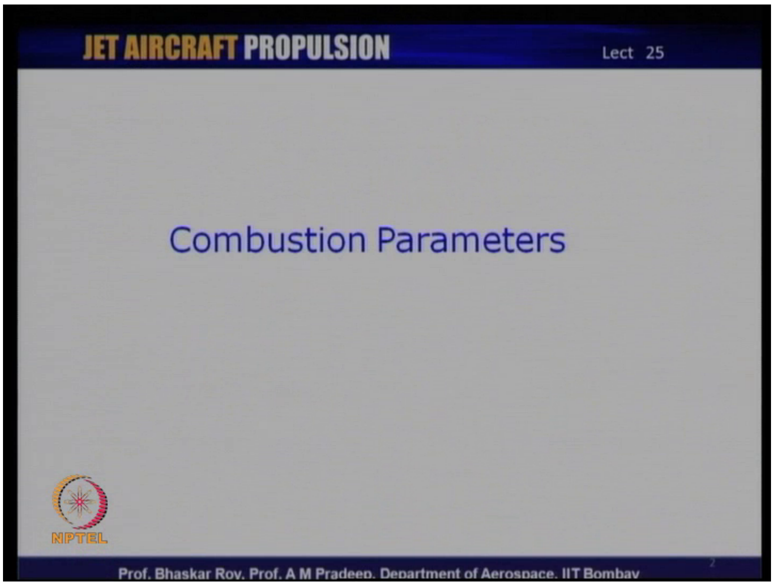

So, in today's class, we look at combustion parameters. The various parameters that help us quantify what is going on inside a combustion chamber. Now, the first parameter we may like to look at is pressure loss. Now, you see when the flow comes from the compressor, it has been adequately compressed. And the amount of compression which is gone through has been decided by the engine designer as per cycle design. And this compression that has already taking place is valid vitally important for the efficiency of the engine and for good performance of this engine.

Now, during the process of combustion, there is every possibility that some of this pressure would actually be lost. It is necessary then that the combustion chamber designer takes every care to ensure that the input pressure in to the combustion chamber is not substantially lost in the process of combustion. And these needs to be taken care of during the process of combustion design or combustion chamber geometry configuration and the overall combustion mechanism design. Let us take a look at how this pressure loss is described and in some sense defined in a very simple manner.

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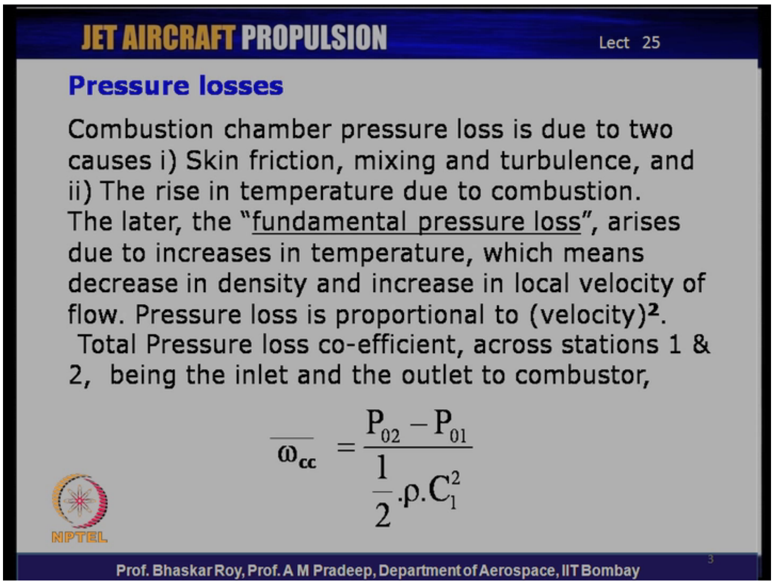

Now, the combustion pressure loss that normally we would be talking about can be said to compose of two different parts. One is the simple fluid mechanic pressure loss or aerodynamic. As the air is going in to the combustion chamber, it is invariably subject to a lot of skin friction, lot of mixing that we have discussed about that is vitally necessary for combustion and turbulence which is also vitally necessary for good combustion. So, these are basic fluid mechanic or aerodynamic pressure losses that take place any fluid flow and in any kind of geometry. The second pressure loss or second kind of pressure loss is related to the rise of temperature due to combustion.

Now, the later one actually often is related or described as fundamental pressure loss; because it is related to the combustion itself. And this is due to the fact that as the temperature rises, the local density actually decreases and the decrease in density pushes the flow faster. And as a result, there is a local increase in the velocity and this velocity increase locally creates a higher pressure loss; because pressure loss is propositional to the velocity squared. So, typically every geometry would have a pressure loss coefficient so to say and this pressure loss coefficient is then multiplied with the velocity square to get the pressure loss. Now, this is what is captured in the definition given below.

That if the flow is flowing from station 1 to station 2 across the combustion combustor, the pressure loss coefficient may be given as P 0 2 minus P 0 1 divided by half rho C 1 square; where C 1 ofcourse is the velocity with which the flow is going in to the combustion chamber and rho is the density of the air. Now, this density of the air is what we were talking about just a while back that locally in some part of the combustor, locally this density may actually go down. And as a result of going down, the local velocity C may go up from inlet velocity C 1 to higher velocities and as a result, locally the pressure loss could actually go up. Now, this is a phenomenon which again can be measured.

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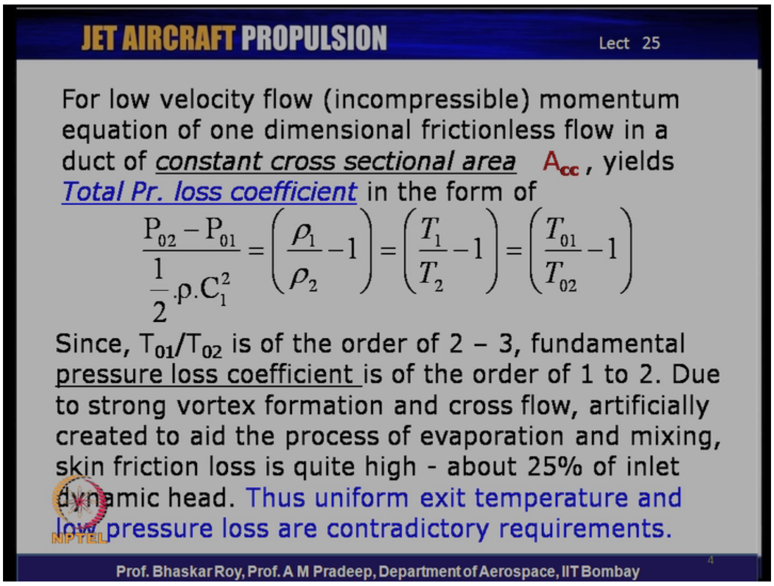

So, both the pressure losses can indeed be measured, if we apply the simple incompressible flow theory. And we assumed to to begin with atleast that the flow is flowing in a constant area; that means, the combustion chamber can has constant cross sectional area from inlet to outlet. If we make that simple assumption, the total pressure coefficient that we get can be written down in terms of the density ratio and then the temperature ratio and o course, the total temperature ratio. Now, we are using incompressible flow theory and assume that the area across the combustion chamber has been held constant. Now, this ratio of total temperatures T 0 1 by T 0 2 is normally of the order of 2 to 3.

That means that is the amount of temperature by which the temperature is cooled down from the initial temperature of the combustor to the delivery temperature at the turbine inlet phase or the compressor delivery phase. So, temperature is often brought down by a factor of 2 to 3 and as a result, the pressure loss coefficient would be of the order of 1 to 2 correspondingly. Now, what happens is due to… if you look at it the other way some other way due to the strong vortex formation and cross flow that is deliberately induced in to the combustion chamber as we discussed in the last class to aid the process of combustion.

These essentially entail certain amount of pressure loss and this pressure loss is often of the order of 25 percent of the inlet dynamic head; that is a ballpark figure. But that is a kind of…

That means, 25 percent of the inlet dynamic head could be lost in various kinds of losses which are absolutely necessary some of it to aid the process of evaporation and mixing and then you have a pressure loss that is inevitable. And as a result, the uniform exit temperature and low pressure loss are contradictory. That means, if you want uniform pressure loss at the combustion chamber delivery and you want a reasonably lower temperature, so that it is comfortable for the turbines.

Then that is contradictory to the low pressure loss requirement; because to achieve those two things, you would invariably lose a lot of pressure. Now, this is something which the combustion chamber designer would have to grapple with at the time of design the combustion chamber. In addition to these, you remember we have restriction of space that is size and volume that is available for combustion chamber. So, all of it together there is certain contradictory pulls; through which, the combustion chamber would need to be configured.

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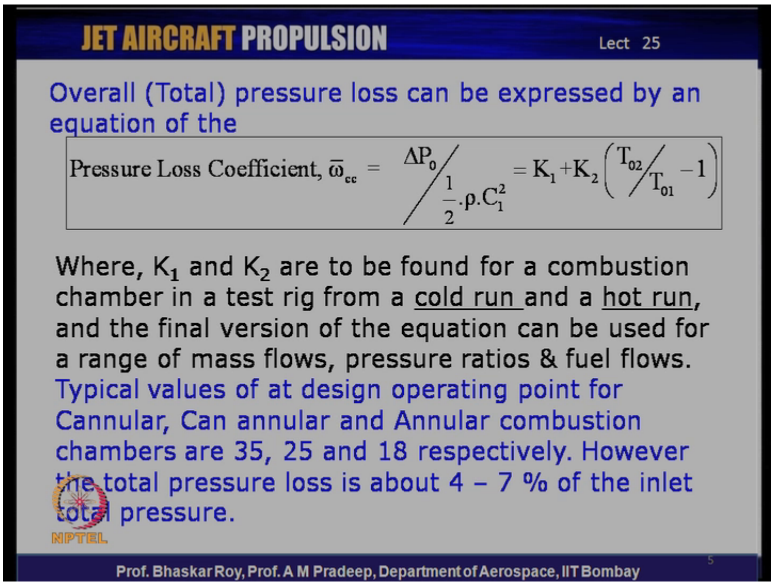

If we look at the total pressure coefficient, we have defined before that is delta P 0 across the combustion chamber divided by half rho C 1 square. Now, this can be written down as we mentioned in terms of two kinds of pressure losses. The first one we said was essentially related to the basic fluid mechanics and the second one is related to the temperature change across the combustion chamber. Now, if you do that, the first one often signified by an empirical parameter K 1 and the second one signified by a empirical parameter K 2. They are found for the combustion chamber through various test rig simulations.

The first one is through a cold run and a second one is through a hot run. Now, the cold run gives you the fundamental fluid mechanic losses and helps you quantify what are the basic losses not withstanding any combustion phenomenon. The second one is directly related to the combustion phenomenon. And hence if there is a temperature rise, there is going to be certain amount of pressure loss and that is called as we said combustion related pressure loss. So, the first one is fluid mechanic pressure loss; second one is combustion related pressure loss.

And for a given combustion chamber geometry, once certain geometry has been decided upon, this can be taken to a test rig and a certain runs or test rig performances can be measured. And these two parameters can be quantified and then they can be put in the equation as given here and can be used for across large number of mass flows and pressure ratios and fuel flows. So, once we get this equation partly from the rig testing and partly from the design parameters, we have a first cut hand equation to give us a reasonable idea about what the pressure losses are going to be across the combustion chamber.

And this is ofcourse to ensure that you do not lose a lot of pressure that has been developed through the compression process. Now, the typical values of design operating point for various kind of combustion chambers; that is the cannular, the can type and the annular combustion chambers are typically of the order of 35, 25 and 18 respectively. These are again as I said ballpark figures. The total pressure loss taken as a total pressure that is delivered to the combustion chamber from the compressor could be of the order of 4 to 7 percent of the inlet total pressure and if the combustion chamber designer's job to ensure that this pressure loss is kept to the minimum as minimum as possible.

So, this is one of the parameters that combustion chamber designer would have to grapple with. During the process of design, it involves simulation. In test rig, it could involve simulation in computation. Computational simulation in both again cold and hot and a certain amount of design variables that would have to be probably iterated for and it depends on what kind of combustion chamber you have whether annular or whether you have a can type or cannular. So, these are the various issues that would come in to picture to keep the total pressure loss across the combustion chamber to the minimum.

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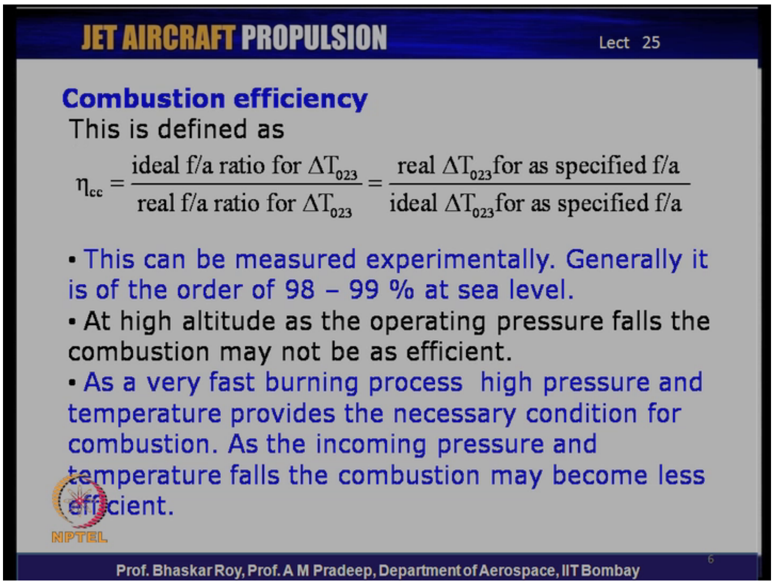

The next parameter that we would probably like to look at is the combustion efficiency. Now, the total pressure loss that we talked about really speaking has nothing to do with the combustion efficiency. As opposed to all the other component that you may have done before, where the pressure loss is directly impacted the efficiency of those components notably the compressors and the turbines. In combustion chamber, the pressure losses do not impact the combustion efficiency and when we are talking about combustion efficiency, we are talking about the efficiency by which the combustion process; that means the heat release process is indeed carried out.

The combustion efficiency can be defined in terms of in two different ways really. One in terms of the fuel-air ratio for a given temperature rise across the combustion chamber or we can write the total pressure total temperature rise across the combustion chamber for a given fuel-air ratio. So, the ratio of these two the ideal and the real is often defined as combustion chamber. Now, as far as one can see in a test rig, it is easier to measure the temperature rise across the combustion chamber. On the other hand, for the operator it is easier for him to measure the fuel flow and the fuel-air ratio. As a result of which, both the definitions are often used alternately to obtain the combustion efficiency.

Now, typically the combustion efficiencies are very high indeed of the order of 98 to 99 percent under sea level operating conditions. Assuming that everything has been very well taken care of and as I mentioned earlier, you could have very high combustion efficiency and you could still have very high pressure losses or you could have very low pressure losses and you can still have somewhat lower combustion efficiency. So, the two are not quite connected to each other. Now, at high altitude what happens is that the operating pressure absolute value of the operating pressure falls and as a result of fall of the incoming pressure, the combustion process may get affected.

Now, combustion as we have discussed before is a very fast burning process and the fastness of the burning process is essentially decided by the high pressure that has been put in the air flow that is coming in to the combustion chamber and that high pressure decides the fastness of the burning process. The high pressure is essentially decides the potential energy of the air or the working medium and this then takes it very close to the critical threshold energy level at which very fast burning process is possible. If the incoming potential energy in terms of high pressure is not really that high, then the fastness of the burning process would be affected.

And as a result, the combustion efficiency would be affected. So, the necessary condition for good combustion is that you have reasonable high pressure that of course signifies the necessity of having a compressor in front of the combustion chamber. So, incoming pressure and as a secondary requirement incoming temperature if they fall, the combustion may become less efficient and this is something which is pretty much acceptable. Because at very high altitudes, your absolute values of pressures are likely to be lower. However, at that high altitude, your thrust requirement for the from the engine is quite often lower.

So, slightly lower burning efficiency may just be acceptable; because your fuel flow or fuel consumption is anyway absolute values of fuel consumption are lower. So, under certain situations, slightly lower combustion efficiency may just be acceptable; whereas under certain other operating conditions, the high combustion efficiency is desirable phenomenon and over entire flight schedule of an engine, it is necessary that combustion efficiency. We means as high as possible to ensure that overall fuel consumption is somewhat on the lower side taken over the entire flight schedule.

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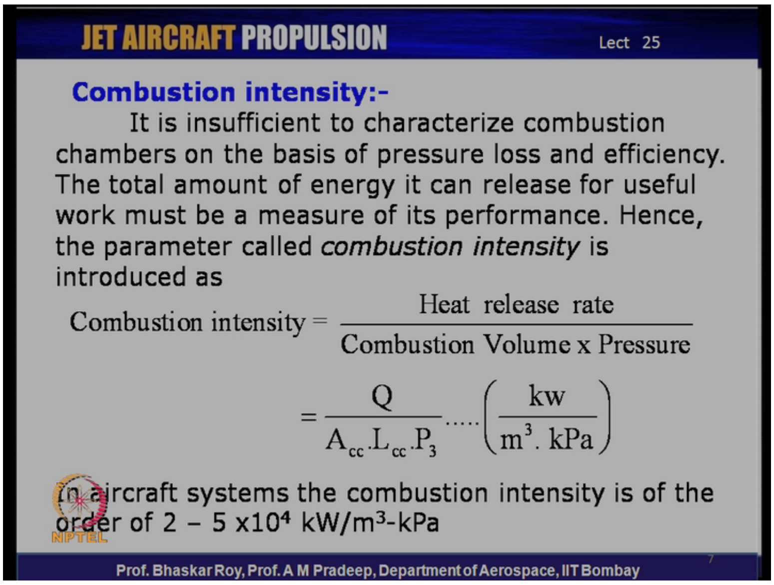

If we now look at some other parameter that is related to the combustion and that infact indeed impacts on the combustion efficiency in some way and that parameter is combustion intensity. Now, combustion intensity is what ofcourse would decide how much heat is released in to the combustion chamber and that is in to the engine. So, the energy input in to the engine is decided by the combustion intensity. Now, combustion intensity is a parameter that can be simply defined as heat release rate divided by the combustion volume in to the pressure. Now, you see here the inlet pressure is important and higher the inlet pressure, we saw higher is the fastness of the burning process. On the other hand, the combustion intensity if it is to be high, it has to have very high heat release rate if the pressure is also very high.

So, we have to heat release rate is decided by number of operating conditions and the basic chemical composition of the fuel. So, and then we have the combustion volume which is decided by the engine designer. So, in case of aircraft engine, the volume available would invariably very low and as a result of which, you need to have very high combustion intensity. Now, this availability of low volume in a typical aircraft engine has number of repercussions. The combustion mechanism that we have discussed in the last class tells us that there are steps of combustion that need to be done in a certain period of time and you need a certain space or volume to do all that within the given time.

On the other hand, as we see here now for combustion intensity to be on the higher side, the combustion volume would need to be as low as possible which corresponds to the requirement of aircraft engine. So, there are again contradictory pulls over here to decide what the combustion intensity could possibly be in actual aircraft engines. The heat release rate Q ofcourse is decided as I mentioned by the fuel flow or the fuel itself. And hence you need to choose a fuel which has high value of Q intrinsically built in to its chemical composition. The typical combustion intensity of the is of the order of 2 to 5 in 10 to the power 4 for most of the aircraft engines in terms of kilowatts per meter cube per kilopascals and we shall see that some of these numbers would probably vary a little during the actual operation of the engine.

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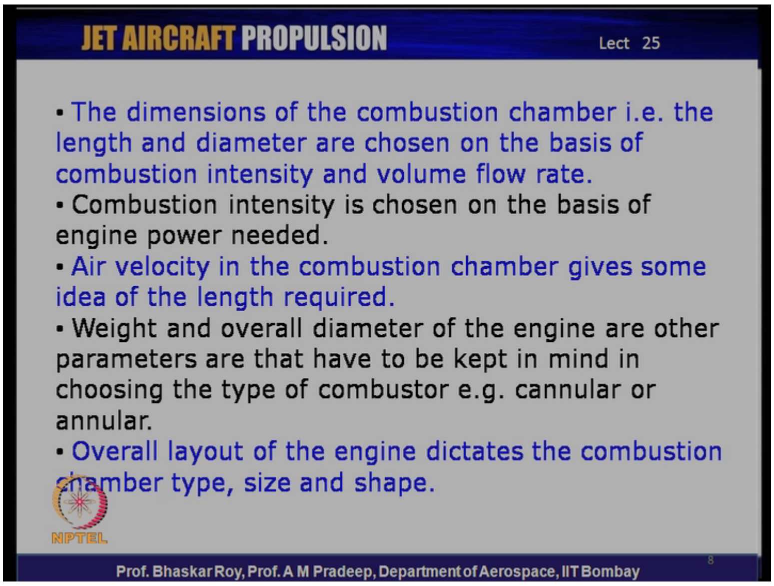

Now, if you look at the dimensions of the combustion chamber, the length and the diameter of the combustion chamber are often chosen on the basis of combustion intensity, and the volume flow rate. Now, the volume flow rate in to the combustion chamber is decided by the engines air flow rate, and the engine air flow rate is decided by various parameters like what is the thrust requirements so on and so forth. So, the combustion chamber we are talking about may be an annular combustor or it could be a can type combustor, where the air is split in to so many smaller combustion chambers. And inside of each of them, certain length, and diameter are required to be decided upon on the basis of the combustion intensity, and the volume flow rate.

Now, combustion intensity is chosen on the basis of engine power that is needed. So, the power or the thrust power that the engine has to produce can be deciding factor on what the combustion intensity is going to be. The air velocity in the combustion chamber as it is coming from the compressor and that gives a certain idea about the length that is required and we have talked about the combustion mechanism. Probably, we will have look at it all over again today again little later and that tells us that the air velocity that is operative inside the combustion chamber does decide what the resident time is of the working medium air inside the combustion chamber to observe the heat release and then carried with it in to the turbine.

So, this ability of the absorption of the heat release in to the working medium air inside the combustion chamber is something that is to be decided by combustion designer. He has to give the combustion a certain length during which the air flows in and then this flow of air absorbs the heat that is released by the burning of the fuel. And then it carry this heat in in the form of high energy along with the high pressure in to the turbine. And certain amount of time and space and of course volume essentially would have to be given for this working medium air to do this job to absorb the energy input.

And this is necessarily to be done in a manner in a control manner and that is why we call combustion a very controlled method of fast burning. The entire process of combustion needs to be controlled. All the time during the process of combustion, there must be a tacit control over the process of combustion. Without that control, we may have either in extreme case an explosion or the other extreme is the combustion process would get extinguished. So, combustion is a control mechanism of fast energy input in to the engine and that control has to be built in to the combustion design.

It is necessary that combustion chamber geometry, the length, the volume, the shape, the size everything is decided at the time of the design; because you do not have a variable geometry combustion chamber as yet. So, the combustion chamber geometry is a fixed geometry. There is no variable geometry combustion chamber. It has to be built in to the design of the combustion chamber geometry and whatever control that can be actually done during the process of combustion operation would have to be taken in to account during the process of design of the combustion chamber.

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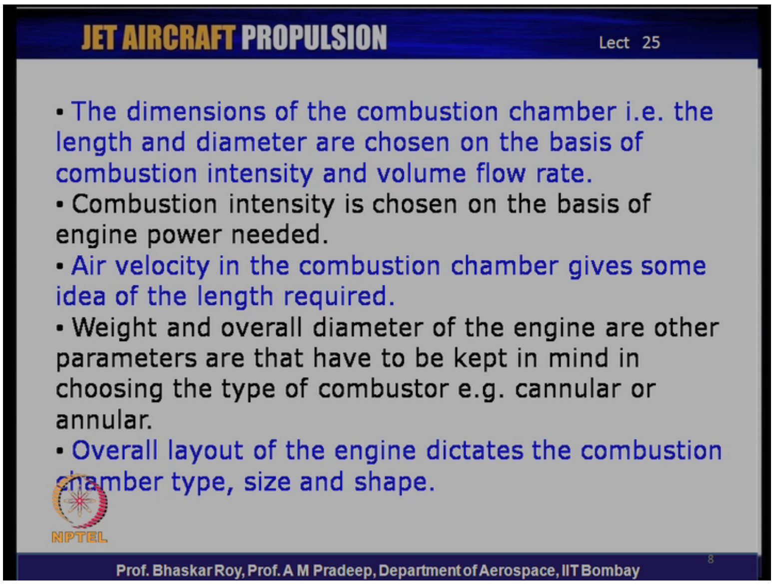

The other things that we we need to look at are the weight and overall diameter of the engine. Now, you may be having an aircraft engine that is necessary to be a small engine. For example, if you have a military engine, you need to make sure that the overall diameter is as small as possible; So that, it fits inside the body of the aircraft. And then ofcourse, it is necessary that its weight is as small as a possible; So that, you have what the engine designers always call the thrust weight ratio. So, if you want to have high thrust weight ratio and a low diameter to fit in to the aircraft, you do not have a lot of space available for the combustion chamber.

And as a result of which, quite often many of the designers go for annular combustion chamber, which is the easier geometry to adopt really speaking. So, the overall layout of the engine would invariably dictate the combustion chamber type whether it is annular or cannular or can type, which is normally not used anymore of these days. So, essentially what kind of combustion chamber design, the size, the shape all that is also decided by the overall layout of the aircraft engine; because it has to go on board on aircraft. It has to fit in to the aircraft. If you have long ways to gas turbine engine, some of these things are hugely relaxed; because this space is not of great importance.

A little more space is not going to hurt anybody. But in aircraft engine, space is premium and there is very strong restriction on the amount of space and the weight that can be given to the combustion chamber. The weight we are talking about weight; one of the reasons is the combustion chambers are wrapped around the basic shaft of the engine. Now, the longer the combustion chamber is remembered the basic shaft of the engine also becomes longer; the engine itself becomes longer and that increases the weight of the overall engine. So, the combustion chamber shape and size is vitally important especially for aircraft engine applications.

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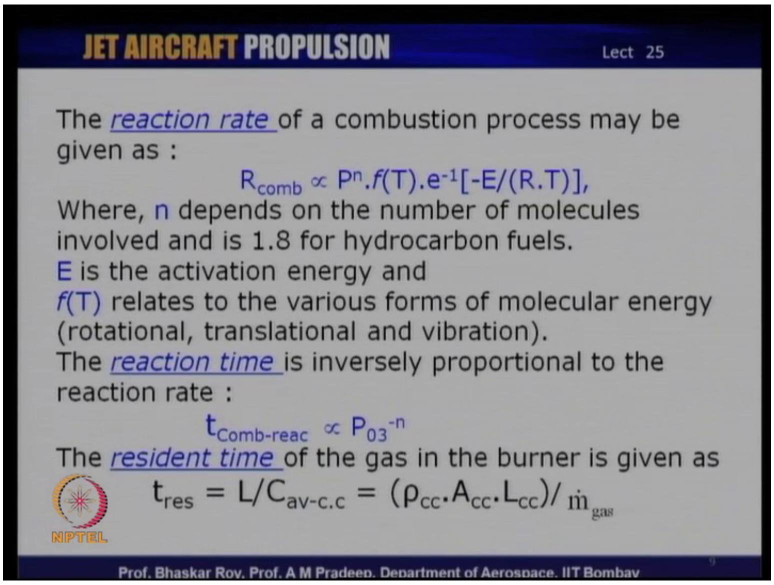

Now, let us look at the other parameter that is very important for the combustion process and this is the reaction weight which is given in terms of number of parameters. Now, pressure to the power n; n depends on the number of molecules involved in the process of combustion and it is normally 1.8 for hydrocarbon fuels which are normally used in aircraft combustion. E is the activation energy and f (T) relates to various forms of molecular energy that is involved in the process of combustion. That is, the rotational, translational and the vibrational energy which are released, when the heat is released.

And and the molecular energy that it acquires from the heat release manifest itself in the form of these three forms rotational, translational and vibrational energy, which is then released to the air that is mixed with the air that is passing through and it acquires all this energy in to itself. Now, that all that together; that is, there is a molecular kinetics; there is a reaction kinetics which is altogether decides what the reaction rate of the combustion process is going to be. Now, reaction rate is important because that decides what the reaction time is going to be and that reaction time is given in terms of again total pressure.

And the value of n that we have talked about and that would decide what the resident time of the gas inside the burner is going to be. Now, the resident time of the gas inside the burner can be given in terms of the length of the combustion chamber divided by the velocity through the average velocity through the combustion chamber. As we have discussed, the velocity may vary a little locally inside the combustion chamber. And the length of the combustion chamber can be decided of course by the density of the combustion chamber. The area across the combustion chamber which to begin with we can assumed to be constant and then all that decided by the mass flow of the gas through the combustion chamber.

So, all the together decides what the resident time is going to be. Now, you see the reaction weight, the reaction time and the resident time are connected to each other. The reaction weight as we just saw is decided by the molecular kinetics or the reaction kinetics phenomenon. The reaction time is decided primarily or directly proportional to the pressure that is available. And hence we have argued that it is necessary that you allow air to go inside the combustion chamber with as high pressure as possible to impact on the reaction type, which as we just mentioned is related to the fastness of the burning process.

And then the resident time which is again related and that is decided as we now see related to the average combustion chamber density, the flow in the inside the combustion chamber, the area, the length of the combustion chamber and then the mass flow through the combustion chamber. Now, these are the parameters that actually impact on the combustion mechanism which we discussed in the last class. This is what the combustion mechanism is all about and the things that we talked about the physics of the combustion that we talked about. We are bringing in a lot of vertices.

We are creating artificial vortex system. We are deliberately slowing down the flow; all that is done essentiality impact on these parameters. These parameters are impacted by the physics of what we discussed in the last class. Maybe we will have look at it again today all over again; to see, that these parameters which we are talking about and as I mentioned, we are not going to talk about molecular kinetics. But they have impact and they can be somewhat controlled in addition to the molecular kinetics through certain physical manipulation of what is happening inside the combustion chamber.

And if we have a good control over what is happening, we have a control over the reaction time; we have some control over the resident time and that resident time permits the entire combustion process to be completed. The heat release to be completed and then the entire heat release to be passed on to the passing air. Air has to absorb the heat and then go on from the compressor to the turbine. Now, this is important and that is why, it is necessary that you do all that within the given resident time. And hence the combustion chamber designer should have reasonable notion of what is the resident time available for the given volume and the given length of the combustion chamber.

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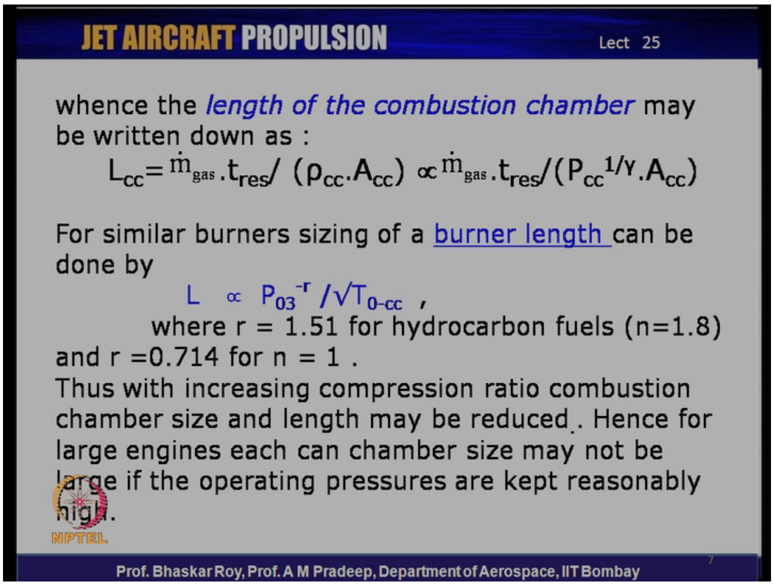

If we now look at how the length of the combustion chamber can be decided from the earlier parameter. We can say that the length of the combustion chamber is directly related to the gas that is fowling, the resident time, the density and the area. And hence we can say that some of these parameters the density can be related through the thermodynamics to the pressure to the power 1 by gamma. Now, what happens is the burning size of a burning length can be decided with the help of essentially the pressure and the temperature. And here what is written is the length is proportional to the pressure to the power minus r divided by root over total temperature T 0-cc of the combustion chamber or at the combustion zone.

Now, where r is 1.51 for hydrocarbon fuel that I used for combustion in aircraft engines and as we have stated before its n is equal to 1.8 and r is equal to point 0.714; for other kinds of fuel, where n is equal to 1. Now, the increasing compression ratio, the combustion chamber size and length may be reduce. Now, this is something which what we are discussing that if you have a high compression ratio, the combustion process can be faster and the heat release rate can be higher and then the combustion chamber size and the length can be reduced.

And as a result of this, we can say that for large engines, the each can of the if you if you consider each can as a combustion chamber, the each can chamber size may not be large if the operating pressures are kept reasonable high. So, the question is what is the pressure operating pressure that you can adopt for the particular engine and then what is the mass flow through the engine that you have with you. And these are the parameters that will impact on what is the combustion chamber length and the size and ofcourse the shape of the combustion chamber. So, these are the things that decide what all the geometry of the combustion chamber is likely to be.

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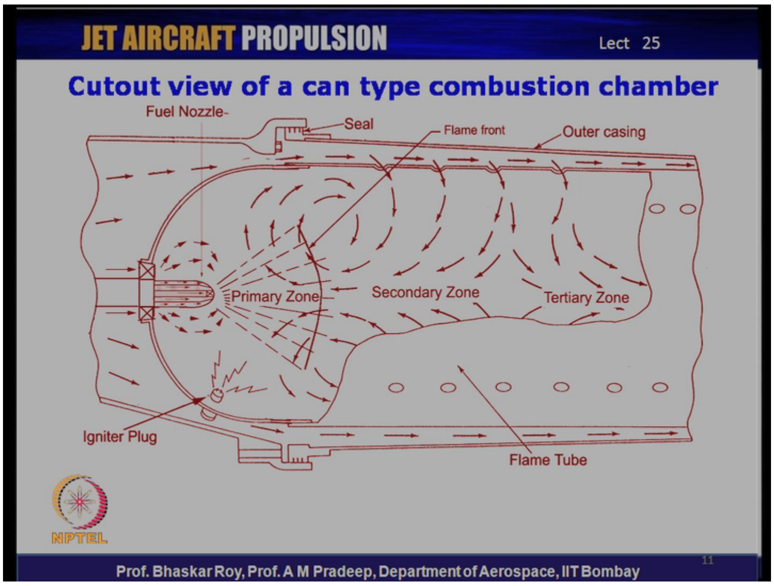

Now, if you go back and take a quick look at how the combustion phenomenon is actually tried to be brought under controller kept under control and as I mentioned, this is normally a fixed geometry combustion chamber. You do not have variable geometry combustion chamber atleast not as yet and as a result of which, once the geometry is created, you are fixed. And again as I may have mentioned before, each combustion chamber for every engine of aircraft use is an unique combustion chamber. You normally cannot use one combustion chamber used in one engine for another engine. Completely new combustion chamber would need to be designed for any new engine that is created.

Now, let us take a look at this combustion phenomenon. The flow as I mentioned is coming from the combustion from the compressor at very high pressure. And as we saw in the last class, about 20 percent or so comes inside the main combustion zone and it comes through what we called swirler. And these swirlers give a huge swirling motion to the flow and then we have this some kind of a bluff body over here which creates more of swirling flow, more of local vertices. And these vertices essentially create a huge recirculation around this zone. As we discussed in the last class and this recirculation zone essentially aids the process of evaporation and mixing. This is pre mixing before the combustion.

We have two rounds of mixing; one before the combustion; one after combustion. The first mixing is before the combustion. This is the evaporated fuel from liquid to gas would need to be mixed with air. So, we have a gaseous mixture of air and fuel before the combustion and these needs to be uniform across the combustion perception. So, in the combustion zone, it is necessary you create a uniform mixture gaseous mixture of air and fuel and this needs to be artificially done through the process of recirculation zone that is created over here. And as I mentioned this is the fixed geometry, so we have to design a priory and ensure that it happens all the time during all the process of combustion during various operated operations of the engine.

Now, if we do that if we do that, we have a uniform gaseous mixture of air and fuel and that goes into the primary zone and this primary zone is what we call the combustion zone. And in this zone, you have this curved surface over here which is called the flame front and as we discussed in the last class, this flame front is where the flame is burning and the heat is being released. So, in the primary zone from here to here over this zone, you have a uniform mixture of air and fuel that is burning that is moving through the zone through the flame front and the heat is being released. At the end of the primary zone, one has to ensure by design that the entire heat has been released by chemical reaction from the fuel in to the air and fuel mixture.

And this released energy now needs to be uniformly distributed across the entire combustion chamber. So, we have the secondary air coming in through this vent holes from the sides. And now this is the 75 percent of the air that was bypassed; 75 to 80 percent of the air that was bypassed. And now they are coming in through this vent holes to create the secondary zone and this is necessary essentially to ensure that you have uniform distribution of energy or heat across the entire combustion chamber volume. So, the uniformity of distribution of heat is extremely important. In certain operating conditions, it may happen that a very small remnant of the burning process or combustion may still be carried on in the secondary zone.

The tertiary zone is extremely important to bring down the temperature to something that is comfortable to the turbine. So, secondary while the secondary zone is important for creating a uniform temperature distribution; the tertiary zone is important for creating a lower temperature zone that is comfortable to the turbine and ensure you still have a uniform distribution of temperature, pressure and finally, delivery it to the turbine with uniform velocity distribution. So, the combustion chamber design and this what we have seen here is a can type combustion is essentially to ensure that you carry out all these steps step by step in a step by step sequential manner.

So, that you have uniform temperature distribution at very high temperature and retain very high pressure as delivered from the compressor and delivery it to the turbine. So, there are number of steps as we can see and as we have discussed before, all these steps would need to be completed in a controlled manner and some are within that, you also have the molecular kinetics or the reaction kinetics which happen essentially in the primary zone during the process of heat release. So, all these things need to be done in a controlled manner. And during the process of combustion, as I mentioned it is fixed geometry combustion, the only control you have is the fuel flow rate.

So, there is no other control and hence the combustion chamber design must necessarily have the geometry control at the time of design itself. Just to complete the picture over here, the can type that we are seeing is quite often is also referred to as a flame tube; inside which, the flame is localized and securely maintained and held. During the entire operation of the engine, it is necessary that at no point of the operation of the engine, the flame is extinguished and hence this is often called a flame tube. To ensure that inside it, the flame is continuously burning and the combustion is continuously taking place.

The ignited plug that you see here is used normally only once during the process of initiation of the combustion. The injection injected that you see here and we will be discussing the injection process later on may be in the next lecture. Actually, ensures that you have sufficient injection of fuel to for the corresponding operating point of the engine and that is done by the engine control system. So, these are the various operating conditions of the combustion chamber that ensure that you have a continuous combustion, you have a control combustion and you have complete combustion given the shape, the size and the space that is allotted to the combustion chamber.

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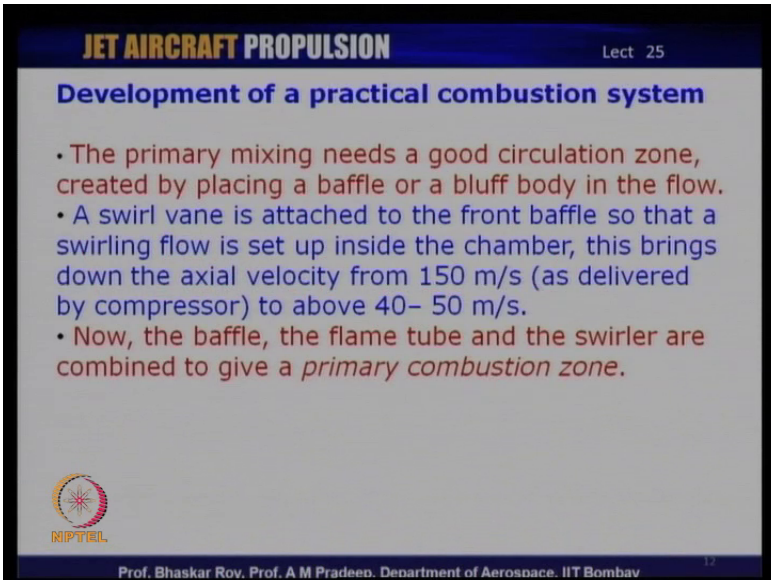

So, we can sum up by saying that the development of a practical combustion system, it requires a good mixing. The primary mixing or the pre mixing before the combustion requires a good circulation zone and this is created by placing baffle or a bluff body in the flow. The swirling vane is attached to the front baffle; so that a swirling flow is set up. You have to create that swirling flow under all operating conditions of the engine and that brings down the axial velocity from 150 which is what is delivered from the compressor to about 40 to 50 meters per second. And this is what could be discussed a little in the last lecture also and the baffle and the flame tube and the swirler are combined to give the primary combustion zone or the primary zone; inside which, the combustion is securely held and continued through the entire process of operation of the engine. So, this is absolutely important to ensure that combustion is continuous, complete and efficient during the entire process of operation of the engine.

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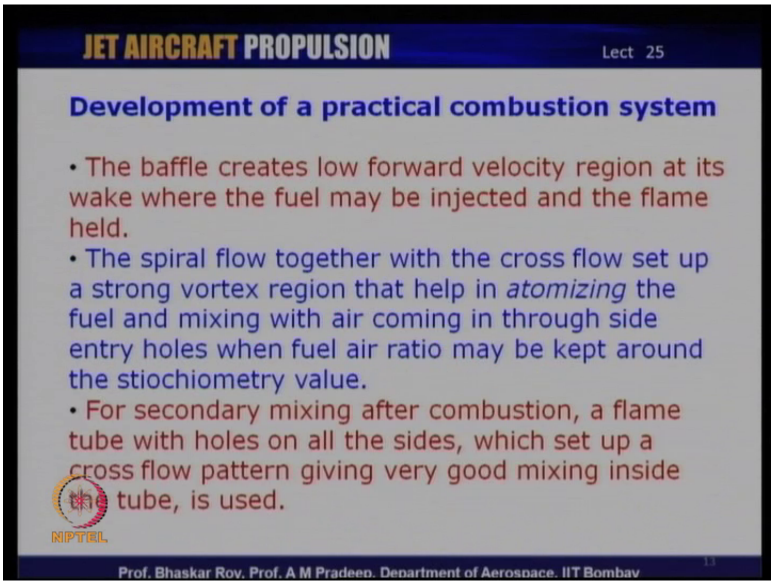

The development of a practical combustion system also ensures that the baffle that you have creates a low forward velocity. The spiral flow that it creates helps what we had called in the last class, the process of atomization. That is the fuel when is injected immediately breaks up in very small droplets as we saw in the last class. And this creation of these small droplets is extremely vitally to the process of evaporation, and mixing and this process as we mentioned earlier is called atomization. And this atomizing is an important phenomenon for the process of efficient burning or efficient combustion.

The secondary mixing which takes place after the combustion is important for uniform distribution of the combustion products and uniform distribution of the heat that is released from the combustion. And then the flame tube is to ensure that this takes place in a secured manner. And the vent holes that are available around the inner liner or the inner flame tube or the inner can ensure that the flow that comes in from the air that comes in creates a secondary zone which ensures you have a uniform temperature profile at the end of the secondary zone through a process of good mixing inside the flame tube.

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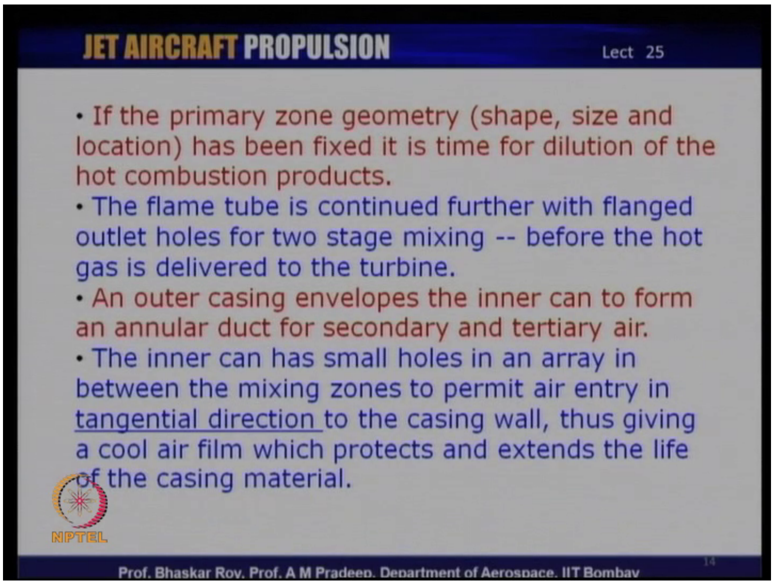

Whereas, in the primary zone, the geometry is fixed; the dilution of the combustion product is important in the secondary zone. The the two stages of mixing; one in the primary zone; one in the secondary zone; it is important that in the secondary zone. For aircraft gas turbine, you may have tertiary zone and this is important for the life of the turbine. The life of the turbine is essentially dependent on the combustion delivery and this delivery is essentially created by the mixing process which may require two stages. That is, the tertiary zone may be required to ensure that the temperature that is going from the combustion chamber to the turbine is something comfortable to the turbine.

The outer casing which normally delivers 75 percent of the air and envelops the entire all the cans that are inside essentially deliver the air the cold air so to say in to the secondary and tertiary zone after the combustion has been completed. So, the 75 percent of the air as we talked about do not take part in the combustion process and this inner can of the flame tube has this small vent holes and this vent holes are designer holes. They have to be designed. So, typical geometry of the vent holes, their positions, their sizes of the holes are to be designed in to the flame hole, the flame tube and they then create a proper mixing process inside those mixing zone. So, creation of those vent holes is extremely important and it is a combustion chamber designer who creates those designed holes.

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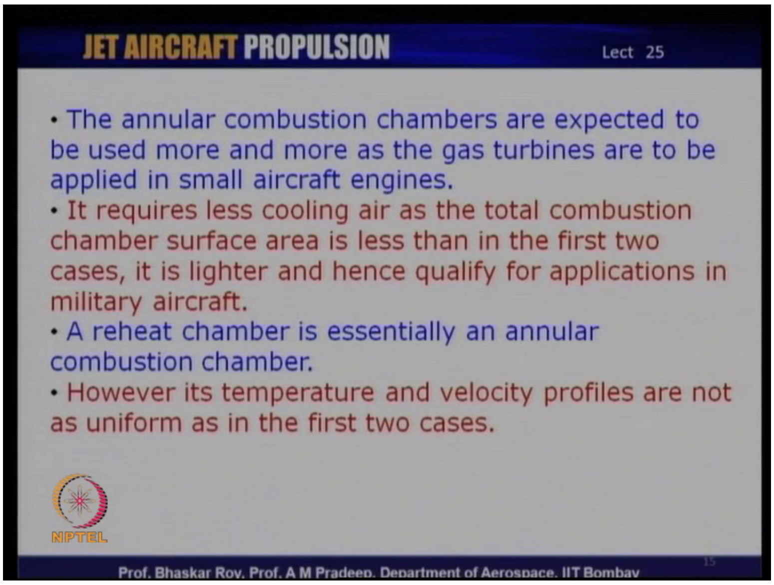

The annular combustion chamber which we have talked about are expected to be used more and more in the gas turbines in the future; because they are easier geometry and they are used in smaller gas small gas turbines even today in large numbers. The issue there is you do not have the localized combustion or secured combustion zone or secured primary zone. All the combustions are taking place in an open annular space. So, the security that is provided by the can is not available anymore. And as a result, it may impact on the combustion efficiency a little and the combustion intensity a little. And hence the annular combustion chamber may have somewhat lower efficiency and may have somewhat lower combustion intensity.

It however, requires lesser of the cooling air for the total combustion process and hence it is lighter, it does not have all the weights of all those cans. And hence it is lighter, and it essentially easily qualifies for application in military aircraft engines. Essentially, an annular combustion chamber is nothing but very similar to the reheat chamber which people have being using for a long time. The temperature and velocity profiles are not as uniform as in the can type or cannular type; because you do not have that kind of control as it is used by using the flame tubes or the can types. The annular combustion chamber may not deliver a very uniform temperature velocity profile on to the turbines.

Now, these are some of the things that the combustion chamber designer would have to take in to account before deciding what kind of combustion chamber he wants to use and what kind of combustion chamber he would like to have for his kind of gas turbine engine. We have talked about combustion mechanism. We have talked about the combustion parameters that impact the combustion mechanism and how by design some of these parameters and some of this mechanism can be kept under control on a continuous basis throughout the operation of the engine. In the next class, we will be talking about certain issues that are related to the operation of the combustion.

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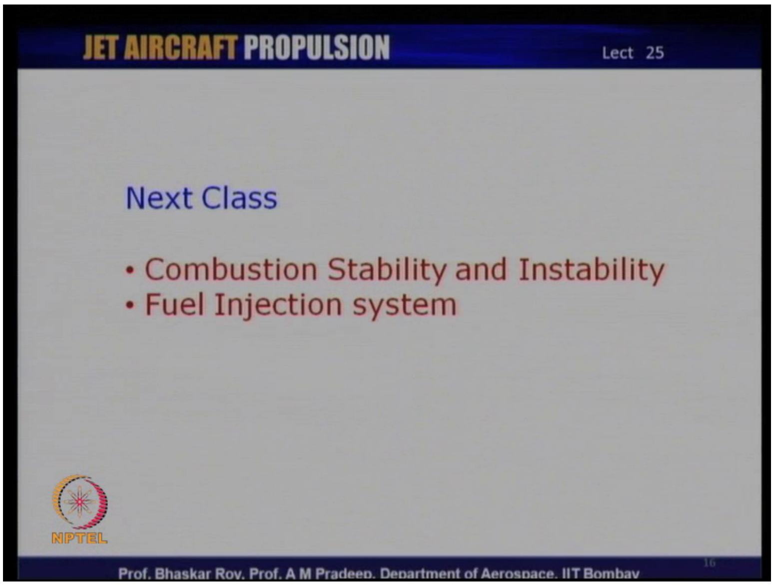

We will be talking about combustion stability, and correspondingly combustion instability. And we will be talking about the fuel injection system how the fuel is injected in to the combustion chamber, and the injectors themselves; that is what we will do in the next class.