Jet Aircraft Propulsion

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Lecture No. # 24

Types of Combustion Chambers: Mechanism and Parameters

Today, we are to going to talk about combustion chambers. Combustion chambers as you know is the place in a gas turbine engine, where fuel is burnt, and energy is supplied from external sources in to the engine; that is the place where energy is put inside the engine for the engine to do work and finally produce thrust for flying of aircraft. So, when we talk about combustion chamber, we are effectively talking about what may be called the stomach of the engine. It is indeed right in the middle of the engine buried deep inside the engine, and that is where the energy input is carried out. Now, the way it is carried out is that fuel is supplied in to the combustion chamber.

Now, this fuel is a chemical entity, and the burning of the fuel releases the chemical energy in to heat energy, and then this heat energy is hardness by various components of the aircraft engine to finally produce thrust. So, the process of release of this chemical energy in to heat energy, and how it is finally supplied to the rest of the components of the gas turbine engine is what we will discuss in this chapter. In today's lecture, we will take a look at the fundamental combustion mechanism. There is a lot of physics, there is a lot of engineering, and there is indeed a lot of fundamental understanding of fluid mechanics that needs to be put together to make a combustion chamber work.

The working of combustion chamber is also subject to a number of theories, some of those theories we will do. Much of the theories including the chemical kinetics or reaction kinetics is beyond the per view of this lecture series;, because that is a very specialized field the chemical reaction. And we will not get in to those issues regarding the combustion mechanism, but we will look at the physics and the engineering of combustion in some detail over the next couples of lectures. So, in today's lecture, let we will take a look at the fundamental combustion mechanism, and how the combustion chambers in aircraft engines look, and how do they indeed perform.

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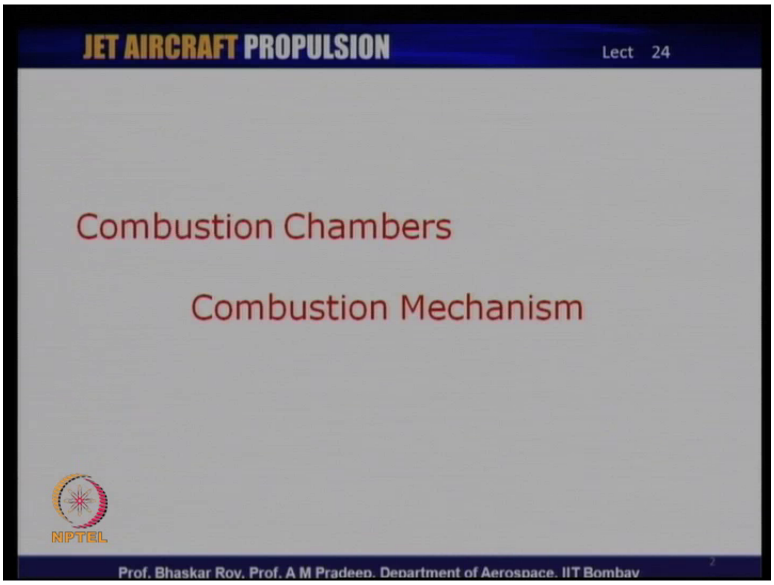

So, let us take a look at the fundamental combustion mechanism of combustion chamber of aircraft engines. Now, combustion mechanism when we are talking about we are as I mentioned, we are indeed talking about the basic physics, and the basic engineering that goes in to making of a combustion chamber. Now, typically a combustion chamber has been designed more than 50 years back, and for one reason of the other that particular design or that kind of design has been used for many, many years. So, the fundamental engineering that goes in to making of a combustion chamber has been settled for almost 50 years now. The basic physics was also understood quite long back.

However, minor modifications and minor improvements have been going on all along and as a result to which each combustion chamber of every particular engine is unique. There is nothing like a generalized combustion chamber design or combustion chamber geometry that you can fit in to any engine. For every engine, a combustion chamber would need to be designed uniquely for that particular engine and because of this, it is necessary to keep an eye on the fundamental issues of the physics and the engineering of the combustion mechanism. Let us take a look at this fundamental combustion mechanism in today's lecture.

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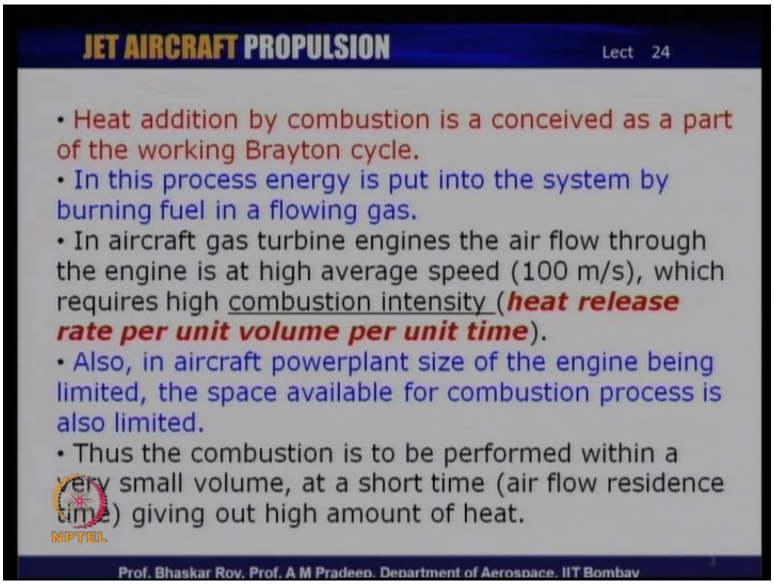

As I was mentioning, the heat addition that is done normally in a combustion chamber is fundamentally conceived as a part of the working Brayton cycle. Now, we know an aircraft engine is fundamentally conceived based on the Brayton cycle the thermodynamic brayton cycle and combustion has to be in conformity with that Brayton cycle conception. In this process, the energy is put in to the system by burning of the fuel in a flowing gas. Now, we have seen that the brayton cycle works in an open cycle. It has a continuous flowing gas, initially flowing air and then it becomes flowing gas and the combustion has to be done in this flowing situation.

Now, that is a different kind of a problem and that is what, we will be looking in to in today's lecture. Now, the aircraft gas turbine engine has the problem that the air flow through the engine is at a average speed of close to 100 meters per second. Now, that is a pretty high speed actually speaking, which requires the combustion intensity is very high. That means, in a very small time if you have 100 meters per second average speed, the resident time in at in any of the elements of an aircraft engine is a matter of fraction of a second. So, in a fraction of a second, you have to release the heat that is available from burning of the fuel.

So, you do have very small amount of time and very small amount of space to complete the process of combustion. And this is one of the challenges of designing the combustion chamber that in a very small space, and of course in a very small time, you have to complete the process of combustion. Space in an aircraft engine is in premium. You are quite often allotted a very small amount of space for doing your combustion job and this puts a lot of pressure on the engine designer to create a unique combustion chamber in which the combustion can be more or less complete.

So, this is a kind of challenge that combustion designer often needs to face with every engine design. In aircraft power plant size as I mentioned, the size is limited and you have to create your combustion within that limited size. That size limitation puts a restriction on the volume that is available for combustion purpose. And the time that is allotted because air is flowing at a very fast space and the residence time of the air inside the combustion chamber is a very small fraction of a second. So, within that small fraction of a second, a very large amount of heat would need to be released inside the combustion chamber and that is a mechanism which we will look at in today's lecture.

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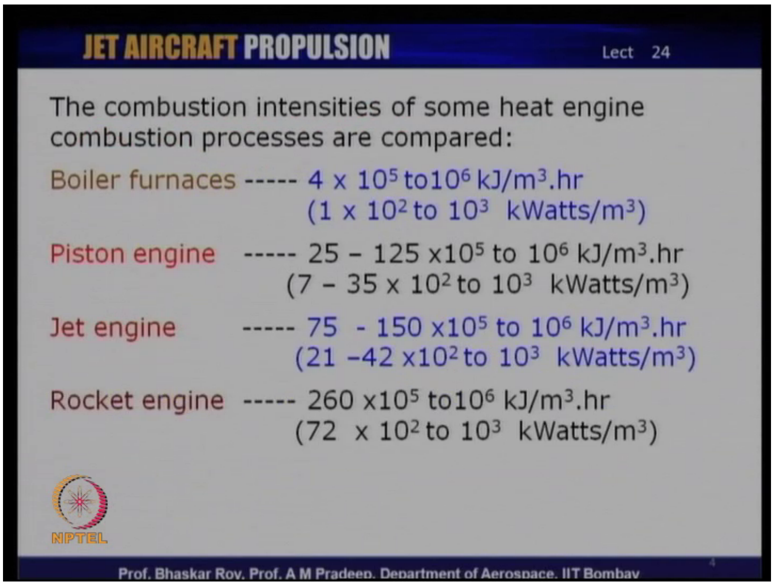

Let us continue with this fundamental understanding. The combustion intensity which I mentioned varies from one kind of engine to another. Let us take a quick look at what are the numbers that we are talking about. If we look at boiler furnaces that are typically used in steam engines, the kind of heat release we are talking about is 4 in to 10 to the power 5 to 10 to the power 6 kilojoules per meter cube per hour. And that is roughly 1 in to 10 10 to the power 2 to 10 to the power 3 kilowatts per meter cube. Now, if you compare that value to the piston engine which is a IC engine also, where you burn various kinds of fuel to get your work done.

Now, piston engine is enclosed combustion chamber, you do not have flowing fluid and you have a captured volume of air in which fuel is burnt and inside that captive combustion chamber which is the piston head, the amount of combustion intensity is 25 to 125 in to10 to the power 5 to 10 to the power 6 kilojoules per meter cube per hour. Now, if you compare that to the jet engine that is used in aircraft, that is of the order of 75 to 150 into 10 to the power 5 to 10 to the power 6 kilojoules per meter cube per hour; that means, its fundamental heat release rate is of a higher order than any piston engine.

And if you go to rockets, the requirement is of the order of 260 in to 10 to the power 5 to 10 to the power 6 kilojoules per meter cube per hour. So, rocket engines do have the highest heat release rate that needs to be a created inside the rocket combustion chamber. So, jet engine comes second in the list of high heat release rates that are needed in combustion chamber. Now, with this kind of requirement of heat release rate, it is necessary that you have a very good understanding of the combustion mechanism. Let us understand how these things happen.

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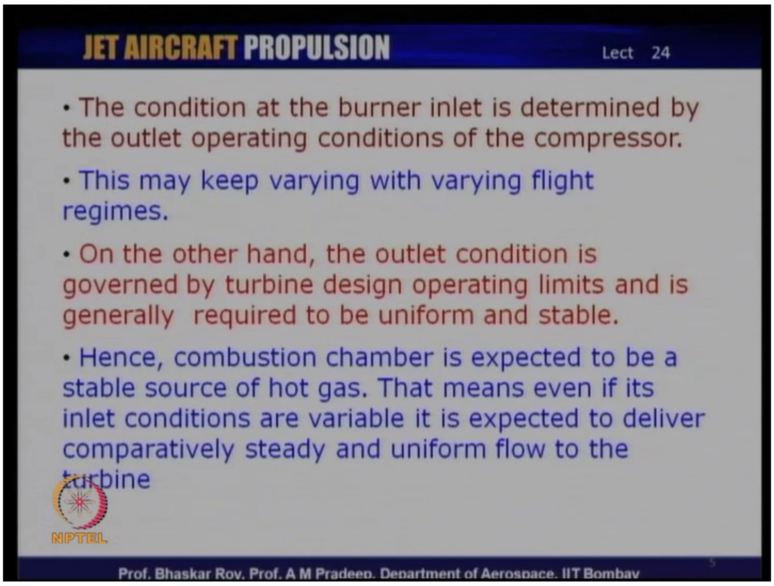

The condition at the burner inlet is determined by the outlet operating conditions of the compressor. Now, the outlet operating condition of the compressor varies with the varying flight regime. Now, depending on whether the aircraft is taking off or it is climbing or whether it is cruising or it is doing maneuvers; depending on all that, the compressor operating condition and its delivery to the combustion chamber would vary in terms of pressure, in terms of temperature, in terms of density and also quite often in terms of the velocity with which they are delivered. Now, this variation obviously has some impact on the combustion chamber performance.

On the other hand, the outlet condition of the combustion chamber is necessarily governed by the turbine design operating conditions and is generally required to be uniform and stable. Now, as we have discussed before, the first turbine that faces the combustion chamber is the HP turbine. Now, HP turbine is what faces the high temperature and high pressure gas coming from the combustion chamber. Now, HP turbine is necessarily a high speed turbine, which supplies a lot of power in a small size to the compressors. So, it is necessary that HP turbine gets a very stable and uniform supply of high energy gas from the combustion chamber.

This is necessary to be done or achieved and assured by design. Now to do that, combustion chamber needs to be created in a manner that within a restricted space and restricted volume, it does provide and supply stable hot gas to the turbine irrespective of whether or not it is getting a stable supply from the compressor. So, combustion chamber in some sense, apart from doing the combustion also needs to stabilize the flow a little, before it delivers it to the turbine. So, combustion chamber in some sense is some kind of a stabilizer also in addition to doing the heat addition to the working fluid.

Now, this stable source of hot gas is necessary to be delivered under all operating conditions especially when the aircraft and the engine is accelerating or decelerating. And this requires that the combustion is always held and it is never allowed to be extinguished or what is known as blown out under all kinds of operating conditions. And we shall see that there are certain parameters which are to be held very strictly within those certain specified limits and those parameters are what we are going to discuss in a few minutes from now. So, this variability that we are talking about and the stability that we are talking about can be quantified and these quantified parameters are what we are going to talk about in today's lecture and carry on in the next lecture also.

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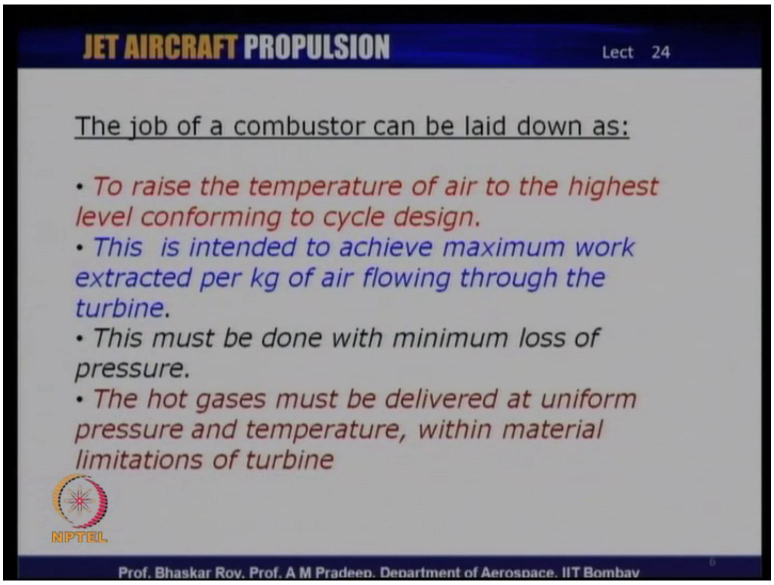

Let us take a look at some of the jobs that a combustion chamber is supposed to do. We can indeed list them: To raise the temperature of air to the highest level confirming to cycle design. Now, this is as per the turbine inlet condition as specified in the cycle design. The turbine inlet condition is indeed decided by the ability of the turbine to withstand high temperature, which is decided by the material signs; the state of art of the material signs and the metallurgy and the cooling technology of an employed intertwined design. So, all of them together decide what should be the compressor delivery temperature. And the cycle design will tell us what the compressor delivery pressure would be which is roughly what combustion chamber receives from the compressor.

So, combustion chamber is supposed to deliver more or less the same pressure with minimum loss of pressure. Now, this is intended to achieve maximum work extraction per unit mass of air flowing through the turbine. Now, we mention that combustion chamber works in a gas turbine engine in a flowing fluid. So, it is necessary that it produces this work working capability or renders this working capability to the turbine in flowing fluid situation. Now as I mentioned, this must be done with minimum loss of pressure; because lot of care has been taken to build up a lot of pressure in the compressor and one should not lose much of it in the combustion chamber.

So, combustion chamber design the engineering of the combustion chamber design must ensure that there is minimum loss of pressure and that is why, the engineering comes in. The hot gases must be delivered at uniform pressure and temperature within the material limitations of the turbine. So, material limitation of the turbine, the cooling technologies of turbine is one aspect. The other aspect is that it should have a uniform profile temperature and pressure profile as it is going into the turbine. Because when it hits the turbine, the turbine has a root as we have discussed in the turbine chapter. It has a tip and the blade is often twisted.

And when the air hot gas hits this turbine blade first the stator and then the rotor, it should have uniform temperature profile from hub to the root to the tip of the turbine going through the stator and then on to the rotor. This uniform it is very important; because the turbines are designed for uniform temperature profiles. Turbines are normally not designed for non-uniform temperature and pressure profiles. So, the combustion chamber has a job to do here; that is, to create uniform flow with uniform temperature and pressure and velocity delivered to the turbine in a annulars form, you remember. The turbine is a annulars construction and so combustion chamber must deliver it to the turbine in an annulars form. So, this uniformity needs to be achieved in that annulars.

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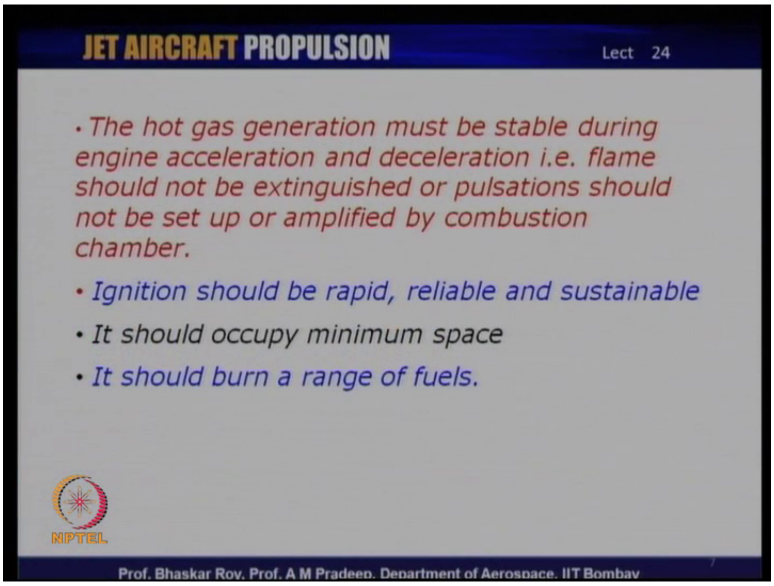

The hot gas generation that must be created. Now, this must be done as I have mentioned during engine acceleration and deceleration. And during acceleration and deceleration, the flame which is created inside the combustion chamber should never be allowed to be extinguished or any kind of pulsations should not be setup or amplified by the combustion chamber. Now, these are distinct possibilities. These can happen during the combustion chamber operation, and combustion chamber designer must ensure that none of these things happen during the operation of the engine, because as I mentioned, these are realistic possibilities. Flame can get extinguished; pulsations can occur, and some of the disturbances that are occurring can get amplified, and if those things happen, it would be absolute catastrophic.

The whole engine would burst like a little bomb, and this is something which is must be avoided under all considerations and under all operating conditions. So, combustion chamber designer needs to ensure that none of these catastrophic things ever happened during the operation of the engine. The other requirements which the engine designer the combustion chamber designer needs to confirm to is that the ignition should be rapid, reliable and sustainable. In a typical aircraft engine, once the ignition is done, it is sustained through the entire operation of the engine.

And ignition is not done every now and then as it is done in piston engine. So, it is not as per the cycle. Ignition once done, it continues indefinitely till the engine is shut down. It should occupy minimum space something we have talked about earlier and we shall see the mechanism how it is done. And the last of the combustion requirements is that it should be able to burn a range of fuels. We will have a look at a few of the fuels that are normally used. They all fall more or less within the same category or what is known as aviation kerosene and but there are variations within that. And we should be able to create combustion chamber, which can burn any of those fuels confirm in to the requirement of the particular engine and ofcourse particular kind of aircraft.

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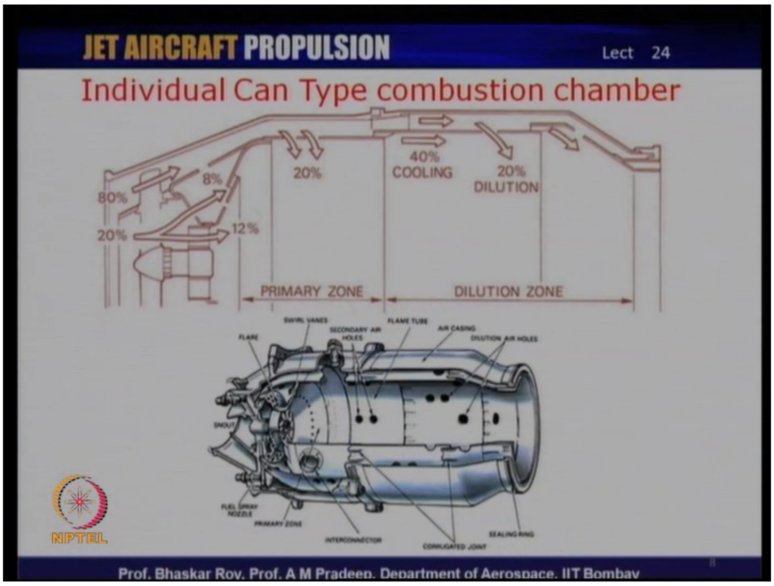

Now with this, let us take a look at some of the combustion chambers that we may like to get ourselves familiar with. Now, the first type of combustion chamber that came in to being in a typical gas turbine is typically referred to as a Can type combustion chamber. In which, the entire flow coming from the compressor is split up in to number of cans and these cans are arranged around in an annulars fashion around the shaft of the engine. So, quite often you would have 5, 7, 9 or fairly large number of cans arranged around the shaft of the engine and the entire amount of annulars air coming from the compressor is split in to so many cans.

Now, let us see what happens inside each of these cans; which each of which is a combustion chamber by itself. The flow is coming from the compressor; high pressure here and then inside the when it hits a can, you can see only 20 percent of the air is going inside over here and almost 80 percent goes outside through the bypass. So, a combustion chamber indeed has a bypass system. Now, this 20 percent of air that goes in; it goes through what is often known as a swirler and this is where, you see the swirler. It creates a swirl and then it goes to this entry port over here and then enters the combustion chamber.

Inside the combustion chamber, this is what we call primary zone and that is the primary zone in the lower picture which is here cutout a real combustion chamber. And this is a primary zone, where the fuel is actually burnt and the fuel air mixture of gas is primarily created. Now, once the fuel is burnt and the primary gas is created, excess of 20 percent of air is allowed to be brought inside the combustion chamber from the bypass system. So, the can has a bypass system and from that bypass, 20 percent comes in here; then 40 percent comes in through various other means and 20 percent more comes in through in the last stages, which is a dilution zone or often referred to as secondary.

And finally, tertiary zone in which more air comes in. So, the hot air that is created here or the hot gas is subsequently cooled to certain temperature, which is conformity with the turbine material. So, this dilution or cooling is often inconformity with the requirement of the of the turbine. So, the amount of cooling that needs to be done is dependent on the turbine material and the turbine design. Because in the primary zone, the temperature that is often achieved is in excess of 2500 degree centigrade; now, that is the kind of temperature which is not allowed to be delivered to the turbine. So, subsequently with this excess air which is brought in to the combustion can, the inner can so to say.

So, you can say you have a inner can and you have outer can and the bypass carries nearly 80 percent of the air in the outer can and then it comes inside and and cools the air to something like 1000 to 1100 degree centigrade and delivers it to the turbine. So, this is how, it is done. You can see that there are two concentric cans over here and you have number of these holes.

These are the holes through which this air comes in the primary, the secondary and the in the dilution zone, in the tertiary zone. So, these are the air wends through which bypass air is coming in; which is cooled air really to cool the hot gas to confirm to the turbine requirements.

You can see some serrations over here. These serrations are indeed openings. These are for actually bringing in cool air tangentially in to the inner can essentially to provide cooling to the inner can. It creates a film a cold film inside the inner can, if this is done here also. So, in every sector of the inner can, certain amount of cold air is brought in tangentially in to the can inner surface and creates a cold film along the entire annulars. And then the inner can is protected by this cold film from the very hot gas created by the combustion. So, the can which is also made of high temperature material also is provided certain amount of cold air protection for its life.

So, that it can perform without getting reshaped or without getting distorted during its entire life. So, the combustion also involves a little bit of cooling of the inner can to protect and extend its life. So, we have a number of things going on over here; air is coming in; it split in two parts. Minor part actually comes in and participates in the combustion process. The major part bypasses the combustion process and comes in later on for cooling purpose. We will take a look at what happens in the combustion process in the subsequent slides. But let us take a look at the other kind of combustion chambers that are used in the modern gas turbine engines.

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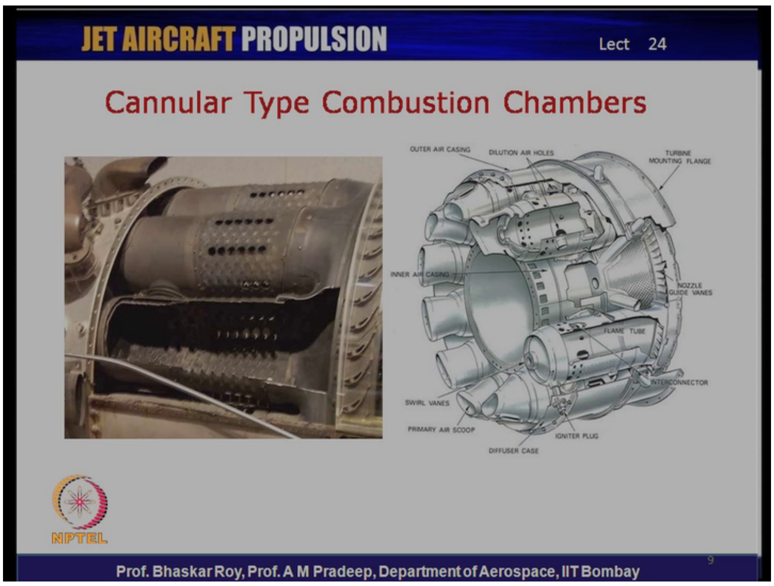

Now, this is what is known as a cannular type combustion chamber in which the flow is essentially again split up in number of cans, which are inner cans. This is an real picture of a can. But the bypass here which I mentioned earlier in the can type is now a common bypass for all the cans. So, we have a common bypass for all the cans and the inner cans are individual cans. And the one of the reasons, many of the modern engines use this particular mechanism of having inner cans to actually perform the combustion process is because the primary zone in which the combustion is carried out gives a protected combustion space to the combustion mechanism. Now, this is very important. When you are doing combustion, it requires certain amount of protection from the vagaries of other aerodynamic and gas dynamic disturbances.

And as I mentioned, this protection is very important for stable combustion and this protection is provided by creating a can an individual can within which, the combustion is done in an isolated manner. And in big engines, even today it is considered a good idea to have a number of cans as I mentioned may be 9, 11, 12, 13 cans within which, the combustion is held in a protected manner. Whereas, the bypass here is a overall annulars bypass and that can go in to any of the cans in the secondary and the tertiary zone for cooling the hot gas. But the primary zone is given a protected zone for protection combustion purposes. We will look into the combustion mechanism in a few minutes. But these can types were created to begin with is to create this protected combustion zone.

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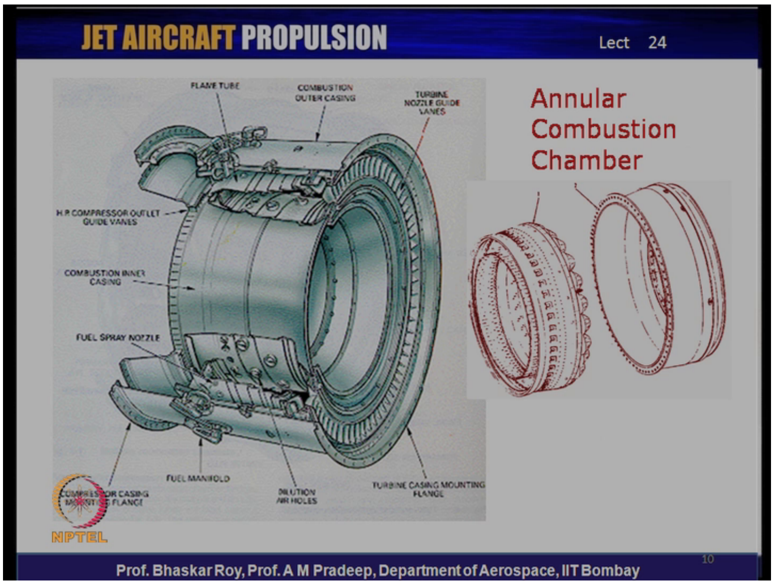

So, let us take a look at the other kind of modern combustion chamber, which is the annulars combustion chamber. Annular combustion chamber, in which the entire annulars of the flow which you supplied from the compressor; you see the compressor supplies air to the combustion chamber in an annular fashion. That annulars itself is carried on through the combustion chamber and delivers to the turbine in an again in an annular fashion. So, from this end, the flow is supplied from the compressor in an annular fashion and this is you have the combustion chamber here, which is annular combustion chamber. You have the primary zone over here and then you have the secondary zone and then you have the tertiary zone and at the end, it supplies in annular fashion to the turbine.

You can see the turbine nozzles or the stator nozzles over here lined up at the end of the combustion chamber. So, the delivery from the compressor and then delivery to the turbine both are annulars. And as a result, this particular combustion chamber is designed to create a design to retain the annular flow that is coming from the compressor and delivered to the turbine and the combustion chamber is indeed created in an annular fashion. So, this is the kind of annular combustion chamber quite often used in the modern aircraft engines specifically in the military engines or medium to small sized jet engines. Most of the engines today are annular combustion chamber.

So, if the engine is small or medium size and more specifically those used in the military aircraft engines, the combustion chamber is most likely to be an annular combustion chamber. Whereas for very big engines used in transport or passenger aircraft, the combustion chamber is likely to be the cannular kind of combustion chamber, which is a can number of cans which are arranged in an annular fashion with a common air bypass surrounding all the cans. So, that these are the various kinds of combustion chambers that had used in the modern jet aircraft engines. We will take a look at some of the issues related to the combustion and then the combustion mechanism.

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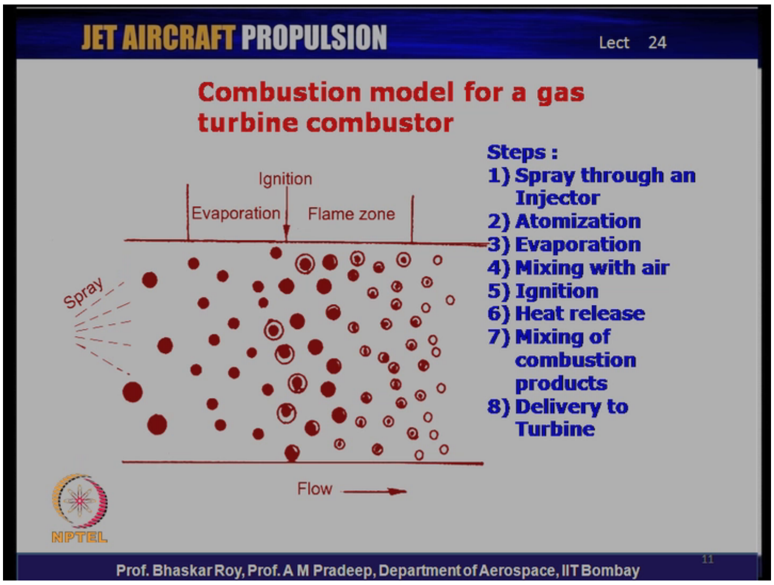

Let us take a look at how the combustion actually happens. What happens is the flow that is flowing through the combustion chamber; somewhere in that flow, you have a spray of fuel. Now, this spray is done by an injection process and we will talk about the injector later on. But first thing that happens is that liquid fuel is sprayed through the injector in to the combustion chamber and this spray comes out in the form of small droplets very small size droplets. Now, these droplets essentially or extremely important what is the size of these droplets. The injector is very finely designed to create very small size droplets and these are the process is called atomization. As the name suggest, that these droplets are supposed to be extremely small.

The idea is at the third step that is required here is evaporation. To heat the process very fast evaporation it is necessary that you have very small droplets and as it is mentioned here, they should be very small almost as if they are atoms. So, that the word atomization comes from that concept that they should be very small droplets. So, that the evaporation process is very fast and then following that the mixing of this liquid fuel evaporated and then mixing with the air. So, the evaporated fuel must mix with the air in a uniform manner and this evaporation process occurs next. Once the evaporation has been completed and here the fuel has been mixed in a certain known proportion, the ignition is initiated.

And once the ignition is initiated, the mixture of air and fuel starts actually burning. And then the burning process releases the heat and there is a burning zone, which is often referred to as flame zone; during which this mixture of air and the droplets of an evaporated fuel actually burnt and this burning zone is where, the heat is released. Now, the release of the heat through the process of burning takes place over what is known as also flame zone. And then once the heat is released, it is necessary that you take care of the combustion products. The process of combustion creates combustion products through the process of various chemical kinetic steps. Those chemical steps we are not discussing in this lecture series.

But there are large numbers of chemical steps and at the end, you create a number of chemical products. The combustion is fundamentally chemically a process of oxidation and this oxidation process creates a number of chemical products and these are called combustion products. It is necessary that these combustion products mixed very uniformly throughout the body of the combustion chamber. So, that they carry the heat uniformly over the entire space given to the combustion chamber. And once this uniform mixing has been achieved and the flow has been diluted by cold air, it is time to deliver it to the turbine. So, this is the fundamental mechanism by which the combustion chamber works.

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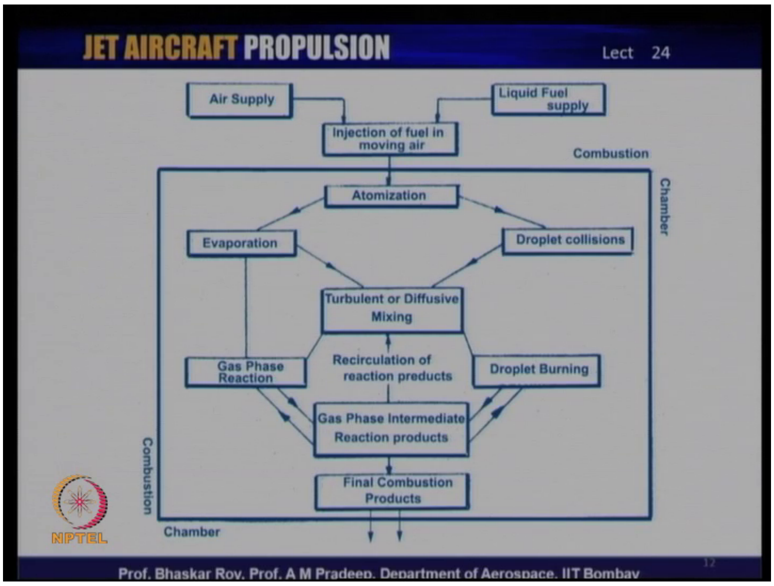

We can put it together in some kind of a flow chart, which will tell us how the combustion process proceeds. You have the liquid fuel that is supplied through the injector and you have the air supply that comes from the compressor and that both of them go in to the combustion chamber. And the injection of fuel in this moving air is done through what we mentioned a process called atomization. These are very uniquely designed injectors and we will discuss them later on in this lecture series. Once atomization is taking place, there are two things that need to be taken care of. One is the process of evaporation, where these fuel need to evaporate and become a gas and then the droplets that are there.

They infact are liquid droplets and they quite often collide with each other. So, the collusion of these droplets often may result in creating bigger droplets and that is something that needs to be avoided. So, one should not allow bigger droplets to be created rather the droplet should break up in to even smaller droplets and so that, they evaporate very fast. So, the process of evaporation needs to be aided one way or the other and then ofcourse, you have turbulent or diffusive mixing. We shall have a look at how this is achieved. This mixing process of air and fuel is extremely important and we shall see how that is achieved in a few minutes and then this we have two kinds of reaction. One is the gas phase that is the evaporated fuel mixed with air goes in to gas phase chemical reaction, where heat is released.

And the other is where the droplets that are still remaining as small droplets start burning and they burn as droplets. So, we have two kinds of burning. One is the gas phase burning; another is a droplet burning and then they create a total reaction process of the combustion and this is what we call combustion. So, we have two kinds of combustion; the gas phase combustion and droplet combustion and when they put together, the combustion is completed. We have the reaction kinetics completed and finally, the combustion products are created, which also carry the heat or combustion with them and they are to be distributed evenly over the entire combustion. So, this is how the entire combustion process proceeds from the beginning of the combustion chamber to the delivery end of the combustion chamber.

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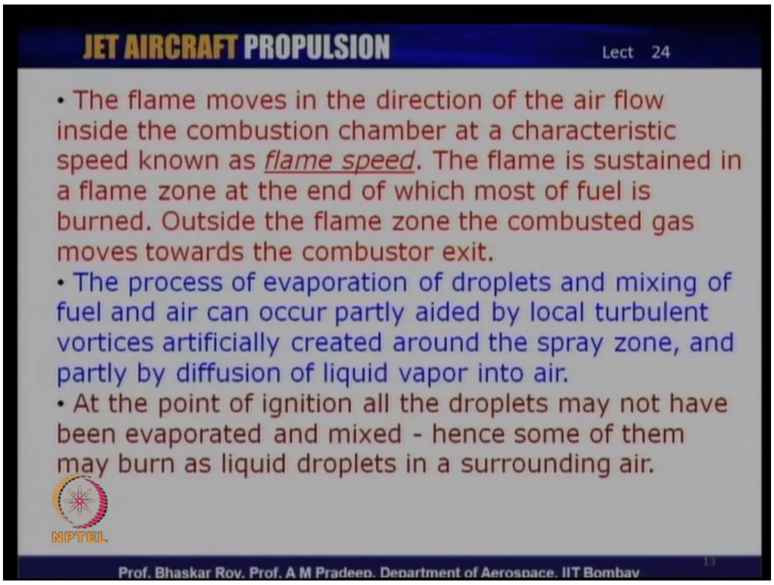

So, we can say that the flame that is created by the combustion process needs to be taken care of. There is you have droplets burning and there you have the gas phase burning. You have two kinds of combustion process going on and it is necessary that the flame that is created for the combustion process is kept under control all the time. Now, this flame that is created moves in the combustion chamber along with the flow of air at a speed; that is known as flame speed. Now, this flame speed is an important parameter and we will go in to it in this lecture. The point is that this flame is to be sustained for continuous combustion. And if the flame is to be sustained for continuous combustion, it is necessary that you held the flame or hold the flame steady throughout the process of combustion.

And if you cannot do that, remember the flame is likely to be extinguished or is likely to create combustion related instabilities; both of which are unwanted phenomenon in gas turbine engine. Now, outside the flame zone, the combustion gas move towards the combustion exit. Now, this movement of combusted gas towards the exit is often aided by the motion of cool air that is coming in and as a result of which, that is something that needs to be engineered in to the combustion chamber design. The process of evaporation of the droplets and mixing of the fuel and air can occur partly aided by the local turbulent vortices, which are artificially created around this spray zone and we shall have a look at this phenomenon in the following slide. At the point of ignition, all the droplets may not have been evaporated and mixed and hence some of them may burn as liquid droplets.

As I mentioned in the last slide, that the combustion may proceed with the droplets also. So, combustion may proceed either in the form of a gas phase combustion or it may proceed in a form of droplet combustion. Both of which indeed are combustion processes; both of which coexists inside a combustion chamber and both of them must finish the combustion process simultaneously and create the combustion products within the so called flame zone which we mentioned. So, within the flame zone, we have two kinds of combustion going on. But both must finish the combustion by the end of the flame zone and deliver the combustion products to the following space in the combustion chamber. So that, in a uniform manner, the hot gas can be delivered to the turbine.

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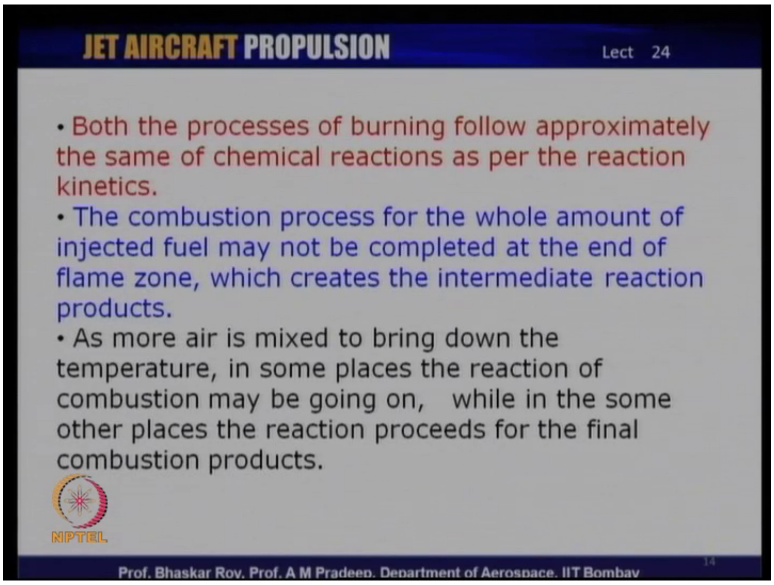

Let us take a look at what happens thereafter. The process of burning then creates the chemical reactions and this chemical reaction kinetics or what creates the release of the heat from chemical bonding that the fuel has. So, the release of the chemical bonds essentially creates the heat release and this is overall as I mentioned is called a process of oxidation, where air supplies the oxidizer. So, air here is oxidizer and fuel ofcourse is the propellant or the chemical unit that participates in the process of oxidation. The combustion process for the whole amount of the injected fuel may not be completed by the end of the flame zone.

Now, this is something a combustion engine designer combustion designer must be very careful about. That process should be as far as possible complete by the end of the flame zone. Now, it is possible that a very small percentage may be one percent may not be completed by the end of the flame zone. And then a certain amount of combustion can continue to happen in the rest of the combustion chamber and then more air is remember are brought inside the combustion chamber to bring down the temperature. So, carrying on the combustion is going to be more and more difficult. Because the it is been cooled down necessarily to aid the delivery to the turbine.

And however, it is quite possible that in rest of the combustion zone, certain amount of reaction is still carrying on; is still going on and in some places, the reaction has indeed been completed and the combustion products have already been created. So, in the secondary or tertiary zone or in the dilution zone, it is entirely possible that a very small amount of combustion is still going on. But most of the combustion 98 percent of the combustion may have already been completed. So, this is how the combustion is indeed done inside the combustion chamber.

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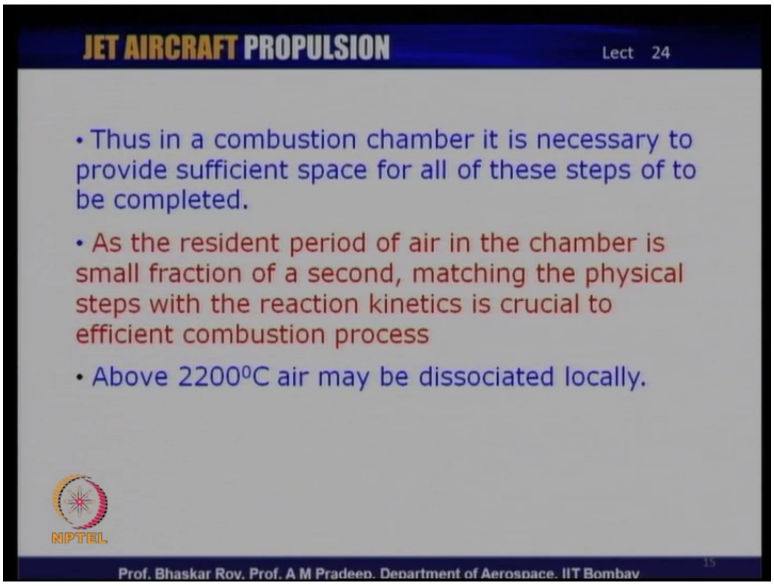

It is necessary that sufficient space is provided for all the steps. We saw number of steps. There was atomization; there was combustion; there is a creation of combustion products; there is a flame zone; you have to give the flame certain amount of space to exist and then the mixing of the combustion products and then finally, delivering it to the turbine. So, there are so many things to be done inside the combustion chamber very carefully. So, that the combustion process is complete in all sense of the word. Now, this needs to be done in a very small space. However, that space needs to be sufficient for doing all these things in a step by step manner. Since the resident period inside the combustion chamber is indeed very small, it is necessary that the physical steps and the kinetics of the reaction are matched in time.

This is extremely important; because you do have small fraction of a second; quite often a very small fraction of a second. And within that fraction of a second, you need to have a physical matching between the reaction kinetics and the physics of the flow and this is important. At the end, you must keep an eye on the temperature. The temperature in the primary zone is very high. It is of the order of 2500 degree centigrade quite often. However, the air above 2200 degree centigrade quite often has a tendency to disassociate locally. So, the primary zone temperature which is often available in the primary zone should not be allowed to go inside the rest of the combustion chamber, where air may disassociate.

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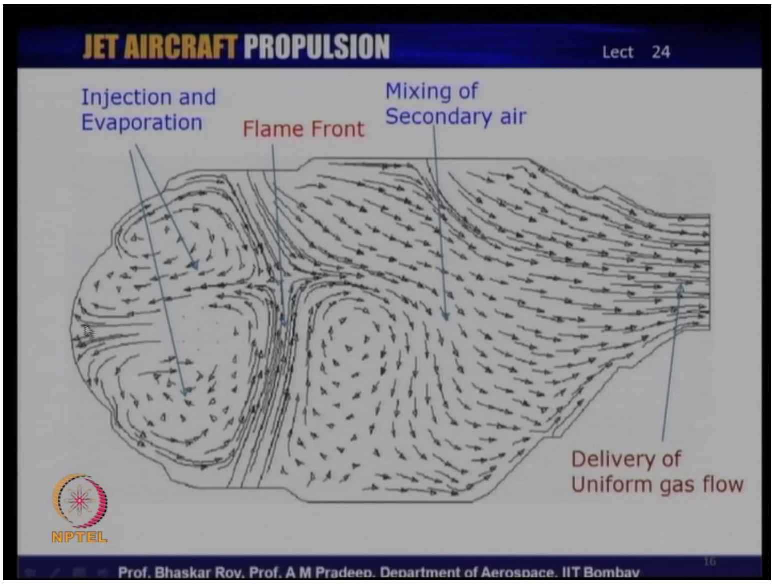

Let us take a look at how the combustion actually is controlled inside the combustion chamber. Now, this is a typical side view of a typical combustion chamber whether it is a can type or whether it is a annular type. The air comes from this end and delivers in to the combustion can or combustion zone primary zone, which could be as as we saw only 20, 25 percent of the air coming from the compressor and in this zone, artificial recirculation is created. Now, creation of this artificial recirculation is extremely important and this is created by elements that are known as flame holders. These flame holders are of various shapes and sizes. We will have a look at them later on.

And these flame holders create artificial recirculation zone; because of which, the air that is coming from the compressor may have an axial velocity of the order of 100 meters per second. As it comes inside through this swirler which we saw, the axial velocity is reduced to nearly 30, 40 meters per second. And then through the recirculation as we are seeing here, the forward movement or the axial velocity is brought down pretty close to something like 4 to 5 meters per second. Because that is where, the flame can be sustained. At high velocities of air, the flame cannot be sustained. The sustenance of the flame requires that the forward velocity is very small.

So that, the so called flame speed matches with the air velocity with which the combustion the gas and the combustion products move. So, it is absolutely necessary that the engineers create a very good recirculation air flow zone over here. So, that the air forward velocities brought to very low value and recirculation which created to aid the process of evaporation. Injection ensures that you have small droplets and that itself is supposed to aid the process of evaporation and then the recirculation of air further aids the process of evaporation. In that small space, very fast evaporation is required.

Because without very fast evaporation and very good mixing, you will not have uniform flame created on the flame zone. So, it is necessary that you have uniformity of the gas or the uniformity of the fuel and air at the end of this zone. So that, uniform flame front is created. Now, flame front of course is the flame with which the ignited gas moves and this moves as at a speed which we called the flame speed and it moves within a certain distance. At the end of the distance, the entire combustion process is over and the flame has produced the combustion products which then moved away from the combustion zone and new flame front is already created.

So, this zone is where, the flame front it initiates the combustion process and the end the other side of the flame front or the flame zone is where, the combustion process is completed. So, combustion is initiated at one end; completed with other end and as you can see that is a very small zone in which the entire flame has to exist and sustain itself to create the process of combustion. Now, once a process of combustion is over and the flame front delivers the combustion products, you again need a process of recirculation and this is what is done by infusing cold air through those air wends. They come in and create again a recirculation zone.

Again here they are coming in tangentially and creating a recirculation zone and they aid the process of mixing of the very hot gas to the cold air. So that, by the secondary end of the secondary air zone, the air or the gas has now achieved a much lower temperature. This lowering of temperature continues in to the so called tertiary zone, where it is necessary to create uniform flow. The uniform flow needs to be created now in the tertiary zone through which the air is now to be delivered to the turbine. So, at the end over here, you must have uniform temperature and pressure. So, this is how the combustion is engineered inside the combustion chamber.

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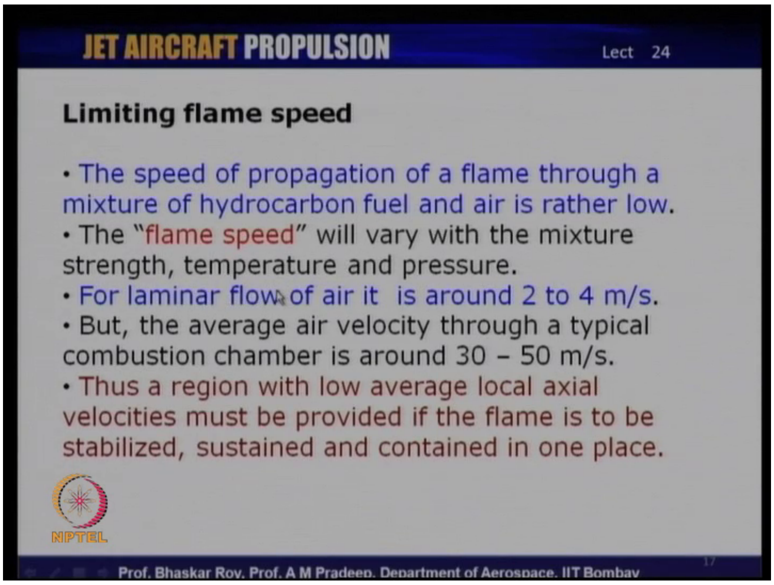

The speed of propagation of the flame through a mixture of fuel which is normally a hydrocarbon fuel and air is rather low and the flame speed will vary with mixture, strength, temperature and pressure. For laminar flow, the flame speed is around 2 to 4 meters per second. The average air velocity through a typical combustion chamber is around 30 to 50 meters per second; it that is even after the swirler. So, which means artificially just around combustion, you need to create air flow of the order of 3 to 4 to 5 meters per second.

Otherwise, combustion there cannot be sustained; flame there cannot be sustained. So, a low average local axial velocity must be provided, if the frame is to be stabilized, sustained and contained in one place and (Refer Slide Time: 43:34) that is exactly what is done over here. Recirculating zone has been created and this recirculating zone indeed actually creates the very low forward velocity 2 to 5 meters per second, axial velocity and lot of recirculation here. So, that this flame front is sustained at that 3 to 4 meters per second on a continuous basis over the entire period of operation of the engine.

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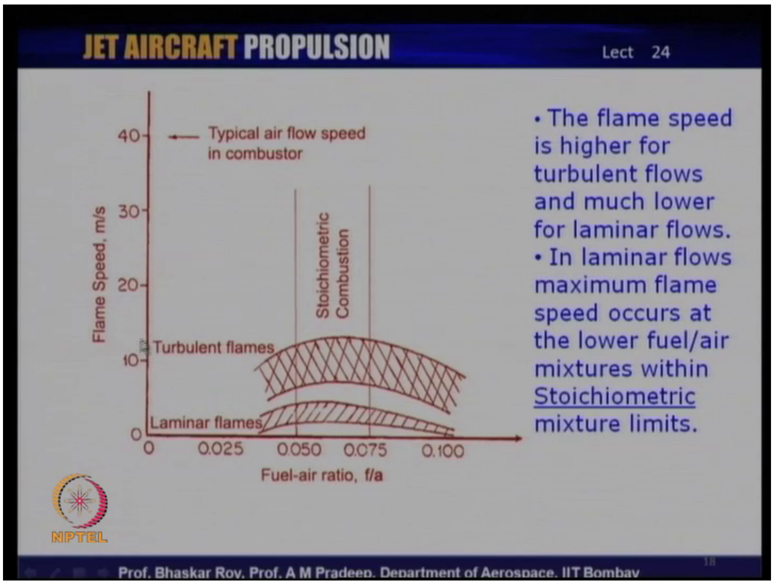

If we look at a simple graph, it tells us that the flame speed depends on whether you have a laminar flow or turbulent flow. If the flow is turbulent, the flame speed can be a little higher. So, the recirculation zone often creates a bit of a turbulent zone and within which, the flame speed can be little on a higher side. Now, the typical air flow speed is of the order of 30 to 40 meters per second and this is where, the flame speed is expected to be; without which, the flame would not be sustained. Now, the fuel-air ratio has a limit; within which, the fuel will burn and this is referred to a stoichiometric combustion or stoichiometric ratio, which is simply the chemically correct fuel-air ratio.

And that has a very small zone within which, the fuel air would burn in a combustion mechanism. So, as we can see here; it may vary from something like 0.05 to 0.75 within which, the fuel-air ratio needs to be held during the process of combustion. If it is more, the fuel will get extinguished because of the richness of the fuel or the combustion will get extinguished. And if it is less, it will become what is known as a lean combustion and the combustion may get extinguished bet because of lack of fuel or too much air. So, too much fuel or too much air will result in extinction of the flame. So, you have to hold the flame within that stoichiometric ratio zone and still hold the air in a low velocity area.

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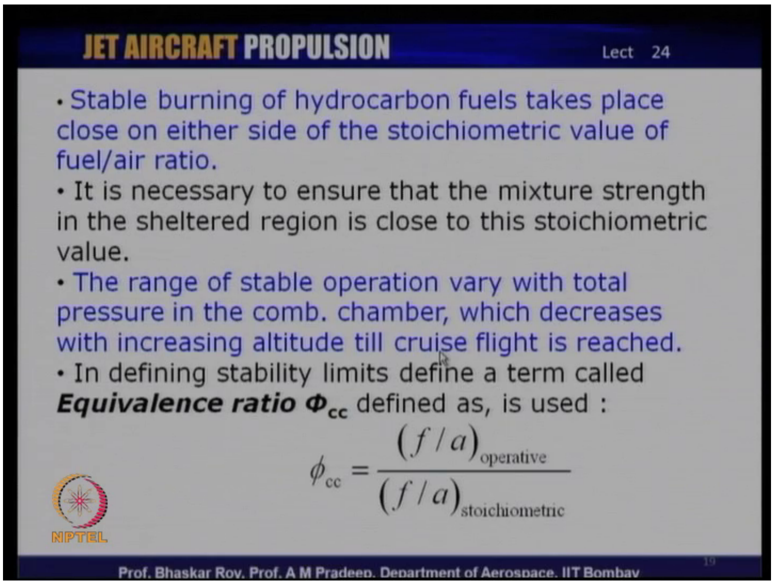

The stable burning of the hydrocarbon fuel takes place close to either side of the stoichiometric has been just mentioned. It is necessary to ensure that the mixture strength is held within those values in that sheltered region. The ranges of stable operation vary with total pressure of the combustion chamber, which decreases with increasing altitude till the cruise flight is reached. Remember as you are flying to higher altitude, the combustion chamber pressure is going down and you have to hold the stable operation. The change of fuel-air ratio from what is operational and what is stoichiometrically correct; this ratio is simply known as equivalence ratio. So, how far you are away from the stoichiometric value is decided by the equivalence ratio. So, this equivalence ratio is going to tell us whether you are rich or a lean fuel and whether you are beyond the sustenance fuel-air ratio or not.

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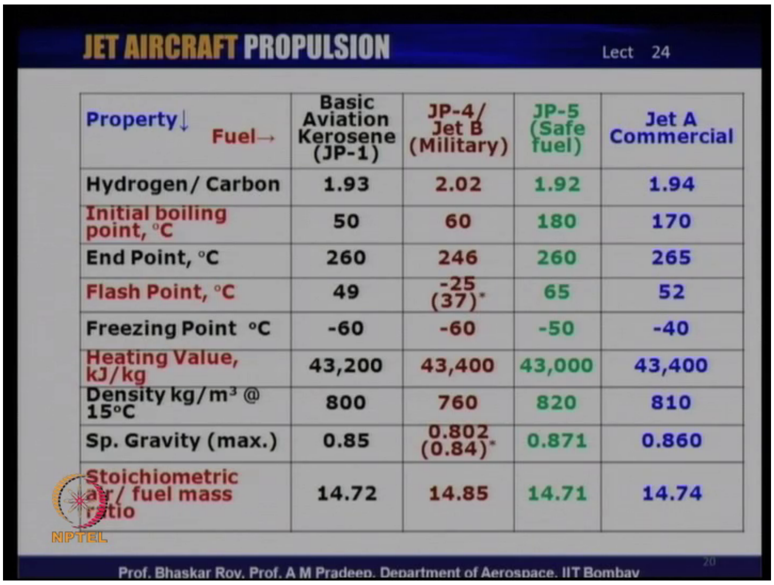

Property↓ Fuel→	Basic Aviation Kerosene (JP-1)	JP-4/ Jet B (Military)	JP-5 (Safe fuel)	Jet A Commercial
Hydrogen/ Carbon	1.93	2.02	1.92	1.94
Initial boiling point, °C	50	60	180	170
End Point, °C	260	246	260	265
Flash Point, °C	49	-25 (37)*	65	52
Freezing Point °C	-60	-60	-50	-40
Heating Value, kJ/kg	43,200	43,400	43,000	43,400
Density kg/m³ @ 15°C	800	760	820	810
Sp. Gravity (max.)	0.85	0.802 (0.84)*	0.871	0.860
Stoichiometric air/ fuel mass ratio	14.72	14.85	14.71	14.74

These are the various fuels that are used in modern aircraft engines. All of them are hydrocarbons as I just mentioned and the hydrocarbon ratio is of the same order nearly 2 of all of them. All of them are some kind of kerosene or the other. However, there is very small difference between some kind of fuel used in military engine and some kind of fuel used in commercial jet airliners and there is a kind of fuel in which it is supposed to be safe fuel because of various reasons. So, one of the reasons is that it has a high initial boiling point.

That means, it does not catch flame very easily and hence it is called a safe fuel. But some of the fuel that used in military and commercial have slightly lower boiling points and you ofcourse have certain freezing points. And this is the heating value which you have used in your cycle calculation and thus, you can see the heating values are more or less constant for all the fuels that are used. Density is of the same order. As you can see here, the density of the commercial fuel is little on the higher side for economic reasons and the stoichiometric values are of the same order of various fuels.

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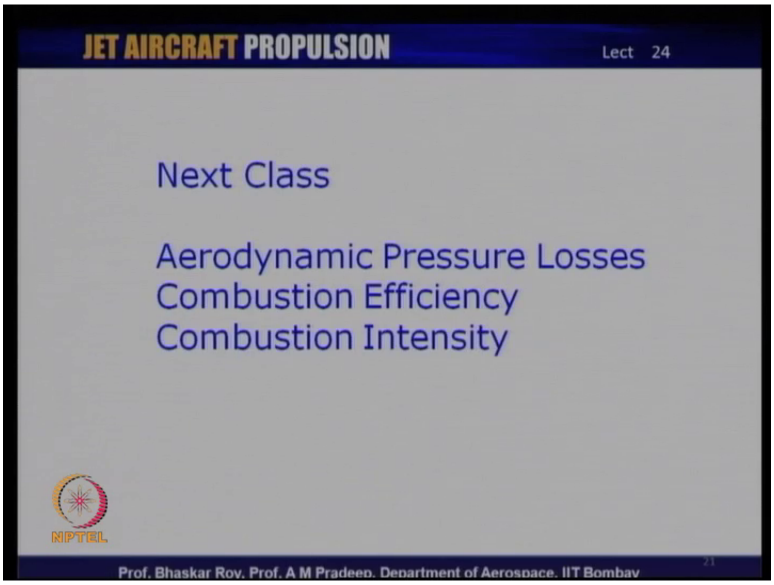

So, we have covered a ground over which we have looked at various kinds of combustion chambers, we have looked at the fundamental combustion mechanism by which the combustion is sustained , and created inside the combustion chamber. We have seen the basic fluid mechanics that needs to be engineered inside the combustion chamber to have a sustained combustion process. In the next class, we will look at some of the other issues of combustion chamber. We will look at the aerodynamic pressure losses that need to be contained, we will look at values like combustion efficiency, and we will look at the combustion intensity, which decides the heat released rate in the combustion chamber. So, these are the parameters that engineers used to decide whether the combustion chamber is good or not so good by design, and we will look at these engineering parameters in the next class.