Combustion in Air Breathing Aero Engines
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Lecture - 48
Aero Gas Turbine Combustors I

Welcome back friends. So, we have progressed deep into this course of combustion in air breathing aero engines. And as you have seen that that So far we have talked about essentially details of chemistry details of one laminar flames, and then fundamentals as well as modeling aspects of turbulent flames.

So, as such this course we can divide into 3 parts and into several modules as you have seen. But the 3 parts as you have seen mainly is the first part can be thought of as fundamentals, where we have looked into the basic chemical thermo dynamics chemical kinetics. Then we have looked into like oxidation mechanisms of fuels, then transport phenomena governing equations of reactive systems. Then we looked into flames then we looked into limit phenomena.

And then we moved on to in the in the second part we moved into turbulent flames right. We looked into the fundamentals of turbulent flows of non reacting turbulent flows how the mechanics of turbulence work how the energy can gets happens through the inertial range, and then we looked into basic aspects of turbulent combustion.

And how we have looked into how the like favre average in differs from normal averaging. And then we looked into then we looked into as such different simplified modeling aspects of turbulent flames simple models based on basically mixing models where we assume that the mixing is equal to reaction. So, once mixing is done it is reaction is almost guaranteed. And then we proceeded into turbulent non premixed flames and then proceeded and in the last class we have done turbulent premix flames. So, all these essentially as you see that all these has been done so that we can understand what happens in a gas turbine.

What happens in a aero engine combustor? Well, But So far we have not talked directly about to the aero engine combustors. So, the idea is that we have built these individual processes we have built we have try to understand processes at very small scales that happens in kinetics. We have are try to understand processes how the oxidation how the fuel breaks down to different to different intermediates and then it goes into products. Then we have see how we can how those reaction mechanisms can be incorporate into incorporating into governing equations.

And with that different kind of flames can be analyzed. So, essentially a 1D so, it is like a hierarchical way of proceeding that we have done. So, all these small understandings essentially fit is into bigger understanding of turbulent flames. And then these turbulent flames understanding fit is onto the understanding of the actual combustion processes in a gas turbine engine. So, in the next part that we will start now we will talk about essentially gas turbine engines that is aero gas turbine combustors. So, all these understandings all these things like kinetics oxidation mechanisms the governing equations 1D flames.

The concepts for 1D flames the pressure drop concepts the limit phenomena concepts ignition extension and then turbulent combustion contuse everything feeds into this thing. Will not exactly show you that how to solve for flame inside a combustor inside a gas turbine combustor, we will tell you because that is too much details that is too much specialized. And you need to look into real papers where this is done and we can give you the references. But the whole thing is that, so all that has been understood all there has been discussed. So, far essentially goes into our forms one or more processes of what happens in a gas turbine engine ok.

So now we will talk about basic aspects of the gas turbine combustors that how does this device look like. How does it function? And so, then it is basically on one hand we have this device level or the combustor level or an engineering level understanding. And on the other side we have already build this fundamental understandings. So, once we can match this to we will be in a perfect position to basically understand or even to go on to solve combustion processes inside this gas turbine combustor or later first scramjet combustor So that is a purpose, that is it is not to this course is not about to show you how to solve for a combustion process.

How to solve, how to simulate a gas turbine combustion inside a, how to simulate combustion process inside a gas turbine engine; but rather this course tells you all about all the fundamental understanding necessary to basically look into gas turbine combustors and the combustion processes in those in these engines. Of course, we will not talk about one aspect because of limitation in time that is called thermoacoustic instability which is also problem in gas turbine combustors. But that is a little bit more specialized aspects and you can look into other courses NPTL courses for understanding thermoacoustic instability there are good courses available.

So, here we will look into these aero gas turbine combustors.

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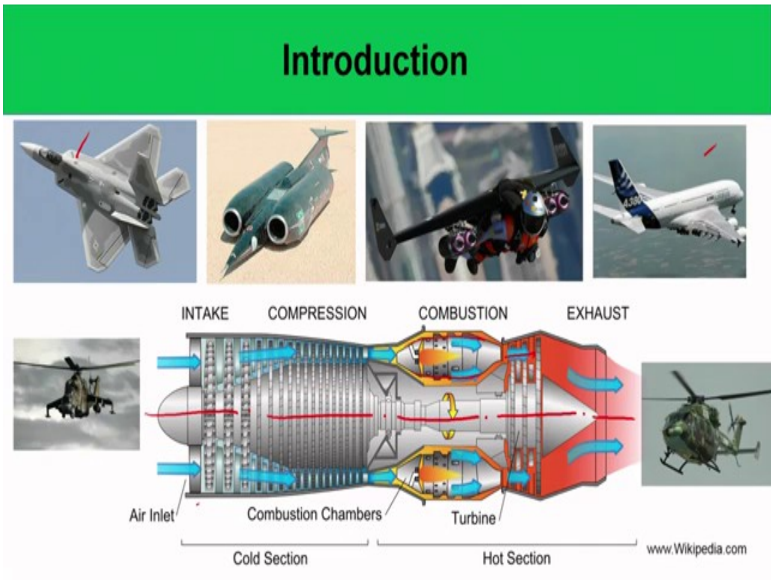

That is the purpose of these lectures; and so the as you see here all these aircrafts, this f 22 this jet pack or this Boeing or this airbus A380 and this helicopters. All this involve gas turbine combustors and gas turbine engines gas turbine engines as such in different forms. So, the gas turbine engine as you if you remember we talked into the in the introductory videos the gas turbine engine is really the workhorse. This really the workhorse of aero space propulsion, commercial or military for either way is gas turbine engine is present in some form of the other.

So, what are the basic aspects of a gas turbine engine? So, this is of course, as you know that the gas turbine engine comes in different variants there can be like a turboprop. There can be a turbofan and there can be a turbojet. And there can be a turbojet with an after there can be a afterburning turbo jet also. So, this is a normal turbo jet engine that we are showing here. So, as you see that the So, the front end of the engine right after the intake is has this, various stages of compressors rotating machinery compressors, and then this compressor. So, what happens is that to basically it works on the principle of a brayton cycle.

So, the air as it comes in is compressed through this compression action of the compressor. And it is compressed to a very high pressure before it enters into the combustion chamber. So, combustor combustion chamber happens in these combustors and then the hot gases go out and turn a turbine. And then this is passed this exhaust gases which is still high temperature is accelerated through nozzle and it exhaust and is and it goes out through an exhaust. And of course, turbine and the compressor has connected through a single shaft. So, the work input to the compressor is essentially comes in from the work output of the turbine ok.

So now of course, you see that the combustor is occupies rather a small section, but that this is not because it is important it is of course, very, very important it occupies small section because the compressor combustor essentially seize the highest pressure inside the whole gas turbine engine because of as you know to extract a work from a brayton cycle or from any cycle you need to add heat at high pressure. So, definitely combustion happens at very high pressure. And that is why the volume of the combustor is rather less because of the pressure is very high ok.

So, typical gas turbine engines like this can consume a very high mass products, and the combustor are designed to operate at very high pressure to accommodate that to basically for achieve high efficiency. And of course, you see that in this kind of combustors it is a cut section. So, of course, it is a it is a it is as it is essentially symmetric or it is access symmetric about this access this central access of symmetry. So, here we are showing essentially this combustor occupies an annular shape in annular occupies rather and annular shape.

So, we will talk about this in the in the following in the following Lectures.

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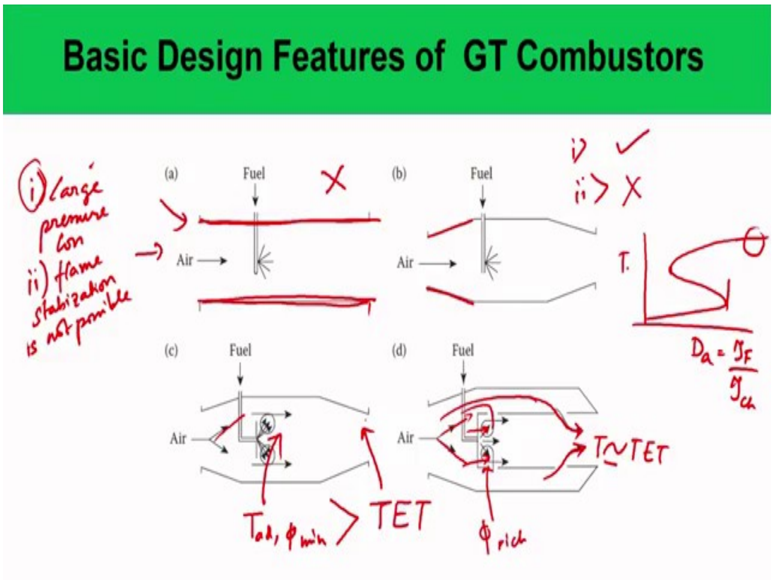

So, what is the basic design feature of a gas turbine combustor? So, of course, you see the combustor is essentially annular duct. So, what we need to achieve in our combustor what we need to achieve in our combustor is essentially, we have high pressure high rather high velocity air coming in. So, because the air that exit is out of a compressor is still high velocities about say 150 to 180 meter per second. So now, this we combustor what we need is the fuel to burnt, we need the fuel to burn in a rather efficiently.

So, what we can do is that we can take a duct like this a constant area duct like this. As you see in this a. And just inject fuel into it and of course, it will burn. So, this is like very classical 1D statistically 1D turbulent flame that we have. And of course, the in a gas turbine combustor the flow combustion really highly turbulent because as you as you know if the pressure is of the order of 30 to 40 bar. So, then we means the turbulence Reynolds number the is very large because the density is very, very large. So, in this configuration we going back to this configuration we can have combustion in this straight duct.

Flow can be laminar turbulent and very, very turbulent we can inject fuel. And why can not we have a flame like this why can not we have a combustor like this. There are 2 reasons the first reason is that, the air comes out of the compressor at a very high velocity as I said 150 to 180 meter per second. So, then if you pass this air this high velocity air through a constant area duct the pressure loss will be very large. So, of course, the pressure drop is professional to the inlet velocity squad. So, and of course, you do not want pressure loss because this pressure loss will be reflected in the will cause a dip in your constant in your ISO bar dip from the ISO bar in your T s diagram.

And that will lead to loss of efficiency. So, you want to minimize the combustor pressure loss as much as possible. You need to maintain it as close to concern pressure as possible. Of course, that is not possible because the combustion process when you are doing combustion in subsonic flows that is in variably it leads to some amount of pressure loss, but even then you want to minimize the pressure loss. So, if you are doing this combustion in this constant area duct, you are incurring huge pressure loss and that you and that we will reflect in the loss of the efficiency of the whole gas turbine engine.

So, this is ruled out. You cannot have combustion in a constant area duct, where the air velocities very high. And the second reason is that you cannot have combustion in a in a velocity, in a just like that that you cannot just expect that we will inject fuel in a very high velocity air and the flame will be stabilized. That is simply not possible, because if it is a even if it is a premixed flame. As you know that it has to then the then the local flow velocity has to match at least the turbulent flame speed, turbulent flame speed can and a normal circumstances cannot reach 170, 180 meter per second in a in a in this kind of engine.

So, it is it is ruled out. So, so 2 things number one this is ruled out because a because number 1, large this involves large pressure loss. And number 2 this flame stabilization is not possible in this. So, the next option is that, first to take care of this what we need to do is that we need to basically slow down the air velocity. So, the air velocity can be slow down if we just increase the cross section area of this before in this section that before entry into the combustor, which we essentially call a diffuser. So, because is a subsonic flow if you increase the cross section area of the flow, then of course, a velocity will reduce by continuity equation remember it is a subsonic flow.

So, we can assume that it is reasonably it can be considered close to incompressible. So, this we can essentially reduce the flow velocity by increasing the cross section area. So now, you can inject the fuel. And then the pressure loss will be less, but this does not satisfy the second condition. So, 1 is satisfied, but 2 that is the flame stabilization problem is still not satisfied. So, because even in this thing your l velocity even if you dislike say if few time slower say 2 time slower. So, from 170 equal to 80 meter per second, you just inject the fuel into the air steam you cannot have combustion stabilize combustion, you cannot have a flame stabilized at 80 meter per second that is not possible ok.

So, then what we do? So, the option is that we can inject the fuel beside or behind kind of a plate. So, this plate or this baffle will essentially is will bypass this surrounding air and this surrounding air will essentially re circulate. And we will inject the fuel in to this re circulation region. So, this will achieve my purpose because this we have this essentially introduce this plate. So, downstream of that plate or some sort of flow reversal mechanism. So, the downstream of this flow of this plate the flow velocity will be very small essentially 0 or even negative.

So, in that if you inject the combustor inject the fuel the fuel will have enough time to mix, and then it can essentially react and then it can burn. So, this essentially comes from the limiting concepts if you remember damkohler number if you remember the T verses damkohler number. That it has an x curve like this. So, you see you cannot have ignition beyond certain you cannot have ignition below certain damkohler number. So, the damkohler number has to be large.

So, this thing is reflected here that is what is damkohler number damkohler number is flow times scale by chemical time scale right. So, essentially to have combustion you need or to ignition and sustain combustion you need operate in this regime. And for that your flow time scale has to be definitely larger than the chemical time. So, these flow reversal methods that is employed here by either by a bluff body or by solar, that we will see later, is very critical to achieve flame civilizations it leads to some amount of pressure loss, but that is unavoidable ok.

But still there is one thing that is left. The thing is that you see this combustor is essentially has a very conflicting requirement. What is it conflicting requirement? So, the temperatures here at the exit of the combustor which is also call that turbine inlet temperature that is about say 1500 kelvin. And so, that is about 1500 kelvin and that is that is a maximum temperature that turbine blade, even with single crystal blade and even with all sorts of coatings, that is my same temperature say turbine blade can withstand under continuous operation. Now So, here the conflict in requirement is that at the exit of the combustor you wanted temperature of 1500 kelvin ok.

But if you want to have hydrocarbon combustion and the adiabatic flame temperature of hydrocarbon combustion to 1500 kelvin, then that is that leads to an equivalence ratio which is typically below the equivalence ratio at which the fuel can burn in this combustors. So, to say that say the 1500 kelvin this turbine inlet temperature or 1400 kelvin this turbine inlet temperature can be achieve by hydro carbon combustion of equivalence ratio 0.4. 0.3 to 0.4, 0.4 say. 0.45 like that, 0.4 0.5. Now you cannot have hydrocarbon combustion a 0.45 is even below the flammability limit more most hydro carbons ok.

Equivalence ratio 0.45 is if we have a full mixture, then the if you go back to our flammability concepts is below the flammability limit of a of any mixture. So, you cannot have combustion at point equivalence ratio 0.45, premixed combustion at 0.45. And or in air fuel if you want in talking term air fuel ratio that it basically need a very large air fuel ratio to achieve this thing. Whereas, the air fuel ratio in which your sustain combustion happen is very less, that is your equivalence ratio at for this kind of combustion to happen it is say about local equivalence ratio in this region should be about 0.7, but the 0.7 will lead to an adiabatic flame temperature much greater than 1500 kelvin or to So, basically what I want to say is that, the margin the equivalence ratio range in which combustion can happen here.

That corresponds to a adiabatic flame temperature which is much larger than the turbine inlet temperature. So, T adiabatic at phi minimum that is the phi minimum where you can have combustion is much larger than the turbine entry temperature or turbine inlet temperature TET whereas, this is TET. So, what you want? You cannot afford to have non sustain combustion. Or you cannot afford to have your turbine blades melt also. So, what do you do? So, what people do is that what the gas turbine engine designer is do is that. So, they create a bypass air ok.

So, this there is split this air here and they allows some amount of air to come inside this region which used call the primary zone, and there we have a essentially it can be even fuel rich combustion. And then they take some air from here and put it downstream and allow that to dilute the products of combustion So that the final temperature that is reached is less than or equal to is turbine engine temperature. So, that is how on one hand you can have sustain combustion, but with the diluting air downstream you can reduce your adiabatic flame temperature or you can reduce your product gas temperature to have a temperature which is suitable for your turbine blades.

So, this is how the whole concept of a gas turbine combustor emerges. Of course, it is much more complex because than this thing because here you have various processes. For example, we have just given you a very simplistic view, but that the most important processes of that you need to inject the fuel at in a liquid form. Because as you have seen the most important reason why we have why combustion is indispensable in this kinds of an aircraft engines and gas turbine engines especially, is because the energy density of the liquid fuels cannot be matched with anything like a battery ok.

So, that is why you combustion is So important for gas turbine engines. But to utilize a liquid fuels you of course, carry the liquid fuel and then you have to inject it and ensure that the burning is proper. So, that is why this liquid fuel atomization and then subsequent combustion of that becomes very, very important. So, that is the thing and then of course, this happens in a very strongly turbulently in environment. And how this whole process of this liquid fuel atomization and then combustion happens in a strongly turbulent environment and that also you need to be understood.

So, these are actually still very active research issues and there is still no direct solution to even simulate these processes with very high degree of accuracy. And so but the idea is that with all the thing is that we have learnt you might be able to develop this things better and better tools and better understanding can emerge; so once again to Summarize the basic design feature of a combustor because this is so important.

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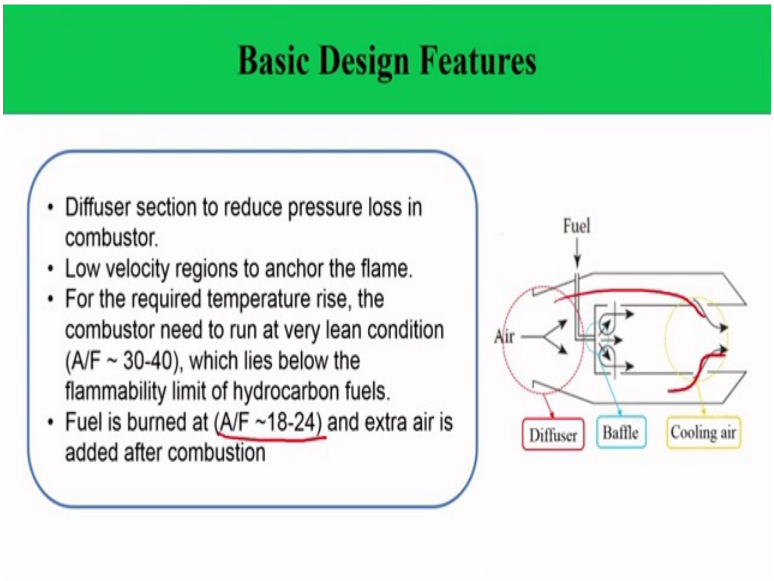

So, first of all we need this diffuser section to essentially reduce the pressure loss in the combustor that is a first thing. And then we give we give without the diffuser your if you it is a if you are allowing the air to flow to this constant area duct.

And the pressure loss will be tremendous, and you will have this special loss reflected in your overall efficiency of the gas turbine engine. So, that is not expectable. So, that is why we have this diffuser section to reduce pressure loss inside the combustor. And then we have this low velocity region which is they are cause by a bluff body or by a solar to essentially anchor the flame; so the low velocity regions to anchor the flame. And then the thing is that for the required temperature rises the combustor need to run at a very lean condition air fuel ratio of about 30 to 40. And this lies below the flammability limit of hydrocarbon fuels.

So, the fuel is actually burned in the primary zone at an at an air fuel ratio of 18 to 24 and the extra air then the remaining air that was that comes out of the compressor, that is added downstream to essentially reduce the temperature of the combustion products So that this can be within the limits that is required for the turbine blades. So, this is the most important design feature of designing a combustor. So, you have this baffles and you have this cooling air that comes in so this is the basically the most important design future of the gas turbine Combustor.

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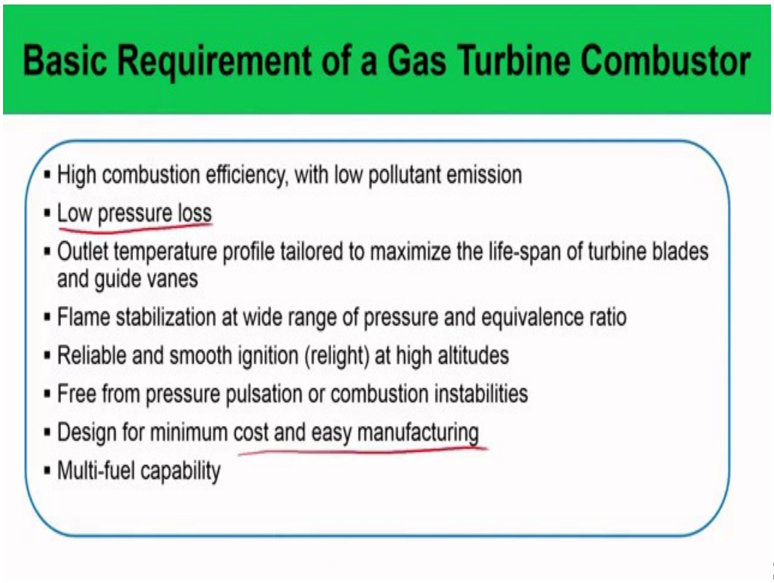

So, what are the requirements, the basic requirement of a gas turbine combustor is that it should have high combustion efficiency with low pollutant emission ok.

High combustion efficiency means that it should not have any unburnt fuel, because fuel costs and also if you have unburnt fuels it typically undergo some steps to basically to create carbon monoxide and hydrogen and of course, carbon monoxide is a pollutant, and when you have unburnt fuel is essentially it is leads to this formation of this suit is smoke and all sort of things as. So, definitely high combustion efficiency also leads to low pollutant emission, but that is not a guaranteed that is high combustion efficiency of course, just a suit guarantee low pollutant and diffusion other steps has to be taken for example, we have to do combustion at a low temperature reasonably.

So, that nox formation is less as you have seen in the zeldovich nox formation mechanism that is a practically 1800 anything below anything above 1800 kelvin temperature leads to formation of nox. Of course, it should first have low pressure loss for reasons already described and the outlet temperature profile should be tailored to maximize the life span of the turbine blades and guide vanes this is very, very important. Because a turbine blades essentially see the highest temperature inside the engine and these turbine blades are continuously impinged on by this hot products. So, they are in the tremendous thermal stress ok.

And they are on a tremendous they can they can melt and it can just in no time under normal material cannot survive in that. So, region amount of research has gone into of basically essentially designing and designing materials for turbine blades and those are also one of the most expensive parts of the whole engine. And then we need to have flame stabilization at a wide range of pressure in equivalence ratio and that is very, very important, and then reliable and smooth ignition at high altitudes. Because if you of course, you want flame stabilization at high range of pressure and equivalence ratio that is true.

But in case it just flame just flows of at high altitude then it must be able to immediately recover and it must be have a must be able to have reliable and smooth ignition at high altitudes. So, of course, you do not want your combustor to be to be in a flame out condition for a long time. So, immediate recovery by is immediate relight at and ignition at high altitudes recovery. And it must be free from pressure pulsation or combustion instability combustion instability is very damaging thing for a gas turbine engines.

Because combustion instabilities are essentially characterized by high amplitude pressure fluctuations and these results from the feedback between heat release and pressure and the pressure and small pressure fluctuations and this gets amplified to create this high pressure amplitudes high amplitude pressure fluctuation speed can damage the mechanical parts and one can also lead to combustion problems. And then we need to design for minimum cause and easy manufacturing that is a very important thing. And it is if possible and diffusion engines are trying to people are trying to develop future engines with multi fuel capability which can if possible works on synthetic fuels like synthetic fuels which are rigid developed by artificial processes and also like bio fuels.

So, to mitigate essentially climate problems, so that is also a very important thing in a in research nowadays that how can we have gas turbine combustor that works on multiple fuels. So, in this then we will go into this in the next part of this class we will go into this different type of combustors. And then we will look into some fundamental mechanisms how we can inject fuels and how the break up in atomize.

So, we will take this up in the next class.