Gas Dynamics and Propulsion

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Lecture - 40
Scramjets

In the last class we were looking at the challenges that we face in designing a scramjet combustor.

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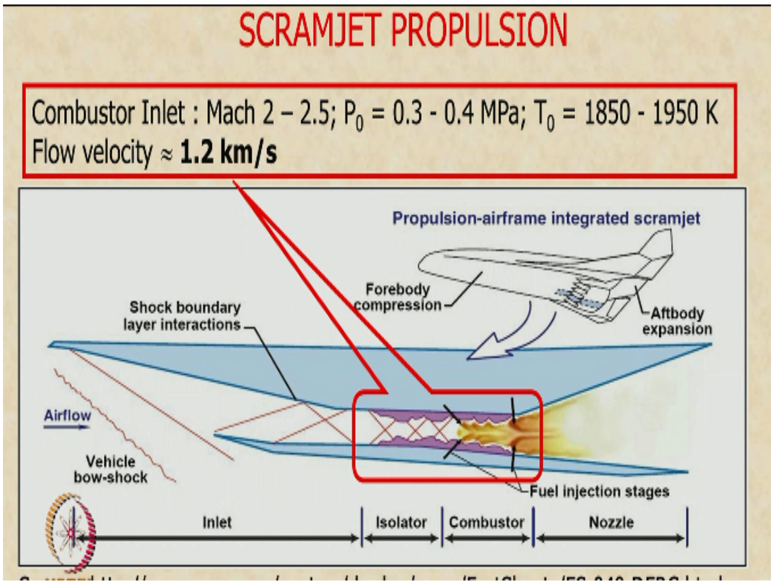

So just to recap briefly what we talked about we said that the flow is decelerated from a freestream mach number of 7.5 to a mach number of around 2 to 2.5 at entry to the combustor as shown here and we also highlighted the fact that the freestream stagnation pressure is around 1 to 1.2 MPa and by the time the flow reaches the isolator the stagnation pressure reduces down to about 0.3 megapascal which means that the stagnation pressure recovery in such high speed intakes is only of the order of about 30% or so.

The most challenging feature probably in designing the combustor has to do with the flow velocity which is about 1.2 kilometer per second. So the axial velocity of the flow in this direction as it enters the combustors is of the order of about 1.2 kilometer per second and current scramjet engine design or looking at combustors which are about 1-meter-long which means that the fuel or the air will stay in the combustor only for about a period of 1 millisecond.

So within this millisecond fuel has to be injected, mixed and burned which is an extremely challenging task. So the choice of fuel is very crucial for a scramjet engine.

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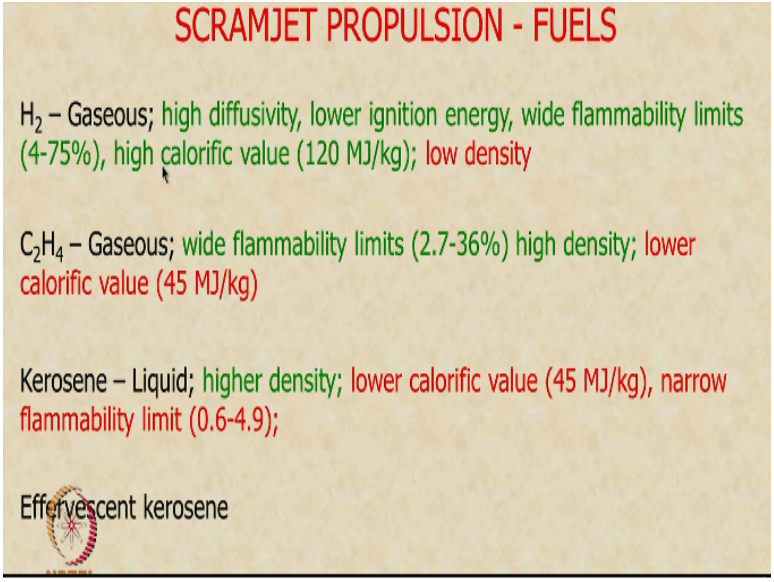

And let us take a look at what kind of fuels have been used in the past. The most popular fuel of course is gaseous hydrogen is the most popular. It has lots of desirable features as I have shown in green here. There are lot of desirable features it has very high diffusivity which means it will try to mix by itself because it moves so fast and the diffusivity is so high the hydrogen will actually mix much better number one.

Number two it has probably one of the lowest ignition energy so it is very easy to ignite which is very desirable and most importantly it has very wide flammability limits. So the flammability limit by volume percentage in air can vary between 4% to 75% by volume in air. So that is an extremely wide range of flammability which is very important in a scramjet combustor.

Because if you are not able to get the fuel mixed properly in stoichiometric proportion they are going to be regions where the mixture is going to be either too lean or too rich. So having a wide flammability limit helps in achieving and sustaining combustion across the cross section of the combustor so that is very desirable and hydrogen also has high calorific value about approximately 3 times compared to hydrocarbon fuels.

Hydrocarbon fuels typically have calorific values between 40 to 50 mega joule per kilogram probably around 40 to 45 and hydrogen has about 3 times as much calorific value. But probably one of the most stringent disadvantages of hydrogen is its low density. Although the calorific value maybe quite high for releasing a certain amount of energy if you want to carry a certain amount of hydrogen let say 10 kilogram of hydrogen.

Because the density is so high the volume or the tank that is required to carry such an amount of hydrogen will be very large that is one of the biggest disadvantages of using hydrogen as a fuel. But it has many of the other desirable features of course we can think of using liquid hydrogen, but then we would need the capability to store cryogenic fuels. So that the tankage becomes complicated there because the fuel has to be stored under cryogenic conditions.

So the accompanying insulation and other things to keep it under cryogenic conditions becomes very stringent. So hydrogen has many desirable properties as you can see here, but the density is a major disadvantage with the hydrogen fuel which has led researchers in the past to try fuels like ethylene for example ethylene is widely used it is a gaseous fuel higher molecular weight which means it has higher density.

And it has reasonably good inflammability limits about 2.7% to 36% by volume in air which is actually quite good, but the calorific value as you can see is about one-third of hydrogen. As I have indicated that in red here, but this is not major disadvantage in terms of because if you compare the amount of ethylene that you have to carry or the volume of tank required to carry a certain amount of ethylene then we are actually benefitting a lot.

The molecular weight of ethylene is about 28 which is 48 times more than that of hydrogen. So you are getting a factor of 14 advantage here, but we are getting a factor of 3 disadvantages in the calorific value. So the advantage more than overweigh outweigh the disadvantage. So ethylene from that prospective is very desirable fuel. Hydrogen will always be the best fuel.

Hydrogen is almost an explosive, but it is only because the density is so low that we are forced to look at other choices. This challenge is not unique to scramjets even automotive applications which want to use hydrogen as a fuel or face to the same constraints. Because the density is so high if you compare standard automobile today it can carry about 30 liters of petrol that is approximately about if you assume the specific gravity of petrol to be 0.8 that is approximately 24, 30 liters of petrol works out to be about 24 kgs of petrol.

So 24 times about 40 mega joule per kg gives you the amount of energy that you are carrying. In order to carry the same amount of energy using hydrogen the tankage atmospheric pressure condition will be very large.

We are going to use it in a compressed form then we cannot use petrol tanks which are made only out of sheet metal. Right now petrol tanks are made out of sheet metal because they are operating atmospheric pressure whereas if you are going to store the gas in compressed form then you need pressure vessels which are going to have thick walls to withstand the pressure difference.

If you want to store the hydrogen as a liquid, then that means you need to be able to store cryogenic liquids which also possess this challenge. So this challenge with hydrogen is ubiquitous is everywhere not just scramjets. Scramjets it is just that in scramjets the challenges are even more than in automotive applications. So ethylene is a good alternative to hydrogen. The next alternative that is widely being considered.

India for example in the scramjet development India is using kerosene liquid, China is also using kerosene liquid because as you can see density is much higher almost factor of 1000 higher than even ethylene almost. So this has much higher density lower calorific value, but the major disadvantage is that it has a very narrow flammability limit compared 2.7% to 36% by volume to 0.62 to 4.9% by volume. If it is more than this, it will not burn if it is less than this it will not burn.

So that means range is very narrow which means if you are going to use kerosene as a fuel renewal scramjet engine what is the most crucial aspect from the flammability what is the most crucial aspect mixing. We need to make sure that the fuel is mixed under stoichiometric proportions at across the entire cross section of the combustor because the flammability limit is so narrow.

Because one fuel that is very interesting and which is also making its appearance these days in scramjet application is something that comes out of an effort that most engineers almost always do. If you remember we talked about propellers and we talked about jets then we said why not have something which combines the best advantages or best features of propellers and the best features of the jet and we came up with the turbofan engine.

Similarly, here why do not we combine the advantages of hydrogen which were these aspects in green and the advantage of kerosene which is this. Remember for hydrogen this is the only disadvantage. It so happens that kerosene that is the only advantage why not combine these two if we can combine these two then we will have a nice fuel right that is what people are doing today that is what engineers are doing today this is called effervescent kerosene or bubbly kerosene.

So what you do is you bubble the hydrogen through the kerosene. So the fuel that is used is neither pure kerosene nor pure hydrogen, but it is effervescent kerosene. So it combines the advantages of both and is actually a very good alternative in these types of applications. So these are the fuels that are used the choice of fuel is very critical as I said because the processes the entire combustion process has to be completed within 1 millisecond which means that the fuel should mix well.

If it is a liquid fuel, then we are adding another time scale we need to worry about that also. So the choice of fuel is very critical in the scramjets because the time available from start to finish of the combustion process is only 1 millisecond. Remember chemical timescale themselves maybe of the order of 10 (()) (10:06) -6 seconds or slightly more than that, but now this is becoming comparable to chemical timescales that is the problem with the scramjets.

The probably the most critical issue in scramjets is that there are 2 important timescales. One is chemical timescale. Chemical reactions themselves with take a certain time to initiate and complete that is usually of the order of about micro seconds approximately the faster reaction will usually be of the order of about microseconds. Now there is another timescale involved in supersonic combustion that is to get the fuel mixed with the air within the flammability limit that you want.

So those mixing time scales are much longer. They probably are of the order of a millisecond or more than that. So you will see that most scramjets combustors the limiting timescale is the mixing timescale. The challenge is not in the chemistry, but the challenge is in getting the fuel mixed with the air that is the most challenging aspect in almost all scramjets combustors.

If we have a liquid fuel, then other timescales come into play and that is the evaporation timescale which is even slower.

So mixing almost all scramjet combustors are controlled by mixing and not by kinetics. So anything that we can do to improve the mixing will be a very good advantage in terms of scramjet combustion process.

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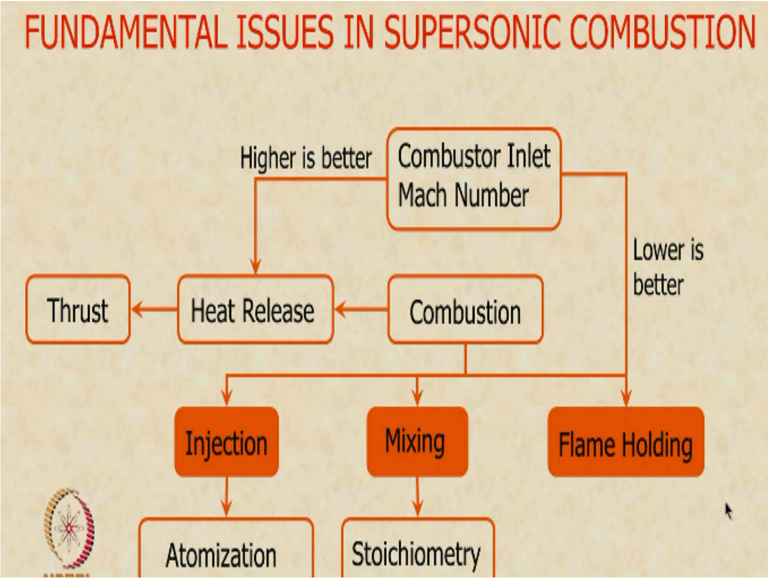

So let us take a look at fundamental issues in supersonic combustion. As you know the basic objective of any scramjet engine is to produce Thrust as shown in this box here. The idea is to produce Thrust and as we saw earlier we produce Thrust by increasing the specific enthalpy of the fluid then converting into kinetic energy. So the Thrust will depend very much upon the heat released that takes place in the combustors.

Now the heat release itself in turn depends upon the combustion process in the combustion process is very efficient then there will be a lot of heat release otherwise heat release is going to be less. Now normally the heat release will depend on the combustion process. Now in a compressible flow a very high speed compressible flow such as the one that we have in a supersonic combustor the heat release as you know is also limited by the mach number at which the flow enters that comes from the Rayleigh curve.

So if the combustor inlet mach number has a certain value then there is only so much heat that we can add in the combustor before it will thermally choke and alter the flow conditions. So you can see that heat release in this case is controlled by two factors number one combustion itself and number two the combustion inlet mach number and if you remember for the supersonic combustors since you are operating on the supersonic branches Rayleigh curve.

The higher the combustion inlet mach number the more heat we can add before it will thermally choke. So higher is better from a heat release prospective for combustion inlet mach number. So these are the two limiting factors in heat release in a combustors and ultimately upon thrust in the supersonic combustor. Now the combustion process itself depends upon 3 factors.

If it is a liquid fuel injection plays a very critical role in the case of a scramjet combustor because the injection strategy determines the droplet size. Smaller the droplets the better they will burn the faster they will evaporate and burn. However, if the droplets are smaller they will not be able to penetrate the flow and mix with the fuel. They tend to be swept downstream by the flow.

The biggest challenge in a scramjet combustor is that if the flow is from this way to this left to right like this. So the flow is moving at a speed of 1.2 kilometer per second from left to right. So if you take a cross section the challenge is to get the fuel to spread across the entire cross section. So the challenge is to get the fuel to move in the span-wise direction and in the vertical direction because this flow is moving so fast anytime you inject fuel the tendency for the fuel to be blown downstream rather than moving to occupy the entire cross section.

So the challenge is to get the fuel to move perpendicular to the flow stream either in the vertical direction or in the span-wise direction. It is only when it occupies the entire cross section that you will get uniform heat release and good combustion. So if you have small droplets because they are so small they tend to get swept downstream by the flow and they will not move across the cross section.

If you have larger droplets they will actually penetrate, but the problem is they will also take a longer time to evaporate. So from a combustion prospective smaller droplet is better, but it is not good from a mixing prospective. So from a mixing prospective larger droplet is better, but it is not good from a combustion prospective. So the injection and the injection strategy plays a crucial role

You need to get droplet diameters typically droplet diameters around 30 microns seem to be ideal force scramjet combustion that is what is generally desired anything less than that is not good more than that is also not good 30 micron is the preferred droplet size in these types of applications for these types of combustors which are about a meter long. The next important aspect in combustion is mixing as we have emphasized this already.

Mixing is the most important thing by mixing what I mean is we take a cross section of the combustor the fuel and the air should be well mixed across this cross section so that heat release takes place across the entire cross section and not in isolated pockets in the combustors that is a very important requirement for the scramjet application. Remember we are talking about very high operating temperatures which means we want the heat release to be more uniform not in isolated pockets.

The other factor which control combustion is flame holding. Now in a supersonic combustor we may actually have a design where we are able to get the fuel to mix and burn, but more than mixing and burning we must also make sure that it continues to burn so that is what we mean by flame holding. How do we ensure that the heat release takes place continuously maybe we can initiate heat release, but we will make it extinguished.

So how do we continue to sustain the heat release is what this flame holding strategy is all about and remember this is a supersonic flow at mach number 2 to 2.5 so we cannot put traditional V gutters. In an after burn and duct we use the v gutters for flame stabilization. If you put the same thing in this flow you will trigger a strong bow shock and there will be substantial loss of stagnation pressure which is not good.

So we have to use aerodynamic kind of flame holding devices for this indirect flame holding which is a challenge and if you think about it the cross flow speed is 1.2 kilometer per second sustaining a flame in such speed is an extremely challenging task. If the velocity has to come down, then flame holding will be easier to do. I can sustain the heat release in the low speed flow, but not in such high speed flows.

So from a flame holding prospective you can see that you will take a look at that also so flame holding is also a challenge and we will see what effects this. So injection as we said depends mostly on atomization of the fuel. We want the fuel to be atomized to typically shorter mean diameter around 30 microns or so that is ideal for this. So we have to design proper atomizes which will accomplish this.

So if you are able to inject droplets with that type of diameter there is enough time for them to evaporate mix and burn. Mixing of course is important for Stochametry. So the fuel and air should be mixed in Stochametric proportions and for hydrocarbon fuel especially liquid fuels the flammability limit is very narrow that is why we talked about flammability limit. So you must make sure they are mixed properly so that the combustion will take place under Stochametry conditions.

Remember because the length of the combustor is so small if the fuel that is injected leaves the combustor without burning then it is not releasing its heat. So the combustion efficiency will go down and the thrust produce will also go down. The ideal thing is to have high combustion efficiency is all the fuel that the inject must burn, but that is not possible to ensure in supersonic combustors.

Typical supersonic combustors which use liquid kerosene as a fuel will have combustion efficiency around 70% to 75% at best that means only 70% to 75% of the fuel burns. Mixing efficiency for such fuels will be of the order of about 80% to 85% which means only 80% to 85% of the fuel actually is mixed with properly with air. Degree of mixing which is another mixing metric is about 90% or so.

Degree of mixing simply looks to see how much of the cross section is occupied by fuel it does not check to see whether the fuel and oxygen at each points earns Stochametric proportions that is mixing efficiency. Degree of mixing simply looks to see how much of the cross section has fuel in it. So typical kerosene combustors will have degree of mixing around 90% or so which is actually a very good metric.

If we can get kerosene to occupy 90% of the cross section that is very good and if we can get the mixing efficiency to about 80% to 85% that is actually very good also because that means in this 90% of the cross section 80% to 85% is likely to burn under Stochametry conditions after that only 75% actually burns and releases its heat. So I can see progressively how things go down.

This also tell you the different metrics that we used to assess the performance of the combustor. Remember mixing all this combustor are mixing controlled. So ensuring good mixing is the key challenge in these types of applications which is why we have so many different metrics for assessing how well it is mixed. Loss of stagnation pressure is also a very good metric for assessing mixing because mixing as you know is thermodynamically an irreversible process.

So the better the mixing the higher the loss of stagnation pressure unfortunately so these are conflicting considerations. So from a flame holding prospective as I said lower combustion inlet mach number is better because velocities are lower I can have better flame stability. So we can see that from a heat release prospective I want the combustion inlet mach number to be higher.

From a flame holding prospective I would prefer it to be lower. So these are the 2 conflicting consideration which we have to live with and design for. So these are the fundamental issues in supersonic combustion. This is the reason why it continues to be challenging. As I said the flame holding is going to be aerodynamic and not mechanical. Mechanical flame holding would mean putting V gutters, but this is not going to work in this case it has to be aerodynamic.

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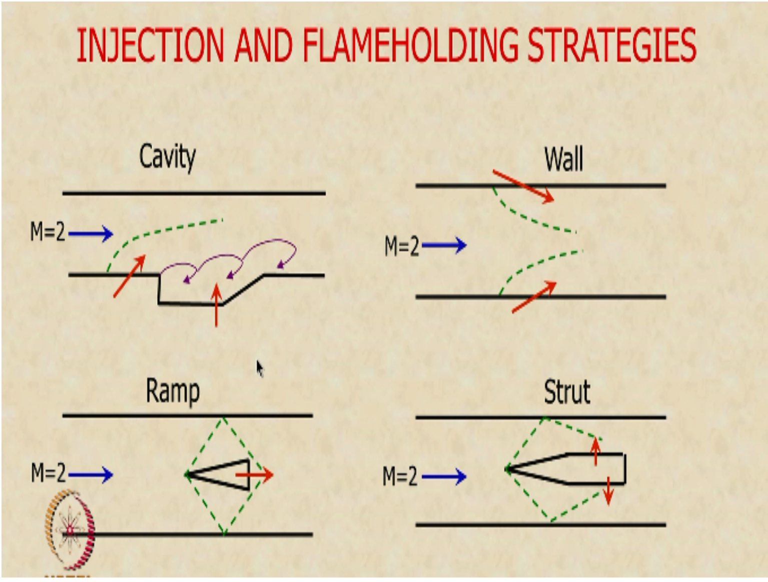

What are the different strategies that have been used in the past for injection and flame holding you can see these strategies here one popular injection strategy is to inject through the wall and also through these types of cavities. These cavities provide these kinds of re-circulating flow and presumably they increase the mixing of the fuel because there is an unsteady shedding of the shear layer from the leading edge of the cavity.

This is the leading edge of the cavity. So this shear layer sheds unsteadily and as you inject the fuel the hope is that these unsteady vortices will actually carry the fuel and mix it better with the air and if you inject a fuel into supersonic stream you can see that there is going to be bow shock ahead of the fuel jet, but this shock is not so strong as to cause this flow to become subsonic.

This is okay this is only a gas jet. There will be a bow shock, but not strong enough to cause the flow to become subsonic. So this is the fuel this is the air and the one in green is actually the shock wave. In all these figures green denotes the shock waves. So shock waves are actually triggered intentionally in these applications to improve mixing because you know that across the shock wave there is a velocity gradient.

Velocity gradient can generate atrocity and improve mixing so that is one reason why you trigger shock waves are controlled strength to improve mixing. This is plain mixing which is through the wall so I can see that there are injectors on the wall. We inject the fuel at an angle and this creates bow shock ahead of the fuel jet, but this strategy will probably have the poorest mixing because in this case since the cross flow velocity is so high.

The fuel that is injected through the wall tends to stay near the wall and if it burns it will try to burn near the wall which is very detrimental for the wall. The heat release will likely melt the combustor wall rather than go into the flow. We want the heat release to go in to the flow not melt the combustor. So the wall injection in that sense is very poor cavities are somewhat better.

Now the other injection strategy is to use something called a Ramp injection. Remember we said just now that if you try to put any obstruction in this fluids the supersonic flow this may cause a strong a bow shock, but the ramps are aerodynamically designed. This is not just about any kind of ramp these are aerodynamically designed and the objective is to create these types of oblique shock waves from the leading edges of the ramp.

And the reflection of the oblique shock waves the dimension of the ramp are such that when the oblique shocks are reflected they impinge upon the fuel jet and the velocity gradient across the shock will then carry the fuel generate atrocity and carry the fuel and mix it with the air that is the idea. So these are aerodynamically design ramps and the dimensions of the combustors, dimensions of the ramp and the angles are such that the shock should focus back on the fuel jet that comes out.

So here we are injecting parallel to the flow here we are injecting normal to the flow, here we are injecting at an angle to the flow. All these other also have been tried normal injection, tangential injection and angled injection. Now in these types of high speed flow if you inject normally that will give you the best penetration in mixing. If you inject tangentially that gives the poorest penetration in mixing, the angled injection going in between.

So a judicious combination of all these have always been tried. So this is injection through a ramp here you are seeing injection through a properly designed strut. Notice that in this case of the ramp and the strut because you have separator flow at the base of the ramp. There is going to be flow separation from this corner at the base of the ramp and there is also going to be flow separation here downstream of the strut.

So these flow separation regions provide actually the region of low speed flow where there is always going to be combustion gases. So these provide the flame holders that we are looking for. So we did not have separate flame holders this is why this type of flame holding is called aerodynamically flame holding. So we create these types of separator flow regions intentionally low speed separator flow regions intentionally for flame holding purposes.

And because these are designed aerodynamically we will not have a problem with the bow shock being too strong. So the injector serves 2 purposes itself to inject the fuel and now it is also designed to provide flame holding. For example, this step here on the wall of the combustor also is useful for flame holding because there is going to be flow separation here inside the cavity and this will provide low speed region which has hot combustion products which acts like a (()) (27:18). So these are strategies that have been tried in the past.

But all these devices have practical issues when you try to scale them up to realistic sizes many of these things do not work as well. The combustors are small they work very well, but when you scale it up to real life sizes they do not really scale very well. So scalability is also a major issue in scramjet combustors.

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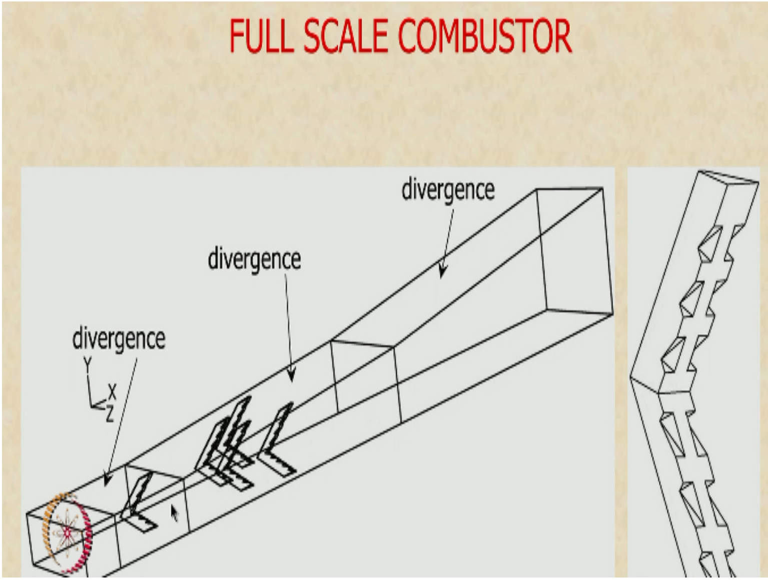

This is cross sectional view of an actual combustor that is being tried out with the DRDO HSTDV vehicle. So this is a full size combustor and you can see what is being done to get the fuel to mix. Remember getting the fuel to occupy the entire cross section is the challenge. So as the saying goes if you cannot get the fuel to go there you put the fuel there. This is the cross section of the combustor if they cannot get the fuel to inject here I would like the fuel to go there.

It is not able to do that because of the cross flow then the strategy is do not inject the fuel here inject the fuel there and that is what this strategy does you can see that each one of these is a strut which runs from the top to the bottom and there are fuel injection holes along this face on both sides. So each one has about 22 fuel injectors along this face. So you can see that here the strut is located right in the middle.

So here the 2 struts are situated further apart. So if now the flow is in this direction the first strut is like this right in the middle. The next 2 struts are located slightly apart. The next 2 struts are located in between these 2. So what have we done by this strategy? I have now covered the entire cross section of the combustor. So if we cannot the fuel to go there put the fuel there that is the strategy.

So you locate the struts in such a way that you cover the entire cross section of the combustor. The hope is that by the time you come into this region the fuel will occupy the entire cross section of the combustor. This is the strategy which is very effective and this particular combustor has degree of mixing about 90 or more as I told you a very good degree of mixing.

So if you look at the exit of the combustor 90% of the cross section is occupied by fuel which is actually an extremely good thing this uses kerosene fuel whether you can get that fuel to burn is the next challenge. The first thing is to get the fuel to mix. So the degree of mixing tells me how much I have managed to spread the fuel, but because the flammability limit for kerosene is so narrow.

If the value of mass fraction or the volume fraction of kerosene is outside the flammability limit then what happens is kerosene may be present, but it is not going to burn because the proportion of kerosene and the air is not within the flammability limit. Remember what we said about the flammability limit for kerosene the flammability limit is between 0.6 to about 4 or so 4% by volume in air.

So if it is outside the flammability limit I may have kerosene, but it is not going to burn which is why we are 2 metrics. One called degree of mixing which only tracks the presence or absence of fuel, but that is not sufficient. Once I have that I need to find out how much of this fuel is actually present in Stochametric proportion or close to Stochametric proportion that is what the mixing efficiency metric does.

So the mixing efficiency for these types of combustors will be about 80% or so that means 90% of the cross section is occupied by the fuel of that only 80% will burn under Stochametric conditions. There are only 80% is within the flammability limit. So what I need to do so the challenge in scramjet combustor design is to get the degree of mixing to be as high as possible that is the first step.

I get the degree of mixing to be as high as possible after I do that now I start looking at mixing efficiency how do I improve the mixing efficiency now. These are the challenges and these combustors works very well in fact someone asked this question about when on put on divergence you see that the combustor actually has a mild divergence here, another divergence here and another divergence here.

These are all very small divergences 2 degrees, 4 degrees and 5 degrees what is the purpose of the divergence in this combustor? “Professor - student conversation starts” To reduce thermal choking. “Professor - student conversation ends” What this does is remember the heat release in the combustor tends to reduce the mach number you know that from your Rayleigh flow anytime you release heat the mach number reduces.

Now this is a supersonic flow. So when I add heat to a supersonic flow the mach number reduces what happens if the supersonic flow goes into a diverging passage what happens to the mach number mach number increases. So we have created competing effects. So the heat release tries to reduce the mach number the divergence tries to increase the mach number. So what happens is I can actually design a combustor where the mach number remains more or less constant across the entire length of the combustor.

So this avoids the thermal choking problem that we were talking about not entirely, but to a large extent for the range of operating conditions that we are envisaging the thermal choking can be avoided by having these types of divergences. Of course in addition to this we also have the isolator as you can see from here. If the heat release is so high that the pressure rise begins to propagates upward.

We also have the isolator which will try to contain the pressure rise in this and prevent it from going into the intake. So we already have divergence which is trying to counter the thermal choking problem and we also the isolator on top of that to contain this within this. Normally what happens in this combustor is we are calling this supersonic combustion ramp jet, but the term is actually it sounds nice but it is actually very difficult to verify.

What exactly do we mean by supersonic combustion ramp jet? There are 2 possibilities. Number one, the flow enters the combustors with supersonic mach number. The flow leaves the combustor with supersonic mach number, but the flow probably is subsonic within the combustor that is one situation. The other situation is we have continuous flow path from the intake all the way to the exit which are supersonic.

So I can draw a streamline or I can draw a line all the way from the inlet to the exit of the combustor and the mach number is supersonic along this line for the entire length of the combustor. Generally, the first type of situation where the flow is supersonic at entry, supersonic at exit, but not inside that is called dual mode scramjet. If there are continuous supersonic paths from the inlet to the exit that is called a pure scram mode.

So there are 2 modes to this combustor dual mode under complete scram mode. Scram mode means supersonic combustion throughout there are supersonic path that are available that is very desirable, but in practice most of these combustors will probably operate in a dual mode rather than in the pure scram mode it may not be possible to avoid that. Any questions? **"Professor - student conversation starts"** Where is igniter? **"Professor - student conversation ends"**

Normally the air that is coming in is so hot that the fuel will be able to ignite when it goes inside this the static temperatures are very high you may not need special igniters for this, but even if they are required they will be provided in the fuel injector itself. You may have a pilot flame slightly ahead of this with the injector that will provide the heat that is required for burning the fuel for the downstream.

Now we talked about fundamental issues in supersonic combustion as a process.

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These are the fundamental issues in developing a supersonic combustor. A combustion process has fundamental difficulties what are the challenges in realizing supersonic combustors that is what this talks about. Now wind tunnel testing of full scale combustor is very difficult to do. Remember we are talking about generally flow rates typical flow rates in these types of applications are of the order of about 8 to 10 kg per second.

Stagnation pressure is 0.3 MPa, stagnation temperature 2000 Kelvin. We are talking about wind tunnel which should be generating and enthalpy for the order of mega joule. Such wind tunnels are available only in very few countries in the world. Russia has one or two, US has, but none of the other countries have such high enthalpy wind tunnels. So even if you develop a combustor it is very difficult to actually test it.

And because the scramjet the operating temperature in the combustor of a scramjet is very high. It is almost impossible to measure anything inside the combustor. We can measure wall static pressure at best that is what people are doing these days. We can take exit gas sampling, but that is not really very helpful because it does not tell us what is going on inside the combustor where the problem areas are, where we need to improve.

So that kind of measurement is still lacking, measuring temperature or any other quantity in these types of environments is very difficult to do and fabrication is also very challenging because we need exotic materials for fabricating the struts and also the walls of the combustors because they need to withstand very high temperature. So if you take this material then machining them to the required tolerances, to the required shapes is an extremely difficult thing to do.

So fabrication is also very difficult to do which is why only probably very few prototypes can be fabricating, you know, fabricating 1 or 2 prototypes is very difficult to do and then testing it is also very difficult to do which means that CFD computational fluid dynamics has be to be used a virtual wind tunnel. We need to have reliable predictions accurate simulations so that we can make good predictions about the pressure rise.

The distributions and all the other quantities that you want and then so you look at a set of designs and then look at our comparative exercise of this different designs and then shortlist 1 or 2 which can be used for final fabrication prototyping and fabrication. That is a strategy that is being pursued by many of the countries today which do not have this high enthalpy wind tunnels simulation in this case are the way to go.

So let us see so we have covered the entire range of propulsion technologies that we wanted to study. We looked at turbo jets, we looked at turbofans, after burning turbo jets, we have seen ramp jets and also scramjets. We have done thrust calculation we have looked at gas dynamics aspects which are important for these types of devices as we said compressibility effects are very important in all these engines probably in the gas turbine combustor.

Since the velocities are very small or the mach numbers are quite small. The gas turbine combustor is the only component is this range of equipment which operates in the incompressible limits. All the other components operate with substantial compressibility effects which was the reason why we studied gas dynamics in such great detail then we looked at the challenges of manufacturing these devices, in designing these devices.

We looked at challenges in designing compressors, operation of compressor, tip clearance. We looked at very challenging issues like that again turbine blades, the high temperature turbine blades, the cooling strategies, the manufacturing strategies like single crystals and then we looked at material challenges you know thermal barrier coating and so on. So we looked at all the challenges that are involved in manufacturing these components.

Then we looked at the thermodynamic cycle aspects, what are the parameters that control the performance for the device we looked at that then we actually did calculations thrust calculation of all this devices except the scramjet and we saw how the thrust varied depending upon the type of nozzles that we used depending upon other conditions whether it is operating at C level or whether it is cruising at 30,000 feet how conditions change, how mass flow has to be adjusted, how the entry temperature to the turbine has to be adjusted.

We looked at all those issues in great detail. I hope that students who go through these lectures along with the text books the lectures follow the text book very closely and the problems given in the text books are also taken from very practical applications. So I hope that students who go through the lecture find the lectures to be very useful studied in conjunction with the text books.

In my opinion, the lectures are not meant to be standalone replacement for the teacher or the textbook. The lecture is an explanation of what is written in the text book. So that is the way I look at this. So I urge the students to use both the materials to benefit the most. You will benefit the most if you use both the materials listen to the lectures, try to figure things out yourselves, read the books also they will also add lot of value to your learning and that is the best way to utilize this type of resource.

So I wish all the students the very best of success in their endeavors and I also would like to thank you for listening to the lecture for being very patient. Thank you.