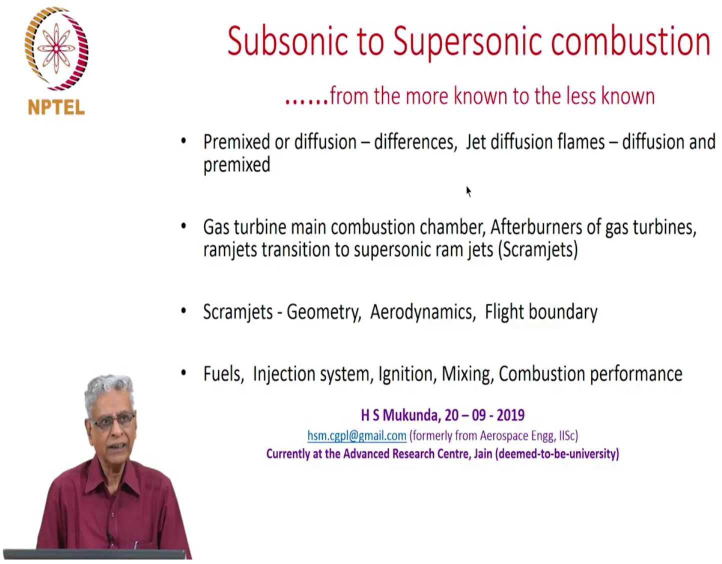
Fundamentals of Combustion for Propulsion
Prof. H S Mukunda
Department of Mechanical Engineering
Indian Institute of Technology, Madras

Lecture – 28
Scramjets – Part I

(Refer Slide Time: 00:16)



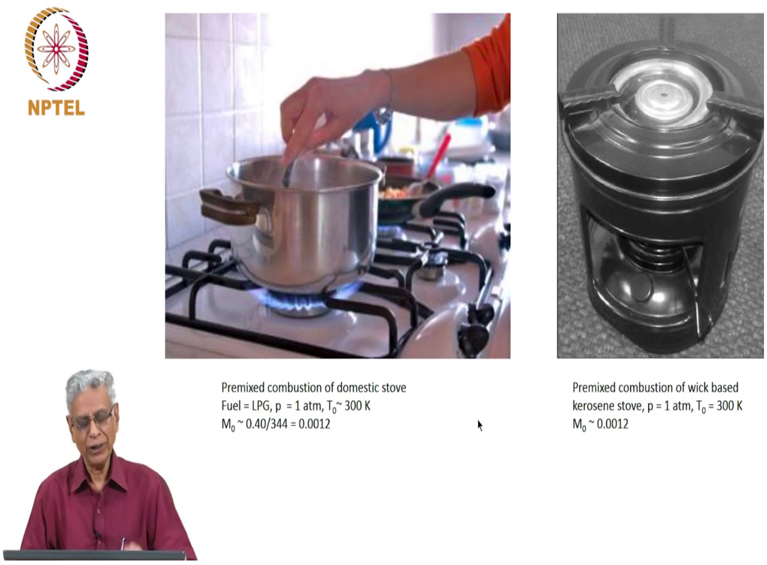
We will begin another subject which you may not all have direct interest in the audience, but it is something that you could know because it is likely to happen in our country seriously.

I have titled it as subsonic to supersonic combustion from the more known to the less known. Here again I just want to emphasize to you that I have been associated with the subject for about 30 years. The DRDO started its work on looking at supersonic combustion late 80s early 90s. And similar thing will done in ISRO. And ISRO has been successful to fly a supersonic ramjet engine. And the development in DRDO has gone through a good free jet test result and some of it I will bring out. In many of the technical deliberations and discussion review committees is involved.

So, I will bring to you some bit of you know known knowledge close to what had happened. Alright, I want to begin by talking about premixed or diffusion differences jet diffusion flame diffusion and premixed more as in intro you may have heard about it will quickly browsed to it. Gas turbine main combustion chamber afterburners of gas turbine ramjets transition to supersonic ramjets. I want to trace the changes which take place from gas turbine to supersonic ramjets.

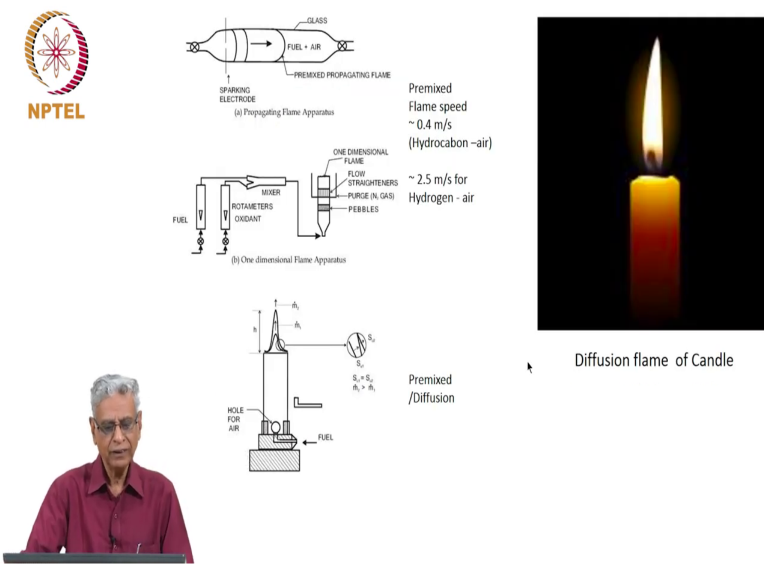
And then we look at issues of scramjets in terms of geometry aerodynamics flight boundary. Fuels injection system, injection mixing, combustion all that as a traditional part you can edit it to propagate.

(Refer Slide Time: 02:17)



This is this is a some more presentation to a group of people in which subject or something like stoves to supersonic combustion. So, I begin with stoves its premixed combustion here of LPG whether it is here or here it is the same. I am just look at a Mach number you know it is subsonic to extremely extant in a very low velocities. And the points when you looking at combustion or pressure and temperature initial temperature 1 atmosphere 300 k about cases.

(Refer Slide Time: 02:57)

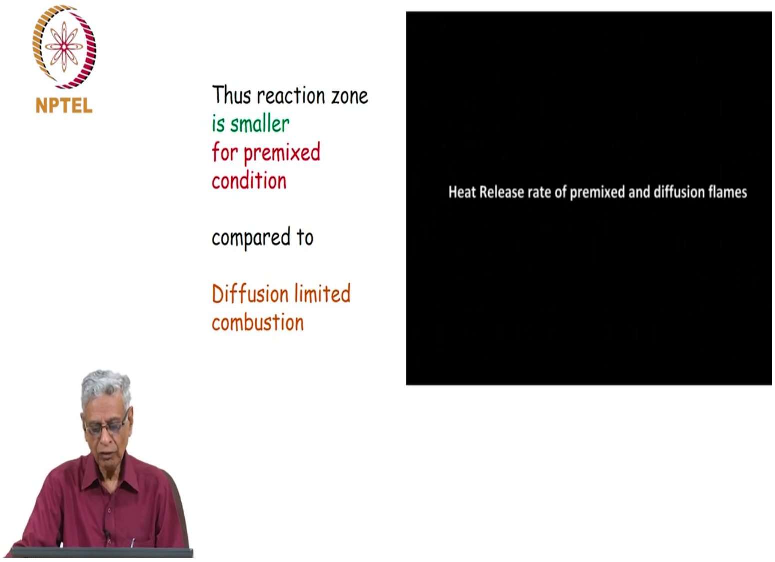


Well this is a something we have looked it significant earlier. The only addition point I want to make at least if you take hydrocarbon air 0.4 meter per second, hydrogen air 2.5 meter per second and you can also have premixed or diffusion or partially premixed situations. And we should keep in mind that of course, diffusion flame which is well known.

(Refer Slide Time: 03:19)

The point I am making here is the reaction zone is smaller for premixed condition compared to diffusion conditions. We had a video so I thought I will play that hopefully you will see how the flames are smaller and we can draw a conclusion.

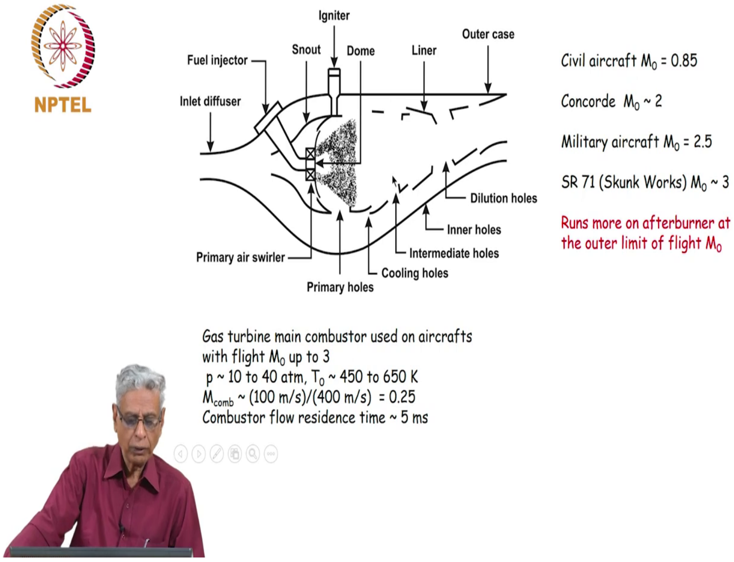
(Refer Slide Time: 03:35)



(Refer Slide Time: 03:39)

You see the flow rate is a same, power is the same and power is the same is more appropriate particules. The flame volume here is much smaller than the flame volume here. And heat release rate is much higher in this case compared to this you may ask a question what does it mean to this? When you are looking at subsonic combustion premixed flame you can afford to do premixed flame you have choice you can also do diffusion flame, but we are look out a supersonic combustion. And you look at diffusion flame as the only alternative or good reasons which we will discuss later.

(Refer Slide Time: 04:35)



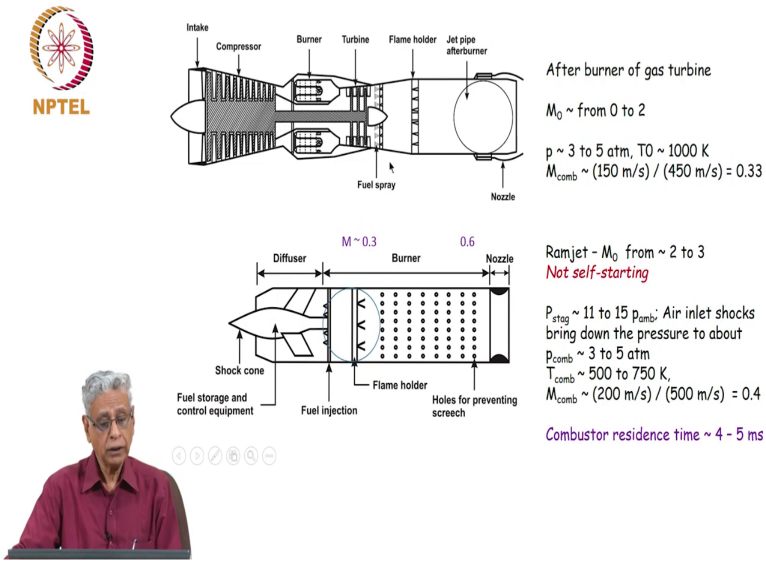
So, we go to gas turbines, gas turbine main combustor which is used on aircrafts and flight Mach numbers up to 3. Go from 10 atmosphere to 40 atmospheres temperatures. Inlet temperatures aware anywhere from 450 to 650 Kelvin dependent on the temperature pressure ratio and that is what this tells you the Mach number in the combustion chamber as move to 0.25.

And we must also know that you must completely combustion in a certain residence time just typically about 5 milliseconds. And if you look at civil aircraft most civil aircraft are 0.85 excepting when you go to concorde which is no longer flying Mach number 2.

Student: Ok.

Military aircraft go up to 2.5 and SR 71 designed by Kelly Johnson Mach number going upto 3. And which runs quite a bit an afterburner at the outer limit of the flight Mach number.

(Refer Slide Time: 05:37)



We look at the combustion the combustion system here which is after the afterburner main combustion system is here afterburner. This the systems which use this can go from Mach number 0 to 2 the combustion the pressure inside the jet pipe or the afterburner is 3 to 5 atmospheres, because pressure here is 10 to 40 atmospheres it drops the pressure in flowing through the turbine and therefore, the pressures here are lower.

The inlet temperatures go up to 1000 Kelvin because the temperature here are about 1400 to 1500 Kelvin and a dropdown here 2000 Kelvin. The Mach number here is 0.33 they move from 0.25 point to 0.33. Then you look at you know ram jet ram jets function only from about Mach 2 onwards may be up to 3 3.5, but usually up to 3 and you have a you know since Mach number is 2 and combustion process has to occur here in subsonic conditions you have a device to a compression system here shock system here to reduce the Mach number in intake which in called external compression intake.

Sometimes it can be mixed compression intake internal compression intake and so on, which produces the Mach number at the entry to the combustion chamber to around 0.3 and you add fuel acceleration occurs here and you go to Mach 0.6.

The hole refer to the fact that they might be bulsar instability to remove the instability you have holes which absorb the acoustic energy in some way you must remember this is not self starting; that means, you cannot run a ramjet to start off.

So, you must accelerate it to Mach 2 and this pre stagnation pressures you know here go from 11 to 15 to time ambient pressure because it is Mach number. And air inlet shocks bring down the pressure to about 3 to 5 atmosphere in the combustion chamber it pressure in combustion chamber from the air that is dumped into it is 500 to 750 Kelvin Mach number is 0.4. Combustion residence time still remains at 4 to 5 millisecond this stage you may ask is the gas turbine combustion chamber self starting is this self starting quite self starting you need a starter on that.

So, you need to run up the rotating system with additional device it can be electric starter or something else, and you bring it up to some speed rotational speed. And then inject a fuel because in the combustion chambers there must be air that air can only be ingested and it has to come from the atmosphere. So, it to run up the system such that you get enough airflow into the combustion chamber, then you begin to inject fuel and spark it. So, that your combustion going on and then it accelerates to its nominal speed.

I just want to bring to your attention a feature which you must have read in newspapers that, indigo airlines has a problem with their engine they had to replace the a engine quite frequently. And one comment which I do not know how valid it is because the indigo pilots use the engines little more roughly shall we say compare to what is expected. That is probably true by my personal experience is that they use the take off period at a much faster rate then what happens with many other airlines.

So, you may ask what is that got to do with the discussion here.

Student: Sir.

I may tell you a bit of experience which as a part of development which took place about 30 years ago, this thing aircraft called Canberra aircraft in the country which was used by services, that Canberra aircraft has three cartridges solid propelling cartridges.

So, the pilot accelerates up to some speed and then he runs the cartridges it spins the turbine system and then of course, fuel injection takes place and so on. The electric starting system takes it to some level and then this cartridge has to come in to bring it to next level. It turned out over a period of time the pilot used to push it at a much lower RPM more of it suppose to be 25 percent of the RPM at 30 percent RPM.

Now, he was require it was not accelerating enough. So, (Refer Time: 10:40) the solid propelling cartridge little at an earlier speed. So, one might think it does not matter it is not a difficult task, but it is a difficult task I will tell you why you introduce the hot gases on to the turbine blades to spin them.

Now, you are suppose to do you know it as per the guidelines of the designers at a certain speed then it accelerates, but if you do it earlier you are essentially shocking the turbine blades. So, they discovered over a period of time that a turbines had to be replaced at a much slower time then the earlier situation, where they would have no such problem.

So, they referred it to us and what we discovered after analysis each that the propellant cartridge while maintaining to the standards once it lowered which means the fuel fraction in the called cartridge was more than what was expected in the normal condition, because of the performance was lower and therefore, they would have never spinning it properly they were trying to do it at a much lower speed than otherwise. Well they did some corrections, but in Canberra aircraft is now outdated so it is not there.

So, all that I am trying to tell you that in starting sequences for gas turbine engines had to be designed carefully because it the spinning takes place and afterwards, when inject fuel you cannot inject fuel much earlier you have to inject only at some stage. And if you do it earlier you are shocking the turbine blades and the life of that system may come down. So, that is the by the by we move to the next.

Student: Sir.

Sure.

Student: Can you come across the (Refer Time: 12:32) ramjet like waited at airport (Refer Time: 12:33) lower number compared to the other (Refer Time: 12:34).

So, why do you say that it is lower number?

Student: If you have consider the normal rocket engine and then like.

Sure, the afterburner are you comfortable with 3 to 4 atmospheres.

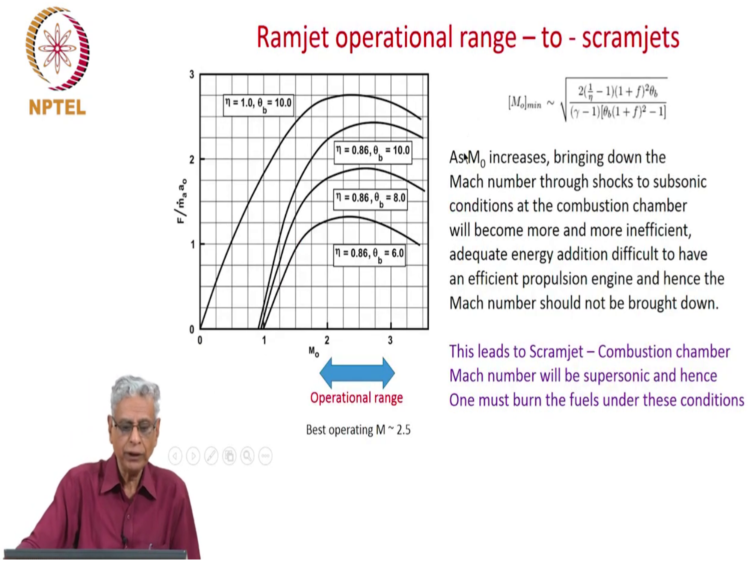
Student: That is the I am telling about that combustion pressure is only 3 to 5 p combustion is only 3 to 5 atmosphere.

See, what happens is there is a loss of pressure in the recovery through the shock system ok. So, the pressure is not necessarily very high here. And you see you in this design I am showing it in some manner, but in actual systems the pressures could be even lower it is all done it high altitude.

See it has to go to at least couple of you know 1000 kilometers not 1000 kilometers about 100 about few kilometers above. The big is operating once it operates at several kilometers the actual pressure is lower. So, the pressure inside the combustion chamber is therefore, lower you understand the.

Student: (Refer Time: 13:39).

(Refer Slide Time: 13:40)



So, look at the operational range of a ramjet now you could make a simple calculation system calculation. And this quantity is called thrust per air flow rate it is a dimensionless quantity it is a measure of compactness of the engine. If you are able to get the same thrust at a lower Mach flow rate the thrust per meter flow rate is higher. Now, we will discover that that number goes to a large value in a Mach number range of 2 to 3. So, this is. In fact, the appropriate range that you could look at.

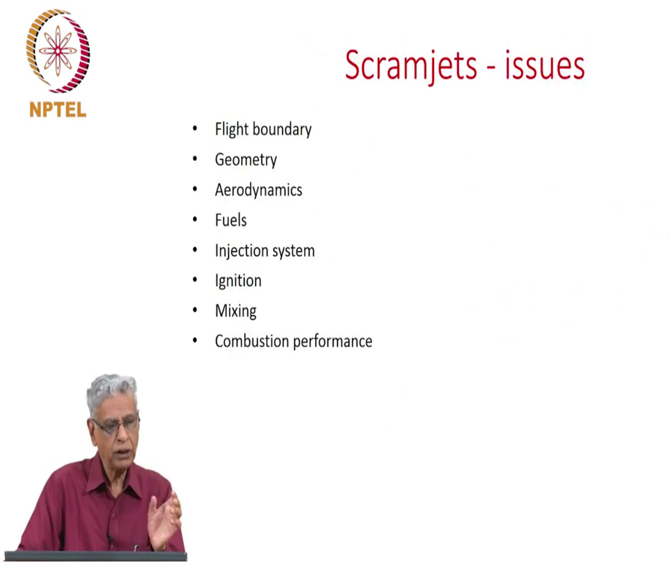
Student: Ok.

But if you add inefficientiation to the system you can actually show that no ramjet ever starts at less than mere about Mach 1. So, you have to keep it at Mach number more than 1. And typically its Mach 2 to 3 and therefore, you have to accelerate the ramjet to that speed and then allow the ramjet to function. And there are ramjets which are functioning like that solid fuel ramjets as a part of missile system one project called Akash uses the such system.

So, what I am saying here as Mach number increases bringing down the Mach number through the shocks to subsonic condition at the combustion chamber will become more and more inefficient. Adequate energy addition difficult to have an efficient propulsion engine enhance Mach number should not be brought down too much. If you go to higher Mach numbers it is far more difficult to bring it down because of the inefficiency of the shock system and also some other features.

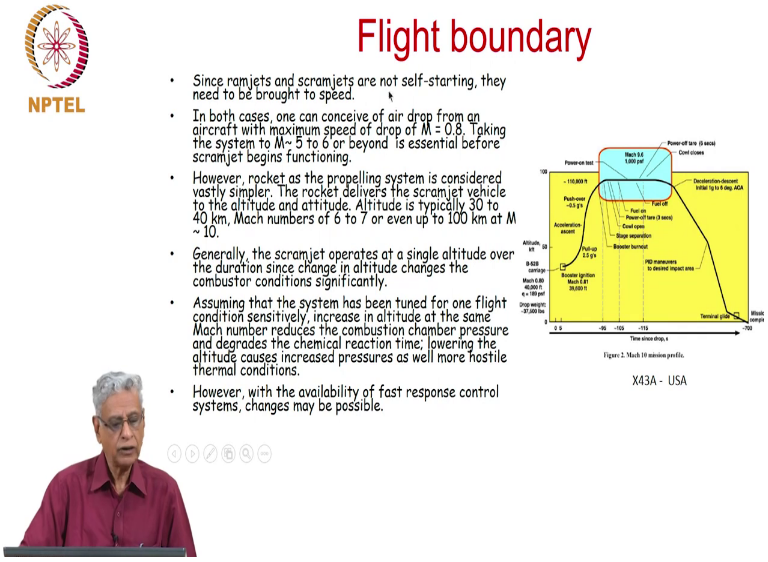
So, this leads to scramjet combustion chamber where you say I do not want to reduce the Mach number to subsonic conditions, but let it remain in supersonic conditions and therefore, a burn the fuels under these conditions. This is the logic which is put together. Actually you can show that when you go to increased Mach numbers the thrust per unit flow rate goes down. So, sharply with inefficiency included that it no longer provides adequate thrust. Therefore, it is compulsory to make sure that you go to reducing the Mach number to near supersonic conditions.

(Refer Slide Time: 15:58)



So, I am assuming that we know why we are in supersonic combustion regime. And we are looking at the issue some of them other points also may get cover we look at flight boundary, geometry, aerodynamics, fuels, injection system, ignition system, mixing, combustion performance.

(Refer Slide Time: 16:17)



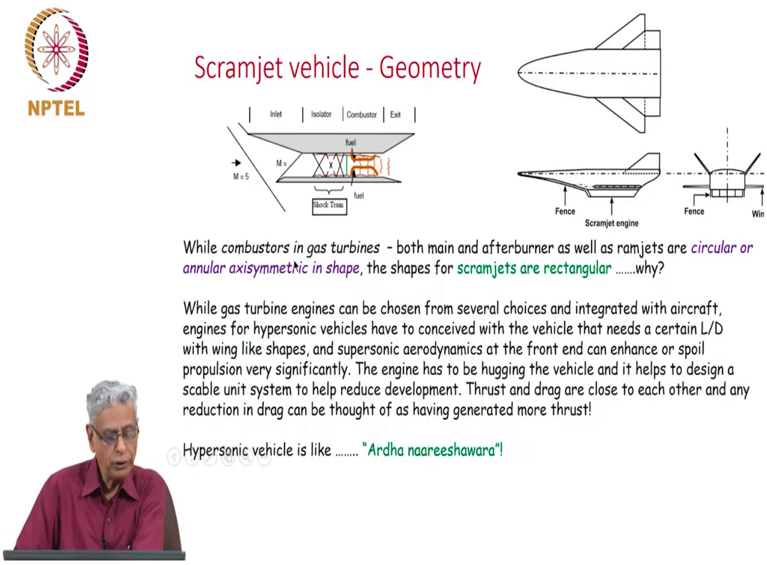
Since ramjets and scramjets are not self starting they need to be brought to speed in both cases one can conceive of air drop from an aircraft with a maximum speed of about 0.8. Taking the system to Mach 5 or 6 in this scramjet is essential before scramjet begins functioning this is something which you can understand.

However, rocket as the propelling system is considered very vastly simpler rocket delivers the scramjet vehicle to altitude. And the right attitude altitude is typically about 30 to 40 kilometers Mach number 6 to 7 and sometimes even up to 100 kilometers when you go to that altitude you can go to Mach 10. This is the case of X 43A you see the altitude is close to 100000 fee 100 kilometers close to and the 30 kilometers roughly. And then you will find Mach number of in this flight Mach number is 9.6 or so 10. And it operating period is about 6 seconds demonstration and it comes down.

Generally, if scramjet operate at a single altitude over the duration since change in altitude changes the combustor conditions significantly. Assuming that the system has been tuned for one sorry one flight condition sensitively, increase in altitude at the same Mach number reduces the combustion chamber pressure and degrades the chemical reaction time; that means, reaction time will be larger lowering the altitude causes increased pressures as well as more hostile thermal conditions. Same Mach number lower altitude means you have more strong shocks and you will have problem and stronger pressure. So, therefore, it is more hostile for the hardware.

However, with the availability of fast response control system it could be possible to change the scenario, but it is too early to say that in the development of the total systems.

(Refer Slide Time: 18:18)



How will the geometry look like it usually the way you have a front shock and system and then you reduce the Mach number. So, levels to think will be appropriate for the combustions chamber into this fuel. Combustion takes place and then you have a nozzle and therefore, you get pressures on the system to produce the thrust this is the broad approach to handling the propulsion.

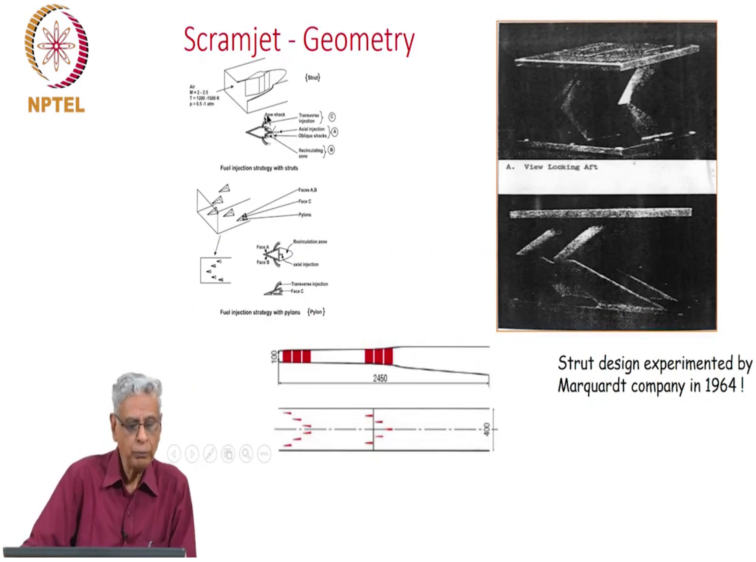
Most usually the geometry here is the rectangular as you can see integrated into the vehicle and not quite circular. So, one might ask a question while combustors in gas turbine engines both main and afterburner as well as ramjets are circular or annular axisymmetric in shape, but the shapes of scramjets are rectangular why is it so?.

So while gas turbine engines can be chosen from several choices you know you can make the same aircraft fly a general electric engine or (Refer Time: 19:20) engine or ARB 200 engine whatever you can make a choice. The and they can be integrated into the aircraft appropriately, but for hypersonic vehicles to be conceived the vehicle that needs a certain lift to drag ratio with wing shapes, and supersonic aerodynamics at the front end these can enhance or spoil the propulsion very significantly.

The aerodynamics content in a hypersonic vehicle is very significant part of the total propulsion. So, the engine has to be hugging the vehicle and it helps to design a scalable unit to help reduce the development. Now thrust and drag are close to each other and any reduction in drag can be thought of as having generated more thrust. Is that quite so true with? Basically it is fundamentally true with any propulsion system, but it is you have a range the thrust to drag a much larger in the case of other engines and aircraft and aircraft this propulsion systems and flight vehicles as well.

Therefore, you have a choice there, but you have very little choice here I want to liken these to what called Ardha naareeshwara! You know at temples where you have Ardha naareeshwara it integrated.

(Refer Slide Time: 20:34)

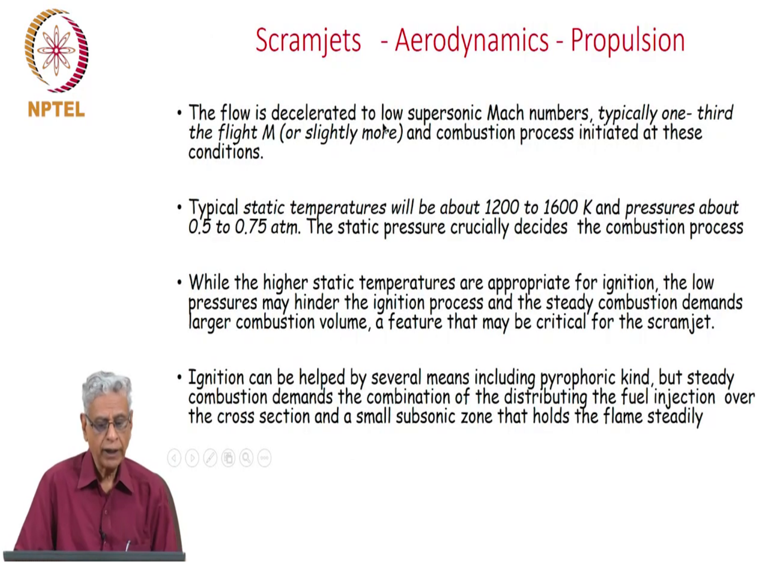


So, that is the point little more about geometry you have a rectangular combustion system. The air enters into the combustion system at Mach 2 to 2.5 something in that range, temperatures in this range is 1200 to 1500 Kelvin. Pressures are low 0.5 to 1 atmosphere. And you have system here to enable you to create shocks and you can introduce combustion system.

So, that we have recirculation zone that is the idea of creating geometry like this you can inject it perpendicular to the stream or along the stream transverse injection, axial injection all other will have some degree of shocks. You have variety of designs which you got developed over a period of time pylons and so on. And one strut design which you will developed in 1964 by Marquardt company you will find a good report on a subject.

So, the ideas have been floating around for a long time. They could not be you know brought up to the development could not be brought out that will be tested for almost now, say 40 years in some way, it is only about 2000 plus that things have happened.

(Refer Slide Time: 21:45)



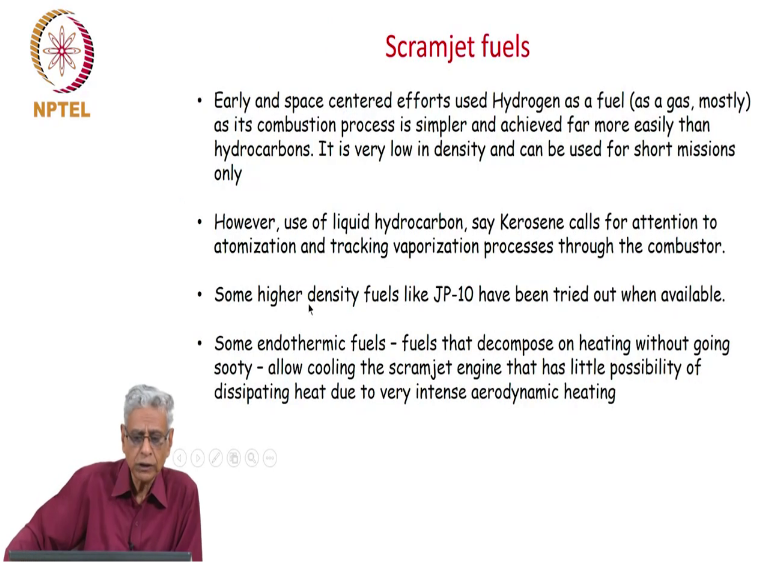
The flow is decelerated to low supersonic Mach numbers, typically a third of the flight Mach number. That is why Mach 6 means Mach 2 for the combustion chamber. And the combustion process has to be initiated at these conditions.

Now, typical static temperatures as I mentioned earlier about 1200 1600 Kelvin and pressures have to 3 force of unit material. The static pressure crucially decides the combustion process. While higher static temperatures are appropriate for ignition, the low pressures may hinder the ignition process and the steady combustion demands a larger combustor volume, and this is a feature which will be very critical for the scramjet. Everything matters a whole lot you cannot be excessive in anything.

Ignition can be helped by several means including pyrophoric; that means, you inject a liquid it ignites with air and therefore, its pyrophoric, but steady combustion demands its a combination of distributing the fuel injection over the cross section and a small subsonic zone may dominate and it holds the flame steadily. This is a debate which has taken place over a wrong time supersonic combustion you will say should not be in a subsonic pocket at all, debate has gone out and this is a subsonic pocket can you call it supersonic combustion.

Now, it is a semantics in some way in the flow domain if a part of the flow is subsonic. How can it so? It does not matter really. So, this is argument counter argument to that, but this argument can go on an academic settings, but flight vehicles at Mach number 6 cannot happen unless the combustion occurs in supersonic mode.

(Refer Slide Time: 23:31)



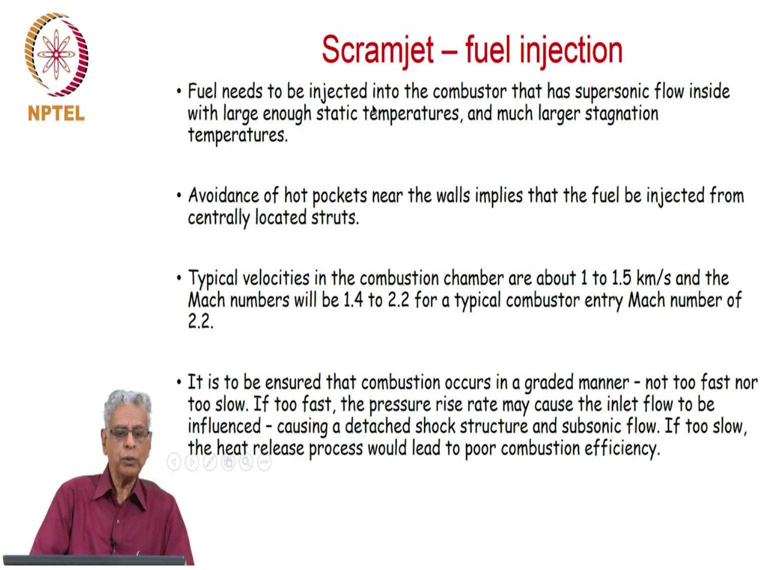
What are the fuels which are possible to use in such system? Early and space centered efforts used hydrogen as a fuel, hydrogen as a gas easy to burn and is achieved more easily than hydrocarbons, but unfortunately it is lower in density can be used only for short missions. If you have a long burn duration then we have to carry lot of hydrogen lot of volume it not possible to design a system its nothing like you can do one thing and other like in rockets, you have do not have too much of choice.

However, use of liquid hydrocarbon say Kerosene calls for attention to atomization tracking vaporization processes through the combustor. So, you cannot escape atomization in such situations. Some higher density fuels like JP 10 have been tried out when available this is very commonly available in US and Russia and so on, including China, but it is not available in our country very much. Some development efforts are going on, but still not adequate.

A something called endothermic fuels these fuels decompose on heating without becoming soot. The problem with kerosene is if you use that as coolant then it decomposes to soot it deposits in the path way therefore, hinders the flow of the liquids it is a serious problem.

So, the choice is that you have to limit cooling if at all or you have to look for other fuels and this endothermic fuels are a choice. Again this required development some development has taken else taken place elsewhere, but it have to happen in our country till one area which is open at the movement.

(Refer Slide Time: 25:20)



How do you inject the fuel? Fuel enough needs to be injected in the combustion chamber that is supersonic flow inside with large static temperatures, and much larger stagnation pressures.

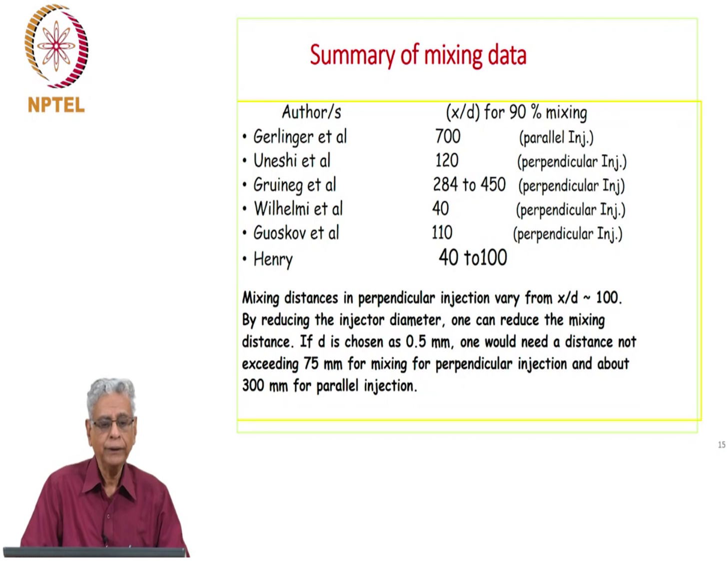
Avoidance of hot packets hot pockets near the walls implies that the fuel be injected from centrally located struts.

You have strut like the one that I showed you about Marquardt that a good design in terms of how to inject a fuel. Typical velocities in combustion chambers are about 1 to 1.5 kilometer per second Mach number 1.4 to 2 even though inlet flow is Mach 2 or Mach 2.2 because they are always stretch which creates shocks and therefore, reduce the Mach number.

It is to be ensured at the combustion occurs in a graded manner- not too fast not too slow. If too fast, the pressure rise rate may cause inlet flow to be influenced. Suddenly, heat release will push this flow. So, the shock will move back into the air intake and the whole flow process gets a completely affected seriously. If too slow, the heat release process would lead to poor combustion efficiency.

So, we need to go through a narrow track of not being too slow or too fast. I am saying that very specially because many times people talk about this problem and this subject which probably we will debate tomorrow I will bring it up tomorrow.

(Refer Slide Time: 26:56)

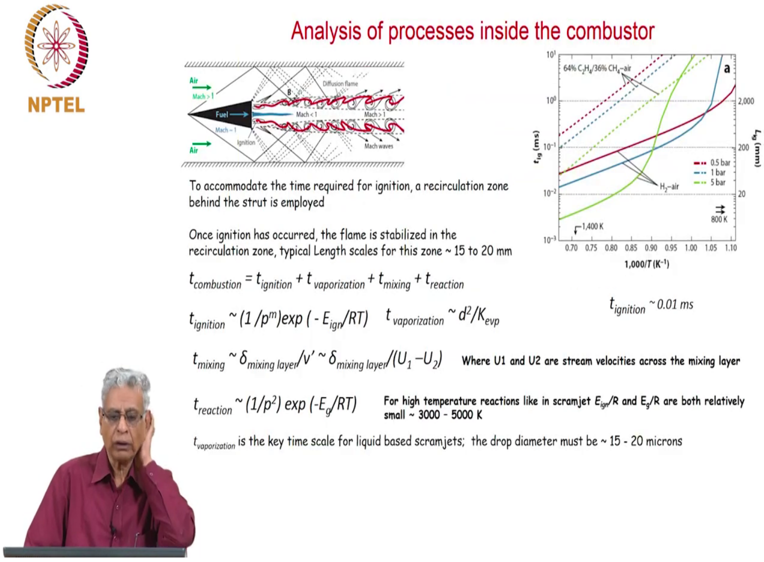


So, it turns out that mixing between the fuel and oxidizer is a crucial issue a lot of work has been done by researchers over a period of time. And the summary is that the length to grid give injector diameter for 90 percent mixing goes all the way you know very poor injection, parallel injection you see 700.

And the lateral injection can bring it down to in 40. Typical, this distances of 100 may not be unregionable. And by reducing the injector diameter one can reduce the mixing distance. And if you injector whole diameter about 0.5 mm it is a standard dimension one would need a distance not exceeding 75 mm for mixing and about 300 mm for parallel injection.

So, either way not a bad issue the typical combustor length will be around a meter in large engines.

(Refer Slide Time: 27:54)



If you look at the processes that occur inside the supersonic combustor is shown here you have a wedge and you may inject a fuel here, because your wedge there is recirculation zone in this domain. And this is a standard way of doing it even then afterburner. So, you do the same thing here, but you must limit the size. So, that the pressure drop because of the presence of this must not be large alright you lose a stagnation pressure and therefore, you lose a performance.

Now, the flow will actually have a mixing layer supersonic mixing layer a subject which has been debated discussed in the last 20 years older. And the mixing layer thicknesses are small because the velocities are large. And you will find a diffusing flame occurring in this domain because the fuel comes here it burns in wholes the steady the flame and further combustion takes place as the flow goes through this. If it is gaseous fuel like hydrogen then the combustion process begins right away if you inject a kerosene then some bit of vaporization is important and then combustion have to take place.

So, If you take the total time for combustion its compose of ignition time, vaporization time, mixing time and reaction time all these are important. And sometimes a simple scaling will tell you what may acquire greater relevance in design if you look at ignition time, it goes as inverse of pressure and favorable in terms of temperature as temperature increases you will find this time comes down, but pressure is lower this time increases. So, it in fact, is.

So, critical in case of the ISRO vehicle there are lots of debates. Whether, the auto ignition will take place or not they wanted to ensure that such a problem will not create difficulties in the first flight. Sometime, the first flight is very crucial if you succeed in the first flight your confidence level is up. And if you have any problem with the first flight you know you really moral is down in some way. And when you are looking at new technology it is all the more important to makes you that succeed right in the beginning.

So, what was (Refer Time: 30:08) you have a mixture of liquid oxygen and liquid or gaseous oxygen and oxygen and hydrogen. And you inject you spark it and create a flame structure like a small rocket and this comes through in this domain in this domain, you can also inject fuel is also injected in other places because you have a hot gas stream if a rocket kind coming up it turns out that ignition process is very stable.

So, to start ignition you do that then you can ask a question it should be turn it off or should it be remaining there all through because it is not obvious that ignition will get sustained at the pressures and temperature conditions. So, it turned out in the case of the ISRO flight it turned off the this system ignition system. And the combustion process sustained on its own. So, it was a good experience to know that ignition was we purposefully should have used of self, but it is not required beyond ignition.

In case of liquid you look at vaporization and vaporization which will go like some d square by K evaporation. Standard expression which you have learned till now and mixing is a difficult subject here, there is a mixing layer here it grows in some manner I think it is very complex you know study has been going on for a long time. It relate mixing layer related to velocity difference divided by some mean velocity and so on at that compressibility effect which has to be accounted I do not discuss that here.

And the difference in velocity is what is required to tell you what the time of mix it is. Reaction as usual goes inverse as the p square of bio molecular reactions. And it is about E by RT is the standard thing. For high temperature reaction like scramjet E ignition by R and E g by R are relatively small. I wanted to bring to your attention something. See whenever you looking at chemistry you are looking at chemistry at 300 Kelvin which are (Refer Time: 32:28) 1 atmosphere and so on where pressures are same in the case of a supersonic combustor, but temperatures are very high 1000 K plus 1500 to about 2800, 3000 Kelvin is the temperature range.

So, the question that sometimes is asked is the chemistry which is valid for 300 K to 3000 K or 2400 K will that same thing be valid in the case of 1500 K to 3000 K. Now, the key point to notice is that as temperature increases E by RT comes down and you will find that the several steps of the chemistry which are relevant here are not so important at high temperature.

So, it is important to keep this in mind 400 million. Then some work using opposite diffusion flame at high temperatures. So, some changes in chemistry will be required, but when you go to fluids like kerosene you are always in trouble because, the droplet vaporization after takes place the molecular.

So, complex the decomposition of that various segments in the presence of air is not so very well understood quite often the chemistry that is shows in there are 2 step chemistry you take any hydrocarbon it goes to CO 2 plus H2 O. And then CO gets oxidized to something else, it is another approach which have been chosen and it is what has been practiced in many places ok. And, but you will I must say that in the case of liquids vaporization time is the key for most scramjets.

Because the moment it evaporates you can take reaction time to be very small it does not matter temperatures are very highly most zones downstream of this place. See inlet around 1500 K as you keep going down stream it turns out that mean temperatures are higher. So, reaction rates are much larger take a point here well the ignition time is about 10 milliseconds in this particular study, but in not likely to be show you most actual situations.