Combustion in Air Breathing Aero Engines
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Lecture - 58
Combustion in Scramjets-I

Welcome back. So, we have arrived at the last technical topic of this course of combustion in air breathing aero engines. And this topic is essentially it is combustion in scramjets. Now many people consider scramjet engines to be the future of high speed air propulsion. And it can be used for various purposes, but apart from that the scramjets engine the scramjet engines there is a inherent beauty in the scramjet engines. It is conceptually very simple it there is no rotating machinery inside the scramjet engine as such ear is compressed just by the design of the engine as such just by the by reducing the cross sectional area.

So, when the when a high speed incoming air passes through a reducing cross sectional area it automatically gets compressed by and also there are some shock trains being that being for that is formed. And then you add heat onto this high pressure high speed air and you can expand that subsequently to generate the thrust. So, there is no compressor in a scramjet engine there is no turbine in a scramjet engine.

So, because there is no turbine there is no limitation of any like theoretically there is no such limitation on the maximum temperature that you have to on maximum temperature that you have can achieve in the combustion chamber at least from a materials point of view, but despite this lack of limitations lack of theoretical limitations or this conceptual simplicity technologically scramjets very, very complex. And scientifically very challenging. And that is what makes the whole thing the and the design analysis and experiment simulation in scramjet combustor and scramjet engines very, very challenging and exciting on the same time.

So, your scramjets has been there for quite some time it has been conceptualized more than fifty years ago, but still we still we do not have a commercially viable commercially available scramjet engine which can take a load from one place to an another. The reason is that the reason is once again that despite this conceptual simplicity scramjet engine suppose you know was scientific and technological complexity. So, here in this lecture on scramjet engines we will just mainly focus on the combustion part of the scramjet engines, but we will get exposed to some of the complexities because unlike in other engines in the scramjet engine you cannot really talk about the combustor in isolation from the rest of the engine. So, it is the full engine has to be essentially understood and treated as a whole to develop the insights for the processes that happens in a scramjet engine.

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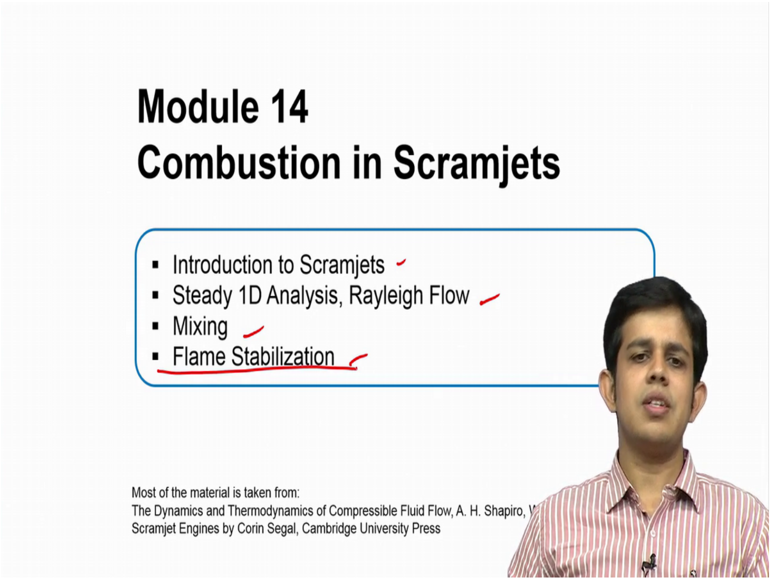

So, this is just this course will be just give you a very brief description and the important features.

So, first will go into the introduction of the scramjets; why do we need scramjet engines when we have rockets? You know we have rockets are very, very high mach number and it can go from all the way from the ground on to moon mars venus neptune anywhere across the across the solar system. Whereas, a scramjets of course, you know that these are air breathing engines and as a result it is it is transportation is restricted within the atmosphere. So, why do we despite the complexity and despite the challenges, why do people still want to develop scramjets when we have rockets? What is I, what is the reason? And then we will go into the steady 1D analysis of 1D analysis of the of the engine a little bit will go into the essentially this rayleigh flow which is essentially a frictionless flow with heat addition and we will see what happens when you add heat onto a high mach number flow. And when the area of the of the flow path does not change, that that creates some complexity.

Then we look into mixing of course, in scramjets mixing is a very, very big problem. And then we will look into flame stabilization. Flame stabilization is also very big problem. We have looked into flame stabilization for an afterburner and the for like flame stabilization in subsonic flows and we have seen the challenges, basically we have seen the flame stabilization was inherent inherently a problem of like you have to ensure that you have sufficient chemical timescales when you would for a given flow residence timescale right.

So, the chemical timescales must always be shorter than the flow residence timescales for flame to be stabilized, but as you know in a scramjet engine the flow residence time scales are very, very short because the scram jets typically operate at about mach number like 6 6 7 and higher. So, the flow residence time is very short. So, your stabilizing a flame in such a very high speed flow is extremely challenging and this is one of the major challenges in a scramjet engine that how do you ensure that the flame is stabilized at different conditions and of high mach number flow.

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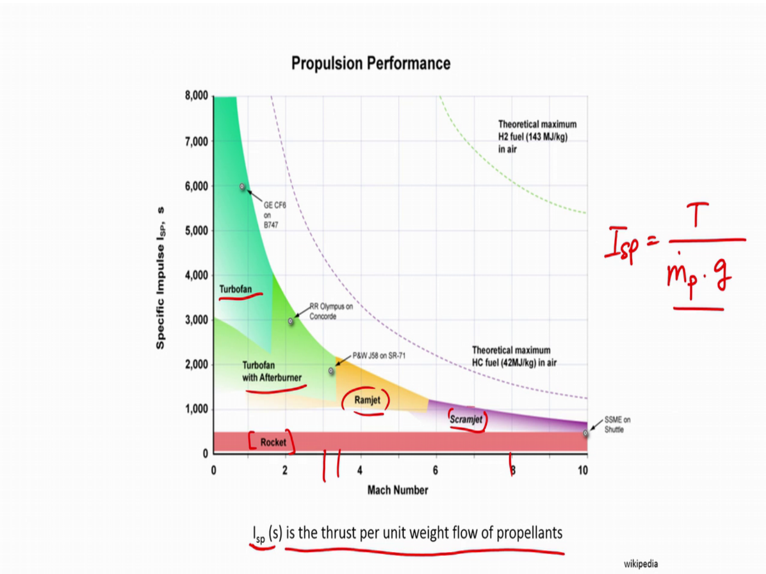

So, here before we go into the scramjet engines we need to take a look into something called a propulsion a parameter that can quantify propulsion performance. And that parameter is was some time is called ISP, which is called the specific impulse. And if it is in unit is of seconds it is essentially thrust per unit weight flow of propellants. Now the question is here is that what is a propellant? If you consider a turbofan or a turbo turbofan engine the propellant is only fuel. So, it is essentially ISP if I write it like this is T divided by m dot mass flow rate of mass flow rate of propellant times g. So, it is that is why it is it is a weight flow weight flow weight flow of propellants if it is. So, that is that the that is if ISP is in seconds it is essentially thrust per unit weight flow of propellants you can also define it is like thrust per unit mass flow of propellants, but then the unit is will change. So, to make it like weight flow we have to multiply by this g.

Now so, you see here we compare the different ISPs the ISPs of different air breathing engines with that of a rocket. Now all air breathing engines essentially have higher ISP or higher specific impulse than that of a rocket because in a rocket you are essentially carrying both the oxidizer as well as the fuel as the propellant. Whereas, in this air breathing engines your propellant that you need to carry is only the fuel. So, immediately that gives rise to much higher ISPs for the or specific impulse for all these, but air breathing engines and with respect to the rocket. And that is why you see at higher mach number for ramjets and scramjets of our ISPs or specific impulse which is more than 2 times than that of a rocket. At a at a mach number from the range of like say 3.5 to 8 where which is typically the regime of high speed propulsion ok.

So, this is the reason that because in a scramjet engine your you need to carry only the fuel whereas, the oxidizer is freely available from the air. The specific impulse of the scramjet engine is higher of the order of about 1000 whereas, in a rocket you have to carry both the oxidizer as well as a fuel. So, for that reason the specific impulse of the rocket is inherently lower than that of any your bidding engine, but of course, as you see at very high mach number this approaches the that of the rocket when you as you go and as you go into like a higher and higher altitudes you if you have to design a if you design an engine which goes into out of the atmosphere then of course, you need to carry the oxidizer. So, then the ISP of the of that kind of a combined cycle scramjet will approach that of the rocket ok.

So, you see that when you consider the specific impulse the turbo fans are really very, very not large. And then of course, it reduces to ram jets and then to scramjets, but still the point is that the specific impulse of a of a ramjet is still more than a factor of 2 higher than that of rocket. So, you basically with a given mass of fuel that you are carrying or the given mass flow rate of propellant or the given weight flow rate of propellant you get you generate more thrust in a scramjet then you generate for a rocket.

So, economically scramjets at least in theory scramjets are much more a viable option for cruising for long distance travel or for cruising from one place to another as opposed to that of a rocket.

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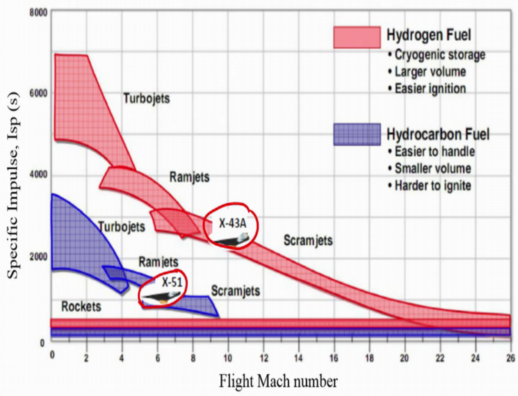

So, here you have you have again the specific impulse, but you see that the specific impulse also depends on the fuel, because the amount of energy that is available depends on the fuel type. So, if it is like the hydrogen best fuel well you see this x 43A, which was the plane before which is a scramjet engine test engine developed by NASA that has a higher ISP then compared to x 51, which was based on the hydrocarbon fuel and which was also tested in this get ok.

So, the advantages of hydrogen a hydrogen fuel is that it can have a cryogenic storage it has a larger volume it case is a it is it is easy to ignite hydrogen is very, very easy to ignite it as a huge flammability limit, both in the lean side. As well in the rich side whereas, if you want to use hydrocarbon fuel of course, it is easy to handle and it has it is for a given volume you get much more energy. So, you can have a smaller fuel tank, but of course, it is much harder to ignite and it has other processes like you it has to be it here if you only using liquid fuel directly into the scramjet it has to first the liquid jet has to break up it has to atomize it has that (Refer Time: 11:23) droplet us just evaporates So on and So forth. So that requires some additional time.

But thus typically if it is a specific impulse then the scramjets with hydrogen fuels are better than scram jets for with hydrocarbon fuels, but practically because air breathing engines are So popular because of the high energy density of the hydrocarbon fuel. And because we have essentially mastered the ability to carry liquid hydrocarbon fuel and once all these problems are settled of course, the this type of liquid hydrocarbon based scramjets engines could emerges the hypersonic engine of choice both for wave and for commercial aviation in the long term future.

So, that is why it is important to know about scramjet engines and how do the operate.

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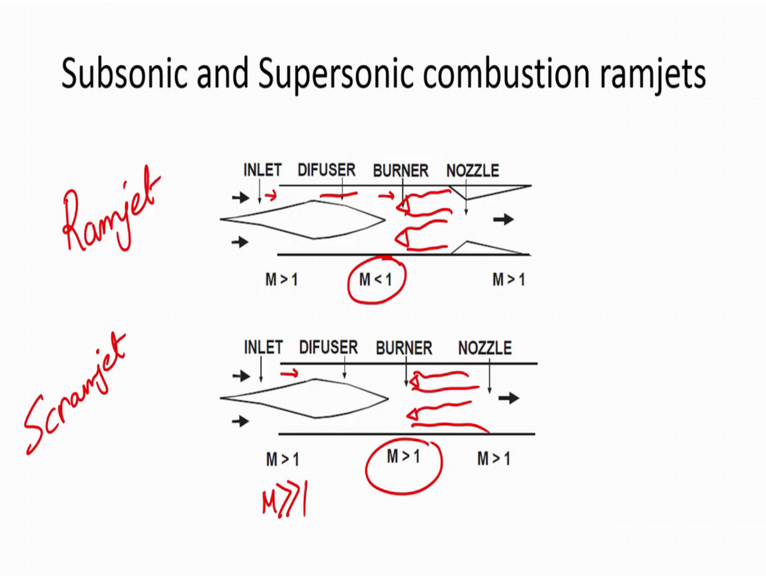

So, here is a difference between scramjets and ramjet engines. Now in principle they are kind of similar that is you compress the air by ramming it into the engine. So, scramjets are nothing but supersonic combustion ramjets. So, in the ramjet what happens is that. So, you have the inlet and then you have So, the in the as it passes to the inlet. So, the air is essentially slowed down it is because the inlet air that is that comes into the engine is supersonic. So, with a converging if you design a converging cross section or the converging flow path. Then the of course, the air would air would essentially slow down into the inside the engine.

And when the subsonic and we are talking about we in this slide we are comparing between subsonic and supersonic combustion ramjets; now scramjets, which are essentially the supersonic combustion ramjets and normal ramjets. So, they work on the similar principle that is they do not have a compressor or any rotating machinery to compress the air. So, in this case the incoming air is compressed by the ramming action of the air into the engine. And that ramming action is created by designing by ramming the supersonic air into a converging flow path which is that is how the inlet is designed as you see here.

So, the supersonic air comes it passes through an area which is reducing, and because the flow is supersonic instead of accelerating it slows down and the pressure increases. And then of course, you have the diffuser and then you have the burner. So, in the ramjet by the time it enters into the burner the series of shock trains if and if there might be a normal shock also have reduced the mach number to less than 1. So, as you know the downstream of a normal shock the flow is always subsonic. So, if there is a normal shock form anywhere inside this engine. So, the flow downstream of that is invariably subsonic.

So, in a ramjet So, this is initially a ramjet. In a ramjet this series of shock trains ensured that the that the incoming supersonic air is transformed into subsonic flow by the time it enters into the burner. So, then in the burner you can have this starts etcetera, and you can have flame stabilization similar to what you have in the afterburner then you can, but still the flow is of course, subsonic and then you can expand it to a convergent divergent nozzle to generate a fast exhaust and which can generate large thrust. So, this is the ramjet.

In comparison in the scramjet which is the supersonic combustion ramjet as the name suggests, the combustion happens in supersonic flow. So, the it will be apparent why it is So? So as such this is in here the mach number of the incoming air is even much greater than one, it is of the order of 6 7 for an efficient operation of a scramjet. So, here you design again it passes through the inlet it is compressed, but it is compressed in a such a manner that there is no normal shock formed anywhere inside the engine. So, it is compressed and then it again passes to the diffuser there is a series of oblique shock trains that is being formed of course. And the pressure rises through these things through as the as the flow passes through these shock trends and the passes through this convergent cross section. By the time it enters into the burner it still remains supersonic because there is no normal shock formed and the scramjet is designed in such a manner that the flow remains supersonic by the time it enters into the combustor.

So, here also you can have different modes of flame stabilization, and then again it passes through the nozzle where the flow is further extend expanded and the flow becomes much mach number becomes larger and then it can be exhausted here to generate the required thrust. So, this is the difference between a subsonic and supersonic combustion ramjet or difference between ramjets and scramjets, that is the flow inside the burner in the ramjet is less than 1 the flow inside the burner In the scramjet is greater than one.

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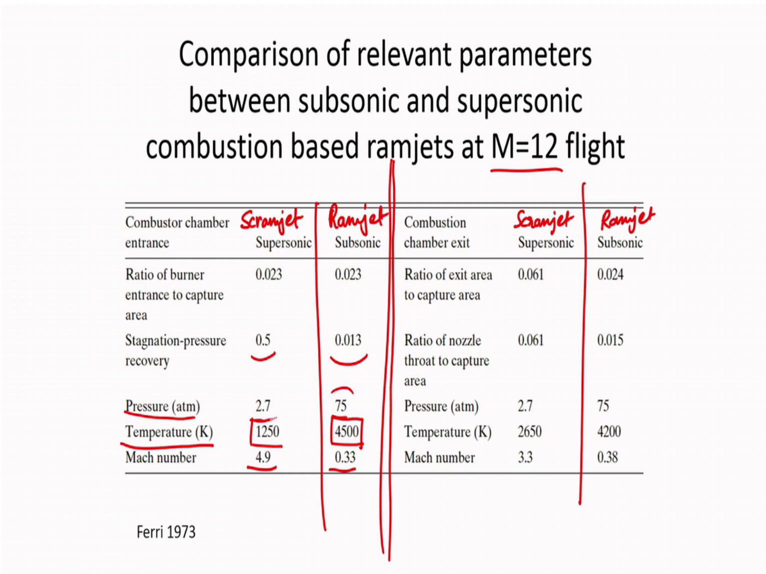
Comparison of relevant parameters between subsonic and supersonic combustion based ramjets at M=12 flight

Combustor chamber entrance	Scramjet Supersonic	Ramjet Subsonic	Combustion chamber exit	Scramjet Supersonic	Ramjet Subsonic
Ratio of burner entrance to capture area	0.023	0.023	Ratio of exit area to capture area	0.061	0.024
Stagnation-pressure recovery	0.5	0.013	Ratio of nozzle throat to capture area	0.061	0.015
Pressure (atm)	2.7	75	Pressure (atm)	2.7	75
Temperature (K)	1250	4500	Temperature (K)	2650	4200
Mach number	4.9	0.33	Mach number	3.3	0.38

Ferri 1973

Now why it is So? Why do we need to have supersonic combustion for high mach number flights? So, as you see here the ramjets are that is for combustion happening in subsonic flows that kind of an engine is only suitable for a limited mach number of say mach number from 3 to 6 app approximately. Whereas, scramjets are suitable for mach number from about 6 to 14 theoretically. At least of hydrocarbon fuels it is from mach numbers is 6 to 9, why it is? So, why can not we have subsonic combustion for high mach number flights? By the way I mean I mean you can have the reason is that there is nothing that prevents having combustion in a ramjet mode that is in a subsonic mode in a mach 12 flight, but then the point is that what will happen, the what will happen is compared here.

So, let us consider a mach 12 flight. And your combustion chamber and the entry into the combustion chamber can be either supersonic or subsonic. So, here in both the cases. So, this is essentially a scramjet. This is essentially a ramjet and this is once again this is a scramjet and this is a ramjet. So, ratio of burner entrance to capture area these are same in both cases stagnation pressure recovery. Stagnation pressure recovery the pt the p 0 inside the stagnation chamber inside the stagnation this p 0 inside the combustion chamber divided by p 0 at the inlet that is can be defined as a stagnation pressure recovery and in a scramjet that is much higher 0.5 of course, here it is much lower because you have a normal shock formed and there are entropic losses which is much higher in this ramjet. And it will be very, very small. So, the stagnation pressure recovery would be very small the pressure here is 2.7 here is 75, enormous pressurize ok.

So, if you are compressing a mach 12 flight, a mach 12 air in to a subsonic air. The pressure rise would be enormous. So, you have to design this will very difficult to design a combustor for such a high speed operation which can have 75 atmosphere temperature this is the key. You see the combustor entry temperature in a scramjet if you are slowing down a mach 12 flight mach 12 air that is entering into your engine at the inlet into say mach 2 at the combustor entry or mach here it is mach 4.9 and the combustor entry the temperature would be 12 fifty kelvin. Whereas, in this case if you are reducing a mach 12 if you are decelerating a mach 12 air to mach 0.33 air at the entry of the combustion chamber in the ramjet the temperature the static temperature at the entry of the combustion chamber before 500 Kelvin.

Why you do need even combustion? What how much increase in temperature can we achieve; when the incoming air is itself 4500 kelvin. And the problem is that even if you do combustion in the 4500 kelvin the it will be as an instead of adding heat it will essentially absorb heat because the dissociation reactions would dominate as such very high temperature everything dissociate air would dissociate also and heat would be absorbed to perform those dissociation reactions. So, it will be essentially counterproductive to have an add heat, but of course, you cannot have a if without adding heat you cannot complete the circle and you cannot generate thrust.

So, thermodynamics will prevent that your you can generating thrust from such an engine. So, it will be like compression you will you will only compress the air from very high mach number flow to very high temperature here and then you will release the same without generating an inert thrust. So, that will be the effect. So, you cannot generate thrust if you are essentially working in a ramjet mode for a mach 12 flight of course. And of course, at a mach 12 flight you cannot have any compressors or a turbine because compressors as you know cannot operate at mach 12 because of the very strong shocks that we form.

So, you see this is the reason why ram jets cannot operate that is combustion cannot and because the dissociation reactions essentially. And the fact that your added enthalpy even if there is no dissociation reaction that enthalpy that you can add to the flow by combustion is minuscule compared to the enthalpy that is already present in the flow in this flow. In terms of the at least in terms of the (Refer Time: 22:47) in terms of the thermal energy. So, you cannot really add much of thermal energy into the flow when you are operating a ramjet when you are operating your engine in a ramjet mode for a mach 12 flight.

So, you have to have combustion in supersonic flow if you are operating at a high mach number limit. So this is, but then it poses big challenge that supersonic combustion is not easy to achieve, because the fact that if your flow is supersonic at the entry of the combustion chamber mach 4.9 forget mach 4.9 even if it is mach 2. You will find that it has a flow velocity of the order of like about 1 kilo meters per second to have combustion sustained in such a flow is extremely challenging and we need the best of our combustion knowledge and design to ensure that we can have a stabilized flame at this high mach number.

So, this is the reason that if you are compressing high mach number flow to subsonic or decelerating the if you are decelerating a high mach number flow to subsonic flow, then the temperature rise would be So enormous that the you cannot really add much of thermal energy to into that highly into that high temperature flow. And even if you add it will be counterproductive because all the dissociation reactions will dominate and essentially the heat the energy added by combustion will be used up in satisfying those in performing those dissociation reactions. So, there will be no energy left for essentially expanding the flow.

So, the only option is to if you want to operate mach 12 engine is that you have to all work in a scramjet mode where your combustion must happen in supersonic air. So, this is the scramjet engine.

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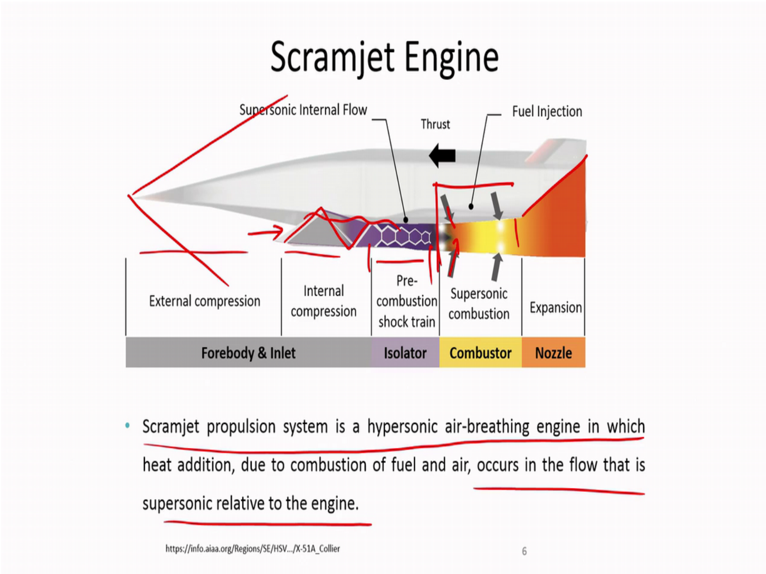

As you see this the shock angles will be quite narrow and that calls for this very sharp coon at the inlet. So, this part will be essentially will you will see that the shocks will form like this and this part the will essentially will also compress the airflow and this will be this part will be characterized by external compression. So, the air essentially enters into becomes an internal flow at this part where there will be internal compress compression. And there will be this shock trains being formed, this oblique shock waves will being formed.

And then you have a kind of a constant area duct which is called an isolator to contain this pre combustion shock train. And then there will be you will add essentially the fuel in this part. So, you will add fuel into this part and the fuel will burn and you have to ensure that you basically increase the cross sectional area to prevent something called thermal choking. And then you increase the cross section area slightly and then you expand the flow by providing a very large diverging duct to essentially accelerate the flow which will generate the required thrust.

So, as you see that what I was saying is that this conceptual it is very sync simple right it is just a variable cross sectional area duct. And of course, then there is like different kind of angles, but because you see that because there is no such rotating machinery it is the flow is very hard to control in this kind of thing. So, the design is to be maculate to ensure the perfect performance of a scramjet engine. And the other thing is that you see that yes we call this portion combustor, but the combustor is essentially very intricately related to the inlet to the to the to the this inlet where we have external compression of the compression of the external flow where you have internal compression and then you have the isolator and then you have the nozzle. So, the whole thing becomes very, very coupled and because there is no such controlling machinery rotating machinery which can be controlled at the at the at the order of the operator the combustor also encounters a wide variety of flow and thermodynamic conditions.

So, another challenge in the scramjet engine is that that because you cannot really control this all this flows here through different kind of machinery your combustion much be designed in such a manner that it must be able to encounter a wide variety of flow parameters and thermodynamic parameters. So, that makes also the scramjet engine design and operation and analysis very, very challenging.

So, to summarize the scramjet propulsion system is a hypersonic air breathing engine in which heat addition due to combustion of fuel and air occurs in a flow that is supersonic relative to the engine. So, that is the hallmark of a scramjet engine that the flow in this in the combustor is supersonic. In a ramjet engine the combustion happens in subsonic air. So, once again I repeat the scramjet engine is characterized by conceptual simplicity, but very high scientific and technological complexity ok.

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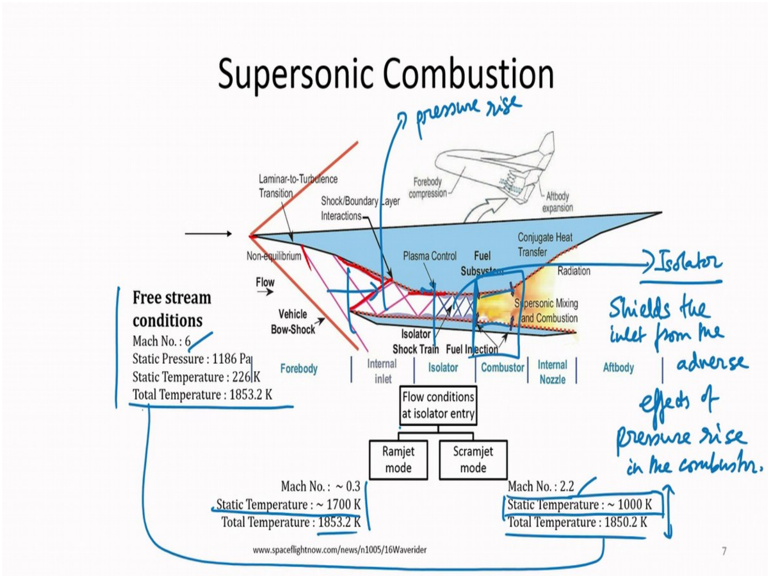

So, what are the processes and what are the what are the typical numbers that one can expect in a scramjet engine. So, before we go into the before we go into the numbers let us describe the process. So, you see that the this nose you have this bow shock being formed large bow shock and there can be some non equilibrium effects here. And then the flow will essentially will flow from a boundary layer along this engine and when there can be a large boundary layer developing and that boundary layer can transition from laminar to turbulence.

And then the boundary layer even becomes more thicker and of course, the larger boundary layer this leads to ready increase drag which you do not want. So, there can be necessary it can might be necessary to bleed off the bottom part of the boundary layer. And then you again have this different in internal add this you have a different kind of shocks forming but oblique shocks no normal shock can be formed in the scramjet engine, because then the flow will transition to subsonic. And then of course, as once again this boundary layer develops you see that you have shock boundary layer interaction. So, as soon as that happens there is chance for the boundary layer to separate because as you know the pressure increases across the shock.

And so, the what happens is that the boundary layer sees and across the shock the boundary layer sees an increased pressure which is essentially an adverse pressure gradient and as you know when there is an adverse pressure gradient the boundary layer separates. So, there can be copious boundary layer separation also. So, one needs to control that you (Refer Time: 30:22) one boundary layer separation.

And then of course, you have this after the external inlet and after the inlet internal inlet you can have isolator, I will come to the isolator and which contains essentially the shock train. And then you have this combustor. The combustor is essentially it comprises of the fuel injection system where you are injecting the fuel and it can have a flame stabilization system. Of course, you have to ensure that before you have the before between the fuel injection system and before you encounter the flame stabilization system there has to be intricate fuel or mixing, because only then combustion can happen.

So, this combustor essentially will have to accommodate the atomization evaporation if you are using a liquid fuel and then you have to accommodate mixing. And then you have ignition combustion all these things and then this we have this large expanded nozzle which accelerates the flow further.

Now, you have seen that in a gas turbine combustor in a gas turbine combustor because the flow into the combustor was subsonic. And because of course, gas turbine combustors the flows are subsonic and because your adding heat into that subsonic flow there was a small pressure drop that you have learnt always, but here you are adding heat into a supersonic flow. So, when you add heat into a supersonic flow and the if the cross sectional area is constant then you have pressurize ok.

Now, when you have pressurize what happens of course, you cannot the flow does not want to go into a region where the pressure is increasing it is a negative pressure gradient that is the force that drives a flow, but of course, the flow can process due to it is own inertia, but it does not really want to go. So, what happens is that in these supersonic flow that is reflected in form of a shock waves can be formed and there can lead to kind of different kind of oscillations. So, what you do not want these oscillations this pressurize which is the pressure is rising in the combustor. So, if I plot the pressure rise only in this combustor part it will be something like this.

So, you do not want this flow to sense this pressure rise despite the fact that it is a supersonic flow, but if it somehow this pressurize it reduces the mass flow rate too much then there is a possibility that there can often be a normal shock being formed in this inlet. And of course, then the whole flow becomes subsonic and your scramjet combustor is lost. And the whole thing is essentially breaks down then becomes a flow becomes. So, subsonic if the temperature rises. So, you really cannot afford that. And this before even that had normal shock forms there is a lot of things in isolations can happen which is called essentially unstart inside the inlet and the isolator. So, you really do not want that.

So, to prevent that what you have is that you design a constant cross section called it is isolator the purpose of which is essential to contain the shock train and to essentially shield to the inlet this isolated essentially this shields the inlet from the adverse effects of pressure rise in the combustor. So, this is the it is really otherwise it is adds to drag and all these things, but this is the thing in that it purpose of ourselves.

So, all other parts are very easy to understand the inlet of course, is for the ramming action where you are designing this reducing cross section. So, that your flow essentially this supersonic flow essentially slows down and did the pressure increases because you to complete the thermodynamic circle and to extract work or it generate thrust you need to add heat only at high pressure. So, this part causes this part causes the pressure rise this part causes the pressure rise this isolated part essentially shields the inlet from the adverse effects of pressurize in the combustor and then in the combustor you add heat, but before that you also add fuel and allow the fuel to mix and then the fuel can get burnt and then increase the stagnation enthalpy of the flow. And then this very high stagnation enthalpy flow can be essentially accelerated; further in this nor in this divergent nozzle to generate large thrust.

So, what are the numbers that we are talking about? So, typical scramjet can operate at mach number 6 and if we look into the numbers that we are interested for the typical scramjet operation. So, it is let us consider this scramjet engine flying at altitude of 30 kilometer at mach number six. So, the static pressure it can encounter is about 0.12 kilo pascal. And the static temperature can be about 226 kelvin of course, it is reduced because of the high altitude. And the total temperature the total temperature is essentially T static plus v square by 2 cp. So, this total temperature is about a 185 3 kelvin, but these are approximate numbers which come out from this for our typical for a scramjet engine. And of course, the total temperature can remain fixed throughout the engine, but the total pressure of course, should reduce because of entropy rise due to friction etcetera and shockwaves etcetera.

So, by the time it enters into the isolator. So, we can consider even the isolator to be part of the combustor. If it is in a ramjet mode then of course, the mach number should be small the mach number is about 0.3, and the static temperature should rise very much 1700 kelvin which is you see that enormously large to for adding substantial amount of heat total temperatures still remain same ok.

So whereas, in the scramjet mode you can have a mach number of it should be supersonic. So, the mach number is 2.2 whereas, you see the static temperature is now good it is about 1000 kelvin whereas, the total temperature can be reduced because of the boundary layer bleed etcetera so, but you know of course, air remains very same close to that ok.

So, now these are the typical numbers. So, you see that why this scramjet mode of operation is preferred because the static temperature that of the flow that enters into the combustor is at much over temperature. And there is room to and heat into the flow, without incurring or without inducing strong dissociation reactions you can add heat into a 1000 kelvin and take it to say 2000, 2200 kelvin, but what will you do at adding heat into this temperature into this flow there is nothing.

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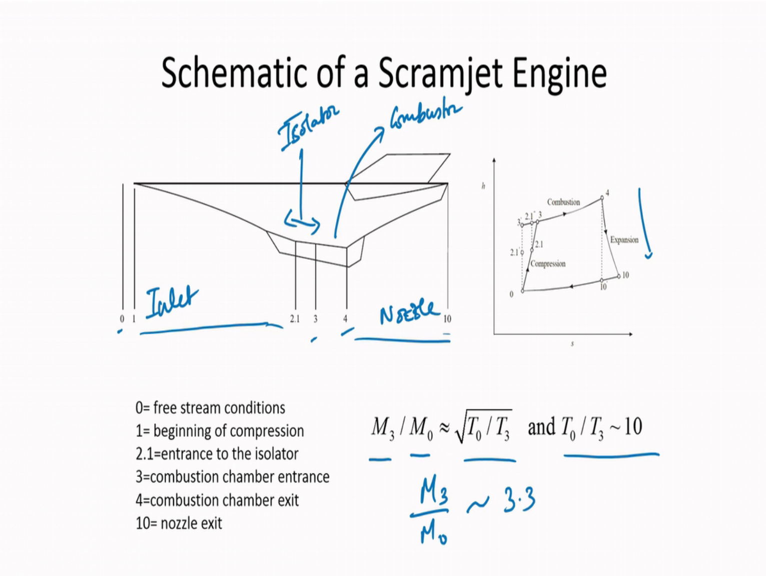

So, this is once again the typical schematic that we were discussing the So, if we one this is also the cycle corresponding to this. So, if this is 0 is the free stream conditions and one is the beginning of compression. So, this part is essentially the compression that happens external plus internal compression is combined and then a 2.1 it enters into the isolator at 3 it enters into the combustor, at for it this combustion chamber exit and then it at 10 from the air it is essentially the nozzle. So, this is essentially the inlet or the intect and this is the nozzle and this is your isolator and this part is your combustion.

So, in the enthalpy entropy diagram you see that of course, this type of compression through shockwaves through different kind of oblique shock waves induces entropy rise entropy is generated. So, from the ideal cycle it deviates 2.1 and then it goes to 3 and then you see a combustion we still consider for the purpose of the cycle we can consider at constant pressure just like in a gas turbine engine we consider that pressure is a pressure drop slightly, but actually we will see that here the combustion the pressure rises substantially it cannot be really linked like it and then it has an expansion process through the nozzle.

So, typically if you have if your inlet mach number is m 0 and your and your combustion chamber and trans mach number is a m 3. Then this relation typically holds and it is essentially been shown that essentially it is for large mach number limit for large m 0 is essentially T 0 by T 3. And T 0 by T 3 is of the order of 10. So, this m 3 by m 0 essentially becomes the square root of essentially 3.33 something like that.

So, you see here if this mach number is 6 this becomes a mach number of 2 or something like this. So, this is the this is the this is the thing that for a vehicle which is flying at a mach of 6, the combustor entry the combustor entry mach number of course, reduces, but it is still supersonic. So, even if the flight mach number is 6 your mach number at the combustor entry is 2.2, but the only thing that remains constant is essentially this total temperature the stagnation temperature, but the static temperature increases because of the compression action and now we have to add the we have to consider this combustor. So, this is the scramjet how the combustor is essentially integrated into the scramjet engine and these are the basic operations of the scramjet engine.

So, in the next part will take up how we can add what happens when we add the heat into a supersonic flow and it is a very fundamental thing but we will still do the analysis because this is a little bit counterintuitive. We are So far in the course we have never discussed what happens to the flow when you add heat into it. So, will discuss that and we will move forward with the different processes that happens in a scramjet engine.

Thank you.