Indian Institute of Technology Madras
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Aerospace Propulsion
Air breathing Engines –
Ramjet & Scramjet

Lecture 5

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We discussed in the previous class about the turbojet, turboprop, and the turbofan, now let us look at the next engine that got developed that is the ramjet.

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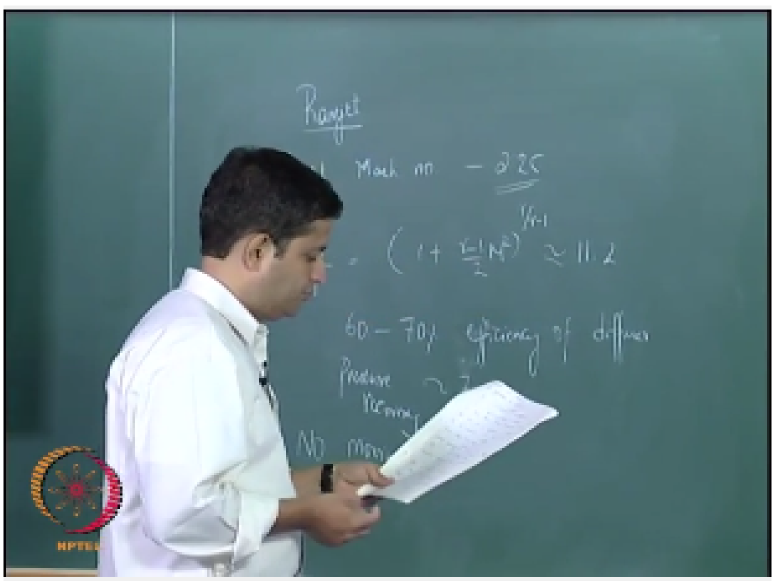

Before I go there I just want to ask you something, suppose I do not add heat I do not have the combustion chamber in a turbojet engine what happens then well it produced draft, and starting if you do not the compressor is wrong then you have the turbine, yes, true so you are saying that if I do not have the heat addition then it is impossible to produce any meaningful thrust okay. Now the concept of Ramjet it is a wall from a turbojet the idea here is let us say I am flying at a very high Mach number of around 2.5 okay right.

So let us do that calculation, if I have a flight Mach number of around 2.25 then what is the stagnation pressure that you get P_0 / P this ratio is yeah goes as $1+ \lambda - 1/ 2\ m^2$ this you will if you do this calculation you will find is around 11.2 right, if you remember when we discussed about the turbojet and when we were talking about efficiencies we talked about diffuser efficiency right and we said diffuser efficiencies somewhere around 60 to 90% and it depends on the flight Mach number.

So even if you assume something like 60 to 70% efficiency of diffuser yeah, so if you assume efficiency of the diffuser to be around 60 to 70% this number works out to be around the actual pressure recovery from this stream works out to be something like around seven, now you have a fluid that is already compressed okay to something like seven times the ambient pressure. So I do not need a compressor so if I do not need a compressor I do not need a turbine and so you do not have any moving parts and that is the essential idea of a ramjet.

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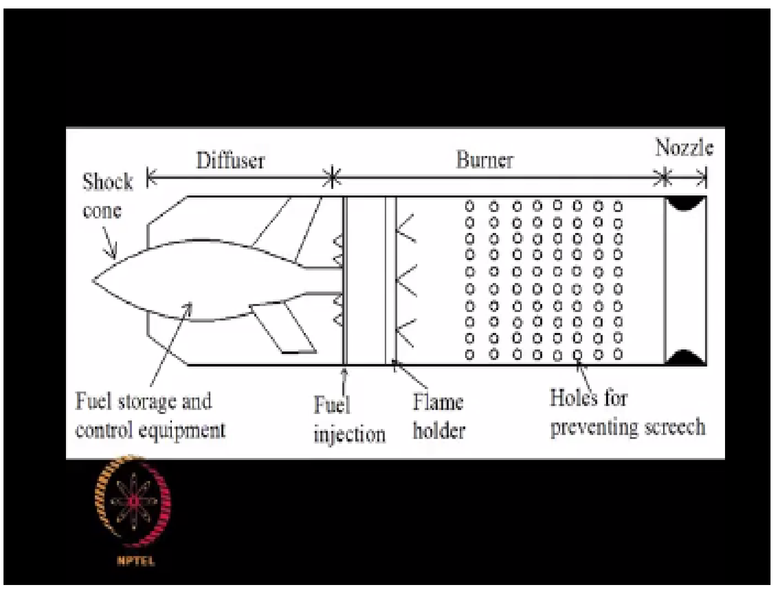

So if you see this figure here this is atypical schematic diagram of a ramjet engine, what you have here is a supersonic diffuser and then you have at this point the pressure of the incoming flow is already higher compared to the ambient pressure okay and then you have fuel injection here and the fuel flame holder here and the combustion takes place and then you have the flow expanding through the nozzle okay.

So you do not have any turbine you do not have any compressor, so a ramjet has no moving parts and that sense it is very simple to design, it operates very efficiently between a Mach number range of two to four okay. Now what do you think if you compare ramjet with a turbojet what do you think would be the thrust-to-weight ratio of this compared to the widget you think would be higher lower will be higher.

So the thrust weight is higher thrust to weight would be something like 160 to 170newton per kg for a ramjet and for a turbojet this is for a ramjet now if you have a turbojet the thrust to weight ratio would be something like 40 to 70 Newton per KG and for a turbofan it will be lower than the turbojet so okay, so the thrust to weight of a ramjet engine is the highest because it has no compressor there is no turbine the very few parts so it can be very light okay what about SFC ?

What do you think would be the SFC of a ramjet compared to a turbojet would it be higher lower or same as turbojet I think it is going to be the same, actually if you look at a ramjet engine that you have here this ramjet engine is very similar to what you have an afterburner in a turbojet engine right what happens to the SFC in the afterburner is it higher or lower than the main engine lower higher right in a turbojet engine the SFC of with the afterburner On is higher than the SFC with the without the afterburner on.

So a ramjet engine is very similar to the afterburner of a turbojet engine and therefore you will find the SFC's are much higher, so if you compare SFC’s a ramjet you will find rounded SF cease to be 60 to 90 milligrams per second this was around 31 to 36 milligrams per second and 16 to 24 milligrams per Newton second. So you see that in the ramjet the SFC's are much higher the main reason for this is you are adding heat in a ramjet at a much lower pressure then what you do in a turbojet meaning with the meaning with only the main engine that is without the turbofan at turbo afterburner on if you are adding heat in the main engine then you are adding heat at a very high pressure.

So therefore the availability is more so you can extract more work out of it remember we are always going to expand only for pressure we can expand only for pressure, so if you add heat at a very high pressure you can extract more workout of it so the availability is more. So in a turbojet engine you are adding heat at a much higher pressure compared to a ramjet engine therefore you will find the SFC of a turbojet engine being lower than that of a ramjet engine okay and one thing about a ramjet engine is that you know somehow you should go to a high Mach number right.

So if you do not to a high Mach number or if you do not go beyond the speed of sound beyond Mach 1then the compression will not be large, so you need it cannot be a self-starting system. So you need something to take it to from zero to two Mach number or something like that from where it can carry on further otherwise it is not a self-starting system that is one of the drawbacks and usually rocket motors are used to take it from zero to the design Mach number and then these things operate at that particular now what are the applications? What are the applications of ramjet these are typically used in resides okay.

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So and in the Indian scenario you have Akash and BrahMos that are ramjets okay there is also an aircraft very famous aircraft that used a ramjet sr-71, sr-71 was a unique design it is a turbojet and a ramjet put together that is the only aircraft that did that and it had a very high yes, so it had a very high mass number because it used that ramjet it could bypass and operate in different Mach number regimes differently at high Mach numbers it was operating as a ramjet at lower Mach numbers differently okay.

So sr-71 was the only aircraft that has used this otherwise it is primarily used in only missiles and if you look at this I put together some data here wherein you see four different missiles okay.

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Ramjet engines

System	Diameter, m	Length, m	Weight, kg	Thrust, kN	Speed (M)	sfc, mg/Ns
Marquardt (MA 212-x AA)	0.38	2.1	35.2	6.05	2.5 (at 12 km)	65.1
THOR (Blood Hound)	0.40	2.6	81.0	13.0	2.0 (at 6 km)	56.6

The diameter and the weight and the thrust and the maximum speed it can go to some of them are Ramjets plane Ramjets and the others are integral ram rockets we will talk about what integral Ram rockets are a little later in the course the first and the last ones are transits okay and the others are other two are integral ram rockets okay fine. Now in a sense from the piston engine plus propeller which was flying at very low speeds we have come from piston engine plus propeller to a ramjet which can take us to something like mark 4 right why not beyond it what is the trouble beyond it why cannot we go beyond Mach 4 with a ramjet sorry back okay, any other like putting the air into Auto near to stagnant condition. So if the Mach number is higher the stagnation temperature will be much higher and okay yeah.

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Scramjet stands for supersonic ramjet, now if you take a look at ramjet were in the flow Mach number as you actually said is brought down from ambient condition to low subsonic inside the combustion chamber if you take a look at that thank you okay, now if we were to do the calculation of what is the temperature at the end of this compression process for different Mach numbers for the entry Mach numbers I will put that as M infinity and if we were to calculate T stagnation we will find that at a Mach number of for the stagnation temperature is somewhere around 980 Kelvin and around six goes to 1 788 Kelvin and 7it goes to 3300Kelvin.

Now the trouble is if you are using kerosene as the fuel okay if we remember our previous discussions the adiabatic flame temperature that you can get with the kerosene air combination is somewhere around 2300 Kelvin now if you look at this table you have T stagnation itself going to something like 2260 at a Mach number of seven. So what it tells you is beyond this point it would be very difficult to add any sensible heat to the flow by burning a fuel right which is why I asked you the earlier question suppose I do not add Heat what will happen right you would not any thrust even here.

So you need to add heat and to be able to add Heat we need to ensure that the temperatures do not go to such high values okay, and what you do in a ramjet combustion is you bring down the velocities to nearly subsonic conditions at the entry of the combustion chamber now the idea is if you don't do that if you let the flow velocities be supersonic even at the entry of the combustion chamber then the temperatures would not be so large and therefore you will be able to add heat and that is the idea of a subsonic ramjet so let us say you have a flight path number of around 8 then in the combustion chamber if you can allow a Mach number of around 2.7 okay then the temperature of flow at the entry point the entry of the combustion chamber will be something like 1200 Kelvin.

Now surely this is a half's temperature but it is still not very large, so there is scope for adding some more sensible heat by burning a fear and then you can expand the flow through a nozzle there is also another problem that I did not talk about here that is once you go to such high temperatures the oxygen and the nitrogen in air they start to react okay and the oxygen content in the air slowly begins to deplete you would not have the same amount of oxygen content if you bring back bring it from bring the flow from somewhere around Mach number seven to around stagnation conditions if you take a look at those numbers of the oxygen in the air it ranges from something like 0.21.

So the oxygen content you see is decreasing, so because of these two problems we have looked at what is known as a scramjet now scramjet it is easier said let us say we can bring down the Mach number from 8 to 2.7 and then do the combustion at 2.7 Mach number it is very easy to say this but very, very difficult to do this the idea of a scramjet has been there for a very longtime more than 30 years now and yet no country has ever flown anything with a scramjet the Americans have recently tested something the Australians have recently tested something the Japanese have a program Indians have a program.

But Indians have only tested it without fuel addition Heathrow has tested it very recently without any fuel additionally aerodynamic testing the Americans have tested it with the fuel addition and they claim to have produced positive thrust we will see why is it that it has taken us this long from the concept to realization stage what are all the difficulties involved with scramjet why is it taking us this long from concept to realization the first problem is if you look at this Mach number here you are not bringing round two stagnation conditions.

So therefore the static pressure in the combustion chamber will be low right because of this now reaction rate between fuel and oxidizer depends on this static pressure it goes as reaction rates goes as square of the square of the pressure typically, now if the static pressure is lower than the reaction rates would not be faster the reaction between fuel and oxidizer is not happening at a much wrapping rate that you want it to be okay. So reaction rates are very low now there is an additional problem you are saying let us somehow bring this Mach number to something like 2.7.

Typically in gas turbine engines as well as in ramjet engines this Mach number would be 0.3 right from point three to nearly ten times that is a Mach number that you are looking at so the flow speeds is very large through the combustion chamber okay flow speeds are large means what? If you have a particular length of the combustion chamber then the residence time of the reactants is very small.

So this is like a double one firstly you have reaction rates lower and on top of it you are saying residence time is going to be small, so it is like a no-win situation that we are getting into right. So that is part of the reason why it has been so difficult for realizing this the other part is if you look at the typical gas turbine engines that we use for aircrafts Boeing makes the effect right Boeing or Airbus makes the airframe and rock and Whitney or ge makes the engines so expertise of engine making and airframe making are not in the same place they can be distributed you can make the aircraft and then match the power and fit this engine and go about it with regards to any other aircraft we are making the airframe for the LCF using a GE engine right now to power it right.

So airframe development can take place separately and the engine development can take place separately this is because there is no great aerodynamic coupling that is there between the two of them the aerodynamic coupling between the structure and the engine is not too large in most systems but in this case there is a very strong coupling between the airframe as well as the engine. So you cannot develop them separately you have to do them together okay and that is one of the major drawbacks.

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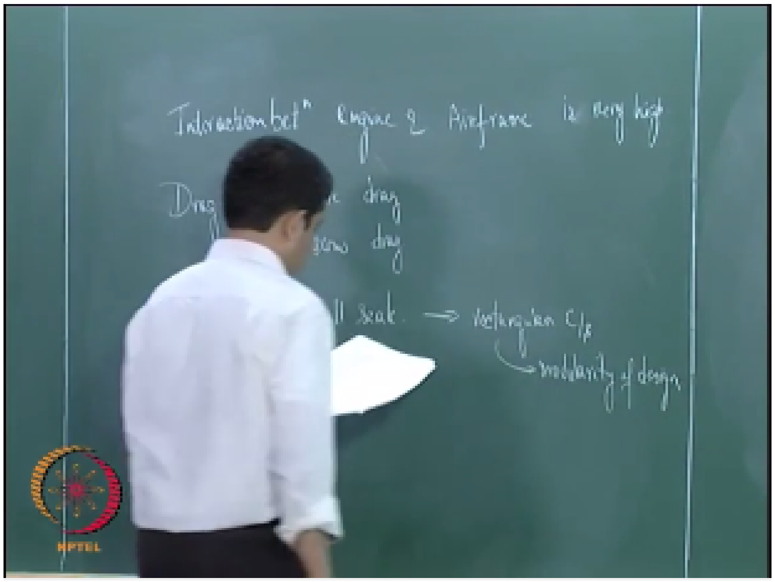

Interaction between engine and air frame is very high in the case of scramjets, so you cannot have expertise in different places you have to have them together which is not always easy okay and even testing you cannot if you are looking at any of the turbo jet or turbo prop engines the engines are developed separately they are tested somewhere else and then they are fitted here all the testing and other things will have to be done on the airframe and the engine being integrated together if you are looking at a scramjet and that is not always easy okay.

The other major problem here is drag, if you look at the drag both the pressure drag as well as the viscous drag is high here because you are going at very high Mach numbers the drag is very high, now you want inside the engine Mach number of 2.7 right if you are wanting that and if you want to ensure a reasonable residence time then the length of the vehicle will have to be long which means that the drag will also be long I mean will also be large okay.

So drag in this case is very large so inmost engine tests flight tests unless people come up with realistic numbers as in they put out these numbers it is very difficult to believe whether the system produced any positive thrust or not okay, please also remember that even on the inside there is a viscous drag because the flow Mach numbers inside the engine is also very large and typically the engine length is comparable to the entire vehicle length in this case, so the drag is a serious problem here very large drag.

And lastly testing of this is very difficult because you need to test for the engine as well as the structure right, so and if you have to build a wind tunnel for testing this it is very expensive because as you go to higher and higher Mach numbers the power required to keep it running for a smalltime is very large ok so testing is a problem you can test only escaped right with a other problem is how good is your scalability that is if you test something at small-scale can you go ahead and use it at a larger scale and be confident that whatever we have done at a smaller scale is going to be valid it is not going to be easy if you have a circular intake.

So which is why people go in for a rectangular intake because you can add them up if you have one rectangular intake and do the testing on that and do everything then you can make a large engine by simply adding up all these rectangular intakes, so that is one way in which people have looked to address this problem okay. So you can have a rectangular cross-section, so that you have modularity of design okay why then are we interested in this we simply seem to be putting too much of problems here we are only stating problems in the way it has been stated makes one feel that there is no hope.

It is also true that people say it is not very easy people in the field were doing this not very easy probably to get an accelerating system in a ramjet scramjet properly possible if you take it to that kind of Mach number somehow it can probably sustain itself that is it can just overcome the drag okay, why do you think people are looking at this what is the motivation for just flying faster is not sufficient now the kind of money that is being invested in this kind of activity is very large there must be some other reason why people are doing this, No okay if you look there to applications always or in this case three applications if you look at a launch vehicle application.

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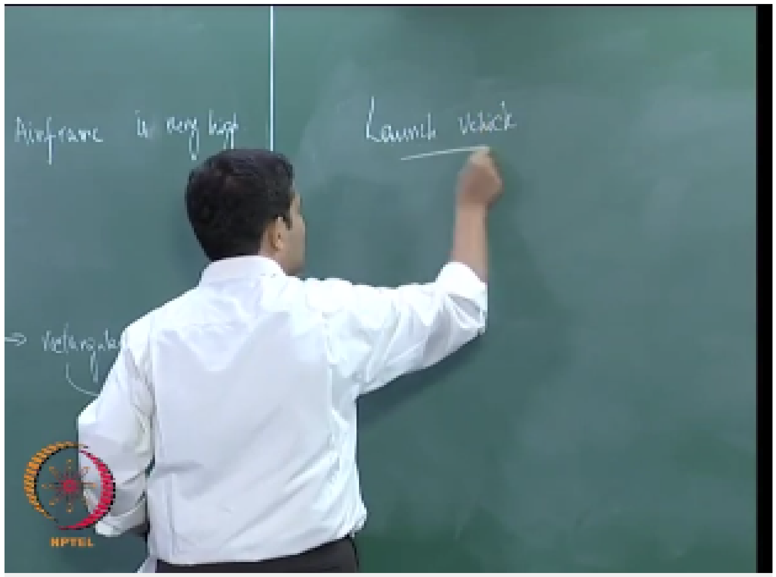

In India both Israel and D are do or pursuing a separate program okay and there must be a reason why they are pursuing it if you look at a launch vehicle reason as in if you are using this to launch something into orbit typically currently launch vehicles use rockets to do this now we will come to what Rockets are a little later in the course but just for this argument Rockets have to carry their own fuel and oxidizer onboard which means that their weight of the system goes up right as compared to that if you look at any of these air breathing engines they will use the atmospheric oxygen which is usually a few times larger than the fuel that is required right.

So they end up using atmospheric oxygen and use carry fuel onboard now with a ramjet we have a limitation of around Mach 4 right that is the limit at which we can go up to right now but if you go for this you can go to a larger Mach number inside the atmosphere and therefore if you can develop this successfully the costs of launching any satellite would be much smaller if you have a large portion of it being everything okay.

That is the idea why is row is pursuing it right now if you look at a military application why do you think a military would be interested in this if you have a missile that is built around yet if it can go at Mach 8 it is very difficult to crack it and shoot it down you might argue that you already have ballistic missiles why the hell do we want all these different kind of things they also go at very high Mach numbers but there is a difference if you look at what a ballistic missile does it is powered only for a part of the flight the remaining part it is going as a stone it can maneuver itself depending on the aerodynamics but it is not powered during the entire flight period okay.

It is only power during a portion of the flight period but if you have this it is powered through the entire period it is flying and therefore your maneuverability is very high not only are your speech high your maneuverability is also high, so therefore it makes it very difficult for the enemy to shoot it down and that is the reason why military is going ahead for this and if you look at any civilian application typically current day technology that we have the San Francisco to Tokyo flight take something like 14 ours okay.

People say that if you have a scramjet engine then you can do this within two hours would not it be nice if you can fly between any two places that were within just two hours, so that is the motivation behind looking at this from a civilian perspective although the civilian perspective is very far away right now people are looking at only the military and the launch vehicle application most innovations that we have will always go through this especially related to aircrafts and aerospace industry will always go through this cycle firstly.

It will be the military that will put it to use or develop the technology for our use then the civilian application comes in right it has been like this for all the engines if you look at turbojet engines turbojet engines were invented for a military purpose and slowly it got changed and mocked and then you have this civilian application that is coming in right so any kind of engine development or any kind of such activity firstly it will be the military application and then you will have the civilian application okay, I think I will stop here and continue in the next class.

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