Introduction to Aerospace Propulsion
Prof. Bhaskar Roy
Prof. A.M. Pradeep
Department of Aerospace Engineering

Indian Institute of Technology, Bombay
Module No. # 01
Lecture No. # 35

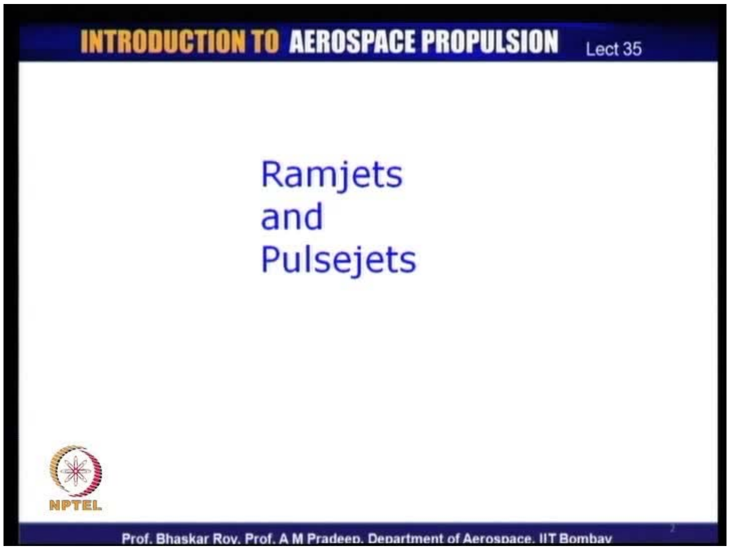
Fundamentals of Ramjets and Pulsejets

You have done a chapter on cycle analysis of jet engines. Today, we will extend that jet engine coverage to working of ramjets and pulsejets, in which the basic cycle understanding that you have acquired for jet engines would be useful. We will also look at the cycles of ramjets and pulsejets which are similar to the cycles that you have done; so, that would be quite easy for you to extend your understanding.

The ramjets and pulsejets actually historically precede those of the turbojet engines. They had actually been used for flying aircraft during the World War 2 and as a result of it understanding of how ramjets and pulsejets actually work, had been created quite some time back. However, the advent of turbojets and various kinds of turbofans actually put the ramjets and pulsejets in some kind of a backburner. Over the years, people realized that they have their utilities, especially the ramjets and the modern version of ramjets known as scramjets, which are used for high speed aircraft typically supersonic or even hypersonic aircraft, where actually you cannot use the turbojets. The turbojets: they have their utility value from subsonic to supersonic up to maybe, about Mach 3 and then beyond that you need different kind of engines or thrusters to create thrust for aircraft or flying vehicles flying at those kind of Mach numbers.

So, the ramjets and scramjets have been revived and various versions of them are now under development in various countries all over the world and some of these fundamental issues of these ramjets and a look at what is a scramjet and a look at what is a pulsejet, we will be doing in today’s class.

(Refer Slide Time: 02:58)

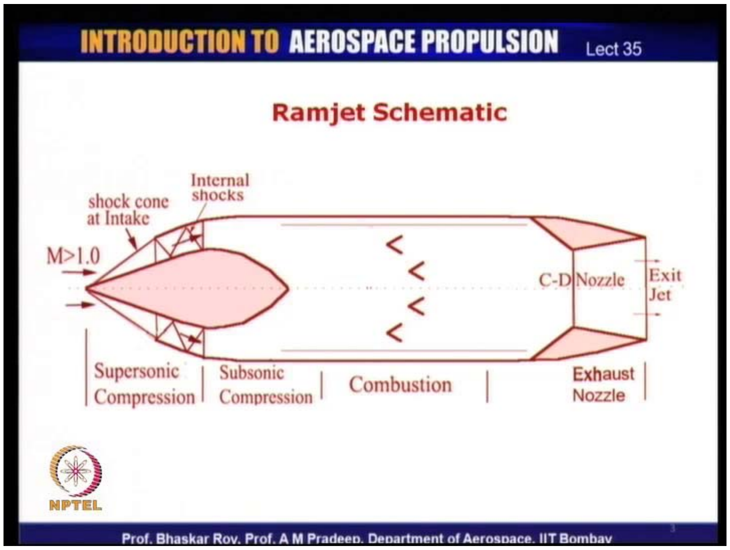


Now, ramjets and pulsejets are very simple devices really. They actually involve jet engine without compressor and turbines. However, if you have done the cycles of jet engines, you would know that there is a process of compression, there is a process of expansion, which is often done through turbine and in the turbo jet engines, the turbines exist essentially for running the compressor.

So, if you do not have a compressor, you do not need a turbine. If you can get rid of the turbine and the compressor, you have a very simple engine configuration, a very simple jet engine and that is exactly what a ramjet actually is. So, ramjet is a jet engine without compressor turbine, there are no shafts, no rotating parts. As a result, it is a very simple jet engine device for making thrust and have been used as I said, for flying aircraft earlier and now they are flying aircraft, missiles and other vehicles. Because of the simplicity of the ramjet configuration, various versions of the ramjet have actually now been conceived. Some of them are still being developed, some of them are still on design board, some of them are being considered along with, you know, various other kinds of engines including turbojet engines and as a result of which, ramjets and scramjets, various versions of them are now under development and a few of them under usage in various aircraft and other flying vehicles.

Let us take a look at what these ramjets are and how do they function.

(Refer Slide Time: 04:51)



If you look at the ramjet schematic, you would see that there is a flow coming from the intake side, which is at Mach number normally greater than 1, quite often the modern usage is Mach number would be pretty close to 5 or even higher. Some of the ramjets or scramjets being used would be at flying Mach order of the order of 8, 9 or 10.

Now, if you have that kind of a Mach number at the entry or the flight Mach number, the flow at the entry is of that Mach number, you require a kind of intake configuration that has a capability to handle shocks because the moment you put a solid body in a high flight Mach number, it is going to create shocks.

So, you need to create situation over here, whereby the shocks are generated and it is necessary that they are designed shocks. So, these shocks are actually designed to operate or be positioned in the intake system of the ramjets and the flow comes in through these shocks and they get supersonically decelerated or diffused or compressed.

First, what we have is supersonic compression through the intake system through a series of shocks. All of these are actually to begin with oblique shocks, ending finally, with a normal shock, at the end of which the flow actually does become subsonic and then you have subsonic diffusion through a normal diffusion process.

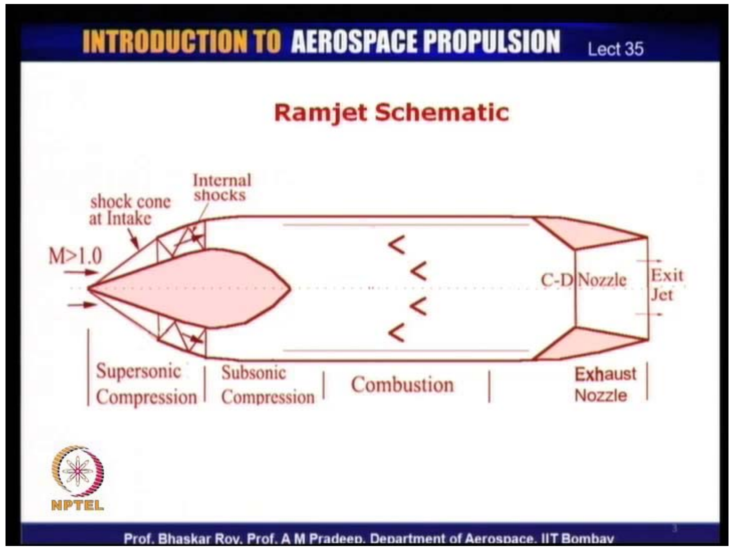
So, you have a supersonic compression followed by a subsonic diffusion or subsonic compression and then a vastly decelerated flow and huge amount of kinetic energy with which it is coming in, is now converted to pressure and this high static pressure air is now fed into the combustion zone.

Now, there is no compressor. So, the entire compression is done by the supersonic and subsonic compression. After this aerodynamic compression process, the flow is delivered onto the combustion zone. What you see here are the flame holders and then you have a normal combustion phenomenon at low subsonic speeds. You require low subsonic speeds to have a good efficient combustion and once the combustion process is over, the flow is allowed to mix up. So, we have a uniform flow profile of temperature, pressure etcetera and energy level and then that is allowed to be delivered or fed in to the nozzle which is quite often convergent divergent nozzle and then this convergent divergent nozzle then exhausts the high temperature gas into the atmosphere back again, thereby creating an exit jet.

So, our intention of this jet engine is to create an exit jet of a higher velocity than what it came in with and as a result of which there is an overall momentum increase across the jet engine for the amount of mass that has come in, with a little bit of fuel addition and this change in momentum created by the jet engine creates the thrust. This thrust would then enable the aircraft to fly. So, the whole engine essentially is there to create a momentum change across the jet engine, thereby creating a forward thrust.

As you see, we have simple elements over here. We have an intake which has to be properly designed to handle the shocks and keep the shock losses to the minimum and then we have flame holders, where you have the combustion. We need a very good efficient combustion and what you see here is the annular combustion chamber and then normally, you would have a C-D nozzle. One of the reasons is the huge kinetic energy which has been converted to pressure, as I mentioned the Mach number quite often here is of the order of 4 or 5 and as a result of which the pressure generated here is of a very high order and hence, it is quite suitable for use for C-D nozzle.

(Refer Slide Time: 04:51)



C-D nozzle is used normally when ideally pressure ratio available that is, total to static pressure ratio available is of the order of at least 2. So, normally you would use it only when the pressure ratio is of the order of 4 or 5 and that is the kind of pressure, which is normally generated and as a result of which, this C-D nozzle now creates a supersonic exhaust jet.

This exhaust jet then has a velocity which is higher. One of the reasons is, we have added energy, we have burnt fuel and added energy to the air and this air, now has extra energy with which it can go out with a high velocity and then this high velocity creates the overall momentum enhancement or increase, that creates the thrust.

So, you see this is a very simple device which can create thrust without needing any compressor or turbine. However, you do see that you have a compression process, you have a combustion process and you have an expansion processes through the C-D nozzle. The thermodynamic processes that you have done in the earlier lectures are still there and hence, we see that it still follows the so called Joule Brayton cycle. So, this is how a ramjet normally would be operative during its operation.

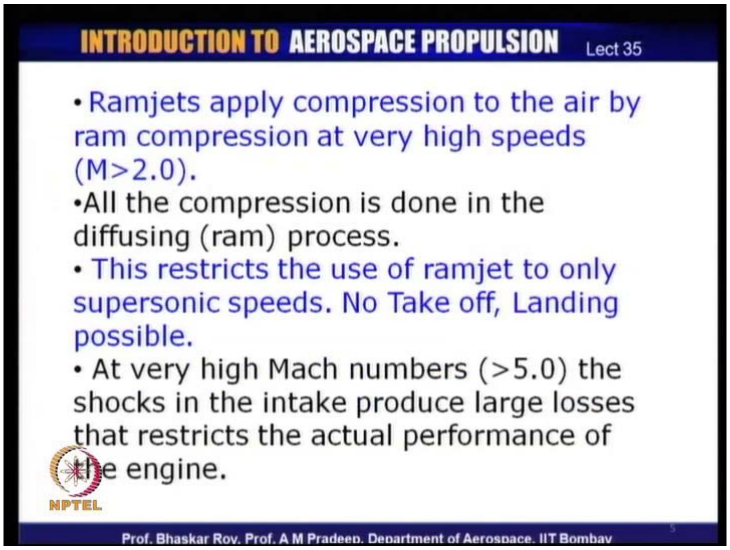
(Refer Slide Time: 11:17)

If we look at what are the key features of a typical ramjet engine, firstly, it produces power by increasing the momentum of the working fluid, which in our case is the atmospheric air that is available.

Now, in contrast to the air breathing engines that we have worked with before, the working cycle is performing without any compressor or turbine and it also does not need an enclosed combustion, which is often used in turbojet or turbofan engines where the combustion is isolated for very high efficiency.

However, in ramjet engines such enclosed combustion is dispensed with and you have a overall annular combustion chamber with flame holders distributed all over the combustion zone and hence, as a result of this, the ramjet is mechanically one of the least complicated jet engines for thrust production and this is very useful for flying vehicles.

(Refer Slide Time: 12:25)

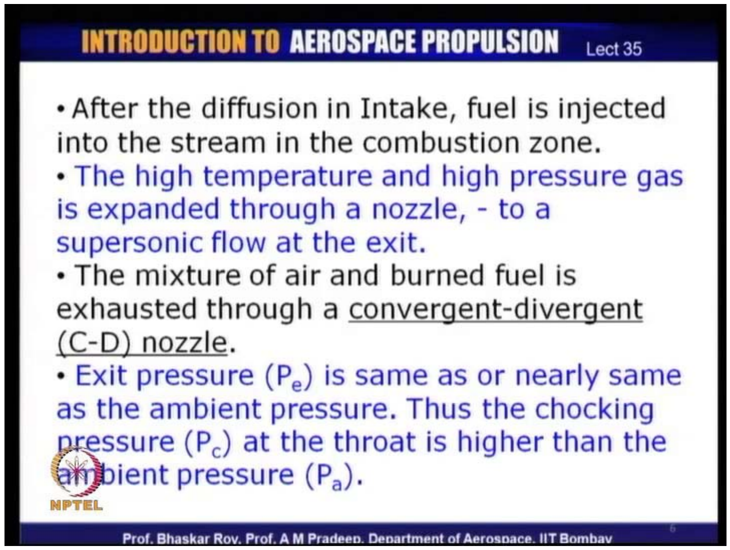


Now, ramjet can apply compression to the air by ram compression and as we have seen, the compression it does is aerodynamic compression or simply called ram compression; part of it is supersonic, part of it is subsonic and this has one issue. Since the compression is dependent on the ram compression or aerodynamic compression, it is entirely dependent on the entry Mach number. Now, Mach number above 2 creates reasonable amount of ram compression, but as the entry Mach number starts going down, the amount of compression that would be available aerodynamically becomes less and less and less. As a result of which, a ramjet is actually very useful in supersonic speeds, but at very low speeds and especially during takeoff and landing, it actually cannot deliver much of compression and if it cannot deliver compression, it cannot really effectively work as a good jet engine.

So, ramjet's utility is restricted to supersonic speeds. It cannot really be used for takeoff and landing of an aircraft. Now, this is one of the problems of ramjet and we shall see that because of this, the ramjet usage is somewhat restricted.

At very high Mach number, as we have seen, the shocks of the intake are present and these shocks produce a large amount of losses. These are aerodynamic losses which manifest themselves in the form of pressure losses. Now, these pressure losses finally, tell on the ramjet performance.

(Refer Slide Time: 14:18)

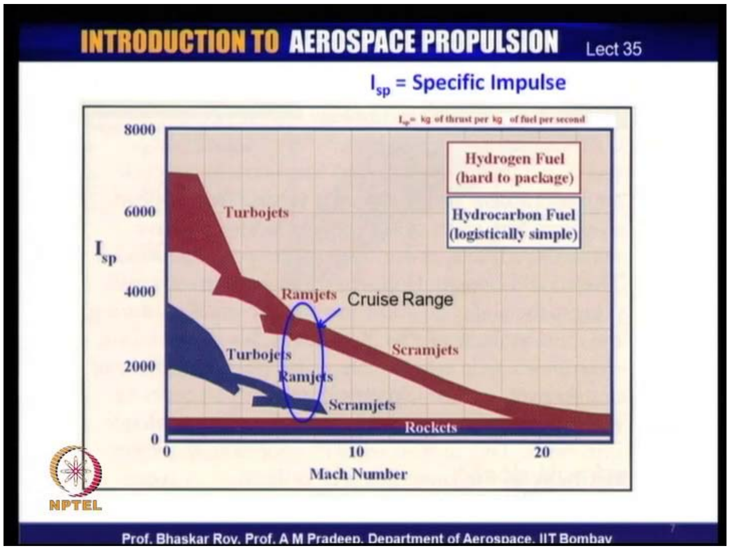


Some of these are the features. The fuel that is injected into the stream is after the diffusion of the flow through the intake system through supersonic and subsonic compression and once the air has been sufficiently compressed and sufficiently diffused to low velocity, the fuel is injected. As a result of which, we get a high temperature, high pressure gas available from the combustion chamber and this gas is what is then released through the nozzle.

Now, this nozzle is normally then a convergent divergent nozzle. You can have only a convergent nozzle with the flow going sonic at the exit phase, which would be the throat; that is possible, but that will have a very little utility value. The real utility value is of nozzle which are indeed convergent, divergent and would normally be used for most of the ramjet application that we know of today.

It is assumed to begin with, that the exit pressure P e is pretty close to, if not exactly the same as the ambient pressure and as a result of which, the flow which goes choking at the throat has to be higher than the ambient pressure. So, P c, the choking pressure at the throat is always higher than the ambient pressure which is at the exit, pretty close to the exit pressure P e.

(Refer Slide Time: 15:56)



So, let us take a look at how the ramjet is, compared with the other jet engines. As you can see here, the graph has been plotted with reference to the Mach number and specific impulse, which is actually thrust per unit weight of flow. Normally, in most of the rockets and other flying vehicles at high altitudes and space, the specific thrust is often designated as specific impulse; that is thrust per unit weight of flow of fuel and whatever other oxidizer are there. Now, in case ramjets and turbojets, the other oxidizer is only air; so, the I sp would be designated accordingly.

Now, what we see here is a comparison between turbojets, ramjets and scramjets. The blue ones over here are ones using the normal hydrocarbon fuels - the air turbine fuels that we know of. These create the I sp configuration; as we see, they are reasonably good I sp configurations at very low Mach numbers.

Now, as the Mach number starts going up, typically the turbojets at Mach numbers about 2.5 or 3, turbojets become less and less competitive and ramjets become more and more competitive and then, upto a Mach number about 7 or 8, ramjets are very good and then from there onwards, you have the scramjets, which actually are the better fuel efficient engines.

Typically, if you have a cruise which is going on say around Mach 8. At this range, you have a choice between ramjets and scramjets and typically, turbojets are out of contention. As a result of which, many of the vehicles that are being planned for various applications today including space travel are built around ramjets and scramjets. Rockets come in to use for even higher Mach number and they have a much lower I sp, but as you can see at very high Mach numbers where the rockets fly to space, rockets actually are the more useful vehicles. At very high Mach numbers above 10, the vehicles using ramjets, scramjets are still being designed; we still do not have them flying as yet.

So, we have flying vehicles which are around Mach 8. Some of them are for military applications and a few of them are being thought out for various kinds of space travels and other kinds of applications.

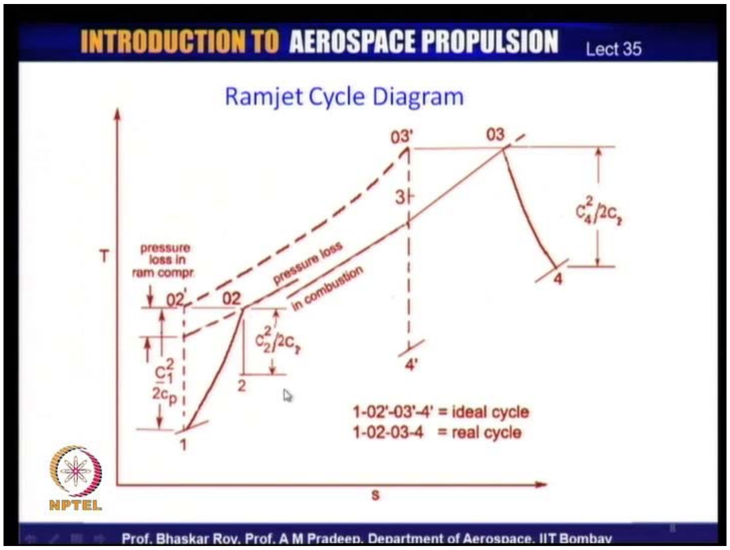
The other thing which you see in the diagram is that it shows 2 kinds of fuel. One is the hydrocarbon fuel which is in blue, the red one is actually hydrogen fuel, where hydrogen is used as fuel and oxygen is either taken from air. In case of rockets, both hydrogen and oxygen would be actually carried by the rocket body in terms of liquid hydrogen and liquid oxygen.

However, in case of ramjets and futuristically in terms of other jet engines, if we use hydrogen fuel you can see, for example, the value of I sp would be of a much higher order than the hydrocarbon fuels. So, if you use hydrogen as fuel, you do get higher I sp of all the jet engines turbojets, ramjets and scramjets going all the way to rockets at very high Mach numbers.

The problem with hydrogen fuel is It is being used already in rockets as I said. However, the problem is essentially is that it is a lighter fuel and as a result of which, you need more space to carry it with you on any aircraft. So, the space required will be more than a normal hydrocarbon fuel, even though hydrogen actually gives a higher I sp and it is also a much cleaner fuel in terms of environmental and pollution effects. However, that is in future and it is possible in future more and more jet engines would actually be flying with hydrogen as fuel. At the moment, most of them are still flying with hydrocarbon fuels or fossil fuels as we know them.

Now, we shall look at the ramjet cycle. Now, cycle you have done. You have done the various kinds of jet engine cycles, you have done the Brayton cycle or the Joule-Brayton cycle, as it is known and you know that it operates on constant pressure combustion phenomenon. Now that cycle concept, that you have already gathered would be now extended to analyzing the ramjet applications and we shall see that the cycle that you have been familiar with now, work more or less the same way.

(Refer Slide Time: 21:42)



If we look at the ramjet cycle, you see that we again have an open cycle. So, the return path from 4 to 1 is open and the ideal cycle is the dotted cycle, which you know operates from 1 to 02 prime and then from 02 prime to 03 prime and then down to 4 prime. Now, that gives you the ideal ramjet cycle, which is what I believe you have already done in some detail and you know how to calculate a Brayton cycle performance. You could actually use the same cycle knowledge to analyze the ramjet cycle also.

The real cycle of a ramjet is slightly different. The path from 1 to 2 is not isentropic; so, it does not go up straight. It goes up with a slight increase in entropy. So, there is a certain amount of efficiency that comes into the picture, which we shall normally be calling isentropic efficiency of the compression process. Then in the combustion process, there is likely to be certain amount of pressure loss most of which is a fluid mechanic pressure loss. That pressure loss needs to be accounted between 02 and 03. So, the 02 and 03 are on two different pressure lines. Ideally, as we know, from 02 prime to 03 prime, it is supposed to be constant pressure combustion.

However, actual combustion is not exactly constant pressure, there is a small amount of pressure loss which is mainly fluid mechanic pressure loss and the combustion efficiency is typically of a very high order in constant pressure combustion. So, we will continue to treat it as more or less constant pressure combustion.

Then you have the expansion process. There is no turbine. So, you have fully expansion in the nozzle and this expansion process is again not isentropic, unlike from 03 to 4. It is non-isentropic process or a polytrophic process and as a result, there is a slight increase in the entropy. So, there is a total increase in entropy from one end to the other and as a result of which, the whole cycle will have certain efficiency which again you are familiar with.

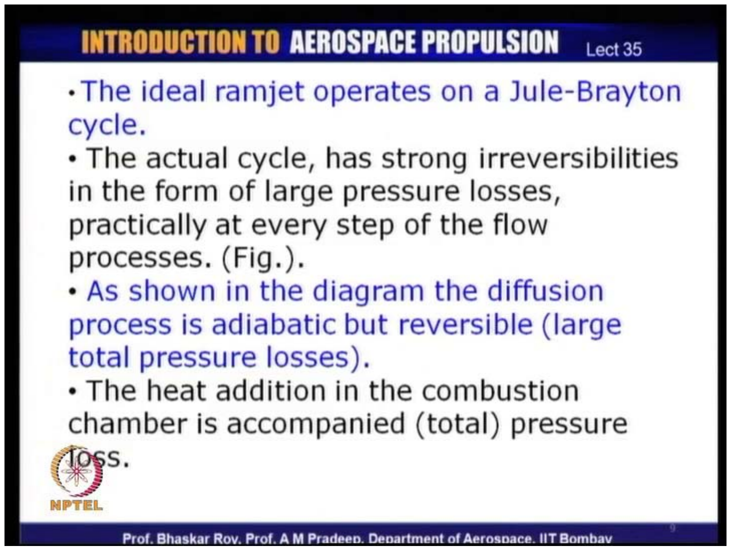
Now, at the entry to the jet engine, you have certain amount of kinetic energy which is shown over here. Now, this kinetic energy is what the flow is coming in with due to the flight and this is the kinetic energy which gets converted to pressure. At the phase of the combustion chamber, it has a much smaller kinetic energy.

So, the idea of diffusion is to create compression and bring down the kinetic energy from very high values to somewhat low values, which are friendly or convenient for combustion purpose. As you might be knowing, combustion at very high speeds is a big problem. It is something which needs to be taken care of separately. So, normal combustion is done. In constant pressure, flowing fluid combustion in jet engines is normally done at somewhat low subsonic speeds. So, we got to bring the flow down to that low subsonic speed and from there, the combustion takes place. (Refer Slide Time: 25:13) It takes the whole air fuel mixture to very high temperature from T 02 to T 03 along this constant pressure line.

So, now we have high pressure and high temperature and the gas is then released from that 03 position through the nozzle and when it comes out, it comes out with a jet of the velocity of the order of C 4 and this has to be higher than the velocity with which it came in. So, typically C 4 needs to be higher than C 1 with which it came in; only then, you get a positive thrust.

The idea of this jet engine is to create a value of C 4 exit kinetic energy, which is definitely higher than the inlet kinetic energy and then you have a good chance; you are assured of a positive thrust. This is how, the cycle of a ramjet engine of which you just had the look at the schematic and the cycle, operates along this Joule Brayton cycle, which you are familiar with.

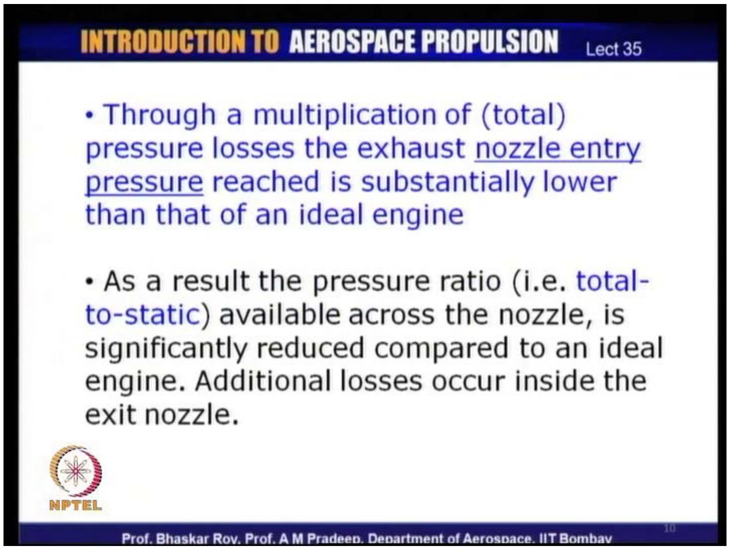
(Refer Slide Time: 26:28)



Now, let us look at how this cycle can be converted to our understanding of how the ramjet actually performs. One of the things is it operates on Joule Brayton cycle; the next thing is that each of the legs of the thermodynamic cycle has certain irreversibilities. Thermodynamically, you have learnt what the reversible and irreversible processes are and in this actual cycle or a real cycle, the legs are actually irreversible and as a result of which, there are certain pressure losses which are accompanied by each of these processes - that is, compression, combustion and expansion and as a result of which, large amount of pressure loss actually takes place.

As shown in the diagram, the diffusion process is adiabatic, but irreversible and as a result, large amount of total pressure losses take place. The heat addition in the combustion chamber is accompanied by again pressure loss. So, you have pressure loss at every step of the jet engine operation.

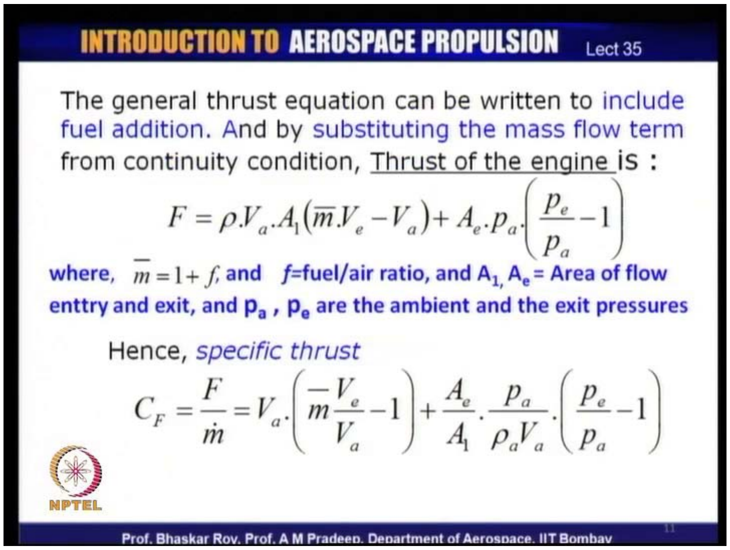
(Refer Slide Time: 27:44)



All these pressure losses when they are put together, you have a situation that the pressure that is available at the entry to the nozzle is somewhat less than the ideal pressure, which one would expect in an ideal engine. Hence, the flow through the nozzle would be somewhat less than the ideal engine flow and the velocity that you would get at the exhaust would be less than the ideal velocity and this is what a real cycle analysis would actually show that the exit velocity would be somewhat less than the ideal. If one is not careful in the design, the exhaust velocity could be substantially lower than the ideal engine, in which case you have to first ensure that you have a ramjet engine that is providing you with positive thrust because it is entirely possible that during certain operating point, the ramjet engine may not produce positive thrust; it may start producing negative thrust because the losses inside the engine could be very high and the exhaust nozzle is not able to produce sufficient momentum enhancement through the nozzle and then the engine would fail to produce positive thrust.

So, this is something which needs to be very carefully estimated before the ramjet engine design is finalized. Of course, certain amount of additional losses do occur inside the exit nozzle which has supersonic flow and as a result of which, certain amount of losses through supersonic fans and shocks can also take place in addition to the friction losses through the surface of the nozzles.

(Refer Slide Time: 29:43)



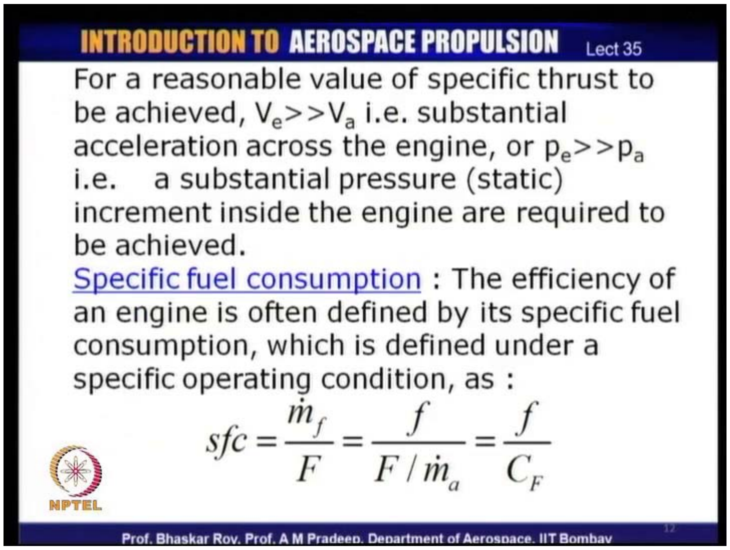
Now, if we write down some of the understanding that we have gathered about how the ramjet engine actually performs, we can write down the thrust of the engine which we say as F, which is the thrust force in terms of rho V A into A 1 which is the mass flow which is coming through the intake of the engine. So, that essentially is the mass flow and then m bar which we are defining here and into V e minus V a and this is the momentum thrust. So, this whole first term is the momentum thrust and then you have the pressure thrust, which is A e into p a and that into p e by p a minus 1

So we have to ensure that p e by p a is either 1 or more than 1; if this is less than 1, this second term is going to give you negative contribution and we certainly do not want that. So, p e needs to be at least equal to 1 or more than 1. As we know, if p e is exactly equal to p a, this component becomes 0, but V e is maximized; so, maximum V e is actually when p e is equal to p a and hence you get maximum V e and then you get maximum momentum thrust and indeed, that is the maximum thrust that this engine can generate when actually p e is equal to p a. So, zero pressure thrust does actually mean maximum momentum thrust and indeed maximum thrust of the engine.

Now, just to define m bar over here; it is nothing, but 1 plus f - small f and small f is nothing, but fuel to air ratio. So, this gives you a slight correction that you need to do to the mass flow for the fuel addition into the combustion chamber. The areas are designated here: A 1 is the entry area; that is, mass flow is coming through the intake, A e is the area at the exit phase of the nozzle and correspondingly, p a and p e are the ambient and the exit pressures of the jet engine. So, that gives you the thrust that may be created by the jet engine and one can easily calculate if these parameters are made available for thrust estimation.

The specific thrust which is normally a figure of merit for many of the jet engines is shown here in terms of C F which is nothing, but F by m dot, m dot is the mass flow that we have shown here and this is now designated in terms of V a into m dot into V e by V a that is, the velocity ratio across the jet engine. So, V e by V a is nothing, but the velocity ratio or the velocity enhancement through the jet engine minus 1. (Refer Slide Time: 32:51) This is the area ratio between the intake and the exhaust, this is p a by rho a V a, entirely from the atmospheric conditions and the p e to p a, the exit pressure ratio that may be available which in ideal phase, we know this could go to 1 and hence, the second term could entirely go to 0. So, that is your specific thrust that you may like to calculate from the data that could be available for simple analysis of ramjet engine.

(Refer Slide Time: 33:26)



What we see now from these equations which have been derived from fundamental principles that the reasonable positive specific thrust to be achieved V e needs to be somewhat higher than V a.

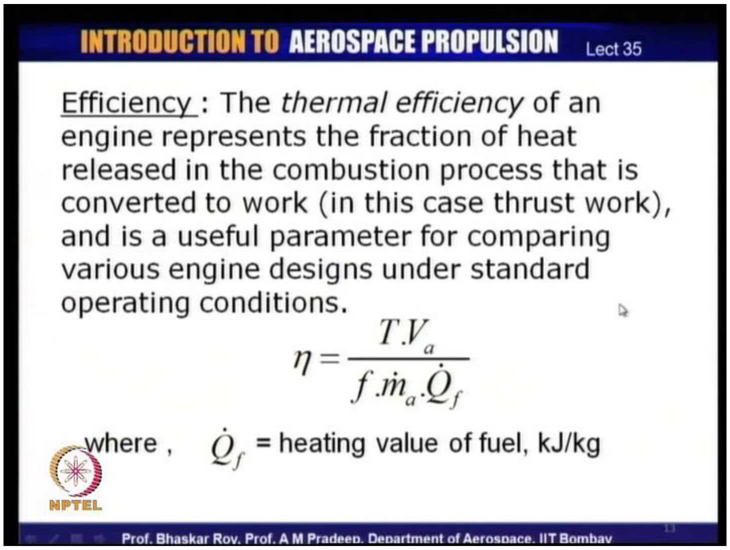
(Refer Slide Time: 33:42) Now, this is what you know the operative velocity ratio is. This can go to 1 and this could go to zero and frankly, we probably would not bother much about it, but this needs to be more than 1 and this needs to be as much more than 1 as possible so that you get substantial specific thrust and as you can see, if this is 1, the thrust generated will be 0; if this is less than 1, thrust generated will be negative.

So, it is necessary that you have a substantial acceleration or velocity change through the jet engine to give you a reasonable amount of thrust. The other possibility is, if p e is more than p a, but as we know if p e is indeed more than p a, your momentum thrust is going to come down. So, you have to keep an eye on both the values. The best bet of course, is always that V e is substantially more than V a to give you more of momentum thrust.

Now, we can look at the other normal figure of merit used for all jet engines and that is the specific fuel consumption. Typically, most of the engines You have already learnt how to calculate thermal efficiency of an engine. However, most of the engines are designated or defined by their specific fuel consumption and the efficiency is often used as a figure of merit for the goodness or the badness of the particular engine. So, sfc is what we normally use as the engine efficiency figure of merit.

This is defined here as before, in terms of m dot f, which is your fuel consumption divided by the thrust that is created and this comes out in terms of small f by C F which is the specific thrust and this is the fuel air ratio. So, if the fuel air ratio of a particular operating point is known and the specific thrust can be calculated, we can get the value of sfc and that stands as a figure of merit for the efficiency of the engine at that particular operating condition.

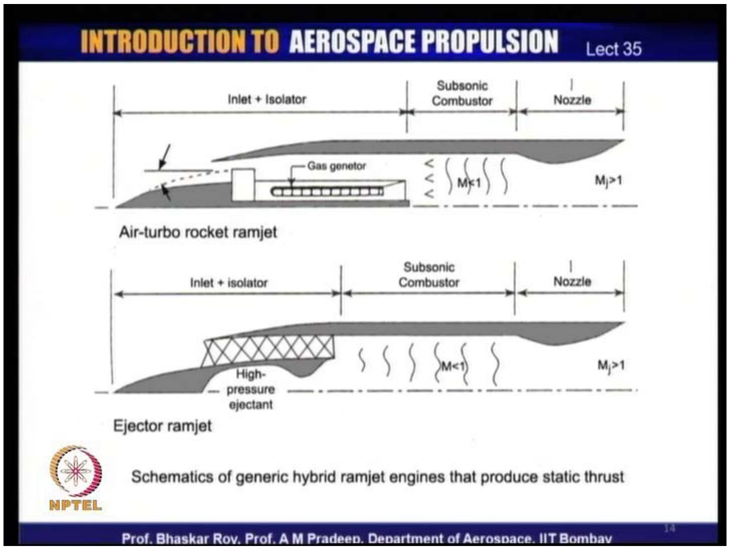
(Refer Slide Time: 36:05)



The efficiency of the engine also can be calculated as per basic definition of efficiency which is normally the thrust work that is created by the jet engine, divided by the fuel energy that has been put inside the combustion chamber in terms of basic fuel energy or heat energy.

Q f is the heating value of the fuel in terms of kilojoules per kg and this is what gives you finally, the thermal efficiency of the ramjet engine. So, you can calculate thermal efficiency of a ramjet engine to designate thermodynamically, what its efficiency value is.

(Refer Slide Time: 36:57)



Having looked at a basic ramjet engine, we can take a look at some of the modern developments of ramjet engine. Many of these ramjet engines are now being developed in terms of very high supersonic flight applications and in those situations, as you can see, you are likely to have a very long intake. So, you have an intake section and then, you have a long what is often known as an isolator - that means, here you can see it goes through a huge number of shocks or what is often known as shock trains.

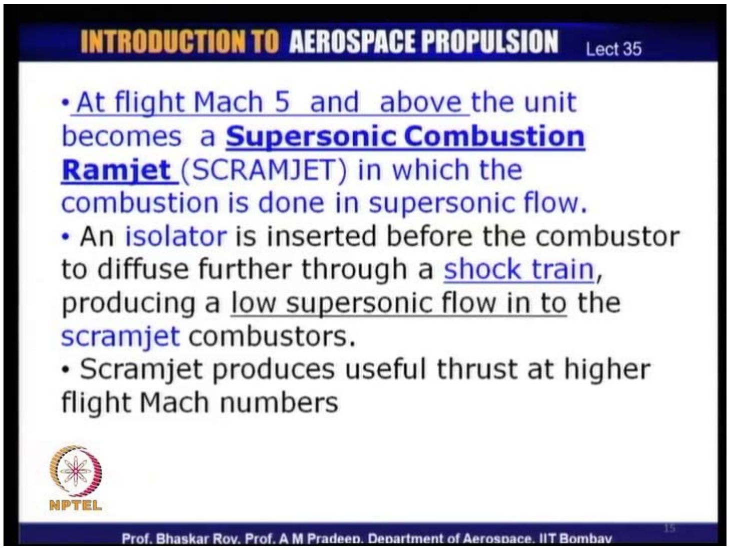
So, these shocks obviously diffuse the flow supersonically, hugely, but they are also loss making propositions. By the time the flow comes out through these shock trains and gets delivered into the combustion chamber quite often, and the combustion chamber, as we see is indeed a subsonic combustor, the flow would have lost substantial amount of pressure having come through all these shocks. As a result of that, as we have just seen the definition of thrust and sfc and specific thrust, there will be some problem in terms of getting a good positive thrust out of this jet engine.

So, some of the designs that people are now developing involve - one for example, using some kind of a gas generated inside, which could be a rocket or which could indeed be an embedded turbojet engine, which operates only when it is required; otherwise, it can be switched off or it can be a rocket which is embedded inside which gives another jet out from here and that mixes with the combustion chamber of the ramjet and two of them together, create the high pressure, high energy gas, which then goes out through a nozzle. So, the combination can then go out through the nozzle to create a supersonic jet.

The other option is to have a high pressure tank over here, which has its own nozzle, and from this tank, you can eject high pressure gas and this high pressure gas coming out through this nozzle mixes with the combustor gas of the ramjet and the combination then goes out through the ramjet nozzle, again creating supersonic jet.

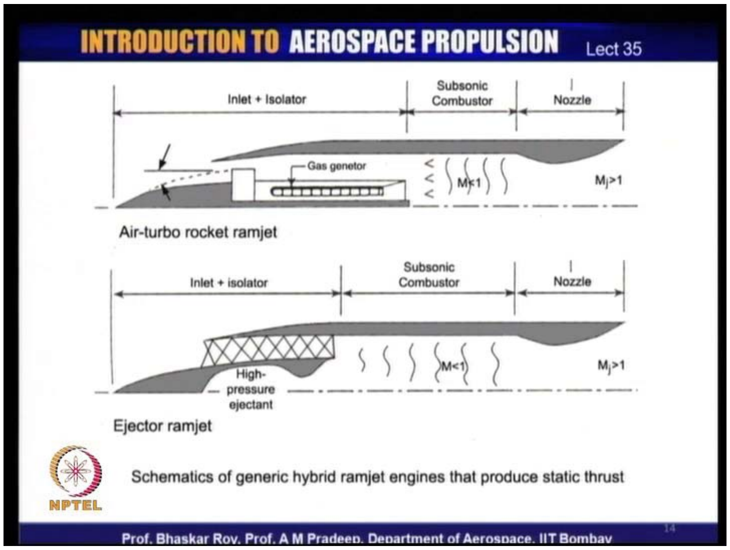
So, many of these possibilities are now being developed and are on the design board. One of the reasons is because, we just discussed that coming through these various shocks, the ramjet would be depleted of its energy and it may not be a very good jet engine device all on its own. Hence, a certain amount of help may be embedded within the jet engine configuration to provide additional energy, which then can be harnessed to create more thrust during flying at very high supersonic speeds.

(Refer Slide Time: 40:30)



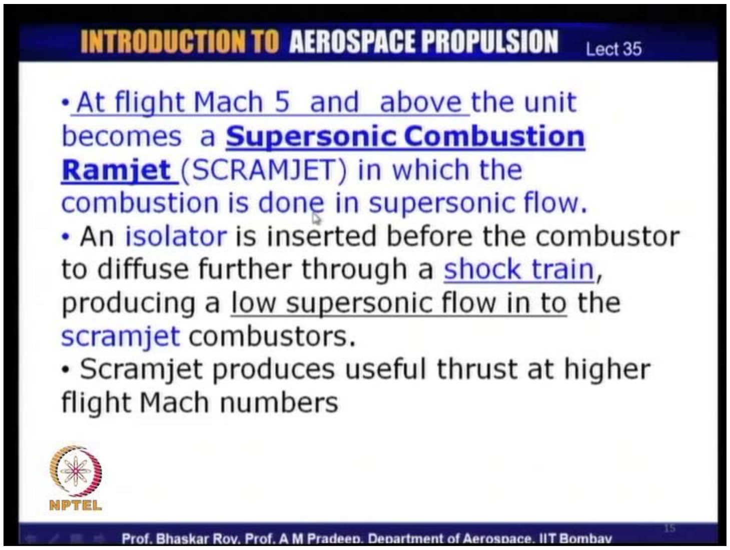
At Mach 5 and above, the normal ramjet cannot diffuse the flow any further to subsonic values for combustion purpose. As we were just discussing that, if you have intake for high supersonic flights, those intakes are full of shocks and as we have just seen, they are full of shock trains. So, the flow is coming through a large number of shocks - maybe 8, 10, 15 shocks, which are inside the intake system which includes an isolator.

(Refer Slide Time: 41:17)



Let us go back just for a minute. This isolator actually is a part of the ramjet and it is called isolator because it is a supersonic isolator, which allows a long train of shocks before the flow is delivered into the combustion chamber. It also isolates the combustion chamber from the intake ambient pressure or temperature changes, which happens with the change of altitude. So, this is often called an isolator because it houses a long train of shocks.

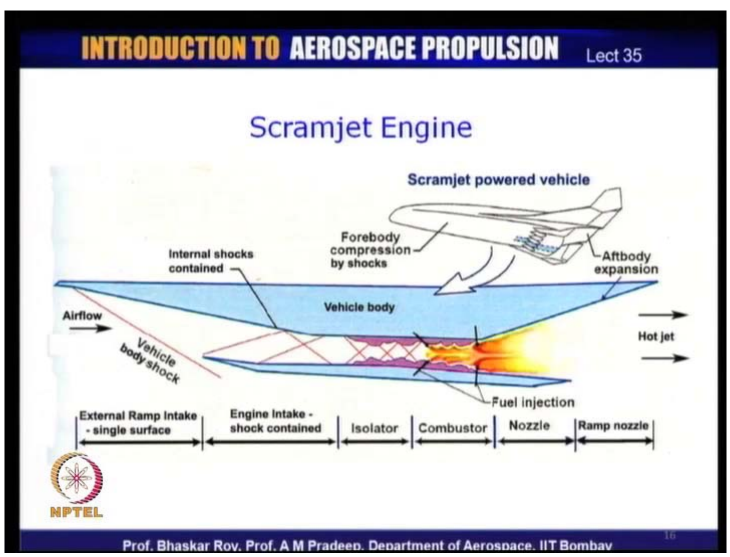
(Refer Slide Time: 41:56)



When you have those train of shocks and if you keep on diffusing, you keep on losing energy, losing pressure. So, at above Mach 5 Mach number, it is not very profitable to have that kind of shock train finally delivering subsonic flow. What is quite often done now is the flow delivered is still supersonic. So, you do not make it subsonic; you keep it supersonic and deliver supersonic flow into the combustion chamber and hence, the combustion designers have now developed a supersonic combustion phenomenon.

This supersonic combustion is now embedded inside the ramjet engine and hence, it is called a SCRAMJET - Supersonic Combustion Ramjet. This now delivers the jet to the exhaust nozzle, which then creates a supersonic flow. So, the combustion is now done in supersonic flow condition, but somewhat low supersonic flow. So, the flow is brought down from very high supersonic flow above Mach 5 to low supersonic flow near about Mach 1 and this isolator is needed to create the shock train so that a low supersonic flow can be delivered into the scramjet combustor. This is physically, a rather long device, a long duct in which the shock train is housed and the scramjet produces a useful thrust only after you have been able to do all that successfully at very high Mach numbers above 5 and one is using scramjet these days for flights up to about Mach 8.

(Refer Slide Time: 43:51)



We can look at a Scramjet engine and indeed, a Scramjet powered vehicle over here, as you can see, the flow is coming through the intake system and then let us say this part is a vehicle body and this is your jet engine and outside the jet engine itself, you have a vehicle body, which is angled over here and it is often called the external ramp intake.

Now, this intake system then has only one surface. The other surface typically is not existing as a solid body before it enters the ramjet. Once it enters the ramjet, you have the shocks immediately inside the ramjet engine itself.

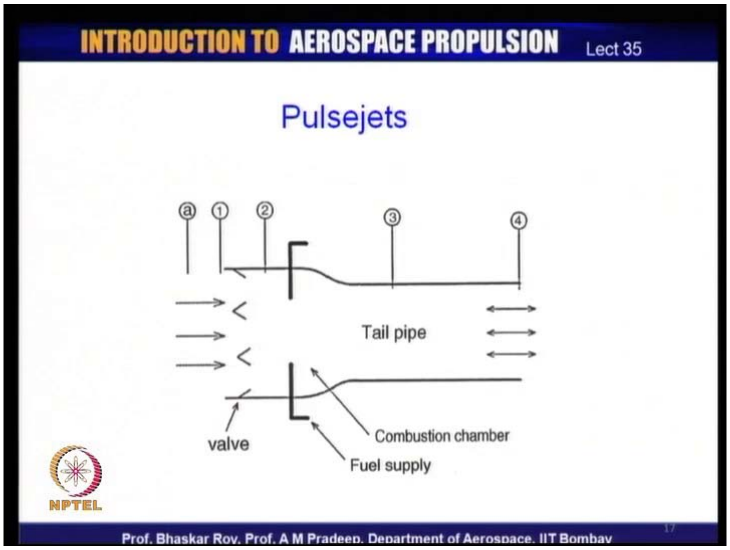
This is normally integrated design of the vehicle and the ramjet. So, the vehicle body and the ramjet are almost designed in an integrated manner and they are housed in one single body; typically, under the belly of the flying vehicle.

So, as the flow comes in, it is high supersonic; it is creating shocks over here and these shocks finally, develop into the shock train and it goes through the isolator, which is what we were talking about and this isolator through a large number of shocks diffuses the flow to low supersonic flow and then this low supersonic flow is delivered into the supersonic combustor. So, this is why it is called scramjet and then the combustion takes place and high pressure gas is then released through the nozzle, which then creates the high velocity jet.

So, this is coming out and again, part of the nozzle has one single surface which is often called ramp nozzle because its ramp is actually part of the vehicle body. So, the flow coming in through a ramp is part of the vehicle body; flow going out also is through the ramp which is part of the vehicle body and the other side of the surface is an open surface.

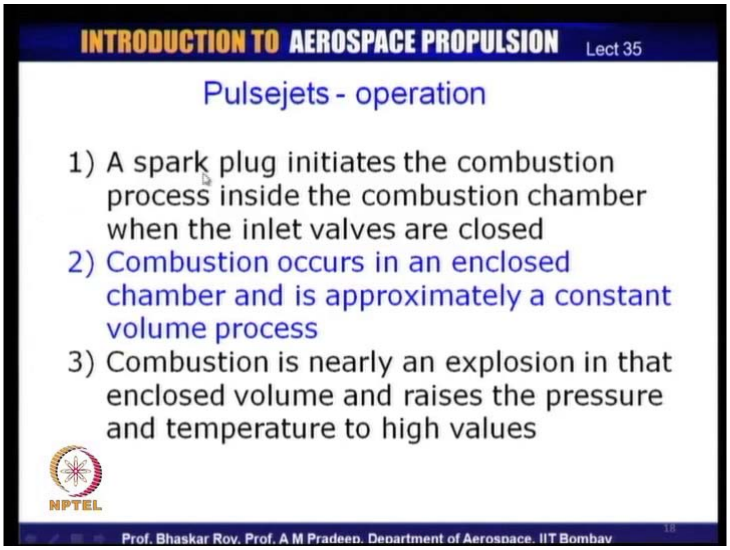
However, we have a nozzle over here which is indeed again, a convergent divergent nozzle and as a result of which you have a supersonic jet that comes out, which is a hot jet and this jet has a velocity, which is higher than the entry velocity. So, this is how a scramjet engine typically operates and gives a thrust during high supersonic flights

(Refer Slide Time: 46:40)



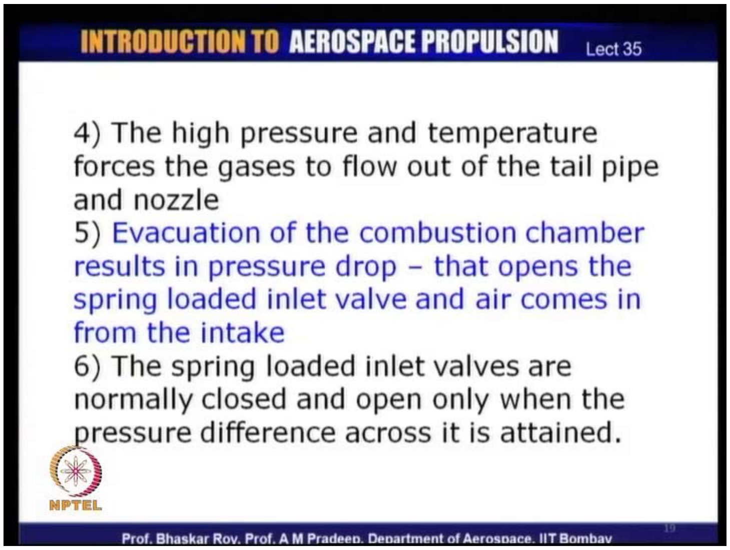
Now, let us look at what is known as pulsejets. Pulsejets are very simple devices and they have been flown long back, even during World War 2. Now, pulsejet actually operates under very simple principle that the flow which comes in, comes in through valves. Now, inside the combustion chamber when the combustion is initiated, the flow goes to high temperature and pressure and the flow is evacuated through a nozzle, which could be a convergent or a convergent divergent nozzle. As it is evacuated, these valves are forced open and the flow comes in. So, let us quickly understand how it operates.

(Refer Slide Time: 47:22)



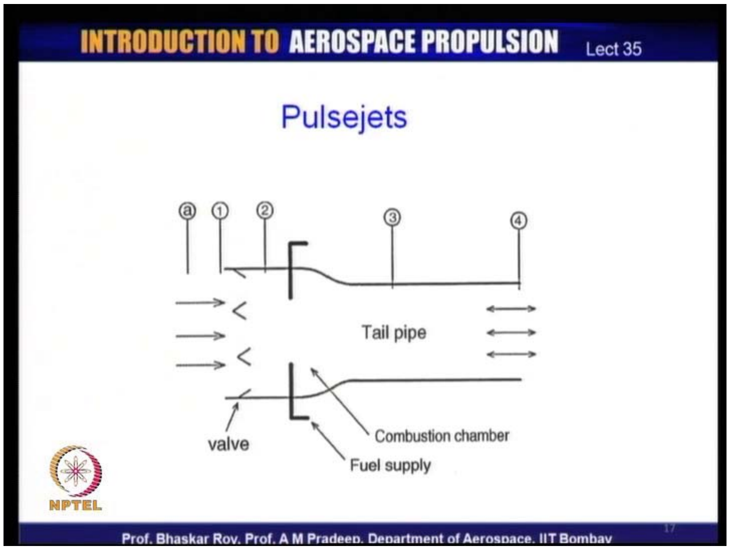
Initially, a spark plug initiates the combustion process inside the combustion chamber and when the inlet valves are actually kept closed; so, the default valve position is closed. Then the combustion takes place, which raises the temperature and pressure to very high values because now the combustion is taking place in an enclosed volume and it is close to what can be called constant volume combustion. So, you have very fast combustion very close to that of an explosion and very fast rise in temperature and pressure; so, it rises to very high pressure.

(Refer Slide Time: 48:04)



This high pressure and temperature gas is forced through the nozzle and it creates a very high velocity jet. Now, this creates the pressure drop inside the combustion chamber and as a result of this drop in pressure inside the combustion chamber, the spring loaded inlet valves are opened and then the air comes in through the intakes, through these valves which are often the reed valves and the spring loaded valves are then closed again as soon as the combustion chamber is full. As I said, the default position is closed and it can open only when a certain pressure differential actually exists across the valve. So, as soon as the combustion chamber is full, the valves are closed and as a result of which, you have operation.

(Refer Slide Time: 49:03)

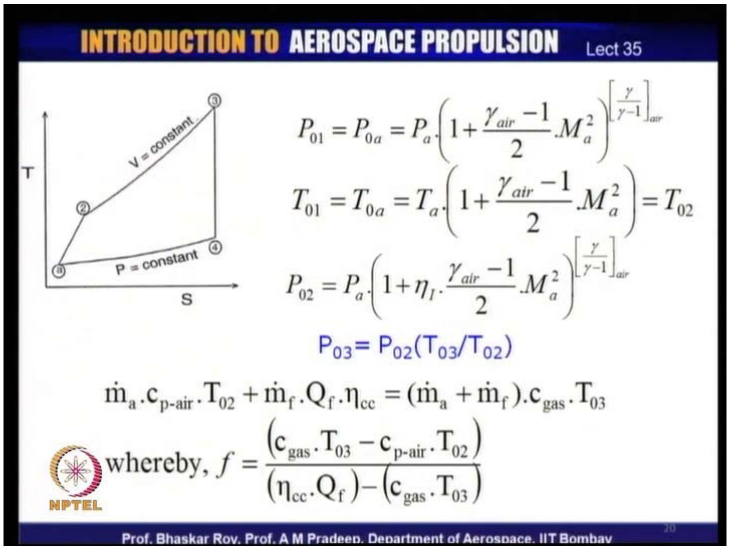


Let us go back quickly to the pulsejet schematic. So, the flow comes in through the intake only when the valves are open; otherwise, they cannot come in. Then the combustion is initiated and takes place in the combustion chamber and the flow is then forced out of the entire jet engine at high velocity through this jet pipe. As a result of which, the thrust is created by Newton's principle or third law of reaction and once it is evacuated, the flow comes in. Now, this thrust creates a motion for the jet engine and the jet engine attached to the flight vehicle, and the vehicle moves. As the vehicle moves, certain amount of air can attempt to come in; it can come in only when the valve is open.

So, this valve opening and closing is a crucial issue in the pulsejet operation and typically, pulsejets operate at around 45 to 50 pulses per second. As you can see, they are very fast pulses and as a result, the thrust creation is indeed quite fast. So, you can create very fast pulses and the jet engine can operate in a pulsating manner to create almost continuous thrust generation.

Now, the combustion is not dependent on the intake ram compression. Pulsejet can be used for takeoff and landing. So, this is a big advantage over ramjet. You can use a pulsejet engine for actually taking off and landing of an aircraft. It has been used in the World War 2 by the Germans for flying their vehicles powered by pulsejet because it does not need ram compression for its combustion and nozzle operation.

(Refer Slide Time: 51:07)



Let us look at the fundamental thermodynamics that you have done, very quickly to the ramjet operation. I have quickly written down here, all the steps that goes through. This is your compression that takes place and then you have constant volume combustion and then it takes it to very high temperature and from where, it is released through the nozzle to create high velocity jet and then, this is your constant pressure return path, which is through the atmosphere.

You have constant volume combustion and a constant pressure return path. So, this is one of the heat engines where you have a dual process of constant volume combustion and constant pressure return path.

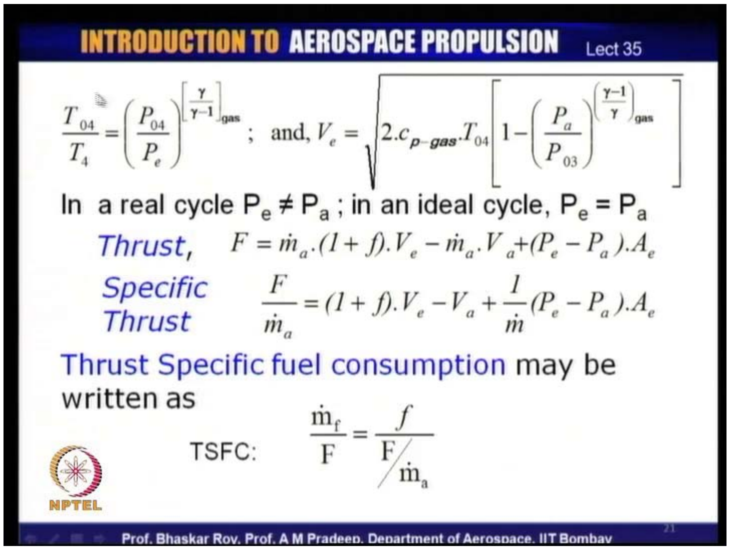
So, the pressure is operational and you can find out from the isentropic laws, the value of the pressure. This is the ideal pressure generation. The real pressure actually uses So, P 02 actually would have an efficiency of the intake process through the valves, embedded into its equation. So, this is the efficiency with which the valve is allowing the flow to come in and then, you have the pressure generation through the combustion process because of the rise in temperature and as a result of which, you get very high pressure and temperature.

So, this is not a constant pressure; this is constant volume combustion and this is from your equation of state. Now, you can write down the work balance or the energy balance.

(Refer Slide Time: 52:39) This is the energy with which the air came in and this is the fuel energy of the burning of the fuel multiplied by the combustion chamber efficiency and this is the energy of the gas with which the gas is now going out.

So, from this energy balance, you can write down the fuel air ratio with the help of the various values of the c p of gas, the temperature of the gas, the c p of air with which it came in and the temperature of the air with which it came in, the heating value of the fuel, the combustion chamber efficiency, the c p of the gas and the temperature of the gas.

(Refer Slide Time: 53:19)



So, all that would give you the fuel air ratio and from which, you can write down the total temperature ratio. The total static temperature ratio which would be equated to the total to static pressure ratio from which you can now, get the velocity of the exhaust jet and that from your isentropic relations, you can write down the velocity of the exhaust jet.

In real cycle, p e is not equal to p a; in ideal cycle they would be equal to each other and Now, again you can write down the thrust equation, more or less the same way that we have written in other jet engines including the ramjet engine which we have done just a few minutes back and the specific thrust exactly the same way. You can write down the specific thrust equation and you can write down the thrust specific fuel consumption, which is as I mentioned, the figure of merit for all jet engines. You can write down all those parameters - the performance parameters, thrust specific, fuel consumption specific thrust and all those things with the help of simple cycle analysis that you have done in your earlier lectures.

So, this is a very simple device - the ramjets and the pulsejets with the help of which, you can create a jet engine, you can create thrust and you can create a vehicle powered by ramjets and scramjets and pulsejets which can actually fly. Now, this is obviously a very simple option that we have. Ramjets and scramjets as we have seen, cannot take off and land, but pulsejets can; they are not dependent on ram compression.

So, we have very simple versions of jet engines without compressors, without turbines. One of them - the pulsejets can take off and land, but obviously they cannot operate at very high supersonic Mach numbers. The ramjets can operate at high supersonic Mach numbers and the scramjets can go to even higher supersonic Mach numbers. So, we have just dealt with certain simple devices, simple jet engines which can operate under various operating conditions creating jet thrust using the jet principle of creation of thrust without the aid of compressors and turbines. These jet engines, all of them actually have been made and flown and they have actually flown the various kinds of aircraft and scramjets are still being developed to fly very high supersonic vehicles in the air, in the atmosphere.

So, we have just gone through a large number of jet engines which give you thrust for flying craft mainly aircraft or missiles or other kinds of crafts through the atmosphere because they use air, as they are all air breathing engines and they are all jet engines.

(Refer Slide Time: 56:30)

Next, we shall be considering a jet engine, which is not an air breathing engine. We shall be talking about rockets and we shall be talking about rocket propulsion and rocket engines. This is what we will be doing in the next class, where we shall open up a chapter on rockets.