Introduction to Aerospace Propulsion
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Module No. # 01
Lecture No. # 36
Fundamentals of Rocket Engines

We have been talking about various jet engines, over the course of many lectures. We have also looked at various thermodynamic aspects, which were covered by Professor Pradeep.

Now, all the jet engines so far we have been looking at and all the other IC engines that we have looked at earlier were all of them, air breathing engines; they were using air available in abundance in the atmosphere, as a primary working medium. The idea in all those engines was to use air and somehow energize the air and get work out of air. So, air was the working medium and as a result of which, all of them were generally clubbed as air breathing engines.

We are going to talk about non-air breathing engines - the engines that do not use air as a working medium, the engines that have to carry its own fuel and in the process, create thrust for flying vehicles.

Now, these non-air breathing engines are rockets, missiles and the various spacecrafts that are being used by various advanced nations for putting craft in space and sending man to moon and even beyond.

These crafts are used for various purposes. Rockets is a generic name for all these kinds of crafts, missiles are used normally for various military purposes and spacecrafts are used for various missions which take man beyond the earth’s atmosphere and then on to moon and to mars and various other missions, even beyond in the galaxy or in future probably out of this galaxy.

So, obviously a large part of the travel of these crafts would have to be outside the earth’s atmosphere. Even some of the missiles that we have, sometimes, travel a part of their journey outside the earth’s atmosphere. As a result of which, it is required that they have engines which do not use air as working medium because obviously, if they are dependent on air, they would not be able to perform beyond the earth's atmosphere.

Some of these fundamental reasons prompted people to develop engines, which could be used to take the craft beyond the earth's atmosphere and these are the rockets and various kinds of missiles, which we will look at and then finally, the spacecrafts.

We will look at some of the engines that have been developed over the years, some of the rockets and various crafts that have been developed over the years and then we will do the basic rocket science that actually makes these rockets work. We would be able to finally look at various kinds of spacecrafts that are being used now-a-days for various kinds of missions.

So, let us take a look some of the rockets that people are using now-a-days for various purposes.

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Rockets,
Missiles,
and
Spacecrafts

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- Chinese used rockets in the 12th century AD against the Mongol attacks.
- In India Tipu Sultan used rockets against the British army in the 18th century.
- The modern rocket scientists, : Contantin Tsiolkovosky of Russia,, Hans Oberth and Fritz Opel of Germany, and Robert Goddard and Werner Von Braun of USA.
- They and many others help develop the fundamental scientific principles of rockets, including multi-stage rockets, for launching satellites and space vehicles.

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Now, the rocket started long back. The history of development of rocket is indeed rather quite old actually and according to the history, rockets were used by the Chinese in twelfth century AD for repelling the Mongol attacks from the north. So, Chinese are normally credited with the inventors of the rockets, as we know today. In India, there is a record that Tipu Sultan used rockets against the British army in eighteenth century AD; that is nearly more than 200 years back.

The modern rocket science have been developed by a number of people in various countries and some of the people who are known as the pioneers are Konstantin Tsiolkovsky of Russia, Hans Oberth and Fritz Opel of Germany, Robert Goddard and Werner Von Braun of USA; Werner Von Braun of course, is from Germany and he switched to US after the World War and continued to contribute to the development of rocket science and engineering in US; he is credited with the development of Saturn rockets.

So, many of these people put together developed, what we call rocket science today including the multistage rockets. Now, multistage rockets - the credit for developing that was actually being given to Konstantin Tsiolkovsky of Russia. He developed the basic science based on which today's spacecrafts are being launched from all over the world. So, he is credited with the person who first conceived the idea of multistage rockets which can be used to take the rocket vehicles beyond not only earth’s surface, beyond earth’s gravitational field and to various other places not only moon, but to other planets.

So, the whole science of that was developed by Konstantin Tsiolkovsky and others of course, have developed various other versions of rockets. Werner Von Braun, for example, developed the German V 2 rocket, which were used indeed during the World War. Some of these developments are credited to these people and laying down the basic foundation of rocket science and engineering.

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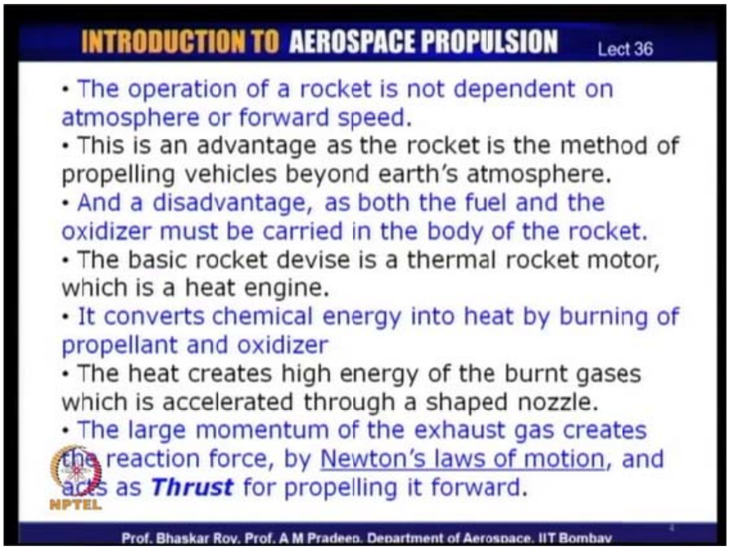

INTRODUCTION TO AEROSPACE PROPULSION Lect 36

- The operation of a rocket is not dependent on atmosphere or forward speed.
- This is an advantage as the rocket is the method of propelling vehicles beyond earth’s atmosphere.
- And a disadvantage, as both the fuel and the oxidizer must be carried in the body of the rocket.
- The basic rocket devise is a thermal rocket motor, which is a heat engine.
- It converts chemical energy into heat by burning of propellant and oxidizer
- The heat creates high energy of the burnt gases which is accelerated through a shaped nozzle.
- The large momentum of the exhaust gas creates the reaction force, by Newton’s laws of motion, and acts as ***Thrust*** for propelling it forward.

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Let us take a look at some of the modern rockets. One of the first thing that you need to know is the operation of the rocket is not dependent on atmosphere nor is it guided by the forward speed, which is the case of an aircraft.

Now, this is an advantage as rocket is the method of propelling vehicles beyond the earth’s atmosphere. So, the atmosphere would have been an impediment, it would have been a resistance to the craft. So, rocket is designed in a manner that it has least amount of resistance and then it can fly out of the earth’s atmosphere. Indeed, when you are out in the atmosphere, outside the atmosphere, the shape of the vehicle becomes less and less important. So, the shape that we are familiar with for aircraft is no more necessary for rockets.

The disadvantage is that there is no air available anymore. Air was the primary working medium for air breathing engines, which means that you have to carry the fuel and the oxidizer. As we know the fuel and oxidizer, both are required for combustion purpose and hence for rockets we have to carry both of them within the body of the rocket, which means you have to carry the weight of both the fuel and the oxidizer, till they are completely used up.

The basic rocket engine is a thermal rocket motor, which is fundamentally a heat engine. We are familiar with the various kind of heat engines; we have done the thermodynamics of these heat engines; we have done the various cycle analysis; we shall see that rocket engines do not quite conform to those cycles, but it still remains a heat engine which means fundamentally chemical energy is converted to heat by burning of propellant and oxidizer and that is fundamental of all heat engines that chemical energy is released by burning into heat and then this heat is converted to useful work.

So, that is the fundamental of heat engine. So, in that sense, a rocket remains a heat engine and then this high energy burnt gas is accelerated through various nozzles; these nozzles have to be shaped properly and we shall be looking into the nozzle science later on, also - how these nozzles are created and shaped. If you do that properly, if you create enough energy and if you have a properly shaped nozzle, then the large momentum of exhaust gas that is created when it comes out of the nozzle body by the reaction force as per Newton’s laws of motion, creates thrust.

So, thrust is created through various physics: first is release of heat, second is expansion of the gas or acceleration of the gas through a properly designed nozzle and if you do that properly, the exhaust gas then gives a reaction and then the Newton’s laws of motion apply and you have thrust that is created by this exhaust gas.

This thrust is what we use for propelling the rocket, first through the atmosphere as it has to be launched from earth’s surface and then through various other rarified medium outside the atmosphere and then out into the space, where there is no atmosphere at all. So, this is the basic mechanism by which a rocket normally works.

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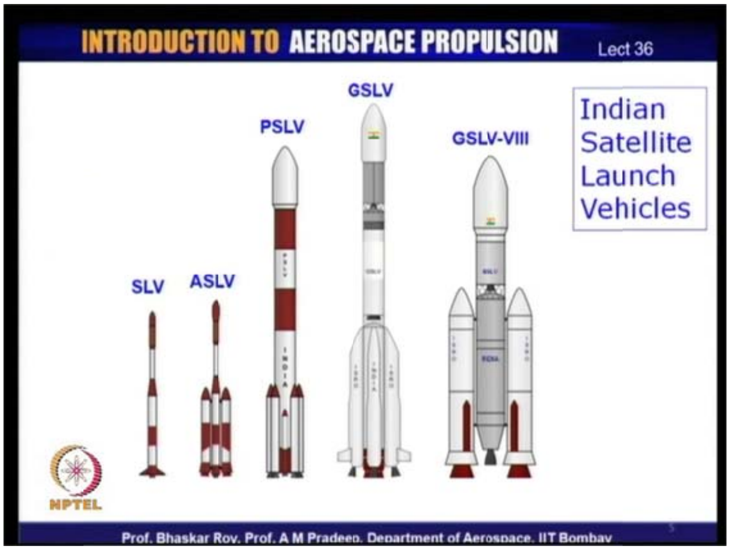

INTRODUCTION TO AEROSPACE PROPULSION

Lect 36

Indian Satellite Launch Vehicles

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We will take a look at some of the more famous rockets that have been used in the recent past. Some of the rockets that we can immediately refer to are the very successful Indian satellite program, which is launched by our ISRO - Indian Space Research Organization and they have been building these rockets for quite some time. Some of the rockets that are shown here are called Satellite Launch Vehicles or SLVs; prior to these, there were smaller rockets which were used for various purposes.

These are the successful launch vehicles that have been launched in the last many years now. It started with a SLV. These pictures are roughly in proportion to their size. So, you can see that the initial SLV that was used was indeed rather small and then we had augmented SLV and this augmented SLV had, as you can see more than 1 rocket. Actually, here there was only 1 rocket housed within the body of SLV and here, you have more than 1 rocket, at least 2 rockets surrounding the body of the SLV.

You could have upto 4 rockets surrounding the body of the SLV and then we have a Polar SLV - Polar Satellite Launch Vehicle, which takes the craft to the polar altitude and this is much bigger, as you can see.

It carries at the tip of the rocket, what is known as payload which is all the instruments that are used for the craft when it is rotating around the earth. So, all those instruments are housed inside it various communication and other instruments the PSLV is also the kind of craft, we are probably likely to use to begin with for our moon mission.

It has, as you can see here, a number of rockets not only the big rocket inside the main body, but some of the smaller rockets outside the main body which also help in carrying this big vehicle up through the atmosphere into the earth's orbit.

GSLV or Geosynchronous Satellite Launch Vehicle is even bigger and it goes into what is known as geosynchronous orbit and this is the kind of rocket which carries again a lot of payload and a modern version of that is GSLV 8, which has gone through 5, 6, 7 and 8 and is being continuously developed for various purposes. These also carry communication satellites, which go around the earth's orbit and allow us to stay in communication with each other all the time.

So, these are the kind of launch vehicles or what is known as satellite launch vehicles that put satellites on earth's orbit for various purposes; some of which are for communication purposes, some of which are for other social purposes and some of which sometimes may be for military purposes. So, these are the Indian rockets which have been very successful rockets that have been used over last many years.

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PSLV launch from Sriharikota Launch base

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This is a PSLV, which is being launched from the Indian launch base at Sriharikota and you need a huge structure to initially hold the rocket vertically and once the rocket is fired, it slowly goes up. When it is going up, it is still held firm and then at a certain point of time, this fixture is released and the rocket goes up in the atmosphere by virtue of the huge gas that is released and the thrust that is created which is directly vertical and completely lifts the whole rocket body up from the launch base, which is a big base created over here. So, the thrust that creates has to completely balance the weight of the entire rocket body and hence, it is quite often known as liftoff; it lifts the entire rocket from the launch base up in the atmosphere.

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Proton Rocket - Russia

Apollo Spacecraft for Moon mission – USA (Saturn Rocket)

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This is a Proton rocket, a modern rocket used by the Russians for launching various satellites to the atmosphere. As you can see, it has a number of rocket bodies outside the main rocket body and those are the ones that create additional thrusts especially during liftoff. As you can well imagine that the weight of this could be quite heavy and you need maximum thrust during the liftoff.

So, maximum thrust creation capability has to be built in and some of these indeed are multistage rockets so that some of these would actually fall off after the whole rocket has gone to a very high altitude. Then the so called, second stage will take over and then after a certain while, the second stage will also fall off and then the third stage will take over and after sometime even the third stage would fall off, leaving only the payload which is the main satellite to go on to its orbit or go on to its mission.

Now, this is Apollo spacecraft for the moon mission used by USA. It was powered by Saturn rocket. Now, Saturn rocket is something very similar to this Proton rocket; so, it would look something very similar and of course, very big. (Refer Slide Time: 17:20) This is the craft that would be housed right on top over here. So, what you see on top over here is simply called technically payload. Now, this is the payload and this is what would be carried by this big rocket from the earth's surface and once it goes to very high altitude, rest of the stages fall off leaving only this, which is also often called the command module, from which a smaller craft would probably land on the moon.

So, this is what goes around the earth's orbit or beyond, as you can see there is a small rocket actually fitted behind it. During its various motions in the space very much outside the earth's atmosphere, if it requires to create some small motions, it can create that with the help of these small rockets. So, this is what you have right on top of a big rocket.

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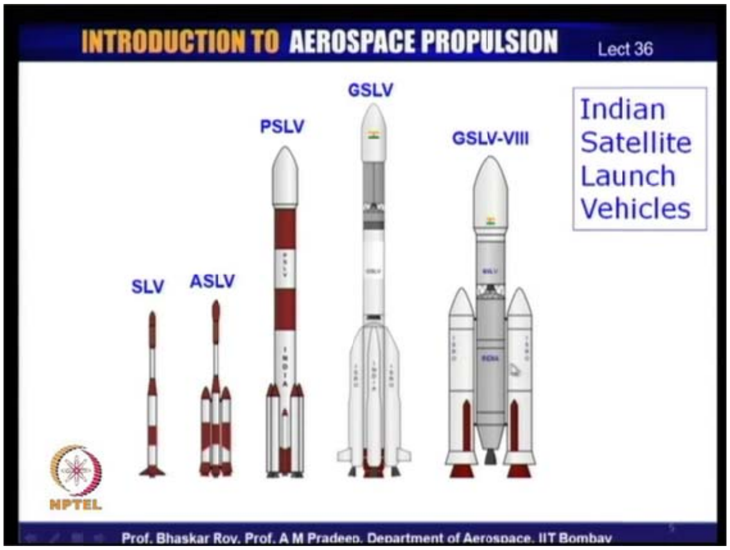
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Indian Satellite Launch Vehicles

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We can see that in our Indian rockets also that it has number of stages. This is the first stage; this is the second stage; this is the third stage. Sometimes, you have 4 stages. This could actually be a fourth stage and then you have the payload on top of it, which is the satellite. This is called satellite launch vehicle. So, the whole of it is a launch vehicle on top of it is the satellite, which is used for various purposes.

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Proton Rocket - Russia

Apollo Spacecraft for Moon mission – USA (Saturn Rocket)

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So, people have been using these for various purposes. USA used it to send man to moon. Russians have also done that and they also send various satellites to the orbit for various purposes, just like our Indian program.

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Space Shuttle Columbia launch

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This is the Space Shuttle Columbia launch and here, you can see that there is a huge big rocket which is the Saturn rocket and strapped on that, is the Columbia which is the reusable launch vehicle. So, rest of the launch vehicle actually is not reusable. Typically, a rocket once it is launched and it goes up most of it falls off and is not reusable; they are completely burnt off and dispensed with. Now, this space shuttle which is strapped on this big Saturn rocket actually goes to space and it comes back and it comes back and lands like an aircraft. So, that is why this is shaped like an aircraft, but it cannot take off on its own and go to space so it is strapped on to a big Saturn rocket and then once it is high up in the altitude actually somewhat outside the earth's atmosphere, the space shuttle gets released from the main rocket body and then it can go around the earth's orbit on its own. As I mentioned, the shape in that kind of orbit does not matter. It could be shaped like an aircraft or it could be shaped like anything and it would still go around the earth's orbit as there is no air resistance involved.

However, when this space shuttle tries to come back to the earth, it has to again negotiate the atmosphere. So, it has to come back through the atmosphere into the earth's orbit and there the shape of this space shuttle shaped like an aircraft again is useful because then it can behave like an aircraft, it can be controlled like an aircraft and then it can land on a airstrip like an aircraft.

So, it actually does so. It actually lands on a runway just like an aircraft does, after it has gone around the earth in space. So, that is why it is called a space shuttle because it comes back and it is reusable; it can be launched again with the help of another rocket.

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Types of missiles

Conventional guided missiles (targetted)

- Air-to-air missile
- Air-to-surface missile
- Anti-ballistic missile
- Anti-satellite weapon
- Anti-ship missile
- Land-attack missile
- Anti-tank guided missile
- Surface-to-air missile (list)
- Surface-to-surface missile
- Wire-guided missile

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Let us look at various kinds of missiles. Missiles are typically used for various military purposes and hence, some of their various configurations may be guarded secret, but we can take a look at all kinds of missiles that are normally used and each of them is designed for the particular purpose.

Now, missiles are used for certain targets. So, you have certain target to which the missile is launched and it has to hit that target. It could be an air-to-air missile, which means it is launched from air maybe, from an aircraft and it is to hit another target which is also in air - could be another aircraft.

It could be an air-to-surface missile, which means it is launched from an aircraft and it is to hit something on the surface of the earth. It could be antiballistic missile which means we will see the ballistic missiles and this missile is supposed to go and hit that ballistic missile. So, to counter a ballistic missile and hence it is called antiballistic missile. So, it has to intercept a missile, while that missile is moving on the atmosphere, intercept the missile and hit that missile. So, it has a purpose of hitting something on the motion in the earth’s atmosphere.

Then we have anti-satellite weapon, where you can send a missile to hit a satellite which may be going around the earth’s surface. So, that is anti-satellite missile and then you have anti-ship missile, which could be launched from air or from surface and it is supposed to hit a ship, which is moving on the sea. So, a ship which is mobile and moving on the sea can be hit with this kind of missile.

Then we have land-attack missile, which is ground to ground missile. We have anti-tank guided missile which is used for hitting or targeting tanks on the surface of the earth. Tanks as you know are armoured bodies and so you need strong missiles to hit them.

Then you have surface-to-air missile, which are often used to be called simply anti-aircraft missiles, where you can send the missile from earth to aircraft that are moving around which could be considered dangerous and hence, you can send missiles from surface to counter those aircrafts.

Then there is surface-to-surface missile, which is the original missile. So, send a missile from one point of earth to another point of earth for some target and we could have wire-guided missile, where the guidance system is wired and these are missiles which are used for various kinds of purposes; the purpose is normally some military purpose.

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Types of missiles

Cruise missiles (has a long cruise flight)

Ballistic missiles (Aim and Shoot)

- Tactical ballistic missile
- Short-range ballistic missile
- Theatre Ballistic Missiles
- Medium-range ballistic missile
- Intermediate-range ballistic missile
- Intercontinental ballistic missile
- Submarine-launched ballistic missile
- Air-launched ballistic missile

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Cruise missiles normally have a long cruise flight very much like an aircraft. That means it sort of flies at a constant altitude, for a large part of its flight. Most of the missiles actually have parabolic or some curved trajectory, which actually means that it does not cruise, but this cruise missile is one of a kind which cruises for a long time in its path which could be hundreds of kilometers and then lands at a particular predetermined place at a target. That is why, they are called cruise missiles. They are designed to cruise at a constant altitude, over a long period of its actual flight.

Now, the ballistic missiles are the aim and shoot kind of missiles, which are used again for various military purposes. The purpose is built into the nomenclature or name of these missiles and they are called tactical ballistic missiles, the short-range ballistic missiles, theatre ballistic missiles used in specific kind of war situation, could be on the top of a mountain or in a very difficult terrain. So, those are called theatre ballistic missiles.

Then you have the medium-range ballistic missiles which can probably go over 100 kilometers or so and then you have intermediate-range ballistic missile which go on for may be few 100 kilometers and hit a target. Then you have the intercontinental ballistic missiles, which are expected to travel over thousands of kilometers to hit from one continent to another. So, it goes from one continent to another; hence, they are called intercontinental ballistic missiles and these obviously go for a very long distance.

Then you have the submarine launch. Submarines, as you know, are under the water ships and they can be launched from under the water so that you cannot even see when they are being launched and these submarine-launched ballistic missiles are again especially designed to be launched from under the water and then we have the air-launched ballistic missiles which are launched from aircraft and have the characteristics of ballistic missile for hitting a target as soon as they are launched.

So, these are the various kinds of missiles and as you can see, they are named after the particular mission for which, they are designed and these are all various kinds of rockets. So, they are all covered by the rocket science that we will be talking about, but each of these rockets is designed for a particular mission. So, the way you design them, the way you design the nozzle, its guidance system everything finally makes a particular kind of missile and as a result of which, they have been given various kinds of nomenclature.

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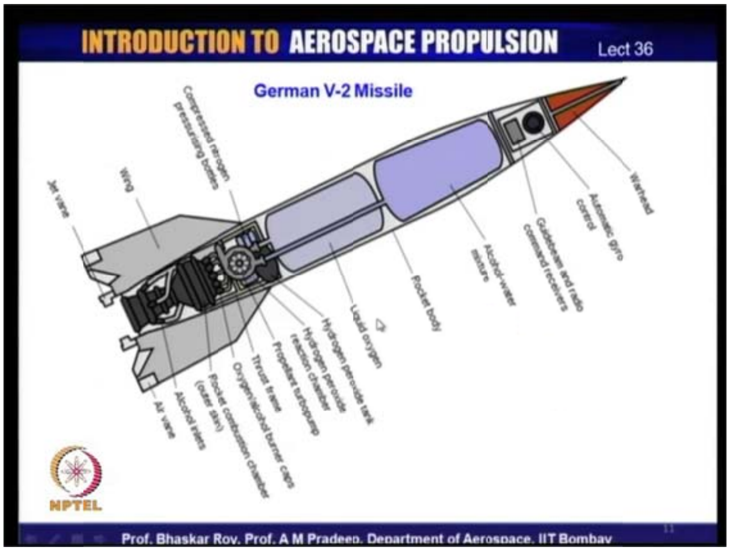

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German V-2 Missile

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This is a old German V-2 missile. The reason I am showing this old missile is because most of the other missiles are guarded secrets. They are secret technology, which are normally not available to the general public and hence, we can look at somewhat older missile, which were actually used during the World War 2.

As you can see here, the missile houses number of components. Right on top, you have the unit that is often called payload or in simple rocket terms we call it payload, but in case of a military application, it would be called a warhead.

Then you have the various control systems, which controls the craft and finally, the warhead on to the target. So, this is the control or gyro control, as it used to be known earlier, which guides the warhead or the payload onto the target and then you have various other systems, the radio system and so on, which are housed over here, for it to be communicated with the ground system so that the ground control can be operated to guide this system onto its target.

The various other systems are there - the rocket body as you can see here, houses all the other system; you have the liquid oxygen that is stored over here and you have the hydrogen peroxide tank which is stored over here and then you have the nozzle, which is at the end through which the high velocity jet finally, comes out and creates a thrust.

So, these are the various kinds of systems that are normally housed inside a typical rocket body - in this case, a particular missile, which have the control system, the navigation system, the fuels and the oxidizers which are stored in tanks, as I mentioned they have to be carried within the body and most of the body of a rocket is typically occupied by the fuels and that is the various kinds of oxidizers and the propellants; they have to be carried in the tanks and they actually occupy most of the space. Then you have the pumps, which pumps these fuel into the rocket chamber or the combustion chamber of the rocket engine and then it goes out through the nozzle. So, the rocket chamber is of this size which is much smaller than the body of the main rocket and a nozzle is at the lower edge of the rocket from which, the high velocity gas comes out.

So this is typically, the body of a rocket, which could be of a missile or any other kind of a craft. They all have certain common features and these are the common features of any kind of rocket that you may like to look at.

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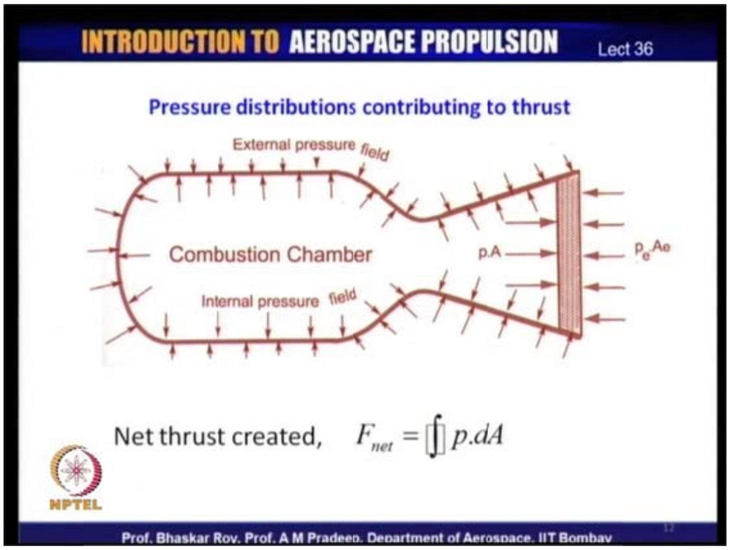

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Pressure distributions contributing to thrust

Net thrust created, $F_{net} = \oiint p.dA$

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Let us try to take a look at the various fundamental science that is contributory to the operation of rocket.

Now, if we look at the fundamental physics of what is happening, you have rocket chamber, which is often called a combustion chamber, in which the combustion is initiated and we shall see what all kinds of combustion is done in a few minutes.

What it creates is, it creates a very strong pressure field inside the combustion chamber and then this high pressure gas is released and it continues to create this pressure field before it goes out through the nozzle. When it goes out, it creates the thrust. Now, this pressure field, as it is seen is inside the whole rocket chamber. If you consider the nozzle and combustion chamber together, they may be called the rocket chamber and this pressure field inside the rocket chamber is acting on the inner surface of the entire rocket chamber.

On the outer surface, you have a external pressure field which may be at earth’s atmosphere or it may be a no pressure field - that means, there may not be any atmosphere at all and the differential of the two when integrated actually gives you the net thrust. So, this pressure field differentiated over the entire area would finally, give you the net thrust in this direction; that is, in the direction which is the axis of the rocket chamber.

If you consider this chamber to be an axi**s** symmetric body, the radial components of this pressure field would actually, nullify all around that means they counter each other and there is no net component acting in any direction as we are looking at an axis symmetric body. Hence, the only component that would be active is the horizontal component or the component parallel to the axis of this craft or this rocket chamber and that net component is the thrust. So, this is how, one can say that the thrust is created. So, this is one of the methods by which, you can use the basic physics to understand how the thrust is created.

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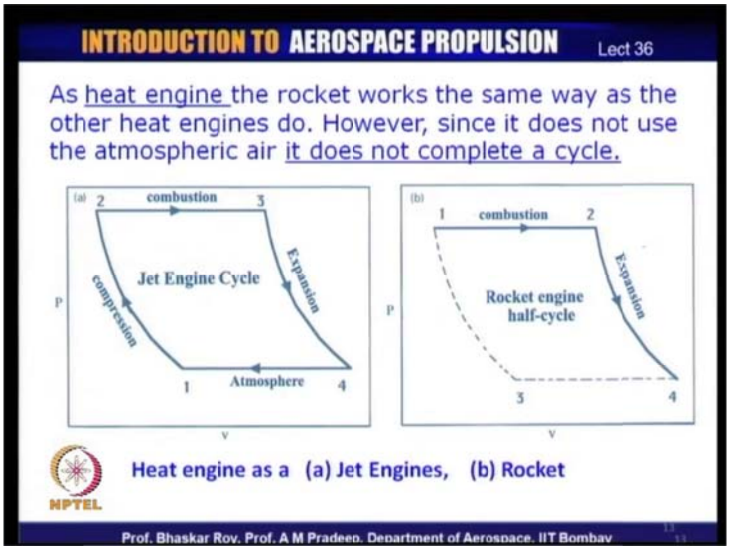

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As heat engine the rocket works the same way as the other heat engines do. However, since it does not use the atmospheric air it does not complete a cycle.

Heat engine as a (a) Jet Engines, (b) Rocket

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Let us look at how the basic heat engine is conceived.

Now, we have looked at various kinds of jet engines. The jet engine cycles you have done and the jet engine cycle works in a cycle; it comes from atmosphere, goes through compression, goes through the process of combustion and expansion and finally, gets released into the atmosphere. So, it acts in a cycle.

In a rocket, we do not have earth’s atmosphere. We do not have air, which means that the working medium has to start on its own, come out through a process of combustion and then come out through a process of expansion and there is no return path; there is no cycle. So, at best one can say it works in a half cycle, but we are not using a medium which goes back to its origin. So, it works through a process of combustion, which is approximately a constant pressure process and then comes out through a process of expansion.

So, even though a jet engine or a rocket, which is also a jet engine work as heat engines, there is some difference in the way they are fundamentally conceived as working heat engines and this is the fundamental difference that the other air breathing jet engines work in a cycle; the rockets do not work in a cycle.

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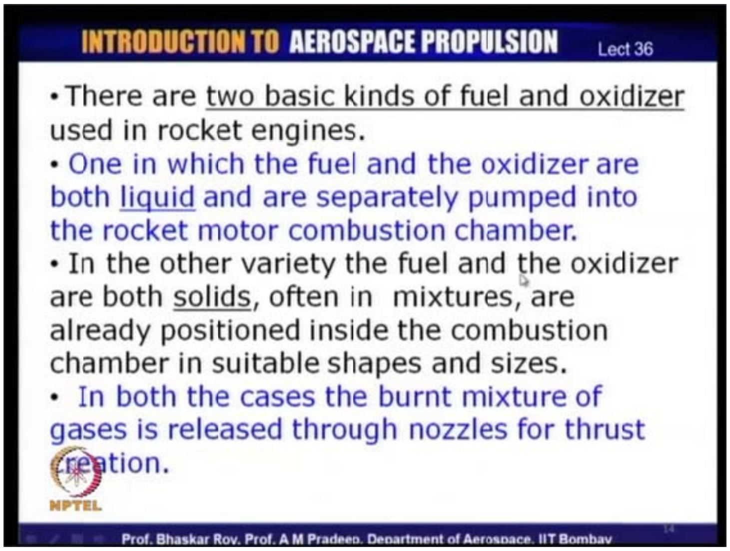

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- There are two basic kinds of fuel and oxidizer used in rocket engines.
- One in which the fuel and the oxidizer are both liquid and are separately pumped into the rocket motor combustion chamber.
- In the other variety the fuel and the oxidizer are both solids, often in mixtures, are already positioned inside the combustion chamber in suitable shapes and sizes.
- In both the cases the burnt mixture of gases is released through nozzles for thrust creation.

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Now, a rocket actually, fundamentally, right from the beginning has two basic kinds of fuel and oxidizer system. One in which the fuel and oxidizer, both are liquid and hence they need to be separately pumped into the rocket motor or rocket combustion chamber. So, you need a pumping unit for each of them separately to be pumped into the combustion chamber and both of them are liquids.

The other variety is, where both of them are solid and both of them could be separate bodies of solids or quite often they are mixtures; so, solids are mixtures and these mixtures have been used for many centuries now, by the Chinese and our Indians for creating rockets. So, the early rockets that we know of, where all solid rockets what we call today - solid propellant rockets and those were the rockets which were used by the Chinese and the Indians and many other people around the earth in the ancient era.

In the modern era, these solid bodies are designed; there are various designer shapes, which we shall look at later on in one of the next lectures and we shall see how those shapes actually contribute to the performance of these solid rockets. In both the cases, once the propellant and the oxidizer are burnt, the mixture of gases that is created is released through nozzles for thrust creation.

The burning process, as you are aware, the combustion process would have to be done in a chemically correct manner, which means the solids or the liquids, that is the fuel and the oxidizer would have to burn in a proper proportion. If the solids are in a mixture, they are to be in a proper proportion; this proportion is extremely important and they are determined by various chemical analysis. So, the process of creating this fuel and oxidizer fundamentally comes from various chemical analyses and that chemical analysis gives you the kind of fuel and oxidizer that you should be using.

We shall see that there are various kinds of fuels and oxidizers for rockets; the choice of fuel and oxidizer for rockets is very wide. There are various kinds unlike in an aircraft where you normally have only one kind of fuel. The number of fuels and oxidizers available for rockets are many. We shall look at some of the more popular ones in the next lectures. So, this is the way, the rocket actually functions.

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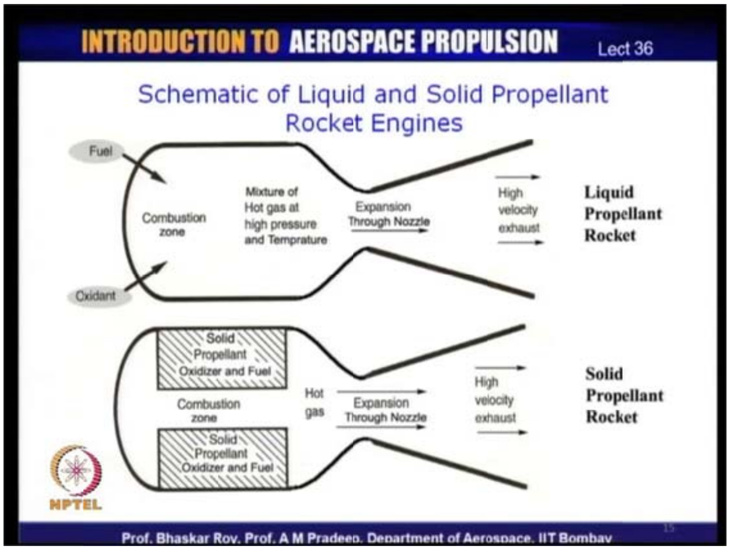

INTRODUCTION TO AEROSPACE PROPULSION Lect 36

Schematic of Liquid and Solid Propellant Rocket Engines

Prof. Bhaskar Roy, Prof. A M Pradeep, Department of Aerospace, IIT Bombay

Let us look at schematic of two fundamental kinds of rockets; one is the liquid, another is the solid propellant rocket. In the liquid, you have the fuels in one tank, you have the oxidizer or oxidant in the other tank and they are pumped separately into the combustion chamber.

Now, this is the combustion zone, in which the combustion is to be carried out, which means, the fuel is to be pumped, they are to be released into the combustion chamber through injectors and these injectors do a number of jobs; that is, it atomizes the fuel, then the fuel is released, the fuel is vaporized, fuel mixes with the oxidant and then the mixture is burnt, that means, a flame is created and then this flame releases the energy or the heat energy into this combustion zone and then the mixture of gases proceeds from the combustion zone where the heating or the combustion process is to be completed - at least 98 percent completion. Then the mixture moves in the combustion chamber forward towards the nozzle; even as it is moving forward, the combustion process may be completed. So, by the time it comes at the beginning of the nozzle, the combustion process is said to be completed and now, it has very high pressure and very high temperature.

This very high pressure, temperature gas is now released through the nozzle which is normally convergent divergent nozzle. So, initially you have a convergent nozzle which makes the flow go sonic. So, at the throat of the nozzle, the flow has invariably reached sonic velocity which is Mach 1 and then it continues to expand through this nozzle to very high velocity - normally high supersonic Mach number with which the gas comes out and helps create thrust. So, this is the mechanism by which the rockets normally create thrust.

In case of solid propellants, you can have a mixture of oxidizer and fuel and a body of that is created. We shall see the various shapes that are created; those shapes are extremely important and they are housed inside the combustion zone. Once they are housed inside the combustion zone, a process of combustion may be initiated.

(Refer Slide Time: 40:43) Let us say at this end - at the further end of the bodies and once the combustion is created in this isolated combustion zone, the gas is created, the process of gasification happens; the solids once they burn, they form into gas and then this gas travels through this opening between the 2 sides. So there may be a circular opening through this and the combustion is continued and then finally, it reaches the beginning of the convergent part of the nozzle. It also goes through a process of choking or going sonic and then it becomes supersonic and is released at high velocity.

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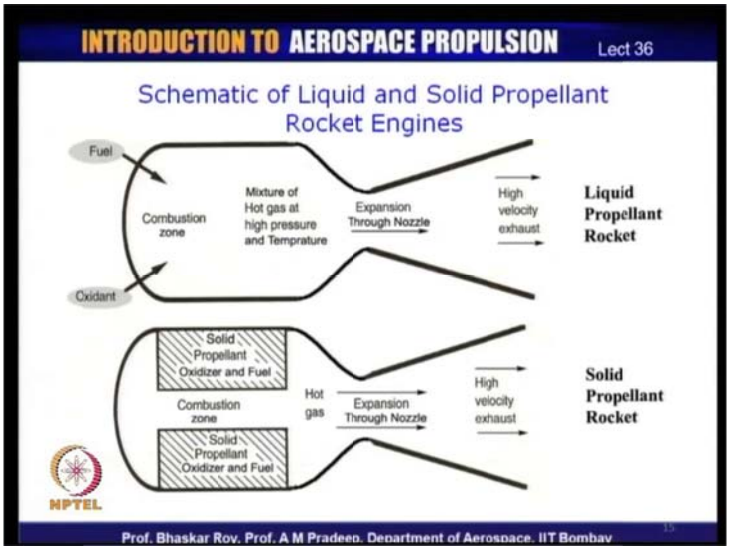

INTRODUCTION TO AEROSPACE PROPULSION Lect 36

Schematic of Liquid and Solid Propellant Rocket Engines

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So, normally as you can see the solid propellant carries the propellant inside the combustion chamber itself whereas, for liquid propellants, the liquids have to be stored separately in other part of the rocket body from which, they have to be pumped into the rocket chamber, which means that a rocket body will have to be now designed to store the fuel and the oxidizer separately. They cannot mix before they are pumped into the combustion zone.

Then they are to be pumped separately. You may require separate pumping capability depending on the pressure at which they are stored, which means a liquid rocket typically would require a lot of space for carrying the fuel, for carrying the oxidant, for housing the pumps and which means that a liquid rocket typically has to be quite big, for it to be justified that you carry all these with you for creation of thrust.

So, typically liquid propellant or liquid propulsion is used only when you need a big rocket, typically for satellite launch vehicles. Most of the missiles tend to be solid propellant rocket, where the solids are housed within the combustion chamber of the rocket.

Some of the bigger missiles like intercontinental missiles could have a combination of liquid and solid which could be multistage. So, the first stage could be liquid to carry the total weight of the entire rocket body or the vehicle body and then later on, once the first stage is released, the next stages could be solid rockets, which are little smaller in size and hence they can carry the vehicle much farther into the atmosphere or beyond the atmosphere. So, a combination of liquid and solid rockets has been also used for various kinds of launch vehicles.

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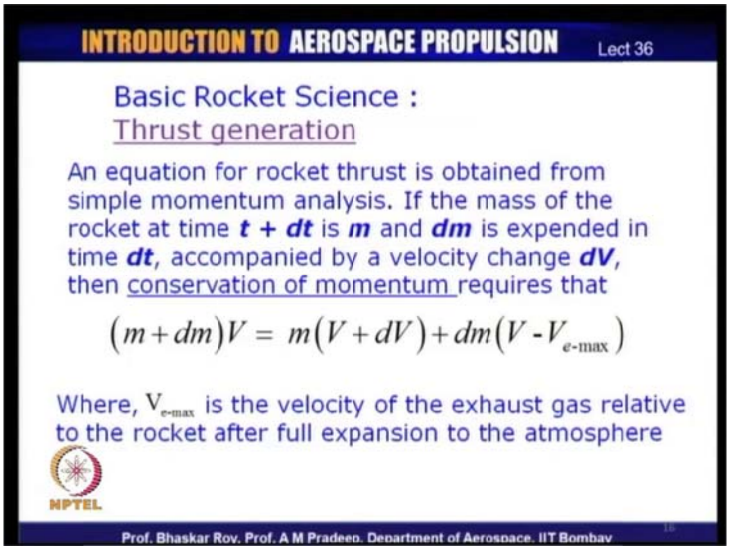

INTRODUCTION TO AEROSPACE PROPULSION Lect 36

Basic Rocket Science :
Thrust generation

An equation for rocket thrust is obtained from simple momentum analysis. If the mass of the rocket at time ***t + dt*** is ***m*** and ***dm*** is expended in time ***dt***, accompanied by a velocity change ***dV***, then conservation of momentum requires that

$$(m+dm)V = m(V+dV)+dm(V - V_{e\text{-max}})$$

Where, $V_{e\text{-max}}$ is the velocity of the exhaust gas relative to the rocket after full expansion to the atmosphere

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Now, let us take a look at various kinds of basic rocket science. How the thrust is generated? You see the rocket science is based on very simple principle actually, you know the Newton’s laws of motion; you know that if you create a large gas energy that is coming out of a body, it will immediately give you a forward motion. It can be done in a very small scale in your laboratory. If you open the end of a balloon and release it, the balloon will move much like the rocket movement.

So, basically, release of the gas will always tend to give you a certain amount of motion and then in a typical modern rocket, the motion needs to be controlled. So, you have a guided system, you have a navigation system. All those systems are housed in the body of the rocket. However, the main problem of the rocket is creation of the thrust.

So, much of the body of the rocket is actually used in storing the fuels, for managing the fuels and then managing the combustion process and then releasing it through the nozzles.

The basic rocket engine is more about its heat engine and less about the craft which is basically, a cylindrically shaped body at the tip of which you have a payload, which goes out for various motions. So, various purpose of the rocket is served by basic fundamental science. Let us take a look at this fundamental science, which governs all kinds of rockets missiles and various kinds of satellite launch vehicles.

Now, if you take a rocket thrust that is to be created, if for example, you have to use a certain amount of mass of the rocket to be used. Now, this mass of the rocket to be used is indeed, the fuel. So, the fuel and the oxidant are to be used let us say, over a period of time and this expended mass of dm is expended in time dt and when it is expended, it creates a velocity change dV of the rocket body itself, then the conservation of momentum gives you the momentum balance.

That means, the mass with which it started, the original mass and the original velocity finally, devolves into the final mass, the final velocity and the mass that is expended that is, the fuel that is expelled through the nozzle and the change of velocity that has occurred to the rocket vehicle.

So, V e-max is the velocity of the exhaust gas, which is relative to the rocket body and as a result of which, you have the motion of the rocket. It is assumed that the nozzle is fully expanded to the atmosphere. So, this is the basic equation of motion of the rocket body itself.

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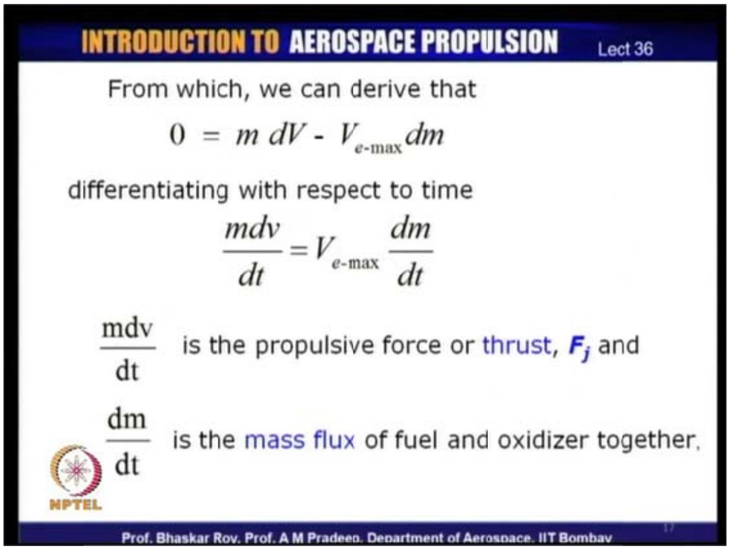

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From which, we can derive that

$$0 = m\,dV - V_{e\text{-max}}\,dm$$

differentiating with respect to time

$$\frac{mdv}{dt} = V_{e\text{-max}}\frac{dm}{dt}$$

$\frac{\mathrm{mdv}}{\mathrm{dt}}$ is the propulsive force or thrust, F_j and

$\frac{\mathrm{dm}}{\mathrm{dt}}$ is the mass flux of fuel and oxidizer together.

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Now, if you slightly work on that equation, we can write that this equation devolves into a much simpler form, which can be differentiated to give you a very simple equation which is m dV dt which is equal to V e-max into dm dt.

Now m dV dt is the propulsive force or thrust, which is m into acceleration - dV dt is the acceleration. So, that gives you the propulsive force or the thrust that you require for this body to be moved and that is the thrust you need to create.

Now dm dt is the mass flux of the fuel and oxidizer together. You remember the rocket carries the fuel and oxidizer and there is no air available. So, this is what is coming out of the rocket body and this is the thrust you need to create to move the entire rocket body through the atmosphere or anywhere else. So, this comes out of the basic motion of the rocket body.

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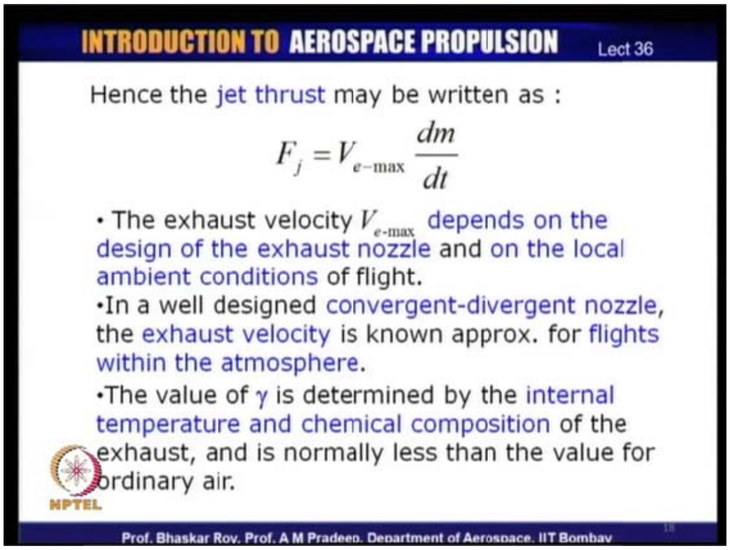

INTRODUCTION TO AEROSPACE PROPULSION Lect 36

Hence the jet thrust may be written as :

$$F_j = V_{e-\max}\frac{dm}{dt}$$

- The exhaust velocity $V_{e\text{-max}}$ depends on the design of the exhaust nozzle and on the local ambient conditions of flight.
- In a well designed convergent-divergent nozzle, the exhaust velocity is known approx. for flights within the atmosphere.
- The value of γ is determined by the internal temperature and chemical composition of the exhaust, and is normally less than the value for ordinary air.

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So, the jet thrust that you need to create can also be written down in terms of the value V e-max with which the fuel and oxidant together are coming out - the jet is coming out and this is the mass flux of the fuel and oxidizer together and that gives you the thrust. So, this thrust must be equal to the thrust which is required for the motion of the body and as a result of which, you have properly matched engine and the rocket body.

Now, this exhaust velocity which is created and which we call V e-max, at the moment we are assuming that maximum velocity has been created; it has worked in an ideal condition, the nozzle is working as an ideal nozzle and then it is expanding into the atmosphere in a complete expansion process and that creates V e-max. We shall see later on, that rocket does not create V e-max all the time. It creates a velocity V e which is not necessarily maximum, at all time of its operation.

Now, this V e-max depends on design of the exhaust nozzle and on the local ambient condition of the flight. So, in a well-designed convergent divergent nozzle, the exhaust velocity can be calculated and is known for flights within the atmosphere. They can be calculated quite easily, reasonably approximately for engineering approximations. The value of gamma is determined for the mass of the gas with the help of the internal temperature and chemical composition of the exhaust. It is normally much less than the value that is used for ordinary air; normally, quite less really at high temperature and pressure.

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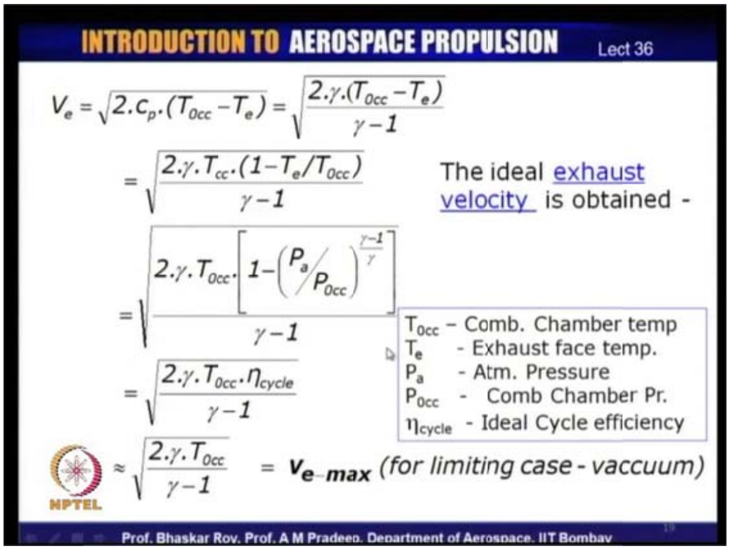

INTRODUCTION TO AEROSPACE PROPULSION Lect 36

$$V_e = \sqrt{2.c_p.(T_{0cc} - T_e)} = \sqrt{\frac{2.\gamma.(T_{0cc} - T_e)}{\gamma - 1}}$$

$$= \sqrt{\frac{2.\gamma.T_{cc}.(1 - T_e/T_{0cc})}{\gamma - 1}}$$

The ideal exhaust velocity is obtained -

$$= \sqrt{\frac{2.\gamma.T_{0cc}.\left[1 - \left(P_a / P_{0cc}\right)^{\frac{\gamma-1}{\gamma}}\right]}{\gamma - 1}}$$

$$= \sqrt{\frac{2.\gamma.T_{0cc}.\eta_{cycle}}{\gamma - 1}}$$

$$\approx \sqrt{\frac{2.\gamma.T_{0cc}}{\gamma - 1}} = \mathbf{V_{e-max}} \text{ (for limiting case - vaccuum)}$$

T_{0cc} – Comb. Chamber temp
T_e - Exhaust face temp.
P_a - Atm. Pressure
P_{0cc} - Comb Chamber Pr.
η_{cycle} - Ideal Cycle efficiency

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Now, these are the equations for which you can calculate the V e; as I said, V e can be easily calculated. This is the energy with which the gas is flowing out, this is the temperature of the combustion chamber with which it started and this is the exit temperature. So, this is a simple governing equation of velocity; you can write from your fundamental thermodynamics that you have done; the isentropic flow that you have done and if you derive this, you can covert the temperature ratio to pressure ratio.

Assuming an isentropic process for the time being, an ideal process and if you do that through the nozzle and finally, you get the cycle efficiency, which is equal to this as you have done in your thermodynamics and for the time being, if you assume that the cycle efficiency is 100 percent, that is 1, you get the V e-max; so, this is V e-max. We started by trying to calculate V e and we can get V e-max by assuming the cycle efficiency to be 1 or 100 percent and if you do that, you get the V e-max, which is for the limiting case that is, in vacuum.

So, this is what you get when the rocket actually flies in vacuum, that is well outside the outside the earth's atmosphere. Otherwise in atmosphere, you can calculate by earlier steps that are shown over here.

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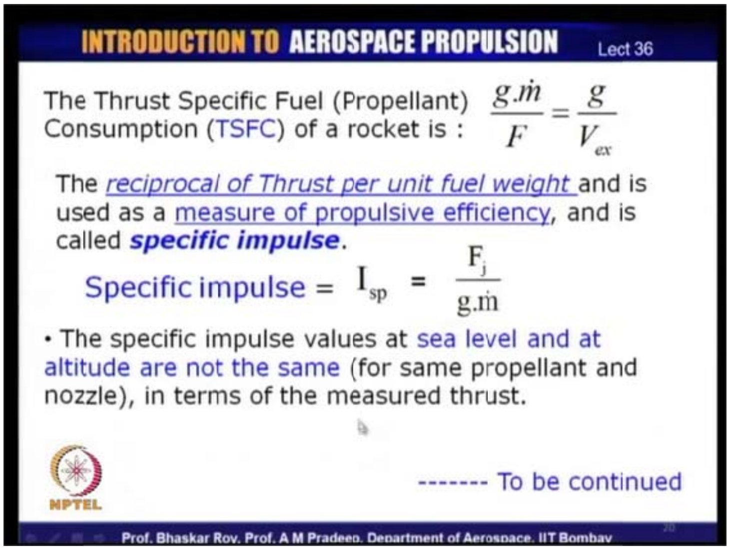

INTRODUCTION TO AEROSPACE PROPULSION Lect 36

The Thrust Specific Fuel (Propellant) Consumption (TSFC) of a rocket is : $\frac{g.\dot{m}}{F} = \frac{g}{V_{ex}}$

The *reciprocal of Thrust per unit fuel weight* and is used as a measure of propulsive efficiency, and is called ***specific impulse***.

$$\text{Specific impulse} = I_{sp} = \frac{F_j}{g.\dot{m}}$$

- The specific impulse values at sea level and at altitude are not the same (for same propellant and nozzle), in terms of the measured thrust.

------- To be continued

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Hence, you can see that we can now calculate with the help of simple physics, the Thrust Specific Fuel Consumption or which is also called TSFC, which is the propellant consumption really, a house inside the body and this is simply given by g by V exit. Now, this is what we calculated in the last slide and g is gravity. So, you can easily calculate your TSFC, once you have calculated the value of V ex and the reciprocal of this is called specific impulse, which is often a figure of merit or measure of the propulsive efficiency of the rocket engine

You remember, this is a propulsive unit and it is an engine and its efficiency needs to be measured. Specific impulse is the figure of merit or the measure of the propulsive efficiency and it is simply the reverse or reciprocal of this TSFC and is expressed in this manner and it is often in most literature, it is simply called I sp - Specific impulse

This specific impulse values at sea level and at various altitude are not same. As we know, the thrust is going to be different and we shall see very soon and you know very well, the value of g would vary from earth’s surface to various high altitude. It is something at earth’s surface which we use all the time in our physics, but once you go to high altitude, the value of g changes and hence, you have to use different values. Hence, the value of specific impulse would vary from earth’s surface at sea level to various altitudes, which the rockets normally would fly. Hence, these are the various parameters that typically specify a rocket and a rocket's operation - the TSFC, the specific impulse and the exit velocity.

We shall continue with this in the next class and we shall introduce a number of other parameters that typify a rocket and its operation. It also quantifies how good the rocket is and what this rocket or what this engine could be used for, whether it could be used for a missile, whether it could be used for a satellite or whether it could be used for any other purpose can be actually found out from these parameters, which we are talking about. We shall be introduced to number of other parameters pertaining to the basic rocket science in the next lecture.