Course Name: Combustion of Solid Fuels and Propellants
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Lecture: 01 Basic Principle of Rocket

Hello, and welcome to the NPTEL online certification course on Combustion of Solid Fuel and Propellants. I hope you have watched the introductory videos on this course. So, today is the first lecture for this course. So, in this lecture we are going to discuss mainly on the basics of rocket propulsion. So, the topic covered under this module will be like the basic principle of rocket, classification of rockets, performance parameters, brief description of solid propellant rockets and application of solid rockets. So, I presume you have some idea about the jet propulsion like in your previous course on introductory jet propulsion course or maybe in aerospace propulsion course or through NPTEL video courses which you have attended previously.

So, I guess you have learned the basics of jet propulsion. Now, jet propulsion can be like mainly categorized into two. One should be like air breathing and other could be non air breathing. So, air breathing means it is taking oxygen from atmosphere that means, it is taking air and it is using the oxygen for the combustion.

So, air breathing engines you can have many of them. For example, like you can have ramjet, you can have turbojet, you can have turbofan, you can have others also like turboshaft. In fact, the IC engines are also like air breathing because it is taking oxygen from the atmosphere. Whereas, the rocket comes under the category of non-air breathing because it is carrying its own oxidizer along with the fuel and that is why the propellant itself is called the fuel plus oxidizer. So, rocket comes under the category of non air breathing.

Now the rocket can also be divided into mainly into three, one is called the solid rocket or solid propellant rocket. solid rocket, second one is the liquid rocket and third one is the hybrid rocket. So, I will give you a brief description of each of them because you might have already learned in previous courses. So, ramjet, turbojet, turbofan, turboshaft those are like under the category of air breathing engines. So, I don't need any kind of introduction to those engines because I am quite sure that you have learned in any point of your other courses. For example, like theory of jet propulsion or introduction to propulsion or aerospace propulsion in any of the courses some descriptions were there on these things.

So, let us not spend time on that. I would rather restrict it to our discussion in the rocket side. So, I will just give a brief idea about the different type of rockets like solid rocket, liquid rocket and hybrid rocket. So, as the name suggests solid rocket means the propellant itself is in solid form. Sometime it is called rocket motor or solid propellant rocket.

So, solid means it is taking the solid propellant in the vehicle or in the rocket. So, if you just draw a simplified diagram it will look like this. So, if you just look at the simplified diagram of a solid rocket. So, you may see there is a fuel sorry there is a propellant grain placed inside the rocket which is in the form of like a solid block of material. I guess you might have heard this terminology it is called propellant grain.

So, this consists of both fuel plus oxidizer. So, it is carrying its own oxidizer for burning. Now, the oxidizer can be in the form of various crystals. For example, like ammonium perchlorate or potassium perchlorate or can be ammonium nitrate or potassium nitrate. And the fuel are generally in the form of polymer, but after curing it becomes solid and that is why you can make this solid block of material.

If you look at the other view of this it may look like this. So, that is the grain. So, the interior of the grain there is a hollow space this is called the grain configuration. Now, this grain configuration can be of different types based on the requirement of the thrust time or pressure time curve this can be like either progressive or regressive or neutral. So, based on the geometry the burning proceeds in that way.

However, that depends depending on the mission requirement the grain has to be designed accordingly, but the major ingredients of this grain it must needs to consist it must consist of fuel and oxidizer. Now, as I said fuel so, this is in terms of the polymeric fuel. Although in rocket literature it is mainly considered the binder because it is binding the all the solid materials impregnated or embedded within it. In actual cases the fuel is the metallic fuel such as like aluminium which is more common. Whereas your oxidizer is again the crystals.

Now, how they are made? If we look at from the processing perspective the both the solid oxidizers and the fuel let's say it is aluminium fuel are actually put into the liquid polymer because in initial state polymer are in liquid form. So, they are mixed together like the solid oxidizer or even the small solid fuels they are churned I mean a simplified form showing this they are churned and then they are pour into a mold and mandrel just to give the shape of the grain. So, once you pour this to here they will take the form of you know some kind of a slurry. Now, if you do the casting and curing so, you have to use some kind of a curing agent just to cure this. Curing agent means it will do the cross linking of the polymer and the polymer will become solid and it will finally, give us the solid block of material or solid block of polymer which is in rocket literature is called grain.

So, since the mandrel was of circular shape it is a cylinder so, you can get a cylindrical hole, but if we need other grain configurations that can be designed based on the you know requirement of the grain configuration. Nevertheless this ingredients are very important for the burning of this grain which we will talk about in the later part of this lectures. Now, let us talk about the liquid rocket in principle how does it liquid rocket look like. So, as the name suggests liquid rocket uses liquid fuel and liquid oxidizer. Very common example you can think of is the liquid, liquid kerosene plus the liquid oxidizer can be like LOX or liquid oxygen.

So, this is one such example. There are various type of examples which you can get it from the literature or from the previous lecture on rocket propulsion course through NPTEL video in other sources. So, I am not going to the detail of this, but if you look at the engine configuration the basic structure of the liquid rocket should be something like this. It needs to have a fuel tank, it needs to have an oxidizer tank and they are of course, initially pressurized with some gas bottle some inert gas bottle and they will be delivered through some. So, this is let us say fuel pump, there will be oxidizer pump also, oxidizer pump and they will be driven by some kind of a you know turbine and that turbine is actually fed through the gases from the gas generator.

Now, the fuel and oxidizers are supplied to the thrust chamber, they are supplied to the thrust chamber. So, thrust chamber is nothing, but it is consist of some you know injectors, it is consisting of combustion chamber and the nozzle for expansion of the gas ok. So, these three parts together are called thrust chamber, this is called thrust chamber. Of course, your gas generator requires some amount of you know liquid fuel and some amount of liquid oxidizer to generate moderate temperature gas to run the turbine and the turbine itself is going to drive the oxidizer pump and the fuel pump which will eventually give the flow of fuel and oxidizer to the main thrust chamber. So, this is the basic principle of liquid rocket.

Now, coming to the hybrid rocket as the name suggests hybrid rocket means it is a combination of liquid oxidizer and solid fuel. So, it can be like so, instead of the propellant grain it will consist of some kind of a fuel grain. If you remember we had the propellant grain in case of solid rocket, but here instead of propellant grain we have some kind of a fuel grain. So, that fuel in terms of some kind of a solid so, this is solid. Now, if we send oxidizer through some kind of a arrangement let us say we have some oxygen as the oxidizer.

So, let us say we have LOX as the oxidizer. So, this is we have like liquid oxidizer and we have solid fuel. So, this type of combination we can call it as the hybrid rocket. So, these are the major categories of solid, liquid and hybrid. However, we actually categorize rocket in terms of their energy sources.

For example, like if it has like chemical rocket, if it has the energy sources from nuclear so, it can have nuclear rocket, it can have like solar thermal rocket, but our discussion is confined within the chemical rocket only and that too the combustion of solid fuels used in solid rocket and the propellants. So, if you look at the focus of this course is only on the combustion mechanisms, understanding of combustion mechanisms of various solid fuels particularly like metallic fuels and the propellants, solid propellants different type of solid propellants. Now, let us go back a little bit to understand the rather I would say brush off some of the basic concept what you have already learned in the previous courses like the rocket equation. So, if you just talk about the rocket equation, you might have already learned about this thing that of very high velocity of the order of like several kilometer per second are required in order to orbiting the satellites or orbiting the bodies around the earth. Even if you want to escape a body from the earth gravitational field, it requires to be very high velocities, but it is not always possible to give very high velocity to the bodies.

In fact, even if you give these velocities to the body, there will be some frictional heating. So, the body may be destroyed in the atmosphere itself. So, the way the velocity is provided by some incremental means like increasing the velocity in a δ v manner or smaller quantities and then slowly it is going to increase. So, the rocket equation tells us the basic of the ideal incremental velocities in terms of others. So, this is not a new things for this course, this is just a brush up or brushing up the materials, what we have already learned from the rocket propulsion or basics of jet propulsion course.

So, let us still for the interest of the participants, let us try to look at the equation one more time. So, what we will consider here is the drag free and gravitational free field and there we are telling that one rocket is moving at a velocity V at a time instance let us say τ. Remember we considering here gravitational free and drag free environment to look at this rocket equation. So, at a time instance τ we have the rocket moving at velocity V. So, these velocities are given with respect to some stationary observer on the ground.

So, he is looking at. So, with respect to this stationary observer the velocity of the vehicle or the rocket is V at a time instance τ we can say the mass of the rocket is M at the time instance. Let us say let us take a later time instance where we can say the rocket has change is mass to another mass and what we say that it has released a mass of δM. So, at time instance $\tau + \delta\tau$ we can say the mass of the rocket has now changed to that $m - \delta M$. So, this is the δM mass. So, the velocity has changed to $V + \delta V$.

Now, if we say that the δM is the ejected mass it has the velocity with respect to the vehicle is Vj. So, let us say we say let us say we consider that the velocity of the ejected mass with respect to the rocket is Vj at a time instance $\tau + \delta\tau$ we can say that this velocity has the maybe you can consider the same direction here. So, it is like Vj. So, now, if we just consider the velocity of the δM with respect to the stationary observer we can say it is going to be like $(V + \delta V) - Vj$ because we said that the mass of the velocity of the ejected mass δM the velocity is Vj with respect to the vehicle. Now, we are considering from considering with respect to the inertial frame of reference or the stationary observer.

So, the velocity will be like $(V + \delta V) - Vj$. So, what we will do is we will just simply consider the momentum of the rocket balance balancing the momentum of the rocket with respect to the inertial frame of reference because that is conserved. So, we will write down the momentum at time instance τ and a time instance $t + \delta\tau$ and we will write down the equation and from there we can actually derive the rocket equation ok. So, I am just going little fast because these are some older stuff we just need to revise some of the things. So, if you write the conditions that since the momentum of the rocket with respect to inertial frame is conserved we can write this.

What you can write? We can write the momentum of the rocket at time instance τ was

$MV = (M – \delta M) (V + \delta V) + \delta M (V + \delta V – Vj)$. Now remember the principle of rocket is nothing, but it is ejected its stored mass be it a solid rocket be it a liquid rocket or hybrid rocket what exactly is doing? If you look at the principle of generating thrust it is nothing, but it is ejecting out its stored mass. For example, like for solid rocket it is burning fuel and oxidizers and then the combustion gas is actually coming out in the nozzle expanding it and it is generating high velocity jet which is producing thrust. In fact, in case of liquid rocket it is burning liquid fuel and liquid oxidizer in the combustion chamber and the product gas is actually expanding through the nozzle and generating high velocity jet which is in turn producing the thrust. So, in principle they are actually ejecting its stored ejecting their stored mass means the mass which was already there in the vehicle it is coming out.

So, the principle of rocket is nothing, but it is ejecting out its stored mass to generate thrust. Now, if you look at the ejected mass is δM. So, if we know the mass depletion rate or the mass ejection rate if we consider the mass ejection rate as the $\dot{M}$ we can write down this δM in terms of $\dot{M}$ is going to be like $\dot{M} * \delta\tau$. So, you can simplify these equations and what about the mass at time instance τ if we consider the initial mass of the rocket is Mi = Mi - $\dot{M}\tau$ okay. So, now let us put these values in this push this relations into these equations what we can simplify we can write the M will become Mi - $\dot{M}$, but let us do some simplification you can see that MV will be cancel out from each side. So, if we do some simplification it will become $(M*\delta V) – (\delta M*Vj) = 0$ okay or we can write this $\delta V = Vj * (\delta M/M)$. So, we have already got the relationship of M which is Mi - $\dot{M}$i. So, we can simply write this equal to Vj we know the relationship of δM which is $\dot{M}*\delta\tau$ and M we know it is Mi - $\dot{M}\tau$, Mi is nothing, but the initial mass of the rocket.

So, this is the initial mass. So, that at any time instance M this means some amount of mass has already burned it has been expelled out like $\dot{M}\tau$ that has been expelled out. So, this is any instantaneous mass whereas, this Mi is the initial mass which is that means, it is contain everything there. Now, if you simplify this thing we can ultimately why we are interested to do this because we want to know that ideal velocity increments in terms of other parameters that is why we have written this one. So, if we know that the rocket is firing for the final time duration τf we can get the ideal velocity increment ΔV

$$\Delta V = \int_0^{\tau_f} \delta V = \int_0^{\tau_f} V_f \; \frac{\dot{M} * \delta\tau}{\dot{M}_i - \dot{M}\tau}$$

So, now, this is ideal incremental velocity because the losses due to gravity or otherwise is not considered in this case. So, if you assume the constant efflux velocity like this one if we assume constant Vj we can take the Vj outside of the integration and we can write that the ΔV will become

$$\Delta V = -V_J \;\; \dot{ln}(M_i - \dot{M}\tau)_0^{\tau_f}$$

$$= -V_f \; ln\frac{M_f}{M_i}$$

So, what we will get we will get minus Vj we will get the so, at time instance τf we will get the final mass. So, it will be the ratio of Mf by Mi whereas, Mf is the final mass. So, final mass means what it rocket consist of the structural mass Ms it consist of the payload mass which we can say like Mpy and the propellant mass which is denoted as Mp some book referring this payload mass as Mu also useful mass useful mass means the amount of mass we are carrying as payload.

So, we can refer to Mu as well in order to be consistent with the book the referred textbook. So, structural mass mass payload mass and propellant mass that gives the total mass which is the initial mass of the rocket so that means, it consist of Ms + Mu + Mp whereas, our final mass will consist only of Ms + Mu just because the all the propellant are only burned in the duration of τf the τf is the burning duration. So, if you like write this equation taking out this negative term inside. So, it will become like,

$$\Delta V = V_f \; ln\frac{M_i}{M_f}$$

Now, this equation is known as rocket equation or this is this was derived by Konstantin Tsiolkovsky.

So, sometime it is known as Tsiolkovsky equation as well. So, this is very important equation because it tells us that the ideal velocity increment is related to the efflux velocity or jet velocity Vj and the initial mass and final mass of the rocket. And, this is again irrespective of any kind of mode of ejections we are talking about like be it a liquid rocket or solid rocket does not matter this equation is equally valid. Now, we can understand that in order to increase the high incremental velocity the jet velocity or the efflux velocity has to be very higher whereas, this mass of Mi/Mf has also to be higher. Now, one parameter we should recall I would I do not say remember I should say we can recall in terms of the rocket propulsion course is the mass ratio of the rocket mass ratio of a rocket which was in common literature they are using it as R_m or maybe some other variable.

So, we are just denoting as R_m which is the m mass ratio, it is the defined as the final mass of the rocket by the initial mass of the rocket.

$$R_m = \frac{M_f}{M_i}$$

So, if you write in terms of mass ratio you can write the ΔV. So, you can if the if you wish to write this equation a. So, our equation a will becomes we can write this as

$$\Delta V = V_j \, ln \frac{1}{R_m}$$

So, this is the modified version of it. Now, the final mass of the rocket consist of the remaining mass because the all the propellants are already consumed. So, the remaining mass is there during its operation. So, mostly it is consist of some structural mass like the you know hardware mass of the rocket some of the you know power supply guidance and control system the some of the inert mass will be there some you know coating and these things. So, we can actually get some relationship of ideal velocity increment with respect to the efflux mass and the mass ratio of the rocket ok. Now, let us try to recall some of the other parameters what we already know already learned in case of with respect to rocket like we said the final mass is the mass of the structure and mass of the structure and the useful mass or the payload mass whereas, the final mass was given as the total mass Mu + Ms + Mp.

So, some of the definitions we can write here like the we know the payload mass fractions is denoted as the payload mass by the initial mass.

Payload Mass Fraction (α) = $\frac{M_u}{M_i}$,

Structural Mass Fraction (β) = $\frac{M_s}{M_i}$,

Propellant Mass Fraction (γ) = $\frac{M_p}{M_i}$

Now, we can modify the ideal velocity increment equation again and we can include these masses. So, it will be like

$$\Delta V = V_j \, ln \frac{M_u + M_s + M_p}{M_u + M_s} = V_j \, ln \frac{1}{\alpha + \beta}$$

because Mu + Ms + Mp we know is going to Mi. So, if you just put it this in the denominator we can actually get this payload mass fraction and the structural mass fraction.

So, I think these are the important equations from the previous one and the this one. Now, our another interest will be to know that what are the influencing parameters on the flux velocity or Vj or how the propellant characteristics or the type of propellants are actually playing a role in increasing the velocity Vj because we have seen that the ideal velocity increment has a very very influencing effect of the Vj. So, we need to know that how other parameters like the propellant characteristic, the temperature, the pressure ratios how they are influencing the Vj. So, I think we can look at this Vj and the influencing parameters on Vj in the next class ok. So, see you all there. Thank you.