Course Name: Combustion of Solid Fuels and Propellants

Professor Name: Dr. Srinibas Karmakar

Department Name: Aerospace Engineering

Institute Name: Indian Institute of technology-Kharagpur

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Lecture: 06 Solid Propellant Rocket-Brief Description

Hello everyone, welcome back. So, we are continuing with our discussion on the NPTEL online course, Combustion of Solid Fuels and Propellants. And we will continue our discussion on the module solid propellant rocket. So, if you recall what we introduced in the last class, we have just discussed the various components of a solid propellant rocket. And we brought our attention mainly to the propellant grain if you look at the white colour stuff inside which is the propellant grain perforation, and the grey colour stuff which is the propellant grain. So, the perforation is nothing but the internal hollow space called grain configuration.

So, we will come to some of the discussions about the grain and grain configuration. So, the various components I think we already discussed, let rather we can say we have already revised some of the things because many of you have already learned the basics of liquid propellant rocket, solid propellant rocket. So, there is no point in discussing those things again, but few things we cannot avoid revising because the focus of the course is the combustion of solid fuels and propellants, but without knowing what kind of solid fuels we are talking about and where it is going to be applicable, that is why we want to just bring some of the basic stuff for solid propellant grain. So, as we now know propellant is a combination of fuel and oxidizer, and they are made into a solid block of material which is known as the propellant grain.

So, this propellant grain is stored in or placed in the interior of the motor casing. So, the outer casing you can see this is the outer casing of the motor. So, it is placed internally in the motor casing. Now, depending on the perforation which is the grain configuration as per the rocket terminology. So, based on the perforation the burning rate will be different.

Now, this burning can either increase with time, it may decrease with time, or remain constant with time depending on like what are the internal perforations used in the grain. Now, here it is shown that only a single grain, but it may be possible that two or multiple grains are placed together to maintain a different thrust time profile. So, with time the thrust is going to change once we have a different configuration. So, now let us look at what is grain and what is grain configuration, we will just discuss this briefly before we proceed further. So, as we said the propellant grain is the shaped mass that is cured from the ingredients.

The propellant ingredients contain the fuel, oxidizer, binder and of course, several other ingredients we will talk about those ingredients after this module. So, if we look at the grain, now categorically the grain can be placed directly into the motor like either we can make the grain separately in a processing setup and we can put the cured grain inside the motor casing or rather we can say we can load the grain in inside the motor casing or we can directly cast the grain within the motor casing itself. So, based on these methods of holding the grain, they are categorized into two types of grains. One is called cartridge-loaded grain, sometimes it is also termed as free-standing grain like if you can look at the grain is processed and cured separately not inside the motor casing. After curing the propellant grain is loaded into the casing and there are a lot of supports you can see forward support, backward support, insulations, and liners that are required to hold the grain.

But the advantage is that if there are issues with any grain you can we can easily change this grain, we can replace the grain because the grains are manufactured or processed separately. But in the case of a case bonded grain, grain is processed directly into the motor casing itself. I mean to say that the propellants and propellant ingredients are mixed and poured directly into the motor casing and the casting process takes place within the motor casing itself. So, the whole process of casting and curing is done within the motor casing itself. So, of course, compared to the cartridge-loaded grain, the freer inert mass is required to hold the grain because since we are directly casting and mold casting and curing the propellant within the motor casing, the requirement of the support materials will be less.

So, generally, in small tactical missiles where the mass of the grain is smaller, cartridge-loaded grain grains are very common. Whereas for a big rocket or rather very huge rocket where the size of the propellant grain is huge, there cartridge grain is not the right way of doing it because handling that large grain is going to be a difficult task like loading it into the motor casing. Rather the grain is processed and cured within the motor casing itself, sorry the grain is cast and cured within the motor casing itself. So, many large rockets use this process of having the case bonded grain. Having said that, now let us look at some of the important terminologies related to the grain and the grain configuration.

Because you see what we are trying to understand in this course, we will try to focus on how the propellant in the grain is going to burn, and what are the underlying mechanisms that the propellant is going to burn. Now, the propellant may contain various types of ingredients. For example, it will have fuel, it will have a binder, it will have oxidizers, it has multiple types of oxidizers, and there may be various types of fuels that can be applicable. So how their ingredients are going to play a role in the burning mechanisms? So before trying to understand the burning mechanism, we must know for what type of fuel, what type of ingredients are we looking for, and where they are applicable.

So, the propellant and fuel we are talking about in this course are going to be applicable to solid rockets only. So, in this course, our discussion is limited to solid rockets only. That is why we are focusing more on revising some of the stuff related to the solid rocket only. Moving forward, we may look at some of the terminologies which are essential for solid propellant rockets. For example, as we said the grain already has the shape mass containing the propellant which is placed inside the motor casing that is the grain.

Now we also said the grain configuration. Now grain configuration is the internal perforation that we give to the grain to have different types of thrust time profiles or pressure time profile. So, if you look at the cavity inside the grain, it may be like a cylindrical one. So configuration means we are talking about the internal configuration. So, this is the cylindrical one.

If you look at the other view of it, it is just a circular cross-section. It may have a different type of configuration. For example, it may have like let us say it will have some square configuration. So internal perforation is square. So, if you look at the other view of it, it will show a square shape.

It may have like star shape. It may have some wagon wheel like this. It may have like multiple cylindrical holes. So multiport geometry. So, the internal geometry of the grain is called the grain configuration.

So, depending on the configuration, the pressure time or the thrust time profile will change. So based on the configuration, it may have a progressive profile burning profile or it may have like regressive or it may have neutral. As the name suggests progressive means it increases with time. So, if you just simply plot the pressure or the thrust with time, we will see that the pressure or thrust is going to increase with time like this. So, this is the progressive pattern.

So if you look at the cylindrical cross-section sorry cylindrical grain or cylindrical grain configuration, you may see that from the initial burning surface area as time proceeds we can see it will reach a burning surface like this at a different time instance. We will keep on going as time proceeds until it reaches the outer until it reaches to final diameter of the grain or the up to the internal liner of the motor casing. So here we can see the burning surface. So this is let us say this is the initial burning surface area Abi that will go up to the final burning surface area here which is like Abf. So it keeps on increasing.

If you look at if you consider the length here that the length of the grain is L, we can find out the initial burning surface area by considering if the diameter of the initial diameter of grain was di, if the final diameter is df, we can write it down or we can just symbolize it with small one; di is the initial diameter of the grain, df is the final diameter of the grain. So, our Abi is going to be equal to-

$$Abi = \pi\, di\, L$$

Because, you have to think about the cross-sectional area of the internal surface of the grain. So, if you look at the cut web view of it, you can see this is essentially the grain. So here we are talking about the internal surface.

So initial surface was like this. This is the half of this. So if the length is L there, this was like diameter was di. So pi di into L that will so basically pi di is going to give us the perimeter of this circle into the length of the grain will give me the burning surface area. So the initial burning surface here is going to be:

$$Abi = \pi\, di\, L$$

Similarly, the final burning surface area will be:

$$Abf = \pi\, df\, L$$

So, as you can see as time proceeds the burning surface area is increasing. As a consequence, the pressure and or the thrust both will increase. So, this type of burning profile is known as the progressive burning profile or progressive burning. Now if the burning decreases with time, we can say the burning features are kind of regressive.

So, this type of burning is called regressive. So, if there is some geometry where we can see that the area is decreasing, we can take one example like let us say rod type of configuration. So, the grain is instead of having the internal perforation, the grain itself is the cylinder. So, what is going to happen? It is going to radially inward burning. So, in the case of a cylindrical perforation, we can say it is a radially outward burning.

So, burning is taking place radially outward. So, there we have seen that it is increasing the surface area, but here the surface area is going to decrease. So, this type of burning will cause a decrease in pressure or thrust with respect to time and that type of burning profile is called regressive burning profile. Now if the burning area remains constant over time, we can say it is going to be neutral burning that the burning surface area remains constant with time. Similarly, the pressure and thrust will remain constant over time.

That type of burning profile is called the neutral burning profile. Now typical example can say it is going to be end burning rocket where the grain is having the constant area.

So this is the grain of the rocket. So, this is propellant grain. Now burning is going to take place longitudinally.

As time passes, the burning surface area will remain constant over time. So, with this type of profile we can get a neutral burning profile or we can say in consequence that pressure and thrust will not change with time. So, it will have a constant pressure or constant thrust profile over time. So, this type of end-burning configuration will give a neutral burning profile. But a combination of two different grain configurations can also give this thing.

So instead of having this end-burning profile, we can have like combination of the rod and tube. We can have two different grains. One will be cylindrical, other will have a rod. So we can have in this grain will have radially outward burning whereas the rod one will have radially inward burning. So, somehow they may compensate each other and it is going to create a neutral type of burning profile.

So, this is possible. It is not only that the end-burning type of burning can only give the neutral burning or end-burning propellant can only give the neutral burning. But there is a possibility that a combination of two different grain configurations can also give us neutral burning. There is a possibility that making the star shape grain by choosing the number of vertices and the angle between the plane surfaces, there is a possibility that we can make the configuration in such a way it can also give the neutral type of burning. So of course, in connection with the solid propellant rocket, we should know these terminologies like what is grain, what is grain configuration, and what are the different types of grain configuration. Now generally radial burning radially outward or radially inward or even longitudinal burning although the propellant grain is three-dimensional, but generally, this type of burning are considered, this type of grains are considered to be two-dimensional grain because the burning takes place either longitudinally or radially.

It can be radially inward or it can be radially outward in case of progressive burning. But there are certain grains where the combination of longitudinal and radial burnings is also possible. There are kinds of grain configurations which are having like three-dimensional nature you can say. So, these are called three-dimensional grains. We will show you some pictures later part of this lecture.

Now, let us talk about the various other terminologies that are important in the case of solid rockets. What is sliver? Sliver is the unburned propellant. So, the remaining propellant which is unburned is called sliver. If you look at certain grain geometry for example, like cylindrical one, cylindrical grain configuration, the burning will continue till the burning surface reaches the final diameter of the grain or the till up to the liner of the rocket inside the motor casing. So, here the chance of unburned propellant is very unlikely.

But let us say if you have a grain configuration something like a square type, the initial burning surface area is a square type. Now, if you keep on generating the burning profile, we will see the corner will become kind of a circular here, rounded shape, the corner will not stay as a corner. So, it will be circular in shape. So, it will continue like this, until it reaches the final diameter. So, it will come like this, like this, like this.

So, there is a chance that some amount of propellant will remain unburned after the burning of the main part of the propellant. So, that unburned propellant is called sliver. So, there are some grain configurations where there is a chance of unburned propellant remaining, which is of course, not expected. And of course, it is undesirable because this is not going to give us the correct I mean required thrust time profile that the grain is designed for. Let us say if this is designed for a particular thrust time profile, but once there is an unburned propellant that will if the temperature and pressure are high enough the sliver will also start burning, but that will cause some kind of a different thrust time profile which is undesirable.

So, of course, a sliver is necessarily not to be present in the case of burning of the propellant. So, of course, there is a chance that some mass will remain unburned which is called a sliver. So, this is another terminology. Now in connection with the burning of the propellant, there are some times which we generally define in the case of solid propellant rocket like if we again draw the thrust time profile or pressure time profile. So, P or F with respect to time we generally get a profile like this.

So, this is the initial known maximum value either thrust or pressure. Some, time as per the literature the 10 percent of the P max. So, let us say this is the 10 percent of the P max and if you just join this with here, we will get two points. So, this 10 percent of this

P max will get some time duration. This time duration is known as the accent time, it is termed as the ascent time.

And, from here if we draw the aft tangent bisector like we can see the pressure is increasing and then it is remaining for some time if it is a neutral type of burning and it is going to tail off or is going to drop. So, if you draw the tangent here aft tangent bisector we can get there is some point we will get. So, we can draw normal here. So, this will give us some points. So, from the 10 percent of the P max till this point, this point is defined this time period is defined as the burning time.

So, this is like an aft tangent bisector. If you follow any rocket propulsion book, I think this type of terminology will be available there too. So, you please revise that it is called burning time. So, I think this terminology also is required to be you know aware of because they are very common in the case of solid propellant rockets. Now, other terminologies are very often used in defining certain things in the design of the rocket. So, like wave fraction, web thickness, volumetric web volumetric loading.

So, we can just look at some of the other things like what is the web thickness. Now, web thickness is defined as the minimum thickness of the grain from the initial burning surface to the insulated case wall. So, if we just look at our typical cylindrical grain. So, what was our initial burning surface area was this.

So, from the initial burning surface to the insulated wall. So, this was the insulated case wall let us say. So, if we just from here if we get the distance this is known as the web thickness or b. So, this is the minimum thickness of the grain from the initial burning surface area to the insulated case to the insulated casing or insulated case wall. For different configurations we can define this one in the same way let us say it is a square configuration. So, the wave thickness for the square configuration will be the minimum thickness of the grain.

So, from this corner to the insulated case wall will be my web thickness. As you know other combinations of grain configurations it can be to the intersection of another burning surface. So, if there is a combination of you know two different type of configurations. So, it can be the intersection of the another grain.

So, that is defined as the web thickness (b). So, this is also very important in terms of burning the solid propellant. Then we define web fraction which is you know symbolized as bf which is defined as the:

$$bf = \frac{b}{r} = \frac{2b}{D}$$

Another terminology is called volumetric loading. It has the symbol Vf which is the:

$$Vf = \frac{V_{propellant}}{V_{chamber}}$$

propellant volume divided by the chamber volume. Chamber volume means the volume available for propellant not only propellant, propellant insulation, and restrictors till the convergence section of the geometry or we can say the chamber is the volume of the propellant to the volume available in the chamber for you know propellant insulation restrictors.

So, it is like the total volume we can say. So, this is the volumetric loading fraction. Now, volumetric loading fraction is not only volume loading, volumetric loading fraction, or Vf. So, why it is important because you know that aerospace vehicles or rocket rockets are volume-limited. So, the available volume for the propellant is limited.

We cannot have abundant space to load the propellant. That is why the density is kind of playing an important role there. The denser the propellant more mass we can put in a constant volume in a restricted volume. That is why we need to increase the volumetric loading somehow by you know I mean improving the volumetric loading. So, that we can see the volume of the propellant we can know and we have to use this volumetric loading fraction efficiently because once the volumetric loading fraction is defined, we know how much propellant volume is available there. So, we have to use that volume of the propellant judiciously by adding by considering the high dense propellant and we can actually improve the volumetric loading fraction.

Now, for designing the various grain configurations of course, various parameters play an important role. For example, flight missions will tell us about the rocket motor requirements, and the grain geometry which is very much related to the pressure time or thrust time profile. What kind of profile we are looking for is it a neutral one or a progressive or regressive one that will tell us what type of configuration the grain is supposed to be? Now, if it is a complex type of grain configuration, we need to look for whether the available propellants or the choice of ingredients can handle that type of grain geometry. That is another important consideration because your propellants would have enough strength to handle that type of complex geometry.

Generally, as you know it is the propellant is chosen or selected basis of based on the propellant characteristic. For example, characteristic velocity the mechanical properties of the propellant or the grain or the strength of the propellant, and the ballistic profile like burning rate. So, they are supposed to be well known before we consider that type consider propellant for particular applications. So, we can say these are interrelated requirements for choosing the particular you know grain geometry. It is not a single requirement that it is fulfilling only the ballistic property or the mechanical property the burning type of burning or the burning profile whether regressive, progressive, or neutral.

It, of course, depends on the various property requirements starting from the flight mission because the flight mission is going to tell us what type of you know what are rocket motor requirements. And of course, they have to be defined before the grain can be designed. So, the choice will very much depend on the inter interrelated requirements. So, I think we pretty much you know covered the terminologies required for us to know the grain and grain configuration.

With that, I think we can close this lecture. In the upcoming lecture, we will go a little further regarding the you-know choice of grain configurations. We will try to discuss some of the basic configurations like cylindrical grain, square grain, and maybe the star shape grain. Thank you.