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: 07 Solid Propellants - Introduction

Welcome back. So, let us continue our discussion on the solid propellant rocket. In the previous class, we have discussed about various terminologies related to solid propellant rocket starting from the grain and grain configurations. What are the different types of burning profile like progressive, regressive, neutral. How the burning profile can actually depend on the different type of different types of configurations. It can be like cylindrical, it can be square shape, it can have multi hole, it can have wagon wheel structure, it can have star shape geometry, it can have rod and tube.

So, depend on the various configuration the burning profile may change. We also have talked about that the radially outward or radially inward type of burning or longitudinal burning, they are generally termed as the two dimensional grain. Now the combination of the radial burning and longitudinal burning sometime they are referred to as the three dimensional grain. If you look at this grain pictures, these are like combination of both radial and longitudinal burning profile.

So, it can have like conosyl. So, it is a combination like cone and cylinder. It can have fin and cone combination of fins, you can see different fins is there. So, it is a combination of cylindrical grain with fin structures in the grain geometry. So, it is termed as the finosyl.

Then it can have like spherical type of grain configuration which is of course, have some slots and cylinders. So, they are you can we can consider them as the three dimensional grain because they are combination of the radial burning and longitudinal burning profile. Or other type of like cylindrical grain or the end burning grains those are although the grain itself are three dimensional in nature, but depending on their radially inward or radially outward or even longitudinal burning profiles, they are actually considered as the two dimensional grain. But where there is a combination of both radial and longitudinal burning profiles, they are termed as the three dimensional grains. So, now, we want to look at further with the very simple burning profiles we have just seen like for example, like the cylindrical grain.

So, if you look at the cylindrical grain, we have seen that the internal perforation is cylindrical. So, if you look at the other view of it in a simplistic structure we can say this is the grain. So, let us say we draw the rocket also. So, the cylindrical grain is having a nature of radially outward burning. So, it is burning radially outward and we have already said earlier that since it is radially outward the burning surface area is increasing over time.

So, the pressure and thrust both will increase over time. Now, if you look at carefully what exactly it is happening that the surface is actually regresses over time. So, at some at certain time instant thus from the initial surface to delta T time instance it will reach to another surface area after certain instant of time it will reach to another then it will keep on moving until it reaches to the case wall or the inner liner of the casing. In case of burning of rocket propellant grain the regression rate or the burning rate is termed in I mean sorry it is generally measured in terms of length regression over time like what is the length regresses over certain period of time. So, and it is termed as r and it is given as the length by time like how much millimeter or how much centimeter per second it has regressed over time.

So, that way it is basically a linear regression rate you can say that how much millimeter per second has regressed this is called the regression rate or burning rate of the propellant. Now, from there one can actually understand that if we know the regression rate since it is a millimeter per second or meter per second if we know the burning surface area we can actually get to know the mass flow rate with respect to the burning rate or the regression rate into the burning surface area into the propellant density. So, if the burning surface area remaining constant we can actually get r into A b into rho a we can get the mass flow rate. If this is also constant we can easily get it for example, like if it is an n burning rocket we can say the burning area remain constant like it is burning regressing like this. So, A b is fairly remaining constant.

So, we can actually get the mass flow rate also kind of constant because that is the product of combustion which is going to come here and that is going to expand in the nozzle same thing here the flame will stay somewhere over here. So, the product of combustion will come here and they will expand the product gases are going to expand through the nozzle. So, this is the nozzle. So, we can relate the mass flow rate with the burning rate or the regression rate because since it is a linear one this will give us the mass flow rate of the or the mass regression rate of the propellant. Now, this can be related to you know depending on the type of burning whether it is going to increase decrease that will definitely tell us the value of R type of propellant not all type of propellant will have the same burning rate.

There are there are propellants which can burn faster or which can burn little better compared to the other propellant. So, depending on the ingredients of course, this burning rate is going to change. Now, coming back to the simple burning sorry simple grain configurations as we talked about one is the of course, the cylindrical grain configuration. So, where the internal perforation is a cylinder. So, if you look at this one it will keep on burning like this the evolution of burning surfaces will continue like this and it will go on ok.

So, one can define the initial burning surface area is A bi equal to pi Di into sorry Di into L. The final burning surface area can be defined as the pi the final diameter into L. In between if wants to know that one can actually do that in between let us say intermediate. So, we need to know the intermediate diameter there and that into L and if there is a delta amount of you know burning has taken place like the. So, what is the wave thickness here? The wave thickness here is B as we have already defined in the previous class.

$$Abi = \pi diL$$

$$Abf = \pi dfL$$

$$Abit = \pi ditL$$

So, this is the wave thickness ok. So, for a different time instance if we know the burning rate from the initial to the that time instance one can actually get the average burning rate. For example, like let us say I want to know that how much time it has taken for delta thickness of the propellant burnt what is the time duration. So, what you need to know is we need to know the average regression rate for this time instances. So, we first find out the value of r i the initial burning rate and for that matter we need to know sorry the we need to know the time period for that.

$$r^- = \frac{ri+rs}{2}$$

So, we need to find out the what is the burning rate was there for that first one then the burning rate was for that particular distance r delta let us say. So, one can find out the average of the burning rate from there by taking this 1 by 2 and from there they can get the time instance for that taken for delta instances delta thicknesses is like delta by r one can find out the time duration taken for burning the delta thicknesses it is like that ok. So, definitely one can look at various grain configurations and try to analyze the things by considering the burning rate. So, we will look at the very very simple configurations like one is the circular one which is the cylindrical grain configurations. So, we can actually get the time duration taken for delta thickness to burn.

$$\Delta t = \frac{\delta}{r}$$

Similarly, one can actually look at the other configuration for example, if we have let us say square configuration. Once we say the configuration means we are talking about the internal perforation the nature of the internal perforation. So, initial cross section is the configuration. So, which is square let us say the each side is like b maybe you can just define in other we can define this slightly different way because we have already defined wave thickness as B. So, let us make it as H remember the length of the grains which is the other side of the board.

So, here the length is like as you said L that is why we got the initial burning surface area as pi dF into L here the final burning surface area was pi dF into L. Now, what about the case for the square configuration if we are asked to find out the initial burning surface area what can we write? We can write the you see it is extended over the length L. If the grain has the length of L each of this H into L that is the you know H times L each side of it. So, there are 4 of it. So, you can simply write 4 H L that is our initial burning surface of the grain.

$$Abi = 4hL$$

Now, we can consider at a different time instance for example, like since the initial time sorry at the first instant or initial burning surface area we are getting like 4 H into L. So, this is like initial burning surface area. Now, if you look at let us say there is a delta is the wave thickness. So, if we keep on moving with this grain it will reach to maximum to the liner or the casing inner casing of the motor. So, it can reach up to here.

So, if this is the thickness let us say is delta we can get the final burning surface you see if we draw it properly initial burning surface was like this. So, the square will remain square till the end, but as you said the corner will become rounded. So, it will be like this something like this. So, this b will become still will have hwill have h here. So, this is h, this is h, this is h.

So, the initial as we had 4 h into L that will be there 4 hL plus we have to consider this part which was which we can get like this is like delta F we had sorry delta we have defined there. So, this is the radius. So, we can get like 2 pi R by 4 that will give us the perimeter of the circle because this is like a arc. So, we need to know the length of that if we consider the length of that we have 4 of them 1, 2, 3 and this 4. So, if we do that we have like 2 pi into delta L.

$$Abf = 4hL + 2\pi\Delta L$$

So, that will give us the final burning surface area this was the initial this is the final burning surface area. So, one can easily you know find out the what is the burning surface area if we know the value of H and value of L. So, some numerical problem one can try that let us say after a certain time instant the it has reached to the value delta or the web thickness is delta what will be the final burning surface area we can easily find out from there. Now, there are some grain configuration which is a combination of you know this square shape and the cylindrical shape. So, we have to use the you know combined form of this based on the geometry and we can use this evolution of burning surfaces and we can actually get the final burning surface area.

Now, if you look at this burning processes as we said earlier that there will be some amount of propellant which will be left out even after the final burning. So, this is like left out propellant. So, it will burn till the web burning web burning is which is the delta in case of this one this was the web burning B we could have defined this as B also because as per our definition web thickness was b. So, we can write this as B also since we have already defined this as H.

So, it can be B. So, 4 H L into 2 pi B L there is a final burning surface area. Now as I said the burning will continue till it reaches to the inner wall of the casing, but if the pressure and temperature is high enough this remaining propellant which was actually the sliver may also burn. So, if you look at the typical pressure time profile or the even if you just simply plot the burning surface versus time what we can get? Initially the burning surface. So, it is starting from the initial surface area it is still keep on continuity till it reaches to the final burning surface. And then if the pressure and temperatures are high enough the sliver may continue to burn, but if you look at the sliver will not having the progressive nature means the surface area is not going to increase further because we are looking at the sliver which is something like this.

So, as the burning continues the surface area will keep on decreasing. So, this is the sliver. Sliver is going to burn, but it will reduce the surface area. So, the surface area is going to here the surface area is going to reduce. So, this part of burning which was basically burning the web.

So, this is called the web burning and this part is called the sliver burning. Of course, sliver is not the intended for the solid propellant because this is the remaining unburned propellant. It is actually changing the intended burning profile if the sliver is remaining. This is a simple configuration that is why we are able to tell you that this is happening like this, but there are some complex geometries where in a different corners there will be some remaining sliver. So, which will gives the different burning profile and that will actually influence the pressure time or thrust time curve.

So, in general in design practice is like we do not want any sliver to be present after the full burning duration. So, sliver is not intended it is like the unburned propellant. One can actually do some you know some calculations with this and try to find out that how much sliver is remaining after the web burnout. Like after web burning if we know some of these you know parameters like a value of h, value of l and then we can know the burning time. After that we can calculate that how much amount of sliver is remaining after the web burnout.

Now, the another configurations as we said was the star safe configuration. So, depending on the number of vertices we can have like if n number of vertices n vertices. So, it will have 2 n flat surfaces like 1, 2, 3, 4, 5, 6.

So, it is like 6.8 star. So, we have 12 flat surface means we are talking about these are the surfaces for each vertices there are 2 flat surfaces. So, if you look at they will keep on burning like this like this. So, one can actually try to see that how the burning profile will depend on the number of vertices and number of you know flat surfaces. The angle between you know them how they are actually going to influence the burning profile of the star safe. So, this is like you know star configuration, star grain configuration.

Since the as I am repeating many times now that since the focus of the course is on the combustion of solid propellant and fuel we are not going into the details of the rocket propulsion side like the internal ballistic of the rocket. So, I would rather request all the participants to refer some of the materials available in the basic rocket propulsion book or even the NPTEL lecture materials where these you know different configurations are discussed and how the evolution of burning surface take place those are pretty much discussed in the in those courses or even in the lecture materials. So, please refer to those that depending on the number of vertices the angle subtended by them like what is the angle let us say if it is angle theta number of vertices is N how they influence the burning profile either you know progressive, regressive or even neutral. So, the star safe you know configuration can have all these all 3 profiles either progressive or regressive or even neutral depending on the number of vertices and the angle subtended by their flat surfaces ok. So, please look at some of the previous you know study materials where you can understand that how they are influencing the burning profiles.

So, I think we will not go further on the grain configurations I am just leaving it to the participants to revise some of the materials. So, that we can come back to the main track of the course and we will focus more on the you know fuels and propellants used for solid rocket all right. So, let us try to look at the various you know propellants used for solid rocket, but before moving into that we have talked about one thing which is called the regression rate in the previous lecture rate r. So, I may forget later on I should at least mention here is that you know the regression rate is the length regression over time. So, it is like millimeter per second or meter per second, but it is defined as the length regression like if it is a radially outward burning.

So, it will like how much radius has you know regresses over time. So, now the question is how it is defined sorry how it is determined that how much millimeter per second has regressed for a particular propellant. So, there are different testing methods choosing a certain propellant of course, it will very much tricky in order to choose certain propellant we need to understand the burning rate like how the propellant is burning. So, there are different methods used step by step like very initial method is the strand burning experiment or strand burner using strand burner it is sometime known as the Crawford strand burner or Crawford bomb where the strand is actually allowed to burn inside a pressurized chamber. So, a small propellant strain strand it may be ignited by the ignition coil, there may be optical section to view it various you know modified configuration of this setup is available of course, it is pressurized with nitrogen.

So, at a different pressure it allow the propellant strand to burn. So, this is propellant strand there may be some you know fuse where located at a specified length L. So, as the burning surface regresses over time. So, the outer surface of the propellant is inhibited means it will only allow to burn from this surface only.

So, the burning will proceed like this. So, one it reaches to the first fuse where it will got cut, it will be start the timer unit. So, maybe this is connected with a timer unit which will load the time until it reaches to the second wire it will give the time delta t. From there since it the fused wire wires were located at a specified length one can find out the value of burning rate by dividing the length over time by time. So, that way one can understand the regression rate for that particular pressure. Now, one can actually do it for various you know R 1, R 2, R 3 and so on at different pressure.

And, it can be you know found out at various pressure how the burning rate is varying. Now, why I am telling this thing because we have brought about this important parameter R, we can later on see that how these burning rate is very much dependent on the pressure. Once we talk about the mechanisms of I mean the burning mechanism of various propellants. Now, this is one method the other method is like you know small ballistic motor where we can actually use a static rocket. Static rocket means we do not allow it to go away it is like hold and we allow it to burn.

So, it will regress and from there actually we can calculate the regression rate. So, the first stage of the testing is the strand burning. So, this requires small amount of materials it does not need to be of very high cost. So, this is the first step for the propellant development. So, if we choose a different ingredients immediately after that we just do the burning rate evaluation by using this coffered burner or strand burning test.

Then, once we have enough confidence we at least get the burning rate versus pressure profile and we know that how the burning rate is changing over different pressure values. We can go to the small ballistic motor test and there we can look at the thrust time profile time profile there. Then finally, if are they are satisfied this will go for further testing like the you know with you know flight testing with instrument. It may be like semi instrumented, but the flight testings with that type of propellant is carried out for that particular rocket with you know instrumentations. So, these are the various testing methods since we talked about this one.

So, that is why it is very much relevant. So, we first begin with this you know coffered burner test to know how the different ingredients are playing an important role there. So, now, we are in a in a state that we can at least you know understand that the burning of the propellant how they are how it is important because it is influencing the eventually the performance of the rocket. And, the burning of the propellant means we are talking about the burning of the propellant grain. Now, we are going to discuss that what are the different ingredients which are going to be essential or there are certain ingredients which are going to influence the burning rate of the propellant. So, our next topic of discussion will be the solid propellants ok.

So, this is going to be we will begin this next module like solid propellants in the next lectures. But, we should you know remember that as you said the propellants must have like the fuel and oxidizer because since rocket is not carrying sorry since rocket is not taking any oxidizer from the atmosphere it must carry its own fuel and oxidizer there. And, since it is a solid propellant the fuel and oxidizer are mixed together. If, you recall our introductory class where we have talked about the different type of rockets solid rocket, liquid rocket and hybrid rocket we have seen that for liquid rocket the fuel and oxidizers are stored in a separate tanks and they are supplied through some you know turbo pumps. Whereas, in case of solid propellant the fuel and oxidizer are mixed intermittently and they are made to have a shaped mast which we now know it is called grain.

So, basically the solid propellants are having must have the combination of fuels and oxidizer plus other you know ingredients. So, in the next class we will start looking at what are the different characteristics of the propellant which are kind of need to fulfill. So, that the choice of you know what are the requirements to be fulfilled by the propellant in order to you know have them in the propellant grain. So, the criteria for selection of the propellants that we will discuss in the next class. Thank you.