Course Name: Combustion of Solid Fuels and Propellants

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Lecture: 08 Solid Propellants-Selection Criteria

Hello everyone, welcome back to the Combustion of Solid Fuels and Propellants course. So, we will continue our discussion on solid propellants. If you recall what we discussed in the previous class, we have mainly talked about grain, which is the solid block of propellant put inside the rocket motor and constitutes major ingredients like fuel and oxidizer. So, it is basically a shaped mass. Sometimes, we can say it is a rubbery mass because the binder is actually a polymer. So, upon solidification, the polymer becomes solidified, and it contains all the other solid ingredients such as oxidizers, fuels in terms of various metal particles, and other ingredients, which we will discuss in the later part of the lecture. Now, we also discussed in the previous class the grain geometry or the grain configuration which is nothing, but the internal perforation of the grain which decide the burning rate or the type of burning rate, how the burning surface area evolute with respect to time.

So, we have discussed the various ah parameters in the context of grain configurations. For example, we have talked about the different types of burning: progressive, neutral, and regressive burning. We have talked about web thickness, web fraction, and the volumetric loading fraction, and after that, we have talked about some simple grain geometry, such as cylindrical shapes and square shapes, and we have talked about star shapes. Now, to get more information on the various grain configurations, the participants are suggested to refer to the available materials either on NPTEL courses or through some textbooks to better understand the major parts of the grain configurations and their relative influence on the burning rate.

Now, since our focus of the course is the combustion of solid fuels and propellants, we will bring back our discussion on the solid propellants part. So, today, we will talk about the selection criteria of solid propellants. What are the major characteristics we must consider when choosing a particular propellant? Of course, rocket motor design is very critical, but we need to understand the various characteristics of solid propellants. Some of these characteristics are common to liquid propellants as well, but since our major focus is solid propellants. So, we will only talk about solid propellants. So, let us look at the propellant characteristics.

So, first and foremost thing, if you remember what we said is the performance of the propellant must be higher. So, if you recall what we said, the rocket's performance must be higher. So, in order to choose a propellant, the first and foremost thing we said we should always think about is that the choice of the propellant will be in such a way that there is always the tendency for it to provide high performance. So, high performance means we are talking about a specific impulse, or you can say, in other words, like the characteristic velocity of the propellant C star. If you recall, the propellant must fulfill several interrelated requirements.

For example, the flight missions will tell us the rocket motor design, and then based on the mission based on the rocket motor design, the designer will decide on the grain configurations, which will tell us the pressure time or thrust time curve. If you recall, we had discussed the pressure time or thrust time curve for progressive, regressive, and neutral types of burning. In case of progressive we have seen that thrust or pressure increases over time. Similarly, for regressive, it decreases, and for neutral, it remains constant. So, the propellant has to satisfy some of the interrelated requirements related to grain geometry.

Now, the major part of the major criteria the propellant must fulfill is performance. There is no compromise on the performance. So, performance means we are talking about the Isp or if you say it is C star. So, if you recall the equation of Isp or you can say the V_J or the exit or the exhaust velocity or the flux velocity that was proportional to the chamber temperature and the molecular mass of the combustion products or we said the molecular weight of the combustion products.

$$Isp \sim \sqrt{\frac{Tc}{Mw}}$$

So, from this equation, we can see that the higher the combustion chamber temperature or the higher the temperature of the combustion gases, the higher the performance.

So, the propellant must provide a higher gas temperature. What does that mean? It must provide high heat release to get high temperatures in the combustion chamber because that will eventually lead to high jet velocity while expanding in the nozzle. So, in order to achieve high performance, the propellant should give us very high heat release, which in turn is going to give the high chamber temperature. On the other hand, since it is proportional to 1 by the square root of the molecular weight of the combustion gas or combustion products, the molecular weight is supposed to be lower. So, we are looking for propellants that can provide a very high temperature in the combustion chamber, and comparatively lower molecular mass of the combustion products are preferred in order to give high performance.

This will give high performance if the chamber temperature becomes larger and the molecular weight of the gases becomes smaller. How are these considerations coming if you look at the heat release from the combustion reaction? So, in order to have a high temperature of the combustion gas, we should also think about it in terms of, like, you know, how this is importantly related to the temperature. So, we can see that delta Hc by Cp will be the chamber's temperature.

$$\frac{\Delta Hc}{Cp} \sim Tc$$

So, in order to have a high chamber temperature inside the combustion chamber, we should also have a lower value of the specific heat of the products.

So, this is specific heat. So, we expect the specific heat of the products to be smaller because that will provide us with a high temperature for a given energy release if the energy release is constant for a given energy release if the specific heat of the products is smaller, then this is going to give us high heat release a high chamber temperature or high temperature of the combustion gases. So, that is another requirement. You know, gamma. We have seen that gamma is kind of weak, a weak influence on the performance in the previous lectures. If you recall, we have seen how V_J is dependent on gamma. So, gamma has a weak influence.

So, it is kind of not that significant compared to the other parameters. So, the major thing is that the chamber temperature has to be higher, and the molecular weight has to be lower to achieve high rocket performance. So, the propellant must ensure that it can generate high chamber temperature. In order to generate high chamber temperature, it is expected that the Cp values of the products are supposed to be on the smaller side. This is the requirement, and of course, the molecular weight of the gases is supposed to be lower.

Now, if we go back a bit from our thermodynamic side, like what we learned in the thermodynamic course, particularly the chemical reactions. If we just look at the consideration of heat release, the heat release from a chemical reaction, or in the case of our combustion reaction, we can say that the heat release from combustion, which is delta Hc, is related to this delta H^0f. So, this is going to be like ni delta H^0f. So, this is for the reactants and the products. So, it is basically the summation of the heat of formation.

$$\Delta Hc = -\left\{\sum mi\, H^0 f - \sum ni\, H^0 f\right\}$$

So, here, delta H0f is known as the heat of formation. I think if you recall your knowledge in thermodynamics, by definition, what we learned in the thermodynamics course was that the heat of formation delta H0f was defined as the energy released or absorbed, and it may be either case. So, the heat of formation delta H^0f what we said that we learned from thermodynamics that heat of formation is the energy released or absorbed. It can be either way, or we can say the value of enthalpy changes when 1 mole of the chemical compound is formed from its constituents. So, the chemical 1 mole of the chemical compound will be formed from its constituents. For example, carbon plus oxygen will form a CO_2 ok, but the condition is that that will happen at the condition 1 bar of pressure and 25 degrees centigrade of temperature ok 25 degrees centigrade temperature 1 bar of pressure.

So, if one chemical compound is formed from its constituents, the energy released is either released or absorbed, or the enthalpy change, you can say, is known as the heat of formation. Now, if you look at the thermodynamic book back side of the book you can find out the values of heat of formation of various compounds where you can see some of them are positive, some of them are negative, some of them are they were largely negative, some of they are having like small negative, some of they are having like small positive. From our earlier equation, we wrote that the heat of combustion was the summation of the heat of the formation of the products minus the heat of the formation of the reactants. Now, it tells us that in order to have very high heat of combustion or very high heat release from the combustion reaction, the heat of the formation of the products should be largely negative. So, if we have largely large negative values of heat of formation of the products, that will be conducive to producing high heat release.

Whereas the heat of formation of the reactants is supposed to be small, negative, or even positive because this positive will become negative here, and that will become positive here outside if you look at the equation. So, this equation will tell us that the influence of heat on the formation of the products and the reactants will give us the, you know, choice of whether it is going to be exothermic. So now, this can be exothermic, or it may be endothermic. So, there will either be positive heat release or heat to be absorbed or negative heat. So, based on the values, we can know whether it is an exothermic or endothermic.

So, the heat of formation has a significant influence on heat release. So, in order to choose the propellants, we need to look at these criteria as well because if we want to have a very high temperature of the combustion chamber products, we need to have very high heat release from the chemical reactions. In order to have a very high heat release from the chemical reaction, the choice will depend on the propellant. Now, propellant will tell us what kind of products will form. Now, the choice is such a way that the heat of the formation of the products will be largely negative, and the heat of the formation of the reactants will be small, negative, or even positive.

So, that will give us a high heat release, and eventually, that will give us a high temperature in the combustion chamber or the combustion products temperature will be high. Now, let us look at the other considerations. We said that the Isp is proportional to, of course, the chamber temperature. The other consideration is it is also proportional to 1 by the molecular square root of molecular weight. So, how do we really look at these criteria in terms of the fuel and oxidizer ratios? So, one parameter is defined is called mixture ratio is called mixture ratio or MR ok. MR is defined as the mass of oxidizer divided by the mass of fuel ok.

$$MR = \frac{M_{ox}}{M_f}$$

Now, one can say that when MR is less than the MR stoichiometric, stoichiometric means the amount of fuel and oxidizer is required for complete combustion. So, if the ratio is stoichiometric, we know the stoichiometric value of that particular mixture ratio for a choice of, you know, the reactants. From there, we can learn the value of this MR stoichiometric. Now, if the MR is less than MR stoichiometric, that means it is actually going to be fuel-rich. So, more fuel is needed than the required amount for the stoichiometry.

Now, why is it important for us to look at the performance curve for solid propellants like the Isp versus MR if someone tries to look at how it is going to vary? If we look at the plot, the maximum performance will not be achieved at the stoichiometry. Rather, the maximum performance will happen somewhere on the fuel-rich side. So, let us say this is our MR stoichiometry. So, this is MR stoichiometry, but the maximum performance is not happening.

So, this is our maximum Isp, Isp max. So, it is not happening at the MR stoichiometry but on the fuel-rich side. So, this side is the fuel-rich side, and this side is the. So, we are talking about here that is fuel rich, but this is oxidizer rich, okay? Why is it so? Because the fuel-rich side will give the products lower molecular weight.

You can understand very easily. For example, if we have CxHy as just general hydrocarbon, if they react with oxygen, and if it is complete combustion, it is going to form CO_2 plus H_2O. But if there is a certain percentage of hydrocarbon that does not go into complete combustion, we do not know the exact you know moles of the products that are forming. So, we just write in this general form. Now, if you write the same equation with a different, you know values, and if we say that the combustion will not be complete. So, we can write that as it may have CO plus CO2, some amount of CO2 may also be present, and then there will be H_2O.

So, you can see the molecular weight of CO is less than the molecular weight of CO_2. So, if the products are not complete combustion products, there is a chance that the molecular weight of the products is going to be smaller than the molecular weight of the products that are formed in complete combustion. So, that is the I mean that is gives us the choice to can run the solid propellant rocket in a slightly fuel-rich condition. So, we can take advantage of you know this Isp is proportional to 1 by the square root of molecular weight. Since the molecular weight is inversely proportional if you make it smaller molecular weight it will improve the performance and that is why in general the mixture ratio is chosen in such a way that it is slightly fuel rich which will enhance the performance.

So, the two criteria I think we understand now that the performance must be higher, the choice of the propellant will be such a way that the performance of the propellant performance of the rocket has to be higher looks like it should definitely provide higher Isp or higher C star. So, in order to do that it must give a high temperature of the of the combustion after the combustion. So, the combustion gases must have a high temperature, or the chamber temperature must be higher, and the molecular weight of the combustion gas must be smaller, which will give us high performance. So, that is the first and foremost choice that needs to be maintained. What are the other choices? Now, if you look at the other criteria, other criteria can be like it needs to have, you know, a burning profile like, you know, reproducible, predictable burning rate.

So, we do not want it to be such an abrupt type of burning. If you recall, we talked about the various testing methods used for solid propellant testing for example, like very initially, when we are just choosing the propellant based on some thermodynamic calculations and if we just decide the type of fuel type of oxidizer used for this composition, we what we generally do we do some burn rate test using a Crawford strand burner or Crawford bomb. And there what we have said is that it is nothing, but it is a closed chamber where we, you know, pressurize it with nitrogen, and we allow the small strand of propellant to burn. Here, it is connected with two fuse wires, which is going to give us the at a specified length how much time it is taking for burning, and from there, we can get the linear burn rate that we have already discussed. It is ignited only through here. It is allowed only to burn from the normal to the strand surface. Other surfaces are inhibited.

From there, we can get the burn rate. So, what it is telling us is that it must have a reproducible, predictable burn rate. During the initial phase of testing in Crawford burner, we found out some burn rates, and later on, once we moved to our ballistic evaluation, if you recall, we said that the second method is the ballistic evaluation or ballistic evaluation motor BEM. So, once we do the testing there, it must have a similar type of burning profile. It does not behave like an abrupt behavior; otherwise, it will be an unpredictable type of burning rate. Even in a strand burner, one day we test it, it should repeatedly give us the same burning rate. So, it is the choice of the propellant should be such a way that it will give us a reproducible, predictable burning rate, and that, of course, needs to fit the requirement of the grain.

If you recall, we said that the grain configuration will tell us the type of burning, and that will definitely be going to tell us the type of, you know, the thrust and pressure profile or pressure time or thrust time curve. So, the propellant must fit that requirement. So, why the reproducible and predictable burning rate is so important? Of course, chamber pressure will influence it. So, there should be minimum variation in the burning rate with the influence of the chamber pressure.

There is an important burn rate law that will not be told right now we. We will talk about while discussing the burning mechanism of the different types of propellants. But rather, I would say that the variations should be the minimum that we can say. It needs to have enough, you know, physical properties. So, this is the second one. The third one, we can say it must have like enough physical properties.

Physical properties mainly we are talking about here, you know, like how they are holding the particles like, you know, it needs to have enough bond strength. Because if you look at the major ingredients of solid propellants, they consist of some kind of a, you know, polymer, polymeric fuel, plus, you know, oxidizer crystals. So, they form a matrix. So, if you look at the propellant surface if you look at inside. So, they will form a matrix, and the polymer is going to hold the oxidizer with some; you know, they will create some matrix, and they are going to hold the oxidizer.

So, the physical properties of the propellants should be good enough that they should know, hold the ingredients properly, and should remain intact, or adequate physical properties should remain over the entire you know temperature operating temperature range it should maintain that ok. So, the propellants would fulfill the requirement that the choice of fuel and oxidizers or other ingredients should be in such a way that it should maintain enough physical properties throughout the operating temperature range. So, this is another criterion. Let us look at the other criteria. If you look at the other properties, you may recall that the aerospace vehicle is volume-limited. I think we have mentioned already that aerospace propulsion devices are they are basically volume-limited like they are volume limited and particularly when you talk about the solid propellants, the denser the propellant, more the compactness of the propellant volume like we can stack more amount of propellant in a small volume.

So, the density of the propellant, the number 4 property will be like, you know, high-density of the propellant. So, that will allow you to know compact. You know it will allow the small volume motor we can put more amount of mass within a small volume of the motor. So, this is another important criterion that we just said about the performance. The density is another important criterion where the propellant is supposed to have higher density like a normal hydrocarbon. They are in the range of, like, you know, 0.8 or 0.9 grams per cc, but once you add the other ingredients, it will become, you know, higher density.

So, that is important in this respect the metal fuel because metal fuel is generally having higher density compared to the normal hydrocarbon fuels. So, once you add the metal fuel into the propellant matrix, they will, you know, increase the density of the overall propellant. So, definitely the solid particles in terms of like oxidizers, the metal particles in particular words, for example, if it is a boron, it will have like 2.3 grams or 2.34 grams per cc. So, if we add the metal particles into the fuel matrix, that will also increase the high density because high density will allow us to choose the small volume motor. So, this is another major criterion in terms of the propellant characteristics. So, I think let us stop here with these characteristics. So, we will continue with the next lecture, okay? Thank you.