Course Name: Combustion of Solid Fuels and Propellants
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Lecture: 26 Combustion of CMDB Propellants

Hello everyone. Welcome to the lecture number 26. We are going to continue our discussion on combustion of solid propellants. In this lecture, we will continue our discussion on the combustion mechanism of propellants. In this lecture, we particularly pay attention to combustion of composite modified double base propellants. Now, if you recall what we learned already in the previous lecture that combustion of double base propellants considered to be like homogeneous combustion, because double base propellant contain the major constituents such as nitrocellulose and nitroglycerin and both of them are not highly energetic.

So, therefore, in order to increase the energy density of the double base propellant, some additional oxidizers are added to the fuel propellant matrix such as ammonium perchlorate. It can improve the you know performance of the modified composite modified double base propellants. The other oxidizers can be added like nitramine type of oxidizers for example, HMX or RDX. So, in this part, we are going to look at how they the combustion mechanism is going to different from the general double base propellants.

So, let us look at what you already learned for I mean just going to quick recap of what we learned for the combustion of double base propellant. So, double base propellant if you recall the major constituents was nitrocellulose plus nitroglycerin along with some you know additives, some plasticizers may be added to improve the processing as well as it can improve some of the performance in terms of providing some extra NO_2 as oxidizers. Now, what we learned in the double base propellant that the propellant is going to degrade in the propellant surface which we call that this type of phase solid phase degradation or we said foam zone. And the primary reaction zone which is known as the feed zone and then we said if the pressure is not high enough there may be some induction zone exist which is kind of silent zone or dark zone and then there will be secondary luminous zone or simply luminous zone. So, this type of you know zone, zones exist in the typical pressure range of like 0.2 to 10 MPa and the existence of these zones are highly pressure dependent if the pressure is high enough then the extent of the dark zone is going to reduce. So, the dark zone is going to shrink and the luminous zone is almost going to merge with the feed zone. So, the feed zone and luminous zone will be almost starting from the you know burning surface and the heat transfer is going to be enhanced. So, in a turn the burning rate is also going to be enhanced. So, that I think we have already seen while we discuss about the combustion mechanism of double base propellant and we have also said that the nitrocellulose and nitroglycerin they are mixed intimately and they form the homogeneous propellant.

Now, the composite modified double base propellant in order to improve the energy density of the NC + NC + NG propellant we are adding some additional oxidizer to make it composite modified double base. So, it can be like AP CMDB where double base propellant is added with ammonium perchlorate crystals or it may be like nitramine CMDB. Here DB plus RDX or HMX oxidizer and we will see that they are very much different in terms of their flame structures or the burning processes. Because double base propellant what we see that the near to the burning surface is going to decompose and is going to form the gaseous you know species oxidizer and fuel species and they are going to mix together and they are going to form like kind of premixed flame there. So, it is very much homogeneous type of burning in case of double base propellant, but once you modify the double base by adding some ammonium perchlorate crystals then this will closely matching with the mechanism like what we have seen for AP based composite propellant.

Whereas in case of nitramine CMDB propellant we may see that the flame structure is not very much different from the double base propellant or the zonal existence what we have seen for double base propellant is almost similar to what we observed earlier it will be almost written there will be some difference because nitramine is going to provide some you know additional oxidizers which will help in you know burning the double base propellant and eventually they will going to they will be going to increase the performance. So, that is the main you know objective for you know modifying the double base by adding some additional oxidizer increase performance. So, in terms of you know flame temperature is going to increase. So, it is going to increase the ISP. Now if you look at the burning mode for typical AP CMDB propellant what do we expect is that in the propellant matrix.

So, if this is the propellant matrix we had for double base propellant which is kind of very homogeneous. Now we are adding ammonium perchlorate crystals in places. So, we are adding ammonium perchlorate crystal to improve the energy density. So, the ammonium perchlorate crystal is going to you know form its premixed flame what we have seen already for general composite propellant like bluish type of flame structures is going to form and the it is going to interact with the dark zone what we have seen earlier that the double base propellant is going to form the feed zone and they are going to form the dark zone. So, the flame is going to interact with the species formed in the dark zone and it is going to enhance the reactions.

So, basically the oxidizer species diffused into the some of the fuel species produced from the DB matrix and it is going to enhance the burning of the fuel species and which in turn is going to improve the performance. Now if you look at the typical flame structures we may see the flame for AP CMDB propellant if you look at this picture they are basically different than the RDX CMDB or RDX means nitramine based. So, RDX CMDB we can see there is a you know gap from the burning surface to the flame you know starting of the flame. So, luminosity is actually going to start from certain height above the burning surface. So, it is like distended from the burning surface whereas, for the AP based composite modified double base propellant we can see it is kind of you know starting almost like near to the burning surface.

Now if you look at what exactly happening there that once you have the ammonium perchlorate crystals present in the CMDB propellant the ammonium perchlorate crystal is going to produce some flamelets. Now depending on the concentration of ammonium perchlorate crystals there will be like number of flamelets will be present. So, if we add like a higher concentration of ammonium perchlorate crystals we are expecting like you know large amount of flamelets will be present and we may see if you look at the this flame structure very closely we may see that the epi particles at the burning surface is going to provide some kind of a bluish flame and these flames are typically like ammonia perchlorate acid flames. The products of those flames are highly oxidizer rich and they will going to you know react with the products formed from the DB flame and they are going to produce some kind of a Eolus flame. Although it is not very clear from the picture, but the closer look can reveal that ammonium perchlorate crystal is going to produce some kind of a bluish flame and then we can see some kind of a you know luminous Eolus luminous flame which is kind of you know due to the gaseous decomposition products of epi and the you know double base propellant.

So, they are inter diffused and they are going to form the luminous zone. Typical temperature as we have seen for the epi premix flame is in the order of like 1300 to 1400 Kelvin and the inter diffusional flame from the DB flame and the ammonium perchlorate premix flame they are going to produce some APDB diffusion flame and the typical temperature in the order of like 1500 Kelvin. So, as we increase the ammonium perchlorate concentration the dark zone what we have seen for the base DB propellant is almost going to be eliminated. So, there would not be any dark zone exist above the you know propellant surface. So, that is why you can see here that the there is no gap between the flame and the propellant surface.

So, it is almost like non existence. Now in case of RDX CMDB propellant RDX is basically the nitramine based CMDB propellant. So, here what is happening since we already said that RDX or HMX they are stoichiometrically balanced material and they will not produce excess oxidizer species or oxidizers fragments. That means, that we are not going to expect what we have seen for the epi propellant flame epi DB propellant flame that diffusional you know flamelets are not going to form here on the burning surface. And the decomposition products from RDX are going to diffuse and they are going to mix with the species formed from the DB matrix and they will be kind of form some kind of a homogeneous gas which will react and produce the luminous flame and it is almost like a premixed flame above the burning surface.

However, the luminous flame is kind of located at a certain distance from the burning surface what we have observed for DB propellant as well. So, this is the basic difference between the epi premixed epi or epi CMDB flame and the nitramine CMDB flame. Now if we have epi perp epi perp ammonium perchlorate particle size smaller then we can expect that like small you know particles are going to form and they are going to form like small flamelets all over the you know all above the surface of the propellant and they are going to mix with the species formed from the DB flame and then they are going to produce like epi DB deficient flame. So, in summary if you say that ammonium perchlorate composite modified double base propellant will be similar to what we have observed in the case of ammonium perchlorate composite propellant. Whereas the nitramine based CMDB propellant will be similar to DB propellant of course, the extent of the dark zone will still be decided by the presence decided by the pressure level in the chamber.

So, if the chamber pressure is very high enough then of course, the dark zone is going to reduce as we have already discussed for double base propellant that once the pressure is going to increase the dark zone will be reduced and almost non-existence once the pressure is very high say like the pressure in the order of like more than 30 MPa or so. Now, burning rate also as we have seen if we decrease the ammonium perchlorate particle size as we observed for the epi based composite propellant that the burning rate was increasing as we decrease the particle size same thing will happen for epi, epi CMDB propellant that if we decrease the epi particle size in the matrix of epi CMDB propellant the we are expecting that burning rate is going to increase and of course, once we increase the pressure the burn rate is going to also increase. Now, few more things I think we should also talk about regarding the epi regarding the nitromine based CMDB propellants that what essentially it is doing that if we recall our discussion on double base propellant the major oxidizers which are going to you know form in the due to the I mean the bond breaking of the NCN-NG because NCN-NG majorly constituting the NO2 bond and they are going to form the major oxidizers like NO2 and NO along with you know other CHO species. So, this is a strong oxidizer this is relatively weak oxidizer and we have already discussed that this NO2 oxidizer is going to play a major role in the reactions of reaction inside the feed zone whereas, the NO is going to play a role in the reaction inside the dark zone. So, since the reactions of NO with other oxidizers other fuel species are going to be slower.

So, the dark zone reaction rate is kind of slower and we have seen that there is no appreciable thermal and mass diffusion take place within the dark zone. Whereas in case of the feed zone since the NO2 is just comparatively strong oxidizer it is going to react with the fuel species and is going to increase the temperature by the exothermic reactions. Now once we are adding the nitromine based once we are adding the HMX or RDX into the double base propellant and making the nitromine CMDB there what is happening it is going to increase the concentration of NO2. So, in case of in case of RDX CMDB propellant or HMX CMDB propellant they are going to increase the concentration of NO2. So, as we have seen that the NO2 contain within the NCN, NG is going to be improved if we add this HMX or RDX within the propellant matrix and that way the overall gas phase reaction is going to be enhanced by the addition of these nitromines.

However, if we talk about the physical structure of the propellant they are going to be slightly you know heterogeneous because we are adding the additional crystals into the propellant matrix. So, the propellant will become heterogeneous. However, the gas phase structure will still be homogeneous just because you know gaseous decomposition products from HMX or the RDX particles RDX crystals are going to mix with the you know gaseous products formed from the base matrix and diffuse they will mix together and they will form the premixed flame at a distance from the propellant surface. So, that way we can say that AP CMDB propellant is going to be like kind of heterogeneous whereas, nitromine based CMDB propellant are still going to be homogeneous considering the fact that HMX or RDX is going to produce the gaseous species which will going to in turn going to mix with the fuel species formed from the base matrix which is like the DB propellant and they will form the you know gas phase mixture and finally, they will form the premixed flame above the propellant surface. So, we should also remember that the luminous flame will be located at a distance from the burning surface and the there will be some preparation zone between the burning surface and the luminous flame and of course, the flame standoff distance is going to be is going to decrease as we increase the pressure.

And the exothermic reaction zone will be formed just above the burning surface where the temperature is going to rapidly increase similar to you know we have seen for the feed zone in case of simple double base propellant. Like if you recall the typical temperature profile what we have seen earlier that the if this is the propellant surface. So, let us say this is the burning surface of the propellant. So, the temperature is going to increase from the unburned temperature to some surface temperature TS then is going to increase in the feed zone it will go to the dark zone let us say this is TD and then in this luminous zone the flame is flame temperature is going to increase further and reach to the flame temperature TF. So, by adding the RDX propellant RDX or HMX into the propellant matrix is going to enhance the gas phase reaction and eventually this is going to increase the flame temperature and which in turn is going to increase the performance or the ISP.

We have to remember that while adding the HMX and RDX this is actually improving the concentration of NO2 which in turn is going to improve the gas phase reactions. The basic difference between the AP and CMDB propellant are that AP CMDB propellant is still heterogeneous whereas, the nitramine CMDB propellant is considered to be homogeneous because it is almost going to behave similar to the double base propellant. So, I think with that discussions we are very much you know conversant with the burning mechanism of various type of propellants starting from like DB propellant then we have discussed about the you know ammonium perchlorate based composite propellant. Then we have discussed about the AP CMDB propellant and we have discussed about the you know nitramine CMDB propellant. So, basic difference are lying between the DB and AP composite propellant and the same thing we can say that AP CMDB is almost similar to this AP composite propellant whereas, the nitramine CMDB is almost similar to like double base propellant.

So, I think with that we can close our discussion on the burning mechanism. Now, we will try to see some of the you know internal ballistic of solid propellant rocket and we just want to look at one more interesting thing what we have already you know told ourselves that the burn rate law says that R equal to A P to the power N for the cases of double base propellant or composite propellant does not matter. This law holds good for both the propellants. Now we have said that A will take care of the initial temperature of the propellant, the composition of the propellant. What about this pressure index N? We know that the pressure index N brings about the pressure effect, but what will be its value like whether it is going to be N greater than 1 or N less than 1, what will be the value of N for the stable operation of the rocket? For stable operation of the rocket.

In order to understand that we need to look at few things like how much, how the mass generation is going to take place inside the you know rocket chamber and how the mass is leaving the nozzle and if we try to look at the equations we may actually try to get an idea about how they are related to each other. So, let us look at some typical N burning you know case where we can simply draw a typical rocket where the grain is kind of like N burning grain. So, we have seen that N burning N is like burning this way. So, once the propellant is burning it is going to produce the gases, product gases, it is generating the product gases and that gases is going to expand through the nozzle. So, what we are saying is that the by burning of the propellant it is going to produce the gas let us say it is generating the gas whereas, mass leaving the nozzle is m dot n.

If we note this denote the throat area as AT we may note this burning surface area as SB. We can denote the chamber pressure as PC. We will try to you know relate the mass generation and mass leaving the nozzle and we will try to see how the value of N is very important in order to have stable operation of the rocket. Here what we what exactly we are doing we are looking at the internal ballistic of the solid propellant rocket. Some of the things we need to remember here that we actually assuming the uniform you know uniform pressure across the entire combustion chamber.

So, PC is constant across the combustion chamber. The combustion gases can be considered to be like you know ideal gas. So, that we can use some of the equations. The boundary rate remain you know constant over the entire burning surface and it is governed by the typical boundary law R equal to A P to the power n. Now if we try to look at the equations we already have seen for the case of mass flow rate through the nozzle we had denoted the mass flow rate through the nozzle in terms of like the chamber pressure, throat area and the characteristic velocity.

I think we have already seen that and if you look at carefully that mass flow rate through the nozzle is linearly varying with the chamber pressure. M dot n is varying with chamber pressure linearly and it is related by the equation M dot n equal to PC At/C*. What about this mass generation M dot g? M dot g we can relate with that mass is generating by the regression of the surfaces because surface is regression. So, mass is generating due to this regression of the surface. So, we can relate the mass regression by considering that we know the burning surface area Sb, we know the mass linear regression rate as R.

So, that is going to tell us the volume regression multiplied by the density of the propellant will tell us the regression of the propellant and regression of the propellant is going to give my gaseous product formation. So, basically the mass generation is done by the regression of the propellant. So, we can relate the mass generation by this equation

$$Sb * R * \rho P$$

So, now we at least got the equation for the mass leaving the nozzle and mass generating in the inside the chamber. Now what we can see here that if we just say that what is the mass accumulation you know inside the chamber, we can simply say the mass accumulation dm dt accumulation.

Will simply become the difference between the mass generation minus mass leaving the nozzle is not it. Now if we say that for steady state operation steady state condition, the mass generation and mass leaving the nozzle should be equal. So, if we equate that we can end up getting if you look at the equations for mass generation we can simply write

$$Sb*R *\rho P =Pc\ At / C^*.$$

Now if you put the value of R in terms of pressure we can substitute R in terms of Ap to the power n. So, we can write

$$Sb * (Ap^n)* \rho P$$

is going to P means Pc here Pc At by C*. So, if you write this in terms of pressure which will become the equation for pressure it will come as

$$\rho P*A*C^*\ Sb/ At\ ^\wedge(1 / (1-n)).$$

So, this equation will gives us the steady state or the equilibrium pressure. So, this equation is giving us the steady state or equilibrium pressure. So, that way simply we can actually get the equation for equilibrium pressure in terms of other parameter like propellant density, the burn rate constant A, the characteristic C*, the burning surface area Sb and the throat area and with the pressure index n. Now, the question is like if n is near unity the value of 1 /(1-n) is going to be very high.

So, any small variation of you know these burning surface area, throat area or the density or the propellant characteristic which will influence the C* that will have significant influence on the equilibrium pressure. A small change in n any small change of this value if this value of n is near to unity there is a huge you know change in the equilibrium pressure. But if you make the value of n very small very very less than 1. So, then there will be very smaller impact of the parameters on the burning surface area or the nozzle you know throat area on the equilibrium pressure. So, now the question is that how do we really know that what will be the typical values of n.

So, that we can actually achieve the stable operation of the rocket. Now, in this consideration what we missed out here that we did not consider the change in the gas volume in the chamber due to the regression of the propellant surface. Because you see in one instance in one instance the regression surfacing regression surface was here. Now in the next instance it is coming here, another instance coming here. So, the gas volume is actually going to change here which we did not consider in this equation.

So, I think our next task is to I mean accommodate the change in the gas volume and just try to see that what kind of additional effect we are going to see on the you know equilibrium pressure equation. So, that we will do in the next lecture. Thank you.