Course Name: Combustion of Solid Fuels and Propellants
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Lecture: 16 Combustion of Double-Base Propellants (Contd...)

Hello everyone. So, we are continuing our discussion on combustion of solid- propellants. And in the previous few lectures we had started discussing about the combustion of double base propellants.

As you know that double base propellant mainly constitutes of nitrocellulose and nitroglycerin with certain other smaller ingredients like plasticizers or small amount of curing agents. But in general we said that the double base propellant are considered to be the homogeneous propellant because the nitrocellulose and nitroglycerin are intimately mixed together and they form homogeneous propellant. Although the individual constituents like nitrocellulose and nitroglycerin they individually can act as both fuel and oxidizers. So, in a sense the nitrocellulose and nitroglycerin can be called as the monopropellant because they have the capability to act as propellant.

However, in case of double base propellant the N C and N G are mixed together and double base propellants are formed. Now, in the previous lectures I think we had begin our discussion on the combustion wave structures of double base propellant. And there we have talked about the various zones of burning of double base propellants like it begin with the preheated zone, then foam zone, feed zone, dark zone and the luminous zone or the secondary flame zone. Now, we also tried to discuss about the the relative importance of each of these zones. So, now let us quickly look at what we have discussed so far related to the different you know zones for combustion of double base propellants.

So, let me just quickly draw the temperature profile of a typical double base propellant working or rather burning at a pressure range you know less than 10 MPa somewhere around 0.5 to 10 MPa pressure range where the dark zone exist. And we will just briefly you know recapitulate the relative importance of each of the zone. And then we will talk about some salient features regarding each of these zones particularly like the dark zone why the dark zone is so important, what is the influence of the dark zone in terms of the ignition delay and how the pressure influences the dark zone, what is the major species there which is influencing the existence of the dark zone. So, we will just kind of you know brush up our discussions what we have already talked so far and some new features we will also we will also try to learn all right.

So, let me just draw the temperature profile of the combustion wave structure of double base propellant. So, if you recall now the profile we are going to draw here it is going to be like a general temperature profile for the pressure range of we are talking about like the pressure range of 0.5 to let us say about 10 MPa pressure sometime we may say it is about 15 MPa pressure as well. Now here we saw that the immediate vicinity of the propellant surface there was a zone we said that solid propellant degradation zone or sometime it is termed as the solid phase reaction zone or the feed zone. Whereas, our solid propellant is somewhere over here which is kind of you know getting preheated here.

So, we can term some zone some in between here is called like preheat zone where the solid propellant is getting preheated or getting heated and then we had sorry I wrote it wrong. So, the very I mean the almost the part of the propellant surface is the solid phase reaction zone or the foam zone. Sometimes it is termed as the solid phase reaction zone and then right after the solid phase reaction zone is the feed zone. So, this one we said this is feed zone where major reaction taken major reactions take place and then after that we said there is a zone exist which is kind of a slow oxidation reaction zone which are the reactions among the products form in the feed zone. So, they will react in the one zone which is known as the silent zone or the dark zone.

Sometime it is known as the induction zone as well. So, here what happens is like slow oxidation of the product form from the feed zone will take place in the dark zone. Now, the reactions are exothermic, but proceed very slowly unless the pressure is kind of a very high. If the pressure is very high then the reaction will be faster otherwise the reaction in the dark zone is going to take place slowly and if the temperature is high enough that also influence the reaction rate of in the dark zone. Otherwise the this zone the reaction is kind of a slow the temperature gradient is also not very high you can almost say that the beginning of the dark zone and the end of the dark zone the temperature is almost similar.

So, we can consider that in the dark zone it is almost like isothermal and the thermal and the mass diffusion is also kind of a negligible. So, if we write this specific about the dark zone we can say that we can you know consider this zone is almost like a isothermal zone and we can say the thermal and mass diffusion are kind of negligible. Now, of course, they it definitely depends on the temperature and pressure in the zone. If the pressure is high enough then obviously, the dark zone existence or the extent of the dark zone is going to reduce that I think we have already talked in the previous classes that if the pressure is very high then it may be almost negligible or almost the luminous zone will just begin from right after the feed zone. And, I think we have already shown one shown some pictures of the flame by some author study where we have seen where we have noticed that once the pressure was increased the dark zone was decreasing and the luminous zone was almost starting from the feed zone.

So, definitely the dark zone is pressure dependent. Now, in case of feed zone we had already said that the major reaction will take place between the you know N 2 plus aldehydes it may be like acetaldehyde or formaldehyde. So, major reaction will take place between the sorry this is the dark zone yes this is the feed zone. So, the feed zone reactions will take place between the N O 2 and aldehydes and they will form you know they will react with other species containing like carbon hydrogen oxygen and they will finally, produce CO NO NO 2 CO 2 N 2 hydrogen and so on. Now, if you look at the zone wise species what you can say that in case of a foam zone or the solid degradation zone or solid phase reaction zones they are majorly responsible for you know by they are majorly responsible for bond breaking like the CO 2 N O 2 bond breaking is going to take place in the foam zone like which is like the solid phase degradation zone like this zone which is almost attached to the propellant surface.

Then in the feed zone the major reaction will take place between the N O 2 and aldehydes. Now, if the pressure is low enough then there is a induction zone or the dark zone exist where thus the reaction rate is comparatively very slow the thermal and mass diffusion rate are almost negligible, but this can be changed if we had the high pressure and high temperature then the dark zone will almost going to be negligible and the luminous zone is going to start right after the feed zone. So, this part is the luminous zone sometime it is termed as the secondary flame zone because primary flame zone is the feed zone where the primary flame exist and the luminous zone is sometime termed as the luminous flame zone or secondary flame zone. So, the final product is going to form sorry final products are going to form in this zone and these products are produced as a result of oxidation reactions with the significant amount of heat release. So, in this zone it will be very very luminous and the heat release will be also going to be very high and the major species produced in this zone are going to be like the mostly like stable combustion products like you know N 2 C O H 2 then C O 2 H 2 O.

We have to remember here the intermediate products like N O and N O 2 will vanish because they are going to you know react further and they are going to form the major combustion products like N 2 C O H 2 and C O 2 in the luminous zone. So, one can actually say that the dark zone is kind of like a preparatory zone for the luminous zone because even though slow reactions are taking place, but some species which are formed in the dark zone are going to finally, react in the luminous zone and is going to produce the final products of the combustion. So, in case of a very high pressure one can see that luminous zone is going to very very going to be close towards the end of the feed zone. So, the luminous zone is going to be almost going to almost start from the end of the feed zone whereas, in the low pressure the induction zone will exist. Now, if you look at the typical temperature profile if you recall what we said earlier like if the initial temperature of the propellant is somewhere about T i let us say then it will go to some unburned temperature of the propellant T u then you can say that it will reach to some surface temperature here almost like T s and then in the feed zone it will go to a temperature till the dark zone.

So, let us say dark zone temperature is T d and in the dark zone we can say the temperature will remain almost constant as we have said that the dark zone can be considered almost isothermal. So, we can have a almost constant temperature and then in the luminous zone or the flame zone the temperature will rise further and it will go to the final flame temperature like T f in the luminous zone. Now, when the pressure will increase the thickness of the dark zone. So, the thickness of the dark zone is going to reduce. So, you can see that the this temperature profile is not going to exist there we can see that the right after the feed zone it will be go straight towards the T f or the final fan temperature.

So, depending on the pressure the existence of the feed zone sorry existence of the dark zone will be decided if the pressure is high enough then the thickness of the dark zone will reduce. Now, in a sense we can say the thickness of the dark zone will decide kind of the ignition delay for the double base propellant. Now, let us look at further in this part that what is actually happening. So, you know generally double base propellant let us go to the next slide. So, you know generally like the DV constituents contain nitrocellulose plus nitroglycerin they are the major constituents of double base propellant.

Now, these N c and N g they majorly you know they contain sorry they contain multiple nitro group multiple N 2 N O 2 functional group. Now, if you look at carefully the nitrocellulose is generally having negative oxygen balance. It is roughly around 24.24 percentage minus 24.24 percentage whereas, the nitroglycerin is you know small positive is having small positive oxygen balance which is around 3.5 percent. So, the combined form is actually can give the fuel rich propellant.

So, the double base propellant constituting nitrocellulose and nitroglycerin is eventually going to give us the fuel rich propellant because the constituents are not majorly fuel rich sorry the constituents are not majorly oxygen rich in a sense that the nitrogcellulose itself is actually having negative oxygen balance. So, the mixture actually going to give the fuel rich propellant, but you know there are there is some advantage of having this fuel rich propellant because this is going to leads to the products containing high percentage of hydrogen. What does that mean? That high percentage of hydrogen means the average molecular weight is going to reduce. How it is going to be beneficial? If you recall the performance which is like the ASP or the specific impulse is proportional to the square root of the molecular weight of the products.

So, if the average molecular weight drops that will eventually helps to improve the performance. So, even though it is a fuel rich propellant it is going to give us better performance in terms of the ISP or even the VGA also similar sense. So, the average molecular weight has the major influence on the performance parameters. So, the fuel rich propellant is somehow beneficial. However, we need to remember that the oxygen balance is kind of important for you know having the oxidation reactions.

So, here the major the oxidation is going to take place because of the presence of the nitro group or any group. So, we can say that higher the NO 2 group higher amount of NO 2 means it will have the higher chance of oxidation of the ingredients containing carbon and hydrogen. Both the cases they are having NO 2 functional groups. So, higher amount of NO 2 means this is the major you know constituents for oxygen containing species. So, higher amount of NO 2 means is going to give us better oxidation of the carbon hydrogen presence in the propellant.

Now, there are some modified double base propellant where we sometime use some kind of a plasticizers such as D DGN this is known as like diethyl glycol dinitrate other oxidizers can be like TE sorry TM ETN trimethyloethan trinitrate. So, they are also containing this plasticizer also contains NO 2 group NO 2 functional groups. So, they also going to give us some you know oxidate oxidating potential. However, the percentage is not high enough that is why eventually the propellant constituting the NCNG and certain amount of procedure, but that also gives us the ultimate you know mixture as the fuel rich propellant. So, even though some plasticizers also going to help in providing some NO 2 functional group, but still the final propellant will still become fuel rich propellant.

But we can take the advantage of the fuel rich propellant by reducing the average molecular weight of the products by forming high amount of hydrogen. Now, of course, one can actually improve the mass fractions of NO 2 by modifying this constituents and that way the oxidating potential of the propellant can be improved because the major you know oxidating potential is provided by these NO 2 functional group. So, if we can increase the NO 2 mass fractions in the propellant possibly the burning will be improved and eventually the flame temperature is going to improve. So, higher the amount of NO 2 means this will eventually increase the flame temperature because that is going to provide like better combustion of the carbon hydrogen present in the propellant and that will you know leads to higher temperature of the products or if we look at the flame temperature in the luminous zone that is going to increase due to this. Now, if you look at the existence of the dark zone what exactly the dark zone is doing is kind of like a it is going to separate the primary reaction zone.

So, we can say the dark zone separates the primary reaction zone. What is the primary reaction zone? Primary reaction zone is the feed zone. So, it is separating the feed zone and the secondary flame zone or the luminous zone or luminous zone at a moderate pressure at a moderate pressure as you said that pressure may be in the range of like you know less than about 10 MPa at a moderate pressure the dark zone will be there. So, dark zone is going to kind of you know separating the primary zone and the secondary zone. So, if we look at the propellant surface if they are burning.

So, this is like the degradation zone. So, right after that the feed zone will be there. So, the dark zone will be in between the very much luminous zone this one and the feed zone. So, this is the dark zone which is separating between this feed zone and luminous zone. Now, one can see one thing that the heat needed to preheat the propellant surface is coming from the flame.

Now, if the dark zone is longer enough then the heat transfer from the luminous zone is going to be negligible. So, the primary heat transfer is going to take place only from the you know flame from the feed zone or you can say the primary reaction zone or the feed zone is going to provide the heat to the propellant for further degradation of the propellant and you know solid phase reactions will take place. So, if the extent of the dark zone is going to be long enough then the heat transfer from the luminous zone is going to be negligible. So, for a high pressure once the dark zone almost cease to exist that time the heat transfer from the luminous zone will be prominent and we can say that the ignition delay time will be reduced. So, in a sense we can say the luminous zone can provide the major heat transfer to the you know preheating of the solid propellant and the further solid phase reaction and finally, gas phase reaction will be improved if we have the you know less extent of the dark zone.

So, in a sense we can say that the dark zone thickness is kind of directly related to the ignition delay. This is important consideration. Ignition delay time between primary and secondary flame. Now, as we said earlier that if there is dark zone of noticeable length almost none of the heat is going to transfer from the luminous zone to the burning propellant surface and the characteristic distance for the heat transfer is going to be too long. So, in that case only the first stage combustion or the feed zone the flame from the feed zone is going to be responsible for providing the heat transfer to the propellant surface.

However, the heat from the luminous zone is going to reach to the propellant surface at higher pressure when the pressure is more than like 15 mega paxel or even higher then the heat transfer from the luminous zone is going to reach to the propellant surface here. Otherwise if the dark zone is kind of a extended to large length or longer distance then the heat transfer from the luminous zone to the propellant surface is going to be negligible. So, there only the primary reaction zone or the feed zone will be responsible for providing the heat. Now, we should also appreciate that the chemical reactions which occur in the dark zone play a major role in the ignition delay times. Now, if you recall the dark zone of the you know solid propellants contains the large amount of if you if you recall we already said this one that this consist large amount of NO which is kind of a weak oxidizer.

And majorly the low reactivity of NO is the major reason is the major reason for the dark zone. Now, NO is going to slowly converted to nitrogen once we come to the end of the dark zone. So, here at the end of the dark zone, NO is going to slowly converted to nitrogen as the final you know combustion products. So, one can actually see that the temperature and species concentration in the dark zone is not going to change too much axially. So, if you look at from the beginning of the dark zone to the end of the dark zone the temperature the species concentration is not going to give us you know sharp difference between the beginning of the dark zone and the end of the dark zone.

However, the there is some you know difference in the gradients in the profile the stress species like some small amount of species which were there in the beginning of the dark zone can actually change significantly across the dark zone. So, we can assume that the structure of the dark zone is kind of a one dimensional it is kind of a isobaric adiabatic and the diffusion of heat and the mass is kind of a negligible or even if it is there it is really small. So, for a modeling perspective one can actually consider this one because this is going to relate to the ignition delay time between the primary and the secondary primary flame and the secondary flames. So, one can actually consider that dark zone is kind of an you know one dimensional adiabatic the concentration is not going to change too much in this zone and the heat diffusion and mass diffusion are going to be negligibly small. So, it is going to be kind of a silent zone or kind of a induction zone for the double base propellant.

Now, once the pressure rises after a certain limit the dark zone is going to reduce and we can see that the luminous zone is going to almost start right after the end of the feed zone. Now, I think we have already seen this in the flame pictures in the earlier classes as well. So, if you look at here the at the low pressure we can see the extent of the dark zone is quite kind of quite long whereas, once the pressure is increased here in case of figure b we can say that see the dark zone has reduced little bit and once the pressure is high enough the extent of the dark zone has significantly reduced and it is almost coming close to the you know primary zone or the feed zone. So, the pressure has a very much you know influencing factor on the extent of the dark zone. So, after a certain range of pressure this the zonal differences what we have already told that preheated zone, foam zone, feed zone and then dark zone and then the secondary luminous zone may not always exist.

So, for a high pressure the dark zone can be almost negligible. So, in that case it will be like the preheated zone, foam zone, feed zone and secondary flame zone or the luminous zone. So, there are various you know studies available some studies have conducted some authors have conducted studies on studies on the concentration of NO on the influencing of the extent of the dark zone, the effect of pressure on the extent of the dark zone. So, those can be referred for better understanding. So, I think with that we close this lecture then I think we will try to understand the mathematical representation of this mechanism of burning rate of double base propellant and we will try to derive some you know equations of burning rate or the linear regression rate and we will try to see how the linear regression rate or the burn rate is going to depend very much dependent on pressure ok.

So, that will be discussed in the next class. Thank you.