Course Name: Combustion of Solid Fuels and Propellants
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Lecture: 14 Combustion of Double-Base Propellants

Hello everyone. We had started the new module combustion of solid propellants in the last lecture and there we talked about the ignition mechanisms in general like how the ignition process takes place in the case of solid propellant. And there we have discussed about that why the ignition source is necessary in order to initiate the you know ignition process. So, the ignition stimuli can be like some kind of gaseous plumes, it may be hot particles, some energy source which can initiate the combustion process. So, if you look at what we discussed in the previous class, in the previous class we have talked about the ignition and ignition pressure as a function of time. Now, if you look at the ignition process, we had said that initially it takes some time in order to you know rise the pressure.

So, that phase we discussed about like three different phases there, induction phase or ignition lag period, then flame spreading and then we talked about the chamber filling. Now depending on the size of the rocket, each process is relevant to like the time the required time for each process will be different. For example, like if the rocket is a smaller port volume or smaller chamber volume, then this process may be faster compared to the larger rocket. Now, for a large rocket this process may takes like you know long time in order to like have the chamber filling and reaching to the equilibrium pressure.

Now, as you also mentioned that equilibrium pressure establishment of equilibrium pressure is necessary in order to sustain the combustion. Because in the event of failure of the sustained combustion, we cannot say that the ignition has been established because ignition might have been initiated, but if you take out the ignition source or the energy stimuli, if it fails to sustain the combustion, then we cannot say that the sustained ignition has been taken place or the combustion will proceed further. I think you might have seen this type of scenarios when you try with the you know firecracker like sometime you ignite the firecracker with some energy stimuli, it can be mastic or can be like some kind of a scented stick. You may notice that the squib will go slightly with some smoke come out, smokes will come out and you will see it is burning and then suddenly it may stop to a situation like here and it is not burning further. So, the ignition was initiated, but it was not sustained.

So, after removal of the energy source, the removal means energy source here is the mastic or the scented stick. So, if you remove this one, your reaction process should continue and the combustion should proceed further. So, the sustained combustion should be attained, then we can say that it has been ignited successfully, but it may so happen that it has stopped burning after certain duration once you take out the ignition stimuli or the energy source. In a similar scenario, if you look at the propellant surface, so if you just think about the you know this is the ignition source, what we said that the ignition source is providing the hot plume which is impinging on the main propellant surface and the heat coming out onto the propellant surface through like three modes of heat transfer like conduction, convection and radiation. So, the initial layer of the propellant surface will get the heat.

So, the temperature will increase of the surface and the soft surface as well. So, soft surface temperature will also increase, the surface will start to pyrolyze and is going to decompose to produce some you know gaseous products. This may contain like the fuel and oxidizer species, they may form the combustible mixture and they may start forming the flame and finally, the flame will be established. So, once you turn off the ignition source, this flame is going to give the heat feedback to the propellant surface for further you know burning of the propellant. That means, once the ignition source is finished, I mean in this case like you know this ignition squib will be burnt out completely.

So, it is not going to present after certain duration. So, once the ignition source is taken out or removed, you know the flame will be established and the flame will give the heat feedback for further pyrolysis rather I would say the further heating of the propellant and of course, the pyrolysis and decomposition of the propellant and that will brings the oxidizing and fuel species to further mixed and burnt and finally, the flame will be established and keep on going. Now, this type of sustained combustion is very much necessary, generally we can say that the ignition is successful. Now, there may be a scenario that if the pressure is not you know sufficient enough, your ignition whatever the ignition process is initiated, you know combustion will not be sustained because the certain pressure is necessary to be present in the chamber in order to have sustained combustion. Now, if the pressure falls to that you know pressure limit, the flame may extinguish.

Although your propellant surface it may still regresses very slowly and it is still going to produce some gaseous substances. So, it may actually you know give the re-ignition process after certain duration. So, it may so happen that the flame will reappear after certain duration. So, it is going to be like a intermittent process that after extinguishments of the first flame, the propellant will still you know slowly decompose and produce the oxidizing and fuel species and the heat is sufficiently although low, but it can still produce the flame once again. So, there will be some pressure fluctuations due to that.

So, we will talk about the you know kind of different type of you know ignition events. Although we want that normal ignition to happen like once we ignite the pressurized should be smooth enough and it reaches to the equilibrium pressure as we discussed in the previous lecture. Now, there may be situations that there are many factors due to which this ignition event will not lead to a sustained combustion. Although ignition has taken place, but the combustion is not sustained because of various reason. So, the sustainable attainment of combustion will depend on many factors like the type of propellants, the composition of the igniter, the heat transfer taking place through like the different heat transfer mode, the flame spreading over the grain surface you see the flame is going to spread over the flame surface.

So, the pressure is going to increase as you see in this phase the flame is going to spread. So, if you look at the port volume here you know the flame is going to spread over the entire port volume. So, flame will be established that will also of course, you know lead to sustained combustion process. The dynamics of chamber filling like how the chamber volume is filled up by the you know product gases that also lead to the sustained combustion. So, there are various factors which are necessary and that will influence the attainment of the equilibrium chamber pressure.

So, finally, we need this equilibrium chamber pressure. Now, the ignition delay or the ignition lag period we also said that there are many factors which is going to affect the ignition delay or the time elapsed duration between the application of external stimuli and the you know steady burning. And mainly they are influenced by the inert heating time like the time for heating up the initial propellant surface, the mixing of the mixing time of the you know gaseous products like basically the gaseous reactants coming out from the pyrolysis the reaction time. So, it is very complex process and sometime it is very difficult to differentiate between the ignition time and how these processes are overlapping on to each other. So, it is very difficult that whether the reaction time or the mixing time or the you know inert heating time are actually dominant.

So, but all together there is a ignition delay time which is already denoted by this you know phase one period which is sometime known as the induction period. So, this part I think we have quite understood in the previous lecture. Now, there are some ignition events we can look at like if you just simply plot the you know ignition events like just try to plot chamber pressure versus time. What we understood already that the normal ignition should take place very smoothly and it will reach to equilibrium pressure. So that way you can actually get the normal ignition.

Now, any deviation from the normal ignition may lead to different scenario like there may be scenario where your ignition stimuli is so high that it is going to give a strong energy input. So, there will be some ignition spike. So, you may see that it may initially gets like high pressure jump or a pressure spike then it is going to drop back. So, this type of you know cases we termed as the misfire. So, it was starting the ignition, but it is not holding it or it is not sustained.

So, this kind of misfire. So, same thing what we discussed in the previous example like if you ignite the firecracker like it suddenly give a zoop sound and then it will just go off. So, it is not you know ignited properly. So, it is going to be misfire. So, in case of a you know rocket process the pressure will suddenly go high just like a pressure spike and will go down.

So, it is misfire, but we want this type of you know normal ignition smooth rise of pressure inside the combustion chamber. Now, there are other scenarios where you know it may give like a pressurized and then it will come back and it will becomes you know steady equilibrium pressure. So, that type of scenario is like a very high ignition peak. So, you can say it is it has very high ignition peak. So, it suddenly go up if the energy stimulus is high enough it may give rise to the pressure and it will go to a sudden you know peak pressure and then it will come down and reach to the equilibrium pressure.

So, that type of you know ignition event is called high ignition peak. So, we want the normal ignition process. There are other scenarios like as I discuss in the just few minutes before that you know your initially the pressure rises and if the pressure is not high enough the flame may actually go off although the regression may take place slowly in the propellant surface and once it is sufficient enough the flame will come back again and it may lead to the increase in pressure. So, this type of scenario is called like the hang fire. So, the pressure is increasing, but it is not sustained the it is not sufficient enough.

So, the on the propellant surface if you look at some slow regression is taking place in the sub surface of the propellant and due to which slowly the oxidizing species and fuel species are forming they will mix they will react and you know they will bring the flame once again. So, once the flames once the flame comes back the pressure will again it will create the product gases and the pressure will keep on rising, but this scenario is kind of need to be avoided because this is very much oscillatory in nature the pressure is increasing then is again falling back and if this if it is sufficient enough again it is giving the combustion. So, this type of scenario is avoided. So, this is another undesirable event of ignition which is called hang fire, but the normal ignition is like we want it to be like a smooth pressurized flame spreading and chamber volume to reach the equilibrium pressure. So, that is called the normal ignition.

So, up to this part I think we pretty much understood the processes you know in general the ignition of or ignition combustion of gaseous substances and the solid propellants fundamentally they are similar, but there are lot many processes involved in case of solid propellant because as we know that the ingredients are you know various types like starting from the solid fuel it may be like the metallic fuel like aluminum there may be solid binder which can act as fuel as well like the polymeric binder for example, like HTPB there will be solid oxidizers for example, ammonium perchlorate. Now the mixture of these various ingredients will lead to like the very complex processes you know starting from like the pyrolysis of the fuel the you know decomposition of the oxidizers the burning of the gaseous species and the oxidizer species of course, before that there will be some stages where the mixing will take place then they will react with each other there may be various type of flames involved in there may be phase changes like here we are talking about the solid propellant. So, the solid to liquid, liquid to gas or may be like solid to directly gases like sublimation process may also take place. So, there are complex processes involved in the combustion of solid propellants. Now in next few lectures what we will try to understand the you know very simplified approaches already you know provided by the various literatures and documented in the various text books.

So, we will try to understand each of the categories mainly the homogeneous propellants or the double base propellant and the composite propellants for example, like AP HTPB propellant and we try to understand the underlying features of the combustion of these main two categories propellants like the homogeneous and heterogeneous propellants. So, with this background I think let us begin our discussion on the combustion of double base propellant. Now before we proceed further we just need to appreciate the various processes involved in case of in general like you know physical processes in combustion of you know solid propellant. Now if you look at the solid propellant surface let us say we just give some exaggerated view of this. So, in general if you say the composite propellant it may have some you know crystals ammonium particle crystal there may be some aluminum particles.

So, this is like typical you know composite propellant if you take the double base propellant they are kind of intermittently mix like for example, NC + NG that gives the double base propellant. In composite propellant we have like the ammonium perchlorate as the oxidizer we have aluminum particles as fuel and these are like the HTPB as the binder which is hydrocarbon. So, that will also act as fuel. So, you can understand that once we ignite the propellant you know the after the surface you know ignition the let us say the flame is established. So, somewhere you know there will be some you know it is region of we can say like this will be the region of exothermic you know gas phase reaction.

Now in this zone the fuel and oxidizer species will diffuse we can say that the fuel and oxidizer species diffuse and they will mix and they will react and they will create the flame. Now the flame is going to give the heat feedback to the propellant surface the unburned propellant surface because if you recall what we said that the sustained combustion will take place only when the heat feedback will be sufficiently high enough to pyrolyze the next batch of you know unburned propellant surface and provide the fuel and oxidizer species mixture and they will mix and react and keep on burning. So, this heat may you know come through like the external heat flux through convection there may be like radiation convection radiation this will provide the heat there will be some heat conduction also in the fuel surface. So, here we can say heat convection heat radiation from the flame heat conduction will also take place. So, that will give the you know increase in the surface and the soft surface temperature now immediately at the surface the fuel will start you know pyrolyze the oxidizer is going to decompose it will provide the oxidizer species fuel is going to vaporize and keep the give the fuel species.

So, the fuel and oxidizer species will diffuse and they will mix and they will burn and they will create this you know high temperature exothermic region where the gas phase reaction will take place. So, we can understand in a very simplistic way that the processes involved in the solid propellant burning is very very you know tedious and involved. So, in order to understand them we have to you know understand these processes in a very simplified approach considering the well established literature like based on the modeling of the various type of propellant category mainly the double base propellant and the composite propellant. So, with this background let us go ahead with the combustion mechanism of double base propellant. So, this is a typical you know picture of nitrocellulose and nitroglycerin based double base propellant.

Here you can see these nitrocellulose and nitroglycerin are kind of mono propellant because they have the capability to burn themselves I mean they alone can work as propellant. So, they are actually having the you know properties of both oxidizer and fuel and they can actually burn on itself if you ignite. So, generally the Nc is kind of fuel rich. So, once you make double base propellant by mixing Nc and Ng, Nc plays the role of the fuel and Nc plays the role of you know the oxidizer. So, the nitrocellulose and nitroglycerin are mixed together to form these double base propellant.

Of course, there are some you know it is combined the Nc plus Ng plus some you know plasticizers are added. For example, like di-optile phthalate or triacetin these are added to make this you know bond properly and double base propellant is made. Now since they are homogeneous propellant they are mixed very intimately and they form the homogeneous mixture. Now if you look at the typical flame structure of this type of propellant you can see that once you ignite this one depending on the various you know pressure you can see there is a gap between the flame and the propellant surface. If you look at this picture carefully I will explain the things in context of the discussion, but let us look at this that there is some gap between the propellant surface and the luminous zone or the flame.

Here you see the gap has been reduced significantly compared to the picture A. In fact, in the picture C you can see the gap has reduced significantly compared to A and B. So, of course, there is some role being played due to which the gap between the flame and the propellant surface is being reduced. Now one can see that since we can say that luminous flame means we can say the significant you know you know exothermic reactions are taking place. So, probably there is there is some zone where like kind of you know darkness is present.

So, that zone may be probably you can say some kind of a preparation zone or kind of a dark zone is is present. Will anyway we will discuss about this various zone, but at least from the figure we can easily look at that one kind of a darkness zone is kind of present between the propellant surface and the flame. So, as if like the flame is kind of lifted here if you are aware of the lifted flame. So, it is almost like a lifted flame structures, but of course, we need to understand what is there in this you know dark region where there is no luminous zone. So, once we look at the mechanism I think we can understand properly that what this zone means and why they are decreasing.

If you compare the figure from A to B to C we can see this zone the the very low luminous zone is actually decreasing once we go from A B C. So, what parameter is affecting that distance reduction. So, in order to understand that we have to understand the various zones of combustion for double base propellant. So, let us look at you know one by one and then we will try to see what are the dominant you know reaction mechanisms playing role in case of double base propellant. So, first of all we have to recall what we already learnt during the discussion of the propellant ingredients you need to recall the composition of nitrocellulose.

So, we said the double base propellant is made of nitrocellulose and nitroglycerin. So, nitrocellulose was the part of hydroxyl radical were substituted by the nitrogen and they were substituted by NO 3 radical. So, initially the the cellulose was there like C 6 H 10 O 5. This was you know some OH radicals were substituted by the nitrate radicals and it gives the nitrocellulose. So, depending on the you know amount of nitrogen the some of OH radicals will be replaced.

So, the the formula we can write in general like let us say degree of you know nitrogen is some like kind of X we can denote that X gives the you know amount of nitrogen done on the nitrocellulose to give this nitrocellulose. So, in general we can use this formula. So, this is our NC and as you said that this is kind of play the role of fuel. So, it is slightly you know fuel rich this is slightly fuel rich. And what we learned during the lecture of solid propellant ingredients that nitroglycerin is kind of you know nitrogen of glycerin.

So, that gives the kind of molecular structure of like this kind of molecular structure. So, NG is slightly oxidizer rich. Now, once we mix this together along with of course, some plasticizer or you can say the other some kind of other additives also and that gives the homogeneous propellant or double-waste propellant. So, this is we already learnt in the previous section. Now, during the burning of this double-waste propellant as we said by looking at the picture the flame picture that probably there will be some some zones exist while double-waste propellant is burning.

Just by looking at this visual what we understood that there is a gap exists between the propellant surface and the flame and as we have seen that something is going on from figure A, B and C that the gap is reducing. So, what we need to understand the zones before we really know the influencing factors which is reducing this gap. So, what are the different zones exist as per the literature like if we say this is the propellant surface what is going to happen once you provide the heat to this propellant surface the immediate you know vicinity of the propellant surface the propellant will start to heat up and some kind of you know solid phase decomposition will take place some you can say solid phase degradation will take place. This type of zone is called the foam zone. As per the literature this is termed as the foam zone sometime it is you know denoted by some other name also like the solid phase decomposition zone or yeah generally it is termed as the solid phase decomposition zone or the foam zone.

So, it is very much you know part of the propellant surface you see it is still part of the propellant surface where the you know some decomposition is taking place. So, in this zone you know some degradation of these propellants will take place and they it will form some species there. So, in this zone probably the most important species are formed are the aldehydes like formaldehyde and acetaldehyde are going to form and they are going to form like the NO2 and NO gases. So, this immediate zone of the propellant surface is termed as the foam zone then very next to it is called the you know feed zone and right after that is called the dark zone what we just had seen in the picture that is called the dark zone and then we have the flame zone or the luminous zone or sometime term as the secondary luminous zone. So, basically what we have seen there in the picture is the very luminous zone which is the flame zone, but there was some gap between there which is which was mainly the you know very low luminous which is like dark zone, but there are other zone exist which are called like the feed zone and the foam zone.

Sometime the foam zone is also termed as the degraded solid propellant zone. Now of course, depending on the extent of this each zone the length will be you know vary for each zone. Now the temperature is also going to vary from this zone because you know this is like the unburned temperature of the propellant. Now it may reach to some you know surface temperature like Ts then it may reach to some high temperature then again in the dark zone what is going to happen we need to see then the flame zone of course, we can understand the flame zone means it is a very high temperature zone. So, we need to understand that the typical you know temperature profile once we start from the propellant surface to the flame zone and how the you know role of these each of this zone in the context of this burning of this you know double base propellant.

So, in the next class I think we will try to you know discuss this each of these zones the various species involved in the reactions of different zones what are the reactions are taking place in each of these zone and what are their significance in terms of the temperature. And in overall what are the zones of this combustion in overall you know burning of the propellants we will talk in the next lecture. So, till then what we need to do is we need to revise this stuff what you have learned already in the previous lectures as well I will just quickly brush up the you know composition of the various you know propellant ingredients like the double base and composite propellant. So, that it will be easier for us to understand that what you are talking about in terms of like various reactions what are the species are forming from let us say for Nc and Ng we are talking about the various species are forming similarly for the composite problem also we need to recall the what are the major you know ingredients used for composite propellant and that will help us to you know understand the mechanisms clearly.

So, let us continue this discussion in the next class. Thank you.