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: 13 Combustion of Solid Propellants - Introduction

Hello everyone, welcome to the online certification course on combustion of solid fuels and propellants. So, we are going to start a new module which is combustion of solid propellants. And this modules will have like the discussion on the various propellant categories we have already talked about in the previous lectures. We had detailed discussion on the various propellant ingredients and then you have talked about the different category of propellants. For example, like homogeneous propellant or double base propellant, then you have talked about the heterogeneous propellant or composite propellant. We have also talked about the modification of double base propellant like composite modified double base by adding some ammonium percolate or even nitramine oxidizers.

And then we have also talked about the a separate category as nitramine propellants. So, what we have learnt there that depending on the ingredients the characteristics of the propellants will change. Now in this module we will try to understand how the various type of propellants behave differently in their combustion processes. And we will try to understand the underlying mechanisms involved for various type of propellants.

So, here we have mainly two categories of propellants one is the homogeneous propellants which is mainly like double base propellant. And the other one is the composite propellants which is like the consisting of mainly like ammonium percolate as oxidizer, polymeric fuel as binder and maybe like aluminum particles as fuel. So, we will try to understand in a very simplified approaches to understand the various reactions, dominant species formation, what are the various zones in these type of combustion processes and so on. And from there we will try to establish the burn rate law which is very important in terms of combustion of solid fuels and propellants. In order to proceed further I think some of the things we need to understand in connection with the combustion processes which is like the ignition.

So, we will also talk about the ignition processes, how the pressure increases over time during the ignition processes, what are the different type of igniters used in solid propellant rocket. And then we will discuss the combustion processes of double base propellant and composite propellant in detail. So, I will just try to show you couple of videos taken from my lab and one of from my previous student who is also developing some rocket facilities in his own laboratory. So, you may recall that we have talked about HTPB as the polymeric binder. So, if we just take HTPB as the fuel and if we just use some curing agent and using

some mold and mandrel if you recall we had talked about the casting process of HTPB that we have to cure it using some curing agent such as like IPDI.

So, you can add some curing agent and you can cure it for certain period of time it may take about 5-6 days even we have to keep it inside a vacuum oven. And once it is dried then the solid block of material which we know that this is called grain. And once you add some metal particles such as like energetic boron particles you can see the color of the grain has now changed. And typically this grain has the cylindrical grain configuration which is like a circular cross section. Now here I am not talked about I have not talked about that oxidizer here because in this study we have studied mainly like you know combustion of solid fuels in presence of oxygen as oxidizer.

So, we have not loaded any crystalline oxidizer in this propellant grain. So, I will just show you some glimpse of you know testing videos which were taken by my student. So, if you look at the typical you know HTPB plus boron burning in a oxidizing environment where the oxidizer is the gaseous oxygen which is supplied from the back side of this. So, the solid fuel grain is contained in this motor casing. So, it is simply burning and you can see the green hue is coming because of the boron particles burning.

Here the boron particles percentage was moderately higher. So, you can see very intense green flame coming out of the nozzle exit. You see it is a very intense flame and you can see some you know streak burnings are also taking place from the particles. I will show you one more time just to give you an flavor of how things work. So, you can understand that the combustion processes of these type of fuels or even propellants are very complex processes.

It involves like multiple processes like phase changes, heat and mass transfer, chemical reaction and so many things. So, in order to understand that we really need to dig up the details of the combustion systems and various processes involved in each of these. Now, I have a very simple propellant strand burning video here which is basically the some boron particles added with potassium nitrate. So, potassium nitrate is another oxidizer. If you recall we have talked about the two different type of oxidizers mainly like in the category of crystalline oxidizer one is the percolate based another is the nitrate based.

So, here the nitrate based oxidizer was used in connection with the boron solid fuels. So, if you look at it is a very short video, but I think you can still see it suddenly some flame will come. You see this is almost like your crackers you know once you burn these crackers in diwali it is almost similar to that. So, basically it is containing the oxidizers along with the fuel that is why it is burning like this. But here since we stopped the oxygen supply it had stopped burning.

So, the flame was on for quite some time and then once the oxidizer work was cut off the flame went off. You can see that it will suddenly went off same thing here also. But the

idea behind giving this to showing these videos are to give you some ideas about how the different type of fuels and propellants burn. So, we need to you know look at the processes involved for example, like decomposition of oxidizers like we talked about the different crystalline oxidizers for example, ammonium percolate and ammonium nitrate. So, once you ignite any solid propellant sample what are the underlying processes happen like starting from the ignition and we need to understand the decomposition behavior of these different type of you know crystalline oxidizers because that play very important role by providing the you know oxidizing environment.

So, we look into this one by one. Now, let us look at some of the processes as I told you because ignition is a very important part of the combustion process. So, we will try to understand the ignition process in detail. If you recall what you have learned in your previous courses like basics of combustion processes or any kind of you know introduction to jet propulsion. If you look at what you learned there some part of the you know combustion processes what we said that once you provide the heat source or the energy source to a gaseous mixture.

Let us say it is a mixture of methane gas and oxygen or maybe mixture of methane and air if you provide the energy source it will lead to some chemical reactions and it will lead to provide some light and heat. So, the combustion will take place, but it may not always true that if you take out the source of energy whether your combustion will be sustained or not. So, the ignition process will lead to a sustained combustion when the energy source was removed. For example, like if you use some spark plug. So, the spark plug is going to provide some initial energy to ignite the combustible mixture.

Now, the combustible mixture may be like various gaseous mixtures like propane and oxygen, propane and air, methane and air, butane and air, hydrogen and air, hydrogen and oxygen. These may be various type of combinations of you know fuel air mixture. Now, if the ignition happens in such a way that it leads to the sustained combustion then the combustion process will proceed further. Otherwise if you remove the ignition source it may fail the combustion process or the flame will be extinguished after a certain duration. So, eventually the combustion I mean eventually you cannot say that this is a successful ignition of the combustible mixture.

Now, similarly for solid fuels or propellants if you provide the heat source on the propellant surface there are several processes happens due to which either the combustion will be sustained or it may be extinguished. Now, if it is a composite solid propellant then of course, it will begin with the decomposition of your solid oxidizers it may be like ammonium percolate. So, the decomposition will take place and it will provide some you know oxidizing species the for case of for the case of ammonium percolate it will begin with some you know premixed flame or sometime it is called ammonium percolate premixed flame. So, we will talk about that process in detail in the discussion of the burning

mechanism of composite propellants. Now, what I try to understand through this plot is this is a typical you know ignition pressure as a function of time.

So, if you look at the plot carefully there are two lines showed here one is the dotted line which is the igniter pressure. So, igniter pressure means the material which is going to ignite the main propellant. So, the igniter has to ignite first. So, igniter is also you know containing some kind of a propellant. Now, this propellant if you recall once we talked about the various categories of propellants we have talked about the igniter propellants also.

Now, the basic difference between the igniter propellant and the main propellant which is inside the motor casing or the main grain of the motor the main difference is that we want very fast you know initiation of combustion in case of igniter propellants. Because the main purpose of the igniter propellant is to provide the initial energy for the ignition to take place. So, the igniter propellant must have the capability to produce high temperature gas with minimum amount of time. So, this process should take place within a fraction of second. So, if you look at the igniter pressure increase you see it is a fast you know increase of pressure.

So, it will provide high gas heat release within a minimum amount of time. And then once it provides energy to the surface of the main propellant grain the propellant surface will start you know decompose it will pyrolyze it will provide some you know gaseous reactants which will start combusting and the pressure will start growing. So, you can see the main pressure profile you may see that pressure is started increasing. So, there are different phases which generally termed as first one phase is called ignition time lag. So, this is the period from the moment the igniter receives you know energy signal and the first surface of the grains burn.

So, this is basically the time gap between the you know providing the energy signal and the first surface of the grain burns. Then if you look at the flame spreading interval which is like phase 2. So, this is the time from the first ignition of the grain surface until the complete you know burning of the grain area. So, that is like kind of you know all the surface of the grain area should be you know ignited in this period. So, that is like flame spreading interval.

So, for a smaller rocket you know this flame spreading maybe slightly lower I mean comparatively lower because for a large rocket this may take longer period of time because this is providing the heat and it will lead to the ignition of the entire surface of the propellant grain. So, we are talking about the entire surface means is the internal surface which is the grain port we are talking about like say it is a cylindrical surface. So, we are talking about the internal surface of the grain. Once the entire surface of the grain is ignited we can say that the flame has spreaded all over the grain and then it will requires to reach to some

equilibrium pressure which is desired pressure of the rocket. So, that phase is called phase 3 which is like chamber filling interval.

So, this duration the it will fill up completely the chamber and it will reach the equilibrium pressure of the rocket and of course, it will flow. So, ultimately once it reaches the product of combustion will flow from the rocket chamber to the nozzle because I think you remember the our configuration we said in our previous classes if you recall we can actually quickly look at that one that typical configuration if you look at. So, it is something like this. So, this is your grain. So, by igniter we are actually providing the initial heat to the surface.

So, it is going to provide some kind of a gaseous products you can say the plume will be able to heat the initial surface. So, that will provide the heat for the decomposition and pyrolysis of the this propellant and once the flame will start building this is going to give the flame. Now, the product of combustion will start flowing from the nozzle ok. So, we are talking about the equilibrium pressure here. So, the process will continue till it reaches the equilibrium pressure.

So, this one we are talking about the equilibrium. So, up to here it will continue. Now, depending on the definitions the ignition will be defined as the you know 10 percent of the initial first max pressure or the ignition pressure. If the 10 percent of the ignition pressure reaches that we talk about the that is the ignition delay time depending on the definitions we follow from the literature generally acceptable literature is the 10 percent of the p max it is generally termed as the ignition delay time ok. So, this is the scenario here that once the propellant start burning.

So, flame spreading means we are talking about that the burning is initiated along the entire surface of the grain. So, entire surface of the grain means we are talking about the all the internal surface of the grain and then it will reach to equilibrium pressure. So, the product of combustion will start flowing through the nozzle ok. Now, question is how to initiate the ignitions? What are the different type of igniters? So, if you look at the different type of igniters there are mainly two types one is pyrotechnic igniter another is the pyrogen igniters ok. Now, the role of the ignition will be like it has to have like satisfactory attainment of the chamber pressure of full gas flow inside the rocket motor.

As we remember we said here that the once the equilibrium chamber pressure filled up I mean reach the gas will start flowing. Of course, gas will start flowing even once it reaches to certain pressure because once the pressure is built up the gas will start flowing through the nozzle. Sometime if the pressure is not you know built up enough sometime nozzle closure is used. Now, some kind of a nozzle small nozzle closure is used. So, once the pressure is built up enough this nozzle closure will come out from the nozzle ok.

But you know the satisfactory attainment of equilibrium chamber pressure with full gas flow is very important and that depend on many factors like of course, the type of the igniter like the characteristic of the igniter the composition and the gas flowing from the igniter the main propellant composition. So, this is your main you know propylene grain and this is our igniter propellant. So, whether it will you know satisfactorily equilibrium pressure will be attained or not that will depends on the type of igniter composition or characteristics of the igniter ignitor propellants how the gas flow is taking place there. The characteristics of the main propellant like the ingredients of the main propellants the heat transfer characteristic because you see the igniter is going to provide the plumes is going to heat or impinge on the propellant surface the main propellant surface. So, the heat transfer characteristics like radiation and convection between the ignition gas and the grain surface that will also play an important role.

The flame spreading how the flame is spreading inside the rocket motor that also play an important role. The dynamics of the filling like inside the free volume how the filling process the chamber filling process is taking place that is also going to play a role on the processes by which like successful you know equilibrium pressure is attained. So, the dynamics of chamber filling is also very important ok. Then the ingredients as I said is very important like some ingredients which are very prompt in you know responding to the ignition stimuli, but some ingredients are not that much prompt in a burning or ignition. So, of course, the ingredients play a very important role in attaining these you know equilibrium pressure ok.

Now, the ignitability of the propellants all also depend on many factors like first and foremost is of course, the propellant formulations what I said that type of oxidizers you we use whether it is a percolate based whether it is a nitrate based or whether it is a nitramine propellants. So, depending on the you know propellant formulations that is very important whether the propellant will be ignited effectively or not. The initial temperature of the propellant like if your surface of the grain. So, if we say the unburned temperature of the grain whether it is very low or moderately you know reach to a certain temperature that is also going to play a role in terms of ignitability ok. The of course, the mode of heat transfer how the heat feedback is coming from the flame to the propellant surface that also depends the roughness of the grain surfaces, the age of the propellant.

If the propellant is too old then maybe ignitability is you know reduced. I think you may take a common example like if you keep your you know firecrackers for a longer period of time let us say you bought it in this Diwali and you had some stock and you keep it for like 2-3 years then you may realize that in third year or fourth year it is going to be very difficult to ignite those firecrackers. So, the age of the propellant is also important because there may be some chemical deterioration due to which the propellant will not ignite easily. The composition of the solid you know particle content of the igniter is also going to play a role that whether it is going to ignite or not. And of course, the igniter propellants is going to

play a role in terms of providing the plume of the hot gases impinging on the propellant surface.

So, I think we must need to understand the ignition process in order to understand the combustion because ignition is a very much important part of the combustion process. Now as I was mentioning about the different type of igniters they are mainly two types of igniters one is the pyrotechnic igniter another is the pyrogen igniter. So, for a smaller rocket the pyrotechnic igniters are sufficient to provide heat to ignite the smaller rocket. So, they are you know basically having some pyrotechnic mixture and that is ignited by some hot coil or ignition coil and that is supplied from some electrical energy. So, once the coil is heated enough that is going to ignite this pyrotechnic mixture.

And the once the pyrotechnic mixture burns this is going to provide the hot plume of gases including some solid particles depending on the composition of the igniter propellants it is going to provide some hot gases and is going to impinge on the propellant surface and that will lead to ignition. So, this is typical you know pyrotechnic igniters. So, there are different type of you know this is the basket type and jet plume tube type igniters are there. So, basically they are under the pyrotechnic igniters. Now, it may not be always sufficient to you know ignite a large rocket using this pyrotechnic igniter in that case a small rocket itself is used to ignite the large rocket.

So, basically the plume from the small rocket. So, if you look at this is a small rocket this plume from the small rocket is going to come and is going to impinge on the propellant surface which is going to ignite the main propellant grain. However, if you look at the pyrogenic igniter it seems itself it is a rocket the small pyrogenic igniter has to be ignited by a pyrotechnic igniter. So, this part is actually the pyrotechnic igniter which is going to ignite the small rocket. So, the pyrogenic igniter is a combination of you know small rocket which is going to be ignited by a pyrotechnic igniter. So, this is going to ignite the small rocket and the plume from the small rocket is going to impinge on the main propellant surface and is going to lead to ignition.

Now, there are various mounting options for igniters like it can be like up mounting which is going to be like internal, it may be external also only the gas will come and. So, if it is here you can see this plume will come and hit the propellant surface here also the gas will come and impinge on the surface. Now, there may be forward like this way is going to provide the plume here and is going to heat up the propellant surface. This is also forward mounting. So, this is going to provide the heat here the gas will come and heat up the propellant surface.

So, ultimately propellant surface will decompose and it will initiate the combustion. Here also same thing here also same thing as we said earlier that main role of the igniter of the propellant is to provide the hot gases which is going to impinge on the propellant surface,

but ultimately it should leads to sustain combustion then only we can say that ignition is successful ok. So, these are the various type of igniter hardwares and type of igniters and the ignition process. Now, with having that background I think we can start looking at the combustion processes in the solid fuels. Now, you know the combustion of solid propellants involves many complex reactions which is going to take place in the form of like solid, liquid and gas phases of heterogeneous mixture.

Now, there are several processes involved as I mentioned earlier the processes may include like change of phases like solid to liquid, liquid to gas. There may be like high speed flows, the chemical reactions, endothermic, exothermic both the heat and mass transfers involved in the processes. So, modeling of these type of processes in a very simplified manner is a very difficult task. What we will try to understand is like from the basic principles and some of the you know experimental data the researchers have model some you know model the combustion processes of the composite propellant and homogeneous propellant. So, we will try to understand some of the established mechanisms available in literatures and we will try to understand the combustion processes of these two type of propellants.

Now, before going into that combustion mechanism of double base propellant let us quickly you know brush off our ideas regarding the different modes of combustion processes like mainly there are two types of combustion mode like premixed and diffusive mode or diffusion mode. So, we understand that in case of premixed mode the fuel and oxidizer mixture it can be fuel and oxygen or it can be fuel and air basically the reactants are premixed prior to the combustion. So, that type of combustion is called premixed combustion. You can see this picture is shown here the typical structure of gaseous premixed flame. Now it can be like a methane plus air mixture, it can be have like propane and air mixture.

So, they are premixed prior to the combustion. So, that type of combustion mode is called premixed combustion. Now you can see the typical you know how the flame temperature is increasing there. So, this is the typical flame temperature profile. Now it is not necessary that it will happen only for this gaseous type of fuel, but the premixed flame can be prevalent in case of solid propellant as well. If you recall that we talked about the DB propellant or the double base propellant which is a homogeneous propellant.

So, upon decomposition of the double base propellant there will be various gases gaseous species will be formed. Now those gaseous species will be like fuel and oxidizers. So, they may mix together and they are going to form the premixed flame. So, in case of double base homogeneous propellant there is a possibilities of the premixed flame. So, in case of premixed flame as per the definition that the reactants will mix prior to the combustion.

Whereas in case of a diffusion flame the fuel and oxidizer diffuse into each other at the flame. So, here actually if you look at the typical Bunsen burner flame here you see the

fuel is coming from here and the air is going to diffuse into the fuel or fuel air will diffuse into each other at the flame surface or at the flame. So, that way they are distinctly different from each other. So, the premixed flame the fuel and air are mixed together or the fuel and oxidizer are mixed together whereas, in case of diffusion flame they are going to diffuse into each other at the flame. So, in case of a solid propellant as well we can see the similar behavior in case of like typical composite propellants where we have the solid oxidizers.

So, you can see the typical oxidizer particles is going to decompose, it is going to provide some oxidizing species whereas, the fuel binder which may be like polymeric binder they will pyrolyze and vaporize and produce some fuel species. So, those fuel species and the oxidizer species coming from the oxidizers may diffuse into each other and they may provide the diffusion mode of combustion and we will see that in case of composite propellants there are two different type of diffusion flames one is the primary diffusion flame another is the secondary diffusion flame or the final diffusion flame whereas, the ammonium percolate oxidizer will have its APPA or ammonium percolate premixed flame.

So, I think with this background we will try to go ahead and start discussing about the combustion mechanism of homogeneous propellant and heterogeneous propellant and of course, we will begin with the double base propellant. We will try to understand what are the different regions available in case of you know depending on the dominance of each of these regions we will discuss about their presence, their dominant reactions, their prominent species, how they are playing a role in terms of like the temperature increase, how they are playing a role in terms of pressure increase and how they are also influenced by the chamber pressure. So, we will discuss about that in detail in the next lecture alright. Thank you.