Course Name: Combustion of Solid Fuels and Propellants
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Lecture: 20 Combustion of Composite Propellants (Contd...)

Hello everyone, so we are continuing our discussion on combustion of solid propellants. And, in the previous lecture we have begin our discussion on combustion of composite propellants. We have discussed thoroughly regarding the various ingredients used in composite propellants.

And, we have said that the decomposition of oxidizer plays a very important role in the combustion processes of composite propellants. And, since we have all also talked about that ammonium perchlorate is considered to be the workhorse oxidizer for composite propellants. So, we will mostly emphasize on the combustion of composite propellants containing the ammonium perchlorate as the oxidizer and HTPB which is another you know workhorse binder for composite propellant. So, we will consider the combination of ammonium perchlorate as the oxidizer and HTPB as the binder or fuel for solid propellant ingredients.

And there we see that how the decomposition of ammonium perchlorate you know produce a certain flame which is going to you know further you know react with the fuel species and that will help in you know burning the fuel species present there and how the you know structure of the flames are coming. So, those we will discuss in detail and then finally, we will try to you know relate the burning rate with pressure as we did for double base propellant. But before that we will just try to understand what are the influencing parameters in the case of composite propellants and then we will write the burn rate law there. So, let us look at the structure of the flame here, but before going to that if you recall that we said that ammonium perchlorate is the most widely used crystalline oxidizer to you know make the propellant formulations for rockets. Now, here we should remember that unlike the double base propellant which are mostly used in you know gun propellants.

So, the perchloratebased propellants are generally not used in gun propellant just because the decomposition of ammonium perchlorate gives the hydrochloric acid which is highly reactive. So, that is going to you know erode the internal surface of the barrel. So, it is not used for the gun propellant application rather it is used for the rocket applications. So, in this case we are going to look at the structure of the flames containing the ammonium perchlorate as crystal, crystalline oxidizer and the HTPB as the binder. The polymeric hydrocarbons although it is it is main role is the binder, but it is going to give us the requisite you know physical shape of the grain by holding the solid particles present in the solid propellant ingredients.

Now, if we increase the propellant solid oxidizer too much then the amount of binder present in the propellant formulation may not be sufficient enough to hold the you know grain in proper shape. Now, the in this discussions we will see that how the composite propellant is going to give us the different flame structures. Now, there are extensive experimental studies and theoretical studies have been performed on the decomposition of ammonium perchlorate and combustion of ammonium perchlorate composite propellants, but we will just try to see what are the you know widely accepted models for the combustion processes of composite propellants. Now, the ammonium perchlorate particles decomposes to produce the perchlorateacid or HClO 4 and the fuel binder decomposes to produce hydrocarbon fragments and hydrogen. So, these you know gaseous decomposition products react to produce heat and they will produce the flame on the burning surface.

If you look at the close view of this now the ammonium perchlorate will you know decompose and they will produce the perchlorate acid as we have already seen there earlier. Now, the structure of the flame if you look at the ammonium perchlorate itself is going to produce some kind of a premixed flame or sometime it is known as the ammonium perchlorate premixed flame. If you look at the morphology of the propellant composite propellant the particles ammonium particles are surrounded by the fuel binder you see this is the binder HTPB. So, the particles which are large crystals or small crystals they are surrounded by the polymeric binder. Now, once the epi particles start decomposing after the ignition.

So, the initial decomposition step of both the fuel and oxidizers are kind of endothermic that we have seen it earlier in the previous lecture because sometime you know liquid layer is also going to form on the surface of the propellant. So, it is going to like whether you know set of products form during the condensed phase reactions of ammonium perchlorate and fuel whether it is going to be less endothermic or exothermic reaction that will you know depend on the reaction. But generally the overall reaction of burning of composite propellants happens to be exothermic in nature. Now, products formed during the overall endothermic reaction get mixed and undergo chemical reaction and they will you know react in the downstream of the regression surface. So, I think you we all recall earlier that the regression.

So, overall you know regression process if we if we remember like the ammonium perchlorate crystals are present which is held by the binder. So, what we said that you know decomposition of ammonium perchlorate will take place NH4ClO4 which is AP. In the previous discussions we have said that this is going to form like NH3 plus HClO4 perforic acid that will further you know going to decompose and providing the oxidizing species HClN and oxygen. Now, this the process of this one will going to have some kind of a you know premixed flame of the ammonium perchlorate particles. So, this is you know known as the ammonium particle sorry ammonium particle premixed flame.

In short we can write this as APPF. So, this is around you know 0.7 MPa or 7 atmospheric pressure that the ammonium perchlorate decomposition combines with the fuel binder and established premixed flame above the oxidizer crystals which is you know known as the ammonium perchlorate monopropellant flame or sometime it is known as the ammonium perchlorate premixed you know flame. You have to note here that the at low pressure the decomposition products of both the fuel and oxidizers are sufficient time to mix before the chemical reaction takes place that is why it is forming. So, some you know amount of fuel vapour is forming there they are going to have like very you know well mixed with the fuel and they are going to produce the APPF flame which is at the generally at the low pressure, but a high pressure the chemical reaction time is really small.

So, the mixing of fuel and oxidizer is going to limit the combustion process. So, this is not going to give us kind of a premixed flame rather this is going to diffuse this is going to diffuse it and this is going to produce this is going to produce a flame with the oxidizing species and the fuel species coming out of the fuel binder and they are going to form the this they are going to form the diffusion flame there. So, eventually this will form some you know diffusion flame there. So, if you look at carefully the processes goes in such a way that ammonium perchlorate will you know decompose and produce the oxidizing species the binder or the fuel which is the HTPB is going to form the fuel species. So, if you look at the pyrolysis of the fuel.

So, if you look at the fuel pyrolysis this will going to form like you know some hydrocarbon species like CH_4 carbon etc and they are going to react with this HCl $HClO_4$ and they are going to form combustion products. So, these are like kind of final reactions combustion products we are looking at like this will form CO_2 plus Cl_2 plus H_2O it may often form like HCl later on by combining Cl_2 and H_2O. What essentially is happening with these oxidizer thing they are going to go there and create some kind of a you know premix flame with the fuel vapor. So, we are turn this as a PPA or ammonium perchlorate premix flame the fuel vapor will keep on coming out from the surface of the fuel binder. So, this is the binder or the fuel because HTPB is known as the fuel binder which is also a fuel because it contains the hydrocarbon.

So, this is acting as a fuel. So, the fuel vapor will come out they will mix with the oxidizing vapor from the ammonium crystals and they will initially form the primary diffusion flame. So, this is a PPA then it forms the primary diffusion flame or PDF. Then the fuel vapor will react further with the oxidizer species and they will finally, form the you know that is going to form the final diffusion flame or the secondary diffusion flame secondary diffusion flame flame which is you know known as the SDF. Now, there are different models present to explain the combustion mechanism of propellants.

However, the models proposed model proposed by the Backstreet, Derr and Price the model proposed by these three scientists like Backstreet, Derr and Price their model is widely used model in explaining the combustion process of composite solid propellants containing ammonium percolate as oxidizer and HTPB as the fuel binder and it is known as the BDB model. So, in our discussions whatever we have said so far we are concerning the you know BDB model and we are talking about these triple flame structures. So, we have talked about the triple flame structure here. So, triple flame structure which is begin with the first flame is ammonium perchlorate premixed flame or it is known as the APPF. Then we have said the fuel bind the species from the fuel binder fuel or binder is coming and mixing with the oxidizing species and forming the primary diffusion flame primary diffusion flame which is known as the PDF and then the fuel species and oxidizing species going to react further and they are going to produce the secondary diffusion flame or SDF.

Of course, the extent of these different flame will depend on depend very much on pressure and with increasing pressure the extent of the you know the reaction rate will change. However, the diffusion is not going to change much with the increase in pressure, but this will definitely increases the reaction rate. Now, so that as the chamber pressure increases the fuel products you know going to find it difficult to get the oxidizing species and mix with the oxidizing species easily. So, we can see that it will have like have two reaction paths one is like oxidizing products and ammonia form AP decomposition and the fuel products and AP oxidizing products will become competitive. So, generally at the high pressure the chemical reaction are going to be very fast.

So, the oxidizer products you know react with ammonia to form premixed flame before the products can mix with the binder that may happen. But at the interface of oxidizer and fuel you know certain portion of the oxidizing products may come into contact with the fuel pyrolysis product and is going to form the primary diffusion form. So, this is the main you know triple flame structure of this model proposed by the back street there and price that you know advocates the triple flame structure which is consisting of ammonium percolate premixed flame, primary diffusion flame and the secondary diffusion flame. The typical temperature you know at the end of the primary diffusion flame is around you know 1400 Kelvin. Typical flame at temperature around 2800 Kelvin the primary diffusion flame forms and the temperature at the final you know division flame or the secondary division flame may be around 3200 Kelvin or 3300 Kelvin.

Now, that is the you know temperature that is going to provide the heat to the regression surface. So, if you look at if you combine this flame together and if you just look at the propellant surface here. So, this is our flame here. So, that flame is going to provide heat feedback to the propellant surface. So, this is our propellant surface.

So, this flame is going to provide heat feedback to the propellant surface which will allow the propellant to further you know decompose and form the oxidizing and fuel species and it keep on burning and that way the regression is of the propellant is going to take place. So, the regression of the propellant take place. Now, that regression we generally you know give in terms of R which may be represented in the unit like millimeter per second that how much length is regressing over time. Of course, the size of the ammonium percolate sorry ammonium percolate crystal the pressure of the system will definitely have a major influence on the you know combustion process that we can look at little later.

So, we need to remember that the extent of these three flame structures or the triple frame structures like containing APPF, PDF and SDF they generally occur above like you know close to like 0.2 to 0.5 millimeter of course, that depends on pressure though depends on pressure. Now, this distance is known as the standoff distance like the flame is at a height from the propellant surface which is known as the standoff distance. Now, if we increase the pressure the standoff distance is going to reduce because the pressure is going to increase the reaction rate. So, that will influence the burning process overall burning process. So, the flame will come closer to the propellant surface which in turn is going to improve the regression of the propellant further and which in turn is going to increase the burn rate.

So, if you look at the you know burn rate experiment conducted in a in a constant pressure environment and keep the fuel burning only in the direction normal to the propellant surface and if you measure the burn rate for various pressure reading starting from a smaller to higher pressure reading we may see that pressure as as the pressure increases the propellant burning rate is increases. So, there are some you know studies available in literature which shows that as the pressure increases the flame will come closer to the propellant surface and thereby increasing the heat transfer to the propellant surface which in turn is going to improve the regression of the propellant. The ammonium percolate particles also play an important role here because you see ammonium percolate particles are in different sizes they are crystals. So, if the ammonium percolate particles are smaller size the FPPF flame or ammonium percolate premixed flame will be in the shorter distance. So, they will also going to give us like you know heat transfer of the propellant surface very quicker and they will you know lead to finally, that will you know lead to the reduction in the distance of the stand up stand up distance because the primary diffusion flame is also will be closer to it and the final diffusion flame or the secondary diffusion flame will also come closer to the propellant surface.

So, eventually we can say that the pressure and the chamber pressure and the AP crystal size are going to play a influencing role in the stand up distance. So, if we increase the pressure the reaction rate is going to increase which will eventually you know reduce the distance between the flame and the propellant surface which will in turn going to improve the regression which in turn is going to you know further degradation of the propellant and it the burning will you know improve. Whereas, the AP crystal size if we make it smaller then the FPPF flame will be shorter that will improve the heat transfer which will in turn is going to have the PDF located near to the propellant surface and eventually the final flame is also going to locate in the surface near to the propellant surface. However, there are there are you know bimodal structures are used for in a in a composite propellants where bigger crystals and smaller crystals are combined together to form the you know composite propellant. So, thereby the dual role is going to play an important role there because you know smaller crystal will reduce the stand up distance whereas, the bigger crystal may have the adverse effect because it is have the longer FPPF you know flame.

Having said that now our role is to find out you know how these you know heat I mean we can model this the flame and somehow relate this with the the burning rate that we can actually finally, end up getting the the influence of pressure on the burning rate as we have seen in case of double base propellant. I think we have already seen in case of double base propellant that the pressure is very much influencing factor on the double base propellant. So, I think that will be our next job to do that how do we relate the burn rate with the pressure. So, in order to do that let me just first at least introduce the things what we are going to do in a very simplified form if we just try to write what we have just said that let us say we have this crystals. So, this is our binder which is nothing, but hydrocarbon which is also acting as fuel.

So, let us say this this type of analysis I am taking from professor Ramamurthy's book which is one of the text book you know mentioned in for this course. So, this we have said this is APPA then we have the you know primary diffusion flames which is from there with the fuel vapour and the oxidizing species and then they will react with each other and they will form some primary diffusion flame here and then finally, the remaining oxidizer and fuel vapour is going to form the final diffusion flame here. So, we have P D F and finally, we have the S D F or the secondary diffusion flame that we have said already. Now when we have aluminum particles present in there because in many occasions in composite propellant aluminum particles are also placed there. So, aluminum particles generally you know burn in a high temperature, but in this simple analogy we are just trying to see that how this ammonium particle ammonium percolate and the H T P B binder are burning in this you know composite propellant.

So, the relevant temperature also we have mentioned in the previous slide. Now we can said that with this combined form of the you know flame we can just say that let us say this is the flame zone this is the flame zone which exist at a distance let us say some distance x which is known as the standoff distance. Here we have the you know propellant surface and then we have the flame zone which is known as the flammable. So, if we look at the temperature profile temperature will you know is going to vary like if this is the propellant surface is going to surface temperature is going to increase and then keep on increase go to the flame temperature. So, this is going to flame temperature this may be the surface temperature this is like the initial temperature of the propellant.

Now, the temperature is going to rise from the surface temperature T S to the final temperature T F in the flame zone. So, here we are saying that the temperature in the flame zone is the T F and the surface temperature is T S. So, that you know tell us the temperature boundaries kind of thing that T S and T F. So, what flame zone is essentially doing it is providing the heat to the propellant surface to further you know degrade and produce the fuel and oxidizing species. So, in the next class what we will do is we will try to do some analysis like heat transfer from the flame zone to the propellant surface will approximate the temperature profile with the linear one like it is varying from T S to T F.

The heat transfer per unit surface area will of course, increase the temperature from T S to T F from the initial temperature T I. So, it will increase. So, some heat is going to go there to increase the initial temperature of the propellant to the final temperature to the surface temperature T S and then finally, the reaction will take place and the temperature will go from T S to T F in the flame. So, we will try to see that how much heat is being absorbed at the propellant surface per unit area and that we will just try to relate with the heat transfer from the heat transfer per unit area of the propellant surface which is coming from the flame. And if you just equate that and somehow if you can relate the you know regression of the propellant like the mass regression rate with the propellant mass regression rate of the propellant with the regression rate like millimeter per second or some length per unit time in that sense if you just try to relate we may come up with the equation which will tell us that how the pressure is going to you know influence very much on the burning rate of the propellant.

So, it is a similar way we will just do the analysis as you did for double base propellant and we will see here also that the R is very much dependent on pressure and we will end up getting the burn rate law. So, I think we can do that simple analysis in the next class. Thank you.