Course Name: Combustion of Solid Fuels and Propellants
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Week: 04
Lecture: 21 Evaluation of Burn Rate of Composite Propellants

Hello everyone. So, we are continuing our discussion on combustion of solid propellants. And, we were continuing the evaluation of burner of composite propellant. We have already somehow introduced the processes involved in combustion of composite propellant. So, we will just quickly look at the various processes involved in the combustion of composite propellant. And then we will try to get a simplified you know mathematical model to understand the burn rate of composite propellant.

And, we want to see that how the burn rate of composite propellant is also going to be a strong function of pressure, which we have already seen in case of double base propellant. Now, as we have already seen that the physically the double base propellant is homogeneous whereas, the composite propellant is heterogeneous in nature. So, of course, the burning process is distinctly different than the double base propellant. And, that we have already started discussing in the previous lecture.

So, today we will try to focus on the evaluation of burn rate of composite propellant. But, we need to make sure that we understand the process very carefully that how the you know the decomposition of crystalline oxidizer play an important role there, how the ammonium perchlorate premixed flame is forming. And, what is this what is this role on donating you know oxygen species, which will in turn going to mix with the fuel species formed from the pyrolysis process. And, that will form the premixed diffusion flame. And, then finally, the final products of a P P F and the P D F you will mix together and form the final diffusion flame or the secondary diffusion flame or S D F.

And, the popularly known model to describe this triple flame structure is the BDP model. So, we will continue our discussion by considering that BDP model. So, let us look at how we can evaluate the burn rate of composite propellant. So, I think in the previous lecture we have shown this one that you know ammonium perchlorate first will decompose once we ignite it, it will decompose it is going to form the you know perchloric acid and ammonia. And, then later it is going to produce some you know oxidizing species some inert products and some oxidizing species.

And, we also told ourselves that the BDP model is considered to be the well describing model for the burning process of composite propellant and the model advocates the triple flame structure. Now, the flame formed due to the decomposition of ammonium perchlorate is known as the premixed flame or sometime it is known as the ammonium perchlorate premixed flame because no mixing with other constituent is involved here. Therefore, this the first flame appears in the decomposition in the combustion of composite propellant involving perchlorate based oxidizer is the APPF or ammonium perchlorate premixed flame. Now, after the ammonium perchlorate premixed flame the oxidizing species will be formed whereas, the binder which is HTPB which in turn a fuel as well because HTPB is simply the hydrocarbon. So, on pyrolysis of this hydrocarbon this is it is going to produce the hydrocarbon species or the fuel species that will mix with the oxidizing species evolved from the premixed flame.

And, that will create the primary diffusion flame which is showing here that O/F flame O/F flame over a or the diffusion flame. So, mainly we can say that the ammonium perchlorate based composite propellant consisting of one premixed flame and two diffusion flame two diffusion flame. The first one is the primary diffusion flame primary diffusion flame and the second one is secondary diffusion flame. And, this triple flame structure is advocated by this BDP model that we have already seen there in earlier case. So, we are considering our discussion based on this BDP model.

Now, the typical temperature of the APPF flame is around 1300 to 1400 Kelvin that we have already discussed in previous class. The primary diffusion flame may go temperature around 2800 Kelvin whereas, this one can go 3200 to 3300 Kelvin. Now, we must appreciate although we are talking about these three different structure of flames, but they are really narrowed in a small region or small thickness above the propellant surface. So, what we are talking about this is the propellant surface. So, if you look at the structure of the or the morphology of the flame we can sorry morphology of the propellant surface they are having scattered you know ammonium perchlorate of various sizes like there will be some bigger size crystals or smaller size crystal dispersed on the propellant surface.

So, the heterogeneity of the propellant surface is going to definitely is going to play a role in this you know formation of this type of you know triple flame structure. So, depending on you know size of the particles the pressure involved in the chamber the flames what we talked about like the premixed flame, primary diffusion flame, secondary diffusion flame have different levels of importance. At low pressure the chemical reactions are slow and it takes long time to you know complete the combustion. So, therefore, at low pressure we can say the premixed flame is the controlling factor or you can say the premixed flame dominates the combustion process in the low pressure. Because during the when the pressure is low the reaction chemical reactions are slow.

So, it takes longer period of time to complete the combustion. So, premixed flame actually tells us that how the combustion will take place for the composite propellant. So, premixed flame is dominant in case of low pressure is low pressure instances whereas, the when the pressure is high enough the chemical reaction take place at a much faster rate because large number of molecules will be available. However, the diffusion will be does not occur that faster rate with increase in pressure as a result of that the diffusion will control the combustion process in the high pressure. So, in a sense we can say that the at low pressure the primary flame controls the combustion process whereas, at high pressures the combustion is controlled by the diffusion or the mixing process because we know that at high pressure chemical reaction rate is much faster.

However, the diffusion process is not improved that way. So, the mixing between the oxidizer species and the fuel species will influence the overall combustion process. Now in the previous lecture I think we have seen this flame pictures earlier for you know various ratio of binder to oxidizer crystals and we have seen that as the you know fuel species is increasing the flame color is changing. Now the purpose of bringing this here just to show you that the thickness what you are talking about it is really like a very you know narrow region about like 0.2 to 0.5 millimeter region where these three flames exist. So, based on the pressure, based on the ammonium perchlorate sizes and of course, there are other parameters involved which would influence the relative importance of the each of these flames. However, for the sake of simplicity we can just consider a narrow region of the flame which is going to you know transfer heat for the pyrolysis and decomposition of the fuels fuel polymeric fuel and the you know ammonium perchlorate crystals. So, flame itself we can consider to be a plane planar region above certain distance of the propellant surface which is considered to be the standoff distance like we can consider this these three flames at a certain plane which is located at a distance you know x star from the propellant surface. So, this is the propellant surface where we have the you know crystals embedded in the polymeric fuel.

So, flame is located at a certain distance from the propellant surface which is providing the heat to the propellant surface for further decomposition of the ammonium perchlorate crystals as well as the you know pyrolysis of the polymeric fuel that is the you know basic of the combustion process of combustion combustion process of composite propellants. Now, if we look at the typical thickness of reaction zone as a function of pressure for APHTB based composite propellant this experiment was conducted at low pressures, but still we can see as the pressure is increasing from you know 0.02 to 0.03, 0.05 and 0.1. So, basically it is like one atmosphere. So, the experiment was conducted from sub atmospheric to you know slightly above atmospheric one can see that the thickness of the reaction zone is actually decreasing as we increasing the pressure as we increase the pressure. So, therefore, the heat transfer is going to be better as the standoff distance is going to reduce once we increase the pressure. So, basically the pressure has an has an important role on the combustion overall combustion process of the composite propellant. So, definitely as we have seen in the double L S propellant in a similar line we can actually say that the boundary rate is also going to be a strong function of pressure, but with some simple you know mathematical relationship we can actually try to see that whether we can you know represent that burning rate are in terms of you know strong function of pressure.

For doing that we just need to consider some simple you know representation of the flame as I said earlier that just you know 3 flame or triple flames are located at a region above the propellant surface at a distance x* where x* is denoted as the standoff distance. Now, this flame is going to provide the heat for further you know decomposition of the ammonium perchlorate crystals and the pyrolysis of the fuel binder. So, what essentially it is doing is it is providing the heat to the propellant surface for the further reactions. So, what we need to equate that the amount of heat coming from the flame is going to be used for heating of the propellant as well as the pyrolysis of the fuel binder. So, heating of the problem means there will be some you know initial temperature of the propellant that will goes to some surface temperature of the propellant T S and once the reactions occurs the it will reach to a flame temperature.

So, if you just plot the temperature versus x we may say that the temperature is you know increasing from the surface temperature T S to the flame temperature T F. So, this is typical temperature profile. So, the temperature increases from the propellant surface temperature T S to the final flame temperature T F. Now, if you consider this to be a linear profile then we can actually try to you know write down the heat transfer due to the you know coming from the flame for you know increase the temperature of the the propellant surface. We can simply write down that heat transfer to the unit surface area of the propellant from the flame surface we can write this as

-kg dT dx.

Now, if you denote this kg as the thermal conductivity of the gas thermal conductivity of the gases in the standoff region. So, we are talking about the standoff region here and if we consider linear profile of this temperature we can simply write that the heat transfer per unit surface area of the propellant from the flame surface is equal to minus kg dT dx which you can write

kg T F - T S by x*

where x* is the standoff distance. Here we have to remember that we have considered the linear temperature profile in the above equation for just the simplicity of the analysis. Now, what exactly is done by taking heat from the flame surface the heat is going to you know increase the the temperature of the propellant from the initial temperature T i to the surface temperature T S and also it is going to supply energy required to vaporize and pyrolyze HTPB or the polymeric binder and decomposition of AP. So, we can say that some heat is required for endothermic reaction and heat required to to raise propellant temperature.

So, whatever the heat transfer is coming from the flame is going to do two things one is going to provide heat for the you know endothermic reaction which is like the pyrolysis of the polymeric binder and the decomposition of ammonium per plate crystals and also it is going to increase the temperature of the propellant from it is initial temperature to the surface temperature. So, if you denote that the net rate net rate of heat absorption at the surface and of course, per unit area we are considering per unit area here. We can simply say that m dot m dot is the rate of vapor released from unit surface area of the propellant that is denoted as m dot t into C C is the specific heat of the propellant into T S- T i + some you know endothermic heat is required for you know converting the fuel and the oxidizer to the vapor or the gaseous state. So, let us consider this is this heat is that as for required for the endothermic reaction which is delta is V, C is the specific heat of the propellant. So, what we can say here that this heat is coming from the required heat is supplied by the flame.

So, we can equate this that heat input to the propellant surface coming due to the heat transfer from the flame with this one which is the heat absorbed by the propellant for you know temperature rise and decomposition and parallelization of the fuel.

We can simply write

$$K\ g\ (T\ f - T\ S) / x^* = \dot{m}C * (T\ S - T\ i) + \underline{\Delta}V$$

and what about our m dot? m dot we have said that m dot is the rate of vapor released from unit surface area of the propellant. Now, if we consider this the mass burning rate of the propellant per unit area we can simply write that m dot is going to be equal to the propellant density into R where R is the linear burn rate, R is the linear burn rate. So, this vapor is coming due to the regression of the propellant. So, as the propellant surface is regressing over time if we consider the linear regression of the propellant is R which is in let us say millimeter per second or you know centimeter per second some you know length regression.

So, if we consider the linear regression of the propellant is R we can denote this m dot which is you know rate of vapor released per unit surface area of the propellant we can relate this with this equation if we replace m dot in terms of $\rho p*R$ we can easily get a relationship with R. So, we can now simply put this in terms of R. So, this will become

$$C * (T\ S - T\ i)\ \Delta H\ V$$

So, what we can write here we can simply write the equation for R will become $(K\ g * T\ F - T\ S / x^*) / (\rho_p * C * (T\ S - T\ i) + \Delta H\ V)$. So, this equation suggest us that if we have increase in flame temperature.

So, C f is the flame temperature. The increase of flame temperature is going to give increase or give rise to the burn rate and that is quite true also because if the flame temperature is higher we expect like more heat transfer from the flame to the propellant surface. So, increase in flame temperature will in turn cause increase in burn rate. If we have increase in you know the initial temperature of the propellant that will also going to improve the burn rate of the propellant. If we lower down the x* if we decrease the value of x* that will in turn is going to help increase in burn rate. So, increase in flame temperature will also going to improve the burn rate.

The decrease in x* is going to increase in burn rate, increase in T i is also going to you know increase in burn rate. So, there are various influencing factor which is going to you know influence of the burn rate. But you know the reaction rate is going to be very much dependent on the pressure as we have seen in case of the double base propellant. If we you know relate this stand off distance with the reaction rate of the propellants we may found out we may find out that the pressure has a you know major you know effect on the reaction rate and that will reduce the you know flame stand off distance. So, as we have higher reaction rate the flame stand off distance is going to you know decrease as we increase the pressure because the pressure has a influence in role on the reaction rate and that will decrease the stand off distance.

So, therefore, in turn we can say that R would R would very much depend on pressure. So, in the similar line we can say that the burn rate or linear burn rate of composite propellant is also going to be expressed as the next as in burn rate law A R equal to A P to the power N what we have seen in the previous occasions for double base propellant. Where N is the pressure index which is bringing the effect of pressure and A is taking care of the other things like the initial temperature of the propellant, the composition of the propellant, the physical nature of the propellant that will be taken care of by A. Now, we can say that size and pressure have very influence in role on the size of size means we are talking about the size of ammonium perchlorate crystals. Pressure type of binders, catalyst so many things I mean these are not just only only parameters, but there are many other parameters which are which are going to influence the burn rate of composite propellant.

So, if we try to get the value of A and N what we need to do is we have to some you know experiment with a constant pressure, we keep on changing the pressure and different pressure we have to generate the value of I mean we have to get the you know data for burn rate and from the curve fitting we can actually find out the value of A and the value of N ok. So, in a similar way the pressure index N and A can be determined from the experimental values. The pressure of interest in solid propellant rocket typically you know ranges. So, the chamber pressure in solid rocket generally ranges from you know 3 to 15 MPa which is like 30 to 150 atmospheric pressure and as we have already mentioned that at this pressure the diffusion flame dominates the overall combustion process. So, diffusion flame dominates the combustion process of composite propellant because at high pressure we have already discussed that at high pressure the reaction rate will be quite high whereas, the diffusion or the mixing of oxidizing species and fuel species will not up to the mark compared to the reaction rate that is why the diffusion flame will be the dominant here in case of this pressure range.

Now our job is to see that what are the different factors which is going to influence the burn rate of you know composite solid propellant. Now we can see that at low pressure the pressure exponent the value of N is generally in the value around 0.5 or so, because they are actually APPF dominates at low pressure and then at high pressure the value of N is in the order of around 0.3 to 0.4 generally beyond 10 atmospheric pressure. So, the value of N in is in the order of like 0.3 to 0.4 whereas, in double phase propellant we have seen that the value of N is generally in the higher side about 0.6, 0.65, 0.56 like that. So, at low pressure since APPF dominates the value in the range of 0.5 however, you know these values will depend on you know different ingredients of the propellants. So, if we just want to bring about the effect of the pressure we need to conduct the experiment mainly the you know strand burning experiment is conducted and the value of A and N are determined and we can actually get this thing from the you know curve feeding of the data. Now looking at as a thickness of the reaction zone we have already said that looking at the pressure if you if we see the different type of propellants here it has been compared with like double base propellant also and some APBAs composite modified double base it is not directly you know composite propellant here it is like APBAs some composite modified double base, but still we can see the effect of you know pressure with the burn I mean the effect of burn rate sorry the burn rate influenced by the change of chamber pressure. So, we can see as the pressure is increasing the burning rate is going to be increased continuously like we can see for double base propellant it is here, but for composite propellant you can see as the AP percentage is increases the burn rate is also going to be increase you can see this here and as the pressure is increasing from 10 atmosphere 20 as per atmosphere the burn rate is also increasing ok.

So, in both case the either double base propellant or composite propellant pressure has an influence in role on the burning rate of the propellant. So, as we have seen in case of double base propellant that it is a strong function of pressure similarly for the composite propellant as well it is also a strong function of pressure. Now what are the other effects which is going to influence the burn rate of the propellant we have to look at carefully. One such you know example is the effect of AP particle size we have already discussed in the discussion of during the discussion of the you know combustion mechanism of composite propellant involving ammonium perchlorate crystals. We have said that as the ammonium perchlorate crystal sizes reduces the standoff distance is going to you know drop or the flame tries to come closer to the propellant surface.

I mean to say that the as the particle sizes of the propellants you know decreases this is the propellant surface the flame is somewhere over here. So, we are considering this flame as a single plane where both where all three flames are there. So, the flame standoff distance is going to reduce as the particle sizes becomes smaller. So, from the experiments also it has been observed now these two plots are showing for two different you know two different combinations one is for bimodal case bimodal means for efficient in packing to improve the packing density the ammonium perchlorate crystals are packed into different sizes bigger and smaller. So, that the smaller crystal can take up the void space created by the you know bigger particles due to the arrangement of the bigger particles.

So, the bimodal cases the mixture of bigger crystal or the larger crystal and smaller crystals are used. So, if you see here for bimodal case as the particle sizes decreasing from you know combination from 350 to 200 micrometer bimodal. So, it is like 4 is to 1 ratio it has been used. So, 350 and 200 here you see it is like 15 to 15 micron and 3 micron combination the here also 4 is to 3 ratio the mixture has been prepared for the crystals. For the pressure effect we can see that is increasing in both cases burning rate is increasing with pressure, but for the bigger crystal we can see the burn rate is lower compared to the smaller crystal.

Here the crystal size is like 15 micron and 3 micron combination whereas, this one is like 350 and 200 micron. So, we can see the burn rate is going to increase as we make the AP crystal lower. In both the cases the oxidizer to fuel ratio is maintained as maintained at 80 is to 20 AP by HTPB ratio. So, for a same you know oxidizer to fuel ratio while decreasing the size of the crystal the burn rate is increasing. Now, if you consider the same thing for monomodal case means only one type of crystal sizes used in the propellant combination there also we can see as the pressure is increasing the burn rate is increasing.

So, there is no difference in that, but as we decrease the particle size the burn rate is actually increasing. So, we can see that this is the 265 micron sizes whereas, this one is 55 there is some discrepancy in the data like this one is also increasing this one is the 55. So, we are supposed to have like this one. So, maybe some discrepancy, but overall we can say that as the crystal size of the ammonium perchlorate decreases the standoff distance decreases and eventually the burn rate is going to increase. So, the pressure and the particle size has an influence in role on increasing the burn rate if we increase the pressure and if we decrease the particle size.

Now in the next lecture we will try to see what are the other effects which are also going to control the burn rate of composite propellant. For example, like type of binder what are the different polymeric binder we used is there an influencing role on the burning rate of the propellant because of the change in binder or the percentage of binder like if we decrease or increase the binder percentage in the propellant matrix whether there is any change in the burn rate. Similarly, there are other effects like catalyst. Now catalyst can be like positive catalyst or negative catalyst means the catalyst can either increase the burn rate or it can decrease the burn rate. So, based on the choice of the catalyst there is an influencing effect on the burn rate of the propellant.

In the subsequent lecture I think we will try to explore on the effect of those parameters. Alright, thank you.