Course Name: Combustion of Solid Fuels and Propellants
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Lecture: 15 Combustion of Double-Base Propellants (Contd…)

Hello everyone. So, we are continuing our discussion on Combustion of Solid Propellants and we began discussing about the combustion mechanism of double base propellants. We had discussed various you know things involved in general combustion of double combustion of solid propellants.

Now, we had initiated our discussion that there are various zones exist in case of combustion of double base propellant or during the burning of double base propellant. So, in this lecture we will try to understand the relative significance of each of these combustion zones for double base propellants. So, let us look at the typical feature of the you know combustion of double base or combustion of flame structure of double base propellant. So, if you look at what we discussed earlier that there is a zone exist between the burning surface and the between the burning zone and the solid surface which is we termed as the foam zone or we said this is sometime termed as the degraded solid propellant zone.

So, basically the degradation of solid propellants is taking place in this zone. Right after this the beneath of the foam zone is the preheated you know preheated solid propellant zone. So, basically the this is the sub surface of the solid propellant and here you know this is the unheated propellant. So, as we told earlier that the heat coming from the flame is heating up the propellant surface. So, the surface temperature and the sub surface temperature are being increased.

Now, in the very immediate you know underneath of the surface there are some degradation of the solid propellant is going on which zone is termed as the foam zone and that is giving some you know some species which are going to react further in the zone called the fizz zone. So, there will be some you know is called the fizz zone and then we said that there is another zone exist which is kind of a silent zone and then we said that there is some very luminous zone present which is the flame zone which we already seen in the picture as well and some you know dark region exist which is called the dark zone or sometime it is termed as the induction zone. It is almost you know invisible. Now, extent of each of these zone depending on many factors particularly the pressure plays a very important role on the extent or the length of these each of these zone particularly the preparatory zone or the dark zone or the induction zone. Now each of these zone has important role to play for example, like the you know foam zone or the degraded propellant zone is giving us the gas phase species which are going to react in the fizz zone.

The product or reacted species is formed in the fizz zone they will go further and they may some react some you know further in the dark zone but of course, the exothermic reactions in the dark zone is bit slower that is why the dark zone is kind of not very luminous and the temperature range is also not very high and after that the flame zone which is the very luminous zone that is going to give rise to the temperature it may goes go as high as like you know 200, 2000 degree centigrade. This zone after the dark zone may be around you know 800 or so here we can say like 300 to 400 in this zone dark zone is kind of not you know going to increase much. So, it is almost like a silent zone very little increase or even not an increase in temperature because that zone is going to give the you know preparation for the next zone. So, now let us look at the various species formed in each of these zone and we will try to understand the importance of these each of these zones. Now once the surface this is the propellant surface once the surface receive heat from the flame the solid surface is going to you know get degraded thermally is going to degraded that is why the term is also called degraded solid propellant zone and undergoes the you know exothermic various exothermic reactions.

Now this degradation zone is very much you know is part of the propellant within the propellant. So, it just you know within the propellant itself right at the propellant surface. So, that zone is called the foam zone. Now in this zone the major species which are formed are the you know gaseous species like NO, NO2 and aldehydes. Aldehyde means like they may form formaldehyde like HCOH or they may form like methyl radical combined with the carbonyl group.

So, because this is the carbonyl group. So, hydrogen radical is connected with the carbonyl group is like HCOH which is formaldehyde it may form like acetaldehyde also acetaldehyde which is CH3COH. So, these are the major species formed in the foam zone. Now these aldehydes and NO2 they will react in this zone, but in general you know this zone is not very exothermic rather it is you know kind of endothermic like the foam zone is not very exothermic because you know this zone is kind of we can say that mostly it is you know degrading the solid propellant. So, this zone is not very exothermic rather it may it may be bit endothermic also, but you know overall you know there is some temperature increase is possible because you know some reactions are taking place which are giving some you know heat transfer to the sorry giving rise to the temperature, but you know this zone is very much close to the propellant surface.

So, the temperature of the propellant surface the preheated you know temperature of the Ts there may be slight increase in temperature in the you know foam zone. So, it may be almost equal to the preheated zone temperature or may be slight increase in preheated zone temperature because the reactions are pretty much you know kind of endothermic and it may mainly gives the degradation of the solid propellant. So, this overall you know these reactions are kind of you know endothermic in nature. Now the thickness of this foam zone is kind of very small it may range from you know depending on the chamber pressure like depending on the chamber pressure the foam zone thickness may vary from like you know 10 to 100 micron. Of course, they are very really small region, but pressure has an influence on the extent of this zone.

So, it is expected that since the since the extent of this zone is very small the temperature of this zone is very much you know closer to the or very much similar to the preheated temperature of the preheated zone preheated solid propellant zone or which is like the Ts. So, Ts and T0 we can say they are kind of very similar. So, now let us look at the next zone where the major reactions are taking place the gas phase species which are majorly reacting in the in the fizz zone and this zone is some kind of a you know you can see the temperature will increase in this zone. Now if we look at the temperature profile here we may see that temperature is going to vary something if we look at the propellant surface draw it like this. So, we said that the foam zone is very much you know part of the propellant.

So, this is you know kind of your foam zone here we said that this is the you know preheated zone, this is we said the foam zone. So, if you just try to look at the temperature profile versus the length what you can say. So, this part is the preheated this is like the unheated zone. So, the temperature will you know rise from the unheated zone to the surface temperature which is like let us say Ts and then it will be pretty much you know almost remain almost the same. So, you can say this almost the same in the this foam zone and then we have the reaction major reaction take place one zone is called the fizz zone.

Here if you look at the temperature profile is going to increase significantly it will go like to this and may reach to some let us say T1. Now in this zone the major portion of the gases which are like NO, N2, NO, NO2 and aldehydes which was released which were released in the foam zone will you know got mixed and they will react exothermically and they will increase the temperature to significantly higher than the surface temperature or the what about the temperature there at the end of the foam zone which was like T0. So, T1 is significantly higher than T0. So, the major you know species are going to form in this zone are like the carbon dioxide, carbon monoxide, water, hydrogen they are going to form here. Now the this zone thickness is also kind of not very large this is also kind of small although you have you know made it little bigger compared to the foam zone because foam zone is compared to be higher than this fizz zone, but just to show you know the temperature profile we have just made it little bigger.

So, this zone is also kind of smaller which is like 1 to 10 micron this one is you know 10 to 100 micron we said it is not up to the scale of course, because this is showing smaller than this one little awkward, but you know just remember that just to show the temperature profile we have just made it you know in a exaggerated way just to show that the temperature is changing from T0 or Ts because Ts is kind of pretty much equal to T0 because the in the degradation zone the temperature is not rising much. So, once it reaches to this one then the next very next zone is we said the induction zone or the you know dark zone. Sometime it is termed as the induction zone and then we have the luminous zone or the flame zone or sometime we said like luminous zone. Now, as we said that the species formed in the foam zone or in the degradation of the solid propellant the species formed there was like NO, NO_2 and aldehydes like it may be like HCOH or CH_3COH formaldehyde or acetaldehyde they will react in the fizz zone and they are going to produce like gases such as you know they will exothermically react and they will produce CO they will they may produce CO_2 they may produce you know NO will also be the NO may be present there also they may produce like hydrogen they may produce water also. Now, of course, one can do some chemical equilibrium calculations and they can try to see that amount of you know these species are forming in this zone, but these are the typical species formed during these within this fizz zone, but we have to remember that fizz zone is kind of you know very much important zone in terms of the reactions because the dominant reactions are taking place here and the major you know increase in temperature is taking place in this zone.

So, you can see the temperature has you know increase from this surface temperature or pretty much the T_0 to the T_1. So, that is the major increase in the temperature. Now, since this fizz zone plays an important role in you know determining the burn rate of the propellant. So, we give due importance to the fizz zone while we analyze the you know combustion process. Now, if you have to model the combustion process in some mathematical you know terminologies we generally give due importance to the fizz zone and we do the you know energy balance by considering some small control volume in the fizz zone itself because the major exothermic reactions are taking place in the fizz zone.

Now, right after the fizz zone is the induction zone or the dark zone which is you know between the fizz zone and the luminous zone or the flame zone. So, in this zone the extent can be you know quite large. So, as you said the dark zone the temperature will may not you know change much. So, it is the dark zone temperature. So, in this dark zone the extent may be like 0.1 to 2 centimeter again depending on the pressure depending on the chamber pressure the extent of the dark zone can vary. Now, in this zone you know whatever the chemical species are formed by during the reaction in the fizz zone they will you know kind of react further in this zone, but the temperature will remain almost constant. We can say that very little heat is kind of liberated in this zone, but however, this zone is going to provide some of the you know species which are going to be instrumental for further you know increase in temperature in the flame zone because after this right after this we have seen that the secondary luminous zone or the flame zone exists or the luminous zone exists which is giving rise to the temperature to the flame temperature. So, the dark zone or the induction zone is sometime called the preparatory zone for the flame zone because this is going to give us the products formed in the dark zone which is going to react further in the flame zone and they will you know give rise to the temperature. Now, so, in this zone we can say that the products formed in the dark zone are going to reacts further like NO_2, CO and H_2O they will react further and they will give a sharp rise in temperature as high as like you know sometime 3000 Kelvin.

Now, this zone luminous zone extent is about in the range of like 100 micron to 0.2 centimeter. Now, this zone provides the heat to the propellant surface if you recall what we said in the previous discussion even here also that this flame zone is going to provide you know heat to the propellant surface through the you know mode of different mode of heat transfer like convection and radiation and then there will be like conduction to preheat the propellant surface. Now, if this thickness of the dark zone is not very large the heat transfer from the flame zone will be you know will be significant and that will you know going to increase in the burning rate of the propellant because that will help in transferring the heat to the propellant surface. Now, if we look at the literature I mean literature is saying that if the pressure is beyond like 7 MPa or 70 atmosphere or 7 MPa the dark zone.

So, beyond this pressure the dark zone almost disappear. What does that mean that you may see that the flame zone will come comes very close to flame zone will come very close to the propellant surface which will actually going to help in you know providing more heat you know feedback to the propellant surface which will eventually you know help in you know creating more gaseous species in the degraded solid propellant zone or the foam zone which will eventually increase in you know further reaction in the fizz zone that will eventually increase the you know regression rate of the propellant. So, the decrease in the dark zone which is some kind of helpful in a sense that it is going to increase the feed feedback from the flame zone to the propellant surface. So, therefore, the pressure dependent of the extent of the flame zone is kind of important sorry pressure dependency on of the dark zone is kind of important in a sense that increasing pressure will give decrease in the extent of the dark zone which will eventually going to you know increase the heat transfer from the flame zone to the propellant surface and that will eventually you know give increase in the regression rate. So, as if you recall the we showed we have seen this picture in the previous lecture that typical flame photograph photographs of the nitrocellulose and nitroglycerin based double base propellant where you see once we ignite the flame in a low pressure condition.

So, this is a typical picture of experiment conducted in Crawford burner or constant you know pressure burner where we you know there is a closed chamber where we keep the pressure constant by you know refilling some you know inert gas and then we let the propellant burn there like a small propellant strand cigarette like strand the propellant contain both fuel and oxidizers. So, you can see these are the ignition lead because these are two electrodes and this is ignition coil. So, once the propellant is once the propellant is ignited the propellant surface will regresses along these normal to the propellant surface you can see there is a gap between the flame and the propellant surface and that is the we call this is the dark zone. So, the degraded solid propellant zone is very much you know part of the solid propellant which you can see it is almost at the propellant surface. So, whatever the distance we are seeing that is typically the extent of the dark zone.

Now, if you increase the pressure as it is mentioned in this literature that if we increase the pressure we may see that the flame zone is coming closer to the propellant surface as you can see there is a significant reduction of these extent of the dark zone in this case. Now, once we increase the chamber pressure even further we can see the dark zone almost disappearing and as if the flame zone is typically starting from the propellant surface. So, what you can see that increasing the pressure is very much important in terms of like the extent of the dark zone. Now, this experiment is typically conducted by considering you know one the closed chamber where you have the propellant strand. Now, if you compare this picture with this one so I am saying that this is the propellant strand and the ignition lead as I said that there will be some ignition coil and you can see this is the ignition lead.

So, that is supplying some you know voltage. Now, if we are inhibiting the propellant circumferentially if we let the propellant burn only on this from this side so as if like a cigarette if you look at the cigarette structure it is like this, this is the filter. So, smoke will come out like this. So, it will typically burn like just like a end burning.

So, it is burning from this side. Similarly, like if you burn a solid propellant strand it is going to burn like in this direction and it will regress over the length. So, in this Crawford burner I think we gave you some brief idea in the previous lectures I believe where we you know filled with nitrogen or some kind of inert gas with some pressure chamber pressure Pc. There if we let it to burn now if you consider a double base propellant in for this example depending on the chamber pressure let us say if it is below you know kind of 3 4 MPa around this pressure you may see that the there is a distance between the you know flame the studying of the flame and the propellant surface. So, there is a gap exist. If you increase this pressure now how the experiment takes place here there is typically one fuse wire is placed while making the propellant strand itself during the processing time.

So, this fuse wire are placed at a pre decided distance L. Now if you connect this unit with some timer unit and if you if you just let this fuse wire cut once the propellant strand burns. So, as the you know propellant surface regresses the flame will establish the due to the high temperature the fused wire will get cut the first fuse wire will get cut number 1 and number 2. So, first fuse wire will get cut and the timer circuit will begin start it will start counting the time. So, if the once is reaches to the second one it will give us the time delta t.

So, now, we know that the delta t time was elapsed in order to burn the distance L. So, from there we can actually get the linear regression rate by dividing the length by the elapsed time. So, that way so, we can say that R is actually typically the linear regression rate L by delta t. So, from there we can get the burning rate for different chamber pressure. Now coming back to this experiment when it increase the chamber pressure higher and higher you may see the extent of the dark zone is somehow coming you know less and less here you can see the gap is even less.

So, the extent of the dark zone is coming you know reduce and reduce further if it beyond the pressure is chamber pressure is beyond like you know 7 MPa you may see that this flame will become kind of attached almost like there is no gap between the propellant surface and the flame. So, that way you know it has an influence on the dark zone because as you said that dark zone is kind of not giving any temperature rise rather it is kind of a preparatory zone for the flame zone, but still if there is a gap between the propellant surface and the flame the heat transfer was very much influence. So, once the flame is coming closer to the propellant surface we can see the heat feedback from the propellant will increase and that will you know influence the regression rate of the propellant. So, we have to actually understand that see the chamber pressure has very much important role in the case of burning of the propellant. So, in the next lecture we need to understand that how this you know chamber pressure is playing a role and how do we really connect this you know burning rate because eventually we need to know that how this burning rate is going to be influenced by the chamber pressure and can we relate this you know burning rate with the chamber pressure.

So, that is going to be our next task that how to connect the influence of chamber pressure on the linear regression rate. So, as you said that the fizz zone is going to be very important one because the major reactions are taking place in the fizz zone. So, we need to understand the various reactions involved in the fizz zone and how they are influencing. So, we have already said that the products or the species formed in the foam zones are reacting in the fizz zone and they are forming like CO, CO2, H2O and hydrogen and H2O and giving rise to the temperature very high as high as like you know 2000 sorry 800 to 900 degree centigrade and then it is going further and then in the dark zone it is almost like a silent zone or the induction zone and then it is going to be very high temperature luminous zone or the flame zone. But since the major reactions are taking place in the fizz zone we need to give like importance to the fizz zone and we will try to do some kind of a analysis in a very in a simplistic method and we will try to see how the burning rate is going to be influenced by the chamber pressure.

So, in a sense we can say that if we increase the chamber pressure the dark zone, extent of the dark zone will decrease, but now we said the increase in chamber pressure, but what will happen to decrease in chamber pressure? So, if you decrease in chamber pressure here we have seen that the dark zone will be like you know very much extended, but there may be situations that the flame may extinguish if we decrease the chamber pressure too much. There may be a possibility that below even 1 MPa that some cases the flame may actually start in some cases you may see that the chamber pressure may actually decrease to a certain limit that your sustained combustion may not be possible in case of a certain chamber pressure. So, in that scenario we have to understand that whether the chamber pressure is too low that the extinguishment of the flame may take place that we already discussed in the case of like the ignition processes like different uneven situation for ignition. So, if the chamber pressure is too low the flame may go off then the slow you know burning or you know decrease of sorry slow burning and the regression of the propellant may keep on going and that it may increase the chamber pressures to certain level so that the flame may reappear. So, the chuffing event may actually happen like the oscillation, oscillatory nature of the chamber pressure like it will increase and then it will go off the flame may go up and slowly there may be some you know regression of the propellant will continue and that may you know bring back the flame again.

So, the chamber pressure will increase again. So, of course, there is a certain you know limit of the chamber pressure below which the flame may not be you know established. So, we have already understood that see as according to literature that the chamber pressure has a very much influence on the dark zone. So, the extent of the dark zone will be reduced as we increase the chamber pressure. Now, in the next lecture we will try to you know give some mathematical you know representation of the this burning rate and we will try to understand how it is you know related with the chamber pressure ok. So, till then you can revise these things, we will continue in the next lecture. Thank you.