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 37 : Erosive Burning in Solid Propellant Rockets-Introduction

Hello everyone, welcome back. So, we are starting a new module which is the last module of this NPTEL online course. The module is erosive burning in solid propellant rockets. Now, this is slightly newer than what we have learnt so far. So, let me give you a brief introduction about the erosive burning in solid propellant rocket. So, just to give you a background what we have learnt so far in the previous lectures.

So, we have discussed about the burning process in double base propellant. So, if you recall in case of double base propellant what we have said that if this is the DB propellant and let us we compare with the composite propellant as well. So, this is let us say composite propellant. In case of double base propellant what we have said that there will be some you know solid phase degradation will take place which is termed as the foam zone.

Then there will be some reaction zone which is called the feed zone. So, this is the foam zone and then if the pressure is low enough there will be some silent zone or induction zone or dark zone will exist and then there will be some you know secondary luminous zone or luminous zone. Now, one thing we did not consider that time that what about the you know gases evolve in the burning of the propellants and that gas can flow on the layer on the surface of the propellant. What will be the effect of that you know gas velocity flowing on the propellant surface? Is it contributing to the burning of the propellant? That part I think we have not considered separately, but we have simply talked about the burning of the solid propellants in the view of you know different compositions and their decomposition reactions the exothermic and endothermic reactions we have considered. However, the gas velocity which is flowing over the propellant surface.

So, let us say we consider the typical you know solid propellant rocket. So, if you have the propellant grains like this after ignition. So, if there is a ignition charge this will provide some you know plume if it containing hot particles hot particles is going to impinge there and is going to ignite the propellant initial surface of the propellant and then once ignite this will try to you know spread the flame. So, there will be flame will be produced and chamber will be filled and finally, equilibrium pressure will equilibrium pressure will be established. So, typical the pressure time curve you have seen already that it may go rise like this and it will reach to equilibrium pressure and finally, it will tail off.

So, this is typical p t curve. Now, if the port volume is smaller. So, this is the port area and this is the throat area. So, for a smaller you know port volume we can expect the pressure rise will be even higher and then it finally, reaches to equilibrium pressure. Now, the scenario for which the gas is going to you know start flowing from the propellant you know even after the ignition from the ignitions also gas is going to start flowing over the propellant surface.

So, what about the effect of this gas velocity flowing over the propellant surface is it contributing to any of the burning processes or is there any contribution coming due to the gas velocity over the propellant surface. Same question will be asked for the composite problem also which is containing the epi particles. So, epi particle is going to give you some premixed flame upon decomposition and then the binder which is typically the hydrocarbon is going to decompose is going to pyrolyze and provide the fuel vapour. The oxidizing vapour coming from the ammonium percolate fuel vapour coming from the binder is going to react each other and initially they will create some primary diffusion flame. And, finally, they will create some final diffusion flame or secondary diffusion flame SDF this one we said PDF and for the ammonium percolate premixed flame we said it is APPF ammonium percolate premixed flame.

And, typical temperature was for ammonium percolate premixed flame is around 1300 to 1400 Kelvin whereas, for PDF it was like 2400 Kelvin whereas, for the final diffusion flame it may go as high as like 3200 Kelvin. So, this thing we have discussed in detail for composite propellant and similarly for double base propellant we have said that this is typically you know homogeneous propellant and the burning will take place you know mostly like a premixed way. Whereas, in case of this one for composite propellant it is heterogeneous propellant and burning will take place with the mixture of like premixed and diffusion flame because APPF this is the premixed flame whereas, these are like diffusion flame. Now, what about the effect of the gas velocity coming due to the high temperature high pressure gas flowing over the propellant surface. So, that will cause some you know erosion of the propellant surface which will in turn is going to increase the burning rate of the propellant.

So, that part I think inherently if you measure the burn rate is already there, but we did not speak it inherently I mean separately the effect of you know the velocity on the propellant surface causing the you know contribution to the burning rate that part is we have not considered, but that part is called the erosive burning. So, what you can say by definition we can say that the velocity dependent contribution velocity dependent contribution to the burning rate of a solid propellant is called the erosive burning. And as you know that the burning rate of a solid propellant depends on a number of parameters like you know propellant composition the fuel oxidizer ratio the particle size of the oxidizer like ammonium crystal size in case of you know composite propellant that is very important because this may important role in the stand of distance which is going to decide the heat transfer taking place due to the heat coming from the flame the of course, the chamber pressure initial temperature of the propellant. So, so many you know factors which is going to influence the burning rate of the propellant. Now we know that the transfer transfer of heat from the propellant from the ah the flame to the propellant surface is going to cause the ah binder to pyrolyze ammonium percolate to decompose and the pyrolyze gases to react close to the you know propellant surface.

Now this involves you know many chemical and physical processes change of phases there will be energy transfer and heat transfer is going to take place. Now this is going to be complicated once the propellant is going to burn in presence of a cross flow of combustion gases in the port of the propellant grain. So, this is the port of the propellant grain. So, if the burning is happening in a situation where there is a cross flow of combustion gas in the port of the propellant grain the burning process will become you know complicated. And the contribution coming from the you know velocity of the gas on the propellant surface is termed as the erosive burning.

So, in this module we will we will try about this we will try to discuss about the different you know ways how to you know ah measure the contribution coming from the erosive burning and what are the influencing factors on erosive burning. For different propellants we will we will talk about the different type of propellants how the erosive burning is being influenced. You know of course, you can understand one thing that you know high performance rockets require high thrust and short burning of the propellant grain. The high volumetric loading is of course, important we already said this thing that high volumetric loading fraction which is typically the propellant weight to the combustion chamber volume is is required in order to have high performance. Now, if we consider the high volumetric loading fraction that means, we may actually load like more amount of propellant inside the inside the chamber combustion chamber volume what is going to cause there is that is going to reduce the the port area to throat area ratio.

So, the port to throat area ratio which is denoted by like A p by A t is going to be lower if we have like high volumetric loading fraction. Now, once you have low port to throat area ratio that is going to cause you know the high velocity gas flowing on the propellant surface which is going to cause the erosive burning. So, if you typically look at the pressure time curve. So, in the upstream location of the propellant grain we may expect the pressure will follow this type of you know initially initial high pressure peak and then we will follow with the equilibrium pressure, but the later part the downstream part of the. So, this will be the typical pressure profile in the downstream part of the downstream location of the rocket whereas, this one is the you know upstream location of the rocket.

So, basically for a low port to throat area you can see the typical you know changes in the pressure time profile. Now, the regular burning rate law what we have learned already that R equal to A p to the power n that may not be appropriate in case of erosion of the propellant where is going to take place. So, we have to consider that the gas produced due to the combustion of the propellant and which is flowing past the burning surface and the downstream of the burning surface and gets out of guessed out of the nozzle what is the cause of this you know sorry the what is the effect of that gas flowing on the propellant surface on the burning. That means, basically we want to see that the effect of erosive burning on the overall burning of the propellant be it double base propellant or composite propellant, but this erosive burning is going to cause a change in the burning rate of the propellant and generally this is expressed in terms of one ratio or one function is called erosion ratio or erosion function which is denoted by epsilon and it is written as R by R 0 where is you know the or maybe it can be denoted as R e also in many book it is denoted as R e.

So, basically R e is the erosion burning rate and R 0 is the linear burning rate you know without any erosion when we are saying that there is no gas velocity without any gas velocity or rather we can say the gas velocity if it is U it is 0.

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So, this is going to give us an estimate about that how much you know percentage of you know erosive burning is contributing to the total burning rate of the propellant. Now, it has been seen that the most effective effect of erosive burning is observed in the early stage of the combustion of the propellant because during that time the A p by A t is considered to be in the lower values because that time A p by A t would be lower and or the smallest. So, we can expect that the velocity of the gases produced from the combustion of the propellant is going to be higher. So, that can actually cause some you know burning of the cause some erosion of the propellant which will contribute to the burning of the propellant. And accordingly you can see the P T curve what we have seen from the theory and the experiment is going to differ because that is going to have you know effect of erosive burning on the overall burning processes.

Now, the erosive effect on the you know it is going to lead to the large variation in the performance of the rocket engines because this is going to prevents the grain from burning in parallel layer as it is generally assumed for the simplicity in performance calculation. So, what is going to happen that due to the erosion we can expect that the flame front reaches the engines casing earlier than the predicted and you know it is going to cause some erosions. So, this will see it is going to easily reach to the casing because it is going to flow of gases passing on the propellant surface. So, this will cause some erosions. So, you may see some kind of a taper structures there that in the downstream side it is going to reach to the casing.

So, this is the motor casing this is the casing it is going to reach to the motor casing quicker compared to the upstream side just because the gas velocity is higher and that will you know lead to erosion. So, this must need to be taken care of while you know analyzing the performance of a rocket. So, now if you look at the different type of propellants. So, one experiment has been you know conducted here this was given by you know Kubota N. If you look at the different type of double base propellant changing the composition to make it like a high energy propellant one reference energy one low energy.

So, let me tell you the what is the composition of high energy propellant. So, here N c was taken as 55.6 percent. N c means nitrocellulose we know by now N g which is the nitroglycerin is taken as 40.4 percent and one more component is added here which is DEP. DEP is plasticizer or stabilizer which is taken as about low percentage. So, it is about like you can say 4 percent about 4 percent. So, that is this was like 95 96 percent and this is 4 percent.

So, this is just one plasticizer or stabilizer this is full form I think you can get it from any of the rocket propulsion book this is typically one plasticizer which is diethyl phthalate. So, in case of high energy propellant what we expect that the burning is going to be higher compared to the reference at a reference propellant is taken as the N c as 50.4 percent, N g as 36.6 percent and DEP is taken as 13 percent. Whereas, in case of low energy propellant the composition is like 47 point N c is 47.5 percent, N g is 34.5 percent and DEP is taken as 18 percent. So, if you look at the adiabatic flame temperature for high energy composition the adiabatic flame temperature is about 2720 Kelvin for reference one which is the middle of the low and high is about 2110 Kelvin and this one is 1780 Kelvin.

So, if you look at the typical burning rate of these propellants with pressure we can see. So, burning rate in millimeter per second and if you plot the pressure in MPa we can see as we increase the pressure you know various pressure will be plot we can expect that. So, this is this is log log plot ok. We can expect that high energy propellant will have higher burn rate sorry this is high energy propellant then the reference wall will be somewhere in the middle and the low one will be somewhere. So, this is low energy double base propellant and this is the reference one reference DB propellant.

So, what we are seeing here is that for a high energy propellant we are expecting that the burning rate is much higher compared to the reference one and the low energy propellant. So, the what is happening exactly as we have discussed in the previous slide that the flow field of the double base propellant during the erosive burning if you look at carefully the flow in the internal port geometry of the internal port of the propellant is considered to be turbulent and the turbulent boundary layer is going to be established. Now, the luminous flame of the high temperature zone is actually staying somewhere above the propellant surface what we have seen already here you see the luminous zone is distanted or located slightly away from the propellant surface whereas, the feed zone you know is going to be located somewhere within the viscous layer where we can expect the velocity is low. So, the feed zone may not be affected much by the cross flow of the gas. So, the burning rain you know remains unchanged when the cross flow velocity is actually low.

Because what we can see that if the feed zone is near to the propellant surface this is going to provide the heat feedback to the propellant surface and it is going to you know increase the burn rate since the cross flow is not affecting much on the feed zone. So, it is not going to be affected due to the erosive burning. However, if the gas velocity or the cross velocity is increased the luminous zone is going to approaches the burning surface and the dark zone is going to be diminished. Because you know turbulent intensity will be increased and the heat flask is going to increase. So, we can expect the burning rate is going to increase also.

Now, the velocity of burn gas from the propellant surface maybe you can just draw another figure to understand properly let me just draw another figure here. So, what I am trying to see is for a double base propellant. So, this is the propellant surface. So, what we can see let us say this is the burning surface of the propellant. So, if you typically look at the velocity profile is going to look like this.

This is the velocity profile. So, let us say the velocity is coming here is u. This will be like the viscous sub layer. And if you look at the velocity of the burn gas coming from the propellant surface burning surface of the propellant some you know let us say small v is the velocity. So, in case of the velocity of the burn gas coming of the propellant surface is high for the I mean we expect that the reaction is very high for the high energy propellant. So, we can expect that for high energy propellant the gas velocity coming from the burning of the propellant which is like the perpendicular to it is going to be high for high energy propellant because the burning rate is high.

So, we can expect that this will be higher because the reaction because the burning rate is higher is higher for high energy propellant. So, what we can expect that the I mean compared to compared to low energy propellant. So, what we are comparing that this velocity the normal velocity from the burning surface of propellant is going to be higher due to the high burning rate of the propellant for high energy case compared to the low energy propellant. And in addition to that the temperature gradient in the feed zone is going to be steep and it is you know it is going to be less sensitive to the we can say this is less sensitive to the cross flow. So, what that mean what does that mean that the effect of the cross velocity or the gas velocity which is this one will be less you know influential for high energy propellant compared to the low energy propellant.

That means, the erosive burning to be effective for high energy propellant it requires to be high velocity. Now I just told you this background before coming to this plot if you look at the erosive ratio and threshold velocity of erosive burning for you know high energy reference and low energy double base propellant. If you understood this background that is why you can see the high energy propellant is less susceptible to you know erosive burning. If you look at here the for high energy propellant the threshold velocity for which the erosive burning to take place is you know much higher compared to the reference or the low energy propellant. Because you can see the threshold velocity for low energy propellant is around you know only like 70 meter per second.

So, this we are talking about the U threshold or other book may be referred to as V threshold. So, this is the threshold velocity. So, typically low energy propellant what composition we have mentioned here the threshold velocity is much lower compared to the reference one and of course, compared to the high energy propellant it is lower. So, it is happening you know somewhere around 200 meter per second and the reason I said that the gas velocity coming from the propellant surface you know normally is higher due to the high burning rate of this propellant because this is high energy category propellant. So, it is going to be less sensitive to the cross flow.

So, it is less sensitive to this U that is why the erosive burning to take place for this high energy propellant it requires to the threshold velocity has higher value compared to the low energy propellant you can compare it here. So, we can say that burning rate is less sensitive to the cross flow in the case of high energy propellant compared to the low energy propellant. So, now, it is going to affect in a higher you know flow velocity range for high energy case whereas, in the low energy propellant you know 70 to 80 meter per second velocity can even cause to you know erosive burning. So, the cross flow is going to be effective even with a low velocity situation.

So, I think you know we understand that even if you have like a propellant loaded in a small rocket motor although it is one end is closed you can see the one end is closed only one side is open. So, we can once we ignite this one it is going to create the though there is no you know velocity coming out from the close end, but it will come out from the open end and that is the cause of this you know the high velocity gas coming out of the open end and this is going to cause the erosive burning. What we just said that this is the cross flow which is passing on the propellant surface and causing the erosive burning.

And, as we can see that towards the downstream side the velocity is going to be will be maximum or we can say the open side the velocity is going to be maximum. And, you know combustion gas generated from the burning surface of the propellant will flows towards the open end. And, in this experiment it has been also shown that for high energy propellant because of the high burning rate of this type of propellant the this normal velocity is much higher compared to the cross velocity.

So, the erosive burning has to take place in case of high energy propellant it requires the gas velocity to be higher compared to the low energy propellant. So, I think this is the comparison we should also remember that the erosive burning to take place for high energy propellant requires the cross flow to be higher compared to the low energy propellant. Now, in the next lecture we will try to see what are the different methods to you know evaluate the erosive burning in case of solid propellant. So, I think we close this one here we will discuss about the various methods proposed by various scientist. Thank you.