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 39 : Methods for Determination of Erosive Function (contd..)

Hello everyone, welcome back. So, we are continuing our discussion with the new module which is erosive burning in solid propellant rockets. In the previous two lectures I think we have spent ah enough time in talking about the ah importance of the erosive ah function or rather we would say like how much contribution is coming from the erosive burning ah because you know the cross flow velocity which is passing on to the propellant surface that is causing the additional burning of the solid propellants and that part is coming due to the I would say like the velocity contribution of burning ah is coming into in the form of erosive burning. So, in the previous lectures we have said that the erosive burning is more prominent when the ah the port area is actually smaller and we have talked about you know in terms of port area versus the port area by throat area and we have consider that ratio as A p by A t.

So, we have said that if port area by throat area is small we can expect that the velocity is going to be higher. So, we have discussed about this thing that so, for a typical motor if this is our port area this is our port area A p and this is the throat area A t. So, we are talking about when the port area by throat area ratio is smaller during that time the velocity of the gases passing on the propellant surface is higher and due to that the erosive burning is more prominent during this phase. And we can expect that at the early you know duration of burning this erosive burning is going to be prominent just because during that period of time we can expect that the burn the the velocity cross flow velocity is going to be higher.

Now there will be many factors influencing the the erosive burning because like what is the temperature of the propellant, how the how the composition of the propellant is going to affect that, what is the pressure inside the chamber, how the you know ignition is going to take place initially because you know initially right after the ignition the hot plume is going to ignite this one and that is going to decide the initial you know peak pressure right after the ignition. So, that is also going to be influential now that is going to give a you know initial velocity starting from the you know igniter and then once the some layers of propellant starts burning then the velocity will further increase. So, if you recall that we have plot the we have plotted the pressure time curve for both upstream and downstream location and the typical you know curve we had P-T curve which we had like this was for you know upstream pressure and then it follows the equilibrium pressure. So, you can see there is a pressurized initially. So, this is typically the pressure at upstream location and if you look at the pressure at downstream location it will follow something like matching with the equilibrium pressure ok.

So, this is the typical pressure trace at the pressure at downstream location ok. Now, of course, the knowledge of burning behavior of the propellant is very much important for design of the rocket motor and particularly for high performance rocket motors the requirement is like is going to produce very high temperature thrust and of course, with a short burning duration and there how this cross velocity is you know playing a role on to the overall burning processes is going to be prime importance. Because in many occasions for high performing rocket you know the volumetric the loading ratio is quite high means the propellant mass divided by the volume of the chamber is going to be quite high and because of that. So, this is typically like mass of the propellant or you can say the weight of the propellant divided by the chamber volume it is generally considered to be higher. So, because of that we can expect that the high loading fraction of the propellant is going to give like the low port to throat area ratio because you are loading too much of you know propellants inside the given volume.

So, we can expect that for high volumetric loading ratio of the propellant is going to give low A p by A t and what we can expect as we as already said that for low A p by A t case we can expect that higher cross flow velocity. So, the effect of erosive burning is going to be you know prominent for low A p by A t ratio. So, I think that part we have already discussed in the previous lectures. Now, we have also talked about the various you know methods for determining the erosive burning typically like there are some laboratory based methods we have talked about that there are various laboratory based methods available and there are some you know actual rocket motor scenario how the measurements are taken place. And if you recall we had also said that the erosive function or the erosive ratio was given as the R by R 0 where R was the you know or R e sorry rather R e where R e was given as the erosion or erosive burning rate where R 0 was given as the linear burn rate linear burning rate when there is no cross flow.

So, U g was equal to 0. So, that is linear burn rate when U g equal to 0 and we had some you know erosion coefficient K which is approximately constant and we have also said something about the threshold velocity which is threshold velocity and it was given as the erosive function or erosion ratio as R R e by R 0 equal to 1 plus K into U g minus U t h. So, we have also said that for different type of propellants like we have we have seen typically for double base propellant and taken for different compositions like we have considered like low energy then one reference energy and one high energy double base propellant we have seen and typically this combination was combination was slightly modified by considering the nitrocellulose plus nitroglycerin plus diethyl phthalate DEP was used with a different percentage and making this you know low energy case reference case and high energy case.

We have also seen the typical adiabatic flame temperature for each case this was the lowest one this is the medium one and this was the high energy case it was the highest one and typical plot of that you know threshold velocity we have seen that for a erosive process to take place or the erosive effect to take place. So, if you just look at the epsilon versus the threshold velocity U t h what we have seen that for low energy propellant we have seen that you know threshold velocity is kind of at a much lower compared to the reference and the you know the high

$$\in = \frac{re}{ro} = 1 + k(Ug - Uth)$$

So, this is the high energy case this was the reference energy case and this was the low energy case low energy case. So, what we have told ourselves that for a high energy propellant where the burning rate is much you know considerably higher in that case the threshold velocity is compared to be higher compared to the low energy case because here you can expect if you look at the propellant surface that the perpendicular velocity is actually the burning rate is going to be higher compared to the cross flow case.

So, if there is a cross flow is happening there, but the cross effect of the cross flow is not dominant until it reaches to a certain threshold velocity which is for high energy propellant it was shown for this typical N c N g and D e p case it was about 200 meter per second. If you recall we had talked that typically about 200 meter per second the erosion going to be effective for high energy propellant whereas, for low energy propellant at much lower threshold velocity the erosion effect can be acting. So, depending on the composition of the propellant there is a chance that the threshold velocity can be higher.

Nevertheless we can expect that the low energy propellant is susceptible to erosive burning at much lower threshold velocity compared to the high energy propellant ok. That much I think we have discussed we have also talked about the various you know type of methods through which the erosive burning can be determined or rather the erosive erosion can be determined and we have said that there are mainly categories in two methods one is the laboratory based methods and other one other category is the engine measurement methods. And, under the laboratory based methods I think we have talked about the typical three different methods one was proposed or given by Marklund and Lake the in case of Marklund. So, basically the idea behind this type of method is that it is intentionally creating some cross flow and letting the propellant pallet or propellant tablets to burn in the cross flow. And, from that you know you can see there are pressure pickup points where the each tablet is having one pressure pickup point.

You see this is basically pressure transducer. So, they are going to have like pressure pickup points for each of the tablets and those tablets are exposed to the high velocity gas coming from the main charge. You can see this is a main you know solid propellant charge which actually going to create the high velocity gas and that high velocity gas will cause erosion to the tablets. And, from there one can actually measure that how much I mean we can actually change the chamber pressure also by changing the throat area here you can see there is a nozzle here. So, if we change the throat area we can have a different condition like A p by A t and of course, the velocity is also going to change pressure is going to change and for different conditions we can get the different erosive burning and from there we can get an idea about the erosive function.

Now, same thing has been done for this case instead of pallet it is having like a strips if you look at this is called strip based method and under the strip based method there are for each strip there are two pressure pickups you can see this pressure pickup 1 this is pressure pickup 2. Similarly for the other strip this is pressure pickup 1 and pressure pickup 2. So, two pressure pickups are there for each strip and again these strips are exposed to the high velocity cross flow. So, you can see the gas frame is coming from the main chamber. In many occasions the composition of the propellant is of the strips are similar to the composition of the main chamber.

Similarly for the tablet also here we have seen this is the tablet. So, it is the similar composition of the main charge and these are the methods where we can actually get an idea about the erosive function. The other method is like using some x-ray flash. So, where the there is a transparent chamber where the x-ray based method using some film this the specimen with you know outside thermal insulations are going to like have some idea about the how the you know erosion is taking place in this propellant sample in which is exposed to the cross flow. So, the cross flow is coming from the main chamber again and that is going to give us that due to different you know cross flow velocity how the erosion of the this propellant sample is taking place that is measured by the you know x-ray based method.

And similarly this is another one is like the gas stream method which is also having the pressure pickup points. So, these are basically proposed by the Marclun and Lake in their setup. There are certain modifications have been done, but basically these are under the category of laboratory based method. Then I think we have also talked about the Zucrose method or Zucrose method there also we have transparent plexiglass windows through which the erosion of the propellant sample is captured using high speed camera. So, you can see there is a high speed camera provided there.

So, it is captured and we have said that this through this high speed camera if we use the optical calibration we can actually get the idea about the bond rate that how the length is regressed over certain period of time. So, if you know the specified length we can get the length by delta t. So, delta l by delta t basically since it is the frame based method. So, we have to use some kind of a optical you know function or basically it is you can see the optical calibration. So, I think we have mentioned already optical calibration which is basically giving the you know calibration from pixel to the physical dimension.

And this is has been used in widely for optical based method like even for you know Crawford bomb scenario I think we have already talked about this one that you know Crawford bomb scenario also if we have the palette type of burning. So, let us say this is a palette holder and palette is burning. So, the palette will regress over time which is only allowed to burn from the stop surface. And if you have this optical windows and if you just take the you know measurements through high speed camera one can actually get the similar type of you know burning rate information. And this has been conducted for various you know pressure situation different chamber pressure.

So, it is almost similar one remember this Crawford bomb situations there is no cross flow involved. So, basically the component associated with this you know non erosive part plus the erosive part. So, the R 0 is going to typically coming in a situation when there is no cross flow. So, we can say that the burn rate measurements conducted using the Crawford burner can give us an estimate of about the R 0 part which is like the non erosive component that there is no cross flow. So,typically there is no cross flow.

So, it is only happening due to the burning of the propellant or the regression of the propellant surface. So, from there you can get the value of R 0 whereas, the R e is the erosive component which is due to the propellant burning of the propellant which is exposed to the high velocity cross flow. Then I think we have also talked about the Nadeau's method in that case the it is the similar situation, but except that solid propellant charge here it is used for hybrid you know propellant where basically it is a hybrid gas generator that solid fuel is actually burned using the you know nitric acid here. So, nitric acid plays in as an oxidizer. So, high temperature high pressure gas comes out from this and it is actually going to you know give the cross flow for the propellant sample.

So, you can see the solid propellant sample is stored here. So, basically it is giving the gas coming from this hybrid gas generator and eventually based on like weight we can actually get the burn rate which is happened due to the erosion of the propellant. And one can actually change the chamber pressure by changing throat area. So, it is a similar method, but again this is also a laboratory based method. Then I think we mentioned about that there are some you know measurements engine measurements engine measurements method.

So, engine measurement is typically kind of like you know direct method and indirect method. So, under the direct method this could be like interruption type of like burn interruption technique. It can be like radiographic or scenario radiographic technique. Radiographic technique means basically using the extra filming radiographic technique and combination of like scenario radiographic techniques. The other technique is the probe technique.

So, these are the typical you know engine measurement methods. So, one can expect that the data obtained from the laboratory based method are different from the engine based method because the scenario is totally different for case of laboratory based and engine based method. Of course, still some correlation can be maintain still some correlation can be established based on two methods, but I would like to you know provide some disadvantage of this laboratory based method that you know whatever we have talked about the laboratory based method one should actually keep in mind that the boundary layer in actual rocket motor it basically develops all along the propellant surface you know all along the grain develops develops all along the grain. So, this is differ from the laboratory based method because for laboratory based method. So, this is for engine based method or engine measurement method.

Now, if you look at the laboratory based method it is going to happen like it starts close to the sample of course, without any mass injection. So, this is this is basically for the lab based method lab based method. Now, what is the scenario here this we can say that the effects of energy and mass transfer processes between the you know surface and the gas which is going to control the erosive effect. So, that is going to be different, but we also need to remember that it is really impossible to it is really impossible to determine the this erosive part and the you know non erosive components simultaneously from the same laboratory experiment it is it is it is really impossible. So, the measurement of R 0 is generally you know use of some special engine if you really on want to measure it.

So, we have to determine or measure using special engine or you know one can see that this can be used some you know Crawford-Bohm based method as well Crawford sorry Crawford-Bohm can also be used in order to get this non erosive component that when there is no cross flow what is the burning rate. But simultaneously getting this information and this information together from the laboratory based method it is it is not possible to do. So, in that case if you look at the direct based method using I mean under the engine measurement methods under the direct method one is the burn interruption techniques. Burn interruption technique is nothing, but we want to stop the burning process you know suddenly or abruptly after a certain duration and then you know there are different ways to do it one can actually quickly open the upstream end of the rocket by you know ejecting some pyro fastener or something.

So, let us say it is burning like. So, let us say there is some you know pyro bolts are there and we are actually allowing it to suddenly you know open it. So, the gas is going to come out from here and that will create sudden depressurization of the chamber and due to sudden depressurization of the chamber we can actually stop the combustion process abruptly. Now, this can actually give us like how much you know burning has take place after the sudden depressurization. So, that way we can actually measure it. Now, after each run one can actually measure the wave thickness at different axial location.

So, at different axial location one can measure the wave thickness that how much has been burned at different axial location ok. So, because this is the wave thickness. So, we can keep on you know measuring at different axial location of the this thing and number of runs can be you know done with same initial conditions, but one can actually interrupt the burning at different you know time interval and one can actually plot the wave burnout thickness, thickness versus time for each you know for each axial location and that way one can actually figure out that how much you know burning rate is there. Now, differentiating this curve one can actually find out the burning rate. Now, of course, the burning rate without erosion can be determined at the you know upstream end of the grain.

So, you know your R 0 is so, one can actually get the burning rate as a function of x and t and if you want to find out the without the burning rate without erosion that can be at the upstream end of the grain. So, by knowing this you know Re and R 0 one can actually you know find out the erosive function ok. So, that can be determined. Sometime you know the static pressure measurement is also determined and upstream and downstream of the grain and if you know the local characteristic flow parameters like static pressure, velocity, specific flow rate, temperature, Mach number, but actually it is very difficult to measure those you know or determine those quantity accurately, but you know because of their coupling with this the regression rate because you know the temperature, the mass flow rate, the pressure, velocity all are coupled with the burning of the you know propellant and as well as the heterogeneous nature of the flow. So, it is really difficult, but however, with this method somehow it can estimate the non-erosive and erosive component of the burning and one can actually determine this.

Now, there are you know one dimensional simplified theories are there where one can actually estimate the you know mass burning rate of the propellant at time t at any axial positions like m dot b at any axial position at and at any time t one can actually have this one by integrating this that how this you know burning rate into it is a function of pressure into dx ok. So, this is basically using the one dimensional simplified theory can be applied where rho p is the propellant density. Now, one can actually estimate the specific mass flow rate which is g x t which is mass flux also. So, specific mass flow rate is nothing, but m dot b x t divided by the port area which is also varying with you know axial location. So, one can actually have the a p as a function of x and t how it is varying and the mass flow rate m dot bx t.

$$\dot{M}b(x,t) = \rho \int_0^x r(x,t)p(x,t)dx$$

So, one can actually use this one. This can be further simplified by taking the total mass flow rate m dot b with correspond which is going to corresponding to this known equation which is like p c a t by c stars I think we already knew this one. So, that can be corresponding to there and one can actually figure out how this can be correlated. Now, there are other techniques as I mentioned that the radiographic and you know cinematography senior radiographic techniques where you know two dimensional motor is used with two rectangular propellant gains and they will be have inhibited in three sides. These are like very old techniques used probably in early 1960s generally x-ray beam is directed towards the motor and the image of the propellants grain is produced on a on a screen which is phosphorescence screen and then it is photographed. So, it is a combination of like cino radiographic techniques.

$$G(x,t) = \dot{M}b(x,t)Ap(x,t)$$

$$\dot{M}b(L,t) = \frac{PcAt}{c*}$$

Advantage of this technique is that the dimension of the grains at each moment or each time instance can be obtained from the photographs because it is a combination of these radiographic and you know high speed imaging techniques. So, that way one can actually get it the instantaneous value of burning rate. So, and if we have the number of runs required for this interruption technique that can be reduced for this you know radiographic or cine radiographic techniques. So, that can be reduced. The other options can be like you know using the probe based method where you know some probes are actually inserted into the propellant surface and that will detect the passing of the flame front.

Most common probes were used with the ionization type. However, the thermocouples on and variable conductivity probes are also used, but again this how to probe this one using this different type of probes accurately that is kind of little bit tricky. However, you know there are experiments conducted for accurate positioning of the probe by means of you know micrometer, dial gauge mounted on the motor casing. These were done you know early you know experiments which were conducted much earlier. Nowadays you know there are various you know improve improved techniques are available particularly like through high speed imaging is combining with the you know the X-ray techniques probably this will improve the you know methods for you know getting the burnt rate directly from the engine measurements.

So, I think this is typically the summary of what we have discussed on the various type of measurement techniques for you know getting the estimate of the erosive burning. One is the laboratory base one category is the laboratory based method, other category is the directly engine measurement methods. We have also talked about the you know disadvantage of the laboratory based method and we also you know discussed that the simultaneous measurements of erosive part and non-erosive part is kind of difficult, but if we have a special type of engines which can give us the non-erosive component R 0 or we can use the Crawford bomb which can give an estimate of the R 0 part.

But eventually the total burning is going to be the function of both the non-erosive part and the erosive part. So, I think in the following lecture what we will try to do is we will try to see that how the heat transfer is going to play a role there and how we can I mean correlate with some of the well established theories or rather I would say like popular theories on the erosive burning. Thank you.