Course Name: Combustion of Solid Fuels and Propellants
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Lecture 38 : Methods for Determination of Erosive Function

Hello everyone. So, we are continuing our discussion on erosive burning in solid propellant rockets. In the previous lecture, we had briefly discussed about the erosive burning, why erosive burning is happening and we tried to relate with our understanding of burning mechanisms for double base propellant and composite propellants. And we have seen that in case of double base propellant as well as in composite propellant, it is inherent that the high pressure, high temperature combustion gases is going to flow on the propellant surface and that is going to cause change in the burning rate of the propellant. In case of double base propellant, we have seen that the high energy double base propellant is less susceptible to erosive burning compared to the low energy propellant. And the reason we have said that the high energy propellant is considered to be you know burned at a higher rate and due to which the velocity coming from gas velocity coming from the propellant surface is going to be you know higher there.

So, the cause or the you know influence of the cross flow is compared to be lower there and therefore, the burning rate is going to be less influenced by the erosive effect. But if the cross flow velocity is higher than we can expect that the erosive burning is going to also happen at a velocity much you know higher than the low energy propellant. So, I think if you recall we had said that the you know erosive function we have represent that and here we have denote is the threshold velocity and we have said that is going to be less susceptible until it reaches to the velocity 200 meter per second. After that it is prominent whereas, for low energy propellant.

So, this is for high energy propellant and this is for low energy propellant. So, the velocity is much higher compared to this low energy one which can happen at even at 70 meter per second that we have seen in the previous lecture. And one more thing we can recall that because of this you know change in the port volume we can expect that the downstream part of the rocket motor we can expect that if this is the propellant grain due to the erosive burning we can expect that the high velocity gas is flowing on the propellant surface. So, now, this is going to cause the erosion and if you look at carefully the downstream part of the propellant grain is going to reach to the casing earlier than the upstream section. So, it is reaching to the this is the motor casing.

So, this is the upstream side and this is the downstream side. So, due to the erosive nature of the burning we can expect that the upstream part will still have some propellants whereas, this is going to reaches to the motor casing. So, that we may cause the discrepancy in the burning profile or whatever the thrust time curve we have generated from the theory this is going to cause to change. And we have also mentioned that in the early stage of burning when the port area divided by the throat area was comparatively lower during that period of time we can expect that the cross flow was higher. So, the erosive you know burning is more prominent when the A p by A t is in the lower side because the gas velocity will be higher during that time.

So, the erosive you know effect will be more prominent when the port volume by throat sorry when the port area by throat area was in the lower side. And we can expect that pressure time profile will be this for the upstream area. And if you just take the profile pressure profile for the downstream case it will follow like this. So, this is the typical p t profile. Now, the second thing we have discussed that what are the different influencing parameters on these the propellant you know gas velocity coming out from the burning of the propellant.

Because you know there are various you know physical and chemical processes involved in the during the burning of the propellants we can expect like the combustion products is going to flow there will be like you know from the flame front radiation heat transfer the convection heat transfer is going to take place during the ignitions the hot particles is going to impinge on the propellant surface. And that will the heat will conduct to the propellant and that will have like the pyrolysis and decomposition of the propellant which will create the further the fuel and oxidizer species who is going to burn there and that will create the combustion products and so on. So, the increase in gas velocity flowing on the burning surface or flowing past the burning surface is going to enhance the heat transfer from the gas to the burning surface of the propellant. And we can expect the burning rate is going to increase and that will cause to erosive burning. Now, erosive burning is generally expressed in terms of erosive function epsilon or sometime it is termed as the erosion ratio and that is denoted as epsilon which is R by R 0.

$$\epsilon = \frac{r}{ro}$$

$$= 1 + k(Ug - Uth)$$

In literature sometime it is written in terms of like 1 plus K into V g or you know U g minus U threshold where R we said that R is the erosive burning rate or we can denote it as R e also. R e is the erosive burning rate, R 0 is the linear burn rate when there is no cross velocity. So, linear burning rate when U g is equal to 0, K is some erosion coefficient which is you know kind of which is almost you know constant, U th is the threshold velocity. And as you said that for different type of propellant this threshold velocity is different we have discussed about threshold velocity comparing. So, this is V th or U th which is the threshold velocity for high energy propellant the threshold velocity is much higher compared to the low energy propellant.

So, the erosive burning is going to be less susceptible for high energy propellant compared to the low energy propellant. So, that part I think we have discussed and we have said that the effect of erosive burning is going to you know cause some large variation in the performance of the rocket and we need to take due care while designing of the solid propellant rocket. Now, there are various influencing factors which will affect the flow velocity like you know it can influence by the chamber pressure several parameters we can say like chamber pressure, the temperature of the burn gas composition of burn gas, nature of propellant, initial temperature of the propellant, shape of the you know port cross section shape of the port cross section. So, various influencing factor which is going to you know influence the flow velocity and eventually those are very much important for the burning rate of the propellants also. Now, we understood this part that yes the high velocity gas is going to flow past the propellant surface which is going to cause the erosions and that is termed as the erosive burning.

So, the total burning is going to be function of like the erosive burning plus or rather we said the linear burning when there is no erosion plus the erosive component of the burning. So, we have to follow this now the question is how to determine the erosive function or erosion function or erosion ratio epsilon which is R e by R 0. Now, there are various methods for determining determination of erosion function or erosion ratio. So, if you just divide this method they are you know termed as mainly they are divided into two categories first one is called the laboratory method and second one is called like direct you know engine measurement method engine measurement methods. Now, this laboratory methods there are mainly proposed by following researchers these are like well known you know methods proposed by the various researchers one is the this Marklund and sorry this is Marklund and Lake method second one is the Zucrose method third one is the Nadaoth methods Nadaoth's method and in case of engine measurement method there are two major categories one is the direct method another is the indirect method indirect method.

Now, in case of direct method there are various techniques available and it has been listed in literature also like you know burn interruption technique. As the name suggests the burn interruption means you are just intentionally causing the burn to stop in between and you can just measure the how much propellant has been regressed and from there we can actually calculate the sorry determine the burn rate and we can actually get an estimate of the erosive portion of the erosive burning rate portion. So, this is like the direct method other direct method categories through you know radiographic radiographic and combination of cine radiographic techniques. And then directly you know inserting some probe that is also a direct method which is called probe technique. At different location of the propellant we insert some probes and from the probe data we can actually get an idea about how much you know regression has happened and due to erosive we can actually try to estimate from there.

So, these are like various methods majorly they are divided by laboratory methods and engineering methods. One thing we should remember that once you estimate the data from the laboratory methods and if we get the data from the engine measurement methods there might be some variations in the data available from both the methods just because in the laboratory methods how the boundary layer is going to form there is going to differ from the engine measurement methods. So, we need to be carefully you know understand and analyze the data from both the methods, but these methods are well you know popular and it has been available in literatures and it has been used extensively. We can talk about you know each of these methods and their relevant setup to understand how these you know experiments are conducted in order to you know determine the erosion function or erosion ratio.

So, let us look at one by one.Initially we begin with this Marklund and lakes method. So, this is typical you know test setup for Marklund and lake method. So, basically a propellant sample is located in a hot gas stream generated by a main chamber. So, this is the main chamber this part is the main chamber. So, one small you know propellant sample is actually located basically these are like a pallet method.

So, you can see there are you know tablets are placed just below the pressure pickup point. So, there are two pressure sensors you can see. So, these are the pressure pickup point there are pallets present there. So, this is the similar composition the main chamber is loaded with the same propellant as the one constituting the sample. So, this one sorry this is the you know pallet you can see here also.

So, these are the tablets. So, basically the propellant sample is located in the gas stream because the hot gas stream is coming from here from the main chamber. The operating pressure and gas flow rate in the test section can be varied by modifying the nozzle throat section. So, if you modify this you know nozzle throat we can actually modify the operating pressure in the this test section. And of course, by which we can actually have data for various you know chamber pressure.

There are two pickup points here and samples are placed there. The hot gas is coming from the main chamber and that is causing the erosion of the pallet and the data has to be taken from there. There are different you know arrangements are possible the you see this is like a tablet method here it is given as the strip method. So, you can see there are for each strip there are two pressure pickup are available for each strip. So, this is the strip this is basically the specimen you can see.

So, again the instead of tablets actually the strips are placed in the hot gas stream from coming from the main chamber. For each strips there are two pressure pickups pickup points. Now, this is actually the tube connected to the chamber and again similar manner the pressure will be varied by changing the throat area of the nozzle. Now, in case of this one also you can see we can actually the way it was done is like by varying the tablet thickness one can actually obtain the different values of burning rate as a function of the gas flow rate coming from the main chamber or gas flow rate in the channel. Now, the in each cases basically the propellant for the strip or the tablets are the similar of the propellant which was there in the main chamber.

Now, it is also you can see there is a method which is replaced with some separate you know chamber and it has been given some small tube it is attached to a small tube which is connecting to the nozzle and the x-ray is used to you know film it the how the regression is taking place. So, this is another you know modified method of Marklund and Lake this is called the x-ray flush method. This one was the pallet method with pressure pickup locations is shown here this is the strip method. So, this is the modified version of the Marklund and Lakes method, but different test setup they have tried with. Now, from this photograph and the initial dimensions of the grain one can compute the web thickness like burnt out web thickness and from there one can estimate the burning rate.

Now, as I said the by varying thickness one can actually obtain various different values of burning rate as a function of the gas flow in the channel and of course, of the pressure because pressure is varying by changing the throat area there. Now, in case of the strips we should see that for each strips two pressures transducer are there to record the pressure with time and as the you know when the flame front reaches the casing. Now, from the strip thickness and the burning duration as given by the pressure transducer recordings one can actually obtain the burning rates at two pressure points of the sample. Now, to determine the erosion function under the sonic stream conditions the sample has to be I mean sample can be located at the nozzle throat in the form of pallets where the streams reaches the sonic velocity. So, let us say if we have to have the conditions for sonic stream conditions one can actually attach the streams at the nozzle throat in the form of pallet and one can actually estimate the or one can actually determine the erosion function under the sonic stream condition.

Now, we should remember one thing that these experiments were mainly intended to you know conducted having the engines having the you know narrow I mean the constriction of the engines like A p by A t was almost close to one almost close to unity. For all these cases this was characterized the major disadvantages of this procedure that many runs are necessary because you know number of tablets with various thickness we have to conduct and these procedures you know considered number of runs to determine the time development of the surface contour. So, that is the major disadvantages in this in this method. Now, in case of Zucrow's method it is similar to in case of Zucrow's method it also resembles the principle to that what is shown by Marklund and Lake setup. Here the propellant is used as a you know solid propellant rocket motor is actually used as a gas generator which was used in the same sample.

So, the propellant was the same propellant was using the main motor the exhaust stream from the you know through a two dimensional test sections the opposite side of these test sections are made of some you know transparent plexiglass windows which can actually give access to framing the event. So, if you look at this one. So, basically the these it is already mentioned here you see these are like plexiglass windows to give optical access. So, once the burning take place one can actually see the regression processes by considering the event or capturing the event using some high speed camera. The only concern with this method is that only one sample can be photograph I mean during the during the run and of course, that is also depending on the framing speed of the camera.

This was the Zucrow's experiment was done in earlier case the framing speed was about like 70 to 720 FPS or frame per second. Similar experiments are conducted by other researchers also following this Zucrow's method and that have been done with a much you know faster rate of you know imaging with like a higher frame rate. But this method is actually limited by only one sample is actually photographed and also the record timings which has to be like synchronized with the other record timing during the run like you know pressure upstream and downstream of the sample. So, that synchronisation has also to be done. Now, what exactly it is doing is like it is allowing to photograph how the you know regression of the sample is taking place.

So, this is another way of method by which the erosive burning is determined this is the Zucrow's method. Now, there are another method as we discussed this is again part of the laboratory method. This method is comparatively the modified method by the Navaros proposed or Navaros conducted. So, in this method the setup is consisting of instead of the solid propellant gas generator this is like the hybrid gas generator which is using the solid fuel. So, this is using the solid fuel instead of the solid propellant what we seen earlier.

So, if you look at the previous case in case of Marklund and Lake we have seen the main chamber was main charge was the similar one as of the travelate or the strip and they are having like the solid propellant here. So, you should remember this is like solid propellant. In all cases they are using the solid propellants to generate the high gas velocity and which is actually giving the erosion here same thing for the strip also. Here also in case of x-ray flash method same thing this is the solid propellant. Now, the change here is here also same thing exhaust from the solid propellant is coming and passing through the sample here, but here the difference is it is using the hybrid gas generator.

So, you should just note it down that this setup consists of hybrid gas generator. So, it is having solid fuel and liquid oxidizer you see this is the HNO 3 which is the liquid oxidizer. So, this liquid oxidizer is pressurized using nitrogen. So, this is the compressed nitrogen you can see compressed nitrogen which is pressurizing the liquid tank and by controlling the flow rate by the flow meter you see there are some valves to control the flow rate and measuring the flow rate by this flow meter it is going here it is being sprayed here and they are actually burning and the gas is going to pass through it and you can see the solid propellant sample are kept here in this chamber. Now, here the solid propellant sample is being exposed to the high velocity gas here.

Now, the what is going to do here is that this setup is going to allow the change of nature of the combustion gas because if you change the combination of the solid fuel and oxidizer this will change the nature of the gas. Now, by choosing the suitable throat area the pressure and velocity in the test sections can be varied. So, the pressure and velocity in the test section can be varied. How you are varying? Varied by choosing the throat size you know choosing a t you can change the throat area and accordingly the pressure and velocity in the test sections can be varied. Now, the this will you know operating characteristics is going to you know give the mass flow rate of oxidizers the average fuel consumption rate during the you know burning we can get the mixture ratio also if you know the mass flow rate of fuel and mass flow rate of oxidizer.

Now, of course, this hybrid gas generator can also be replaced by the solid propellant gas generator also depending on the setup actually, but in this case it was two parallel samples were placed in the test chamber. Now, from the recording of the thing I mean this is the modified sorry from the recording of the burning process what one can do is one can actually at any instant of time one can record the burning rate of each sample and the port area because this the samples are actually you know viewing through the quartz window. Now, that can actually give us the data of burning rate at different you know conditions which is set by the I mean what we are set by the pressure and velocity variations by changing the suitable AT and through which are different conditions we can actually find out the burn rate. Now, the major thing we should remember here is that it is very much influenced by the gases coming out from the main chamber to the test sections and as we said that this is going to influence the composition of the gases also. So, that much you know considerations should be given.

Now, remember that pressure and test pressure and velocity in the test sections are adjusted by choosing the suitable throat area. The operating characteristics to lead the I mean is going to determine the oxidizer mass flow rate m dot o, the average fuel consumption may be m dot f. So, the total flow rate we can actually get m dot o plus m dot f and the mixture ratio will be given as the m dot f by m dot o. So, this is the change in case of Nadeau method we have seen here. Now, the gas velocity one thing we forgot to notice in case of the Jack Rose method we did not mention this thing.

$$MR = \frac{m{\cdot}f}{m{\cdot}o}$$

If you look at the Jack Rose method the burning velocity is determined or the burning rate is determined by the how much distance it is burned which is let us say some distance delta L by delta t. So, how the distance is regressing over time we can actually measure it with some maybe some optical constant because it is filmed through the high speed camera some optical factor may be let us say some optical factor may be mentioned there. So, that factor has to be taken in a bomb type of if you recall though we have talked about the Crawford bomb. There also if you try to measure the burn rate of the propellant sample if we just view it through some optical window. So, this is burning let us say this is optical window if you film this through some high speed camera we can actually see the similar behavior like at a particular distance how much time it is taking.

So, delta L by delta t is going to give us the burn rate. So, maybe some optical factor like let us say this is going to give us a pixel we are filming this using the high speed camera. So, that are that will give us you know pixel by pixel frame will be given like pixel by pixel. So, one can actually do the conversion like pixel versus the physical scale like the millimeter let us say physical dimension. So, if you know the factor then you can simply multiply that optical factor and you can actually get the burn rate by the unit millimeter per second in the unit millimeter per second.

So, this is the optical measurement technique even nowadays also this type of techniques are followed, but we are actually concerned about the erosive burning determination. So, various methods have been tried. Major laboratory methods as we discussed is the methods by Marklund and Lake. In another method laboratory method is by Zukros and the last one we have discussed is the Nadaud’s method. So, I think we close today's lectures by summarizing these methods we have discussed so far.

Now, we will talk about the other you know methods for determining the erosive function or erosive ratio which was like R e by R 0 by considering the direct measurements through engines like this was the laboratory methods. So, as I said there will be some difference between the laboratory based data and the engine measurement data. So, we will talk about the what are the different methods used for erosive function measuring the erosive function using engine measurement methods in the following lectures

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