Course Name: Combustion of Solid Fuels and Propellants
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Week: 04
Lecture: 22 Effect of Various Parameters on Burn Rate of Composite Propellants

Hello everyone. We are going to continue our discussion on Combustion of Solid Propellants. And since last class I think we have talked about the combustion of composite propellant and we have discussed about the evaluation of burn rate of composite propellants. In today's class we will try to see that what are the different influencing parameters which are going to affect the burn rate of composite propellants. For example like we already talked about the effect of ammonium perchlorate crystal size and the effect of burn rate on composite propellants. So there are other parameters which are going to be influential in the composite propellants burning rate.

So certain parameters are like effect of initial temperature, gas velocity, transients like transient means stops and starts, vehicle acceleration etcetera. And there are other parameters like the binder, type of binders, type of different catalyst it can be positive catalyst or negative catalyst. So I think we will proceed accordingly step by steps. So first let us look at what we learned already with that you know initial recapitulation we can just move ahead with the various I mean affecting parameters alright.

So in the previous lecture I think we wrote the equation of burn rate and we said that the linear burn rate of composite propellant was written as R equal to A P to the power N where we had said that this is famous burn rate law or Villiers law or Senrober's law. Here we said that A takes care of the effect of ammonium perchlorate particle size or crystal size, the temperature, the composition of the propellant and N brings the effect of pressure. So N is also known as pressure index. Now we want to elaborate the each of these things separately in that sense the effect of ammonium particle size I think we have already discussed that if the particle size reduces the flame stand of distance because if you recall the heterogeneity of the propellant is the main concern in this case and that is why the process of burning is also heterogeneous it is not homogeneous propellant. So ammonium particle crystals produces the premixed flame first upon decomposition of ammonium perchlorate and the fuel vapour is going to mix with the oxidizing species present due to the decomposition of ammonium perchlorate they will create some initial you know diffusion flame which is PDF or primary diffusion flame and then the final product of the ammonium perchlorate flame which was termed as the APPF I think we have already said that and then they finally, the product of APPF and PDF are going to mix and going to produce the secondary diffusion flame or the final diffusion flame and this model was known as the BDB model and we consider this model to describe the burning process of composite propellant.

Now in order to understand the various you know influencing parameters we have discussed the effect of pressure because if you recall the pressure has very much influential effect and that is why in this equation pressure is very important and the equation was written as R =AP ^n. Now what is happening due to pressure that we already said that in the during the low pressure region or sorry during the low pressure regime when the chamber pressure is low during that time the APPF or the primary diffusion sorry the premixed flame is influential or dominant whereas, once the pressure increases the reaction rate is comparatively faster or the reaction rate is going to be increases going to increase with increasing pressure, but the diffusion or the mixing process between the fuel species and oxidizer species is not going to improve due to the increase in pressure. Due to which the burning process or the combustion process will be controlled by the diffusion flames. So, therefore, due to the diffusions. So, therefore, during the high pressure the combustion is controlled by the diffusion whereas, in the low pressure the combustion is controlled by the ammonium perchlorate premixed flame.

So, the effect of pressure we have already said and the effect of pressure is also going to be influential that is going to reduce the you know the it is going to increase the burn rate. So, it is going to improve the stand off distance also. We have also talked about the size of the ammonium perchlorate crystals if they are lower in size that means, the APPF flame is going to be shorter. Similarly, overall the stand off distance is going to be smaller and if the stand off distance is smaller we can expect the higher heat transfer from the flame to the ah unreacted propellant surface which will eventually get more heat and that will you know ah helps to pyrolyze the fuel, it will decompose the ammonium perchlorate and eventually it will improve the you know burn rate. The effect of ammonium particles ammonium perchlorate particle size and the effect of pressures we have discussed in the previous lectures.

Now, since A is taking care of the you know temperature effect composition of the propellant we should look at separately how the temperature is is going to play a role in you know influencing the burn rate. Because if you look at the heat transfer from the propellant I mean the heat transfer from the flame is going to provide you know some heat required for heating of the propellant and the endothermic reaction. So, what is going on here the initial temperature of the propellant will become you know surface temperature T s. So, the initial temperature of the unburned propellant has certain role because what intuitively what we can say is that if the initial temperature of propellant is higher we can expect that it requires less amount of heat for this you know heating of the propellant. So, in a sense if the unburned propellant temperature is in the higher range we expect that this will actually going to improve the burn rate.

So, in in literature also it has been said that if the ah you know the unburned propellant temperature is in the higher then definitely it is going to improve the burn rate. So, we want to just see the effect of temperature of the propellant on it is you know burning. Before moving into that you know we want to see a more generic form of the burn rate equation sometime it is expressed in terms of like

$$R = A p^n + B.$$

So, this is like a more you know generic or more general form of the of the burn rate law where A and B are empirical constant whose values can be you know ah dependent on the initial temperature of the propellant grain ah for particular propellant. Now, for very high pressure cases like in case of artillery where the chamber pressure is very high such as in the case of this linear burn rate law has been developed which is known as the Murat-Ars law and it is written as in the linear form

$$A = R = A p^n + B.$$

So, you know this type of you know form of the burn rate law is also applicable for you know in certain cases or certain applications where you know the chamber pressure is very high. Otherwise the generic burn rate law is invariably applicable for both the double base propellant and composite propellants. Later on I think we can see that this is also applicable for the other composite propellants and we can also see the influential effect of those composite propellant. For example, like the modified composite modified double base propellant nitramine propellants. So, I think in these you know subsequent lectures we will also try to look at the influencing parameters in case of those type of propellants where you know the certain different type of oxidizers are used and due to which the double base propellant will become like composite modified double base like it may contain some amount of ammonium perchlorate or some amount of nitramine oxidizers.

So, due to which the the homogeneous nature of the double base propellant will change. So, that will become a different you know category of propellant which is called the composite modified double base. So, there also we will try to see how the burn rate is going to be influenced by the effect of you know various oxidizers and effect of AP also. So, we will we will talk that part separately. Now let us look at the effect of this you know temperature in a more you know detailed manner.

So, there is some temperature sensitivity parameter we generally define, but what about the other influencing parameters? We said that A can take care of the composition of the propellants. Now once we say composite of the propellant that means, there will be different things like for example, like binder will be there are different type of binders can be used, there are different type of catalyst can be used, there are different type of metal particles can be added into added into the propellant ingredients. So, those will be taken care of by the A. So, the experiments what we generally conduct to measure the burn rate for example, like the Crawford strand burner or even the you know ballistic evaluation motor. So, if we use the Crawford burner or the BEM method, we generally perform the experiment for various pressure and we get the data of burn rate for various you know various pressure.

And we actually do the curve fitting and finally, from there we can find the value of A and N using the curve fitting. So, these both of these methods are very effective, there may be some difference in the burn rate data between these two methods due to some variation like you know Crawford burner actually we are using some strand and we are letting the strand to burn from its you know top surface. And the circumferential surface will be inhibited thereby we are getting the normal directional burning. So, we can have you know some for a specified length how much time is taken to burn from there we can actually get the burn rate data and we can do it for various pressure. In case of ballistic evaluation motor what we can do is we can change the different you know nozzle throat area and we can actually change the chamber pressure variation.

I mean we can achieve the chamber pressure variation and from there we can actually you know get the burn rate data. And we can see that there may be some you know variation of burn rate from this type of you know evaluations with the actual you know motor situation. So, from the actual rocket engine and the burn rate calculated from this you know experimental method there may be some variations like 10 to 12 percent has been reported. So, that can be a activity to you know specific grain geometry there may be some influence of turbulence present in the you know gas inside the port volume maybe the heat transfer due to radiation will may have some may play some influencing role there. So, in actual rocket engine of course, the burn rate depends not only only the you know composition, but also on other factors.

So, we can actually look at many such influencing factors for considerations for example, like the major factors which you know influence the the I would say like major parameters which influence the burn or burning rate of propellant in actual rocket engine. First one is of course, the chamber pressure which we already talked in detail that chamber pressure plays very important role here because that is going to influence the reaction rate and that will eventually you know influence the burn rate this part we have already discussed. In fact, the in the burn rate law equation pressure is placed a very important parameter there that R equal to A p to the power n. We can say that initial temperature of the propellant. So, this is like the T i some book it is referred to as T u or unburned temperature of the propellant.

So, the temperature initial temperature of the propellant also has a role the temperature inside the chamber of course, the combustion gas temperature. What about the gas flowing on the propellant surface? Now, the depending on the type of propellant the effect of the gas flowing on the propellant surface. So, what you are talking about is like you know inside the chamber. So, once the propellant starts burning. So, this is the regressing surface the flame is going to produce established here.

So, the combustion gas is going to produce. So, the gas is going to flow at certain velocities. So, what is going to do is going to rewrote some of the propellant surface due to the gas velocities. So, is there any effect of the gas velocity on the propellant surface regression which will in turn is going to affect the you know burn rate. So, that part is also going to be influencing factor depending on the you know the velocity magnitude like whether it is a higher velocity magnitude or in the lower side based on that it may have some influencing factor on the burn rate.

There will be like the you know acceleration of the vehicle like the motor, acceleration or spinning of the rocket motor that may also have influence on the you know burn rate of the propellant. So, I think there are various influencing parameters like you know type of the binders, what about the different type of binders if we use, is there any effect on the on the propellant burn rate, what about you know use of different catalyst. Basically they are burn rate modifiers. Now, they may have both you know positive and negative ok. So, these are like various influencing factors which may you know modify the burn rate of the propellant.

Of course, based on the prevailing conditions inside the rocket this will the relative influence may change in certain cases the temperature may be influencing factor, sometime the you know the acceleration or spinning of the vehicle may also going to influence the burn rate. So, I think we will try to look at each of these you know in a certain detail just to be you know prepare ourselves to understand that various influencing parameter which will be required, the knowledge will be required during the time of design. So, in order to understand the initial temperature of the propellant or effect of initial temperature of the propellant generally it is you know understood by considering one temperature sensitivity coefficient. Now, if you just recall what we have discussed regarding the burning of composite propellant or in general like the propellant that the propellant gets heated during the combustion as heat is you know conducted from the propellant burning surface. So, once the heat is coming from the flame the heat is going to conduct to the propellant surface to the unburned propellant end.

So, this is like the unburned propellant end and this is like the burning side of the propellant. So, flame will be somewhere over here. So, the temperature is going to increase from the initial temperature T s sorry initial temperature T i to the surface temperature T s ok. And then you know the flame is going to happen and the final temperature is going to go to the flame temperature. But you see the initial temperature of the propellant is going to vary based on like the heating of the unburned propellant.

Now, the effect of the initial temperature is actually contained in the constant A of the burn rate law. What you already said that

$$R = A p^n$$

where A is actually taking care of the effect of the initial temperature. However, the effect due to change in you know initial temperature on the burn rate can be expressed by a temperature sensitivity coefficient ok. Now, in literature it has been shown that if we have a different you know initial temperature of the propellant there is a increase in burn rate. So, if we have like increase in initial temperature different initial temperature we can see that burn rate is going to increase for a similar range of pressure operation like similar range of chamber pressure we have seen that I mean it has been reported in literature that if the initial temperature of the propellant increases the burn rate is supposed to supposed to increase.

Now, this you know the effect due to change in initial temperature of the propellant has been described in a manner by considering a temperature sensitivity coefficient and it is defined as the the change of burn rate due to change in temperature and it is defined as 1 by R dr / dr dt by at certain pressure. So, for a particular pressure how the you know burn rate is changing due to change in initial temperature. Now, in this case this value of the sigma p will be like it may be expressed in terms of like percentage per degree centigrade or degree or Kelvin or simply like the number some number by per degree centigrade or you know per Kelvin. Generally it is you know order of like 0.003, 0.004, 0.005 like that ah. Typical values of double base propellant for DV propellant is generally in the higher side. So, it is like higher temperature sensitivity it is in the order of 0.005 per degree centigrade whereas, Cp for composite propellant is in the order of 0.003 degree per centigrade. So, you know higher sensitivity desirable for missile application compared to satellite launch vehicle because DV propellant is common one for you know gun prop common application is the gun propellant or for missile application.

So, higher sensitivity is required there and we can see that temperature sensitivity is actually higher for double base propellant. Now, from this equation actually if we know a reference burn rate for a reference temperature if we know a burn rate for a given you know temperature given initial temperature we can actually find out the burn rate for a certain temperature. For example, like if we simply express this equation in terms of you know R we can write dr by R ∑ p dt and we can integrate it and we can write this as

$$(R2/R1) = e^{\wedge} \sum p * (t2 - t1).$$

Now, if we know the value of R1 at initial temperature of t1 we can actually find out the value of R2 at a temperature t2. So, that means, if R1 is you know known for a reference initial temperature the burn rate of a burn rate of a propellant at any temperature let us say t2 can be determined from the from this equation.

So, this equation is kind of a very handy in you know getting the burn rate from the temperature sensitivity coefficient if we know a reference you know burn rate value at a different at a given temperature. Now, if you look at this plot it has been plotted for temperature sensitivity characteristics of AP, HTPB composite propellants. Now, generally like once the burn rate is increases the value of sigma p or value of temperature sensitive coefficient is going to decrease. You see once the particle size decrease we can expect that the burn rate is going to increase. So, here you can see the burn rate is actually increasing from you know here is around 3.5 or so, it is increasing to more than 5 or 6. So, once the AP particle size decreases the burn rate is expected to increase if we add like catalyst, catalyst can influence the burn rate. So, it will act as you know positive burn rate modifier. So, it can increase the burn rate. So, this is going to increase the burn rate in a sense the temperature sensitivity coefficient is going to decrease as we increase the burn rate.

Similarly, in this route also if we increase catalyst and also if you decrease the ammonium perchlorate particle size which in turn is going to decrease the sorry which in turn is going to enhance the burn rate and eventually that will decrease the value of sigma p. So, sigma p has some influencing effect due to you know particle size of the ammonium perchlorate and the catalyst addition. So, we have to you know get the combine effect of the temperature sensitivity coefficient due to other values like due to catalyst addition and the AP particle size reduction. However, in from the experiments this has been reported already. So, these values are given for composite propellant is generally in the lower value whereas, for double base propellant the value is in the higher side as you can see here.

Now what about the other things we just said that there are many influencing parameters for problem in general for example, like we have said that the effect of gas flow. Now there is a if we look at the general you know situation for solid rocket. So, if we recall the ignition process we said that once igniter is going to ignite the propellant surface. So, igniter is going to provide the plume hot plume to the propellant surface that will get heated the this will creates decomposition and pyrolysis of the fuel and binder or the oxidizers. So, that will create the regression surfaces the pyrolyzed products from fuel and the oxidizing species is going to react and they are going to form the flame.

Now you see the the gaseous products along the you know metal or metal oxides formed during the burning of solid propellants and they will move along the you know lateral surface of the grain. Now when the gas velocity exceeds now there is a chance that gas velocity will always not be very high. So, if the gas velocity exceeds certain threshold value it will enhance the burn rate of the propellant even under like quiescent and one condition. Now this you know burn rate dependence on the lateral velocity of you know combustion products is termed as the erosive burning.

Now we have a separate module for this one. So, I will not go detail into this I just want to write down the influencing parameter here that is why we just brought it here. So, the due to the you know velocity of the gas effect of you know gas flow on the propellant surface. Now literature has shown that you know the for a low threshold for low gas velocity generally the the effect is not that much prominent. However, as the gas velocity increases the effect on the burn rate you know is going to be significant. So, we cannot really neglect it and also it has been you know reported in literature that low energy propellant the the burn rate remains constant until you know it goes the gas velocity goes to the order of around you know 60 to 70 meter per second and beyond certain threshold velocity the burning rate increases as the gas velocity increases.

Now this gas velocity of course, will depend on the type of propellant. So, this is going to you know depend on types of propellant. Now we should note one thing is that that high energy propellant is not that much sensitive is less sensitive to convective flow velocity of combustion gases compared to the low energy propellant. So, low energy propellant is more you know sensitive. Of course, this part will you know discuss more in detail you see this is one example given from the literature that erosive erosive burning ratio and threshold velocity.

Now if you look at for the low energy propellant the erosive ratio values are given for different cross flow velocity for a high energy propellant is kind of a less sensitive whereas, the low energy propellant is kind of more sensitive due to the you know cross flow velocity of the gases. Now since we have a separate module on the erosive burning let us not go into this go into detail of this one I think we will bring this one again while we discuss about the erosive burning, but at least for the time being you know for the completion of the different types of influencing parameter on the burn rate we just wanted to talk about this. So, for just introduction purpose we just we just need to know that this is you know effect of gas flow on the burn rate ok. Now in the next lecture I think we will talk about the other effect for example, like effect of transients like effect of stops and starts of the process burning process, what about the vehicle acceleration. So, and of course, the other parameters for example, like the effect of composition of the propellants composition in the sense like the type of binders, the different type of catalyst or burn rate modifiers it may be positive catalyst or negative catalyst and how they are actually going to take actually going to influence on the burn rate like what about the different you know composition reactions and how they are influencing that we are going to talk in the following lecture alright.

You see these are already mentioned here. So, I think we will discuss this thing in detail. Thank you.