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 34 : Ignition and Combustion of Boron Particle

Hello everyone. So, we are continuing our discussion on combustion of metals path to 2 and in this lecture we will begin our discussion with a new topic which is ignition and combustion of boron particles. However, I think the last part of the previous lecture which was the consideration of Knudsen number and its relevance to particle combustion I think we are talking about that. So, I think we will first finish that discussion and then we will continue with the ignition and combustion of boron particles. So, let us look at what we discussed in the previous lecture. We had said that the Knudsen number is also important because this is going to give us another length scale to the metal combustion.

$$Kn = \frac{2\lambda}{dp}$$

If we compare the particle diameter with the mean free path of the ambient gas. Now, this length scale is going to tell us that if the particle diameter is very small then we have to see that whether the continuUm exist or not or the macroscopic behavior of the particles whether we can really consider or not. So, if we just consider the Knudsen number definition what we told our self in the previous lecture that by definition Knudsen number was denoted as Kn and it was given as 2 lambda by particle diameter or basically the mean free path by the particle radius. So, here lambda is the mean free path mean free path of the ambient gas and dp is the particle diameter.

$$\lambda = \frac{1}{\sqrt{2}\pi\sigma^2 N}$$

Now, if you compare this again we can write the equation for mean free path from the kinetic theory we can get this is 1 by square root of 2 pi sigma square into N. So, where sigma is the molecular diameter of the molecule, N is the number of molecule number of molecules of course, per unit volume. So, from kinetic theory we can actually write the lambda will become like 2 mu by p 8 pi RT to the power half where mu is the viscosity of the gas and p is the pressure. So, what we can say if Kn is 1 this is kind of you know we can say limiting regime for limiting regime of particle combustion. Of course, that will depend on depending on pressure and temperature because you see in our mean free path equation from kinetic theory of gas we are writing this 2 mu by p into 8 by pi R 2 to the power half pi RT to the power half.

$$\lambda = \frac{2\mu}{P\left(\frac{8}{\pi RT}\right)^{\frac{1}{2}}}$$

So, it is like pressure is there temperature is there pressure and temperature are relating the mean free path and that way it is relating to the Knudsen number where 2 lambda by dp. So, we can say the limiting regimes can be considered to be like Knudsen number is going to be equal to 1. Now, if you consider at pressure equal to 1 bar or 1 atmosphere we can say if the particle diameter is of the order of like 100 nanometer we may see that Knudsen number will coming close to. So, the particle diameter 100 nanometer or even or even smaller Knudsen number will coming almost close to 1 of course, no sorry is going to be greater than 1 because see we are talking about like 100 nanometer. So, if we do that this will come Knudsen number is going to be greater than 1.

What does that mean? The particles cannot be considered as the macroscopic particles in the continuum gas. That means, these particles are now behaving almost like the larger diameter molecules. Let us say there the molecular diameter of the gases are like this and if you are if our particle diameter. So, this is our particle actually. So, these are this is our particle and this is our molecular of the gas.

So, we can say the particles will be will behave similarly to the two large larger diameter molecule. So, it will be very difficult to distinguish the particles and the gaseous molecules present there. So, if the this is the particles they are almost of the similar order of length scale. So, what we can expect here is that the reactivity of the nanoparticles will be very much influenced by this and in that case the kinetic rates will be important there. This will be more influence and influential than the transport rate.

So, you can say the spatial non uniformity may not exist at all because of you know smaller diameter it is almost closer to the diameter of the larger molecule of the gas. So, in that case the transport rate or even energy will not affect much and not very much from the particle surface to the you know away from the surface, but within the particle itself there may be some spatial non uniformity of the transport rate there is a non uniformity between within the particles, but however, particles and the surrounding it is almost going to be you know non existence. So, we can say the kinetic rate will be the more influential compared to the transport rate of reaction or even energy. Now, due to this there is a appreciable you know interest has been given for nano size metal particles for combustion applications, but we of course, need to consider this length scale just to give an idea about its relevance to particle combustion. That is why we need to consider the Knudsen number if it is coming greater than unity then of course, the features which is going to be change compared to the macroscopic particles and this consideration will come into the picture and we must need to you know consider this one while analyzing the behavior of the particles in the combustion reactions ok.

So, I think with that we close the discussion on the regimes of combustion relevant to particle combustion we already said that the main two modes of combustion we have talked about the kinetic control and diffusion control. Now, this if the particles are particle diameters are coming too small then it is giving another you know relevance to the particle combustion regime which is giving a new length scale another length scale to the problem. That is why if the particles are becoming too small let us say 100 nanometer or even smaller in that case the particle diameter will be considered to be equal almost close to the diameter larger diameter of the molecules of the gas or the ambient gas in that case the kinetic rate will be more important compared to the transport rate and this analysis is going to be pertinent there. So, I think you we can read more about this in order to understand further. However, I think we can close our discussion on the combustion regimes of metal particles.

Now, we will move ahead and look at the combustion mechanisms for boron particles and aluminum particles. Now, let us begin our discussion why boron is so important in case of you know using aerospace propulsion system particularly like in propellant application. So, let us look at that part. I think in general discussions we have already talked about that why energetic particles are so important for you know propellant application, but now we are looking at the motivation behind boron particles as fuel additives or you can say if it is a propellant case then we can say it is going to act as fuel because if you recall the ingredients for solid propellant we have said that metal particles are going to be used as fuel whereas, HTPB or polymeric binder will be just like the binder. So, in that case we can say that boron can be the fuel for propellant or if you use it in a liquid fuel combination then it can be fuel additives.

So, the major question here is why it is important to consider the boron particles as fuel additives or even fuel. So, here it is actually compared with like you know traditional hydrocarbon fuels for example, like HTPB or paraffin wax we also compare this with the liquid fuel here. So, if you look at the left hand side graph I think we have already seen it while we discuss about the metal particle combustion at the very beginning we have talked about that the various you know metal particles can be considered to be fuel, but the major consideration we have given to the volumetric energy content or volumetric heating value and there we have said that since beryllium is highly toxic it is going to produce highly toxic oxide. So, beryllium is not considered for real application. So, when the second candidate is coming as the boron whereas, boron has the highest volumetric heating value and that is very important for volume limited propulsion system.

So, research is going on for several decades on how to use boron particles in you know propulsion application. So, if you compare with the boron particles with that of polymeric fuel such as like HTPB or even with the paraffin wax you can see the heating value of boron both from the gravimetric and volumetric basis it is quite higher than HTPB or paraffin wax. Now, if you consider to be the liquid fuel you see this is a this plot is given this figure is given for the comparison of boron heating value with that of JP 10. So, JP 10 is one of the you know jet fuel which is used for liquid engine and if you look at the change in the volumetric heating value if we add boron particles into the liquid fuel you see the volumetric heating value of JP 10 which is 0 percent boron particles means pure JP 10 you may see that the heating value is about 39.4 mega joule per liter.

Once it is added with 10 percent boron it has changed to 42.3 with 20 percent this is 46.2 with 30 percent 49.4. So, we can see that volumetric heating value is increasing as we increase the particle loading within the liquid fuel.

So, you can see this is the picture of the boron loaded liquid fuel. If we consider the density, density of JP 10 is 0.94 now adding boron particles the density is also going to increase. Now, if we recall our discussion that why energetic particles are so important it is from the density specific impulse point of view that if the density of the particles is higher than the normal hydrocarbon fuel it is good that we can have like a you know higher packing there with the limited volume and also the volumetric heating value is going to be higher. So, compare these two parameters we can say that boron loaded hydrocarbon fuels either it will be in solid form or in the slurry form is going to be beneficial of course, theoretically.

But there are some issues with boron particles because of that it is not yet utilized in practical combustion system, but the promise is like if we can utilize the boron particles it is going to be one of the promising alternative fuel pathways you see it is written here also that can you seed boron nanoparticles with hydrocarbon fuel to increase the energy density. Now, density of boron is higher than the density of hydrocarbon fuels almost three times which is also important for volume limited propulsion systems. Now, if you look at the potential application of boron particles in ramjet application. So, in propellant I mean in propellant directly using boron particles in propellant there are issues with ignition and combustion and boron particles that will I think we will talk in later part of the lecture. However, you know there is there has been an increasing interest in high energy density fuels for you know in combustion and propulsion applications where you know it has been given that if we can increase the energy density of the particles energy density of the liquid fuel by adding energetic boron such as like in slurry form which actually going to combine the you know advantage of liquid fuel because the issue is like how we can supply the fuel into the combustion chamber.

So, if we use the slurry fuel just by pumping as if like the liquid fuel then we can directly burn the liquid fuel in the combustion chamber. So, one way of sending the particle loaded liquid fuel by pumping, but of course, there are issues like whether we can efficiently atomize the particle loaded liquid fuel which is in the form of slurry whether we can burn those properly or not. So, the use of boron slurry or gel fuel in ramjet type application if we just inject those and burn in the combustion chamber and the energy released by the you know burning of boron particles that will enhance the combustion chamber temperature and eventually that will help in increasing jet velocity and of course, that will enhance the thrust because if you recall our performance I s p is proportional to the square root of the combustion chamber temperature. So, if we increase the energy density of the fuel by adding boron particles to the liquid fuel in a way that is going to release energy upon combustion which way the temperature of the product is going to increase and that will enhance the performance. So, that is the main intention of using boron particles in the liquid fuels in the form of slurry.

Now here I have written gel here just because you know in case of slurry the major problem with slurry is the sedimentation because you are mixing some solid particles into a liquid. So, you have the liquid now let us say you are just adding some solid particles to it. How can you suspend these particles for longer duration because we are talking about something around 20 to 30 percent or even more percentage of loading into the liquid fuel. So, at some time some point of time what is going to happen that you will have almost like clear liquid and all the particles will be settled at the bottom of this beaker or the tank of the fuel. So, how do you suspend these particles for longer period of time for use in the engine application.

So, that is why the gel fuel is another approach because gel has the capability just like act as solid when it was not been stirred or pressurized, but it is going to act as liquid under shear. So, if we have like a gel form if we form this liquid fuel and form a gel network then it is not just a liquid it is going to form some kind of a semi-solid type of structures where it is going to hold the particles into the gel network. So, there is no way particles is going to settle is going to stay there for longer period of time. So, one approach can be like if we can have like slurry fuel where we can hold the particle or suspended the particles in longer for longer period of time and you can pump them into the combustion chamber you see we are actually atomizing it or since the sedimentation is a problem in case of slurry the other option can be like gel fuel where we are we are making the liquid fuel into gel and in that gel network we are suspending the energetic particles. So, boron loaded in slurry or in gel fuels can be one of the prime you know important fuel for ramjet applications where it is going to burn here and is going to increase the temperature upon the release by oxidation of boron and eventually that is going to increase the VJ which is going to you know increase the performance of the motor or of the propulsive device.

The other way can be thought of like by using the air breathing propulsion system where we are adding boron particles directly into the into the solid fuel grain. So, we are just adding boron particles into solid fuel grain and using the air as the oxidizer we are using the air intake and taking the air through ram compression and that is going to you know going to supply as the oxidizer for the this fuel and this is fuel regression will happen and the flame is going to form and that flame is going to supply energy for the further regression of the solid fuels and the combustion gas will come here it will be expanding in the nozzle ok.

This is another way of applying energetic particles directly into solid fuel. So, if you recall we said that if we have a HTPB let us say which is a very thick viscous liquid you add boron particles with HTPB put curing agent and make the form of a solid fuel grain. Remember we are not talking about propellant here we are talking about just a solid fuel, but of course, the other approach can be like we can add oxidizer to it and make this a grain we cure it solid it will become solidified and we can have the grain just like this.

So, that fuel is now loaded into here ok. So, this is a solid fuel grain that is why we are taking oxidizer from the outside. So, one advantage is that in the ramjet application that we are not carrying any oxidizer from the oxidizer with the fuel itself we are just carrying these only solid fuel oxidizer is taken from the atmosphere through the ram compression and that way the ISP of the vehicle is going to increase tremendously. So, there will be like some primary combustion and then additionally since boron has the problem of burn problem of having complete combustion. So, additionally some bypass air will be again taken inside and further combustion will take place which will ensure the complete combustion of boron there in the secondary chamber.

So, this is another approach of using boron particles in solid fuel application. The newer approach which is like the ducted rocket with hybrid gas generator there is one approach that we can directly use boron particles into solid propellant. Remember this is we are talking about the solid fuel you see this is for the solid fuel, but we can make the grain by adding the oxidizer and fuel both we can have we can add ammonium percolate as well into the this matrix and we can make the solid propellant. Now, how they are burning whether is going to burn fully or not that will of course, depend because the major issue with the boron particles combustion is it is not fully burned and in a limited residence time its full energetic potential was not utilized till date. So, the most of the studies involved earlier was considering the micro boron as it is written here.

There are some studies are being conducted that if we can reduce the particle size to nano scale then there is a high chance that surface reactions will be higher and that way it is can improve the you know ignition of boron particles and that way it is going to burn properly which may actually you know lead to complete combustion of boron within the given residence time of the combustor. Now, there are number of research have been conducted which has been focused on you know how to have full fledged combustion of boron particles and use of boron particles you know within the given residence time for particle ignition and combustion. So, the major focus was given on how to you know initiate how to enhance the boron particle ignition and that way improve the combustion of the boron. So, in this lecture after having this background I think what we will try to see that how the boron particle is going to ignite in a environment where what are the issues boron particles are facing and how we can improve them. So, we will talk those in detail by considering the available mechanism.

You see another motivation has been mentioned here that if we compare the solid rocket motor consisting of you know 15 percent aluminum, 15 percent binder and 70 percent AP and if we compare that with solid fuel ramjet where we can load up to 55 percent of boron with 45 percent binder AP may be you know optional because since we are going to use like ramjet. So, there air is going to consider as the oxidizer there oxygen from air will be used as the oxidizer. So, we do not have to carry much of the oxidizer directly into the solid fuel. So, in that case you know the range can be increased 1.5 times to 2 times you can see here.

If you compare the ISP also you can see the ISP can be almost like close to like 2.5 or so, 2 to 2.5 based on like how much boron we can load and you can burn. So, this calculation was given of course, that the boron particles energy was fully utilized and that is the calculations given there. So, there is a enormous potential of boron particles if we use them in the solid fuel application or directly in solid rocket applications.

So, this figures is actually gives us the promise that if we can burn boron particles properly there is a huge potential that boron can give. So, you know there are many research researches are doing this how to use the boron particles in solid rocket applications directly in the form of you know propellant or the in the form of solid fuels where the additional oxidizer can come from the directly from the atmosphere. So, many are actually proposing that boron loaded fuel will be best suited for ramjet application where the oxygen can come directly from the atmosphere through the ram compression process and this can be done in a you know two stage combustion. The first stage will be used for some primary combustion and then later part we can use the additional you know ram air to further increase sorry further burning of the partially oxidized particles and lead to like combustion of boron particles there. You see this is like a hybrid based gas generator where we can use the oxidizer separately just to partially burn the boron loaded solid fuel and then rest of the part is going to burn there in the secondary chamber.

So, there is a primary chamber. So, here you can see the oxidizer is used as the gaseous oxidizer. So, gaseous oxidizer is going into the primary chamber where primary chamber it is basically the solid fuel there is no oxidizer present in there only the gaseous oxygen is going there to partially burn the fuel first and the remaining combustion will take place in the secondary chamber here where the oxygen is coming from the atmosphere through the ram compression process. Now, if you just look at the solid fuel ramjet there is actually difference is that this is like solid propellant is there. So, there is going to burn there then is going to take the ram air for further compression and is going to produce the thrust ok. Here it is actually taking the air directly from the intake it is burning here, but this is like a two stage combustion in case of hybrid gas generator because it is taking primary oxidizer as the oxygen it may be in the form of like a oxidizer the stored oxygen or maybe in the form of like cryogenic mode like liquid oxygen that may go into the primary chamber and burn and rest of the you know oxidation is going to take place in the secondary chamber where the air is going to be compressed through ram compression and go into the secondary chamber.

In this case it is directly taking from the only in the secondary chamber whereas, the primary zone combustion will be in the form of you know combustion of propellants. You see this is like fuel enriched solid propellant. So, some solid oxidizer will be mixed here and that will lead to the primary combustion and then it will the products from the primary combustion will come from the through this valve and go into the secondary chamber and here actually you can see that air is being taken through this inlet and secondary combustion is going to take place. But in summary what we can say that if it is possible to use the energy content of boron particles there is a tremendous potential available to enhance you know the range and the ISP of the vehicle if you can burn boron properly. Now, the issue with boron particles is that the most of the boron particles are actually covered with a native oxide layer.

This is the native oxide layer which is covered the core boron part. So, this layer is actually going to protect boron particles from you know reacting with outside oxygen. So, if you have the outside oxidizer here this is actually going to you know protect it from the oxidizing the core boron with the with the outside oxygen. Interestingly the oxide layer the melting point of the oxide layer or the boron oxide is much lower which is like 722 Kelvin than the core boron and that will create some kind of a molten layer, but it is still going to protect there. So, we can say it is going to be wetting the surface of the boron core and that is actually keeping the surface from the direct contact with the oxygen.

So, it is not allowing the boron to react with the oxygen it is kind of act like a protecting layer and because of that you know the ignition is delayed, ignition delay is happening because of that. So, this is boron oxide layer is acting as an inhibitor you can say this is acting as an inhibitor for ignition ok. And that has been reported by you know numerous literature that oxide layer native oxide layer present on the boron surface is the major reason that it can cause the ignition delay of boron particles. Now, the once the once the boron oxide layer gets evaporated then the core boron is going to have access to oxygen and it is going to react with oxygen and it is going to combustion is going to take place. So, there is you know said that ignition of boron depends on the balance between the rate of B203 production and vaporization above a critical temperature the vaporization of B2O3 exceeds the production of B2O3.

So, that way it can actually have the like the bare burning of boron particles. Now, there are some proposed ignition mechanism exist whether the oxygen diffuses through the molten oxide layer the others has proposed that the boron ox boron actually dissolved through the molten layer and react with oxygen. So, there are some you know contradictory mechanisms exist on the ignition of boron particles. So, in the following lecture I think we will directly look at the ignition of boron particles and we will try to understand the various mechanisms and you know possible hypothesis given by different researchers just to have a general understanding. And we also briefly talk about what are the ways researchers have tried in order to improve the you know ignition and combustion of boron particles.

Because we can see theoretically boron has tremendous potential in you know improving the performance of the aerospace propulsion system. So, by which you know if it can be utilized fully it can improve the performance of the vehicle. However, still now it has not been used in practical you know propulsive application just because you know issue with the ignition and combustion of boron particles. So, we will try to understand the ignition mechanism of boron particles and the ways how it is being tried to improve the ignition of boron particles. And I will try to bring some of my you know students work in this scenario just to have the relevance that how different type of work has been done along with some of the literatures work ok. So, we will continue in the next lecture. Thank you.