Course Name: Combustion of Solid Fuels and Propellants
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Lecture 36 : Ignition and Combustion of Aluminum Particle,Recent Future Developments on Metal Fuels

Hello everyone. We are continuing our discussion on combustion of metals. In the previous lectures, I think we have talked about in detail regarding the ignition and combustion of boron particles. And if we recall our previous discussions on the glass main criteria that some particles or some metals can burn heterogeneously whereas, the other metals can burn homogeneously. Now, based on the glass main criteria what we understood that if the volatilization temperature of the oxides is greater than the metal boiling point temperature, then the there is a possibility that metal can burn in vapour phase or homogeneous mode. Whereas, if the metal boiling point temperature is higher than the oxidation, oxidizations, oxides volatilization temperature, then the metal can proceed burning in heterogeneously.

So, in that context the boron particles combustion happen in heterogeneous mode or surface reactions can happen heterogeneously. In case of aluminium particles, if we recall the boiling point temperature of aluminium oxide is actually lower than the metal boiling point temperature is much lower than the oxides boiling point temperature. So, in case of aluminium the homogeneous combustion is going to take place. So, we just please refer to the table what we already discussed.

So, basically what is going to happen the adiabatic flame temperature of aluminium the combustion is going to typically greater than the boiling point temperature of aluminium. So, the flame temperature for aluminium is going to be greater than the boiling point temperature of aluminium. So, we can expect that the heat feedback from the flame is going to cause aluminium to vaporize and is going to have like the vapor phase combustion or homogeneous combustion. If you remember the typical values we had for the boiling point of aluminium is around 2791 Kelvin. So, there is a chance that this is at 1 atmosphere pressure.

So, there is a chance that you know flame temperature can go as high as like 4000 Kelvin which is you know easily can evaporate the aluminium. So, at the particle surface the aluminium can evaporate and the vapor of aluminium is going to burn homogeneously in the gas phase. So, we can see that some flame is going to happen at a distance from the particle surface. Of course, if we recall our discussion also that we have talked about like aluminium plus oxygen as the oxidizer, but if you change the oxidizer there is a possibility of you know transition from homogeneous combustion to heterogeneous combustion. As we recall that if we burn aluminium particles in presence of you know CO 2, then of course, the adiabatic flame temperature will be much lower than the boiling point temperature of aluminium.

So, in that case it can have like heterogeneous combustion. Whereas, if we just consider the aluminium plus oxygen in oxygen environment we can expect that the combustion will take place homogeneously. So, the particle is going to have it will have some kind of a detached flame like this with the smoke trail we can see here. So, we will talk this in detail, but before going into that what is exactly the application of aluminium particles in the rocket motor. If you see we have talked about the propylene ingredients and there we have mentioned that HTPB is considered to be the binder, ammonium percolate was considered to be the oxidizer and aluminium particles were considered to be the metal fuel if you recall with some other you know curing small quantity of curing agent or plasticizers are used.

So, if you look at the propellant surface, typically the propellant will consist of the ammonium percolate and there will be some you know aluminium particles present into it. I am just putting it these are like micron size aluminium particles. So, aluminium particles are dispersed within the propellant matrix. So, as you recall for a composite propellant there is a triple frame structures. So, initially it will have some ammonium percolate premixed flame.

The HTPB binder fuel vapor is going to pyrolyze and vaporize it is going to produce fuel vapor that is going to mixed with the oxidizing vapor and they will create some primary diffusion flame. So, this is your APPF is going to create some primary diffusion flame. So, this is like PDF and then we have final diffusion flame or SDF. These were the trivial frame structures we understood in the discussion during the burning of composite propellant. Now, the particles aluminium particles are actually coming out.

So, if you look at here separately. So, the flame zone is somewhere over here. So, aluminium particles are coming out and they are burning in the flame zone. So, the temperature is very high enough. So, the agglomerated molten particles are actually at the surface it is going to lift off from the propellant surface and you know since there is a flame there is a combustion gas.

So, it will be entrained by the gases and it will undergo the combustion. So, if you look at each of the flame each of the particles they will have the this type of envelope flame. Now, what is going to happen that during the combustion of aluminium some you know oxide is going to form some native oxide may also present on the particle surface. So, during the combustion some fraction of the oxide is going to diffuse back. So, if you look at closely some of the oxide is going to diffuse back and so, it was like a capping of the particle was there.

So, some of the oxides is going to diffuse back and deposit onto the particle surface which actually going to merge with the. So, initially let us say there was a particle surface there was a native oxide layer. So, as the flame go on the aluminium particles is actually burning some of the oxides are actually going to merge with the this native oxide cap and is going to increase the thickness here. Now, due to the surface tension force it is going to pull off and the oxide together to the oxide cap and it is going to separate from the molten particle. So, this is your aluminium the temperature is high enough.

So, the aluminium becomes like a molten aluminium. So, the cap is actually separating out near to the bottom and the of course, some of the fraction of the B203 can also sorry some of the fraction of the Al_2O_3 can actually go to go and evaporate as well. So, that will actually leads to the lead some of the places where aluminium can actually react with that and the oxide smoke is going to come out and it can create some white you know white trail. Sometime it is been observed that the these particles and smoke is going to actually dampen the acoustic instabilities in a rocket motor. So, the amount of smoke produced during the combustion of aluminium is kind of important because that is going to you know interact with the acoustic instability in the rocket motor and it has been observed that somehow it is going to you know mitigate or it is going to dampen the acoustic instability.

Now, the oxide cap can also lead to some you know fragmentation jetting effect from the particles. This is you know is going to form some crack and is going to lead to the oxidation of aluminium and is going to react with the oxygen. So, if we recall our discussion that if we compare the burning of metal particles with the burning of liquid fuel droplet, it cannot be exactly simulate with the metal particle like the aluminium particle case just because you know the oxide capping is actually not allowing the full burning or exposing the complete aluminium molten aluminium to burn in the oxidizing environment. So, we cannot really compare this with the normal hydrocarbon fuel droplet where we have the envelope flame, but here there is a problem that some of the part of the aluminium is actually covered with the this oxide cap. So, just one to one comparison is kind of not possible because it is the mass transfer or the mass consumption rate is not distributed because the oxide capping is actually covering some part of the molten oxide.

If you look little closely what are the model exists there. So, this is the typical smoke trail. So, what I was talking about that if this is the aluminium particle. So, oxide cap is going to come here and is going to cover at the bottom of the particle. So, this is the oxide cap.

So, this is going to you may see that you know oxide products are actually there some of the oxides are actually diffusing back and it is merged with the oxide cap. So, it is covering some of the you know molten aluminium which is actually not exactly same as the hydrocarbon fuel droplet, but of course, the metal aluminium is going to evaporate, the vaporized aluminium will be there. There will be oxide products like ALO, ALO2 intermediate oxides product. So, this is typically the flame zone. And of course, you know the species diffusion will take place like you know oxygen, hydrogen, CO_2, CO, hydrogen also.

There will be some heat radiation, conduction of heat is also going to happen due to the conduction through the gas. So, this I am talking about you know taking out some is kind of a exaggerated view of any of these particles. So, what I have just shown here is this. If you look at how the each of the aluminium particles are burning in the gas entrainment because there is a flame. So, the particles is going to burn in the gas phase and if you look at the each of the aluminium particles this is the you know typical model of the you know physical model of the burning of aluminium particles where we can see that there will be a smoke trail covering the you know particles.

It is some the flame is you know some somewhere distant from the particle surface because as we said that it is the particle surface to vaporize and vapour proceeds homogeneously. So, this is the vaporized aluminium which is proceeds homogeneously in the gas phase and is going to burn at some distance from the particle surface which is creating this you know envelope flame and we can see the smoke trail also. Now, aluminium suboxides you know condense to form the liquid aluminium oxide due to the heat release from the flame jolt if it is sufficient this is going to you know dissociate some of the molten aluminium oxide. Now, the maximum temperature at the dissociation temperature of the oxide is going to mantle until all the oxides are dissociated. Now, the position of the flame zone like where the flame is going to stay or the thickness of the flame zone is going to be the function of the oxidizer concentration and the pressure in the chamber or pressure in the location.

So, that will tell us what will be the location of the flame zone. However, this is like a generalized you know model of the burning of aluminium in the you know propellant containing HTBVAP or composite propellant where the each particle is actually having this type of burning profile. Now, one can actually think of the particles may have like micron size aluminium or nano size aluminium. So, due to the you know size effect there may be different stages of burning also like in some cases how the heat transfer is going to take place how the diffusion is going to take place. So, various stages of oxidations can exist depending on the how the heat transfer from the gas to the particle is taking place.

Now, the heat and mass diffusion inside the particle is going to also happen how the melting of the you know aluminium core is happening how the phase transformation is happening in the oxide layer how the oxide layer is going to crack and leading the oxidized to react with the molten aluminium. So, that all is a actually influence the mechanism how the mass diffusion across the oxide layer is taking place how the you know heterogeneous chemical reactions like aluminium with oxygen is going to take place all is going to you know influence the burning of aluminium particles. So, stages of oxidations is going to vary as per the literature for different size of particles. So, for micron size particles and nano size particles you know they are going to different due to the particle size. Now, of course, the these cracks and opening is going to give the pathway for the molten aluminium to react with oxidizing gas and that will you know you know result in energy release and eventually this is going to you know important for the ignition of the particles.

Now, in case of micron size particles because the size is bigger comparatively with the nano size particles the ignition may not be achieved because of that you know high volumetric heat capacity. So, the stages of oxidations may vary between the micron size particles and nano size particles. So, the comparison between the micron size particles and nano size particles I suggest that the participants can refer to literature on you know detail literature on aluminium particle you know combustion for containing like the micron size versus nano size. One can get more detail you know idea about what are the different stages of oxidations happening, but in general as I said that it involves this type of features and I am just trying to relate that what is exactly happening in a composite propellant containing aluminium particles as fuel in a you know HTPB AP based composite propellant. So, if you look at typically one single particles that will you know behave like this type of features ok.

And, as per the Glassman's criteria we have said that this is like aluminium particles going to bump burn homogeneously or the gas phase reaction can take place whereas, in case of boron particles we have said that heterogeneous reaction can take place as per the Glassman criteria. Now, I just want to give you some glimpse of you know ideas what you know various studies are being conducted. This is I am going to show you some of the you know glimpse of results we obtain in our laboratory. If you recall during the introduction I had promised that I will show you some of the results obtained from my research groups. So, they have conducted various experiments involving like you know boron particles loaded in liquid fuel.

So, this is what you are seeing right now it is the burning of a single droplet it is a single droplet hanged on a quartz fibre and the droplet containing the jet fuel or just you know representative hydrocarbon fuel plus boron particles. And, these are typically experiments are conducted there that you just ignite the particles, let the particle burns. So, we have conducted the experiment for various you know commercially available particles. So, the features are actually different if you look closely that you see the particles are actually. So, the typically yellow flame are actually due to the burning of hydrocarbon fuel or the jet fuel and you can look at the typical you know features of boron burning which is having like the green flame.

So, particles are actually coming out and burning in the flame zone and it is creating that green flame. So, the idea behind this is if you recall that once you compare the heating value of various metal particles what we what we told ourselves that if boron has high volumetric energy content can we really mixed boron particles in liquid fuel or in solid fuels. So, this is one such you know idea and we try to see if we just you know look at the droplet combustion how the particles are burning in a single droplet. So, this is a typical droplet combustion features we tried to plot this you know d diameter square versus time. Remember this we tried to relate with the d square law.

So, we tried to plot this d by d 0 square versus time and it is not exactly same as the hydrocarbon droplet, but of course, it is following some linear train with some fluctuations because the droplet diameter is actually you know swelling and contracting because you can see there is a swelling and contraction of diameter is happening and some of the areas there are ejections particles are coming out. So, those are called like micro explosions due to the internal vapour formation they are trying to shattering the droplet and causing the droplet to fragment. So, this is typical you know droplet combustion features which we conducted in our laboratory. The other thing is like how the you know micro explosion and secondary atomization are taking place because once you mix particles in a liquid droplet once you try to evaporate them the particles will try to agglomerate in the droplet surface and they are going to you know create some kind of a layer which is actually does not let the vapour to come out. So, depending on the morphology of the particles this layer maybe have like a impermeable layer depending on the particle structures whether it is a amorphous particles or crystalline particles.

So, that will lead to you know high vapour pressure inside the this domain and that will cause to break up of the droplet which is you know possible mechanism for micro explosions as reported there by one of my student. Now, we had also conducted boron loaded jet fuel in a spray combustion environment because ultimately what our role is that we want to mix the particles into liquid fuel and we try to burn in a combustor environment just to see whether the liquid as the liquid fuel is burning whether you are able to burn the boron particles or not. So, this is a typical you know swell stabilized spray combustion setup where we actually burning boron as a slurry. So, we have like boron loaded in liquid fuel. So, as what essentially we are doing we are just injecting the boron particles through liquid fuel.

So, there is a spray. So, we are expecting once you ignite this there we are expecting that the boron should burn here we should measure the temperature and just to see whether it is giving in a energy release or not. We are not going into the detail of it I just want to give you some glimpse of ideas that if we can you know load boron particles into liquid fuels how we are going to see that how the boron particles are burning. So, this is a typical you know experimental approach through which we can see how the boron particles are burning. The other approach so, I can show you some you know results from the set from the experiments that typical you know liquid flame liquid fuel is going to burn just like a green yellow flame. Whereas, the boron particle burning is containing you know that yellow then white which is boron combustion and that green envelope which is going to give us the emission of BO2.

As we mentioned in previous lecture that BO2 emission correspondence to the emission from the BO2 emission correspondence to the one of the intermediate species and that gives the green light. So, typically you know we can perform the various experiment various you know measurements like spectroscopic measurement we can conduct the temperature measurement just to see whether boron particles have burned properly or not. So, these are the approaches one can look at that how the particles can be loaded in liquid fuel and you can burn it. So, I will just show you some video from the experiment as well after you know completing this PPT. So, now the problem of you know boron particles if you load in a typical liquid fuel system what is going to happen you have let us say liquid fuel you are trying to load some you know solid particles.

So, you are churning it maybe with some thing you may add some kind of a surfactant or some you know some ingredients which can actually lead to have improvement of stability of the particles, but you know after some time it may so happen that particle is going to sediment. So, you may see that you have a clear liquid and at the bottom the particles are actually settled down which is not really expected I mean expect in the sense which is not really the requirement for particle loaded fuel because we want that particle to be dispersed. So, just with the normal liquid you cannot actually have it you know stabilize the particles for a longer period of time what you can do is we can actually either do some modification that the particles settle down for you know longer period of time or did do not settle at all. One of the options can be you can make the liquid into gel. So, make the liquid into gel and hold the particles in that gel matrix so that the particles is not going to settle down.

So, you may see that you know particles are almost staying there, but now you are actually making you know more complex in the system because atomizing the gel will be much difficult than the liquid fuel. So, there is another problem we are bringing in the system we have made the gel, but now how to atomize them properly and burn them properly. So, these are some of the you know droplet combustion studies conducted by one of my researchers that they have loaded boron particles in a gel fuel and they burn the droplet. You can see that typical you know burning of boron loaded cases you can see green light is shown here. So, this is with normal air atmosphere, but if you increase the percentage of oxygen there you see this is conducted at 50 percent oxygen, 50 percent nitrogen.

This was conducted 100 percent oxygen. So, once we increase the percentage of oxygen in the ambient you can see that the oxidation of boron is much more you know efficient as you can see it is a tremendous amount of green light is produced here it is like a you know vigorous burning of particle is taking place. So, as you increase the oxygen percentage even more you can see the intensity of the burning is even higher. So, that way you can see and on top of that you can see it has been observed that the sorry I think it was shown in the same picture actually anyway. So, basically we are trying to show here that once we increase the oxygen percentage it is going to increase the burning of boron particles. On the other hand if you see in this case we have used the magnesium as one of the additives.

If you recall that to improve the ignition of boron particles what we said that researchers have shown that easily ignitable metals can actually improve its ignitability. So, you can see if you use the magnesium as the additive we can actually improve the ignition of you know boron particles. So, these are different ways that boron particles can be applied. Now, I just want to complete this by showing you some of the applications you know for boron based fuels. Now, these applications can be ducted rocket with a hybrid gas generator like we can use the solid fuels loaded with boron particles we can use some oxidizers the partially burnt product can come into a ram combustor.

So, basically this is a dual combustor mode. So, it is going to further burn here and the high temperature high pressure gas is going to come here through the nozzle and is going to expand and give the high velocity jet. So, whole idea is that if you want to utilize boron particles we must have to you know complete the combustion of boron particles then only the full energetic potential can be utilized. The other you know applications can be like marine applications where you know water augmented hybrid propellant ram rocket. There also we can think of using some energetic particles and we can try to burn the fuel in terms of the fuel grain here as you see here. Here actually we are going to add the particles while making the fuel grain we can actually add particles here also we are actually adding the energetic particles.

So, the metal fuels can be you know added to increase the energy density of the fuel. So, there are various applications where we can see metal has you know tremendous application potential. This is one news articles we have just encountered that boron powered Chinese missile will work in the air and underwater. So, you can just look at this one this is like a very futuristic idea that the boron powered missile can actually work both in water and air.

So, this is like a in a dual mode it can be operational. So, what kind of you know fuel combinations they are trying so, that they can use boron particles into the solid fuel matrix and that can be used in both you know marine application as well in air. So, this is like a ambitious project we can say. So, I think with that we close this discussion on the application of energetic particles or energetic metals in propulsion application. I mean I can tell you that there is a huge research scopes in this area. So, if someone is interested to explore further on this one, one can actually look at the literature what are the different work is going on in this area and how the you know ways the researchers are finding ways to you know improve the ignition and combustion of boron particles in order to utilize the boron particles in propulsion application.

So, before we stop I would as I promised I would show you some you know video. So, this is typically a hydrocarbon fell flame as I told you this is a just a jet 1 flame. So, you can see the typical you know bluish flame is shown here. So, this is a typically a combustor which is having like optical access.

So, you can look at it. So, this is a typical flame just need jet A 1. Now, if you just simply load boron particles into the liquid fuel how is going to burn you see it is completely different. You see what I told you earlier that the boron particles burning having like bright yellow, white glow and the green emission is due to the formation of $BO2$ or $BO2$ is actually responsible for having the green light here. So, this is typically the flame containing you know boron particles in jet A 1. So, I think with that we close our discussion on this part I have one more video to show you just with the you know solid fuel burned in a rocket firing mode.

So, you can see this is a typical features containing the boron particles burning you see the green hue is shown here. So, I think there is a lot of scope in this area one can actually look at it if they are interested they can look through the literature interested to work on they can find some interesting in a problem statement and how to utilize the boron particles in practical propulsion systems ok. So, with that I think we close our both the modules on metal particle combustion. Now, we will just wait to complete the last module which is the erosive burning in the week 8. Thank you.