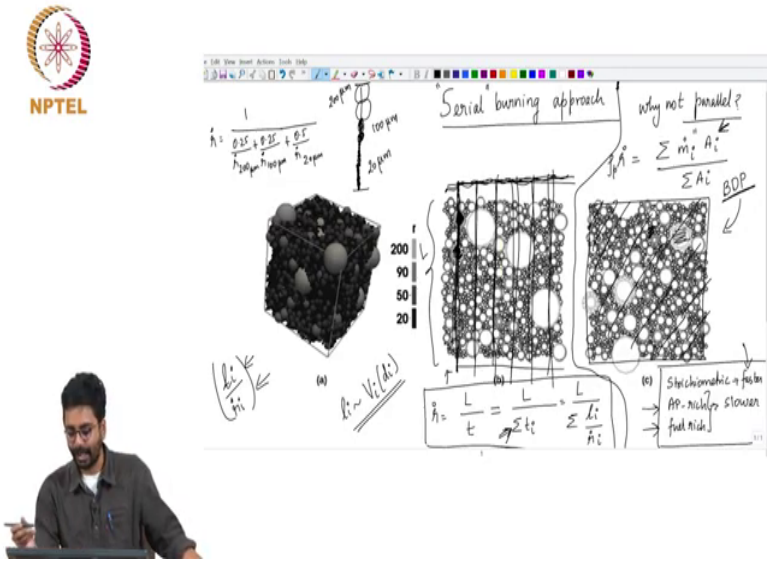
Fundamentals of Combustion for Propulsion
Dr. S Varunkumar
Department of Mechanical Engineering
Indian Institute of Technology, Madras

Lecture - 18
Effects of AI – extended HeQu1D model

Let us continue with the discussion of composite solid propellant modeling. What I want to discuss now is, how to account for the effect of aluminum addition in composite solid propellants.

(Refer Slide Time: 00:30)



Before I go into the details of the model, I will just give a quick recap of the basic modeling approach that has being used; which is the serial burning approach, ok. What I did not explain

in detail when we spoke about this last time is; why serial burning and why not parallel. Let me just explain first, what is what I mean by serial and what is meant by parallel.

In the serial burning approach, what we have being doing is to look at lines passing through propellant like this, ok. And the question that we are asking is that, if we ignite this section of the propellant here at the top ok, how long would it take for it to burn through this length L, ok? The burn rate of the propellant is taken as; in this case the burn rate of the propellant is the length L divided by time, ok. This length as you can see for this line that I am highlighting now, this line along the length of this line there are particles of different sizes.

And we already saw that, because the oxidizer to fuel distribution is different for different particles sizes; larger particles are generally oxidizer rich, smaller particles are fuel rich, ok. Therefore, the burn rate of each particle size is different and therefore, the time it would take for different segments of this line to burn will also be different, ok. So, if you look at this particular line, it intersects some larger particles here; for example, this is a large particle that it intersects, this is another large particle that intersects, between these two larger particles it goes through a segment of smaller particles, ok.

So, the time for burning of this line will be the sum of the time for each of these line segments composed of particles of different sizes, ok. So, this will be the sum of the time. And that time we saw is the fraction of the length occupied by a particle of a particular size, which be called as l i divided by the burn rate of that, ok. So, this is a basic idea of the serial burning approach.

Now, what is done is, of course, if I took a different line, I will get a different burn rate or I may get a different burn rate; it can be higher, it can be lower. So, the propellant burn rate is simply taken to be the burn rate of the statistically averaged path or the statistical particle path; which is nothing, but we take a large number of such lines. And then average the number of particles of a particular size, but occupies a fraction of that line, ok. And as it turns out that is simply proportional to the volume fraction of that particular size. Therefore, l i will

be proportionally; l i is the fraction of an averaged line occupied by a particle of size d i, will be simply proportional to the volume fraction of that particular size d i.

So, if you draw a random line through a cube containing spheres of different sizes; the probability that the line intersects a particle of size d i is proportional to the volume occupied by that particle, ok. So, this is the serial burning approach.

Student: Sir.

Yeah.

Student: That (Refer Slide Time: 4:41) total the income.

Total time for a line for the average line.

Student: Average line.

Yeah, you can do it in see, because the way the averaging is done; if all the lines are have the same length, I can calculate the time for a large number of lines and then average it. Instead what we are doing is, we are calculating the average line and calculating the time for it, it is essentially the same.

Student: Sir.

Yeah.

Student: But the (Refer Slide Time: 5:09) sum of the time.

Sum of the times for individual particles of a, I am sorry it is the sum of the time for different particles.

Student: Ok.

For example 20 percent of the line could be occupied by particles of size 200 microns. Let us say ok, I think just for clarity I will give one example; let us say we have such a average line, it is possible that, let us say one fourth of the line is occupied by particles of size 200 microns, ok. Let us say another one fourth is occupied by particles of size 100 microns, ok. Let us say the rest of the line is occupied by particles of 20 microns, ok. Let us say this is the statistically averaged path for the propellant that we are considering; it has 25 percent of the line occupied by 200 microns, 100 another 25 percent occupied by 100 microns, the rest 50 percent occupied by 20 microns.

So, the burnt rate for this propellant would be the length of the line which is arbitrary taken to be 1; I will you can scale, so that a number of particles are appropriately scaled divided by the sum of the time, ok. The sum of the time and this case will be 0.25 divided by r dot of the 200 micron particle plus 0.25 divided by r dot of the 100 micron particle plus 0.5 time 0.5 divided by r dot of the 20 micron particle that is it, ok. This will be the particle, ok.

So, that is the serial burning approach, ok. Let us look at the other approach which is called the parallel burning approach. In this instead of, we imagine in the serial burning approach case that the question was; that if we ignited the propellant at the top, how long would it take for this length to burn off? Equivalently in the parallel burning approach the question is; if we ignited the propellant on the top here, this entire if we ignited the propellant here on the top ok, what would be the mass flux of the gases that come out form that section, ok?

So, here particles are burning in parallel, here particles are burning one after the other and therefore, it is called serial. Here we are igniting the top of the propellant which I have hatched here; the question is, if we ignited this at various instances of time how much mass flux will come out of this surface, ok? That mass flux divided by the density average density of the propellant will be the burn rate of the propellant.

Here the burnt rate of the propellant or the mass flux coming out of this surface rho p r dot will be the sum of the mass burn rate of particles of different sizes, mass flux multiplied by the area, the surface area of each one of these particles divided by the total area, this will be the mass flux, ok.

So, here also of course, the heterogeneity is accounted; for example, you have different particles; here you have a large particle, here you have some small particles ok, they will burn at different rates. And for example, it is possible that the larger particles which are AP rich will burn at a rate that is closer to that of AP; moderate size particles which are almost stoichiometrically mixed will contribute a lot of mass flux, and very small particles which are fuel rich may contribute less mass flux than these stoichiometric, ok.

One issue with this is that, or one issue which was identified with this approach; this is the approach that BDP module used. The weightage that is given to particle of a certain size is proportional to its surface area, ok. And all the particles are assumed to regress at about the same rates, ok. So, in the vertical direction, we cannot review different mass flux is in this direction, but the surface regression will be limited by the slowest burning case.

So, the weights are assigned using the surface area and therefore, as you can see; if you have see this the stoichiometric parts will burn faster, the AP rich parts will burn slower, so will the fuel rich parts. So, the conclusion from this approach was that, the weights assigned to smaller particles were usually higher, ok. That is a conclusion that came out of this approach that, the weights that are assigned to smaller particles which; smaller particles are stoichiometrically burning particles are usually higher than the weights assigned to this, ok.

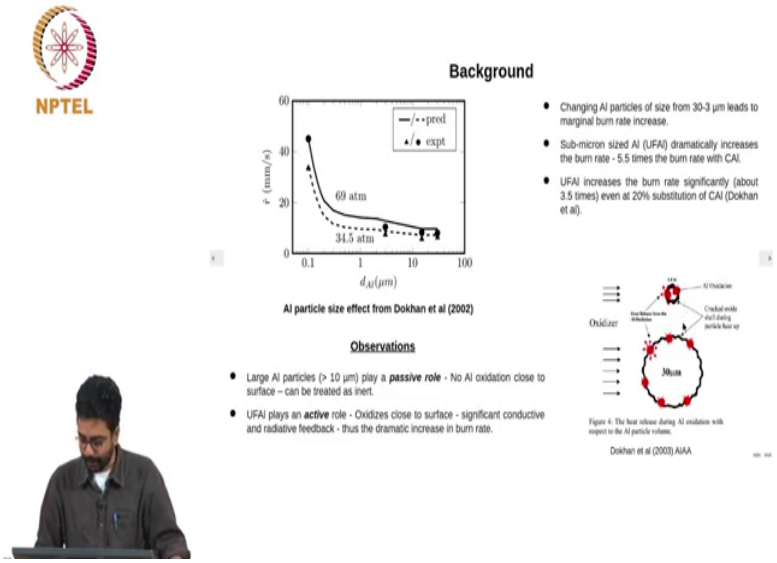
So, what happened was that, the burn rates were typically over predicted and so, where the index. So, especially in cases where the AP distribution was very wide, that you had a bimodal or a trimodal distribution with very large AP sizes, moderate AP sizes and very small AP sizes; the burnt rates were always over predicted, because the weights that were assigned to the faster burning particles were always higher, ok. But in this case if you see, the weights come through the time contribution of the particles; and therefore, if you have, even if you

have a large fraction of faster burning moderate size particles, the time contribution of that will be smaller. Because the time contribution for that segment will be the length fraction divided by the burn rate, ok.

So, larger the burn rate, smaller is the time contribution from that particle. So, this approach seems to capture this behavior accurately, where the weights are correctly assigned. The weights that are assigned through the time estimates seem to be more appropriate for a realistic situation than the weights based on the surface area, ok. So, this is a quick recap, I thought I will give you on; why we are adopting the serial burning approach, what serial burning approach is, and why we are not using the parallel burning approach, ok.

So, with this let us move on to the effect of aluminum ok; the Extension of the Heterogeneous Quasi 1 D Model to include Effects of Aluminum.

(Refer Slide Time: 12:39)



Little bit of background actually, I would like you to look at this plot; what is shown here is the same composition ok, which this if I remember right a 68 percent AP, 18 percent aluminum, and rest is HTPB. The same composition, but what is changed is the aluminum particle size; the aluminum particle size is changed from 30 microns to 15 microns, then to 3 microns and all the way up to 0.1 microns, ok.

So, the 30 micron and 15 micron are typically the sizes that are used in practice, 3 micron can be considered in intermediate size and 0.1 micron belong to the class of ultra-fine or nano aluminum, ok. What is observed here is, at pressures of both 34.5 atmospheres and 69 atmospheres; changing from 30 micron to 15 micron has no effect on the burn rate ok, the burn rate remains roughly the same. 3 microns you can see small increase in the burn rate, and the burn rate increase or the burn rate change with 0.1 micron is dramatic ok; the burn rate goes up by factor of 4 or 5, ok.

So, the conclusion from this is that, changing A l particle size from 30 micron to 3 micron leads to marginal burn rate increase. Sub micron sized aluminum or ultra fine aluminum dramatically increases the burn rate; it is in fact 5.5 times the burn rate with the conventional aluminum. The 30 micron and 15 micron are called conventional aluminum; the 0.1 micron is called the ultra fine aluminum.

So, ultra fine aluminum this is an important point, because it is known that processing a propellant with 18 percent nano aluminum can be quite difficult because of its cost issues. So, what was done in the study by Dokhan et al is? They instead of substituting all the conventional aluminum with ultra fine aluminum; ultra fine aluminum was substituted in smaller quantities and they found that ultra fine aluminum increases the burn rate significantly instead of 5.5 times, about 3.5 times even at 20 percent of substitution of the conventional aluminum. 20 percent of the 18 percent aluminum was substituted with ultra fine aluminum, and they found a burn rate increase of 3.5 times, ok. What does this mean, ok?

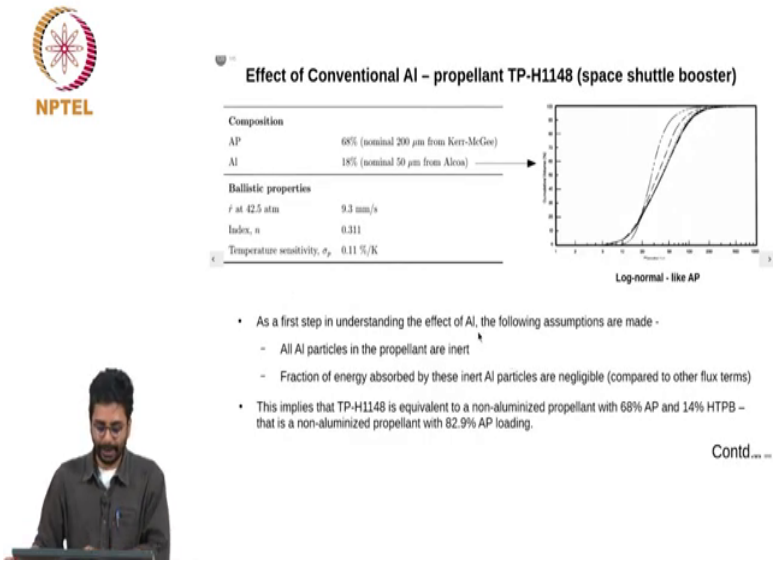
So, large aluminum particles that is greater bigger than 10 micron play a passive role, we do not do anything; close to the surface to affect the heat flux that comes to the surface to have an effect on the burn rate. So, there is no oxidation of aluminum close to the surface; and therefore, large aluminum particles, here large is greater than 10 micron can be treated as inert, as far as the heat flux as far as the effect of those particles on the surface heat flux is concerned. Of course, they go down stream, react, release heat and contribute to specific impulse; but they do not play any active role close to the surface. On the other hand, ultra fine aluminum plays an active role; it oxidizes sufficiently close to the surface increasing significantly the conductive and radiative feedback; and therefore, the dramatic increase in burn rate that is observed, ok.

One mechanism that is suggested for the effectiveness of ultra fine aluminum as opposed to conventional aluminum is; if you look at the burning of a conventional aluminum particle, both these particles have an oxide layer coating on top of it. And for the 30 micron aluminum particle with the metal, the metallic aluminum in the core the surface with aluminum oxide; the metallic aluminum becomes accessible to oxidizing agents only after the outer oxide layer has melted and vaporized away, ok.

On the other hand, if you decrease the particle sizes to nano sizes; we know that the surface to volume ratio increases drastically. And therefore, the volume expansion because of the melting of the aluminum in the core is start to actually crack the crack open the oxide coating, thereby exposing metallic aluminum through oxidizing environment very close to the surface, ok.

So, this is thought to be the mechanism for which can explain the dramatic increase in burn rate.

(Refer Slide Time: 17:11)



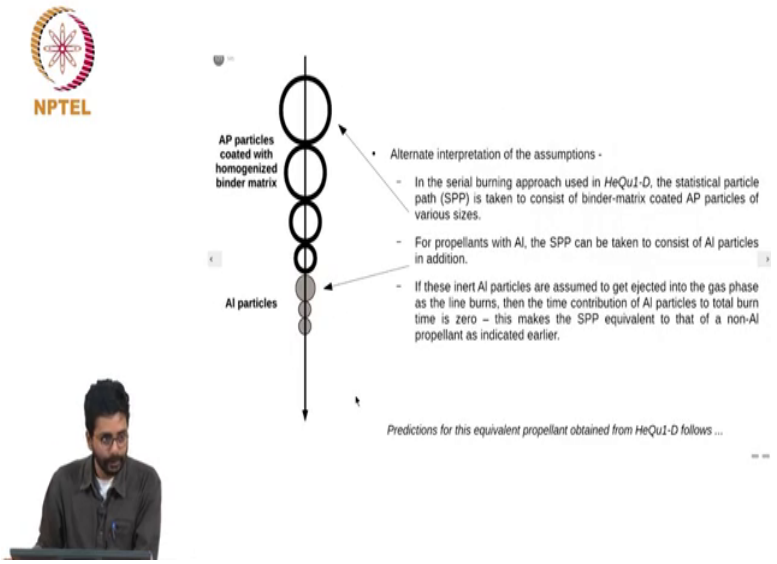
Let us look at the effect of conventional aluminum of the kind that is used in the space boosters, also used in propellant TP H 1148 which is used in the space shuttle booster. The AP is 68 percent, nominal size is 200 microns; aluminum as you see here is quiet large, it is 50 micron 18 percent. Burn rate at 42.5 atmosphere is 9.3 millimeters per second, within index of 0.311 and temperature sensitivity of 0.11 percent per Kelvin, ok.

The aluminum particle size like AP is also log normal, ok. As a first step in understanding the effect of aluminum, the following assumptions are made based on the conclusions we arrived at from the data shown in the previous slide that; all aluminum particles in the propellant are inert as far as conventional aluminum is concerned. This implies that in the space shuttle booster propellant; the propellant itself can be considered equivalent to a non-aluminized

propellant with 68 percent of AP and 14 percent HTPB, which is equivalent to a non aluminized propellant with 82.9 percent aluminum I am sorry 82.9 percent AP loading.

The only extra effect that needs to be accounted for is the energy that is used for heating up and melting of aluminum as it goes through the surface, goes through the condense phase and into the gas phase.

(Refer Slide Time: 18:35)



Student: (Refer Time: 18:35).

Yeah

Student: (Refer Time: 18:37).

Yeah.

Student: (Refer slide Time: 18:40) as you said that if we use the aluminum or burn 10 micron particle it acts as an inert. So, how it increases the first stage, only by multiplying.

It will increase the final temperature of the gases also, it will not have a significant effect on the molecular weight; if it all it will only bring it will increase the molecular weight a little bit, but that is not defined. What the significant effect comes, because of the increase in flame temperature, the final equilibrium temperature.

Student: Ok.

Yeah.

Student: Other question is what is the heating time; if let us say I have a 10 micron particle and 1.1 micron particle, the heating time for both the particles remains the same?

No it will be different.

Student: It will be different, for the small particle it will be small.

Small particles will heat up faster yeah, small particles will heat up faster, V proportional to D square, I mean inversely proportional; smaller the particles faster will be the heat yeah, I am sorry proportional to D square whatever I said first is correct. It just conduction problem; larger the size, more is the heating time.

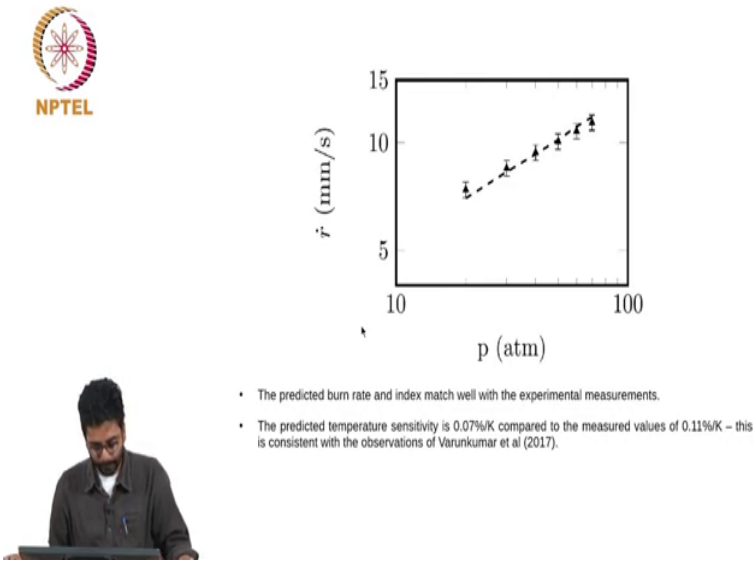
Student: Yeah.

So, the equivalent propellant or an alternate interpretation of assumption is that, in the serial burning approach used in the heterogeneous quasi 1 D model, statistical particle path is taken

to consist of binder matrix coated AP particles of various sizes. For propellants with the aluminum, the statistical particle path can be taken to consist of A l particles in addition as well. If these inert al particles are assumed to get ejected into the gas phase as the line burns, then the time contribution of the aluminum particles to the total burn time is zero. This makes the statistical particle path equivalent to that of a non aluminize propellant as indicated earlier; but remember that the heating up and the melting enthalpy are accounted for as it goes through.

And other strategy would be to simply homogenized the aluminum with the binder and take care of it, that is also something that is tried and it is equivalent to what is described here.

(Refer Slide Time: 20:30)

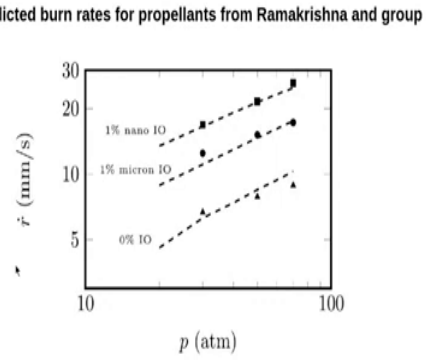


So, predictions for with this assumption are shown here; the predicted burn rate then the index match well with the experimental measurements. Let the predicted temperature

sensitivity is 0.07 percent per Kelvin compared to the measured value 0.11 percent per Kelvin. Anyway let me mention this, in the model, the data that is used for estimating parameters is the data that is available for ultra-pure AP. It is known ultra-pure AP burns at 3.3 millimeters per second at 20 atmospheres in surface temperature close to 870 Kelvin's, and has a temperature sensitivity of 0.16 percent per Kelvin, between 0.16 percent per Kelvin to 0.18 percent per Kelvin. It is known that impurities present in AP increases the temperature sensitivity, ok.

So, the data, the reason why the predicted temperature sensitivity is lower than the observed temperature sensitivity is that; that the AP that is used in the actual propellant will have some impurities in the from potassium or sodium depending on the cube that was used to synthesize ammonium and chloride and therefore, may have had a higher temperature sensitivity. What this means is that; at least in different applications where as low at temperature sensitivity as possible is preferred, the best strategies seems like to use ultra-pure AP to minimize or to keep the temperature sensitivity at a minimum possible value.

(Refer Slide Time: 22:07)



Student: Sir.

Yes sir.

Student: Sir actually the one of the reasons that we test out (Refer Slide Time: 22:13) thing known that one of the cation, metafin, kerosene 5 to 6 Kelvin on a very low burn rate when you compared to a (Refer Slide Time: 22:22)

Ok.

Student: And it is because of the aging some burn rate can modified or do whatever ways that we can avoid us burn aging rate to that to a solid propagate.

That is you know separate field of investigation in itself; if this is what you are saying is based only on one test, I do not want.

Student: Get some 8 to 10 base degree below we have (Refer Slide Time: 22:46)

Yeah.

Student: So, happen that the we found that one of the equation is cannot equal to; then subsequently there is a lot of yearly a gas like process.

All from around.

Student: Around the.

The same time.

Student: Around the same time.

Ok.

Student: And found to be have a same behavior.

Ok.

Student: If I reduce the burn rate.

If all if you have fired some 10 motors from the same you know.

Student: I do not think I do not know the number exactly.

Around the same time and get about the same burn rate, it is likely to be because of aging yeah and the yeah.

Student: (Refer Time: 23:21).

I mean that is about all I can say, yeah.

Student: There is a propellant happen (Refer Slide Time: 23:26) I do not know sir.

Yeah.

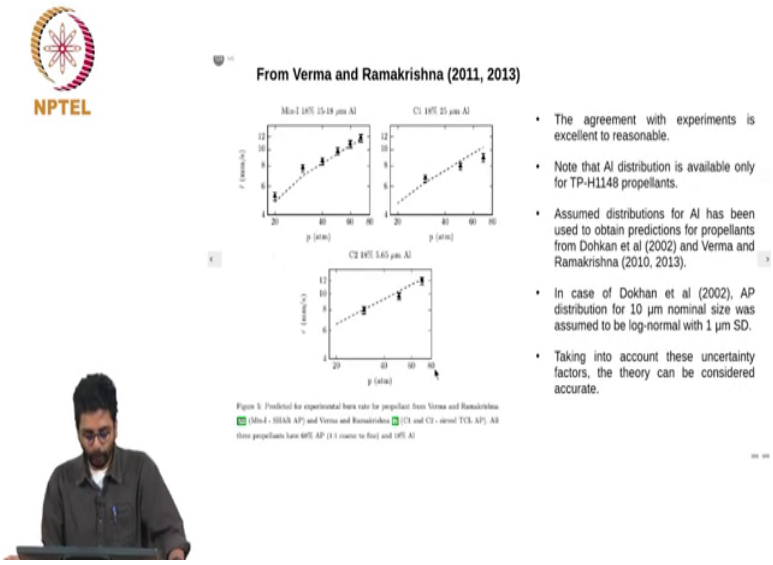
Student: What I mean is there are life related issue, in some of the characters like copper chloride detective decomposed it filled up like and therefore, well effective that thing clinically modify the burn rate (Refer Slide Time: 23:41).

Yeah.

Student: Therefore, it is possible that, so called aging is related to (Refer Slide Time: 23:48).

Yeah and more predictions for propellants, aluminized propellants with no ion oxide, micron sized ion oxide and nano ion oxide; I you just want to say that the productions are good in good agreement with the data and therefore, the model can be used for predicting burn rates with aluminum catalyst and inhibitors of various catalogs, ok.

(Refer Slide Time: 24:18)



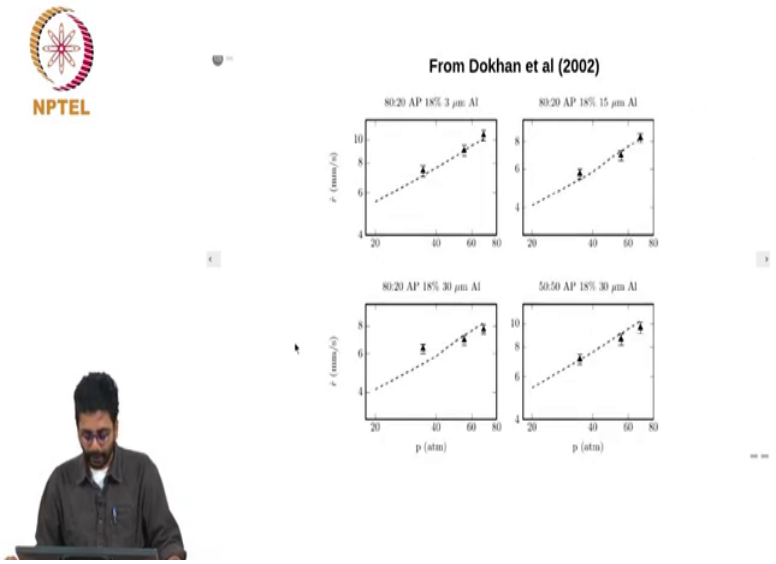
More predictions and comparison with the data; the agreement with the experiments is good excellent to reasonable. Note that A 1 distribution is available only for the space shuttle booster; for other cases it has been assumed that all the aluminum is conventional aluminum, especially in the case of a 15 to 18 micron aluminum and the 25 micron case.

In the case of 5.65 micron aluminum it was assumed that, there is a small fraction of it which is smaller than 1 micron which contributes to some heat flux at the surface to explain the observed burn rates, ok. So, assumed distributions for aluminum has been used to obtain predictions for propellants from Dokhan et al and Verma and Ramakrishna. In case of the propellants from the paper by Dokhan, AP distribution for 10 micron nominal size was assume to be log normal with 1 micron standard deviation.

The point I want to make is that, when you want the predictions to be good enough for you to make decisions on which composition to go forward with; the important information that, the important inputs that are required for the code are detailed AP particles size distribution and also detailed aluminum particle size distribution. Just to make sure that there are just to find out how; what fraction of the particles are smaller than 1 micron and what fraction of the particles are larger than 1 micron. It looks like if the aluminum nominal size is between 15 and 18 micron, then the fraction that is smaller than 1 micron is negligible.

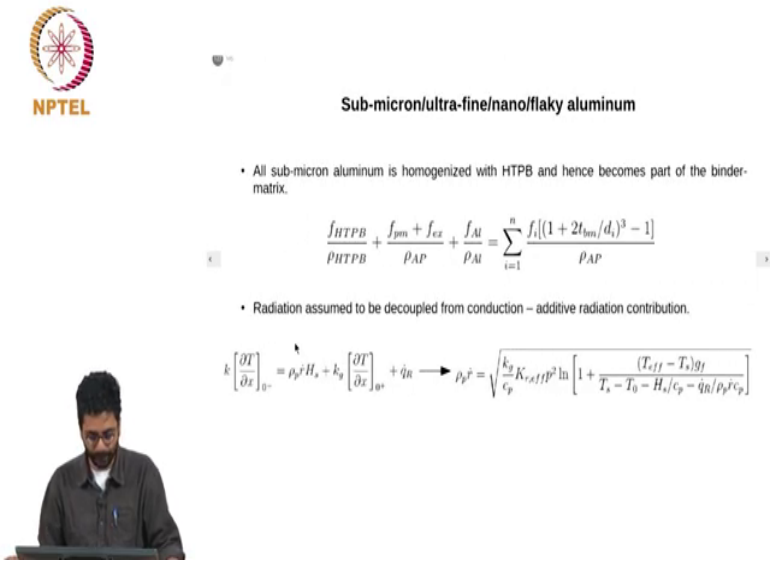
But if it is 5 micron or 3 micron as we saw earlier, it could be significant.

(Refer Slide Time: 25:57)



Again more predictions for conventional aluminum, I do not want to go into the details.

(Refer Slide Time: 26:04)

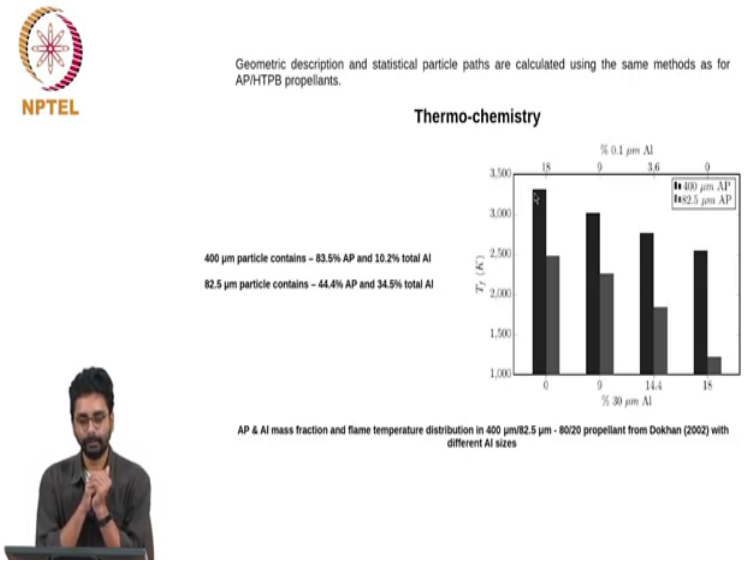


Again more predictions, that is how the effect of conventional aluminum is accounted for in the model essentially saying that there is no effect, ok. But it is not the case when we have sub micron or ultra fine or nano or flaky aluminum, all these aluminum particles can then close enough to the surface contributing to the heat flux.

What is done in this case is that, all submicron aluminum is homogenized with the binder and hence becomes part of the binder matrix. This formula we saw earlier, all that is done is the aluminum is also homogenized with the binder, it is fine enough to be considered homogenized; and it is homogenized with the binder, while estimating the thermo chemical properties and the binder thickness, binder thickness and the oxidize at the fuel ratio and therefore, the thermo chemical properties also.

Radiation assume to be decoupled from conduction; therefore, the contributions from conduction and radiation are taken to be additive. And therefore, the heat flux balance at the surface has an additive radiation term, in addition to the conductive heat flux that comes from the gas phase. So, the burn rate equation will get modified with the radiation term getting in cooperated here.

(Refer Slide Time: 27:21)



Geometric description and statistical particle paths are calculated using the same methods as for AP HTPB propellants, it is essentially the same.

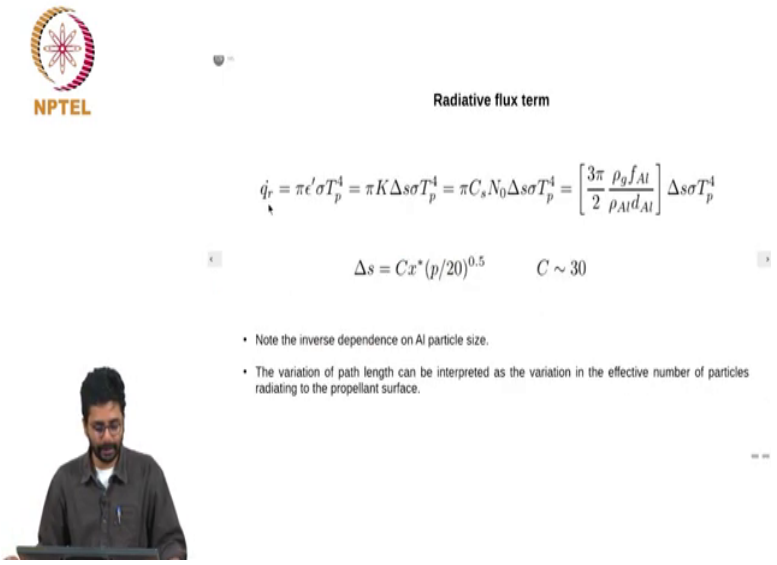
This is an important point; remember that all AP particle sizes are coated with the same thickness of pointer matrix, ok. What it means is that? A 400 micron particle or a coarse

particle will have in proportion to the amount of AP will have less binder and therefore, less aluminum also, compared to a particle let us say 100 microns or 80 microns, ok.

So, this is a particular case, where the propellant is a bimodal propellant with 400 micron AP and 82.5 micron AP. So, the 400 micron AP particle here contains 83.5 percent AP and 10 percent total aluminum; on the other hand 82.5 micron AP will have 44 percent AP and 34.5 percent aluminum. This is the same the same thing can happen for inhibitors and catalogs also; because the inhibitors and catalogs are also added to the binder and therefore, the amount of catalogs in proportion to the amount of AP percent will be much smaller for coarse particles compared to fine particles. And this is the reason why, when you use the same catalogs, but when you change the AP to, when you change the course AP to fine AP ratio in a propellant; the relative increase in burn rate or the incremental increase in burn rate can be different.

So, the AP and aluminum mass fraction and flame temperature distribution in the 400 micron 82.5 micron which is in the fraction of 80 to 20 from Dokhan et al is calculated here. And the important conclusion is this that, the amount of AP and aluminum are very different for holds particles and fine particles.

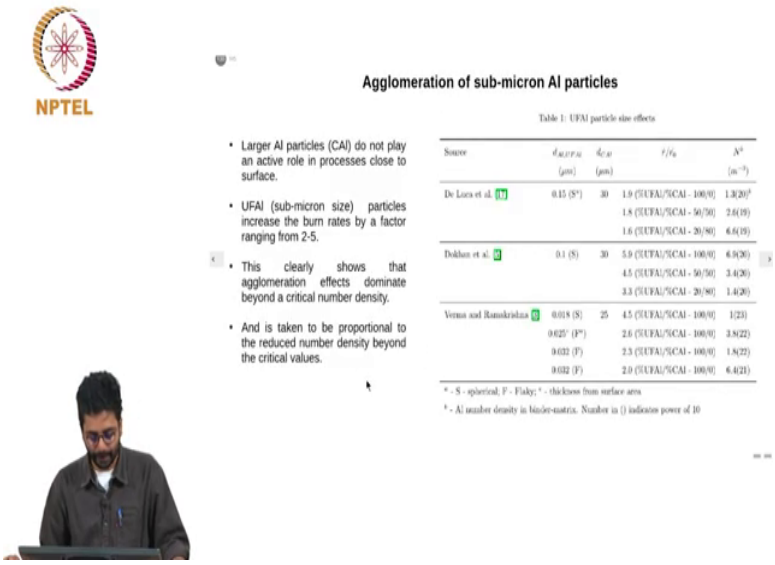
(Refer Slide Time: 29:15)



A simple model is adopted for the radiation; I will not go into the details, I want to just emphasize that the radiative flux depends on the surface area which is radiating, ok. And here the surface area is dependent on the number of particles and if these two effects are accounted for; the final expressions for radiation will show that the radiative flux that comes to the surface is inversely proportional to the size of aluminum, which is consistent with our expectation that smaller the aluminum particles size, larger is the radiation contribution from a aluminum particles, ok.

So, note the inverse dependence on A l particle size; the variation of path length can be interpreted as variation in the effective number of particles radiating into the propellant surface.

(Refer Slide Time: 30:04)



And other effect that needs to be accounted for accurate prediction is, smaller particles tend to a agglomerate; even if you are careful to avoid agglomeration when these particles are getting integrated into the propellant, when they come out of the surface they will agglomerates, these particles will agglomerates, ok. Larger A l particles do not play an active role in processes close to the surface; but ultra fine aluminum particles increase a burn rate factor of at least 2 to as high as 5. This clearly shows that agglomeration effects dominate beyond a critical number density; because if you do not account for a agglomeration, the burn rates that you get must be much higher than a factor of 2 to 5.

And therefore, is taken to be proportional to the reduce number density beyond the critical value. So, the critical value is calculated from the predicted burn rates; we make a prediction without accounting for agglomeration, it matches with the data only when the fraction of the ultra-fine aluminum is below a certain critical value and that number is taken to be the critical

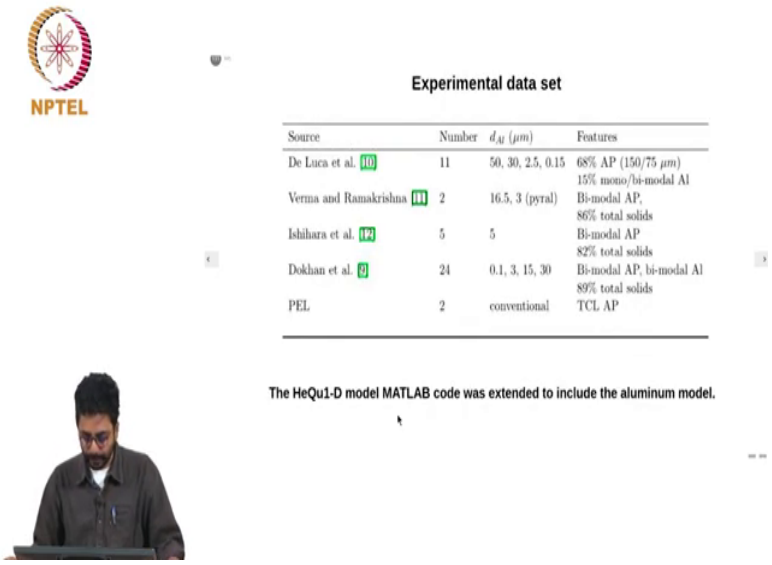
number density for agglomeration, beyond which agglomeration will become important, ok. That is what is shown here; the critical number here is obtained for this; here the critical number is for the case with 20 percent ultra fine aluminum and 80 percent conventional aluminum.

The critical number is 6.6 times 10 raised to 19 particles per meter cube and when the number goes beyond this; this must be 2.6 into 10 raised to 20 not 10 raised to 19. When this number goes beyond this; the agglomeration, the extent of agglomeration is taken to be the ratio of the number densities. Similarly here at 20 percent ultra fine aluminum, the number density is 1.4 times 10 raised to 20; it increases to 7 times 10 raised to 20 when you go to all ultra-fine aluminum, ok.

So, the conclusion is that; one it is difficult to process with 100 percent ultra fine aluminum or 18 percent which is the absolute number, the other thing is that the enhancement in the burn rate that you will get may not be very significant. Because by adding more ultra fine aluminum, you are increasing the number density and more particles will agglomerate; and the relative increase in burn rate at some point will saturate, ok. So, may be your better off with some substitution of conventional aluminum by ultra-fine aluminum, instead of replacing all the conventional aluminum with ultra fine aluminum.

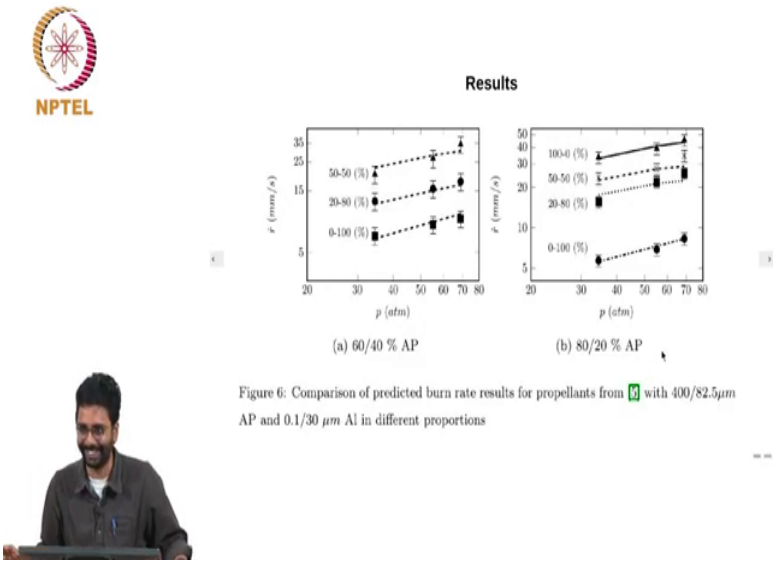
That is the conclusion from the effects of agglomeration and the relative number densities.

(Refer Slide Time: 32:42)



This is the experimental data set that is used for validating the approach shown here; the MATLAB code which, the MATLAB code implementing the software is implementing the theory is extended to include the aluminum model.

(Refer Slide Time: 32:56)



Results I just want to say that, the predictions are in good comparison with data; but the critical number density is in input that is required for this model. And therefore, the assessment of the enhancement of the burn rate because of addition of ultra fine aluminum requires systematic substitution at different levels, so that the critical number density can also be evaluated, ok.

(Refer Slide Time: 33:24)

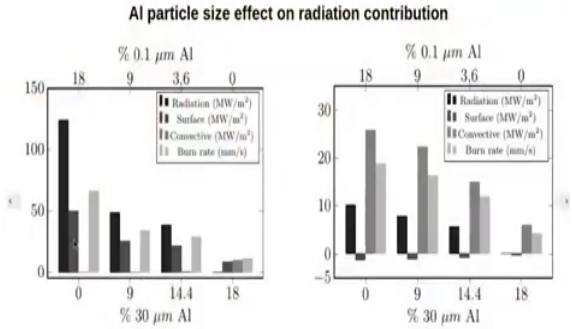


Figure 4: Radiative, surface and convective fluxes and corresponding burn rates of particles constituting the propellants shown in Fig. 3b calculated at 69 atm

The question is the hypothesis was the radiation that contributes to the increase in the burn rate. This is just to show that it is indeed radiation that contributes to the observed increase in burn rate. In fact, the numbers are pretty high. What is shown here on the left is the radiation the different, the magnitude of different terms in the surface heat balance equation. For a case that has 18 percent, 30 percent 18 percent 30 micron aluminum and 0 percent nano aluminum all the way up to no 30 micro aluminum or no conventional aluminum and all ultra fine aluminum, ok.

So, this is the conventional propellant, where the radiation is negligible and all the other terms balance each other and the magnitude of the flux is about 10 to 15 mega Watts per meter square, ok. And as we substitute as the conventional aluminum is replaced by ultra-fine aluminum; the radiation flux goes up significantly in fact, it goes up so much that, the conductive flux becomes negligible in comparison to that. And the surface heat balance is

simply between the radiative flux; the surface heat release and the flux that goes into the condense phase, ok.

As the fraction of nano aluminum is increased to 18 percent all nano aluminum. Look at the flux that is coming to the surface; it is 125 mega Watts per meter square ok, that is 10 times as high as what you get in a conventional aluminum conventional propellant with conventional aluminum, ok. And the heating rates that will be experience by the propellant surface will be 100, 1000 Kelvins per second or much more than that; might be 100, 1000 Kelvins per second even here, it might be an order of magnitude higher in this case, ok.

The same thing is shown; this is for the 400 micron particle, this is for the 82.5 micron particle. The it is the effects are not dramatic as dramatic as it is here; because this particle size is fuel rich and therefore, the overall temperatures are not as high as it is here, ok.

(Refer Slide Time: 35:47)

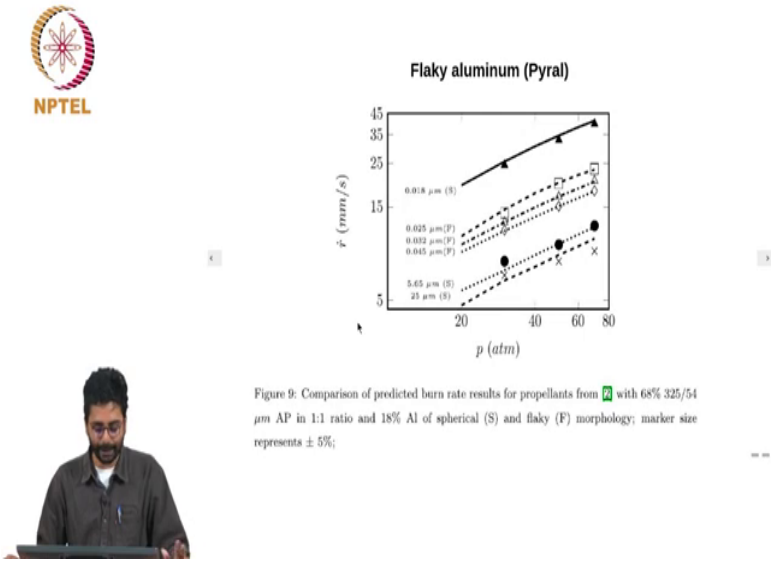
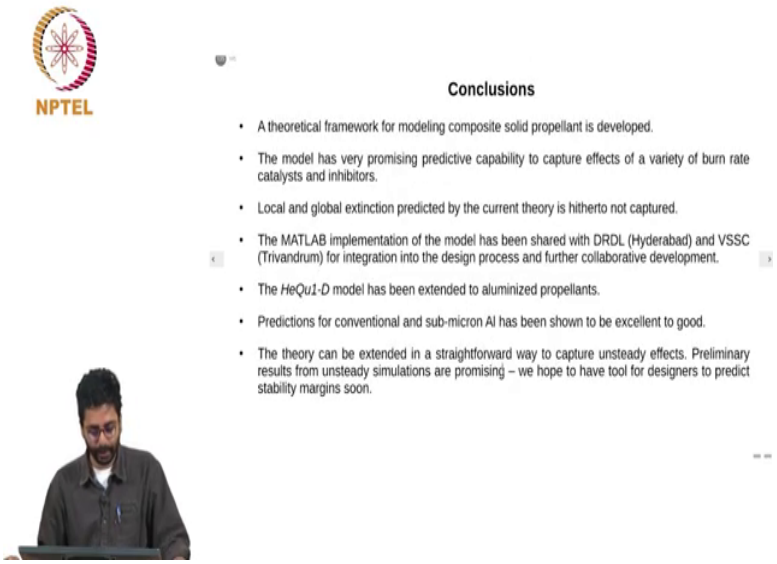


Figure 9: Comparison of predicted burn rate results for propellants from [2] with 68% 325/54 μm AP in 1:1 ratio and 18% Al of spherical (S) and flaky (F) morphology; marker size represents ± 5%;

Again flaky aluminum can also be accounted for, the effects of flaky aluminum can also be accounted for in this model. I just want to mention that the predictions are in good comparison with the data; for spherical denoted by S and also flaky aluminum.

(Refer Slide Time: 36:03)

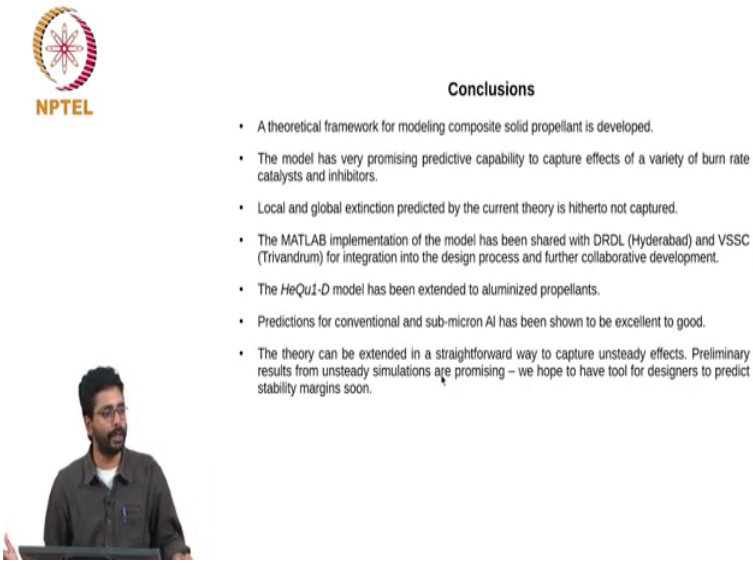


So, summary of this part is that, the theoretical model for predicting the burn rates is extended account for the effect of aluminum. The MATLAB implementation of the model is now available with DRDL He model and VSSC for integration to the design process and further collaborative development. Predictions for conventional and submicron aluminum has been shown to be excellent to good. The theory can be extended in a straight forward way to capture unsteady effects also.

(Refer Slide Time: 36:37)

And this is what I want to discuss in the next section; but before we go there I if there are any questions, I will happy to answer in this part.

(Refer Slide Time: 36:47)



Student: (Refer Time: 36:51).

Yeah.

Student: (Refer Slide Time: 36:52) what is the typical percentage you know if aluminum particles for the agglomeration; will it only depends on the percentage or it also depends on surface temperature.

Well, it depends on the percentage, it depends on the size, depends on the percentage, it depend on the number density and it may also depend on the temperature; but the fraction and the size effects is to be the most important. Because close to the surface temperature are roughly the same about 1000, 1200 Kelvin's.

So, the number the fraction and the size effect comes because; for a given fraction, the same effect as at home using your spray. So, if you have a 1 mm droplet, you break it down into the same volume into 10 micron droplets; the number of particles that are there are much higher.

Similarly here if you have the same mass with 30 micron aluminum and 0.1 micron aluminum; the number of particles with 0.1 micron aluminum is much higher than what it is with 30 micron aluminum. And that means that, you have a large number of very small particles that are closed to each other; smaller the particles they are also other effects, surface dominated effects that come into picture.

Student: (Refer Slide Time: 38:09) radiations you know it is without considering any agglomeration there.

It is with agglomeration, the agglomeration effects is what is shown here.

Student: The variation effects was shown for all ultra-fine particles.

All ultra fine particles accounting for agglomeration.

Student: Ok, so after accounting for agglomeration.

The effective particle size that is taken to radiate to the surface is calculated after correcting for agglomeration.

Student: (Refer Time: 38:37)

Yeah.

Student: Then the burn rate should increase know.

That is increasing.

Student: But what you have said in the first slide is; if I am changing the from 18 percent to from 18 percent conventional aluminum to completely ultra-fine aluminum the increase is not that effected then the.

That is not what I said.

Student: (Refer Time: 38:59).

No that is not what I said; if you go from conventional aluminum to all ultra-fine aluminum.

Student: Ultra fine aluminum.

The increase in burn rate is 5 times.

Student: 5 times.

Dramatic.

Student: Yeah but.

Dramatic is a word that is appropriate for describing it. What I said was; if there was no agglomeration, you would have gotten a much higher increase in burn rate.

Student: Ok.

It is only 5 times here; if there was no agglomeration, you would have probably got 10 times increase in burn rate. And therefore, simply increasing the amount of ultra fine aluminum

because of agglomeration, will not give you know proportional increase in burn rate; because the effective particle size that is radiating will increase as you increase the fraction.

Student: I thought that it is not a accounting, this with a graph shown this.

This is experimental data by the way.

Student: That the experimental data that model work it is not clear, not including the agglomeration; but you are including know.

Agglomeration is included, that is what is in this slide; the effective size is taken to be the actual size multiplied by the actual number density divided by the critical number density. Therefore, at the critical point you will have the same size radiating, at higher fractions will be a larger AP particle a larger aluminum particles that is radiate to the surface; that is the effect of agglomeration or rather that is how the effect of agglomeration is accounted for in this model.

Student: Sir.

Yes sir.

Student: With this particle size that we have been emphasizing on submit (Refer Slide Time: 40:23).

Yeah.

Student: How will you evaluate the particle size?

Student: What we are using sir?

Sorry.

Student: What the technique you see using to evaluating the particle size?

I.

Student: Slightly use laser.

I think I all I want to say is some light scattering techniques.

Student: Laser diffraction.

Yeah.

Student: We use.

Some.

Student: Laser diffraction.

Laser diffraction. So, one of the light

Student: Malvern.

Scattering techniques.

Student: Malvern.

Yeah, any of the light scattering techniques probably requires a better resolution than the commonly available equipment; but that is what will be use yeah.

Student: The second thing that, we have log normal (Refer Slide Time: 40:58) lot of distributions are there, rather have we any bias towards the measuring problem.

Well, it looks like when you start see there are these particles are synthesis by certain methodology, and there are large number of independent random processes that are happening during the syntheses as well as grinding. And therefore, what no analysis of particle sizes of different kinds of materials; ammonium perchlorate, aluminum, droplet size distributions from space all seem to be very close to a log normal distribution. So, you know.

Student: Before random there is no bias towards any.

The logarithm of a diameter is normally distributed; if you ask me why is the diameter itself is not normally distributed?

Student: We do not.

I do not know.

Student: Yes.

But you know I would assume that, there is some role of central limit theorem that is making these distributions normal in logarithm of that parameter. If there is a universality to it, I guess there is universality.

Student: Yes.

To it, just that I do not know what it is.

Student: But there may be some physics playing role.

I am sure.

Student: We are not.

Yes.

Student: Really explored it.

Yeah, right the answer might also be there, just that I do not know yeah.

Student: So.

Yeah.

Student: Sir this slide which you talked about thermo chemistry.

Student: Base on the.

Yeah.

Student: Yeah sir, it here like this thing like 83 percent AP and 10 percent aluminum and the when you go for a lower sized particle sized like a less closer AP.

Yeah.

Student: We have the percentage of aluminum increases. So, thing has been like has been used as a analogy from the like from the experiments we had or there is some other basis for this thing.

This is simply based on the way the binder matrix is distributed in this model.

Student: No how like this thing that, for low; if you have a bimodal distribution for a lower for a less closer AP.

Student: Will be having the binder matrix will be more rich in aluminum as compare to a (Refer Slide Time: 43:05).

The binder matrix is not more rich in aluminum, the binder matrix.

Student: The.

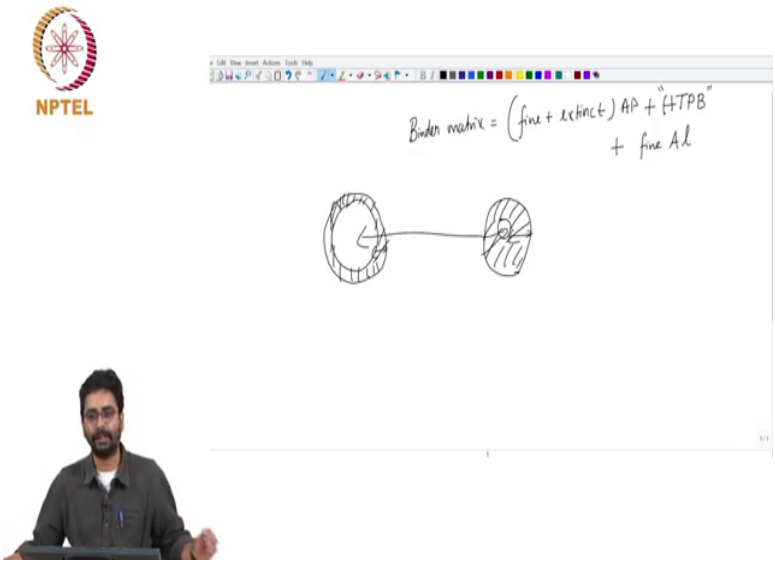
Composition is uniform.

Student: The like whatever surrounds that.

No.

Student: The AP matrix.

(Refer Slide Time: 43:22)



The binder matrix composition is uniform. See the binder matrix has, the binder matrix is composed of fine plus the extinct AP. This we saw earlier plus all the HTPB, including all the agents that are used for curing and cross linking everything, ok. This is I will put HTPB within quotes, because I am not referring to the monomers or something like this, it is entire fuel binder plus fine aluminum. This is the binder matrix and therefore, the composition of the binder matrix is fixed, it is the same reason.

The why Coaser particles have smaller amounts of binder and the smaller particles have larger amounts of binder is because we coat them with the same thickness, coat them with the same thickness. I want you to imagine that this thickness is same as this same as this thickness, ok. Just that this now will have lot more binder than AP.

You may ask what is the basis for this; there is some experimental evidence that is suggest that this is this approximation is, ok. But what I would say is that, assuming this gives us a certain oxidizer to fuel ratio; which says that the distribution is very wide, that there are particles which are almost pure AP, there are particles half of it is binder.

This seems to be that, the predictions are in good match with data; seems to indicate that this is closer to reality when it comes to the oxidizer to fuel distribution within the hydrogenous propellant, ok. Of course, we could have, we know we can try many things; I can assume that thickness is proportional to the diameter; the thickness is proportional to the surface area all that is possible. But this simple approximation or a simple assumption seems to be in agreement with reality, data from reality any other questions?