Fundamentals of Combustion for Propulsion
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Lecture – 13
Erosive burning

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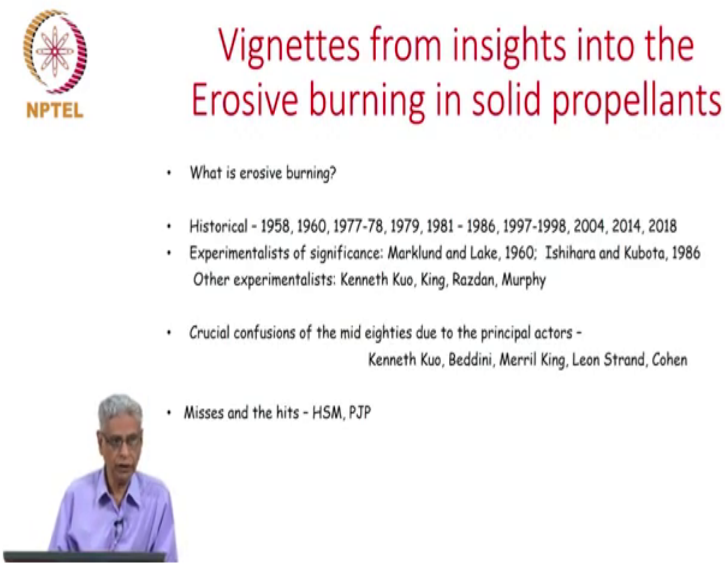

I am setting it in a slightly different tone; the subject is a bit old in sense, we did work on this about 20 years ago, 20 little more like 20 years ago and many issues related to this have got resolved. So, what I am taking is vignettes from insights into the erosive burning in solid propellants. So, I will ask question what is it erosive burning, some historical content about it from 1958 onwards till even recently.

There have been many experimentalists working in this area of significance; there is somebody called Marklund and Lake in 60s, Ishihara and Kubota in 1986, Kenneth Kuo, King, Razdan, Murphy there are many people who are well known in this subject. There were the crucial confusions in the mid-eighties due to principal actors; Kenneth Kuo, somebody called Beddini, Merril King, Leon Strand, Cohen. And so, we have misses some what we did and some hits. For those who are doing research quite bit of education how life proceeds in academia.

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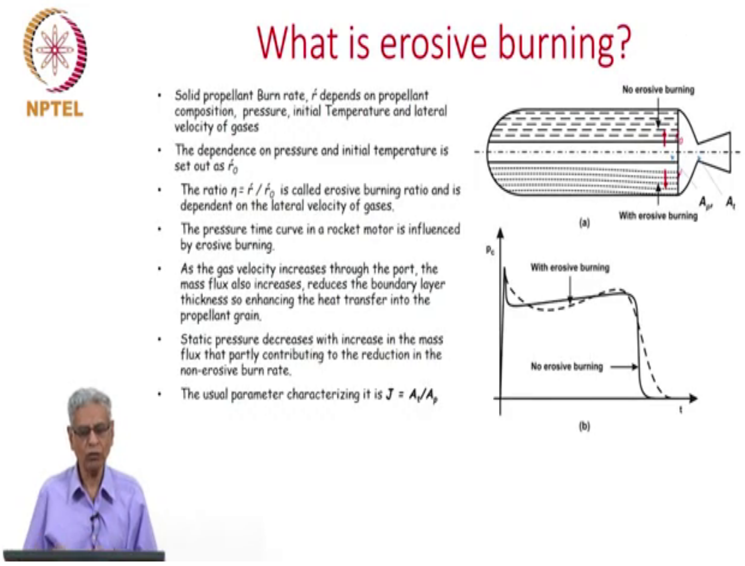

So, let us ask what is erosive burning? You have seen that the solid propellant is casting to the motor and when ignition takes place it starts burning in the radial direction here. Now when there is no erosive burning, all the layers move at the same speed the burning rate. But when there is erosive burning, the fact that the flowing gases in the port and if this velocities are very high; then the Reynolds number is quite high. This produces essentially a boundary layer next to the surface and that causes extra heat transfer compared to the places at the heading, this leads to larger burn rate.

But we tamper that with the fact that, as velocities increase, this is stagnation pressure loss of a flow through the port, this reduces in fact a static pressure. There is some balance between the reduction in static pressure, which influences the burn rate and the fact that the heat transfer which is larger because of the boundary layer and this relative effect will control the erosive burning. Typically, this occurs at high solid loadings which I will come to in a moment.

And the way do you see the pressure time curve from a rocket motor; you will see that, when there is it when there is only no erosive burning, you will find a sharp pressure peak because of ignition, then it may become nearly straight. But as with erosive burning, you will find a long tail right in the early part; this related to burning area variations at the early times, ok. The solid propellant burn rate r dot depends on the propellant composition, pressure, initial temperature and lateral velocity of gases.

The dependence on pressure and initial temperature is set out as r dot naught. The ratio which you take of r dot of such a situation with r dot naught is called the erosive burning ratio and it is dependent on the lateral velocity of the gases. The pressure time curve in a rocket motor is influenced by erosive burning as I have shown here. As the gas velocity increases through the port, the mass flux also increases, reduces the boundary layer thickness so enhancing the heat transfer into the propellant grain, a point alluded to a moment ago.

I also said static pressure decreases with increase in the mass flux that partly contributing to the reduction in the non-erosive burn rate. Normally the parameter which characterizes this from early times is called J, did a throat area to port area; this is the port area and this the throat area. And the throat you know that you have acoustic speed and the port area is very large, you know the velocity is small; but as you keep having a larger value of J, which means that the port area is much larger than the throat area, the velocities here will be small. Let us see what happens next.

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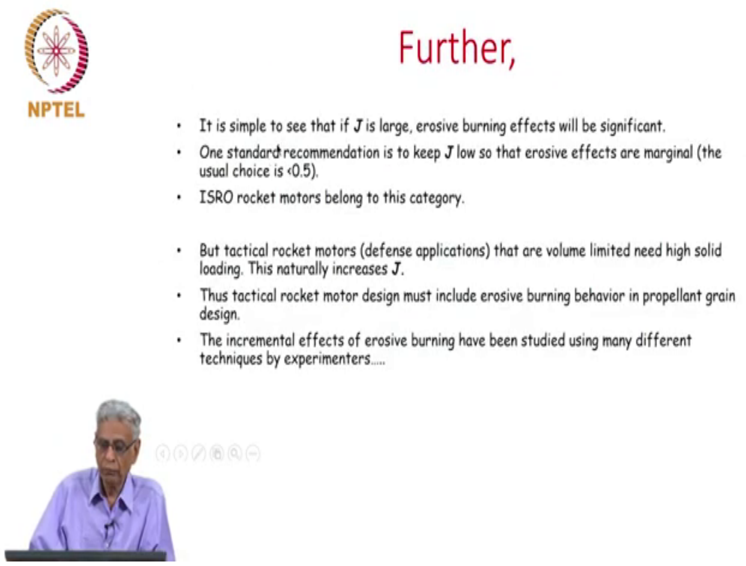

So, when well the way I have expressed here J is A t by A p, sometimes it is also written as A p by A t; but if J is closer to 1, then it turns out that J is large means closer to 1, erosive burning effects will be very significant. The standard recommended value for J it should be low less than 0.5; that means, the cross section at the port is twice as large that the throat and the velocities will therefore, be smaller.

ISRO rocket geometry belongs to this category so generally they are not bothered about erosive burning. Am I right, am I right that you are not bothered about erosive burning; but practical rocket motors meant for defense applications, in fact, they are all volume limited largely and they need high solid loading. This naturally increases J tending towards 1. Thus the tactical rocket motor design must include erosive burning behavior in the propellant grain design. The incremental effects of erosive burning have been studied by many different techniques by experimenters Merril King this study like this.

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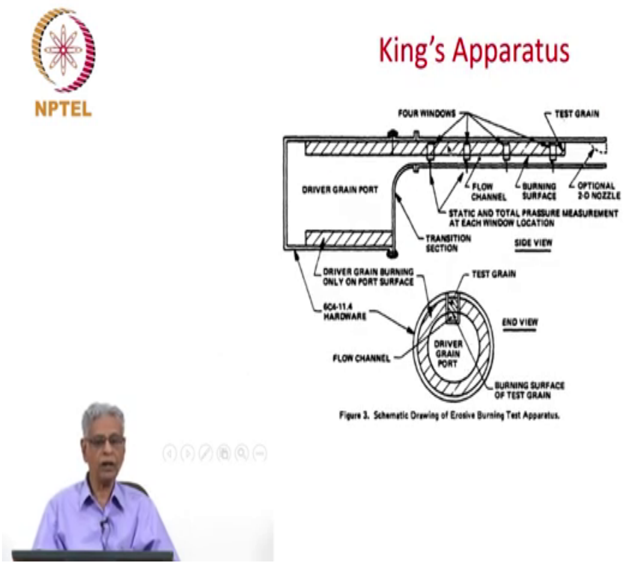

You have propellant which is burnt it has produces gases which go past a test grain here and you can measure the pressures here, you can measure the you can also do videography whatever and that way you know how the propellant is burning in the test grain.

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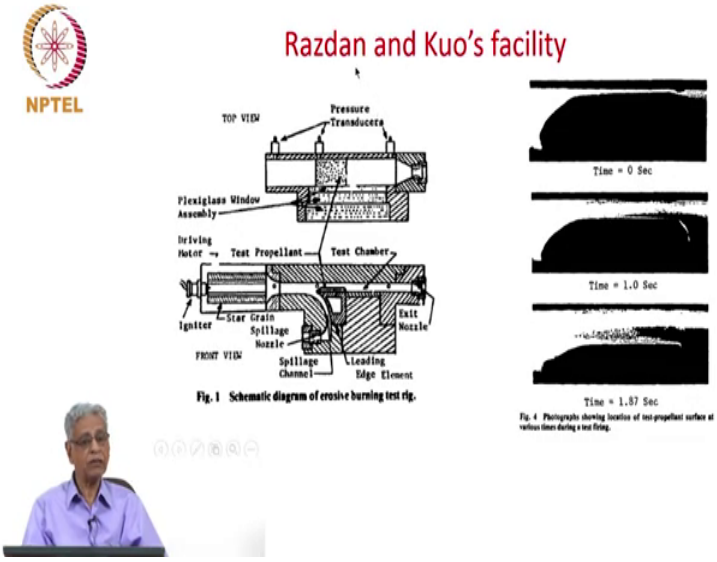

There is another facility alluded to Razdan and Kuo in which you have a propellant which you have a motor where produces hot gases and the test grain is here and your pressure transducers here to measure the pressure variation; because of the excess mass flow that comes from the erosive burning. Use this information, you also do photographic work and you know how things vary with time in terms of propellant grain shape.

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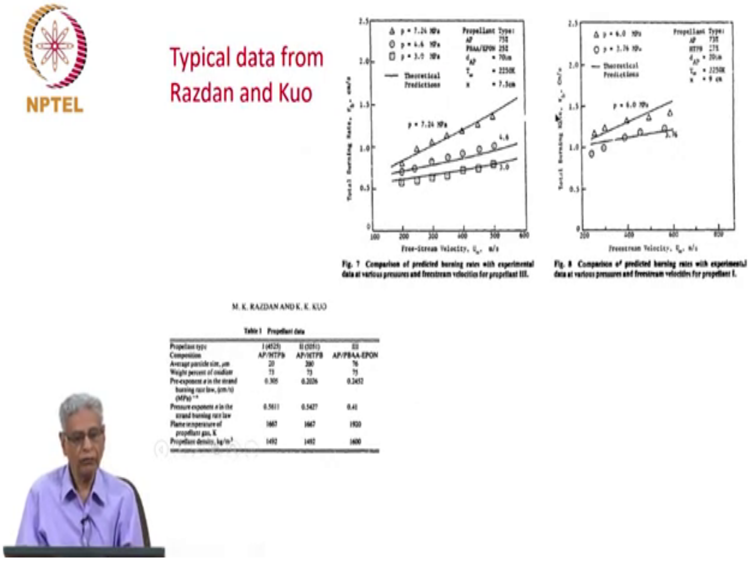

Well if you take typical data from Razdan and Kuo, you have got the total burn rate here which is the actually what you observe the total burn rate and you have free stream velocity; you will discover that as a function of pressure you will plot this data about how the total burn rate varies as a function of free stream speed. Then you offer total burn rate as a function of free stream speed from different class of propellants and they claim that with the theoretical predictions they have got results which are consistent.

You will discover that there are various propellants here with particle sizes some 20 micron, 200 micron and something else here; the combinations are AP HTPB as well AP PBAA in epoxy. And the pressure index which is coming from non-erosive part is also different in these cases, ok.

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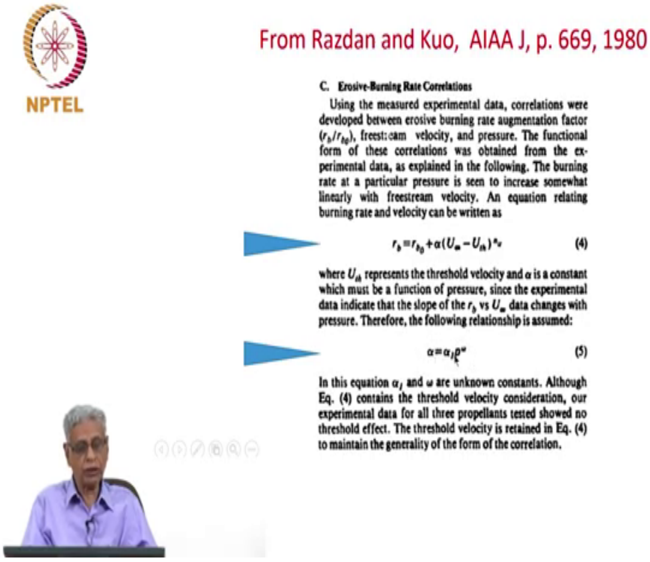

And if you look the summary of the results from Razdan and Kuo, their erosive burning correlations have such feature; the total burn rate is the burn rate because of non-erosive effect plus something to do with velocity correction. And there is a threshold velocity below which erosive burning will not act and then with actual velocity you will find a correlation shown here. And some of the other correlations use a coefficient which is a function of pressure, in which these are all constants.

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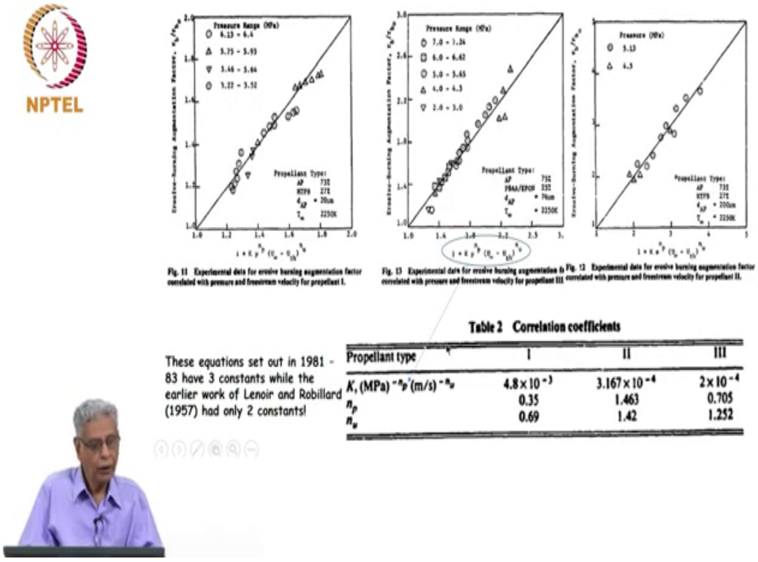

You will see the data presented in correlations like this, which are complex functions of a pressure and velocity. And you have plot where your data is put together and the claim is that this correlation is good. So, these equations are set out in the 1987, in 1881-83 period they have 3 constants; whereas in fact the earlier work of Lenoir and Robillard had only 2 constants. So, we hope that increase of understanding reduces the constant not increase them and you discover that is what is happening in these studies.

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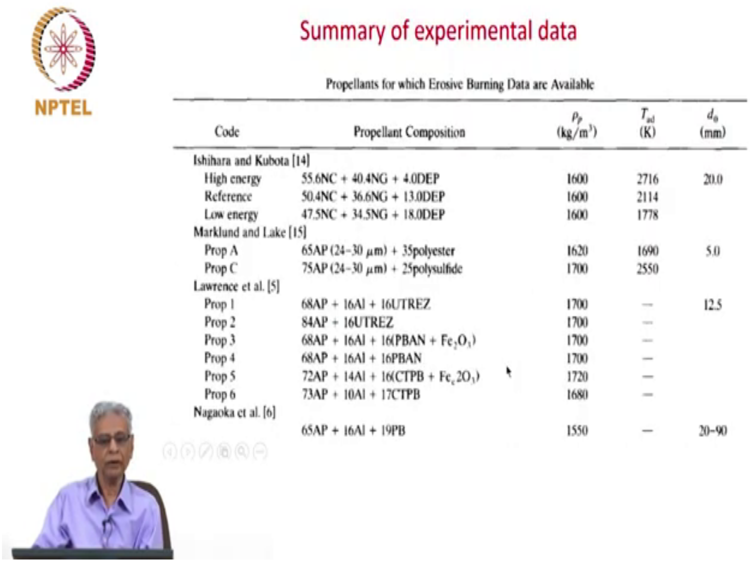

Propellants for which Erosive Burning Data are Available

Code	Propellant Composition	ρ_p (kg/m³)	T_{ad} (K)	d_0 (mm)
Ishihara and Kubota [14]				
High energy	55.6NC + 40.4NG + 4.0DEP	1600	2716	20.0
Reference	50.4NC + 36.6NG + 13.0DEP	1600	2114	
Low energy	47.5NC + 34.5NG + 18.0DEP	1600	1778	
Marklund and Lake [15]				
Prop A	65AP (24–30 μm) + 35polyester	1620	1690	5.0
Prop C	75AP (24–30 μm) + 25polysulfide	1700	2550	
Lawrence et al. [5]				
Prop 1	68AP + 16Al + 16UTREZ	1700	—	12.5
Prop 2	84AP + 16UTREZ	1700	—	
Prop 3	68AP + 16Al + 16(PBAN + Fe_2O_3)	1700	—	
Prop 4	68AP + 16Al + 16PBAN	1700	—	
Prop 5	72AP + 14Al + 16(CTPB + Fe_c2O_3)	1720	—	
Prop 6	73AP + 10Al + 17CTPB	1680	—	
Nagaoka et al. [6]				
	65AP + 16Al + 19PB	1550	—	20–90

But put together the data from various sources you know from Japanese work, early work of Marklund and Lake, several other people from US and Japan and so on.

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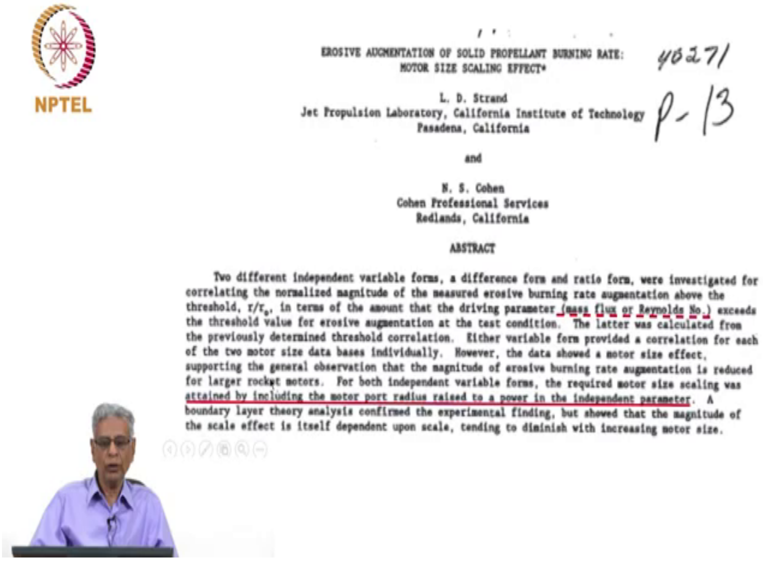

EROSIVE AUGMENTATION OF SOLID PROPELLANT BURNING RATE:
MOTOR SIZE SCALING EFFECT*

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ABSTRACT

Two different independent variable forms, a difference form and ratio form, were investigated for correlating the normalized magnitude of the measured erosive burning rate augmentation above the threshold, r/r_o, in terms of the amount that the driving parameter (mass flux or Reynolds No.) exceeds the threshold value for erosive augmentation at the test condition. The latter was calculated from the previously determined threshold correlation. Either variable form provided a correlation for each of the two motor size data bases individually. However, the data showed a motor size effect, supporting the general observation that the magnitude of erosive burning rate augmentation is reduced for larger rocket motors. For both independent variable forms, the required motor size scaling was attained by including the motor port radius raised to a power in the independent parameter. A boundary layer theory analysis confirmed the experimental finding, but showed that the magnitude of the scale effect is itself dependent upon scale, tending to diminish with increasing motor size.

Now, I will make a point here to say that, the recent work of Strand and Cohen more recent work shall we say. We said that the, for both independent forms, the required motor size scaling was attained by including motor port radius raised to the power as an independent parameter. You know it is a free playground for people to increase the number of constants, increase the number of parameters, ok.

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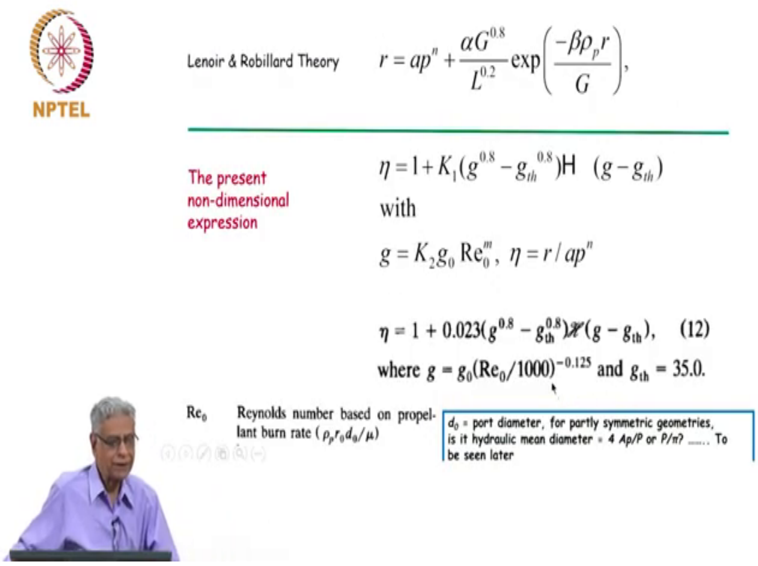

Now, I just show you the results from the Lenoir and Robillard theory, which was there for a long time its accepted also by large number of people. This is the non-erosive burn rate expression; this is the result because of erosive burning. There are two constants here; alpha and beta, ok. Now, we spend some time looking at this confusion that we should condense it into dimensionless quantities.

In any case part of the dimensionless quantity can be obtained by dividing the burn rate by a p c n a p n and also a p n comes here and you will get, you should get a non-dimensional expression from this. Now, this was done by looking at the data from various sources and I will show you what they are.

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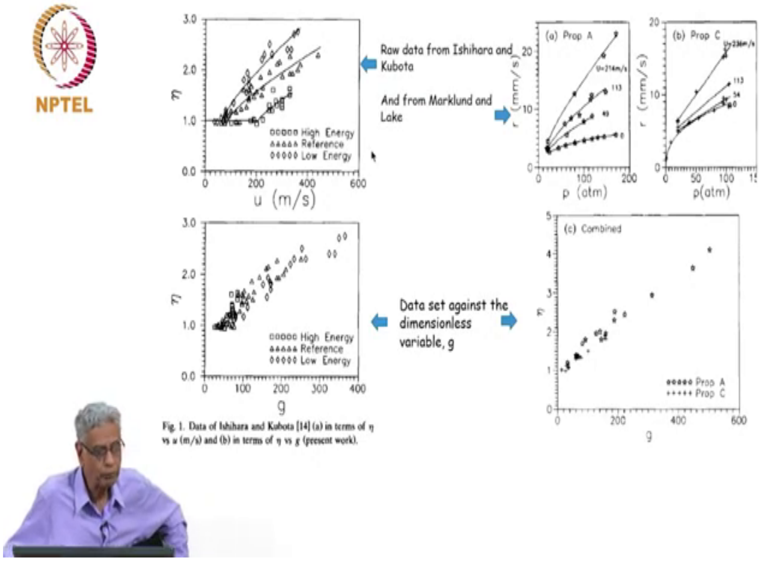

If you look at the data of the erosive burning rate to the normal burning rate with velocity you will see that, the you get these three curves; this is the raw data from Kubota, also raw data from Marklund and Lake. Now, if you see that you plot that with respect to a parameter g, which I have identified here; and you may ask me how is it that we got it, I will come to that question a little later.

Assume that we have somehow got this quantity called g, which is the ratio of the mass flux of the hot gases to the mass flux coming from the surface which is g naught and a correction due to Reynolds number and you put that together. You see Reynolds number is put together in terms of rho p r dot naught d by mu and d naught in the port diameter and there are other questions here which we will come back to later.

And if you take this parameter, the quantity that we are seeking is eta and the parameter where on which it depends is g; you make that plot here, all this data collapses into a single curve. g is what you have obtained for from each of the experimental points, you can compute the value of g, put that here and you will get this particular set of data cluster.

And you look at the data from Marklund and Lake, all this data set just by choosing the coordinate axis properly that the parameter properly; you will find this data goes into this set of points which are essentially clustered around a single curve. Now, this is the one which gave a hint that the behavior of erosive burning is not as complex as was seen in these expressions which you see here; it is very complex and probably not so complex in the expression here be Lenoir and Robillard. And in this case, you do not have any independence of a constant; all the data condenses into a single curve as you see here, ok.

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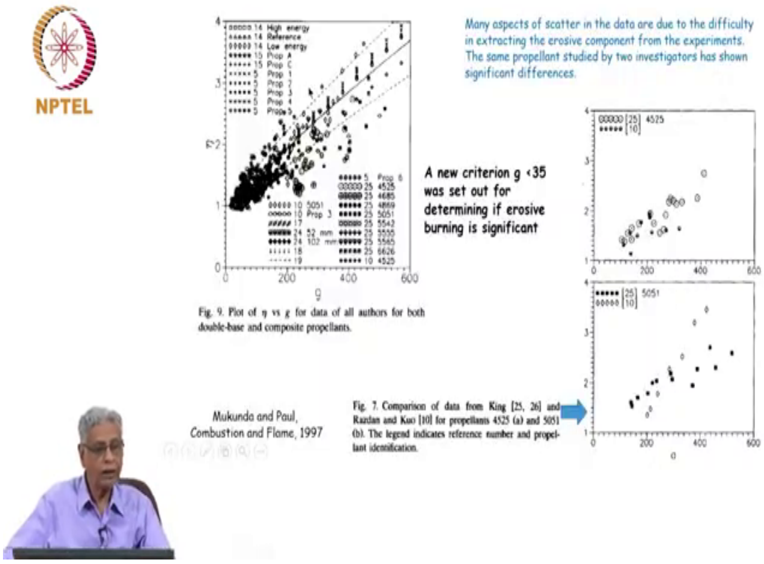

So, therefore, all the data which we had got here from all the experimenters are put together into this plot. Now, you will see that there is also scatter here from various experiments; we have to argue that some of the scatter is not related to genuineness of the expression, but is dependent on the accuracy of the experiments. We showed that the same propellant fortunately there was data available with the same propellant being examined by both Kenneth Kuo as well as King.

And the data show that there is a sufficient scattering of the data plotted in the same format. The same format, the same the data of both the people is put together; you see for two of these propellants, there are sufficient scatter. Now this scatter has not come about from anything else, excepting the accuracy of the experiments.

So, you cannot, you know you will be subjected to a following position; you have a theory and you have experimental data, you are scattering that. Now, this with the you will you trust the theory or will allow the scatter to be relevant, this is the question which you will come up with. And all this data will you see that the trend which is very clear cut; but the data, some of the data here are subject to a larger amount of error. So, we take a position that will accept this particular expression, we tend to ignore some of these scatter which is present here, ok.

So, we suggested this law, which you see here and indicated to DRDL that they should test out this using, test out this expression in the designs of their rocket motors. They did that for a period of time, it became integrated into the design procedure at DRDL for about 8, 9 years. And they came up you know with some questions and we thought that everything was wonderful we had kept quiet, but is not really so, they came up with some questions.

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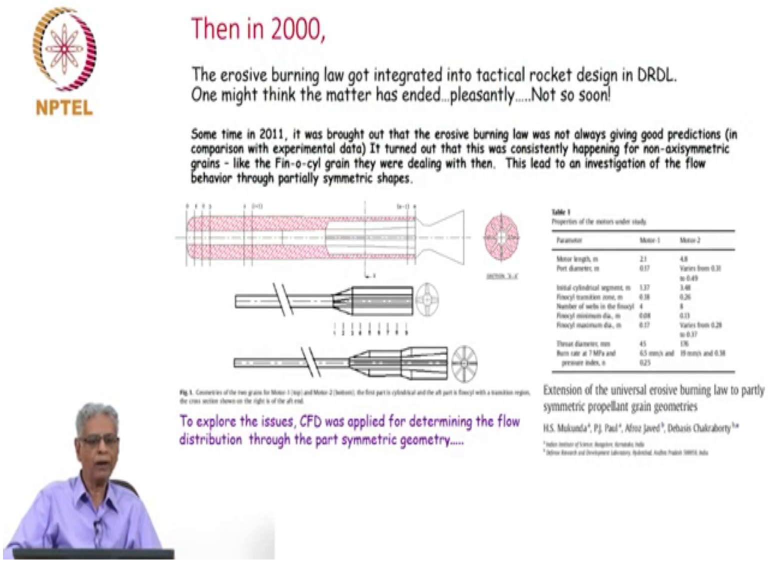

In 2011 they brought out that erosive burning law was not always getting good giving good predictions in comparison with the experimental data of actual rocket motors. It turned out this was consistently happening for non-axisymmetric grains, like Finocyl which was talked about by Dr. Varun; that they were dealing with them at that time. This led to an investigation of flow behavior through partially symmetric grades.

Now, the propellant grain is additionally cylindrical, as you see here is cylindrical until this point of time and here there are fins that is why it is called fin on cylinder geometry. And you will see that there is several motors of this class, you can see the cross section here, this is the port, which is from this point to this point, but cylindrical here. There is some technical data for two motors; 2.1 motor and meter long and 4.8 meter long and some port diameters of various dimensions and so on are put together.

Now, to us it was not immediately clear, why the law was not working. So, we thought it may be related to the fact that the asymmetry or non-axisymmetric position leads to the flow behavior which can be very intensely coupled to the erosive burning. So, work was done by doing CFD simulations.

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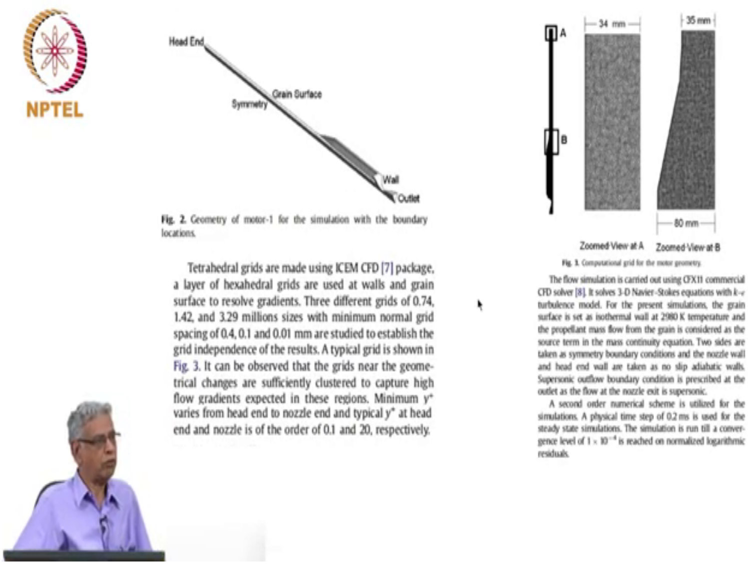

Literally go for some DRDL, who spent time on this subject with his team and he made calculations of the flow behavior in the port. Now there is lots of details we provided here about what kinds of gridding that was used to make calculations, which more 04.5 million and 3.3 million grid points and grid sizes and all that, to account for the capturing as good flow behavior as possible was put together here.

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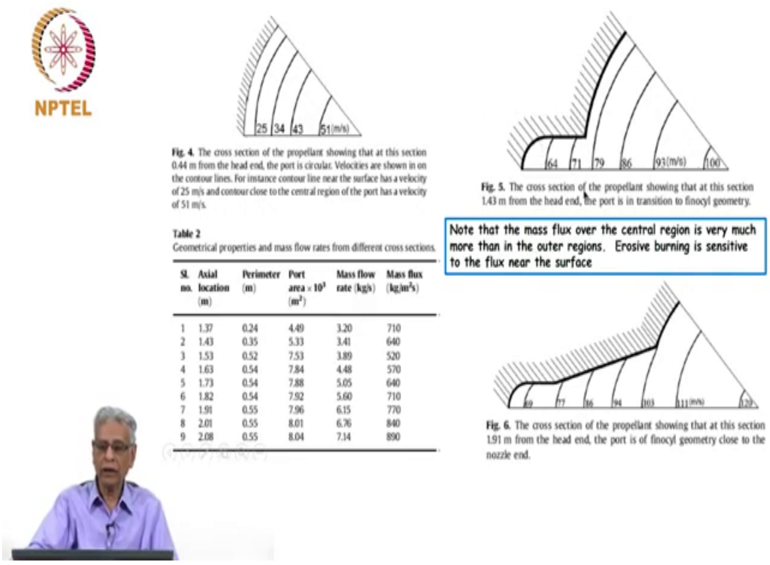

And the result of that you will see that, in the flow inside this portion is such that; the flow velocities are very large and near the outer parts, the flow velocities are very small. And you will see that in over here, the velocities are go close to 100 meters per second inside the port that center of the their; but near the wall, it comes down quite significantly. Now having known this, we are putting a lot of effort to calculate the gradients, the heat flux coming into the surface and so on; like a complex you know calculation procedure was put together.

We said that, we must simplify it in some manner and we uncovered that a very simple way of dealing with it is to treat that, you know that the actual, we actually use a characteristic dimension d.

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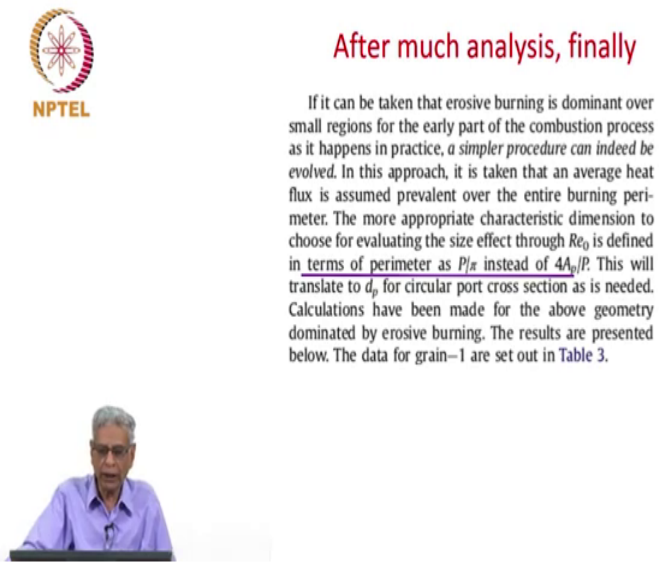

What do you do normally when you have complex geometries; you will see average diameter which is you know 4 times area by the perimeter. That is the classical way of doing the obtaining in engineering; if you have flow through of pipes, the flow through pipes and so on, you will use 4 A p by P. We found that that is not the correct thing to do; we should use something like P by pi that is a perimeter by pi, which is essentially diameter in the case of a circle. In the case of a complex shape, you will get slightly larger dimension.

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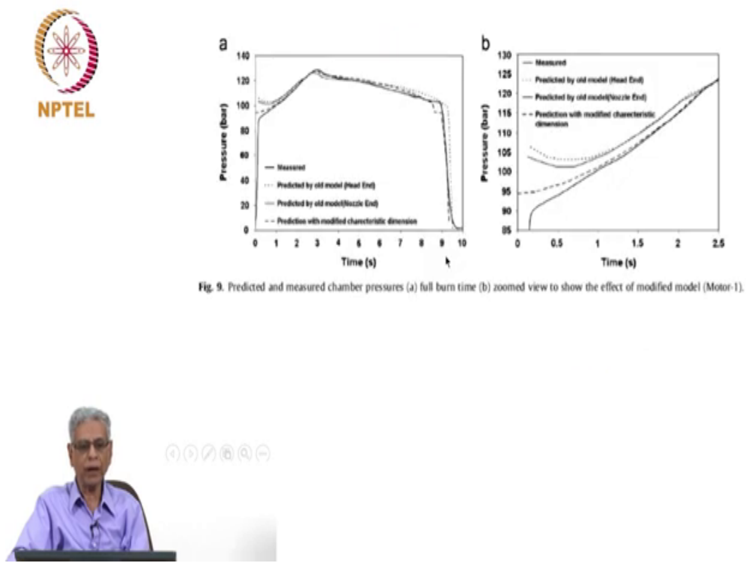

Now that is the kind of approach we took and when this was done; we found from the calculations, you have the measured data here, we have predicted by the old model which showed actually very high much higher pressures than what you have got here. But when the new model was put together, we found that the pressure was closer to what we what was observed experimentally, which is also shown here in an enhanced manner.

You see this is the old model, this is the modified corrected dimension. And so, you will find that the correlations between the prediction and the burn time and the time the behavior is well captured.

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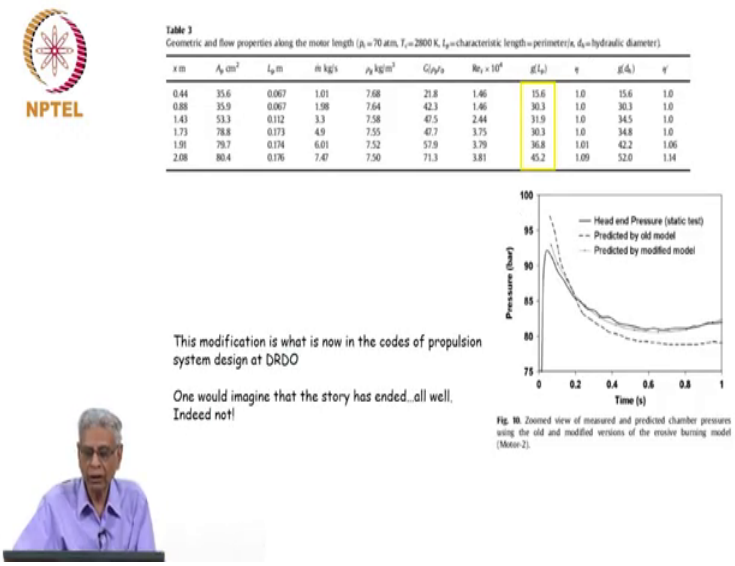

When this was put together, they have been using this code now for all this grains; both at DRDL and there are some other lab called ASL, they used this. And we thought that we have done the job adequately.

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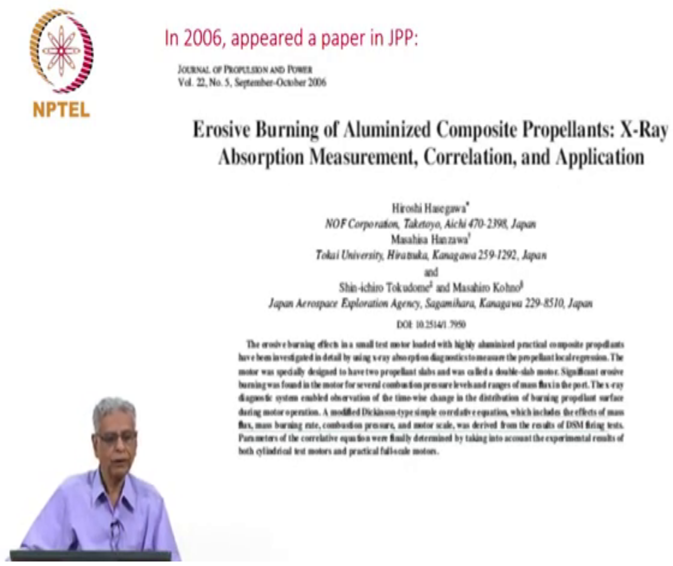

But it turned out that there is a paper that appear in 2006 in Journal of Propulsion and Power, you will see that here. And there addressed the question of Erosive Burning of Aluminized Composite propellants using X-rays and measurement, correlation and application. What they did essentially was, they also referred to our paper and use this.

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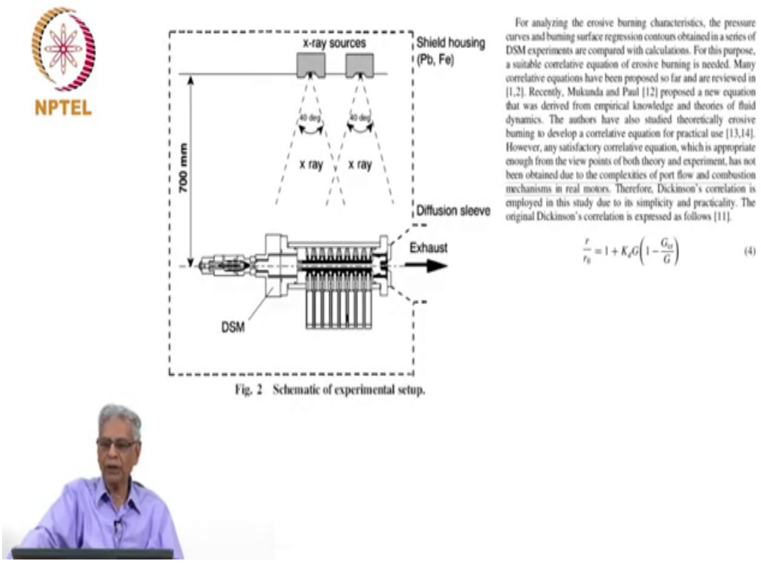

And they found something very strange, I will come back to this experimental stuff later.

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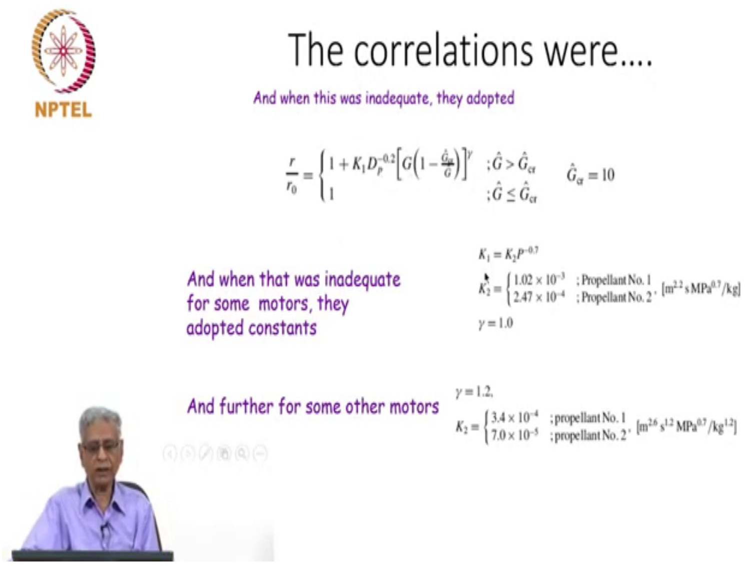

They made calculations using our expression and found that it was not doing well. And so, they said that we must write a more appropriate erosive burning law; they wrote a law like this, which contains explicitly the diameter of the port as well as the mass flux to the port and various other aspects of constants which were changing with every other propellant.

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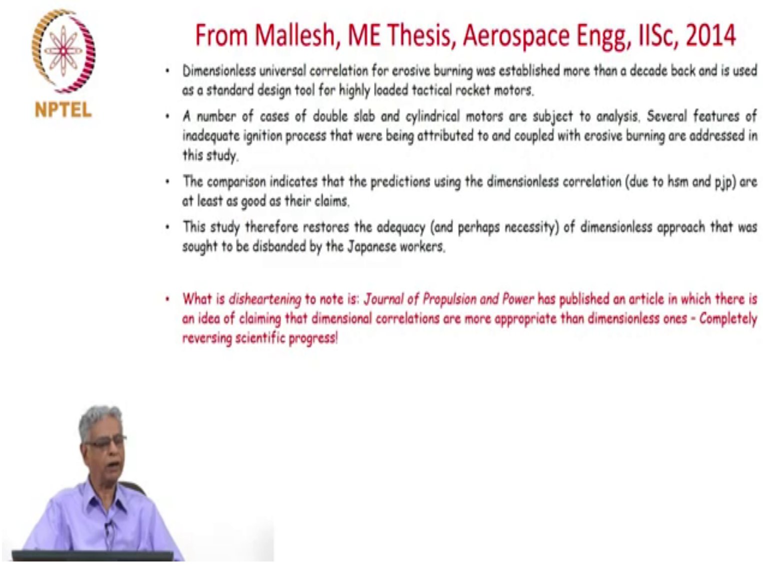

It appeared to us that this is somewhat ridiculous. So, there is somebody who came and joined to do a M E, a piece of M E research. And when the analysis was done, we tracked down the reasons why there are errors in the; not errors, differences in the results of the Japanese workers is because of the fact that they used in the they used in the geometry the thickness which was used in the port of very small.

And the measurements would contain error, small changes would lead to lot of error. And we made analysis of that and found that particular choice of geometry for getting erosive burning was not exactly the most appropriate one; but it requires a lot of analysis to come to that conclusion. But that did not matter really; the fact of the matter is that they said there is a dimensionless correlation; they said that is not good enough. It could be not good enough; but you should seek a dimensionless correlation of a different kind that is what science tells you.

However, they said no, we will use a dimensional correlation and show that it works. And it saw the curious that the journal does not need to worry about the fact that you know, you are discarding dimensionless correlation and using a dimensional correlation. And so, that is what I call as very disheartening to note that, the review process has found that; a dimensional correlation is more appropriate than a dimensionless correlation. And it is quite contrary to whatever engineering science tells you about the way real life is. So, this is the point I wanted to make to you.

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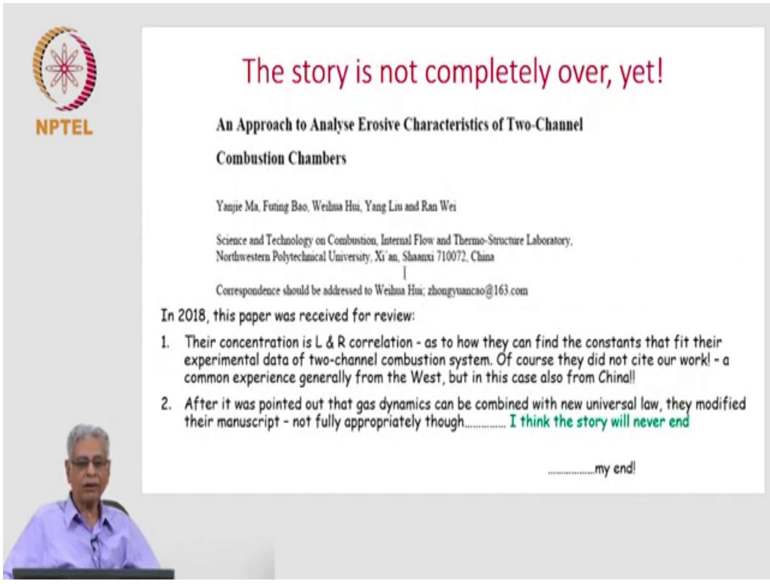

But I thought the story was over, but it is not quite over yet; I think people keep working on this field every other place sometime or the other and it came to me for a review. And again they had ignored the work which we had done; but they also had formed some other correlation to fit and so on. But we told them that you review, look at this correlation and see if it makes sense; if it does not make sense, then make arguments again in favor of whatever you are doing.

Well they did some corrections and showed that it this you this does a better job than what they thought it would do and we thought that with the end of the story. But I actually think that, you will find somebody else coming later point of time and saying; look I have another calculation procedure which I will do, I will ignore the earlier ones, I will do something else.

I think the story will never end, we should be always alert in trying to progress science by establishing what we are doing, is what it looks to me at the moment. So, this is what I wanted to tell you about the story on erosive burning.