

Fundamentals of Combustion for Propulsion
Prof. H S Mukunda
Department of Mechanical Engineering
Indian Institute of Technology, Madras

Lecture – 13
Erosive burning

(Refer Slide Time: 00:17)



Vignettes from insights into the Erosive burning in solid propellants

- What is erosive burning?
- Historical - 1958, 1960, 1977-78, 1979, 1981 - 1986, 1997-1998, 2004, 2014, 2018
- Experimentalists of significance: Marklund and Lake, 1960; Ishihara and Kubota, 1986
Other experimentalists: Kenneth Kuo, King, Razdan, Murphy
- Crucial confusions of the mid eighties due to the principal actors -
Kenneth Kuo, Beddini, Merrill King, Leon Strand, Cohen
- Misses and the hits - HSM, PJP




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 So, I will ask question what is it erosive burning, some historical content about it from 1958 onwards till even recently.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,

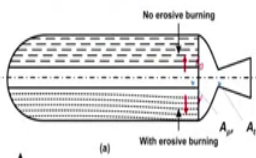
King, Razdan, Murphy there are many people who are well known in this subject. There were the crucial confusions in the mid-eighties due to principal actors; Kenneth Kuo, somebody called Beddini, Merrill King, Leon Strand, Cohen. And so, we have misses some what we did and some hits. For those who are doing research quite bit of education how life proceeds in academia.

(Refer Slide Time: 01:27)

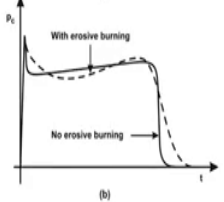


What is erosive burning?

- Solid propellant Burn rate, \dot{r} depends on propellant composition, pressure, initial Temperature and lateral velocity of gases
- The dependence on pressure and initial temperature is set out as \dot{r}_0
- The ratio $\eta = \dot{r} / \dot{r}_0$ is called erosive burning ratio and is dependent on the lateral velocity of gases.
- The pressure time curve in a rocket motor is influenced by erosive burning.
- 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.
- Static pressure decreases with increase in the mass flux that partly contributing to the reduction in the non-erosive burn rate.
- The usual parameter characterizing it is $J = A_p/A_b$



(a)



(b)

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 temper 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 \dot{r} depends on the propellant composition, pressure, initial temperature and lateral velocity of gases.

The dependence on pressure and initial temperature is set out as \dot{r}_0 . The ratio which you take of \dot{r} of such a situation with \dot{r}_0 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.

(Refer Slide Time: 04:43)



Further,

- It is simple to see that if J is large, erosive burning effects will be significant.
- One standard recommendation is to keep J low so that erosive effects are marginal (the usual choice is <0.5).
- ISRO rocket motors belong to this category.
- But tactical rocket motors (defense applications) that are volume limited need high solid loading. This naturally increases J .
- Thus tactical rocket motor design must include erosive burning behavior in propellant grain design.
- The incremental effects of erosive burning have been studied using many different techniques by experimenters.....

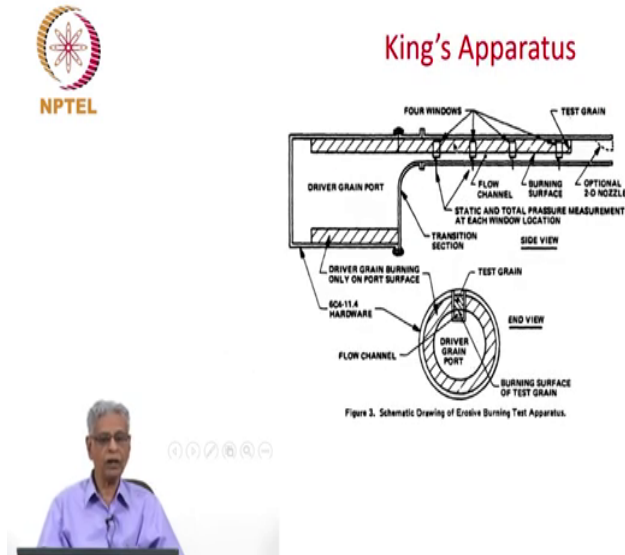


So, when we see the way I have expressed here J is A_t by A_p , sometimes it is also written as A_p by A_t ; but if J is closer to 1, then it turns out that J is large means closer to 1, erosive burning effects will be very significant. The standard recommended value for J it should be low less than 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 Merrill King this study like this.

(Refer Slide Time: 05:55)



You have propellant which is burnt it 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.

(Refer Slide Time: 06:17)



Razdan and Kuo's facility

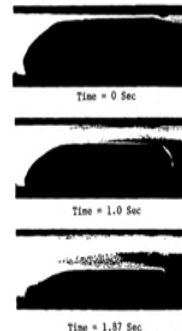
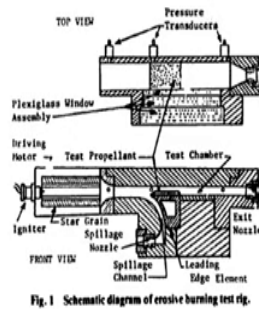


Fig. 4 Photographs showing location of test-propellant surface at various times during a test firing.



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.

(Refer Slide Time: 06:43)



Typical data from Razdan and Kuo

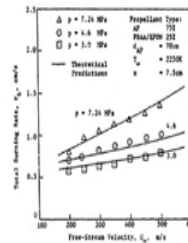


Fig. 7 Comparison of predicted burning rates with experimental data at various pressures and freestream velocities for propellant 10.

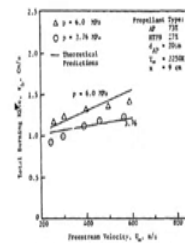


Fig. 8 Comparison of predicted burning rates with experimental data at various pressures and freestream velocities for propellant 1.

M. K. RAZDAN AND K. K. KUO

Propellant type	10G25	0.0503	83
Composition	AP/HTPB	AP/HTPB	AP/PBAA/EPDM
Average particle size, μm	20	200	70
Weight percent of oxidizer	75	75	75
Pressure exponent n in the steady burning rate law, $\text{cm/s} \cdot \text{atm}^{-n}$	0.385	0.209	0.3457
Pressure exponent n in the steady burning rate law	0.501	0.3427	0.41
Plane exposure of propellant, cm^2	1867	1867	1933
Propellant density, kg/m^3	1492	1492	1490



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.

(Refer Slide Time: 07:47)



From Razdan and Kuo, AIAA J, p. 669, 1980

C. Erosive-Burning Rate Correlations

Using the measured experimental data, correlations were developed between erosive burning rate augmentation factor (r_s/r_b), freestream velocity, and pressure. The functional form of these correlations was obtained from the experimental data, as explained in the following. The burning rate at a particular pressure is seen to increase somewhat linearly with freestream velocity. An equation relating burning rate and velocity can be written as

$$r_s = r_b + \alpha (U_\infty - U_\Delta)^{\alpha_1} \quad (4)$$

where U_Δ represents the threshold velocity and α is a constant which must be a function of pressure, since the experimental data indicate that the slope of the r_s vs U_∞ data changes with pressure. Therefore, the following relationship is assumed:

$$\alpha = \alpha_1 p^w \quad (5)$$

In this equation α_1 and w are unknown constants. Although Eq. (4) contains the threshold velocity consideration, our experimental data for all three propellants tested showed no threshold effect. The threshold velocity is retained in Eq. (4) to maintain the generality of the form of the correlation.



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.

(Refer Slide Time: 08:23)

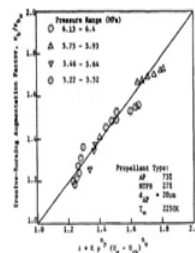


Fig. 11 Experimental data for engine burning augmentation factor correlated with pressure and freestream velocity for propellant I.

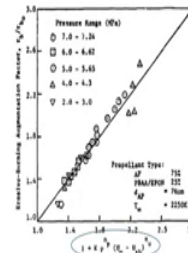


Fig. 12 Experimental data for engine burning augmentation factor correlated with pressure and freestream velocity for propellant II.

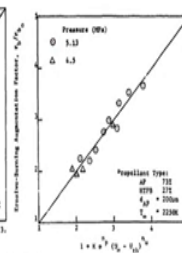


Fig. 13 Experimental data for engine burning augmentation factor correlated with pressure and freestream velocity for propellant III.

Table 2 Correlation coefficients


Propellant type	I	II	III
K_1 (MPa) $^{-n_p}$ (m/s) $^{-n_u}$	4.8×10^{-3}	3.167×10^{-4}	2×10^{-4}
n_p	0.35	1.463	0.705
n_u	0.69	1.42	1.252

These equations set out in 1981 - 83 have 3 constants while the earlier work of Lenoir and Robillard (1957) had only 2 constants!



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 1981-83 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.

(Refer Slide Time: 09:01)





NPTEL

Summary of experimental data

Propellants for which Erosive Burning Data are Available


Code	Propellant Composition	ρ_p (kg/m ³)	T_{ad} (K)	d_b (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 μ m) + 35polyester	1620	1690	5.0
Prop C	75AP (24–30 μ m) + 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 ₂ O ₃)	1700	—	
Prop 4	68AP + 16Al + 16PBAN	1700	—	
Prop 5	72AP + 14Al + 16(CTPB + Fe ₂ O 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.

(Refer Slide Time: 09:17)



EROSIVE AUGMENTATION OF SOLID PROPELLANT BURNING RATE:
MOTOR SIZE SCALING EFFECT* 40271

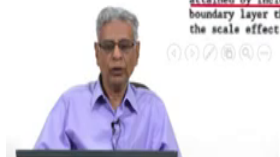

L. D. Strand
Jet Propulsion Laboratory, California Institute of Technology
Pasadena, California p-13

and

N. S. Cohen
Cohen Professional Services
Redlands, California

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_0 , in terms of the amount that the driving parameter $\sqrt{p_0} (1/r_0 - 1/r)$ 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.

(Refer Slide Time: 09:45)



Lenoir & Robillard Theory

$$r = ap^n + \frac{\alpha G^{0.8}}{L^{0.2}} \exp\left(\frac{-\beta \rho_p r}{G}\right),$$

The present
non-dimensional
expression

$$\eta = 1 + K_1 (g^{0.8} - g_{th}^{0.8}) H (g - g_{th})$$

with

$$g = K_2 g_0 \text{Re}_0^m, \quad \eta = r / ap^n$$

$$\eta = 1 + 0.023 (g^{0.8} - g_{th}^{0.8}) H (g - g_{th}), \quad (12)$$

$$\text{where } g = g_0 (\text{Re}_0 / 1000)^{-0.125} \text{ and } g_{th} = 35.0.$$

Re_0 Reynolds number based on propellant
burn rate $(\rho_p r_0 d_0 / \mu)$

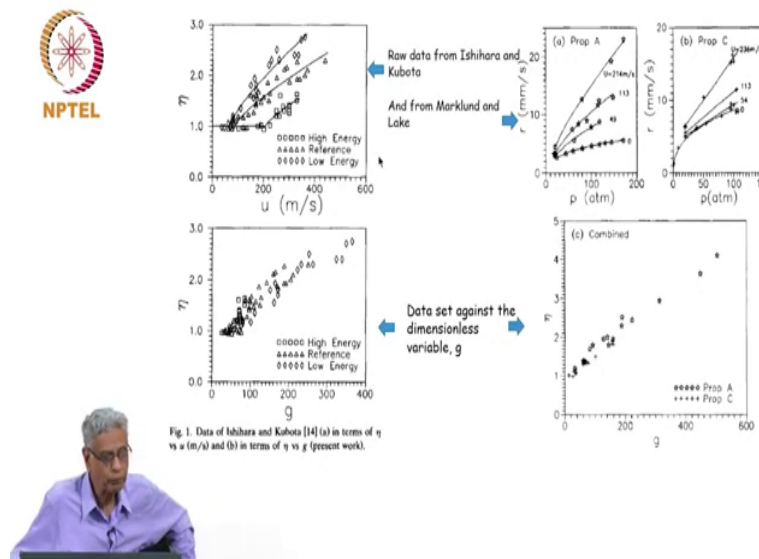
d_0 = port diameter, for partly symmetric geometries,
is it hydraulic mean diameter = $4 A_p / P$ or P / π ? To
be seen later



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^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.

(Refer Slide Time: 10:37)



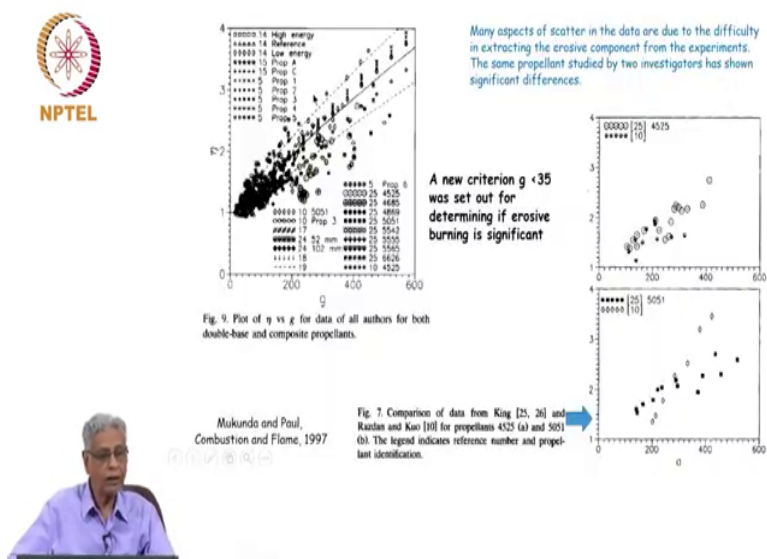
If you look at the data of the erosive burning rate to the normal burning rate with velocity you will see that, the you get these three curves; this is the raw data from Kubota, also raw data from Marklund and Lake. Now, if you see that you plot that with respect to a parameter g , which I have identified 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 $\rho p r \dot{\eta} d$ by μ 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.

(Refer Slide Time: 12:55)



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.

(Refer Slide Time: 14:49)



Then in 2000,

The erosive burning law got integrated into tactical rocket design in DRDL. One might think the matter has ended...pleasantly....Not so soon!

Some time in 2011, it was brought out that the erosive burning law was not always giving good predictions (in comparison with experimental data) It turned out that this was consistently happening for non-axisymmetric grains - like the Fin-o-cyl grain they were dealing with then. This led to an investigation of the flow behavior through partially symmetric shapes.

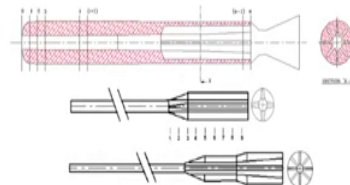


Fig. 1. Geometry of the two grains for Motor 1 (top) and Motor 2 (bottom). The first part is cylindrical and the all part is finned with a constant radius. The cross section shown on the right is of the all end.

Table 1
Properties of the motors under study

Parameter	Motor 1	Motor 2
Motor length, m	2.1	4.8
Port diameter, m	0.07	Varies from 0.07 to 0.08
Initial cylindrical segment, m	1.07	1.48
Fin-o-cyl transition zone, m	0.08	0.26
Number of wells in the finned	8	8
Fin-o-cyl transition dia, m	0.08	0.07
Fin-o-cyl transition dia, m	0.07	Varies from 0.26 to 0.37
Thrust diameter, mm	45	176
Burn rate at 7 MPa and pressure index, s	0.53 mm/s and 0.23	0.6 mm/s and 0.38

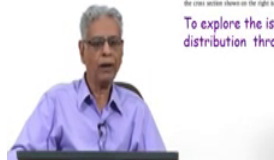
Extension of the universal erosive burning law to partly symmetric propellant grain geometries

H.S. Mukunda^a, P.J. Paul^a, Anirudh Jaiswal^a, Debasis Chakraborty^{b*}

^aIndian Institute of Space, Bangalore, Karnataka, India

^bIndian Institute of Space, Bangalore, Karnataka, India

To explore the issues, CFD was applied for determining the flow distribution through the part symmetric geometry....



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.

(Refer Slide Time: 16:31)

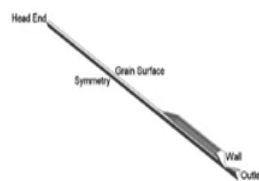


Fig. 2. Geometry of motor-1 for the simulation with the boundary locations.

Tetrahedral grids are made using ICFM CFD [7] package, a layer of hexahedral grids are used at walls and grain surface to resolve gradients. Three different grids of 0.74, 1.42, and 3.29 millions sizes with minimum normal grid spacing of 0.4, 0.1 and 0.01 mm are studied to establish the grid independence of the results. A typical grid is shown in Fig. 3. It can be observed that the grids near the geometrical changes are sufficiently clustered to capture high flow gradients expected in these regions. Minimum y^+ varies from head end to nozzle end and typical y^+ at head end and nozzle is of the order of 0.1 and 20, respectively.

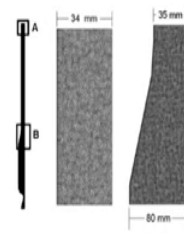
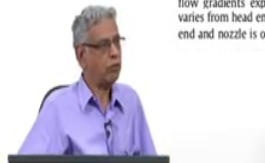


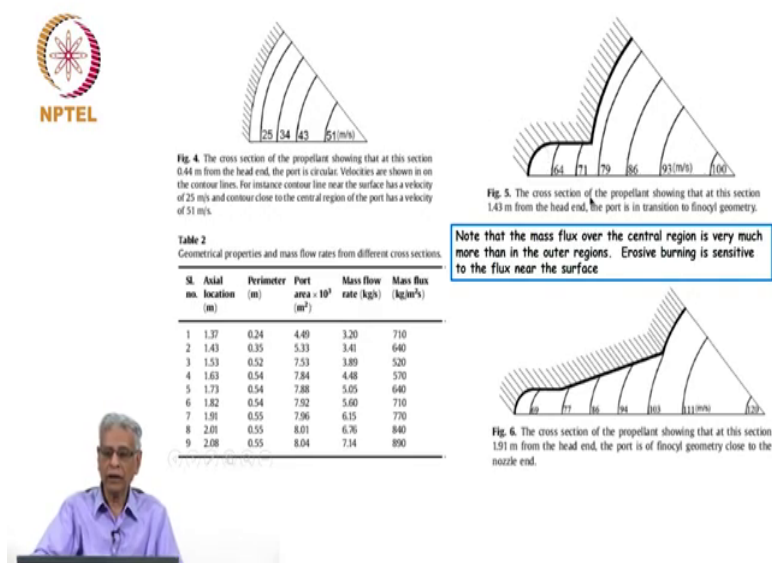
Fig. 3. Computational grid for the motor geometry.

The flow simulation is carried out using CFX11 commercial CFD solver [8]. It solves 3-D Navier-Stokes equations with $k-\epsilon$ turbulence model. For the present simulations, the grain surface is set as isothermal wall at 2980 K temperature and the propellant mass flow from the grain is considered as the source term in the mass continuity equation. Two sides are taken as symmetry boundary conditions and the nozzle wall and head end wall are taken as no slip adiabatic walls. Supersonic outflow boundary condition is prescribed at the outlet as the flow at the nozzle exit is supersonic.

A second order numerical scheme is utilized for the simulations. A physical time step of 0.2 ms is used for the steady state simulations. The simulation is run till a convergence level of 1×10^{-4} is reached on normalized logarithmic residuals.

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.

(Refer Slide Time: 17:07)



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 .

(Refer Slide Time: 17:55)



After much analysis, finally

If it can be taken that erosive burning is dominant over small regions for the early part of the combustion process as it happens in practice, *a simpler procedure can indeed be evolved*. In this approach, it is taken that an average heat flux is assumed prevalent over the entire burning perimeter. The more appropriate characteristic dimension to choose for evaluating the size effect through Re_0 is defined in terms of perimeter as P/π instead of $4A_p/P$. This will translate to d_p for circular port cross section as is needed. Calculations have been made for the above geometry dominated by erosive burning. The results are presented below. The data for grain-1 are set out in Table 3.



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 π that is a perimeter by π , which is essentially diameter in the case of a circle. In the case of a complex shape, you will get slightly larger dimension.

(Refer Slide Time: 18:41)

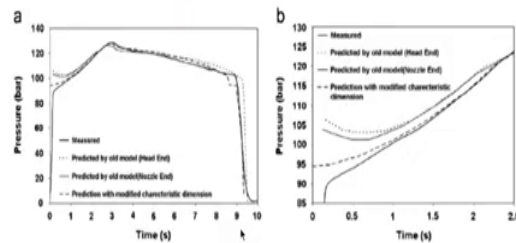


Fig. 9. Predicted and measured chamber pressures (a) full burn time (b) zoomed view to show the effect of modified model (Motor-1).



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.

(Refer Slide Time: 19:23)



Table 3

Geometric and flow properties along the motor length ($p_0 = 70 \text{ atm}$, $T_0 = 2800 \text{ K}$, $L_0 = \text{characteristic length} = \text{perimeter} \times L_0 = \text{hydraulic diameter}$)

$x \text{ m}$	$A_0 \text{ cm}^2$	$L_0 \text{ m}$	$\dot{m} \text{ kg/s}$	$\rho_0 \text{ kg/m}^3$	$G/\rho_0 L_0$	$Re_0 \times 10^6$	$g(L_0)$	η	$g(L_0)$	η'
0.44	35.6	0.067	1.01	7.68	21.8	1.46	15.6	1.0	15.6	1.0
0.85	35.9	0.067	1.98	7.64	42.3	1.46	30.3	1.0	30.3	1.0
1.43	53.3	0.112	3.3	7.58	47.5	2.44	31.9	1.0	34.5	1.0
1.73	78.8	0.173	4.9	7.55	47.7	3.75	30.3	1.0	34.8	1.0
1.91	79.7	0.174	6.01	7.52	57.9	3.79	36.8	1.01	42.2	1.06
2.08	80.4	0.176	7.47	7.50	71.3	3.81	45.2	1.09	52.0	1.14

This modification is what is now in the codes of propulsion system design at DRDO

One would imagine that the story has ended..all well. Indeed not!

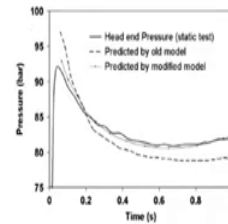


Fig. 10. Zoomed view of measured and predicted chamber pressures using the old and modified versions of the erosive burning model (Motor-2).

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.

(Refer Slide Time: 19:41)



In 2006, appeared a paper in JPP:

JOURNAL OF PROPULSION AND POWER
Vol. 22, No. 5, September-October 2006

Erosive Burning of Aluminized Composite Propellants: X-Ray Absorption Measurement, Correlation, and Application

Hiroshi Hasegawa^a

NOF Corporation, Taketoyo, Aichi 470-2398, Japan

Masahisa Hattawa^b

Tokai University, Hiratsuka, Kanagawa 259-1292, Japan

and

Shin-ichiro Tokudome^c and Masahiro Kohno^d

Japan Aerospace Exploration Agency, Sagamihara, Kanagawa 229-8510, Japan

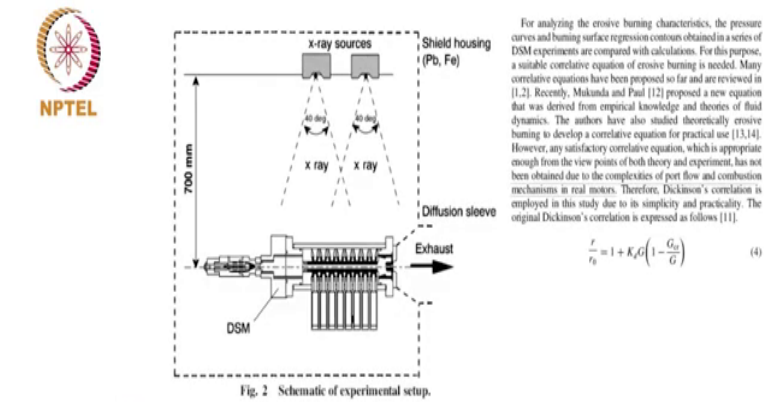
DOI: 10.2514/6.2006-1790

The erosive burning effect in a small test motor loaded with highly aluminized practical composite propellants have been investigated in detail by using x-ray absorption diagnostic to measure the propellant local regression. The motor was specially designed to have two propellant slabs and was called a double-slab motor. Significant erosive burning was found in the motor for several combustion pressure level and ranges of mass flux in the port. The x-ray diagnostic system enabled observation of the time-wise change in the distribution of burning propellant surface during motor operation. A modified Dickinson-type simple correlation equation, which includes the effects of mass flux, mass burning rate, combustion pressure, and motor scale, was derived from the results of DDM firing tests. Parameters of the correlation equation were finally determined by taking into account the experimental results of both cylindrical test motors and practical full-scale motors.



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.

(Refer Slide Time: 20:05)



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

(Refer Slide Time: 20:11)



The correlations were....

And when this was inadequate, they adopted

$$\frac{r}{r_0} = \begin{cases} 1 + K_1 D_p^{-0.2} \left[G \left(1 - \frac{\dot{G}}{\dot{G}_a} \right) \right]^\gamma & ; \dot{G} > \dot{G}_a \\ 1 & ; \dot{G} \leq \dot{G}_a \end{cases} \quad \dot{G}_a = 10$$

And when that was inadequate for some motors, they adopted constants

$$K_1 = K_2 P^{-0.7}$$

$$K_2 = \begin{cases} 1.02 \times 10^{-3} & ; \text{Propellant No. 1} \\ 2.47 \times 10^{-4} & ; \text{Propellant No. 2} \end{cases} \quad [\text{m}^{2.7} \text{s MPa}^{0.7} / \text{kg}]$$

$$\gamma = 1.0$$

And further for some other motors

$$\gamma = 1.2,$$

$$K_2 = \begin{cases} 3.4 \times 10^{-4} & ; \text{propellant No. 1} \\ 7.0 \times 10^{-5} & ; \text{propellant No. 2} \end{cases} \quad [\text{m}^{2.6} \text{s}^{1.2} \text{MPa}^{0.7} / \text{kg}^{1.2}]$$



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.

(Refer Slide Time: 20:39)



From Mallesh, ME Thesis, Aerospace Engg, IISc, 2014

- Dimensionless universal correlation for erosive burning was established more than a decade back and is used as a standard design tool for highly loaded tactical rocket motors.
- A number of cases of double slab and cylindrical motors are subject to analysis. Several features of inadequate ignition process that were being attributed to and coupled with erosive burning are addressed in this study.
- The comparison indicates that the predictions using the dimensionless correlation (due to hsm and pjp) are at least as good as their claims.
- This study therefore restores the adequacy (and perhaps necessity) of dimensionless approach that was sought to be disbanded by the Japanese workers.
- What is disheartening to note is: *Journal of Propulsion and Power* has published an article in which there is an idea of claiming that dimensional correlations are more appropriate than dimensionless ones - Completely reversing scientific progress!




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.

(Refer Slide Time: 22:25)



The story is not completely over, yet!

An Approach to Analyse Erosive Characteristics of Two-Channel Combustion Chambers

Yanjie Ma, Futing Bao, Weihua Hui, Yang Liu and Ran Wei

Science and Technology on Combustion, Internal Flow and Thermo-Structure Laboratory,
Northwestern Polytechnical University, Xi'an, Shaanxi 710072, China

Correspondence should be addressed to Weihua Hui: zhongyuancao@163.com

In 2018, this paper was received for review:

1. Their concentration is L & R correlation - as to how they can find the constants that fit their experimental data of two-channel combustion system. Of course they did not cite our work! - a common experience generally from the West, but in this case also from China!
2. After it was pointed out that gas dynamics can be combined with new universal law, they modified their manuscript - not fully appropriately though..... **I think the story will never end**

.....my end!

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.