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The Energy Diameter Effect

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THE ENERGY DIAMETER EFFECT

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Abstract. We explore various relations for the detonation energy and velocity as they relate to the inverse radius of the cylinder. The detonation rate-inverse slope relation seen in reactive flow models can be used to derive the familiar Eyring equation. Generalized inverse radii can be shown to fit large quantities of cylinder results. A rough relation between detonation energy and detonation velocity is found from collected JWL values. Cylinder test data for ammonium nitrate mixes down to 6.35 mm radii are presented, and a size energy effect is shown to exist in the Cylinder test data. The relation that detonation energy is roughly proportional to the square of the detonation velocity is shown by data and calculation.

Keywords: size effect, diameter effect, detonation velocity, detonation energy, cylinder test
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INTRODUCTION

The size (diameter) effect is the well known decrease of detonation velocity with decreasing radius. Plotting the detonation velocity as a function of inverse radius [1], the extrapolation to zero produces the detonation velocity at infinite radius, which should agree with that calculated by CHEETAH [2] or any thermo-chemical code. We have suggested that, as the radius decreases, the fraction of the explosive that remains unburned increases [3]. In terms of the burn fraction, F, which is the fraction of explosive burned, we estimated that

$$F_e \approx \frac{E_o}{E_o^D} \approx \left(\frac{U_S^2}{D} \right) , \qquad (1)$$

where F_e is the burn fraction at the back of the reaction zone, E_o and U_S are the detonation energy and velocity at some finite radius R_o, and E_o^D and D are the corresponding values at infinite radius. While this relation was derived assuming a single overall chemical reaction, which is not true, it is helpful in estimating energetic effects.

The energy variation in Eq. 1 is seen in measured data from the Cylinder test, where the square of the confining copper velocity is proportional to the detonation energy at three standard relative volumes [4, 5]. This relation has traditionally been used on near-ideal explosives, where changes of cylinder size have little effect. Shots using ANFO have tended to be large in order to avoid non-ideal effects.

In this paper we present new experimental results for ANFO cylinders where we have deliberately shrunk the copper cylinders down to as little as 6.35 mm inner radius in order to look for the energy effect. Also, we used explosives near half-density, which are weak, but tend to continue detonating down to small sizes. This new cylinder data is combined with older cylinder experimental results to explore various relations for the detonation energy and velocity as they relate to the inverse radius of the cylinder. We find that the data is consistent with an energy size effect.

ANFO DATA

Table 1 lists the data taken recently on ammonium nitrate mixes in small size cylinders. This data is plotted in Figure 1 as a function of inverse radius and a size effect is seen. The energy E_o is at the relative volume of 2.2, which corresponds to the scaled outer wall displacement of 6 mm. This relative volume, which is the first of the cylinder standards, is often taken as a measure of the metal-pushing power of the explosive. The straight dashed lines in the figure are meant to be representative of the variation in energy. There are too few data points to properly determine whether energy varies linearly with inverse radius. In fact, as we conclude below this is not generally true.

TABLE 1. Copper cylinder shots for various ammonium nitrate mixes.

Explosive	density (g/cm^3)	remarks	Detvel (mm/μs)	Expl. Radius (mm)	Cu thick (mm)	Measured Scaled Wall Velocity (mm/μs)			Det Energy Density E_d(v), (kJ/cm^3)		
						6	12.50	19.00	2.2	4.4	7.2
AN85/Al10/S5	0.988	5 μm Al	3.38	12.70	2.52	0.670	0.785	0.848	1.13	1.49	1.71
AN85/Al10/S5	0.993	5 μm Al	2.95	6.36	1.36	0.588	0.692	0.743	0.94	1.25	1.41
AN90/Al10	1.044	5 μm Al	3.67	25.41	5.21	0.712	0.821	0.888	1.33	1.70	1.95
AN90/Al10	1.002	95 μm Al	3.49	25.43	5.19	0.674	0.782	0.835	1.18	1.53	1.71
AN90/Al10	1.023	20 μm Al	3.07	12.72	2.58	0.614	0.724	0.782	0.98	1.30	1.49
AN90/Al10	1.023	20 μm Al	2.64	6.35	1.36	0.516	0.595	0.642	0.73	0.93	1.06
AN90/Al10	1.023	20 μm Al	2.64	6.35	1.36	0.509	0.601	0.658	0.71	0.95	1.12
AN79/NM21	1.200	Kinepak	5.13	12.71	2.606	0.890	0.967	1.008	2.12	2.40	2.56
AN79/NM21	1.050	Kinepak	3.92	6.35	1.360	0.680	0.782	0.827	1.27	1.61	1.77

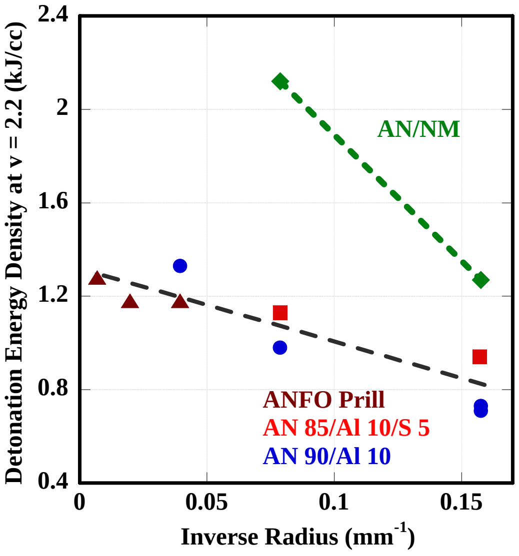

Figure 1. Size effect for explosives at a relative volume of 2.2. The explosives are: AN/NM (diamonds), ANFO prill (triangles), AN/Al/S (squares) and AN/Al (circles).

We can go further with the data analysis by plotting scaled values. We compare the dimensionless scaled energy from Eq. 1 at a fixed relative volume to a dimensionless inverse radius. We define a generalized dimensionless inverse radius as the following

$$\left(\frac{1}{R_o}\right)_g = \frac{D}{\langle v \rangle R_o} , \qquad (2)$$

where <v> is the average detonation rate in μs^{-1} [3]. This plot is shown in Figure 2 and the higher rate AN/NM is brought into line with the other points.

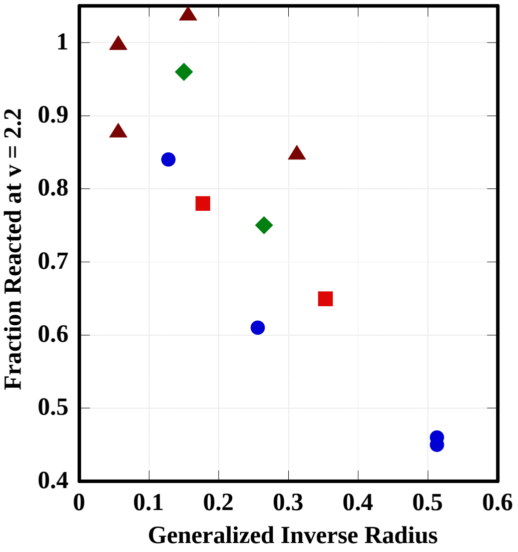

Figure 2. Generalized inverse radius plot derived from Figure 1. The same notation is used.

Next, we go to our JWL library for all explosives and plot the total detonation energy, E_o (JWL), and the detonation energy at v = 2.2, E_d (2.2, JWL) as a function of detonation velocity [4]. E_o (JWL) is a somewhat mythical value because it requires expansion of the gas products to infinite volume, so the extrapolated value from CHEETAH is usually used. The result of all these values is shown in Figure3, and is given by

$$\begin{aligned} E_d(2.2, \mathrm{JWL}) &\propto U_S^{2.2} \\ E_o(\mathrm{JWL}) &\propto U_S^{1.6} \end{aligned} . \qquad (3)$$

The last step in using Eq. 1 requires knowing D, the infinite radius detonation velocity. This can be calculated using CHEETAH, but thermo-chemical codes have most trouble with detonation velocities. It can be found by extrapolating the size effect data, but most of the data is on small cylinders, so that few points near zero are available. Also, extremely non-ideal explosives often have concave-up size effect curve shapes, so that D is larger than we think. After estimating D, the results are shown in Figure 4 and the dashed line fitted to Eq. 1 is just slightly below the data.

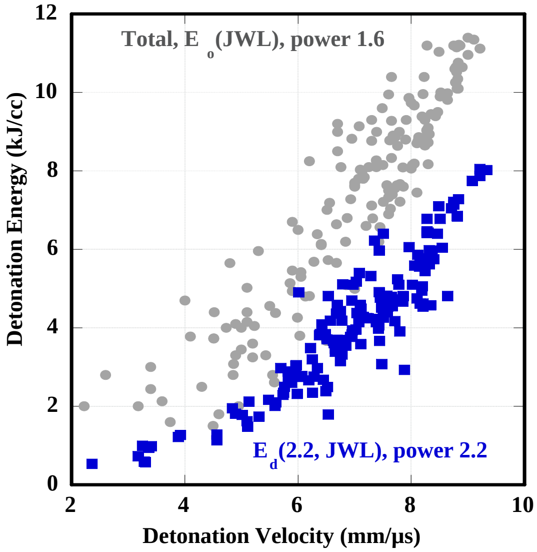

Figure 3. Near-squared dependence of energies taken from JWL's.

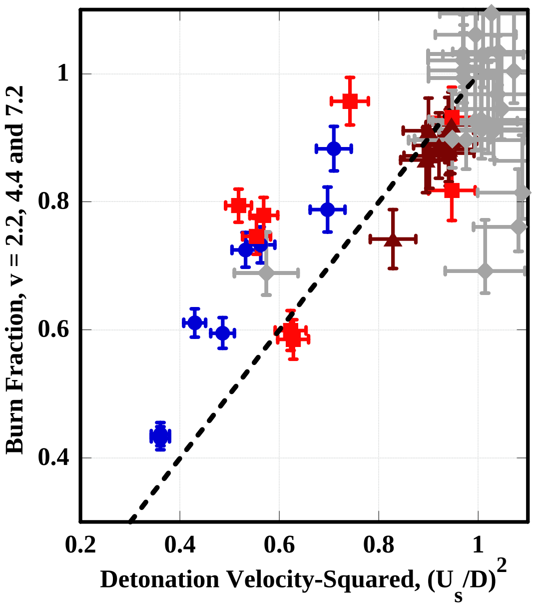

Figure 4. Cylinder test burn fractions versus dimensionless detonation velocity-squared. The points are: AN mixes, this paper (circles), older AN mixes (squares), LX-17 (triangles) and other (diamonds). The dashed line is Eq. 1.

We finally calculated the burn fraction using simple JWL++ with a single detonation rate [6] and these results are shown in Figure 5. The simple reactive flow model also shows that the relation from Eq. 1 between burn fraction and detonation velocity approximately holds.

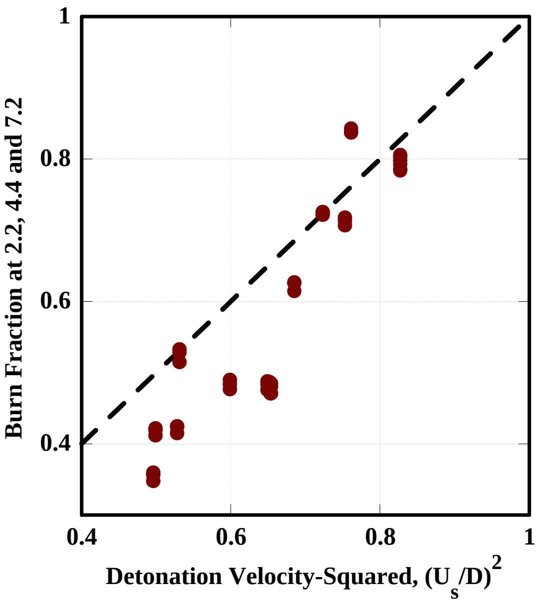

Figure 5. Calculated AN 90/Al 10 burn fractions versus dimensionless detonation velocity-squared with the dashed line being Eq. 1.

CONCLUSION

In conclusion, the data does support the idea of an energy size effect. The detonation energy varies roughly as detonation velocity squared. Thus knowledge of the detonation velocity size effect can be used to determine the energy size effect. If the velocity size effect were linear, then one would expect a quadratic energy size effect.

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