Cylinder Test Wall Velocity Profiles and Product Energy for an Ammonium Nitrate and Aluminum Explosive

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Abstract. Ammonium nitrate mixed with aluminum powder forms a non-ideal explosive often referred to as ammonal. Non-ideal detonation can result in significant energy release behind the detonation sonic surface that does not contribute to the detonation velocity, but may affect the expansion energy of the product gases. In this work, we use scaled cylinder expansion tests to characterize the product energy variation with scale for ammonal. The results of two cylinder tests with 50.8-mm and 72.6-mm inner diameters are compared to prior data at other scales. We find that cylinder wall velocity increases with increasing charge diameter and also with increasing charge length.

INTRODUCTION

Increasing charge diameter in a rate-stick experiment (unconfined, cylindrical explosive charge) or cylinder test has a positive effect on detonation velocity, both for ideal and non-ideal explosives. This well-known phenomenon is referred to as the diameter effect. Non-ideal explosives are much more sensitive to confinement and diameter effects, exhibiting increased detonation velocity and confiner-acceleration performance with increased charge diameter and confinement [1, 2, 3]. This difference in behavior is due to the fact that ideal explosives react promptly, releasing more energy before the sonic surface, while the slower reactions in non-ideal explosives may continue behind the sonic surface. The rate of these post-detonation reactions is likely dependent on temperature, so the higher temperatures associated with larger diameters may result in higher energy release. In the present work, we examine this phenomenon in ammonal cylinder tests.

The cylinder test is a standard explosive performance test in which the ability of the explosive to perform work on the confiner material is measured. In the test, explosive is placed inside a confiner tube, which is typically composed of annealed OFHC copper. The test is instrumented to measure the detonation velocity and the position or velocity of the confiner outer wall as a function of time. The detonation front-shape may also be measured with high speed imaging.

Commonly used performance metrics derived from the Cylinder test are the Cylinder Energy and the Gurney Energy. The Cylinder Energy includes just the kinetic energy of the confiner, whereas the Gurney Energy is a measure of the product energy available to drive the confiner [4]. In the present work, we report cylinder-wall velocity-profile fit parameters for ammonal composed of 90% ammonium nitrate and 10% aluminum powder, by mass. We also report the Cylinder Energy and Gurney Energy associated with these wall expansion profiles. Results are reported at varying positions along the length of the test to demonstrate the non-ideality of ammonal.

EXPERIMENTAL

The experimental configuration is shown in Fig. 1. To prepare the shot, the ammonium nitrate and aluminum was premixed in a 9:1 mass ratio, and then loaded into the tube. The loading process was conducted by pouring the ammonal into the tube and tapping the outside of the tube to settle the particles. After loading, a window with a reflective coating for imaging the detonation breakout on a streak camera was placed inside the breakout end of the tube against the ammonal.

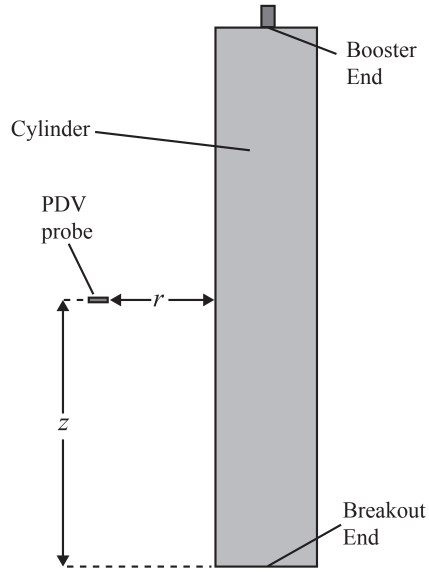

FIGURE 1. Experimental configuration for the 50.8 mm and 76.2 mm cylinder tests.

TABLE 1. PDV probe locations for the 50.8 mm and 76.2 mm cylinder tests. Distance z is measured from breakout end of tube.

	50.8 mm Cylinder		76.2 mm Cylinder	
Probe #	Distance z (mm)	Distance r (mm)	Distance z (mm)	Distance r (mm)
1	94	144	151	151
2	94	144	151	165
3	196	144	304	144
4	196	144	304	146
5	296	144	456	166
6	296	144	456	163
7	387	131	608	162
8	502	131	761	146

In the experiments, the ammonal was initiated at the top, and the detonation traveled down the length of the tube. Shorting wires located on the outside of the tube recorded the passing of the detonation to provide the bulk detonation velocity, and PDV probes located at the positions indicated in Table 1 recorded cylinder wall expansion profiles. All probes were aligned 90° to the tube wall.

The confiner was composed of alloy 101 copper, annealed for ductility to maximize the length of the recorded expansion profiles. The ammonal was blended using 99.8% pure aluminum powder, with a 10% mass fraction diameter (D10) of 2.05 μm, D50 of 4.53 μm, and D90 of 10.59 μm. The ammonium nitrate was 98% pure, and the prills were ground in a grain mill to a D50 of 850 μm.

EXPERIMENTAL RESULTS

Detonation velocities and fitting parameters parameters for the cylinder wall expansion data are provided in Table 2. The fitting parameters correspond to a least-squares fit to the equation described by Hill [5],

$$v_0(t) = \frac{v_\infty((t+1)^\omega - 1)}{\frac{2v_\infty\omega}{a_0}(t+1)^\omega - 1}, \quad (1)$$

where v_0 is the cylinder wall velocity component normal to the direction of detonation propagation, t is time after jump-off, and v_∞, ω, and a_0 are parameters determined in the fitting process. The values reported are the average observed by the probes whose locations are reported in Table 1.

In Table 2, fitting parameters from the 50.8 mm and 76.2 mm diameter cylinder tests and prior tests reported by Souers et al. [6] are provided. In addition, the Cylinder Energy and Gurney Energy, computed using the provided parameters, are reported. While there are small variations between tests conducted at the same scale, the overall trend of increasing Cylinder Energy and Gurney Energy with test scale is apparent. It should be noted that all tests reported in Table 2 were conducted with 90/10 AN/Al mixtures, but there were variations in particle sizes, which are reported for the prior tests by Souers et al. [6]. Some of the differences in velocity profiles may be due to these variations. The Gurney Energy results are also presented graphically in Fig. 2, where the strong dependence of Gurney Energy on test scale is apparent.

TABLE 2. Velocity profile fit parameters and energies for ammonal Cylinder tests. Tests indicated by * were reported by Souers et al.[6]. E_{19} and G_{19} indicate the Cylinder Energy and Gurney Energy, respectively, at scaled displacements of 19 mm.

Test Scale	Ammonal Density (g/cc)	Detonation Velocity (mm/μs)	v_∞ (mm/μs)	a_0 (mm/μs^2)	ω (–)	E_{19} (kJ/g)	G_{19} (kJ/g)
0.5*	1.023	2.644	804.03	260.23	0.16185	0.211	0.915
0.5*	1.023	2.644	843.28	268.97	0.14305	0.216	0.904
1*	1.023	3.068	947.17	375.00	0.19796	0.306	1.32
2*	1.044	3.673	1037.5	296.84	0.14305	0.384	1.63
2*	1.002	3.486	990.16	335.71	0.16953	0.349	1.54
2	0.968	3.516	1035.4	329.51	0.15913	0.379	1.72
3	0.953	3.824	1036.2	342.05	0.16508	0.401	1.85

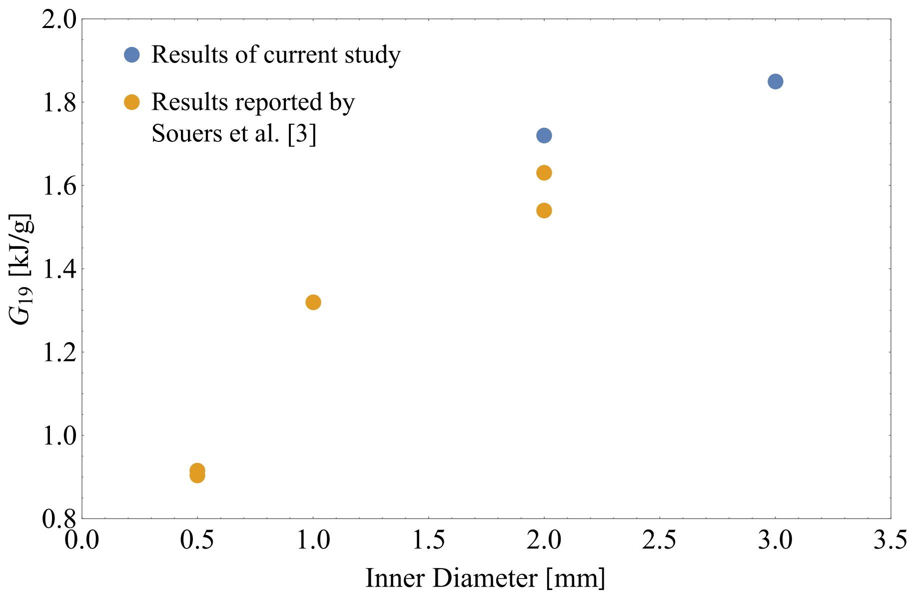

FIGURE 2. Gurney Energy computed at 19 mm scaled cylinder displacement for ammonal tests at various sizes.

CONCLUSIONS

Two ammonal cylinder tests were executed and compared to prior tests using 90% ammonium nitrate blended with 10% aluminum powder. The measured velocity profiles were fitted to a commonly used fitting form to facilitate analysis, and Cylinder Energy and Gurney Energy were computed for cylinder tests of 4 different inner diameters: 12.7 mm, 25.4 mm, 50.8 mm, and 76.2 mm. Comparison of the Cylinder and Gurney Energies as a function of cylinder test diameter showed the specific energy always increased as the scale of the test was increased.

While the results reported here do not prove a mechanism for this result, examination of the cylinder wall velocity profiles shows energy continues to be transferred to the cylinder wall at times beyond 50 μs after the passage of the detonation. In prior work, we found that post-detonation heat release also increases as the distance from the booster increases [7]. The combination of these results suggest that significant heat release occurs in the post-detonation expansion. This late-time heat release increases as the scale of the test is increased, presumably because larger tests maintain higher product temperatures during expansion. This mechanism has been suggested for other non-ideal explosives, including ammonium nitrate-fuel oil (ANFO) blends [3]. Differences in energy output between the 50.8 mm and 76.2 mm test were smaller than those between the 12.7 mm and 25.4 mm tests, indicating that specific energy release as a function of diameter follows a schedule of diminishing returns. These results indicate that the detonation performance of ammonal is highly non-ideal.

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