Acceleration of plates using non-conventional explosives heavily-loaded with inert materials

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Abstract. The detonation behavior of high explosives containing quantities of dense additives has been previously investigated with the observation that such systems depart dramatically from the approximately “gamma law” behavior typical of conventional explosives due to momentum transfer and thermalization between particles and detonation products. However, the influence of this non-ideal detonation behavior on the divergence speed of plates has been less thoroughly studied and existing literature suggests that the effect of dense additives cannot be explained solely through the straightforward application of the Gurney method with energy and density averaging of the explosive. In the current study, the acceleration history and terminal flyer velocity of aluminum flyers launched by packed beds of granular material saturated by amine-sensitized nitromethane is reported. It was observed that terminal flyer velocity scales primarily with the ratio of flyer mass to mass of the explosive component; a fundamental feature of the Gurney method. Velocity decrement from the addition of particles was only 20%-30% compared to the resulting velocity if propelled by an equivalent quantity of neat explosive.

1. Introduction

The launch of plates by conventional high explosive (HE) is well categorized by a variety of models of increasing complexity. The simplest models, like the Gurney method, consider only a partition of the effective chemical energy between the flyer and the expanding detonation products using a simplified depiction of the expansion process. The partition is governed solely by the charge-to-flyer mass-ratio. More sophisticated models rely on solving the full expansion process using a polytropic equation of state, or more rigorously and accurately, an equation of state fitted directly to experimental cylinder test data [1].

A less studied configuration is the launch of plates by non-conventional explosives whose post-detonation expansion deviates significantly from an approximately polytropic behavior with ratio of specific heats ($\gamma$) around 3 that is observed in most explosives. Such an explosive can be formulated by mixing high-density inert additives with a conventional HE. In this system, the detonation wave is smeared out compared to a classic ZND detonation due to the “percolation” of detonation wavelets around the particles, shock transmission and detonation re-initiation through the particles and then thermalization and momentum transfer between particles and the detonation products while the decomposition reaction is ongoing [2, 3]. As the detonation products continue to expand, the particles are further accelerated by aerodynamic drag and can eventually redeposit energy back into the flow during particle deceleration. These effects combine
to yield a complex, non-equilibrium multiphase expansion whose average ratio of specific heats can approach 6 to 8 [2, 3]. If a flyer plate is present, impingement of the particles on the surface of the plate may also provide a significant mechanism for momentum transfer as suggested by plate dent tests for mixtures of HE and tungsten [2, 4].

Previous work on explosives containing high-density additives has focused on mesoscale calculations and non-equilibrium equations of state to better predict detonation pressure and velocity and to model the explosive dispersal of particles [2, 5–7]. Voskoboinikov studied the effect of inert additives on plate launch velocity and found that the velocity was governed by the volume fraction, density, and dynamic compressibility of the additive [8]. In the current study we have extended plate velocity measurements to explosive systems with very large inert volume fractions by saturating packed particle beds with sensitized nitromethane (NM). The effect of heavy amine dilution on plate launch velocity was also measured.

2. Gurney Model

The simple analytic framework first proposed by Gurney and later expended upon by numerous others provides a useful tool for examining the velocity at which flyers are thrown [9, 10]. Gurney’s method distills the complex expansion and acceleration process into a terminal partition of the chemical energy of the explosive into kinetic energy of the flyer and kinetic energy of the expanding detonation products. The detonation product expansion is simplified by assuming a linear velocity gradient and uniform density. This allows for the integration of expressions for energy and momentum conservation to produce scaling laws that are a function only of the charge geometry, the ratio of explosive mass to flyer mass(es) and a characteristic energy of the explosive. A schematic of the Gurney system for a planar configuration of explosive sandwiched between two plates is depicted in figure 1.

![Figure 1. Schematic of Gurney asymmetric slab system.](image)

The terminal velocity of the flyer is given by:

\[
V_m = \sqrt{\frac{2E}{2}} \left[ \frac{1 + A^3}{3 + 3A} + \frac{N}{C} A^2 + \frac{M}{C} \right]^{-\frac{1}{2}}
\]

(1)

Where:

\[
A = \frac{1 + \frac{2M}{C}}{1 + \frac{2N}{C}}
\]

(2)

Here \(\sqrt{2E} \) is the experimentally determined Gurney energy, \(M\) is the mass per unit area of the flyer, \(C\) is the mass per unit area of explosive, and \(N\) is the mass per unit area of the tamper.

The accuracy of the Gurney method not only in predicting qualitative but also quantitative behavior within the range of applicable \(M/C\) ratios is often considered surprising given the simplicity of the model. This can be reconciled, in part, by considering the comparatively self-similar nature of the detonation product expansion process for conventional explosives with
\( \gamma \approx 3 \), which occurs largely along the Chapman-Jouguet isentrope [1]. In these cases, a maximum quantity of kinetic energy is delivered at essentially the same expansion ratio (approximately 2 for normal detonations and 7 for grazing detonations) regardless of the conventional explosive used, and thus the terminal velocity of the metal is proportional only to the energetic content of the explosive. This situation is ultimately well captured by the Gurney model, which essentially only considers the partition of effective energy at some final expansion ratio.

The applicability of this simple Gurney-based theory to non-conventional explosives will be subsequently considered. To account for the addition of inert liquid, the Gurney energy of the base explosive (in this case NM) is assumed to be scaled by the mass fraction of NM present, and a new diluted explosive density is substituted. For the packed bed systems, the equivalent mass of neat liquid explosive is assumed to act on a Gurney asymmetric sandwich with an effective flyer composed of the physical flyer plus one half of the mass of the packed bed and an effective tamper composed of one half of the mass of the packed bed. While crude, this approximation represents the fact that the expanding products must transfer momentum to the particles, while part of the bed may partially restrict expansion away from the flyer. Clearly a better understanding of the momentum partition can be derived from multiphase hydrocode calculations, and the following experimental work is designed to guide such simulations.

3. Experimental Setup
A planar flyer swept by a grazing detonation within the test explosive was used to determine the plate launching behavior. The flyer and explosive system was suspended above a support base via two vertical PVC slabs with break-away tabs. The grazing detonation was initiated via a multi-channel line wave generator (LWG) to ensure planarity. The LWG was filled with NM and 10% diethylenetriamine (DETA) by weight. It was initiated at the apex by a strip of rubberized explosive to ensure planarity through the thickness. The test explosive was separated from the LWG with a thin (1.5 mm) PVC spacer. The test explosive thickness was 24 mm, except for a single test with a 10.4 mm layer used to measure the flyer velocity for a neat explosive charge with a mass equal to the liquid saturating the packed beds. The explosive layer was sealed with a 3 mm thick PVC sheet. The flyer was 6061-T6 aluminum with a thickness of 6 mm. The flyer was 76 mm wide and 127 mm long. To mitigate against velocity decrement due to lateral expansion edge effects, the flyer was surrounded by a spall ring made of aluminum strips of equal thickness. The width of these strips was selected such that the portion of explosive subtracted via the “trapezoid” method did not encompass any of the explosive region directly above the

**Figure 2.** Rendering of the charge.

**Figure 3.** Photograph of a charge filled with a packed bed of steel media saturated with nitromethane.
flyer [11]. In principle, this allows for the main flyer to be uniformly accelerated free of edge effects closer to the ideal velocity while the mechanically decoupled spall ring lags behind. A schematic of the charge and a photograph of a charge filled with NM and steel particles are depicted in figures 2 and 3, respectively.

Plate velocity was measured via Heterodyne Laser Interferometry using a pair of optical collimators mounted in the support base. The probes were angled normal to the flyer and 15° from the normal respectively to split the difference in error introduced from the Taylor angle of the flyer. A standard Photon Doppler Velocimetry analysis was performed to extract the velocity history of the flyer.

Two neat liquid explosive systems and two packed bed systems were tested. The liquids were NM sensitized with 10% DETA at two loadings (10.4 mm and 24 mm of explosive) and NM diluted with 45% DETA by mass at a loading of 24 mm. The packed beds were standard steel and glass blasting/peening media with total thicknesses of 24 mm. The steel was S-100 cast steel shot (SAE J444 standard) with a nominal diameter of 280 micron, and the glass was Potters #10/AE Ballotini impact beads with a nominal diameter of 120 micron. The media packed to volume fractions of 57% for the steel and 58% for the #10 glass.

4. Experimental Results

Figure 4 shows the velocity history of all of the experiments, while figure 5 shows the velocity history of the two packed bed experiments compared to the neat liquid experiment of similar total explosive mass. All experimental terminal velocities, predicted Gurney velocities and relevant properties are summarized in table 1. All PDV velocities have a ± 20 m/s error bar factoring the inherent error in the analysis method and the effect of Taylor angle.

![Figure 4](image_url) Velocity histories for all experiments. Note different scale compared to figure 5.

![Figure 5](image_url) Velocity histories for packed bed experiments compared to neat liquid experiment containing a similar mass of explosive.

Excellent agreement was observed for the terminal velocity for both sensitized nitromethane loadings using the Gurney Energy provided in Walters and Zukas [12]. Note that the base Gurney energy of 2.41 km/s was scaled to 2.17 km/s to account for the presence of the sensitizing DETA and the minor tamping effect of the PVC cover was included. Percent errors were 1% and 5% for the high and low loadings respectively. This agreement simultaneously illustrates the validity of the Gurney model and suggests that the experiment is properly tailored to avoid lateral expansion effects from dominating the terminal velocity of the flyer.

Greater deviation is observed for the heavily diluted experiment (55/45 NM-DETA), where the velocity is under-predicted by 243 m/s for a percent error of 20.5%. Better agreement between a Gurney calculation and the experiment can be obtained by considering only the ratio
Table 1. Summary of results. Tampers are calculated for the neat liquids by considering the marginal influence of the PVC lid. Effective $M/C$ and $N/C$ ratios for the packed bed cases are calculated by partitioning half of the bed mass into the flyer (plus the aluminum flyer) and half into the tamper.

| Explosive       | $M/C$ | $N/C$ | $\sqrt{2E}$ (km/s) | $\rho$ (g/cc) | Predicted Vel. | Measured Vel. |
|-----------------|-------|-------|--------------------|----------------|----------------|---------------|
| 90/10 NM-DETA   | 0.64  | 0.17  | 2.17               | 1.12           | 1590 m/s       | 1607 m/s      |
| 90/10 NM-DETA   | 1.47  | 0.38  | 2.17               | 1.12           | 1010 m/s       | 1067 m/s      |
| 55/45 NM-DETA   | 0.68  | 0.18  | 1.33               | 1.05           | 940 m/s        | 1183 m/s      |
| Steel+NM        | 6.14  | 4.65  | 2.17               | 1.12           | 574 m/s        | 894 m/s       |
| Glass+NM        | 2.96  | 1.48  | 2.17               | 1.12           | 755 m/s        | 785 m/s       |

of nitromethane mass to the flyer mass ($M/C = 1.24$, $N/C = 0.32$) in the calculation and using the Gurney energy of the neat NM. In this case the velocity is over-predicted, but only by 57 m/s. A slower acceleration and the absence of shock reverberations within the flyer are consistent with a lower detonation pressure compared to neat NM. Flyer push is also sustained longer compared to the either of the sensitized cases. This may be due to decomposition of the excess DETA and/or an elongated rarefaction wave timescale in the products.

An unexpected result is obtained for the packed beds (Steel+NM, Glass+NM). Despite containing substantially more mass and more massive particles to accelerate and entrain, the saturated steel system accelerated the flyer to a greater terminal velocity than the glass system. One possible explanation is that appreciable momentum transfer from particles to the flyer occurs at later times. The greater inertia of the heavier and larger steel particles would magnify this effect. A comparison of the PDV traces for the packed beds does indicate a slower decay in the acceleration of the flyer in the steel case. There is also a small but appreciable rise in the velocity even after the curve turns over. While the glass and diluted cases show similar behavior, it is not to the same degree as for the steel case. Although the Gurney approximation used to estimate packed bed velocities recovers a velocity decrement, it shows poor quantitative agreement with the results. This highlights the need for multi-phase hydrocode simulations to determine a more representative momentum and kinetic energy partition than could be incorporated into a Gurney-like scaling law. A rough estimate from comparing the packed bed results with the neat liquid result of comparable explosive mass is that acceleration and of heating of the particles only accounts for a 20%-30% net loss of effective propulsive energy.

5. Conclusions

While the quantitative accuracy of the Gurney method has been shown to break down in the case of flyer propulsion by the non-ideal expansion of detonation products containing entrained dense particles, the key concept that flyer velocity scales mostly with the quantity of explosive material remains valid. The slower initial acceleration observed in the packed bed systems is consistent with previous observations of a detonation pressure and impedance governed initial velocity. The sustained drive observed in these systems further illustrates that, while the average detonation product $\gamma$ may be large, the assumption of a polytropic equation of state with $\gamma$ greater than 3 would yield an incorrect velocity versus expansion ratio history.

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