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Experimental Investigation of Thermally Ignited PETN Detonators

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1 Introduction

Assessing the behavior of pentaerythritol tetranitrate (PETN) explosive during an accident, such as a fire, is imperative for high consequence safety analysis in a variety of applications. Of particular concern is the unintended ignition and violence of a PETN containing detonator that could potentially initiate an explosive train. An accompanying charge can be initiated by a detonation (i.e., deflagration to detonation) or by flying debris from a deflagration in the PETN detonator. Previous work on deflagration to detonation transition of confined pristine PETN indicates that a run-to-detonation length of at least 15 mm is required; the length increases for PETN density less than and greater than 70% the theoretical maximum density (TMD) [1]. The study by Sáenz and Stewart [2] gives a thorough review of previous experimental work on DDT in PETN; the minimum run-to-detonation length across a range of PETN initial density is approximately 15 mm.

In this study, experimental work on sealed thermally ignited detonators of length shorter than 15 mm is presented. An analysis is performed to determine if DDT of the energetic material occurs considering different heating rates applied to the detonator outer surface. Finally, the violence of the thermally ignited detonators is quantitatively assessed based on the velocity of the detonator closure disc following ignition.

2 Methodology

2.1 Experimental Setup

In the present study, Teledyne RISI RP-87 detonators were heated to ignition. A cross-sectional cut of the detonator is shown in Fig. 1 (a). The detonator consists of low density PETN (23 mg and 900 kg/m^3) and high-density PBX 9407 (94 wt % RDX, 4 wt % FPC-461 fluoropolymer) output explosive (44 mg and 1690 kg/m^3). The energetic material and header are all contained within a brass sleeve and stainless steel cup.

A detonator was placed inside of a cylindrical aluminum holder surrounded by a mineral insulated band heater (Watlow 150 W). A schematic of a cross-sectional cut of the heating fixture is shown in Fig. 1 (b); the magenta region is the band heater, the detonator is shown in red, and the aluminum holder is shown in dark grey. The fixture has two feed-throughs for two K-type thermocouple probes, shown in black in Fig. 1 (c), with a sheath diameter of approximately 1.6 mm (0.040 in.). Two bores were located along the

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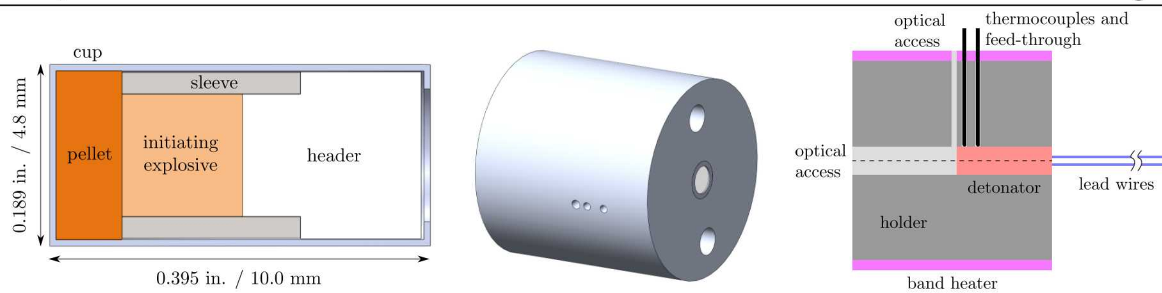


(a) RP-87 detonator (b) Detonator holder (c) Heating fixture

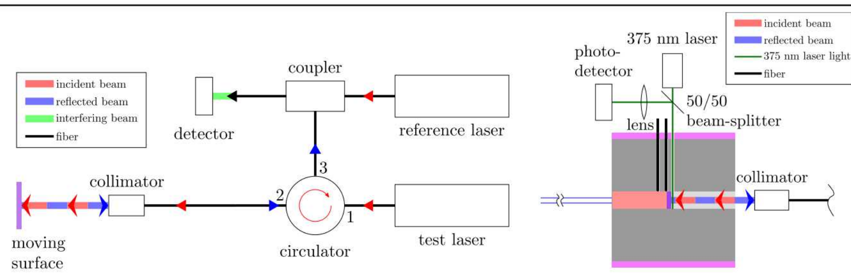
Figure 1: (a) Cross-sectional cut of RP-87 detonator; (b) isometric view of CAD detonator holder; (c) schematic of detonator heating fixture, the dashed line corresponds to the detonator and detonator holder axial centerline.

centerline axis of the holder and normal to the circumference of the holder intersecting the centerline axis; both bores were used for optical access, one for viewing the detonator closure disc and the other looking into the centerline axis bore. The thermocouple closest to the closure disc was used along with a proportional, derivative, integral (PID) controller to heat the holder at a user-specified heating rate. The closure disc refers to the base of the can, with a thickness of 0.16 ± 0.01 mm and diameter of 4.8 mm adjacent to the pellet in Figure 1 (a), that detaches in the event of a high-pressure build-up. For the remainder of this paper, the closure disc will be referred to as a “flyer”.

2.2 Optical Setup

Photonic Doppler Velocimetry (PDV) [3] was implemented to measure the velocity of the flyer during ignition. PDV is a single point diagnostic that measures the velocity of a surface through changes in frequency, i.e., light incident on a moving surface will have a slightly different frequency than the light reflected off of the surface. Experimentally, the interference, or beat frequency, was measured by using a fiber-based PDV setup illustrated in Fig. 2 (a). A fiber-coupled laser source (test laser) sends out light at a wavelength centered at 1550 nm. The fiber (shown in black) is coupled to port 1 of circulator 1; a separate fiber is connected to port 2 that delivers the laser light to a GRIN lens collimator. The light (shown in red) exits the collimator with a waist diameter of 0.5 mm FWHM at a working distance of 15 ± 5 mm and is incident on the moving surface (shown in purple). The reflected light (shown in blue) enters the collimator and is coupled to the fiber connected to port 2 of circulator 1. The light exits through the port 3 fiber and enters a fiber coupler; the reflected light is combined with light from a reference laser. The interfered light is then delivered to a photodetector via fiber. In the absence of movement of the surface, interference of the reference light and test light leads to a beat frequency of zero, however, the reference light can be modified to a different frequency such that interference of the reference light with the test light leads to a non-zero beat frequency.

Since the study focuses on thermal ignition, it was important to design an alternative triggering mechanism for the PDV system. In a standard detonator experiment, the PDV system can be triggered by the electrical firing system, however, this was not an option in the present study. The alternative chosen was to trigger the PDV system off of the motion of the flyer. Figure 2 (b) shows a 375 nm laser beam (green line) that passes



(a) Schematic of PDV setup (b) Schematic of trigger setup

Figure 2: (a) Schematic of fiber-based PDV setup and (b) schematic of detonator and detonator holder along with triggering mechanism; 375 nm laser: Coherent OBIS 375LX 14 mW, photodetector: Si Variable-Gain Avalanche Detector (Thorlabs APD430A2), 50/50 beam-splitter: 1/2 inch UV fused silica (Thorlabs BSW19), and lens system: one plano-convex 12 mm diameter and 25 mm focal length and one 12 mm diameter and 72 mm focal length (Edmund Optics 48029 and 36708).

through a 50/50 beam-splitter and is incident on the inside cavity of the detonator holder. Since the cavity is cylindrical, the beam initially converges after reflection and later diverges; the reflected beam reflects back onto the beam-splitter and is focused on a photodetector. During an ignition event, the flyer, purple region in Fig. 2 (b), moves axially towards the collimator and interrupts the 375 nm laser beam. The interruption is observed by the photodetector as a sharp drop in intensity. This sharp change in intensity serves as a trigger for the PDV system.

Figure 3 (a) shows an example PDV signal ($t = 0 - 5$ μs) of a flyer that is suddenly accelerated at approximately 0 μs; the flyer movement is produced by functioning a pristine RP-87 detonator. The high density of the signal illustrates the high beat frequency. An inset shows the PDV signal over a smaller time range of 1.00 to 1.01 μs.

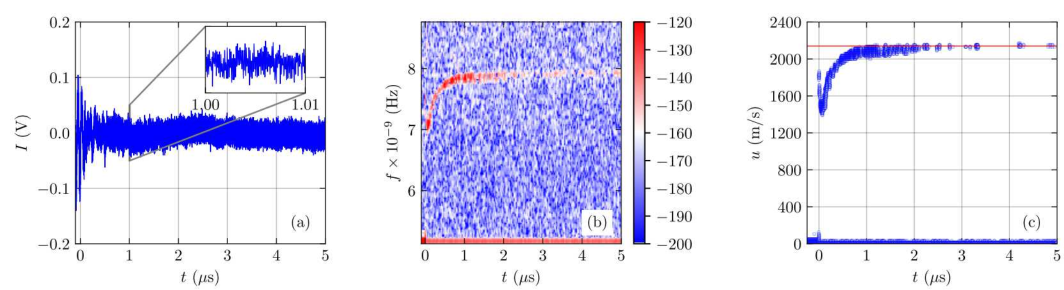


Figure 3: Example of (a) raw PDV signal and corresponding (b) spectrogram calculated using a Windowed Fourier Transform (spectrogram units are in dB); (c) flyer velocity (symbols) calculated from the dominant spectrogram frequencies ($I_f > -145$ dB); the solid red line highlights the flyer final velocity.

A discrete windowed Fourier Transform is applied to the raw signal as follows,

$$G(m, \omega) = \sum_{n=0}^{N} I_n w_{n-m} e^{-j\omega n}, \tag{1}$$

where I is the raw signal, n is the time index, m is the segment index, w is the window function, and ω is the frequency. The window function used in the present study is a Bartlett function,

$$w = \frac{2}{M-1}\left(\frac{M-2}{2} - \left|n - \frac{M-1}{2}\right|\right), \tag{2}$$

where M is the window size. The spectrogram of the raw signal is obtained by,

$$\text{spectrogram}\{G(m,\omega)\} = |G(m,\omega)|^2. \tag{3}$$

Figure 3 (b) shows the computed spectrogram (units in dB) based on the raw PDV signal shown in Fig. 3 (a). The dominant frequencies (high amplitude) are extracted from the spectrogram and plugged in to Eq. 4 to obtain the flyer velocity, u, shown in Fig. 3 (c). The strong signal intensity (-120 dB) shown at approximately 5.1 GHz corresponds to back-reflection of the PDV light off of optical elements within the PDV system and does not correspond to motion.

$$u(t) = \frac{\lambda_0}{2} f(t) \text{ where } f(t) = f_d(t) - f_0, \tag{4}$$

In Eq. 4, f is the beat frequency, f_0 and f_d are the frequencies of the incident and doppler shifted reflected light, and λ_0 is the laser wavelength. Figure 3 (c) indicates that the final velocity of the pristine RP-87 flyer is 2140 ± 40 m/s. Figure 3 (c) shows a sharp rise in velocity to approximately 1850 m/s due to arrival of the von Neumann spike (start of detonation reaction zone); the spike in velocity is expected for a flyer thickness that is less than the reaction zone length of the explosive [4]. In the present study, the flyer has a thickness of 0.16 ± 0.01 mm and the reaction zone length over a range of RDX containing explosives is $0.28 - 0.37$ mm [5, 6].

3 Results

3.1 Overview

Ignition tests were performed for heating rates, α, between 0.02 K/s and 0.81 K/s ($1.2 - 48.6$ K/min) and a nominal initial temperature and initial pressure of 298 K and 100 kPa, respectively. Figure 4 shows the ignition delay time, τ, results for RP-87 as a function of the heating ramp and surface temperature at ignition, T_{ign}. The ignition delay time is defined as the start of heating to ignition. Figure 4 (a) shows experimental results and calculations of $\ln \tau$ as a function of $\ln \alpha$. The calculations were obtained by running a 1D reactive calculation [7] accounting only for heat conduction and chemistry. The chemistry was modeled with a 4-step reaction model for PETN [8]. The experimental and modeling results are in good agreement in Fig. 4 (a). Figure 4 (b) shows that a variation in ignition temperature of approximately 40 K leads to a variation in delay time of almost 2 orders of magnitude.

3.2 Velocity

An example PDV result is shown in Fig. 5 for a heating rate of 0.26 K/s (15.6 K/min). Figure 5 (a) shows the velocity calculated from the PDV signal (markers) and the filtered velocity (line). The filtered velocity in was obtained through time averaging over a window of 0.2 μs and outlier removal using a threshold of

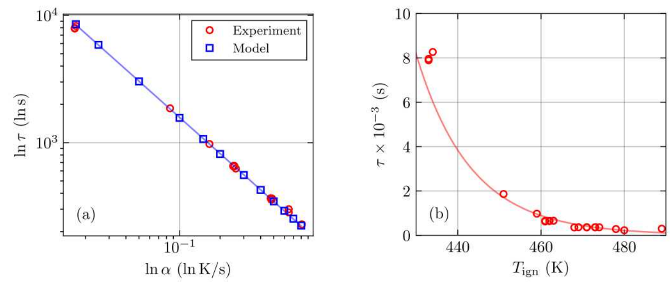


Figure 4: (a) Ignition delay time as a function of heating ramp and (b) ignition temperature; the solid red line in (b) is there to guide the eyes.

2 standard deviations. The flyer reaches a velocity on the order of 2500 m/s approximately 40 μs after initial flyer acceleration. The flyer then decelerates over approximately 30 μs before impacting the PDV collimator probe. The initial flyer velocity from 0 to 30 μs appears well defined in Fig. 5 (a); later, the velocity exhibits significant scatter at the peak and subsequently before impacting the collimator probe. The scatter in velocity is either a result of flyer breakup (multiple fragments with a distribution in velocity) or tilting of the flyer during its travel that leads to steering of the reflected PDV beam (shown schematically in Fig. 2 by the thick blue line reflecting off of the moving surface) away from the collimator probe.

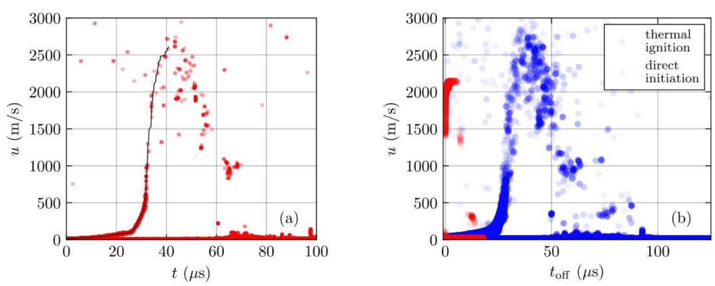


Figure 5: (a) Velocity scatter (red) and filtered and continuous (black) trace of a single thermal ignition experiment; (b) velocity scatter of pristine detonator (red) and twelve overlaid thermal ignition experiments (blue).

Figure 5 (b) shows a comparison between the pristine and thermally ignited detonator flyer velocity. The flyer velocity data from all the thermal ignition cases (blue markers) are overlaid on top of each other to illustrate that there is no effect of the heating rate, ranging from 0.02 to 0.81 K/s, on the flyer behavior. A higher peak flyer velocity is achieved by the thermally ignited detonators than the pristine detonators. However, a faster flyer velocity is not an indication of DDT of the energetic material in the thermally ignited detonators. The impulse, J, imparted on the flyer by a pressure transient, P, in the detonator due to a reactive front can be estimated as,

$$J = \int_0^t F\mathrm{d}t = A\int_0^t P\mathrm{d}t. \tag{5}$$

By relating force to momentum,

$$A\int_0^t P\mathrm{d}t = \int_0^t \mathrm{d}\left(mu\right) = mu(t), \tag{6}$$

where A and m are the surface area and mass of the flyer, respectively. To calculate the pressure history,

$$P = \frac{m}{A}\frac{\mathrm{d}u}{\mathrm{d}t} = \rho b\frac{\mathrm{d}u}{\mathrm{d}t}, \tag{7}$$

where ρ and b are the density and thickness of the stainless steel flyer, respectively. Numerical differentiation of the filtered thermal ignition flyer velocity data yields a peak pressure calculation of a little over 1 GPa (shown in Fig. 6), whereas, the pristine detonator peak pressure is approximately $30-40$ GPa. The experimental Chapman-Jouguet (CJ) pressure of PBX-9407 at a density of 1600 kg/m^3 is 28.7 GPa [9]; a larger pressure is observed in the RP-87 since the PBX-9407 pellet is pressed to a higher density of 1690 kg/m^3. The lower pressure observed in the thermal ignition case compared to the pressure obtained with a pristine detonator indicates that DDT does not take place, despite the high flyer velocity achieved via thermal ignition. The results shown in in Fig. 6 are representative across the heating rates tested.

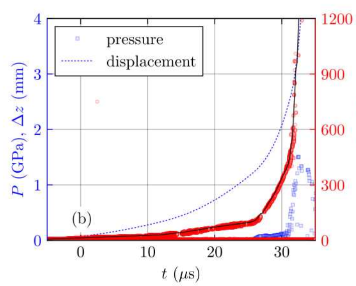


Figure 6: Pressure calculation (blue square markers and left-axis) based on Eq. 7 and using the velocity profile shown by the red circle markers (right-axis); the flyer travel distance is shown by the blue dashed line (left-axis).

4 Conclusions

In this study, the flyer velocity of pristine and thermally ignited RP-87 detonators was measured via Photonic Doppler Velocimetry. A velocity analysis across the heating rates tested ($0.02-0.81$ K/s) indicated that there is no effect of heating rate on the behavior of the RP-87 flyer. Additionally, comparable peak flyer velocities were achieved across all heating rates. An impulse analysis of the flyer resulted in peak pressure calculations inside the detonator of $1-2$ GPa. The low pressure of the thermally ignited detonators is an order of magnitude smaller than the CJ pressure of PBX-9407, therefore, there is no deflagration to detonation transition. This study indicates that although DDT does not take place in thermally ignited RP-87 detonators, the flyer still reaches a high velocity that could potentially initiate an accompanying charge.

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