First attempts in cylinder expansion testing

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Abstract:

The paper deals with cylinder expansion testing of sensitized nitromethane (PLX) confined in copper and aluminium tubes. The experiments were instrumented with Photonic Doppler velocimetry (PDV) and high speed framing camera to track expansion of the tubes. The PDV velocity-time records of the cylinder wall were converted to displacement-time profiles and then a fitting procedure was employed to find pressure-volume dependence of the expanding detonation products. The results compare to those obtained using Explo5 thermochemical code as well as to the literature data. An average Gurney velocity value of 2344 ± 40 m·s^{-1} *was found. The results obtained with aluminium tubes were slightly lower than those with copper tubes. High speed photographs showed that there was no premature breakage of the tubes, although common materials were used.*

Keywords: cylinder expansion test, photonic Doppler velocimetry, PLX, nitromethane

1 Introduction

The cylinder expansion test is one of the most valuable tools for performance characterization of explosives. The tested explosive is confined in a metallic tube and initiated from one end. The test is based on measurement of tube widening caused by expansion of detonation products of the tested explosive. The parameters which can be determined by means of cylinder test are primarily Gurney velocity, detonation energy, and p-V expansion path of detonation products. The latter can be used to determine Jones-Wilkins-Lee (JWL) equation of state parameters of the detonation products. Detonation pressure can also be determined when close range expansion data are available. [1]

Typical inner diameter of the tube employed in the test is 25.4 mm with a wall thickness of 2.54 mm. However, other diameters (12.7 mm [2], 19.05 mm [3], 50.8 mm [4], 101.6 mm [5]) are also used occasionally. The most common tube material is oxygen free high conductivity copper (Cu-OFHC) which is used because of its high ductility in order to allow large expansions without cracking. The wall thickness is usually chosen as 1/10 of the tube diameter. The wall velocity has been originally measured using electrical contact pins or streak camera recordings since 1960's. Photonic Doppler velocimetry [6] recently became a method of choice for this kind of testing.

This work shows some of the first attempts to perform cylinder expansion tests in the Institute of Energetic Materials instrumented with PDV diagnostics.

2 Experimental

2.1 Materials

Four cylinder expansion tests were performed using nitromethane (95%) sensitized with ethylenediamine (5%). This liquid explosive mixture is also known under abbreviation PLX (Picatinny Liquid Explosive). A copper and aluminium tubes were used as a confining material. The copper tubes were made of Cu-DHP (>99.9% Cu, phosphorous deoxidized) without annealing. The copper tubes had outer diameter 17.9 mm and wall thickness 1.43 mm. The aluminium tubes were made of AW-6060 alloy (>99.5% Al). The outer diameter of the aluminium tubes was 20.0 mm and wall thickness 2.1 mm.

2.2 Detonation velocity measurement

The velocity of detonation was measured directly in the cylinders using discontinuous method using two fiber optic probes connected to photodiodes and an electronic counter (prototype device currently commercialized by OZM Research). The sampling frequency of the counter was 50 MHz which corresponds to a time resolution of 20 ns. The probes were inserted in holes drilled in the charge casing 100 mm apart, the first hole being 80 mm from the detonator. The holes were covered from the inner side by aluminium tape to avoid spilling of the liquid.

2.3 Cylinder expansion measurement

The cylinder expansions were tracked using single channel photonic Doppler velocimeter (prototype device produced by OZM Research) with bare fiber probes. The electric signal produced by the PDV was recorded using high bandwidth digital oscilloscope (Tektronix DPO70000 series). Bare fiber probes were fixed to aluminium holders in a position of about 11 mm from the cylinder wall. The probe axes were inclined towards the detonator by 5° relative to the cylinder wall normal (figure 1) in order to improve PDV signal quality [7].

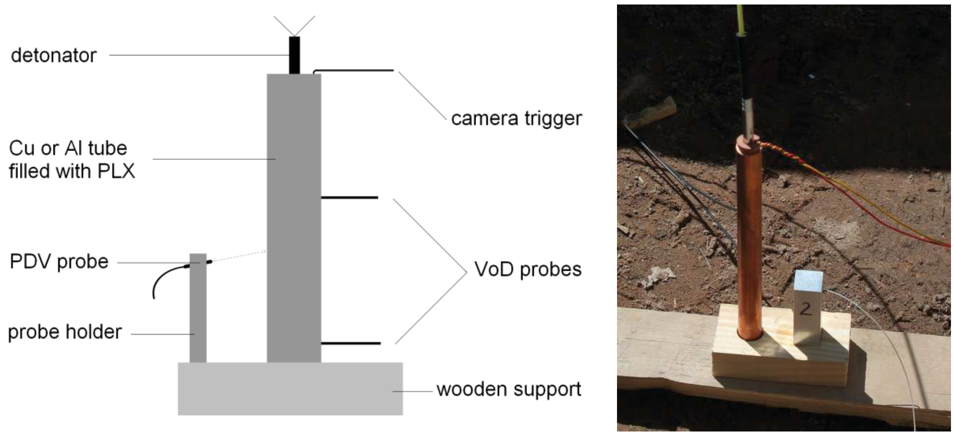

Figure 1: Scheme (left) and photograph (right) of the experimental setup

2.4 High speed photography

Two of the experiments were captured using UHSi 12/24 ultrahigh speed camera (Invisible Vision) equipped with Samyang 800 mm f/8 mirror lens. The camera was protected from fragments by a concrete barrier with a viewing slot with a mirror which tilted the axis of image projection by 90°. The shutter speed was 200 ns at a frame rate of 300 000 frames per second. The recording was triggered using an ionization pin inserted in the tested explosive charge close to the detonator. Twelve frames were captured in each test. Back illumination of the charge was performed by detonating a small explosive charge topped with aluminium powder placed on the ground 1 m behind the tested charge as it is shown in [8]. No light diffuser was used. The illuminating charge consisted of 10 g Semtex 1A plastic explosive and 30 g of paint grade aluminium powder wrapped in aluminium foil laid on it.

2.5 Thermochemical code prediction

Calculation of detonation parameters was conducted using the latest available version of Explo5 V6.03 thermochemical code [9]. Fundamental fluid Exp-6 equation of state (EOS) according to Byers-Brown's approach [10] for description of detonation products was used. The Chapman-Jouguet detonation parameters and states of detonation products along their expansion isentrope were calculated.

3 Results and discussion

According to available literature, detonation properties of PLX are very close to NM, e.g. the detonation velocity of PLX being just 0.8% lower than NM [11]. The detonation velocity averaged from all the experiments was $D = 6242 \pm 19\ \mathrm{m \cdot s^{-1}}$ which compares well with literature values for PLX (Table 1).

Table 1: Detonation velocity of PLX compared with calculated and literature values.

Detonation velocity $\mathrm{m \cdot s^{-1}}$	Charge diameter mm	Reference
6242	15	this work
6165	24	[11]
6220	36	[12]
6220	305	[13]
6320	-	Explo5

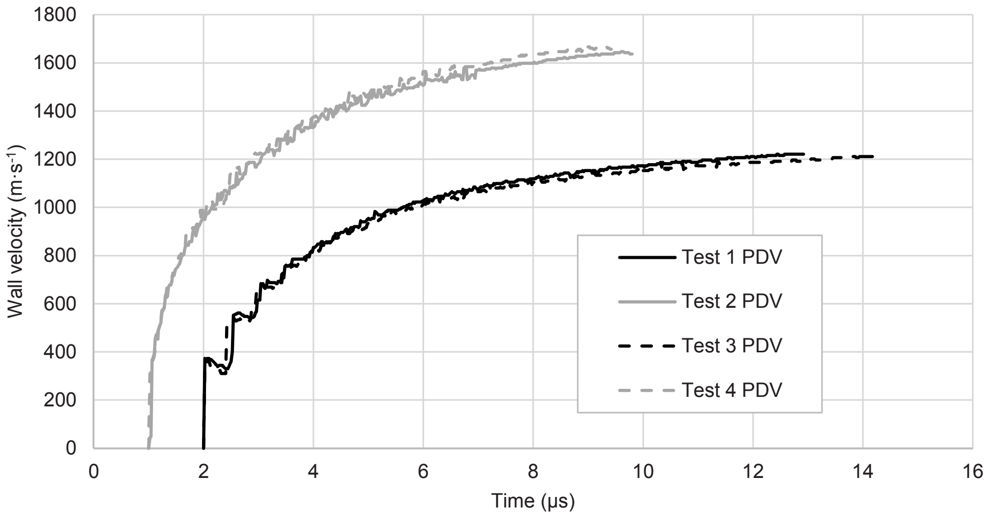

Figure 2: Cylinder wall velocity-time and displacement-time profiles obtained with PDV (both profiles are artificially shifted in time)

The experimental wall velocity profiles are shown in figure 2. It can be seen that the acceleration is smooth in aluminium and stepped in copper. This can be explained by the fact that the shock velocity in aluminium is higher than the detonation velocity of PLX [14-15].

Gurney velocities (G) were calculated from the wall velocities at specific volumes of $V/V_0 = 7$ (v_7) and charge geometry parameters (explosive and cylinder mass per unit length, C and M respectively) via the Gurney equation for cylindrical explosive charge [16]:

$$\frac{v_7}{G} = \left(\frac{M}{C} + \frac{1}{2}\right)^{-1/2} \tag{1}$$

The cylinder wall velocities (v_2 and v_7) were read out directly from the velocity profiles (figure 2) at times which corresponded to specific volumes $V/V_0 = 2$ and $V/V_0 = 7$. The values of v_7 were then used for calculation of Gurney constants using equation (1). The difference in Gurney velocity between the two experiments is 2.6% and 1.8% in copper and aluminium, respectively. The differences could be probably caused by local variations in the wall thicknesses. The overall average value of $G = 2344 \pm 40$ m·s^{-1} was found. However, it can be seen that the results obtained with copper tubes are higher compared to those from aluminium tubes. If only the results from copper tubes are considered, perfect match can be seen with the recent literature value of 2390 m·s^{-1} [2] obtained with similar copper tubes. The cylinder wall velocity and Gurney velocity data are shown in table 2.

The experimental outer wall velocity-time profiles were transformed to outer wall displacement-time profiles by integration. The inclination of the probes by 5° was neglected and the displacement was assumed to be radial. It can be seen from the figure 3 that the profiles obtained using PDV are almost identical for the pairs of shots in copper and aluminium. The corresponding profiles obtained with PDV and high speed camera do not match well especially in test 2 probably due to low dimensional tolerances of the tubes. However, the high speed photographs showed that both Al and Cu tubes expanded without premature cracking. The only gas leakage occurred through detonation velocity probe holes but these were far away from the PDV spot (figure 5).

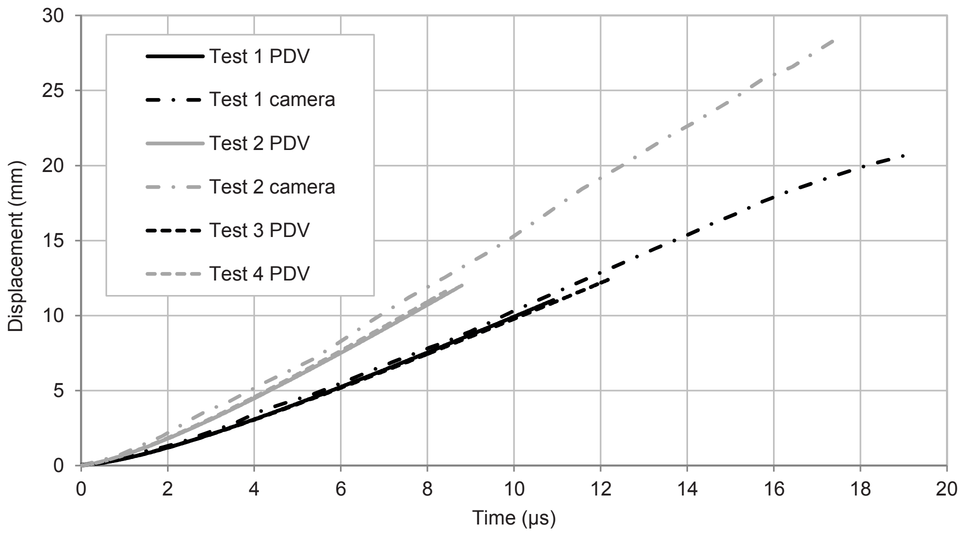

Figure 3: Cylinder wall displacement-time profiles obtained with PDV and high speed camera images

To calculate p-V relationship from the measured experimental data, a combination of previously published procedures was used. The central cylinder surface positions r_m were calculated according to [17]. These $r_m(t)$ data were fitted to a function from [18]:

$$r_m(t) - r_{m0} = \frac{v_\infty t g(t)}{\frac{2v_\infty}{a_0} g'(t) + g(t)} \tag{2}$$

where r_{m0} is initial radial position of the central surface of the cylinder, t is time, v_∞ is the asymptotic radial wall velocity, a_0 is the initial radial acceleration and $g(t)$ is a function of time:

$$g(t) = (1+t)^\omega - 1 \tag{3}$$

with ω as a parameter. The virtual time origin ($t - t_0$ instead of t) was used to enable a better fit. The four parameters v_∞, a_0, ω and t_0 were obtained by fitting. Based on the initial acceleration a_0, the detonation pressure p_{CJ} was calculated according to [1]:

$$p_{CJ} = \frac{M a_0}{2\pi r_{i0}} \tag{4}$$

where r_{i0} is initial inner tube radius. The equation (2) was differentiated analytically to obtain radial velocity and radial acceleration. The resulting back-calculated radial wall velocities v_7 matched the experimental velocities within about 1% in the case of copper and 2.6% in the case of aluminium tubes. The asymptotic radial wall velocities v_∞ and detonation pressures p_{CJ} calculated using the PDV data are shown in table 2. The detonation pressures are at the upper range of values published in literature (12.5 to 13.8 GPa) [1]. Pressures and corresponding specific volumes during the cylinder expansion (figure 4) were obtained as described in [17].

Table 2: Summary of the results for PLX cylinder expansion tests. The wall velocities v_2 and v_7 were read directly from the PDV records, Gurney velocities G were calculated using equation (1), the asymptotic velocities v_∞ were obtained by displacement-time regression, and detonation pressures p_{CJ} came from equation (4).

Test no.	Tube material	v_2 m·s^{-1}	v_7 m·s^{-1}	G m·s^{-1}	v_∞ m·s^{-1}	p_{CJ} GPa
1	Cu	1012	1232	2405	1334	13.9
2	Al	1318	1642	2293	2032	13.7
3	Cu	993	1201	2344	1304	13.8
4	Al	1342	1672	2335	2152	14.0
Explo5	-	-	-	-	-	12.4

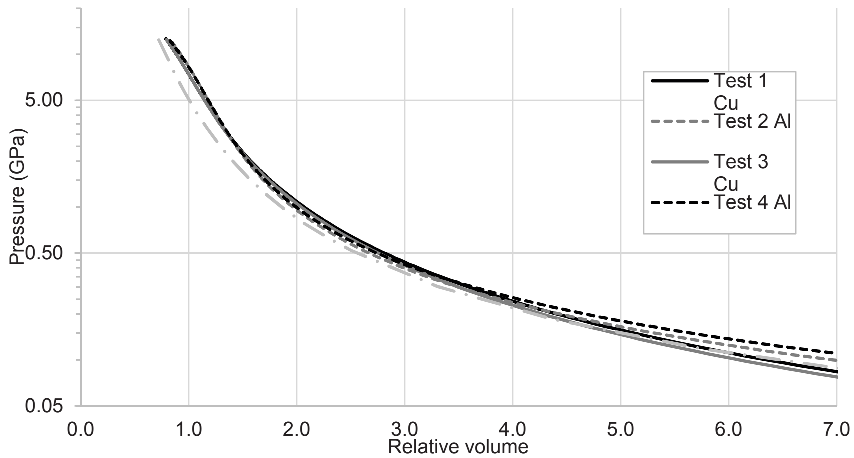

Figure 4: Pressure-volume dependence for PLX detonation products

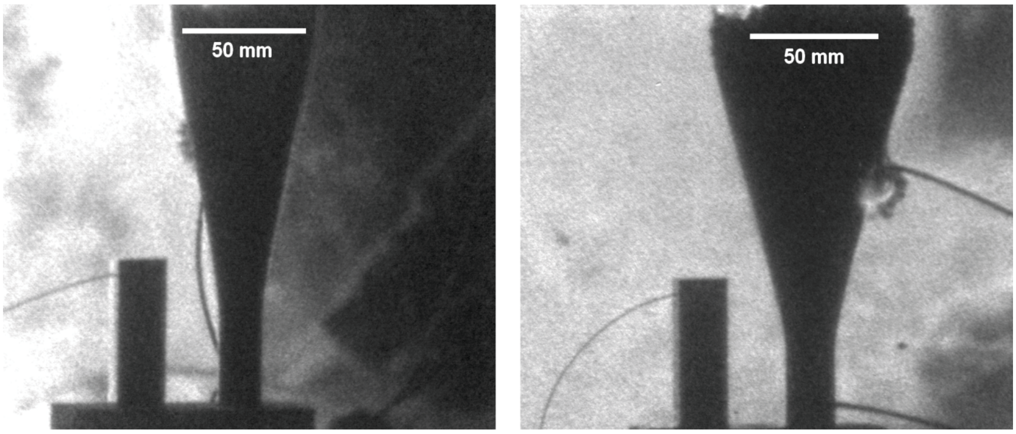

Figure 5: High speed images of the expanding cylinder at 200 ns exposure time (Cu tube – left, Al tube – right)

4 Conclusions

The photonic Doppler velocimetry proved to be a valuable technique for cylinder expansion test instrumentation. All the measured profiles show full path of the wall between the original position and the probe tip. The high speed photographs also showed that the integrity of the tubes was not impaired at much more than seven-fold expansion. The Gurney velocities are in accordance with the most recent literature data and the p-V data correspond to the Explo5 thermochemical code predictions. The detonation pressure values are at the upper end of the range published in literature.

The shot to shot variation within 3% is not as good as expected and was caused by insufficient dimensional precision of the metallic tubes. The wall thickness of the tubes is a crucial parameter which should be preferably determined directly in place of the PDV probe spot. The range of p-V data was limited by the use of bare fiber probes. The use of parallel beam probes should therefore be preferred.

Acknowledgments

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