

Full Paper

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Urea-Hydrogen Peroxide (UHP): Comparative Study on the Experimental Detonation Pressure of a Non-ideal Explosive

Francis Halleux ^{*[a,b]}, Jean-François Pons ^[a], Ian Wilson ^[a], Chris Stennett ^[a]

Romuald Van Riet ^[b], Michel Lefebvre ^[b]

Abstract: Carbamide Peroxide, an adduct of Urea and Hydrogen Peroxide (UHP) industrially used as a solid source of hydrogen peroxide, exhibits the behaviour of a tertiary explosive but a detailed performance characterisation is still lacking in the literature. In this work, we calculated a 20% experimental TNT equivalence for brisance, i.e. the shattering effect from the shock wave transmitted from the detonating high explosive into adjacent materials, by experimental indirect measurement of UHP detonation pressure. We determined a 3.5 GPa detonation pressure for 5 kg unconfined UHP charges (0.87 g/cm³, 120 mm charge diameter) by measuring the attenuated shock wave velocity (ASV) in adjacent inert materials using passive optical probes. Particle velocity measurements at the interface of a PMMA impedance window carried out with Photonic Doppler Velocimetry on scaled-down charges of 90 g UHP under heavy confinement (0.85 g/cm³, 30 mm charge diameter, 4 mm thick steel) are consistent with ASV results in the PMMA acceptors but further investigations are required to determine the detonation pressure, using a small-scale experimental set-up. The ASV method has proven reliable to assess the brisance of a non-ideal explosive for risk assessment purposes.

Keywords: Urea hydrogen peroxide, Non ideal explosive, Detonation pressure, Passive optical probes, Photonic Doppler Velocimetry

1 Introduction

Carbamide Peroxide, an adduct of Urea and Hydrogen Peroxide (UHP), is industrially used as a solid source of hydrogen peroxide. Like other oxidisers such as ammonium nitrate (AN) [1], or AN-based explosive compositions [2], it exhibits significant non-ideal detonation properties at the 10-cm scale. To the best of our knowledge, the explosive behaviour of UHP was rather recently studied in the literature and a detailed characterisation of UHP detonation performance parameters is still lacking. Hussein carried out ballistic mortar experiments and thermochemical calculations to assess the relative explosive strength of mixtures containing urea and/or peroxide [3]. Matyas investigated UHP sensitivity, thermal properties and detonability at large-scale [4], while preliminary work from the authors demonstrated UHP detonability at small-scale and highlighted UHP charges non-ideality by Velocity of Detonation (VoD) dependence on charge diameter and confinement. Additionally, UHP relative explosive strength was further assessed from experimental underwater bubble energy and airblast parameters (long distance blast wave) measurements [5-6].

Within the scope of a performance assessment, one of the key parameters still to be addressed was the brisance, the shattering effect from the shock wave transmitted from a detonating high explosive into adjacent materials. Examples of standardised tests [7-8] available to assess the relative brisance of explosives include the Hess test, evaluating the compression of a lead cylinder, the Kast's method, using a copper crusher

or the plate-denting test [9]. The latter has proven effective to correlate the indentation of a witness plate with the experimentally determined detonation pressure of conventional military explosives but extrapolation to a material such as UHP might be questionable taking into account (major) differences in detonation products composition, particularly water content, and very low detonation temperature [6]. Considering the non-ideal behaviour of UHP, it was decided to quantify the brisance of UHP through its predominant parameter, the detonation pressure (P_{det}) [8-9], as illustrated in Figure 1.

The detonation pressure can be calculated from thermodynamical codes, estimated using empirical correlations from VoD and loading density (ρ) [10-11] or determined experimentally. Considering the time-scale of the phenomenon and the severe conditions of pressure and temperature [8], direct measurement of the detonation pressure using in situ gauges [12] such as Polyvinylidene fluoride (PVDF) piezoelectric [13] or Manganin piezoresistive sensors [14] is challenging and not yet widely applied or validated, especially when considering kg-scale non-ideal explosive charges.

[a] F. Halleux, J.-F. Pons, I. Wilson, C. Stennett
Centre for Defence Chemistry
Cranfield University Defence Academy of the United Kingdom, Shrivenham SN6 8LA, United Kingdom
*E-mail: F.Halleux@cranfield.ac.uk

[b] M. Lefebvre, R. Van Riet
Department of Chemistry
Laboratory for Energetic Materials
Royal Military Academy of Belgium
Brussels 1000, Belgium

However, indirect measurement methods are also available to determine the detonation pressure, observing the shock wave properties in inert well-characterised adjacent materials (impedance matching) and not interfering with the detonation wave [15].

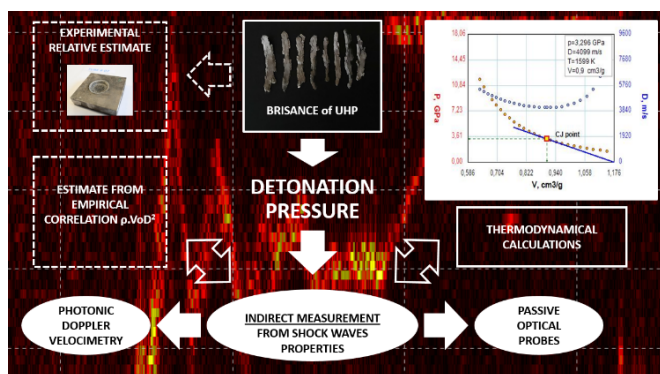


Figure 1. General approach – UHP brisance by indirect measurement of the detonation pressure.

In this comparative study, we investigated UHP detonation pressure respectively at large and small scale using two distinct indirect methods, respectively measuring shock then particle velocities. First, at large-scale, using an optical system, we looked at the Attenuated Shock Velocity (ASV) in different inert materials. Secondly, in an attempt to study large-scale behaviour from lab-scale experiments [2, 16, 17] and avoid time-consuming, expensive and potentially hazardous large-scale experimental campaigns, we used Photonic Doppler Velocimetry (PDV) in combination with a Polymethylmethacrylate (PMMA) impedance window (IW). One of the key advantages of this method, compared for example to the flyer plate method [15, 18], is the potential ability to capture the whole particle velocity history of an explosive/inert material interface from one single shot. It is however limited to transparent contact materials. The experimental detonation pressure is compared to the predictions from thermochemical calculations (using the ideal model) and discussed, together with the overall accuracy of the calculations and their limitations when dealing with non-ideal explosives. The experimental detonation pressure is further compared to the estimate from empirical correlations based on VoD and loading density. An experimental TNT equivalence of UHP for brisance is proposed. We assess the reliability and accuracy of the experimental methods and the level of agreement between large-scale and small-scale results, particularly the validity of the small-scale setup for quick assessment purposes.

2 Experimental Section

In line with our initial work, we further used commercial lab grade UHP (97%) purchased from ALFA AESAR. We had determined the average particle size by dry sieving with 85% of the particles retained in the 600 μm mesh and 15% in the 1000 μm mesh. Using the

standard enthalpy of formation of UHP calculated from calorimetric measurements, thermochemical calculations were carried out with the Explo5 code (V6.06.02) [19]. We initially used the theoretically based equation of state (EoS) molecular fluid EXP-6 [20], which predicted lower detonation pressures and enabled the determination of the Jones-Wilkins-Lee (JWL) coefficients required for the numerical modelling in Ansys Autodyn [5-6]. However, for comparison purposes, we also performed the calculations with the Modified Becker-Kistiakowski-Wilson (M-BKW) EoS, as this equation of state provides greater accuracy for explosives with a low detonation temperature and a high dipolar molecules content in the detonation products [21]. UHP ideal detonation parameters, such as detonation velocity, pressure and polytropic exponent, were compared to experimental data.

Building upon initial measurements carried out at loose density (0.75 g/cm^3), where self-compaction phenomenon and density gradient were observed for large charges, it was decided to increase the UHP charge loading density to 0.85 g/cm^3 ($\pm 0.02 \text{ g/cm}^3$), 59.4% of the reported 1.43 g/cm^3 [4] Theoretical Maximum Density (TMD), to achieve more uniform loading and homogeneity. This density was also easily obtained, without heavy pressing equipment, which sounded realistic in a terrorist perspective, as UHP, within the scope of our research, was also studied as a potential emerging threat.

In the following subsections, we present the selected indirect methods and respective experimental set-ups to investigate the detonation pressure at large and small scale.

2.1 P_{det} by ASV (large-scale campaign)

The ASV method consists of measuring the arrival time at different depths in an inert acceptor in contact with an explosive charge using optical probes, and extrapolating the shock velocity at the explosive/inert interface [22]. The light signal is emitted by the ionised air at the bottom of the holes drilled to insert the probes. This method neglects the Von Neumann (VN) spike, as it does not lead to air ionisation due to its very small impulse. In this study, we selected a charge diameter of 120 mm, a trade-off between the impact of the diameter on the performance characterisation and the practical charge size. In this charge diameter (PVC casing, 2.5 mm thick), we previously recorded an average VoD of 3.520 km/s for unconfined UHP, about 90% of the VoD extrapolated at infinite charge diameter from our experimental data [6]. We fired 10 cylindrical charges (two shots for each acceptor) containing approximately 5 kg UHP ($L=5xD$, $\rho=0.87 \text{ g/cm}^3$, 60.8% TMD) and initiated by a bespoke moulded conical 350 g C4 booster (Figure 2, top left) and a standard N°8 military detonator. Building upon the results from a preliminary ASV campaign (86.4 mm charge diameter) carried out to select and design the inert acceptors, we prepared two disks (thickness 32 mm; diameter 120 mm) of five different materials with well-characterised shock properties [10, 23] in an attempt to cover a wide range of shock impedances and construct the (reflected)

Hugoniot of the detonation reaction products of UHP: Aluminium 7075, Magnesium alloy AZ31B, Polymethylmethacrylate (PMMA), Polytetrafluoroethylene (PTFE) and Polymethylpentene (TPX). As TPX was only available in 50 mm diameter rods, we filled the outer part with 1-pentanol, a liquid with an acoustic impedance very close to that of TPX [23], in an attempt to mitigate the interferences with the boundaries. Figure 2 gives an overview of the experimental setup. Each UHP charge was in direct contact with the acceptor. Eight optical probes were inserted into the acceptor. The probes consist of a bare glass optical fiber with a core and sleeve diameter of 50 μm and 1 mm, respectively. The fibers were stripped to the core on 1-2 mm and the cores properly cleaved with a ruby scribe. To insert the probes into the acceptor, eight holes (1 mm diameter) were drilled at the following depths by 4 mm increments: 4, 8, 12, 16, 20, 24, 28 and 32 (all-through, isolated from the charge by a 30 μm layer of Al tape). The depth of each individual hole was re-measured after drilling (precision ± 0.01 mm) for accurate shock velocity records. All holes were located at an identical 15 mm radial distance from the charge axis to minimise the effect of the radius of curvature (ROC) of the detonation front. In fact, using the method described in Reference [24], an average experimental 180 mm relative ROC of the detonation front had been determined for 86.4 mm diameter UHP charges during the preliminary ASV campaign. The distance between probes within the acceptor disks was optimised in such a way that the arrival times were not influenced by the shock wave distortions caused by the holes. The whole measurement zone (30 mm diameter) was also chosen sufficiently small with regard to the acceptor diameter (120 mm) to limit the influence of lateral relief waves on the shock propagation.

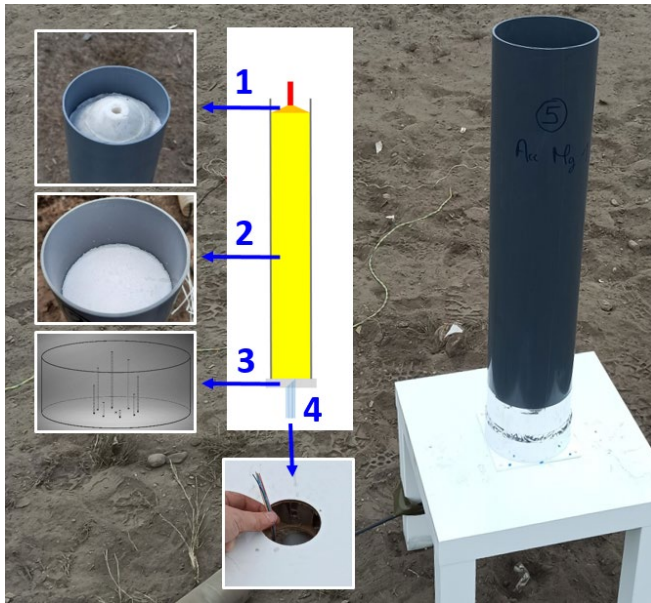


Figure 2. UHP (5 kg) – P_{det} by ASV – Experimental setup: (1) Initiation; (2) UHP charge; (3) Drilled inert acceptor; (4) ASV optical probes.

We used a passive light acquisition system OPTIMEX 64 (OZM research) to track the light signal (250 MHz sampling frequency) from the shock wave generated by the detonation of UHP and propagating through the inert acceptor attached to the tested explosive charge. The shock velocity in each inert material was then calculated from distance-time records using a linear regression, which was preferred to the parabolic one suggested in [22], taking into account significant differences between both experimental setups. In fact, Künzel et al. made use of 40 mm diameter charges and recorded the light signal up to 20 mm deep into the acceptor, giving a charge diameter to depth ratio around 0.5. We used 120 mm diameter charges and measured up to 28 mm deep in the acceptor, which corresponds to a charge diameter to depth ratio around 0.2. We also used longer charges ($L=5xD$ compared to $1.5xD$, including booster, in [22]). For those reasons, the decrease of the shock velocity due to the rarefaction wave is expected to be slower in our setup, which supports our choice for a linear regression.

For the sake of simplicity, a polytropic EoS was used to characterise the UHP detonation products and determine the detonation pressure from the ASV measurements. First, the reflected Hugoniot in the pressure/particle velocity plane (P, u), is expressed as a function of the polytropic exponent (Γ), with the initial density of the charges (ρ_0) and the velocity of detonation (VoD), as input parameters:

$$P = \frac{\rho_0}{2} \cdot \left[\frac{5 \cdot (VoD)^2}{\Gamma + 1} - 4 \cdot (VoD) \cdot u + u^2 \cdot (\Gamma + 1) \right] \quad (1)$$

In this equation, Γ is the only unknown as the previously determined averaged velocity of detonation of 3.520 km/s [6] is used. Then, we express the Hugoniot of a transmitted shock in a given acceptor material as a function of the shock velocity in the acceptor material (i) at the interface with the explosive, U_i :

$$P = \rho_{0,i} \cdot U_i \cdot u_i = \rho_{0,i} \cdot U_i \cdot \frac{U_i - C_{0,i}}{s_i} \quad (2)$$

where $\rho_{0,i}$ is the density of the acceptor material and $C_{0,i}$ and s_i the parameters of the empirical Hugoniot of the acceptor materials [23]. By continuity, both the pressure in the acceptor material at the interface and in the detonation gases after interaction are equal [10]. By equating equations (1) and (2), we then obtain a model for the shock velocity in the acceptor material with Γ as only parameter. The optimal value of Γ is then determined by using a least-square methods minimising the sum of square of the errors between this model and the experimental values of the shock velocity at the interface, taking the nature of the acceptor into account. Using this optimal value of Γ , the detonation pressure is finally calculated by using the relation [7, 10]:

$$P_{\text{det}} = \frac{\rho_0 \cdot (VoD)^2}{\Gamma + 1} \quad (3)$$

2.2 P_{det} by IWM (small-scale campaign)

In line with our previous work on detonability and detonation performance of UHP at small scale, we further used the following charge geometry: 4 mm thick steel confinement, Inner Diameter (ID) 30 mm, Outer Diameter (OD) 38 mm, Charge Length (L) 150 mm ($=5 \times \text{ID}$). The initiation train consisted of an 8 g C4 (PE8 for PDV) booster in a bespoke conical cup holding a N°8 standard military detonator. At that time, the stationarity of the detonation wave after 2 to 3 charge diameters was assessed by measuring the indentation of a witness plate resulting from the detonation of 1 to 6 diameters long UHP charges [5]. In this work, we could further confirm stationarity by monitoring the VoD of UHP along the whole confinement sleeve using 19 GOF, with 7.5 mm between probes (Figure 3).



Figure 3. UHP (90 g) under heavy confinement – VoD stationarity assessment using 19 GOF.

For the PDV campaign itself, a total of 12 devices were fired. The confinement steel sleeves were filled with approximately 90 g of UHP ($\rho = 0.85 \text{ g/cm}^3$, 59.4% TMD, slightly compacted). The OPTIMEX 64 (OZM research) passive light acquisition system (250 MHz sampling frequency) already presented in Section 2.1 was further used but in another configuration to record VoD. The setup included a total of 8 GOF, with 7.5 mm between probes, and the first probe located 90 mm ($3 \times \text{ID}$) from the booster charge, as explained previously. The probes were inserted in all-through holes drilled in the confinement sleeve and sealed by a piece of 30 μm thick aluminium tape.

In order to measure surface velocities, we used a first generation photonic Doppler velocimeter. This equipment included a 1550 nm laser source, emitting laser light from a fibre-coupled collimator with a 75 mm working distance and a 220 μm spot size. The reflected (Doppler-shifted) light was mixed in the interferometer, and a Thor Labs PDA-8GS photodetector amplified the intensity of the beat signal. We used a Tektronix 6 GHz bandwidth oscilloscope, sampling at 5 GHz, to record the electrical output from the photodetector. A Hamming window Fourier transform with variable window width was used to process each velocity record, producing a time-resolved power spectrum image, which was manually digitised to analyse numerical time-velocity

data. We used PDV in combination with the Impedance Window Method (IWM) [15, 25] in an attempt to determine the P_{det} of UHP at small scale.

Building upon preliminary results from our first attempts to determine the detonation pressure of UHP using the IWM [26], the initial experimental setup was slightly modified (Figure 4). We used two separated parallel steel rod stands (10 mm diameter) and a bespoke impedance window holder to avoid any contact between the PMMA and the confinement sleeve, while ensuring good contact between the aluminium interface and the UHP granular bed. The holder (Figure 4, top right) was also designed to position the laser probe on a reproducible way, aligned normal to the surface to get the strongest signals, at about 2 mm standoff from the PMMA window, facing the centre of the mirror interface. The laser probe was directed at a 100 μm thick aluminium mirror interface (28 mm diameter) placed between the end of the test specimen, directly on the granular bed (no surface preparation) without touching the steel confinement sleeve, and the 4 mm thick PMMA impedance window (28 mm diameter), to record the motion of this interface. The OPTIMEX generated the output trigger signal to start the PDV instrumentation, so that the beginning of the visible trace effectively corresponded to the detonation wave arrival to the explosive/inert interface.

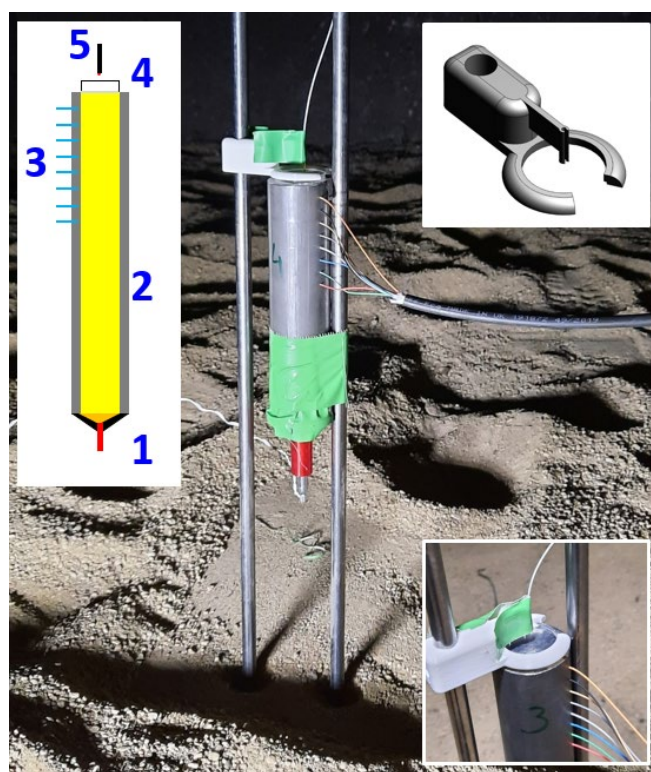


Figure 4. UHP (90 g) – P_{det} by IWM using PDV – Experimental setup: (1) Initiation; (2) UHP charge under heavy confinement; (3) VoD optical probes; (4) Impedance window; (5) PDV laser probe.

When it comes to the determination of P_{det} , anticipating on the results (Section 3.2), the intention of the authors was to apply on UHP the following method, which has proven effective for more ideal and homogeneous materials [15]: identifying the Chapman-Jouguet (CJ) state on the recorded particle velocity profile (u) from two linear regressions, respectively from the initial VN spike and the following Taylor wave, then using the generalised EoS for detonation products (Equation 4) [10] to estimate the Hugoniot of the reacted UHP and the Rayleigh line (Equation 5), with u_{CJ} as an input parameter for both.

$$\frac{P}{P_{CJ}} = 2.412 - 1.7315 \frac{u}{u_{CJ}} + 0.3195 \left(\frac{u}{u_{CJ}} \right)^2 \quad (4)$$

$$P = \rho_0 \cdot VoD \cdot u \quad (5)$$

3 Results

3.1 P_{det} by ASV (large-scale campaign)

Figure 5 provides an example of distance-time record with linear regression, while Table 1 summarises the results of the 10 ASV firings (2 per acceptor), including the measured shock velocity (U_i) determined from linear regression and calculated particle velocity (u_i) and initial pressure in inert material P_i .

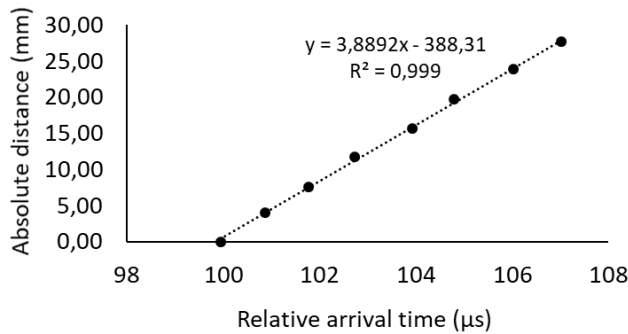


Figure 5. Example of distance-time record with linear regression – Shock velocity in PMMA.

Table 1. ASV campaign (5 kg UHP, 0.87g/cm³, charge diameter 120 mm).

Shot	Acceptor	ρ_0 (g/cm ³)	C_0 (km/s)	s (-)	U_i (km/s)	u_i (km/s)	P_i (GPa)
1	PMMA	1.186	2.598	1.516	3.971	0.906	4.266
2	PMMA	1.186	2.598	1.516	3.889	0.852	3.929
3	TPX	0.830	2.07	1.58	3.841	1.121	3.574
4	TPX	0.830	2.07	1.58	3.855	1.130	3.614
5	Mg AZ31B	1.775	4.516	1.256	5.249	0.584	5.438
6	Mg AZ31B	1.775	4.516	1.256	5.272	0.602	5.636
7	PTFE	2.153	1.841	1.707	3.056	0.712	4.684
8	PTFE	2.153	1.841	1.707	3.064	0.717	4.727
9	Al 7075	2.804	5.200	1.36	5.613	0.304	4.781
10	Al 7075	2.804	5.200	1.36	6.105	0.666	11.397

When it comes to measurement uncertainty, we calculated the particle velocity (u_i) from the measured shock velocity (U_i) in an inert acceptor and then used this value to further calculate the initial pressure P_i . For this reason, the error on P_i is proportional to the square of the measurement error on U_i . Moreover, as the Hugoniot in the U - u plane is an affine function, the error on particle velocity u_i can increase quickly, especially at low particle velocities. Due to the high shock impedance of aluminium and the rather low detonation regime, the error on pressure was too large. The shocked state (P_{Al} , u_{Al}) was disregarded and the UHP detonation products Hugoniot was then constructed from the shock states (P_i , u_i) in the four remaining inert acceptors (Figure 6). The steady-detonation state was found at the intersection of the experimental reflected Hugoniot and the Rayleigh line, corresponding to a P_{det} of 3.46 GPa. Despite the choice of a rather low shock impedance material such as TPX, we could not encompass the steady-detonation state and its determination required a slight extrapolation.

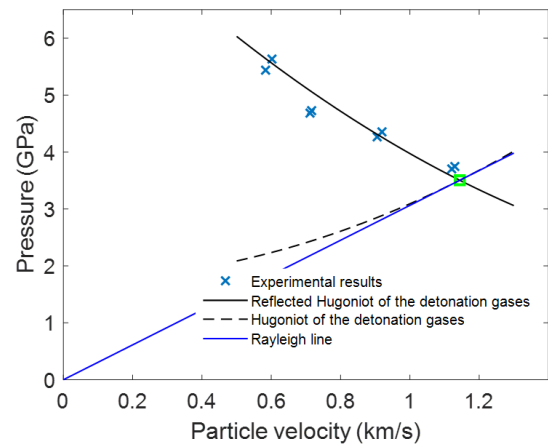


Figure 6. UHP steady-detonation state (green) at the intersection of the reflected Hugoniot and the Rayleigh line.

3.2 P_{det} by IWM (small-scale campaign)

Reproducible VoD results with an average 3.297 km/s (± 0.014 km/s for 95% confidence interval) for 90 g UHP charges (0.85 g/cm³ loading density) under heavy confinement were obtained. These results are consistent with previous work from the authors on small-scale detonability of UHP [5] and the confirmatory shots carried out with 19 probes located all along the confinement sleeve to assess the stationarity of the detonation (see example on Figure 7). The overdriven state due to the 8 g C-4 booster is obvious in the first charge diameter (30 mm), while stationarity is already observed after two charge diameters.

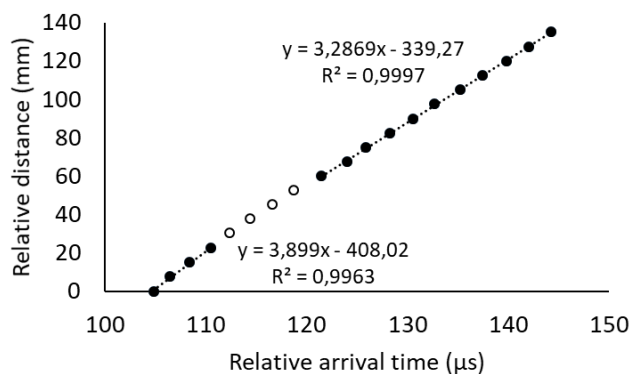


Figure 7. UHP VoD (0.85 g/cm³, heavy confinement) – Initial overdriven state from the 8 g C4 booster, transition and stationarity after two charge diameters.

These preliminary results confirm the consistency of our small-scale PDV setup, the output trigger signal being generated after 3 charge diameters to start the velocimeter, so that the beginning of the visible trace effectively corresponds to the arrival of a stationary detonation wave to the UHP/PMMA interface. Figure 8 shows an example of such a trace, typical for non-ideal explosives [26], including the arrival of the detonation wave, the initial velocity scatter due to the heterogeneity of the explosive, the shock transit time through the PMMA, typically 1-3 μs depending on pressure, then a second trace, at approximately twice the interface velocity, which corresponds to the free surface velocity of the PMMA window.

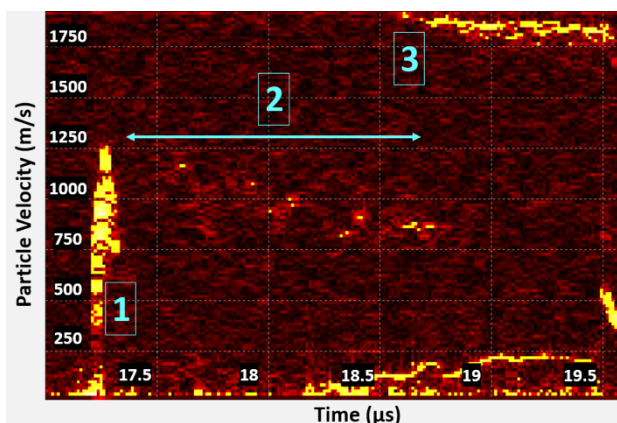


Figure 8. PDV – Example of time-resolved power spectrum image (1 shot): arrival of detonation wave (1), transit time through PMMA (2), free surface velocity (3).

From the 12 shots carried out in the same configuration, only 5 shots could capture the motion of the interface, the other 7 only providing the PMMA upper free surface velocity trace. Digitised time-velocity data of these 5 shots are combined in Figure 9. We arbitrarily selected the last 500 ns of the record in the PMMA window, when the signal seemed to stabilise after initial velocity scatter, and determined an average 877 m/s (± 18 m/s for 95% confidence interval) particle velocity at the explosive/inert interface, a value consistent with ASV results, i.e. particle velocities calculated from shock velocities measured in PMMA

(Table 1 in Section 3.1). The limited number of records of the interface motion highlights the relative difficulty to carry out IW experiments on coarse granular explosives, when compared to pressed, melt-cast, cast-cured [15] and of course homogeneous liquid explosives [27].

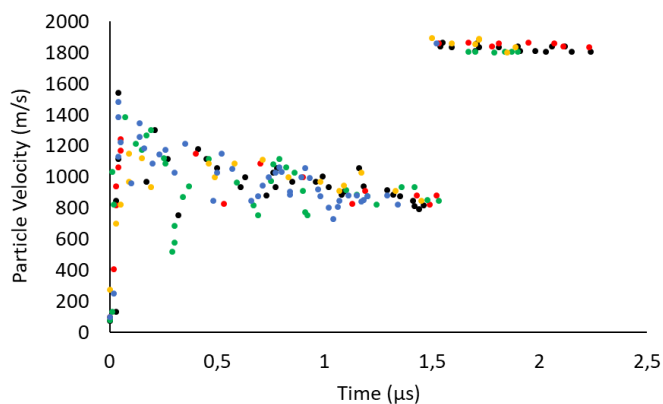


Figure 9. PDV – Digitised time-velocity data (5 shots) with average 877 m/s particle velocity at the UHP/PMMA interface.

The determination of P_{det} would require further investigations, as our current velocity records do not allow us to properly determine a CJ state, which is usually determined by a change of slope in the particle velocity profile [15]. Due to the limited thickness of our impedance window, we cannot even confirm that we captured the whole reaction zone and, hence, the CJ point. In fact, the PMMA window thickness is clearly a limiting factor, particularly when dealing with non-ideal explosives where longer reaction zone lengths are expected. Further experiments should hence be carried out with thicker PMMA windows, allowing for longer record, in an attempt to identify changes in slope of the velocity trace. However, in the current small-scale charge geometry, the maximum window thickness should not exceed 15 mm, about half the charge diameter, to avoid the effect of side relief waves on the velocity traces.

Considering other potential improvements of the experimental setup, the contact surface between the window and the explosive specimen could be improved by filling the voids between the UHP grains at the interface. Possible preparations to fill the voids include the use of silicon grease or epoxy, surface dusting with smaller UHP particles or a combination of both. Silicon grease has proven effective to ensure a good contact between plasticised explosives and the aluminium interface of the IW [15] but, in the case of UHP, the authors speculated that its application on a coarse explosive granular bed might lead to jetting effects, producing high-velocity material [28], and early disruption of the interface. The choice of the aluminium interface is also a key parameter. It should be reflective enough, thin enough to just act as a mirroring interface but thick enough to withstand initial shock arrival and deformation and reflect the laser beam along the path

to the probe sufficiently long to provide a useful PDV record. The use of multiple measurement points could be investigated. In fact, using a single probe (point measurement) is a limiting factor, particularly when the upper part of the interface starts deforming and the laser beam is not reflected anymore along the path to the probe. The point measurement is also dependent on the position of the probe which could be an issue when dealing with a heterogeneous material, with either air gaps or UHP particles in contact with the Al interface. Finally, the sampling frequency should also be increased, shortening the Hamming window duration, giving a better time resolution and, hence, minimising the reading error on the PDV capture.

4 Discussion

Table 2 summarises and compares the ASV experimental results and the ideal thermodynamical predictions from Explo5 using the EXP-6 and M-BKW EoS. Experimental P_{det} and Γ are consistent with data available in the literature on explosives detonating at comparable regime, such as ANFO [10]. Using empirical correlations for comparison purposes, we first estimated detonation pressure (Equation 6) [10], from the 3.52 km/s experimental VoD and 0.87 g/cm³ loading density (ρ_0) (Table 2), obtaining 3.14 GPa, a result in good agreement with our experimental data.

$$P_{det} = \rho_0 \cdot (VoD)^2 \cdot (1 - 0,7125 \cdot \rho_0^{0,04}) \quad (6)$$

We further calculated a consistent 2.2 polytropic exponent, using Equation 7 [29], a correlation which has proven effective to reliably estimate the Γ of CHNO explosives over a wide range of loading densities (0.2-2 g/cm³).

$$\Gamma = 1,819 - \frac{0,196}{\rho_0} + 0,712 \cdot \rho_0 \quad (7)$$

From the ratio of the experimental P_{det} of UHP and a 1.64 g/cm³ TNT reference [10], we derived an estimated 20% TNT equivalence for brisance, a result in good agreement with previous preliminary brisance assessment from underwater shock pressure carried out by the authors [6].

Table 2. UHP – Comparison of experimental data and thermodynamical predictions

	ρ_0 (g/cm ³)	VoD (km/s)	u_{CJ} (km/s)	P_{CJ} (GPa)	Γ (-)
ASV large-scale*	0.87	3.52	1.13	3.46	2.1
Explo5 (EXP-6)	0.87	4.19	0.96	3.50	3.4
Explo5 (M-BKW)	0.87	4.46	1.09	4.21	3.1

* 5 kg UHP, 120 mm charge diameter, L/D = 5, no confinement

Comparing experimental P_{det} to thermodynamical predictions using the ideal model, we find an excellent level of agreement. This good fit between measured

and ideally calculated detonation pressure could potentially come both from errors in measurement and errors in calculation, knowing that typical detonation pressure measurement error is around 10-20% [28], which is also roughly the margin error of the calculated detonation pressure of non-ideal explosives using the ideal detonation model [30]. Moreover, the calculated detonation pressure is controlled by the EoS, with value up to 20% higher using M-BKW EoS instead of EXP-6.

Depending on the choice of the EoS, the predicted ideal VoDs are about 20-25 % higher than experimental value (maximum 1% expected measurement error – [28]) and higher than the 3.94 km/s extrapolated at infinite diameter from experimental data [6]. As a result, Explo5 calculates Γ higher than 3, which is rather the expected order of magnitude for typical military explosives, with 1.5 to 1.8 g/cm³ loading density [10], (one of) its predominant parameter [29]. As the polytropic exponent describes the rate of pressure release along the detonation isentrope [31], the difference between experimental and calculated Γ value from Explo5 suggests that the predicted isentrope shape, especially in the low pressure region, using the ideal model does not adequately model the detonation product expansion. This limited accuracy could be explained by the low detonation temperature (1500 K) and the specific detonation products of UHP, particularly a rather high water content (triatomic polar molecule), when compared to conventional CHNO explosives, such as TNT [6]. Improvement of the modelling of non-ideal detonation should include kinetics of reaction in the chemical reaction zone and radial expansion of the products [30], which would however considerably increase the complexity of the study.

Two experimental methods, at two different charge scales, have been investigated in an attempt to assess the P_{det} of UHP.

On the one hand, the ASV method allowed for determination of the detonation pressure on the constructed experimental Hugoniot of explosive detonation products, using 5 different inert acceptors. The first advantage of this method is the fact that one single shot leads to the determination of a point on the Hugoniot of the detonation gases, which is of particular interest with non-ideal explosives for which large quantities have to be used. Moreover the method is not limited to transparent materials as other optical techniques. The major issue with this method is the indirect determination of the parameters of interest. In fact, we calculate the particle velocity from the measured shock velocity in an inert acceptor and then use this value to further calculate the initial pressure at the interface, making the error on pressure proportional to the square of the measurement error on shock velocity.

On the other hand, for quick assessment purposes, we investigated the use of IWM using PDV for scaled-down UHP charges. Current observations are limited to a particle velocity at the UHP/PMMA interface

consistent with the calculated particle velocities in PMMA acceptors from the ASV method. However, the use of the IWM at small-scale on a coarse granular heavily confined low-density non-ideal explosive in small charge diameter has proven challenging, even if potential improvements have been identified. An alternative small-scale PDV-based method could be the Disc Acceleration eXperiment (DAX) [32], which has proven effective and reliable in providing a rapid evaluation of explosive performance, ie detonation velocity, pressure and expansion energy. Future work will investigate the application of the method to UHP, a non-ideal material with rather low detonation regime, using a scaled-up DAX charge geometry ensuring a steady detonation.

5 Conclusion

Within the scope of a performance assessment, the brisance of UHP was quantified through its predominant parameter, the detonation pressure (P_{det}). In this comparative study, we investigated P_{det} respectively at large and small scale using two distinct indirect methods. We determined an experimental 3.5 GPa detonation pressure for 5 kg unconfined UHP charges (0.87 g/cm^3 , 120 mm charge diameter) by measuring the shock wave velocity in adjacent inert materials using passive optical probes, which corresponds to an experimental 20% TNT equivalence for brisance. This experimental detonation pressure is also consistent with the thermochemical predictions from Explo5, taking into account the margin error due to the use of an ideal model for the calculations. Particle velocity measurements at the interface of a PMMA impedance window carried out with Photonic Doppler Velocimetry on scaled-down charges of 90 g UHP under heavy confinement (0.85 g/cm^3 , 30 mm charge diameter, 4 mm thick steel) are consistent with ASV results in the PMMA acceptors but further investigations are required to determine the detonation pressure, using a small-scale experimental set-up. The ASV method has proven reliable to assess the brisance of a non-ideal explosive for risk assessment purposes.

Symbols and Abbreviations

Al:	Aluminium
AN:	Ammonium Nitrate
ANFO:	Ammonium Nitrate Fuel Oil
ASV:	Attenuated Shock Velocity
CJ:	Chapman-Jouguet
D:	Diameter
DAX:	Disc Acceleration eXperiment
EoS:	Equation of State
GOF:	Glass Optical Fiber
ID:	Inner Diameter
IW(M):	Impedance Window (Method)
JWL:	Jones-Wilkins-Lee
L:	(charge) Length
M-BKW:	Modified Becker-Kistiakowski-Wilson
Mg:	Magnesium

OD:	Outer Diameter
P_{det} :	Detonation pressure
PDV:	Photonic Doppler Velocimetry
PMMA:	Polymethylmethacrylate
PTFE:	Polytetrafluoroethylene
PVC:	Polyvinyl chloride
PVDF:	Polyvinylidene fluoride
ROC:	Radius of Curvature
TMD:	Theoretical Maximum Density
TNT:	Trinitrotoluene
TPX:	Polymethylpentene
UHP:	Urea Hydrogen Peroxide
VN:	Von Neumann
VoD:	Velocity of Detonation

Γ :	Polytropic exponent
ρ :	Loading density

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