Detonation of Highly Porous Explosives

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**Abstract.** Electromagnetic measurements of particle velocity histories at the interface between the loose packed explosive and PMMA window were carried out. Coarse grained (several hundreds µm) RDX, HMX and PETN were tested. In order to register both the average dynamics and the expected velocity pulsations, small gauges were used with the working arm of about 1 mm, i.e., not much larger than the explosive grain size. In a majority of shots distinct velocity peaks were observed well above the Chapman – Jouguet level, which was odd given the highly heterogeneous structure of the materials. However, in some experiments the chemical peak could not be defined against the strong flow fluctuations, which may indicate a non-classical convective propagation mechanism. An analysis of the gauge response to non-uniform flow field justified the reality of these fluctuations. The results, along with our previous study[[1]](#endnote-1) lead to the concept of the shock and convective mechanisms acting in parallel. Each mechanism may prevail at different parts of the detonation wave front.

**Introduction**

According to Zeldovich – von Neumann – Dӧring (ZND) theory,[[2]](#endnote-2) the detonation wave is a complex phenomenon consisting of a leading shock, a chemical reaction zone, a sonic Chapman – Jouguet surface and finally an expansion wave. This model, for its classical simplicity and clarity, was widely accepted well before any experimental confirmations.

Nevertheless, there exist systems for which the ZND model seems to be hardly suitable. For low density explosives (0.2 – 0.8 g/cm3), prepared by a distribution of explosive grains in a foam plastic, the convective propagation mechanism prevails.[[3]](#endnote-3) It is quite natural that shock stimulation meets difficulties without direct contact between the individual grains, and jets of the reaction products suggested by Apin[[4]](#endnote-4) become more effective as a propagation agent.

At the natural filling density, the grains are in contact with each other but the volume fraction of empty space is still substantial (about 40%), and the jets of reaction products still may propagate through the pores. Results of Dremin et al. dating from the 1960s[[5]](#endnote-5) were in general agreement with the ZND model. However, the time resolution available at that time (about 0.1 µs) is not adequate today because it is comparable with or larger than the characteristic detonation reaction time.

There exist several observations pointing to the importance of a convective propagation mechanism in porous[[6]](#endnote-6) and loose packed explosives.[[7]](#endnote-7),[[8]](#endnote-8) Recently, we studied low density PETN, RDX and HMX using VISAR diagnostics.1 In coarse grained materials two different detonation regimes were registered. One was the standard ZND profile with distinct von Neumann peak, but in several experiments sharp flow pulsations were observed which does not agree with the ZND paradigm.

In the present work, the same explosives were explored using the electromagnetic method. Again, mostly von Neumann peaks were found but violent chaotic pulsations were observed in several cases.

**Experimental**

We intended, as far as possible, to reproduce the conditions of previous VISAR tests.1 Thus, certain modifications of standard electromagnetic method were needed.

Magnetic System and Gauges

The magnetic field was created by a Helmholtz coil 12 cm in diameter, 2×10 turns. 1 kA current pulse was generated by a 20 µF capacitor charged to 3 kV, and maximal magnetic induction was 0.15 T.

To record the expected flow fluctuations, we used small electromagnetic gauges of about 1 mm long active arm. The typical effective gauge area was 0.5 square millimeters, close to that of the VISAR laser spot we used previously,1 so the comparison with the VISAR experiments was possible.

An experimental assembly is shown in Fig. 1. The Π – shaped gauge was cut from 9 µm thick Al foil glued to the flat surface of the PMMA window (horizontal in Fig. 1). The explosive was poured into the plastic tube of 18 mm inner diameter and 25 mm long. The axis of the charge was perpendicular to the window interface and passed through the sensitive arm of the gauge. The detonation was initiated through an explosive lens 20 mm in diameter. The estimated time resolution was about 5 ns, and the steepest fronts justified this estimate.



Fig. 1. Electromagnetic test setup.

The sensor was protected by the 50 – 100 µm thick epoxy layer. In contrast to the commonly used gauges, the width of the conductors (around 0.5 mm) was not negligible. We found that the effective arm length $L$ should be defined as an average value between the external width and the gap width, as shown in the top of Fig. 1.

Effects of Heterogeneity

Numerical analysis of the gauge response to the non-uniform flow was performed. The action of the explosive products on the window material was simulated using an acoustic approximation, assuming that different spots of the interface start to move at different time moments. The spread was $τ=^{d}/\_{D}$, here $d$ is the grain size and $D$ is the detonation velocity. For typical $d=300$ µm and $D$ = 5 µm/ns, $τ=60$ ns. It was found that gauge dimensions play an important role. Point sensors (i.e., those much smaller than $d$) react not only to the nearest non-uniformity, but to remote parts of the moving interface as well and register high amplitude oscillations for quite a long time after the velocity at the interface becomes uniform (retardation effect). For larger sensors, the output signal is averaged, and the sensor area of $ 4d^{2}$ is enough to suppress this unwanted noise. The averaged VISAR velocity was fairly close to the electromagnetic one, though the level of oscillations was slightly higher, due to nonlinearity of the VISAR converting procedure. Thus, the VISAR method turned out to be quite robust which was hard to expect from a subtle interferometric technique. Detailed analysis can be found in a special paper.[[9]](#endnote-9)

Polarization and Protective Layer

The front of the velocity peak was preceded by strong polarization noise which could distort the signal. An example is shown in Fig. 2. Particle velocity history in RDX (1.1 g/cc initial density, 160 µm grain size) is spoiled by the polarization signal P which, through capacitive coupling with the gauge circuit, starts before the arrival of the wave front to the gauge. This noise may continue after the main velocity front F, producing a false impression of velocity oscillations.



Fig. 2. A profile disturbed by the polarization.

This problem was solved in a standard way[[10]](#endnote-10) using the thin grounded electrode, or needle, put out upstream for 2 – 3 mm, and 3 mm off axis. The effect is demonstrated in Fig. 3.



Fig. 3. A profile cleared of the polarization noise.

All experimental conditions were the same as in Fig. 2 except the presence of the needle whose tip was 2.2 mm above the PMMA interface. The polarization noise P was effectively discharged and the noise practically died out prior to the front F of the velocity profile. As a result, the velocity history is definitely more smooth than that in Fig. 2.

The horizontal lines labeled CJ in Figs. 2 and 3, as well as in the following figures, mark the Chapman – Jouguet level calculated using the thermodynamic data of Tanaka[[11]](#endnote-11) and the PMMA shock adiabat.

The need of protective epoxy layer is clear from Fig. 4. Without protection, one gets a noisy signal with oscillations which well exceed the average amplitude.



Fig. 4. A profile without the epoxy protection.

In this shot with HMX (1.26 g/cc, 430 µm grain size) the polarization was grounded, but direct contact of the detonation front with the gauge resulted in chaotic pulsations around the CJ level, owing to the separation of the electrical charges in the plane of the wave front. The same pulsations, but without the positive average component, were observed with zero magnetic field, i.e., they are produced by the non-uniformity of reactive medium. Low resistance of the gauge (under 0.1 Ohm) should short-circuit this noise, but the Al foil presumably gets broken rather early by the flow turbulence without protection.

Hence, given all precautions discussed above, the pulsations, if any, registered in the experiments to be presented below should be regarded as manifestation of real velocity and pressure fluctuations within the detonation wave.

**Results**

In low density coarse-grained explosives, it was not easy to expect the detonation to follow the ZND model. Surprisingly, in a majority of tests we got rather good illustrations of ZND theory.

Fig. 3 demonstrates a result typical for RDX. The interface velocity jumps to the amplitude well above the CJ level and gradually decreases afterwards. Thus, a classical von Neumann spike is observed despite the strong heterogeneity of the material. Moreover, practically no noise was seen around the ZND profile. RDX had the smallest grain size among the explosives tested (160 µm), so the active gauge area could hold about 20 grains, and the granular noise was effectively averaged. The same behavior of RDX was observed earlier.1

HMX had the largest mean grain size (430 µm). Generally, the profiles obtained with HMX were more noisy. Nevertheless, rather smooth histories were also registered. Two profiles for HMX at 1.28 g/cc are compared in Fig. 5.



Fig. 5. Two different profiles for HMX.

The profile (a) is similar to that of RDX, but profile (b) is quite different, to the extent that it cannot be regarded as ZND-type structure. As was pointed out above, such results might be expected, and most surprising fact is that they were rather scarce. Of seven tests with HMX, two were of non-ZND type, compared with one of two shots in the previous work.1

PETN was an intermediate case between RDX and HMX, with the mean grain size of 260 µm. Accordingly, we obtained intermediate results, with one non-ZND profile in eight shots. The granular noise on ZND profiles was stronger than in RDX but less pronounced than in HMX. In the previous paper,1 both PETN tests were of non-ZND type.

In experiments with fine grained explosives, good ZND peaks were obtained, as in the VISAR tests.1 The same can be said about PETN based plastic and RDX pressed to 1.7 g/cc.

**Discussion and Conclusion**

Since the von Neumann spike is a generally recognized signature of ZND regime, deviations from this structure should indicate non-classical processes. In Fig. 5, rather slow velocity increase at the front of the profile (b), as well as strong flow pulsations, allowed us to suggest the non-ZND process. The natural assumption is that in such cases the stochastic convective flows of the hot gases may serve as the propagation agent.

In the loose packed charges, grains and pores are distributed in a random way. Therefore the detonation front should be, to some extent, wrinkled and convective processes seem to be inevitable at the grain scale. The question is, whether the convection plays a leading role in the wave propagation.

The most unexpected result of the present study was that ZND profiles prevailed, in spite of the highly porous structure of the materials. To explain such behavior, one might refer to fast crushing of the grains in the compression front and closing of the voids. The characteristic time of this process, if estimated as $^{d}/\_{D}$ ratio, should be 50 – 60 ns for HMX and PETN and 30 ns for RDX. The observed velocity fronts varied from 5 to 30 ns, and were, on average, less than the above estimate by 2 to 4 times. Thus, the homogenization is remarkably fast, which is the reason why the concept of shock can be used for low density explosives.

To conclude, the results indicate that both shock driven and convective wave can propagate in loose packed explosive. Apparently, for the same charge, in different parts of the wave front either shock or jets can dominate as a leading process, depending on the details of the local placement of the grains.

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