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OPTIMEX: Measurement of Detonation Front Curvature with a Passive Fiber Optical System

Jiri PACHMAN,[1*] Martin KÜNZEL,[1,2] Karel KUBÁT,[1]
Jakub SELESOVSKY,[1] Roman MARŠÁLEK,[3]
Martin POSPÍŠIL,[3] Michal KUBÍČEK,[3] Aleš PROKEŠ [3]

[1] *Institute of Energetic Materials, University of Pardubice, Czech Republic*
[2] *OZM Research, Bliznovice 32, Czech Republic*
[3] *Department of Radioelectronics (DREL), Faculty of Electrical Engineering and Communication, Brno University of Technology, Czech Republic*
[*]*E-mail: jiri@pachman.eu*

Abstract: The ability of a newly developed independent passive optical system OPTIMEX to measure the detonation front curvature is demonstrated on charges of pressed explosive A-IX-1 (RDX/ceresin-stearin mixture with 95/5 wt.%). The charges, with length to diameter ratios of from one to four, were prepared from cylinders with diameters of 21 mm, 30 mm, 40 mm and 50 mm pressed to a density of 1.66 g/cm^3. Such charges detonate with a velocity of 8220 m/s. The detonation curvature was obtained using 8 optical fibers and the results were compared with photographs acquired by an ultra-high speed framing camera UHSi 12/24.

Keywords: detonation front curvature, detonation shock curvature, A-IX-1, RDX, OPTIMEX

1 Introduction

The detonation wave propagating through an unreacted explosive charge is, in the simplest theory, smooth and planar. This could suggest that modelling detonation is a fairly simple and straightforward task. Unfortunately, in reality a detonation front is neither planar nor smooth due to the rather complex nature of detonation phenomena. The geometry of the wave depends on a number of explosive charge parameters, defined prior to charge initiation, such as:

- chemical composition of the explosive,
- density of the charge,
- charge dimensions – diameter, and length to diameter ratio,
- confinement,
- type of initiation,
- initial temperature.

The modelling is therefore rather complicated and often simplified by calibrating models using experimentally determined detonation wave parameters. The shape of the detonation front enables modellers to skip the problematic and computationally intensive description of the reaction zone structure, and, for example in the case of the simple detonation shock dynamics (DSD) approach, enables direct calibration of a particular explosive [1-3]. The information obtained from an experimentally determined detonation front shape may also be used for validation of higher order DSD or numerical simulations using full reactive Euler equations, even for highly non-ideal explosives [4]. Papers have also been presented using this information for the determination of reaction zone kinetics [5, 6].

A number of techniques have been applied to study detonation front curvature and a fairly large amount of data is available in the open literature for military [7-9] as well as commercial [10, 11] explosives. The most suitable, and historically probably the most frequently used methodology to determine detonation front curvature, is based on the observation of a detonation wave emerging from the bottom of a cylindrical charge using a streak camera [3, 8, 11, 12]. Various fitting procedures are then applied to find suitable formulas fitting the experimental data [3, 8]. Other methods employ flash X-ray [13, 14] or various probes positioned in contact or close to the base of the cylindrical charge. Piezoelectric [15] or shorting [16] pins were demonstrated to work well, although with much inferior spatial resolution than the streak or X-ray cameras. This limits their use in certain types of experiments such as the edge effect studies described in [3, 10].

In this contribution we demonstrate the ability of a newly developed device employing multiple fiber optical probes, called OPTIMEX, for the determination of detonation front curvature. The measurements were done without a streak camera or an external data acquisition unit such as an oscilloscope. Methodology data evaluation, taking into account the non-discontinuous nature of the light pulse is demonstrated, the results are compared to high speed framing camera results and the detonation front curvature is demonstrated on various charges differing in diameter and length to diameter ratios.

2 Experimental

2.1 Material

The A-IX-1 composition made of 95% (m/m) of RDX and 5% (m/m) ceresin/stearin mixture (60/40 m/m) was pressed to cylindrical pellets with dimensions 21 mm × 40 mm, 30 mm × 30 mm, 40 mm × 40 mm and 50 mm × 50 mm (diameter × height). The density of all of the pellets was 1.66 ± 0.008 g/cm^3. The detonation velocity, *D*, measured using a fiber optical probe experiment was 8224 m/s, with a standard deviation of 12 m/s. The charge heights were chosen to cover length to diameter ratio (L/D) intervals from one to four. Plastic explosive Semtex 1A (20 g) was used as a booster and was initiated by a standard industrial electric blasting cup with initiating efficiency not less than that of a standard number 8 detonator. Although 20 g may seem to be a fairly large amount of explosive considering the charge sizes, its effect was not significant for two reasons. Firstly the detonation velocity of Semtex 1A is lower than that of A-IX-1, and secondly the detonator was pushed all the way through the booster to touch the surface of the A-IX-1 charge.

2.2 Explosive charge assembly

The shot assembly is schematically illustrated in Figure 1 for L/D = 2. The real experimental arrangement using 8 fibers along the entire diameter of the charge is shown in Figure 2. Charges with diameters 30, 40 and 50 mm were assembled from segments with L/D = 1, and charges with diameter 21 mm were assembled from cylinders with L/D = 2. Assembling the charges from individual cylinders is the only practical way of preparing longer cylindrical charges. Pressing the entire charge with L/D = 4 in a single piece creates difficulties in maintaining a constant density along the charge even when pressing stepwise.

Square transparent PMMA plate (window) 10 mm thick was drilled perpendicular to its surface with 8 holes of 1 mm diameter. A photograph of the window was taken and the distances between the holes were determined therefrom. The window was then pressed against the bottom surface of the charge and fixed with tape without any glue to maintain a thin air layer between the surfaces as shown in Figure 3. The alignment of the blasting cup with the charge axis was assured by a centering plastic cylinder.

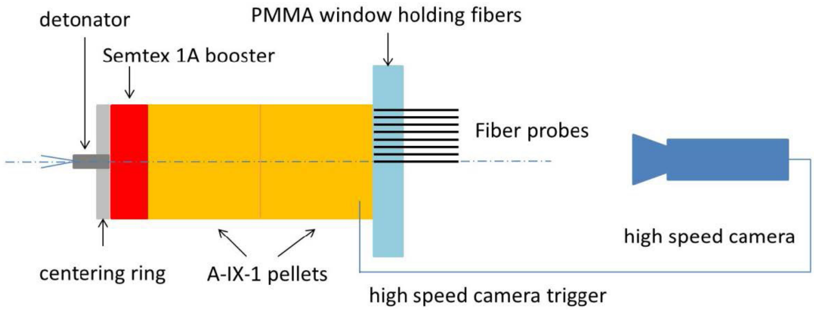


Figure 1. Schematic diagram of the experiment (variant with L/D = 2 and 8 optical probes evenly spaced along the charge radius).

Figure 2. Experimental arrangement showing the positions of the blasting cup, centering ring, booster charge, the two HE pellets, trigger and the PMMA window serving as the fiber holder (variant with L/D = 2 and 8 optical probes evenly spaced along the charge diameter).

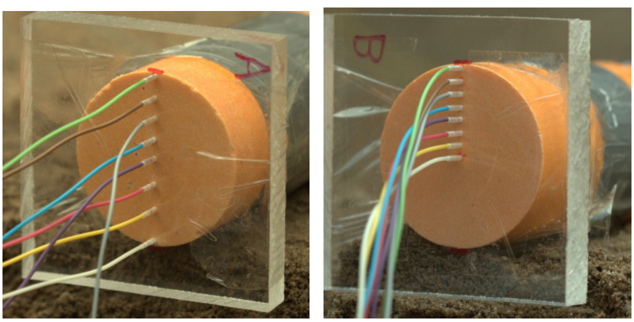


Figure 3. The two charge arrangements with fibers either spaced out along the entire diameter (left) or only along the radius, from the charge centre to its edge (right).

2.3 Ultra-high speed photography

The high speed photography was performed using an ultra-high speed framing camera UHSi 12/24 produced by Invisible Vision Ltd. The camera was set to the 12 frames option, 25 ns exposure and frame rate from 10 M fps to 50 M fps based on the expected detonation front curvature. There was no additional illumination of the charge. The camera was triggered by a shorting probe placed on the surface of the A-IX-1 charge, 7 mm from the charge bottom. The use of a telephoto lens was necessary to keep a safe distance and to obtain reasonable resolution at the same time. The only reasonably long lens we had to hand was a Samyang 800 mm mirror lens with a fixed aperture of f/8, and was therefore used for all experiments.

2.4 Passive fiber optical system OPTIMEX

The OPTIMEX system employed in this work was a development version equipped with 8 glass multimode 62.5/125 µm fibers with ST connectors at the end passing into the device and simply cut by scissors at the end passing to the fiber holding window. Figure 4 shows a more recent development version with 4 ports for plastic and 4 for glass fibers.

Figure 4. OPTIMEX 4 + 4 system during outdoor trials (left) and the final prototype of a handheld 4 + 4 version complemented with a graphical display and keyboard as a user interface (right).

A block schematic of the 8-channel OPTIMEX system is shown in Figure 5. The system consists of three main functional subsystems found on three jointly connected printed circuit boards – an analogue front-end subsystem, a digitizer subsystem and a microprocessor/microcontroller subsystem. The analogue front-end subsystem converts the emitted optical signals to electrical analogue signals by passing through the set of optical/electrical converters, amplifiers and low-pass filter components in each of the 8 channels. In the digitizer board, the analogue electrical signals are then sampled by the dual-channel Analogue/Digital Converters (ADC). The digital data are stored in the internal memory of a Field Programmable Gate Array (FPGA) of Xilinx Artix-7 family. The system is equipped with 12-bit ADCs, with a sampling rate of 250 MSa/s (4 ns time resolution), necessary for front curvature measurements or VoD measurements of fast detonating energetic materials, but it is possible to slow down the sampling through digital decimation down to 5 kSa/s (*i.e.*, 200 µs time resolution) for applications requiring longer recording times at lower temporal resolution.

The data can be communicated to the user through a user interface served by the microprocessor (µP) board. The µP board serves also for the setup of measurement parameters like triggering modes (*i.e.*, the data acquisition could be triggered by any of the data input channels, a selected input channel or even by an external electrical event), pre-trigger time interval, vector of distances between the measurement probes *etc*.

Besides the handheld version of the OPTIMEX system with 8 input optical channels, a modular laboratory version was also developed. In such a modular platform, *N* digitizer boards are connected through a common data and trigger bus and clocked by a common clock (CLK) signal in order to coherently measure the optical information from the 8*N* fibers.

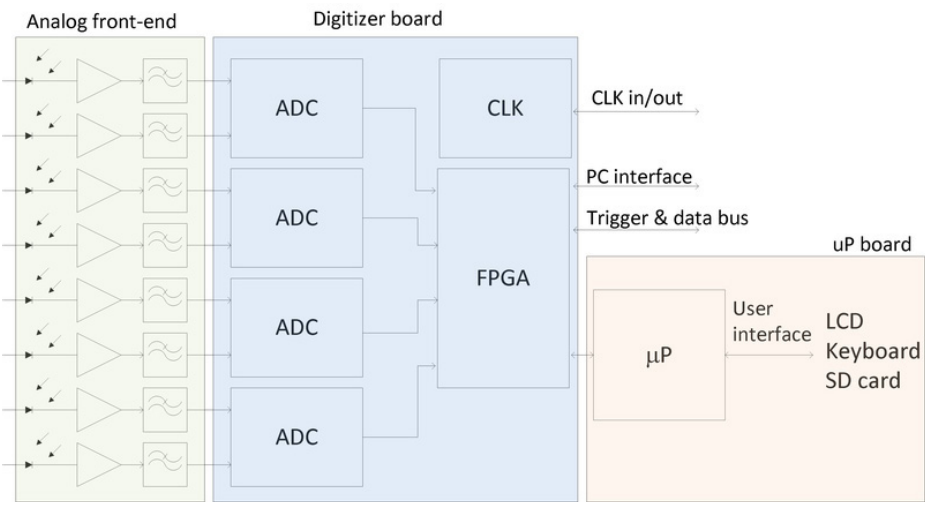


Figure 5. Block schematic of the 8-channel measurement system OPTIMEX.

3 Results and Discussion

3.1 Evaluation of UHSi records

An example of a single frame obtained by UHSi is shown in Figure 6. The light ring of highest intensity corresponds to the detonation front breaking out of the explosive, or more precisely air compressed by the emerging wave against the PMMA window. Fibers of the OPTIMEX system are visible as dark lines in the center of the figure.

The light intensity of particular pixels along the horizontal frame line in Figure 6 is shown in Figure 7. The two highlighted peaks indicate pixels with the highest intensity and represent the detonation front position. A pixel position is converted to a position in mm either by using a calibration frame or from a known distance in the shot frame itself (*e.g.* charge diameter). The curvature of the wave front can be obtained from the known time between 2 frames, the distance deduced from the frames and known detonation velocity. The 25 ns exposure time is short enough so as not to smear the light trace above an acceptable level. With very planar waves this could be a problem and the exposure time would have to be reduced. It is further evident, that the light generated by the detonation products in the early stages of their expansion is about as intense as the light emitted by the detonation wave compressed air.

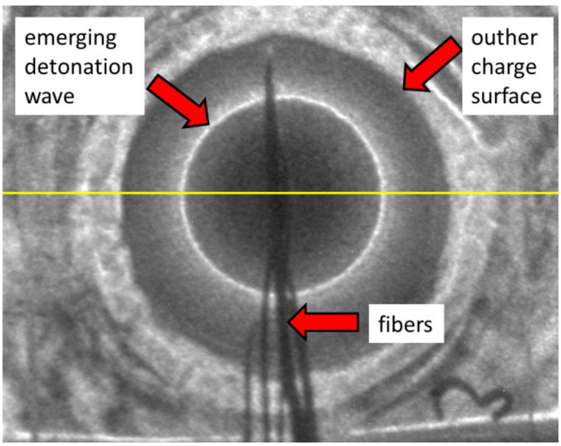


Figure 6. Example of a UHSi frame showing the position of the detonation front, charge outer surface and the OPTIMEX fibers (exposure 25 ns).

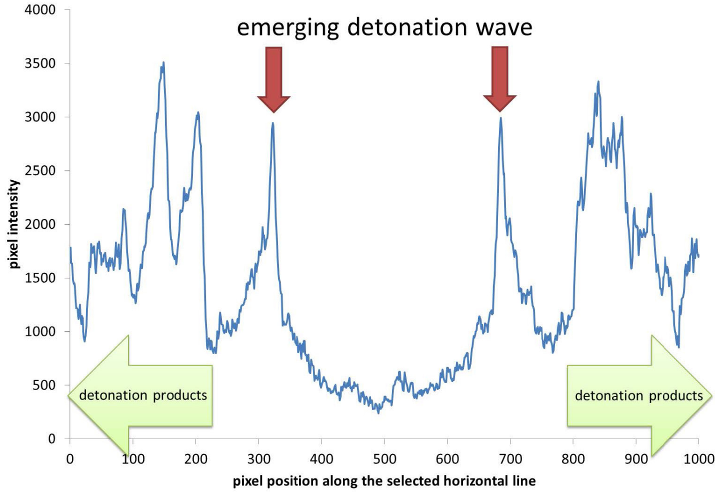


Figure 7. Evaluation of the position of the detonation front emerging from the face of the charge.

3.2 Evaluation of signals recorded by the OPTIMEX fiber probes

The light pulse generated by the detonation wave does not exhibit a discontinuous course in time. Unlike pressure in shock or detonation waves, the light intensity increases gradually even when the probe is inserted into the explosive. We observed, that the majority of explosives we tested show some level of transparency, differing significantly among various types of explosive. There is also an effect of charge homogeneity which affects its light emission on a scale similar to that of explosive's particle size. Figure 8 shows the typical gradual increase of light intensity that may, but does not have to, sharply increase. The length of the optical cable and the state of the cut fiber end collimating the light into the fiber were found to affect the signal quality. The light intensity observed before the arrival of the detonation wave can therefore reach a significant level and may be channel dependent. Finding a reasonable characteristic point on the light intensity curve that would represent passage of the detonation front is therefore not exactly straightforward and not an easily automated task.

In experiments with larger charges of inhomogeneous explosives such as ANFO, standard 1/2.2 mm plastic optical fibers may be preferred as the cut ends can be easily polished and their aperture is much wider allowing diminishing effects of the small scale charge inhomogeneities. The OPTIMEX system was designed and tested to accommodate both types of fibers.

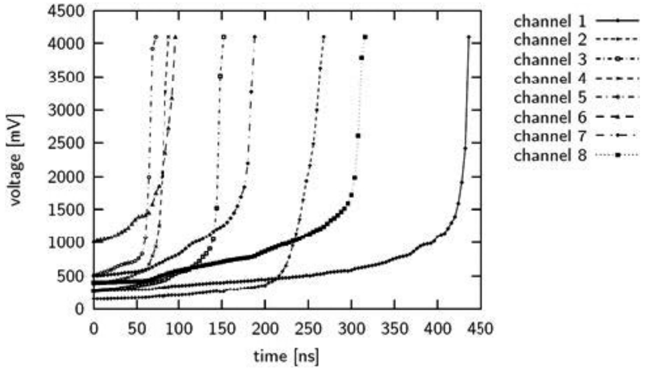


Figure 8. Intensity of light acquired by the fiber probes as a function of time. 4096 is a bit depth (12 bit) and on this diagram represents the cut-off value.

3.2.1 Influence of threshold level

Methods based on defining some fixed threshold value therefore tend to fail. Not just because of the mentioned unreproducible cut at the end of the fiber or their varying length but also because each explosive tends to provide different light intensity. A device set to work fine with one explosive therefore does not have to work with a different one. Figure 9 shows the resulting shape obtained by applying various thresholds to the data from Figure 8. It is clearly seen, that above about 1500 the resulting shape of the detonation front does not depend on the threshold any more for this particular charge.

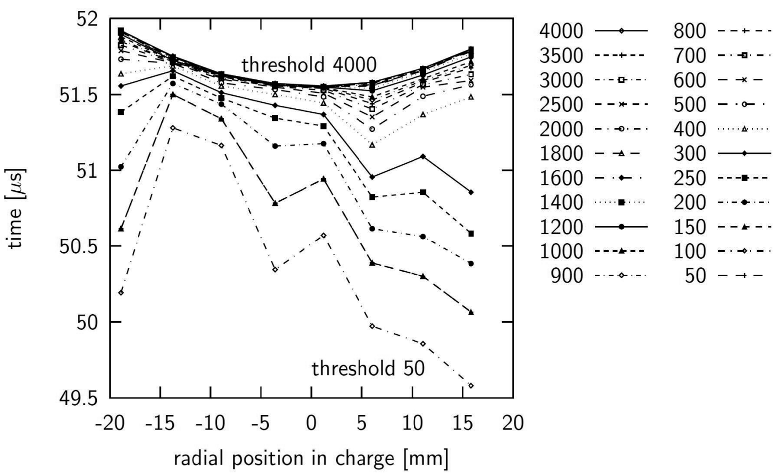


Figure 9. Data from Figure 8 evaluated at different thresholds (in legend).

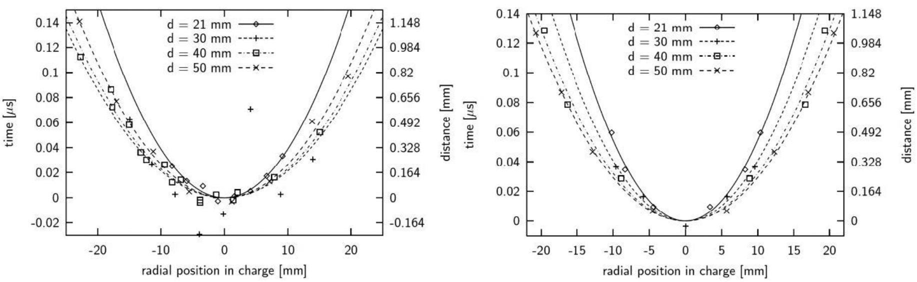
The above mentioned could lead to the conclusion that using some threshold at 95% of the bit depth would lead to reliable and an easily automated evaluation procedure. There is however a problem, that not all signals are of the same intensity and may need to be adjusted prior to applying this method. Other methods have been proposed and are described elsewhere [17].

3.2.2 Effect of charge diameter on the detonation front shape

The diameter of the charge significantly affects the detonation front curvature [3], especially in the cases of non-ideal explosives. The ratio of the steady or final curvature radius to charge diameter is, according to Cooper [18], constant for a particular explosive. Assuming that the charge diameter is large enough to ensure optimal detonation parameters, charges with a lower diameter would exhibit a more curved front (smaller detonation front radius). This is what we have observed, as shown in Figure 10.

It must be noted however that the accuracy of the detonation front curvature estimation is affected by the small number of channels and the methodology used for the evaluation mentioned in the previous subsection. The scatter observed, especially in the case of the 30 mm charge, shows the limits of the approach using only 8 channels. Furthermore, the A-IX-1 explosive is close to ideal and significantly above the critical diameter, resulting in a relatively small detonation front curvature and also relatively small differences in curvature among the tested diameters.

The two graphs in Figure 10 are intended to demonstrate the ability of the two techniques to acquire the wave profile. For higher precision measurements a larger number of fibers than 8 would be needed to improve the resolution of the OPTIMEX system.



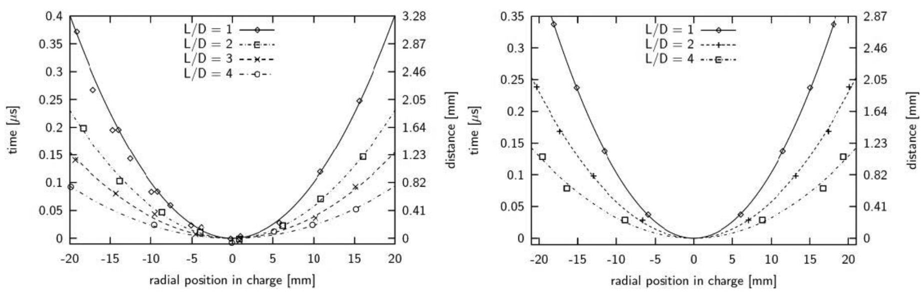
OPTIMEX 8 UHSi

Figure 10. Influence of charge diameter on the detonation front curvature for L/D = 4. Data from the OPTIMEX system were evaluated with the threshold set 5% below saturation.

3.2.3 Effect of length to diameter ratio on the detonation front shape

Detonation of a cylindrical charge may be initiated by various methods affecting the shape of the detonation front close to the initiation point or plane. Initiation by an explosive plane wave generator, a booster charge slightly overdriving the detonation or a flying plate, generates a front that is close to a planar shape in the early stages and fairly quickly acquires a steady form determined by the charge properties. However the most common way of initiating high explosive is the use of a detonator, which is relatively small and compared to the charge size can be considered a point initiator. In our tests we used blasting cups with an external diameter 8 mm. The detonation front initiated by the detonator therefore expands in a rather spherical way before reaching the charge's outer surface and then changes curvature as it travels along the charge length to achieve a steady shape that does not change further. The distance (defined by the length to diameter ratio) required to achieve this "steady" or "final" state depends on the explosive type and the charge arrangement. In general it takes a length equal to 3-5 diameters [17] to achieve this state.

The results presented in this study were measured with charges having L/Ds in the range of from one to four. The shapes obtained, measured using both OPTIMEX and high speed imaging (UHSi), are presented in Figure 11. The gradual decrease in the detonation front curvature with increasing charge length is clearly demonstrated. Final comparison of the performance of the OPTIMEX system *vs*. UHSi 12/24 camera is provided in Figure 12 for 40 mm charges with L/D = 2 and L/D = 4.



OPTIMEX (threshold 3000) by UHSi 12/24

Figure 11. Experimentally determined detonation front curvatures as a function of length to diameter ratio for a 40 mm diameter charge.

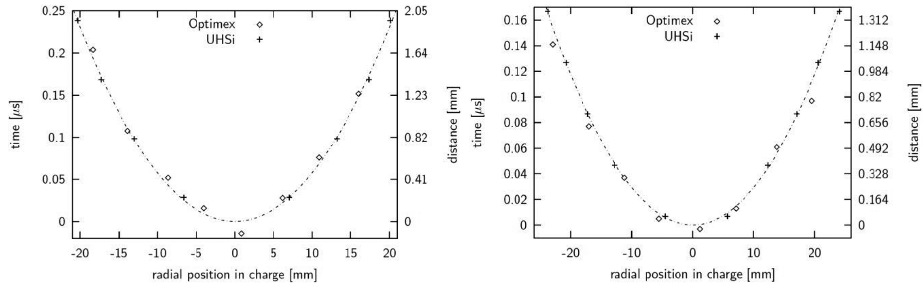


Figure 12. Comparison of detonation front curvatures measured by an 8 channel OPTIMEX and UHSi, diameter 40 mm, L/D = 2 (left) and L/D = 4 (right).

4 Conclusions

The detonation wave curvature (DWC) was measured using the development version of an eight channel passive fiber optical system OPTIMEX, and visualized simultaneously for validation purposes by an ultrahigh speed framing camera UHSi. The following conclusions can be made based on the results obtained:

- the light transmitted to the fiber from the detonation zone does not create discontinuity in the acquired signal; it gradually increases its intensity up to the point of DW breakout; the level of intensity for threshold evaluation must be above this value,
- the results obtained from the eight optical fibers match nearly ideally the results obtained by ultrahigh speed imaging,
- in the case of long charges (L/D = 4) the initial transient state related to the initiation diminishes, resulting in a relatively small effect of the charge diameter on the DWC,
- as expected the length of the charge plays a significant role on the DWC and can be studied using the optical fiber methodology presented.

The higher number of measuring channels of the table top version enables simultaneous measurement of detonation front curvature and detonation velocity.

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