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Dynamic processes in a shock tube of a non-electric initiating system of the Nonel type
Procesy dynamiczne w rurce detonującej nieelektrycznego systemu inicjującego typu Nonel

Roman Zakusylo*⁾, Viktor Kravets, Yaroslav Reva, Daryna Zakusylo

Shostka Institute of Sumy State University, 1 Leonid Kadeniuk Street, 41100 Shostka, Ukraine
* *E-mail:* r.zakusylo@ishostka.sumdu.edu.ua

ORCID Information:
Zakusylo R.: 0000-0003-3823-4040
Kravets V.: 0000-0002-5231-0778
Reva Ya.: 0009-0001-8047- 0920
Zakusylo D.: 0000-0003-0804-9725

Abstract: *A complex laboratory methodology has been developed to investigate the dynamic processes occurring during the detonation progress in a shock tube used in nonelectric initiation systems of the Nonel type. Key operational characteristics of the detonation phenomena and shock tube behavior are assessed. The system uses piezoceramic sensors and recording equipment which ensure a sufficient level of measurement accuracy, within ±5%.*
The research establishes the fundamental mechanisms of detonation in low-velocity regimes, driven by fine crystalline explosive material deposited on the internal wall of a shock tube. Timing and amplitude parameters of shell deformation under the progressing shock and detonation fronts were registered. It was possible to record the transmission of a shock wave induced by an electric discharge into a detonation wave progressing along the shock tube channel. The mechanisms of propagation and loading of shock waves progressing in a shock tube whose internal walls were not covered with explosive material, were also registered. The rise, development and formation of a stable detonation process was examined. The moments of detonation onset, acceleration to peak, and attained parameters were determined.
Streszczenie: *Opracowano kompleksową metodykę laboratoryjną przeznaczoną do badania dynamiki procesów zachodzących w rurce detonującej, stosowanej w nieelektrycznych systemach inicjacji typu Nonel. Przygotowano specjalistyczne stanowisko laboratoryjne do oceny kluczowych parametrów eksploatacyjnych rurki detonującej. System zbudowano z wykorzystaniem czujników piezoceramicznych i urządzeń rejestrujących, zapewniających wystarczający poziom dokładności pomiaru w granicach ±5%. Przeprowadzone badania pozwoliły na ustalenie podstawowych mechanizmów detonacji w warunkach niskiej prędkości, podtrzymywanych przez przereagowanie drobnokrystalicznego materiału wybuchowego umieszczonego na wewnętrznych ściankach rury uderzeniowej.*

Zarejestrowane zostały parametry czasowe i amplitudowe deformacji powłoki w warunkach udaru i detonacji. Uzyskano rejestrację rozwoju fali uderzeniowej wytworzonej przez wyładowanie elektryczne i jej przejście w falę detonacyjną rozprzestrzeniającą się wzdłuż ścianek rurki detonacyjnej. Przeprowadzono również badania mechanizmów rozwoju i tłumienia fal uderzeniowych w rurkach bez naniesionego materiału wybuchowego. Przeprowadzono rejestrację procesu rozwoju, narastania i formowania stabilnego procesu detonacji. Dokonano określenia momentu wytworzenia detonacji, przyspieszenia do piku oraz uzyskiwanych parametrów.

Keywords: *shock tube, wave processes, detonation, piezoceramic sensors, low-velocity detonation parameters*
Słowa kluczowe: *rurka detonująca, procesy falowe, detonacja, czujniki piezoceramiczne, parametry detonacji o niskiej prędkości*

1. Introduction

Relevance of the research. Research into the initiation mechanisms from electric discharges and the formation of intense mechanical oscillations in the shock tube shell material is vital for improving modern non-electric initiation systems. Specifically, maintaining detonation transition along shock tubes coated with sensitive explosives can help to refine analogs of such systems, making them more reliable and efficient in practical employment.

Literature context. Th. growing use of industrial explosives has shown a widespread adoption of non-electric initiation systems in blasting operations. These systems rely on shock wave transmission in plastic tubes, enabling safe and reliable ignition under complex geological conditions. Non-electric initiation systems are characterized by enhanced safety and ease of use, ensuring reliable blasting even under difficult mining and geological conditions. They also allow the design of short-delay blasting patterns with a wide range of delay intervals.

A well-known example is the *Nonel* system, which uses a plastic shock tube whose internal surface is covered with a thin layer of secondary explosive. Upon triggering by an electric discharge, the rise of a shock wave occurs which transforms into a detonation wave which progresses at approximately 2000 m/s – regardless of the tube's length. The generated shock wave carries enough energy to initiate a secondary explosive but is weak enough not to deform the plastic shock tube. Thus, the tube functions primarily as a signal conduit. Several examples illustrating the features and behaviours of such systems are referred in [1, 2, 4, 6-8]. Since the processes in the shock tube are very fast and similar to detonation processes in low-velocity explosives, the research methodology is comparable to traditional approaches based on the use of sensitive sensors and oscillography [6, 7, 9].

Objective and research tasks. The purpose of the study was to examine the formation and dynamics of specific wave processes occurring in a cylindrical plastic tube whose internal walls were coated with sensitive explosive. Under the action of the energy impulse introduced by an electric discharge, the resulting shock wave sustains wave motion along the axis of the polyethylene sheath. The developed experimental set is intended to register the dynamics of shell deformations as well as acceleration, onset and parameters of detonation wave progress in the channel.

The research task included the experimental identification of the sequence of conditions necessary for initiating and sustaining detonation within the shock tube under steady-state conditions.

2. Experimental. Methodology of laboratory investigations

The test object was a polyethylene tube with an outer diameter of 3.2 mm and an internal diameter of 1.3 mm. Test segments varied in length from 150 to 1000 mm, depending on the specific experimental objective. Material properties of the tube:

- density: $\rho = 940$ kg/m³,
- elastic modulus: $E = 0.760$ kPa,
- Poisson's ratio: $\nu = 0.4$.

The inner surface was coated with octogen (HMX), equally applied at a dosage of 16 mg/m over the tube length. Under a microscope, the explosive particles ranged in size from 0.05 to 0.3 mm, with a spatial distribution of approximately 1.8 to 2 mm. The initial impulse was generated by an electric discharge device. One end of the tube was sealed with a piezoceramic pressure sensor, installed 0.08 mm away from the end to avoid responding to detonating waves in the shock tube. The pressure wave profile was fixed, and the signal of a calibrated sensor was measured in volts with an accuracy of up to 5%, according to the oscilloscope readings. In addition, the experiments also used small CTS-19 piezoceramic plates, 1×1 mm in size and 0.3 mm thick, at the end pressure sensor (Figure 1).

Strain gauges were glued to the outer surface of the shock tube. As the detonation process spread, the strain gauges readings made it possible to register circumferential deformations of the outer surface of the tube. The signals from the strain gauges were sent to C 8-13 and C 8-17 oscilloscopes.

3. Results. Registration of detonation processes

Typical oscillograms from the piezoceramic sensors show wave arrival and intensity at various points along the shock tube (Figure 1a, b). The distance between the piezoceramic gauges was 50 mm, and the signal arrival time was determined from characteristic points on the oscillograms with an error of $\pm 10^{-6}$ s. Figure 1c shows an oscillogram obtained by the pressure sensor during the initiation of the detonation process in a 1 m-long polyethylene shock tube. In seven experiments, the first pressure peak, rising within 1 µs/s, reached $(20 \pm 5) \cdot 10^5$ Pa. In a secondary peak, over several microseconds, the pressure rose to 25×10^5 Pa, returning to baseline P_0 in 150×10^{-6} s.

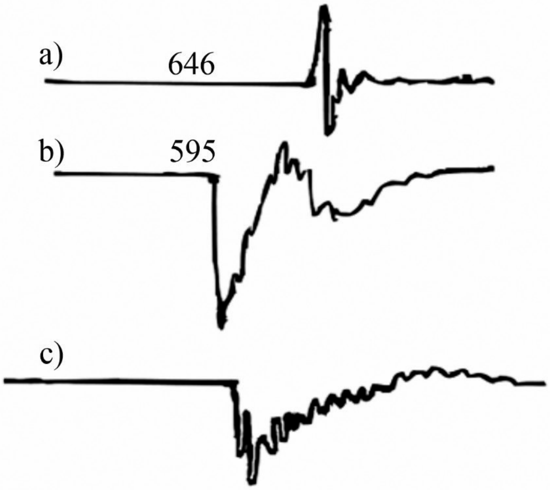

Figure 1. Signals type: a, b – from side piezoceramic plates, c – from end pressure piezoceramic sensor

In Figure 2, the results of measurements of the detonation wave velocity along the inner channel of the polyethylene shock tube at different distances from the initiation source are presented. The experiments were carried out using tubes of 0.5 m (1) and 1.0 m (2) lengths.

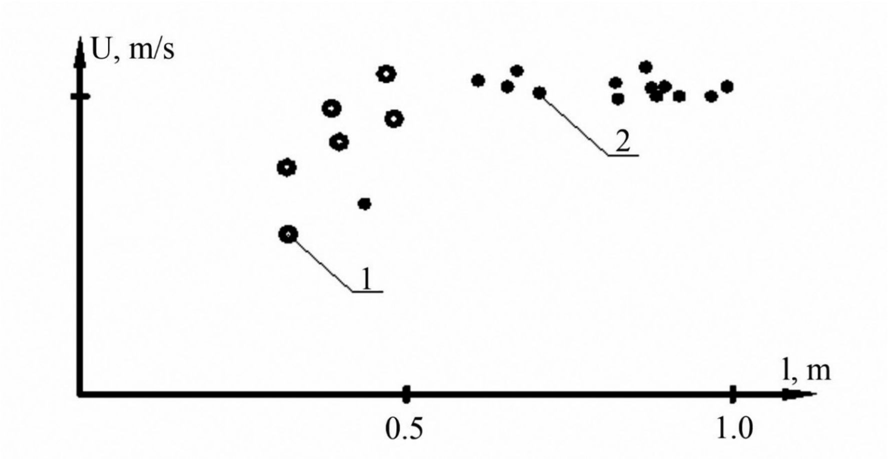

Figure 2. Detonation wave velocity: 1 – shock tube 0.5 m length, 2 – shock tube 1 m length

The experiments showed an acceleration phase of the detonation over the first 0.5 meters of the shock tube, followed by a stable transmitting velocity of approximately 1000 m/s (Figure 2). This implies that pre-detonation decomposition and stabilization are completed by 0.5 m from the ignition point – an important consideration for designing industrial blasting networks.

At 0.44 m from the ignition point, the oscillograms (Figure 3) captured two different responses:

- one from the shock wave (early-stage impact),
- another from the detonation wave (late-stage sustained combustion).

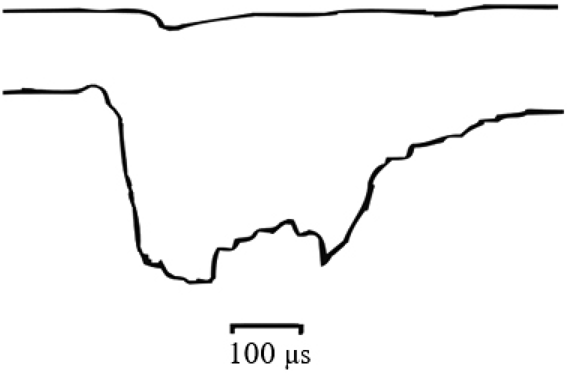

Figure 3. Oscillogram of the deformation of the detonation shock tube: 1 – shock wave action, 2 – detonation wave action

The evaluation of signal amplitudes, taking into account the different channel sensitivities, showed that their values differ by a factor of 20. Thus, it can be concluded that the errors in measuring the deformations of the detonation shock tube caused by the effect of the electric explosion at distanced greater than 0.44 m from the initiation point, do not exceed 5%.

Deformation profiles were compared at distances of 0.28, 0.4, and 0.9 m (Figure 4). Results clearly illustrate the transition from a pre-detonation combustion phase (Figure 4a) to a fully developed detonation wave in the shock tube (Figures 4b and 4c). The amplitude of the strain gauge signal increases. The front becomes steeper and the overall signal duration decreases.

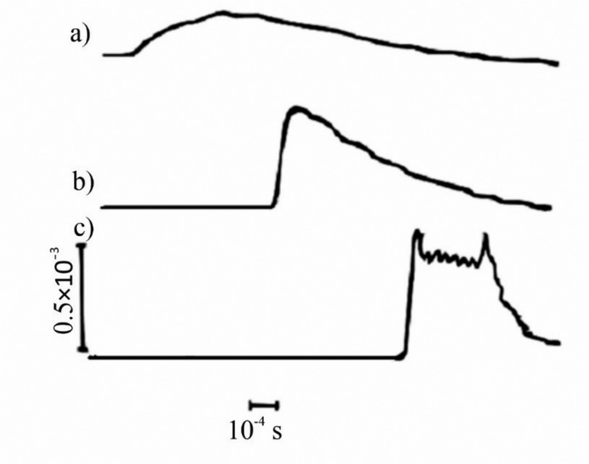

Figure 4. Shock tube deformation at: a – 0.28 m, b – 0.4 m, c – 0.9 m from the initiation point oscillogram

At 0.9 m, in the stable detonation zone, the average circumferential strain was 0.5×10^{-3}, with an impulse duration of $4\cdot10^{-4}$ s. Based on the data in Figure 2, the differences in the waveform shapes in Figures 4b and 4c can be explained. At a distance of 0.4 m from the source of the electric explosion, the shock tube deformed in shock mode (Figure 4b), but the signal amplitude was still insufficient to start the initiating process. This developed fully at a distance of 0.5 m (Figure 2), which was confirmed by the different signal shape in Figure 4c. Since all three waveforms showed the sequence of detonation development in the same shock tube sample along its length, their evolution supports the proposed hypothesis of a vibrational mechanism of detonation development in the shock tube.

4. Conclusions

- The presented data are mainly of methodological value, since they can form the basis for further research into reliable non-electric safe initiation systems for hole charges and for quality control. Analysis of the results shows that the comprehensive laboratory method allows determination of the main operational characteristics of *Nonel* type shock tube with sufficient accuracy – measurement errors mostly do not exceed 5. Energy fluctuations of the initiating electric explosion have practically no effect on the run-up distance of the detonation wave in the shock tube, which was about 0.5 m.
- Deformation evolution process on the run-up detonation distance in the shock tube confirms the hypothesis based on a vibration mechanism detonation process.
- It is established that the pressure impulse at the end of the shock tube opposite the initiation point is fully sufficient (2.0-2.5 MPa) to trigger detonation in special intermediate capsules. The low detonation velocity (1000-2000 m/s) allows the shock tube to be used as a short-delay element and to build blasting networks with the required variable delay intervals while using less tube material.
- The strength of the shock-tube shell and the quality of the explosive coating on the inner surface of the polyethylene tube are confirmed by the stability of the detonation and deformation parameters obtained across the series of experiments.

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