Regularity of low-speed detonation processes in the shock-tubes

Roman Zakusylo

PhD, senior lecturer
Shostka Institute of Sumy State University,
Shostka, Ukraine
E-mail: r.zakusylo@ishostka.sumdu.edu.ua

Viktor Kravets

PhD, professor
The National Technical University of Ukraine
"Kyiv Polytechnic Institute"
Kyiv, Ukraine

Abstract
The paper presents the results of studies of low-speed detonation processes in shock-tubes. The complex methodology of experimental studies of basic performance of the tubular detonating waveguide providing a sufficient degree of accuracy with an error of no more than 5% is applied. The mechanism of initiation by an electric explosive, development and low-speed damping of the shock front in the fiber cladding material deposited without explosives and detonation formation process along the length of the waveguide with a deposited layer of explosives is established. The points of its nucleation and growth to maximum velocity of detonation in the area of 0.5 m length and maintaining it at a constant level over the whole length in the range of values (for test samples) of about 1000 m / s are fixed.
Keywords: LOW-SPEED DETONATION; SHOCK-TUBE; ELECTRIC EXPLOSION; STRAIN GAUGES; WAVEFORM

1. Introduction

Using the example of the USA as the leading consumer of industrial explosives and their means of explosives, one can notice the spread of new types of non-electric initiation systems of well and blast-hole charges, which are based on the movement of shock waves channel [1-2]. They are characterized by high security, ease of use, provide a trouble-free blasting under the most difficult geological conditions and permit the development of the circuit short-delay blasting with wide ranges slowdowns intervals. The best known system is “Nonel”, which has structure based on a hollow plastic cord – waveguide, which inner surface is coated with a layer of an explosive reaction mixture [3-7]. During the initiation, this mixture decomposing the waveguide channel in the atmosphere forms and supports a shock wave (SW), which moves at a speed of about 2000 m/sec, regardless of its length [8-10].

2. Methodical positions of laboratory researches

The object of research is a coaxial polyethylene sheath. It is a tube of circular cross-section with an external diameter of 3.2 mm, an inner diameter of 1.3 mm. These values were obtained using the MBS-1-56 microscope with magnification. The length of the tubes studied varied from 150 to 1000 mm depending on the purpose of experiments.

Physical and mechanical properties of the tube material: polyethylene with a density ρ= 940 kg/m^3; modulus of elasticity E = 0.76·10^9 Pa; Poisson’s ratio ν= 0.4.

Two types of plastic tubes have been investigated. Some tubes were without internal coatings and others have explosive - hexogen sprayed uniformly on the inner surface of the tube at a flow rate 25.10^{-6} kg / m of length of tube. It should be noted that the observations of spraying the explosive under a microscope indicates that it contains grains of explosive up to 0.3 mm with a grid of locations around 1.8×2 mm. Subsequently, a polyethylene tube with explosive sprayed onto the inner surface will be called shock-tube.

Investigations were performed in a pilot plant designed for this purpose. The length of the test tube with plastic was placed on a flat surface of the wooden panel, to which it was attached by clamps. At a distance of 10 - 15 mm from the start of the tube through small holes pierced with a needle, thin (0.07 mm diameter) copper wires of 15 mm long were placed. Their ends outside of the shock-tube were soldered to the central conductor of the coaxial high-voltage cable. The high voltage from pre-charged capacitors of discharge unit was applied to them at a specified moment.

In the electric discharge unit as an energy storage device, high-voltage capacitors of type IMK-25-12 with total capacity 4.8·10^{-6} C are used. The pressure pulse inside a polyethylene tube was created at the moment of electric explosion of the conductor, thus the forming gap was shorted mechanically. The period of oscillation process, generated by an electric explosion of conductor equaled about 10^{-4} sec ±20%

The opposite end of the polyethylene tube was closed by piezoceramic pressure sensor leaning against it with a clearance of 0.15 mm. The sensing element of a piezoceramic sensor PZT-19 with a thickness of 0.3 mm and a size 1×1 mm was soldered to the coaxial high-frequency antivibration cable AVK-3 with silvered flat surface of the piezoelectric element arranged perpendicular to the axis of the cable. After the acoustic protection of the side surfaces of the sensor and filling with a mixture of epoxy, pressure sensor had the shape of a cone, the base of which was an area that takes the action of the pressure wave. So that pressure sensor does not react to pressure waves, which propagate along the shock-tube material, it is installed at the same distance.

When calibrating the pressure sensor, the correspondence between sensor value in millivolts and pressure value in a wave propagating through the channel of the diaphragm shock tube was established.

If the shock wave propagates through the channel with a speed W_1 and has the Mach number

$$M_1 = \frac{W_1}{a_1},$$

the pressure in the shock wave is defined as

$p = \dfrac{p_2}{p_1}$ function and is expressed:

$$\frac{p_2}{p_1} = \frac{2\gamma \cdot M_1^2 - (\gamma - 1)}{\gamma + 1} \qquad (1)$$

where p_1 and M_1 are, respectively, the pressure and velocity of sound in the gas before the movement of the wave front, γ is the ratio of specific heats of the gas.

The shock tube used for the calibration of sensors, has a rectangular internal section 210×140 mm. The chamber and the channel filled with air at atmospheric pressure are separated by diaphragm, which is the material selected depending on what intensity of wave is desired to obtain. The air chamber is pumped to a pressurized breaking through the diaphragm.

By measuring the propagation velocity of the direct shock W_1, the ratio allows us to calculate the value of the pressure jump, which acts on the calibrated sensor and produces an electrical signal of a fixed value.

To measure the time of passage of the shock wave of a predetermined distance, the sensor, which allows us to measure the velocity of the wave with an accuracy of ±2% , was used. Using the relation (1), we can calculate the value of the pressure drop in the shock front with a relative accuracy of ±2% %. Temperature measurements were needed to determine the speed of sound in the air a_1 at which the wave moves.

According to the oscillograms, profile of the pressure wave was fixed, then the signal of calibrated sensor was measured in volts with precision of ±5%.

Thus, for each sensor sensitivity was defined as a number which indicates which sensor gives a signal in volts when acted upon by a pressure wave with certain amplitude (in experiments about 10^5 Pa). The relative error of calibration was about 10%.

Specificity of fixing pressure wave, which moves by inner bore of small diameter polyethylene tube (1.3 mm), allows a pressure sensor to be placed just with overlapping the end cutting of the tube. Therefore, sensor calibration was performed with a similar sensor placed at the end of a small (20 - 50 mm) length of the spent tube ET, the other end of which was entered in the channel of the shock tube through the orifice hole in the end steel plate. Varying length of the tube in the range of 20 - 50 mm does not make significant changes in the waveform calibration of pressure waves.

In addition to the calibrated pressure sensor relatively small (1×1 mm) plates of piezoceramic sensor PZT 19 of 0.3 mm in thickness, glued to the outer surface of the plastic tube, were used in the experiments. The signals from the sensor were removed with the help of short lengths of thin copper wires 0.1 mm in diameter; they were soldered to the silvered surfaces of the piezoceramic plates at one end and to the coaxial cable antivibration AVK-3 at the other end. The electrical signals obtained when deformation of the sensor were applied to the electron type S9-8 oscilloscopes with digital readout of the time coordinate. The use of two piezoceramic plates with a known distance between them made it possible to calculate the average speed of the shock wave propagation through the tube between the piezo elements with an error of approximately 5%.

After registration of parameters in the detonation process of shock-tube, polyethylene tube is used again. With each new experiment, the wire with identical size was set; it initiated the trigger pressure pulse at electric explosion.

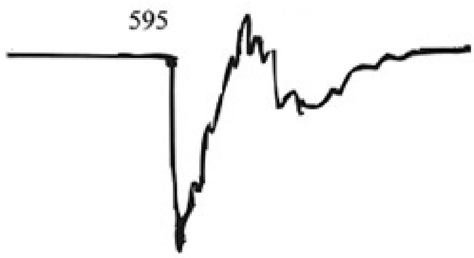
In the first experiments, the nature and speed of propagation of the pressure wave moving through the channel shock-tube were determined. In ten experiments, electric explosion of standard conductor of length 15 mm was performed not in the middle of the tube, but at 3 - 35 mm from its end, gummed beforehand with thin rigid plate approximately 5 mm in diameter. This pulse did not produced detonation before the process in the inner channel shock-tube, but generated a weak longitudinal pressure waves, which speed (D) was also calculated from the known distance between the piezo elements and the time interval between waveform characteristic points.

Fixing deformations of polyethylene shock-tube was performed with using strain gauges of type 5P1-1-200-B-12 (base is 1 mm, gauge factor - K = 2.12), included in the potentiometric circuit. Strain gauges are glued to the outer surface of the tube in the circumferential direction so that the propagation of the detonation process sensor data allowed registering a deformation of circumferential outer surface of the tube and hence determining the variation of the radial displacement tube wall in time. The signals from the strain gauges were applied to storage oscilloscopes S8-13 and S8-17.

3. Regularities of low-speed detonation processes in domestic samples of shock-tubes

Typical waveforms that were recorded by oscilloscopes S9-8 when submitted signals with piezoceramic plates glued on the outer surface of the shock-tube are shown in Figure 1 a, b. The distance between the piezo elements is (50±1) mm , signal arrival time is counted from the characteristic waveform points with an error of ± 10^{-6} sec.

a)



b)

c)

Figure 1. Type of signals:
a, b - from piezoceramic side plates;
c - from mechanical piezoceramic pressure sensor

Figure 1 shows the waveform recorded by mechanical pressure sensor for initiating the process of detonation in a shock-tube length of 1 m. The first pressure peak with an increase in pressure for 1 microsecond in seven experiments had values $(20 \pm 5)\cdot 10^5$ Pa. In another peak for a few microseconds, the pressure increases to 2510^5 Pa, followed by decline in about $150\cdot 10^{-6}$ sec.

Results of measurements of speed detonation inner bore shock-tube at different distances from the source of the explosion are shown in Figure 2. Experiments performed using 0.5 m (1) and 1.0 m (2) length tubes.

In the initial zone of origin of the detonation process, it is impossible to perform the measurement because of the large electrical interference, which arises on the channels of the recording apparatus due to electric discharge. Experiments show that after the electric explosion mechanical process of transformation of the explosive sprayed on the inner surface of the shock-tube is happening with increasing speed in the channel shock-tube of half-meter length (acceleration phase). The detonation process occurs further at a constant speed of about 1000 m/sec. Thus, it can be concluded that the pre-detonating process of decomposition of sprayed explosive for this shock tube occurs at an interval of 0.5 m from the initiation point.

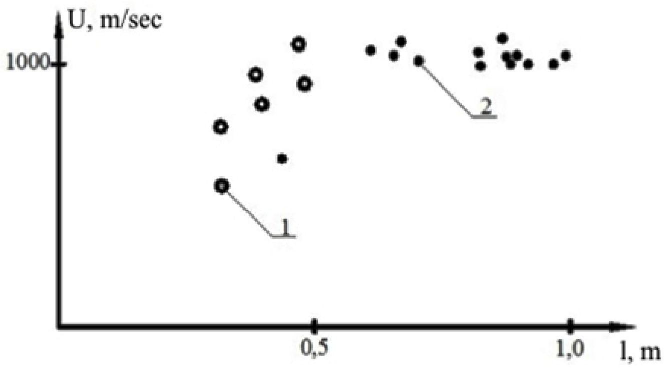


Figure 2. The speed of the detonation wave:
1 - in a tube 0.5 m in length; 2 - in a tube 1.0 m in length

The graphs in Figure 3 show the waveforms of the polyethylene tube ST deformation process at a distance of 0.44 m from the point of initiation. The bottom waveform shows the deformation of the outer surface of the tube ST in the process of propagation of the detonation wave. The upper curve, which represents the dependence of the surface of the tube deformations on the time, was recorded by the same sensor that recorded the pressure wave at the time of ST detonation by electric explosion. Signal evaluation with different sensitivity channels showed that their values differ by 20 times. Thus, it can be concluded that the errors in measurement of ST deformations arising due to the action of electric explosion at distances greater than 0.44 m from the initiation point are not higher than 5%.

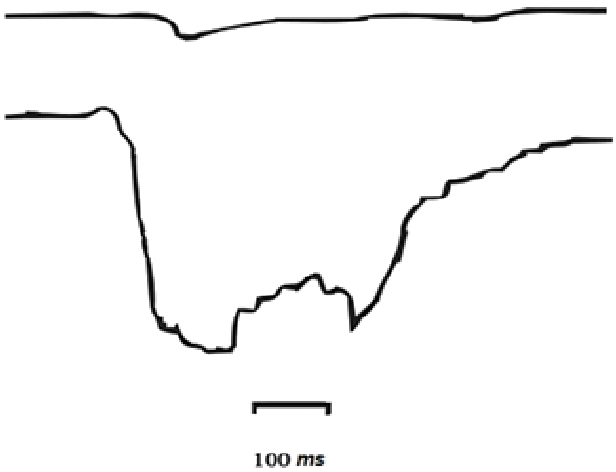


Figure 3. The oscillograms, fixing process of deformation of the tubular shock-tube: 1 - when the action of the shock wave; 2 - when the action of the detonation wave

For comparison, in Figure 4 the same scale waveforms of ST tube deformation at distances of 0.28 meters (Fig. 4 a), 0.4 m (Fig.4 b) and 0.9 m (Fig. 4) from the initiation point are given. The pre-detonating combustion process and the formation of the detonation wave in the channel of the detonating cord are clearly traceable. Amplitude value of strain gage signal increases, the front becomes steeper; the total duration of the signal is reduced. At a distance of 0.9 m from the electric discharge, where the detonation process is definitely stabilized, the average value of the circumferential deformation reaches $0.5\cdot 10^{-3}$, and the pulse duration was $4\cdot 10^{-4}$ s.

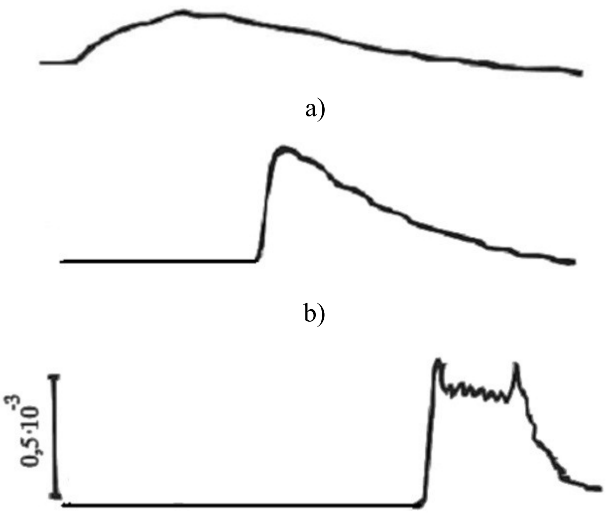


Figure 4. The oscillograms of deformation of the tubular waveguide at a distance from the initiation point:
a) – 0.28 m; b) - 0.4 m; c) – 0.9 m

These materials have primarily methodological importance, as they can serve as a basis for further research to establish a reliable means of a non-electric safe initiation blast-hole charges and quality control. As the analysis of the results, the complex technique of laboratory research provides a definition of the basic performance waveguide type "Nonel" a sufficient degree of accuracy - measurement error preferably does not exceed 5%.

4. Analysis of research results

In comparison with known samples, investigated shock tube has a significantly lower detonation velocity. This is due to the size of the sprayed particles of the explosive. With regard to the strength of the waveguide's sheath and quality of explosive spraying on the inner surface of the polyethylene tube, a sufficiently high level of stability is confirmed and obtained in a series of experiments detonation waveguide parameters.

Energy fluctuations of initiating electric explosion almost have no effect on the length of the acceleration of a detonation wave in the waveguide, which amounted to about 0.5 m. Furthermore, the pressure pulse at the opposite from the site of initiation end of waveguide (2.0 - 2.5 MPa) is entirely sufficient to initiate detonation in a special intermediate primers. The relatively low detonation velocity (1000 m / s) allows using the shock-tube as an element of short slowdowns and forming explosive network with the necessary steps variable decelerations with less consumption shock-tube.

5. Conslusions

Application of the complex method of experimental studies of basic performance characteristics of the tubular waveguide detonating provides a sufficient degree of error of 5% and can serve as a basis for further research to establish a reliable and secure means of initiation industrial charges.

The mechanism of initiation of electric explosion, development and low-speed damping of the shock front in the waveguide's sheath material without deposited explosives and formation of detonation process along the length of waveguide with a deposited layer of explosives was established. The points of nucleation and growth to maximum velocity of detonation in the area of 0.5 m (acceleration zone) are fixed maintaining it at a constant level over the whole length within the range of about 1000 m/sec. At the output of the shock wave from the waveguide, peak pressure at the front end is about 2.5 MPa at times of pressure rise and fall - 1-2 microseconds and 150 microseconds respectively.

Strain gages, used in the experiments with the base 1 mm and glued on the outer surface of waveguide, fixed circumferential deformation the shell in time with a relative error 5%. Registered gage signals at a fixed distance from the entry end of the tube allows obtaining time and amplitude parameters of deformation process in the shock and detonation mode with a guaranteed opportunity to distinguish between the time and the process for passage of the shock wave tube by electric explosion and of a detonation wave from the explosion of dusty explosive mixture in the channel waveguide.

References

1. Baron V.L., Kantor V.Kh. (1989) *Tekhnika i tekhnologiya vzryvnykh rabot v SShA* [Technique and technology of blasting in the USA]. Moscow: Nedra. 376 p.
2. Zakusylo R.V., Kravets V.H., Korobiichuk V.V. (2011) *Zasoby initsiiuvannia promyslovykh zariadiv vybukhovykh rechovyn* [Means of initiation industrial charges of explosives: monograph]. Zhytomyr State Technological University, ational Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute". Zhytomyr: Zhytomyr State Technological University. 208 p. Available at: http://kpi.ua/en/about#sthash.VNAlEWNF.dpuf. –
3. Graevskiy M.M., Kutuzov B.N. (2000) Tekhniko–ekonomicheskoe sopostavlenie elektricheskikh i neelektricheskikh sistem initsiirovaniya zaryadov VV [Technical and economic comparison of electrical and non-electric systems for initiating explosive]. *Gornyy zhurnal* [Mining journal]. No5, p.p. 54–59.
4. Instruktsiya po ekspluatatsii sistemy "Nonel"' [Instruction manual for the "Nonel" system]. Swedish National Testing and Research Institute. 1998. 55 p.
5. Bykov D.H., Frolov O.O. (2000) Perspektyvy vykorystannia neelektrychnoi systemy initsiiuvannia "Nonel - Yunidet" v umovakh VAT "Poltavskyi HZK" [Prospects for the use of non-electric initiation system «Nonel - Unidet» in terms of «Poltava GOK»]. *Visnyk Natsionalnoho tekhnichnoho universytetu Ukrainy «KPI». Seriia "Hirnytstvo"* [Journal of the National Technical University of Ukraine "KPI". A series - "Mining"]. No 3, p.p. 69-71.
6. Guzya A.N. (1983) *Mekhanika kompozitsionnykh materialov i elementov konstruktsiy* [Mechanics of composite materials and structural elements]. Kyiv: Naukova dumka, Vol. 3. 264 p.
7. Kravets V.H., Frolov O.O., Marharian A.Z. (2003) Eksperymentalni doslidzhennia ekspluatatsiinykh kharakterystyk khvylevodu systemy initsiiuvannia typu «Nonel» [Pilot studies of operational characteristics of a waveguide of initiation system of type "Nonel"]. *Visnyk Natsionalnoho tekhnichnoho universytetu Ukrainy «KPI». Seriia "Hirnytstvo"* [Journal of the National Technical University of Ukraine "KPI". A series - "Mining"]. No 9, p.p. 59-66.