



Influence of the Initiation Energy on the Velocity of Detonation of ANFO Explosive

Vječislav BOHANEK*, Mario DOBRILOVIĆ
and Vinko ŠKRLEC

*University of Zagreb, Faculty of Mining,
Geology and Petroleum Engineering,
Pierottijeva 6, 10002 Zagreb, Croatia
E-mail: vjecislav.bohanek@rgn.hr

Abstract: ANFO explosives have been widely used for blasting operations in mining and civil engineering. From a scientific point of view, ANFO is interesting due to its non-ideal detonation. There are numerous factors that affect the velocity of detonation of ANFO explosives. This paper presents measured velocities of detonation of ANFO explosives initiated by various initiation methods and initiation energies. ANFO explosives were tested in steel pipes, and detonators and boosters of different masses and initiation energies were used for initiation. The initiation energy of a detonator was determined using the underwater initiation capability test. The influence of the equivalent shock energy and the equivalent bubble energy on the velocity of detonation of ANFO was also determined. These measured results contribute to a better understanding of the non-ideal detonation of ANFO explosives.

Keywords: ANFO, initiation energy, velocity of detonation

Introduction

Ammonium nitrate fuel oil (ANFO) explosives are simple, two-component explosives that consist of ammonium nitrate(V) prills and fuel oil. ANFO is an explosive which, despite having a low velocity of detonation and detonation pressure, is characterised by a high blasting efficiency due to the large volume of gas generated [1]. Due to its properties related to safety, a simple manufacturing

process, low price, and satisfactory blasting and technical properties, ANFO is the most widely used civil explosive. ANFO is also known for its non-ideal detonation behaviour. In most cases it does not exhibit the ideal behaviour as predicted by thermohydrodynamic theory. Non-ideal explosives differ from conventional explosives in that they are usually high-porosity, low-density materials where the fuel and oxidizer are not mixed on a molecular level [2]. In some cases of non-ideal explosives, the fuel and oxidizer are mixed on a molecular level (*e.g.* ammonium chlorate(VII)).

Research on the influence of individual factors on the detonation parameters of ANFO have been carried out by a large number of workers. Their papers, recently published, present the influence of the characteristics of ammonium nitrate, such as grain size, density, porosity, *etc.* [3-5] on the velocity of detonation of ANFO. The influence of adding aluminum powder of different particle sizes and in varying percentages on the detonation parameters of ANFO was also investigated [6-8], as well as the influence of adding different percentages of milled dolomite [9]. The influence of the explosive charge diameter and the density of ANFO on the velocity of detonation were also investigated and these data are available in the literature.

ANFO can be initiated by various initiation devices with an initiation energy sufficient to cause the detonation process in the explosive. Different initiation methods result in different velocities of detonation of the explosive charges and different quantities of the released energy on which the blasting efficiency depends. The research presented in the present paper is directed towards determining the influence of the initiation energy of the initiation device on the velocity of detonation of ANFO.

Materials and Methods

Materials

The means of initiation must have sufficient energy to initiate the explosive or the detonating cord/shock tube, with which they are intended to be used [10]. The initiating capability of a detonator is determined by the underwater initiation capability test. The underwater initiation capability test is carried out using reference detonators (No. 1 – No. 5) with copper housing and a predefined explosive charge mass.

The reference detonators were manufactured according to the EN 13763-15 standard. Pentrite (PETN) was used as the base charge of the detonator. The dimensions and mass of the explosive charge of each reference detonator are

presented in Table 1 and their construction is presented in Figure 1. The mass of the initial charge for all detonators was 0.30 ± 0.01 g.

Table 1. Dimensions and mass of explosive charges of reference detonators

Detonator	PETN (g)	A (mm)	B (mm)
Ref. det. 1	0.25	53	41.6
Ref. det. 2	0.4	53	38.8
Ref. det. 3	0.6	53	34.8
Ref. det. 4	0.8	65.5	43
Ref. det. 5	1.0	65.5	39

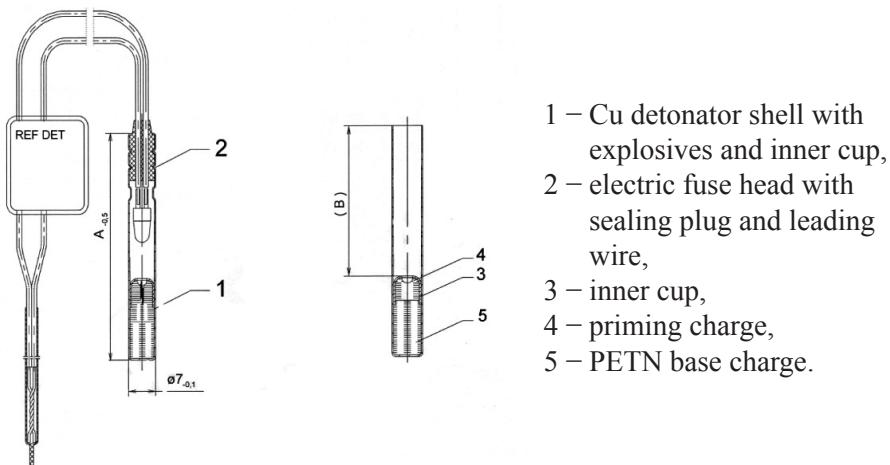


Figure 1. Construction of reference detonator [10].

The samples of ANFO tested, for which the velocity of detonation was measured, were initiated by the reference detonators and PETN boosters of various masses. According to the manufacturer's data, the density of the AN used was 822 kg/m^3 , with a minimal oil absorption of 6% and at least 90% of the particles had sizes between 1.0 and 2.83 mm. The fuel oil density was 842 kg/m^3 (at 15°C) with a kinematic viscosity of 3.02 (at 40°C). The ammonium nitrate/fuel oil combination was 94.6% ammonium nitrate and 5.4% fuel oil; the density of the explosive was 823 kg/m^3 .

Methods

Underwater initiation capability test

The underwater initiation capability test is based on the principle that the detonation of an explosive charge under water generates a spherical shock wave and a volume of gas, which expands and then collapses as the bubble rises through the water. The shock-wave and the volume of gas are determined by the energy released. By measuring the shock-wave pressure and the time between the shock wave peak pressure and the first collapse of the gas bubble, the energy output of the detonators can be calculated [10]. The calculated energy output parameters of the detonators are equivalent to the shock energy and the equivalent bubble energy.

The detonator and pressure sensor were placed in the water tank at a depth of 400 ± 5 mm and at a separation of 400 ± 5 mm. The distances between the sensor and the detonator and between the sensor/detonator and the container walls are defined according to the EN 1763-15 2004 standard [10]. The relative positions of the detonator and pressure sensor in the water tank is shown in Figure 2.

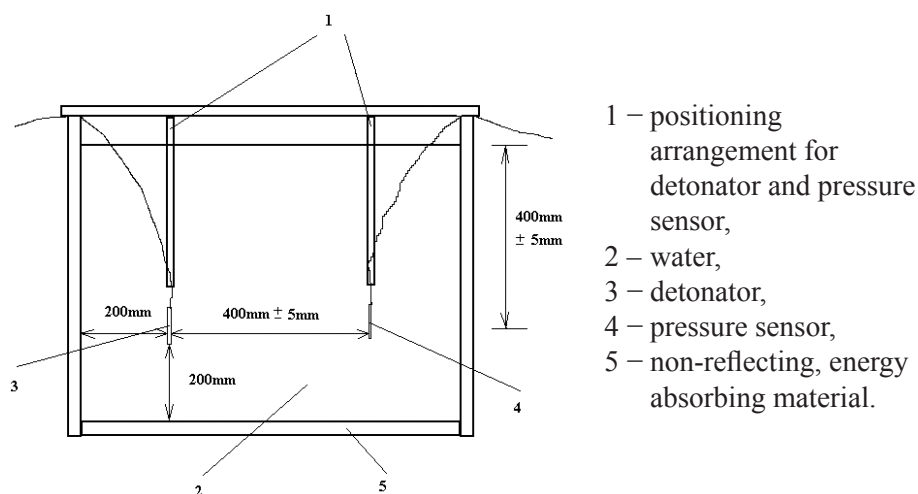


Figure 2. Position of detonator and pressure sensor in the water tank [10].

In order to measure the shock wave in the water and the pressure of the gas bubbles, a piezoelectric pressure sensor, PCB – model 138A05, intended for use in water, was used. It consists of a measuring element, a tourmaline crystal placed within an oil-filled tube. The signal from the shock wave, transformed into an electrical signal by the piezoelectric effect, is amplified and transmitted to the

recorder (LeCroy Waverunner 64 Xi oscilloscope). By taking into consideration the predefined sensor constant and the value of the electrical signal voltage, the pressure value can be calculated.

The shock wave energy in the water, as a result of the detonation of the detonator, can be calculated with sufficient accuracy according to the formula for the equivalent shock wave energy (E_s) and the equivalent bubble energy (E_b). Since it is the equivalent energy, *i.e.* the value of the energy released, the equivalent shock energy is expressed in Pa^2s and the equivalent bubble energy in s^3 . The calculation of the real energy, *i.e.* the energy density, the energy transmitted by a shock wave on unit area of the wave front, is based on hydrodynamic equations of state for fluids affected by a shock wave [11].

Figure 3 shows a typical measurement diagram of the pressure measured in water.

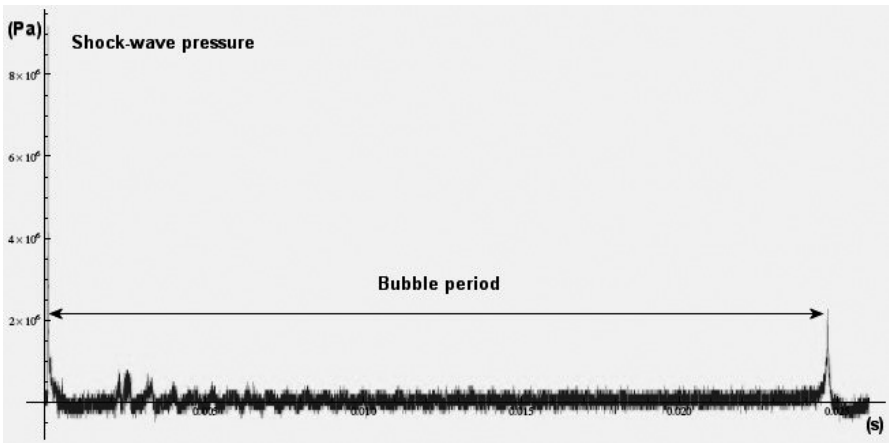


Figure 3. Typical measurement diagram of the pressure measured in water.

The equivalent shock wave energy is calculated from the measured data for an individual shot from equation (1):

$$E_s = \int_{t=0}^{t=\theta} (p)^2 dt \tag{1}$$

where:

- E_s – equivalent shock wave energy (Pa^2s),
- $t=0$ – starting time for pressure increase,
- $t=\theta$ – the time (s), at which the shock wave pressure decreases to value P_{max}/e , where P_{max} represents the peak value of the measured pressure, and

e represent the base of the natural logarithms, and

p – measured pressure values (Pa).

The equivalent bubble energy is calculated from equation (2):

$$E_b = (t_b^3) \quad (2)$$

where:

E_b – equivalent bubble energy (s^3) and

t_b – bubble period (s), between the shock wave pressure peak and the first collapse of the gas bubble produced by the detonation gases.

Based on equations (1), (2) and the EN 13763-15 standard, application to the calculation of the shock wave energy and the bubble energy was designed in Mathematica computing software.

Velocity of detonation measurements

The velocity of detonation was measured by the electro-optical method using the electronic timer Explomet-Fo-2000 according to EN 13631-14 standard [12]. The device can measure the velocity of detonation on five segments. The method measures the time necessary for the detonation wave front to traverse the distance between two points. The velocity is calculated on the basis of the measured time and the predefined distance. The accuracy of the time measurement was $\pm 0.1 \mu s$ in a total duration of up to 10 000 μs . The ANFO was placed in steel pipes of $\varnothing 61/55$ mm and length of 500 mm. The velocity of detonation was measured on 4 segments. The sensors (P1-P5) were placed at separations of 100 mm. The distance between the initiation point and the first sensor (P1) was 50 mm. The velocity of detonation measurement setup is shown in Figure 4.

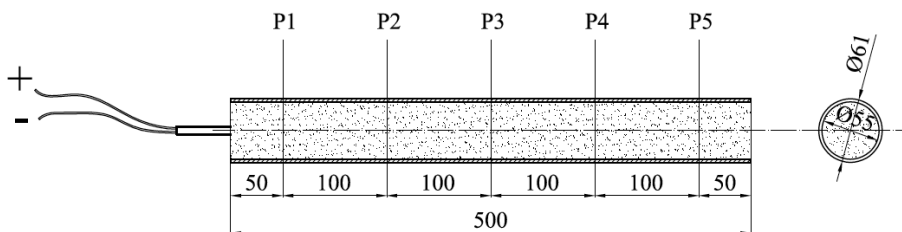


Figure 4. Measurement setup for the velocity of detonation.

The velocity of detonation measurements were divided into two groups. The samples initiated using reference detonators numbers 1 to 5 were tested in the

first group, and the samples initiated by the PETN boosters of various masses were tested in the second group. PETN boosters of 20, 50 and 100 g were used.

Results and Discussion

Results of the underwater initiation capability test

A total of 10 detonators were detonated for each type (number) of reference detonator. The average values of the maximum measured shock wave pressure, the equivalent shock wave energy E_s , the bubble period t_b and the equivalent bubble energy E_b for each reference detonator are presented in Table 2. Figure 5 depicts the dependence of the values of the measured peak pressure on the explosive mass, Figure 6 depicts the dependence of the shock wave energy on the explosive mass, and Figure 7 depicts the dependence of the bubble energy on the explosive mass. Due to the large mass of the explosive charge, it was not possible to detonate the boosters in the water tank. The maximum pressure value, the equivalent shock wave energy E_s and the equivalent bubble energy E_b of the boosters were calculated according to the formulae presented in Figures 5, 6 and 7. The results of these calculations are presented in Table 3.

Table 2. Average values of the maximum measured pressure, equivalent shock wave energy E_s , bubble period t_b and equivalent bubble energy E_b for each reference detonator

	Explosive mass (g)	Max. pressure (MPa)	Energy $E_s \times 10^6$ (Pa ² s)	Bubble period t_b (ms)	Energy $E_b \times 10^{-6}$ (s ³)
Ref. det. 1	0.25	5.29	204.00	20.29	8.35
Ref. det. 2	0.4	6.48	311.08	22.48	11.36
Ref. det. 3	0.6	7.68	453.46	24.68	15.04
Ref. det. 4	0.8	9.03	581.73	26.23	18.04
Ref. det. 5	1.0	10.82	720.97	27.53	20.88

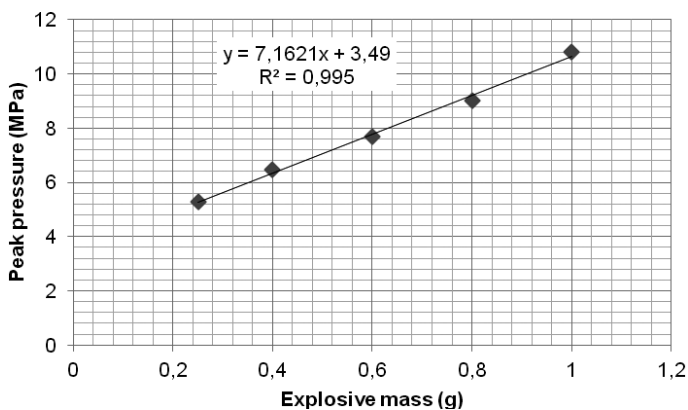


Figure 5. Influence of explosive mass on the measured peak pressure values.

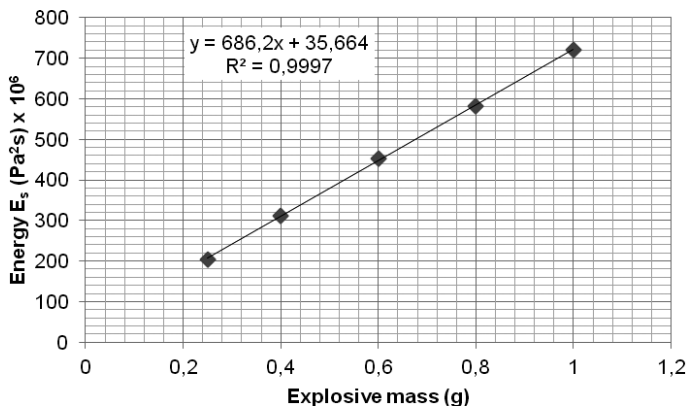


Figure 6. Influence of explosive mass on the equivalent shock wave energy E_s .

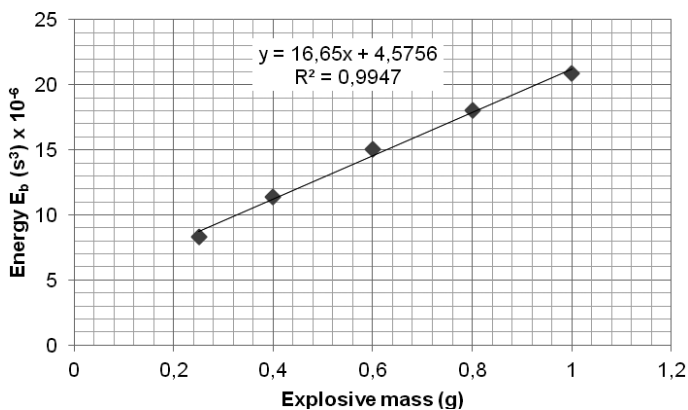


Figure 7. Influence of explosive mass on the equivalent bubble energy E_b .

Table 3. Calculated values of the maximum pressure, equivalent shock wave energy E_s and equivalent bubble energy E_b for each booster

	Explosive mass, (g)	Max. pressure (MPa)	Energy E_s $\times 10^6$ (Pa 2 s)	Energy E_b $\times 10^{-6}$ (s 3)
Booster 1	20	146	13760	335.58
Booster 2	50	362	34346	832.08
Booster 3	100	720	68656	1659.58

Results of the detonation velocity measurements

The measured velocities of detonation of ANFO initiated by the reference detonators are presented in Table 4, and the measured velocities of detonation of ANFO initiated by the PETN boosters are presented in Table 5.

Table 4. Measured velocities of detonation (D) of ANFO initiated by the reference detonators

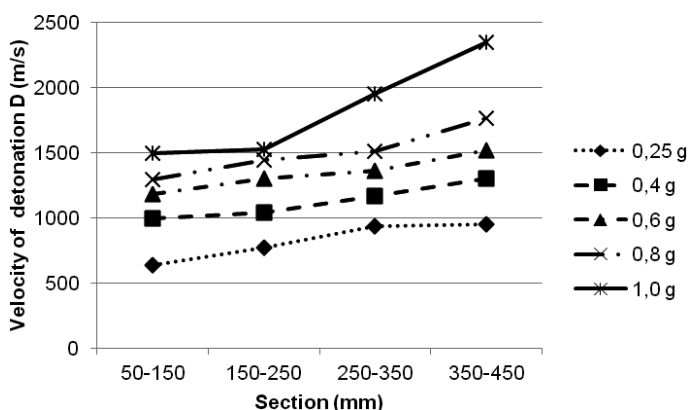
	Initiation	Explosive mass (g)	D, P1-P2 (m/s)	D, P2-P3 (m/s)	D, P3-P4 (m/s)	D, P4-P5 (m/s)
1	Ref. 1	0.25	685	*	*	*
2	Ref. 1	0.25	590	785	892	997
3	Ref. 1	0.25	*	763	980	914
Mean value			638	774	936	956
1	Ref. 2	0.4	*	*	1168	1322
2	Ref. 2	0.4	934	1115	1200	1356
3	Ref. 2	0.4	1060	965	1149	1241
Mean value			997	1040	1172	1306
1	Ref. 3	0.6	1353	1538	1364	1547
2	Ref. 3	0.6	1064	1149	1315	1488
3	Ref. 3	0.6	1135	1230	1410	1529
Mean value			1184	1306	1363	1521
1	Ref. 4	0.8	1328	1445	1546	1869
2	Ref. 4	0.8	1182	1337	1637	1821
3	Ref. 4	0.8	1377	1548	1353	1603
Mean value			1296	1443	1512	1764
1	Ref. 5	1.0	1639	1481	2331	2659
2	Ref. 5	1.0	1245	1451	1745	2092
3	Ref. 5	1.0	1608	1645	1795	2309
Mean value			1497	1526	1957	2353

Comment: * No result

Table 5. Measured velocities of detonation (D) of ANFO initiated by PETN boosters

	Initiation	Explosive mass (g)	D, P1-P2 (m/s)	D, P2-P3 (m/s)	D, P3-P4 (m/s)	D, P4-P5 (m/s)
1	PETN 20	20	3086	2762	2949	3003
2	PETN 20	20	2512	2958	2967	3105
3	PETN 20	20	2659	2624	2762	3021
Mean value			2752	2781	2893	3043
1	PETN 50	50	2825	2976	3012	3115
2	PETN 50	50	2786	2950	3086	3247
3	PETN 50	50	2625	3096	2695	3205
Mean value			2745	3007	2931	3189
1	PETN 100	100	3125	3279	3367	3425
2	PETN 100	100	2898	3225	2915	3460
3	PETN 100	100	2994	3135	3311	3484
Mean value			3006	3213	3198	3456

A graphical representation of the average measured velocities of detonation on the individual segments for initiation using the reference detonators is given in Figure 8, and of the average measured velocities of detonation for initiation using boosters is given in Figure 9.

**Figure 8.** Measured velocities of detonation on individual sections, initiation by reference detonators.

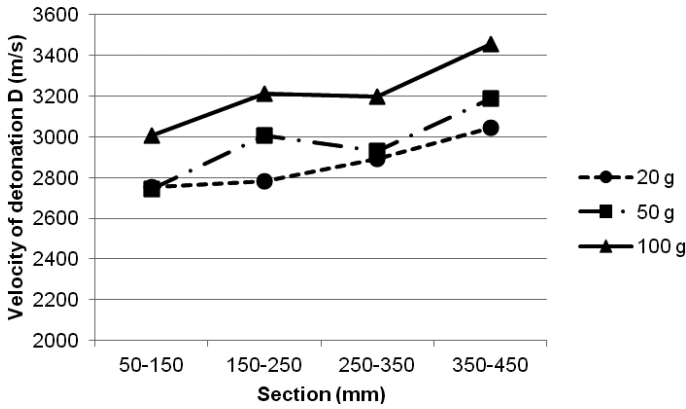


Figure 9. Measured velocities of detonation on individual sections, initiation by boosters.

Following the measurements, the values of the equivalent shock wave energy and the equivalent bubble energy of the reference detonators and boosters were compared to the measured velocities of detonation of the ANFO. The relation between the shock wave energy and the measured velocities of detonation for the ANFO initiated by the reference detonators and boosters is presented in Figure 10, and the relation between the equivalent bubble energy and the measured detonation velocities is presented in Figure 11.

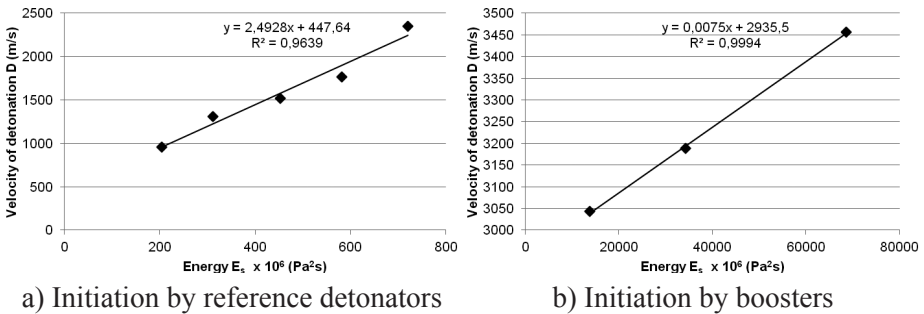


Figure 10. Dependence of velocity of detonation on the equivalent shock wave energy E_s .

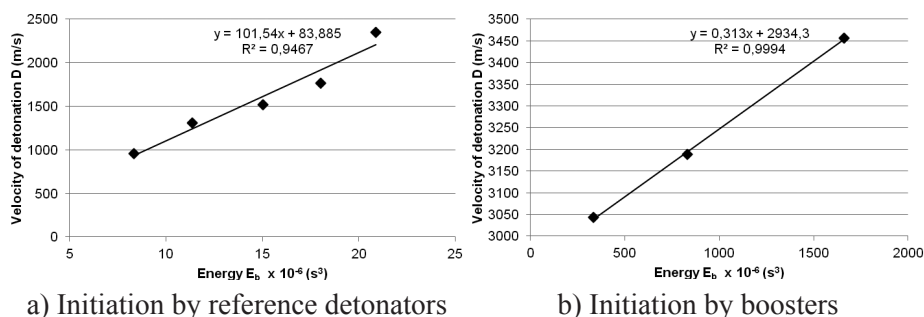


Figure 11. Dependence of velocity of detonation on the equivalent bubble energy E_b .

Discussion

The correlation curves that represent the influence of the explosive charge mass of the reference detonators on the measured peak pressure, the equivalent shock energy E_s and the equivalent bubble energy E_b are presented in Figures 5, 6 and 7. The influence of the mass of the PETN charge of the detonators on the peak pressure, the equivalent shock energy and the equivalent bubble energy is expressed by linear equations with high determination coefficients (0.995, 0.9997 and 0.9947 respectively). This means that the equations are suitable for calculating the peak pressure, the equivalent shock energy and the equivalent bubble energy of the boosters.

Explosions can generally occur in two ways, the first is deflagration and the second is detonation. Deflagration is a rapid, high energy release combustion event that propagates through an explosive material at subsonic speeds, driven by the transfer of heat. Detonation is a supersonic reaction and is propagated by a shock wave through the explosive material. According to Table 4, the lowest measured velocity was 590 m/s in the test where the ANFO explosive was initiated with reference detonator No. 1. This and other low measured velocities indicated that it may be a process other than detonation and the measured velocity can be called the velocity of explosion. A low reaction velocity may also be the reason why the instrument did not measure the velocity in some sections when the ANFO was initiated with reference detonators No. 1 and No. 2. For all other shots there was a result in each section. The shots with no results were not included when the mean value was calculated. In all cases, the lowest velocities of detonation were measured in the first section, from 50 to 150 mm, and the highest velocities in the last section, from 350 to 450 mm. In the majority of shots the measured velocity of detonation increased in all sections from the initiation point to the end

of the pipe. However in some shots the velocity of detonation first increased and then decreased in some sections. This may be caused by deflection of the flexible optical fibre probes in the explosive. There was a variation in the measured velocity of detonation for individual sections by the same means of initiation. The greatest differences between results were recorded in the first section, while the results of the last section have the least variation of measured values. When measuring the velocity of detonation of explosives according to the standard, the first probe should be placed at a minimum distance of five diameters of the explosive charge from the point of initiation. In this way, the measurement of a stable velocity of detonation is ensured. This fact also explains the differences between the measured results for the first section.

It is obvious from Figure 10 and Figure 11 that the velocity of detonation of ANFO increases simultaneously with the increase in the value of the equivalent shock energy and the equivalent bubble energy of both detonators and boosters.

Conclusions

Based on the results and discussion, the following conclusions were made:

- It is possible to initiate an explosion of ANFO in steel pipes using detonators with a minimum quantity of explosive charge of 0.25 g (ref. detonator No. 1).
- The velocity of detonation of ANFO increases with the increase in the mass of PETN in the initiating device.
- The dependence of the velocity of detonation on the equivalent shock wave energy E_s and the equivalent bubble energy E_b , is expressed by linear equations with high determination coefficients, and indicates that there is a strong relation between the initiation energy and the velocity of detonation of ANFO.
- In the cases of initiation of ANFO by the reference detonators, a significantly greater increase in the velocity of detonation in relation to the initiation energy was noticed compared to the initiation of ANFO by boosters.
- In the cases of initiation of ANFO by the reference detonators, the equivalent shock wave energy E_s changed from 204×10^6 to 721×10^6 (Pa²s), the equivalent bubble energy E_b from 8.35×10^{-6} to 20.88×10^{-6} (s³), and the increasing velocity of detonation ranged from about 960 to 2350 m/s.
- In the cases of initiation of ANFO explosive by boosters, the equivalent shock wave energy E_s was changed from 13760×10^6 to 68656×10^6 (Pa²s), the equivalent bubble energy E_b from 336×10^{-6} to 1660×10^{-6} (s³), and the increasing velocity of detonation ranged from about 3040 to 3460 m/s.

Acknowledgements

The results presented were obtained within the scientific project 'Emulsion explosives, initiating devices and environmental influence of blasting', supported by the Croatian Ministry of Science, Education and Sports.

References

- [1] Mahedavan E.G., *Ammonium Nitrate Explosives for Civil Application*, WILEY-VCH, Weinheim, **2013**.
- [2] Jackson S.I., Kiyanda C.B., Short M., Experimental Observations of Detonation in Ammonium-nitrate-fuel-oil (ANFO) Surrounded by a High-speed, Shockless, Aluminum Confiner, *Proceedings of the Combustion Institute*, **2011**, 33(2), 2219-2226.
- [3] Miyake A., Takahara K., Ogawa T., Yuji Y., Wada Y., Arai H., Influence of Physical Properties of Ammonium Nitrate on the Detonation Behaviour of ANFO, *Journal of Loss Prevention in the Process Industries*, **2001**, 14, 533-538.
- [4] Zygmunt B., Buczkowski D., Influence of Ammonium Nitrate Prills Properties on Detonation Velocity of ANFO, *Propellants Explos. Pyrotech.*, **2007**, 32(5), 411-414.
- [5] Buczkowski D., Zygmunt B., Influence of Ammonium Nitrate Prills Porosity and Dimensions on Detonation Velocity of ANFO Explosives, *New Trends Res. Energ. Mater., Proc. Semin.*, 5th, Pardubice, **2003**, 45-51.
- [6] Zygmunt B., Detonation Parameters of Mixtures Containing Ammonium Nitrate and Aluminium, *Cent. Eur. J. Energ. Mater.*, **2009**, 6(1), 57-66.
- [7] Maranda A., Paszula J., Zawadzka-Małota I., Kuczyńska B., Witkowski W., Nikolczuk K., Wilk Z., Aluminum Powder Influence on ANFO Detonation Parameters, *Cent. Eur. J. Energ. Mater.*, **2011**, 8(4), 279-292.
- [8] Maranda A., Papliński A., Gałęzowski D., Investigations on Detonation and Thermochemical Parameters of Alumized ANFO, *J. Energ. Mater.*, **2003**, 21(1), 1-14.
- [9] Buczkowski D., Zygmunt B., Detonation Properties of Mixtures of Ammonium Nitrate Based Fertilizer and Fuels, *Cent. Eur. J. Energ. Mater.*, **2011**, 8(2), 99-106.
- [10] EN 13763-15:2004, Explosives for Civil Uses – Detonators and Relays – Part 15: Determination of Equivalent Initiating Capability.
- [11] Cole R.H., *Underwater Explosions*, Princeton Univ. Press, Princeton, **1948**.
- [12] EN 13631-14:2003, Explosives for Civil Uses – High Explosives – Part 14: Determination of Velocity of Detonation.