Scientific Journals
of the Maritime University of Szczecin

Zeszyty Naukowe
Akademii Morskiej w Szczecinie

2017, 49 (121), 77–83
ISSN 1733-8670 (Printed)
ISSN 2392-0378 (Online)
DOI: 10.17402/205

Received: 29.04.2016
Accepted: 13.02.2017
Published: 17.03.2017

Experimental verification of the concept of the use of controlled pyrotechnic reaction as a source of energy as a part of the transport system from the seabed

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Key words: deep sea mining, transport from the sea floor, blasting materials, pyrotechnics, experimental verification, source of Energy

Abstract

In this article the authors discuss the concept of using pyrotechnical materials for transportation in deep sea environment. The use of pyrotechnical materials in underwater transportation involves their use as a source of energy (needed, for instance, in emptying the ballast tank). The authors presented the experimental verification of the usefulness of pyrotechnical materials in transporting from great depth. In the experiments, a modified composition black powder was used as source of energy. In the research the authors focused on two methods of controlling the pyrotechnical reaction effects, i.e., mechanical suppression of the blast, so as to reduce its negative effect on the housing of the transporter, and control of the pyrotechnical reaction itself. The obtained results confirm the possibility of using pyrotechnical materials in transportation of deposits from considerable depth.

Introduction

Ongoing depletion of land mineral resources and, on the other hand, an increase in the consumption of some raw materials cause an increasing interest in underwater exploitation of mineral resources. This is an impulse for increasingly intensive research and development of mineral resource technology exploration from sea and ocean floors. The scope of this interest includes not only crude oil and natural gas. Sea mining of the shelf area (Karlic, 1984; Depowski et al., 1998) provides many metal materials, such as titan, zircon, tin, gold, platinum and iron sands. Diamond, phosphorite, gravel and sand deposits have been effectively explored, not to mention such resources as sulphur and bituminous coal deposits. Great hopes are pinned upon extensive land polymetallic nodules and seafloor massive sulphides (SMS) (SPC, 2013). While the exploration of shelf deposits up to the sea depths of 200 m has been relatively well developed, the deposits stored at higher depths pose major challenges for researchers and constructors. These are pioneering works and as of today only Nautilus Minerals has been conducting big-depth exploration on industrial scale in the Solwara zone (depth ca. 1600 m) (Nautilus Minerals, 2016).

For Poland, the Clarion-Clipperton zone is particularly important. It is characterised by a high average concentration, over 10 kg/m^2, at the highest concentration of metals: 25–28% for manganese, 1.14–1.25% for nickel, ca. 1% for copper and 0.21% for cobalt. The resources of this zone, according to recent research, were estimated at $34 \cdot 10^{12}$ kg including $7.5 \cdot 10^{12}$ kg of manganese, $340 \cdot 10^{9}$ kg of nickel, $265 \cdot 10^{9}$ kg of copper and $78 \cdot 10^{9}$ kg of cobalt (Abramowski & Kotliński, 2011; Kotliński 2011). An industrial mining area is one from which it is possible to extract $1.5 \cdot 10^{9}$ to $4.0 \cdot 10^{9}$ kg of resources annually. The Szczecin-based Inter Ocean Metal lot, which has a surface area of 75 000 km^2, can assure these rates of extraction for a 25-year period, particularly through the exploitation of the B_2 area

(Kotliński, 2011). Unfortunately, these resources are deposited at 4200 to 4500 m of depth.

The biggest problem in opencast marine mining is transportation from the depth to the surface. Despite the numerous studies, current solutions (Karlic, 1984; Depowski et al., 1998) based on CLB method (with continuous line bucket), HP (hydraulic pumping) or air-lift ALP method (air-lift pumping) are nowhere near ideal. They are mostly energy-consuming and thus generate high costs. This is why less energy-consuming methods have been sought.

In this paper, the authors want to show the concept of the use of explosives in marine environment, where they would be used as the energy source for emptying ballast tanks. This concept is the subject matter of patent applications of the authors (Filipek & Broda, 2015a; 2015b). Commonly known for their destructive force (Dyja, Maranda & Trębiński, 2001), explosives (pyrotechnical materials) are characterised by rapid growth of pressure in time. It seems that the use of explosives as the source of energy used for underwater transport of objects is inconvenient. The authors try to prove in this paper that it is possible to control the process of combustion and that the process can be implemented as the source of energy in transport.

In 1876, Berthelot, on the basis of Bunens and Sziszkow's research (Urbański, 1985), derived an equation (1) for black powder distribution during explosion:

$$16KNO_3 + 6S + 13C \rightarrow 5K_2SO_4 + 2K_2CO_3 + K_2S + 8N_2 + 11CO_2 \quad (1)$$

Recent research (Papliński, Surma & Dębski, 2009) has shown, however, that the combustion products of black powder cannot be described by any single simple equation because of the problem with determining precise carbon composition. The composition depends on many factors, such as the type of wood used for the combustion or time and temperature of combustion and pollution after dry distillation. The research clearly showed that the black powder combustion products could be divided into three groups:

1. 55.91% of solid products: sulphur carbonate, potassium sulphate, potassium sulphide, sulphur, potassium nitrate, carbon, and ammonium carbonate;
2. 42.98% of gas products: carbon dioxide, nitrogen, carbon oxide, hydrogen sulphide, hydrogen, and methane;
3. 1.11% of water.

In 1907, Andrew Noble (Urbański, 1985) stated that it is possible to use black powder consisting solely of potassium nitrate – thus without sulphur. He proved that sulphur is the material which improves the explosive properties of black powder by lowering its initial temperature of distribution, increasing sensitivity to impact, increasing the volume of gas emitted in the explosion (sulphur reacts more quickly with potassium than CO_2 does), and preventing the emergence of CO. Research on black powder consisting of only two components, potassium nitrate and carbon, was continued by many researchers, including Oza and Shah (1943) and Blackwood and Bowden (1943) (Urbański, 1985; Brown, 2000).

Research on the combustion process of pyrotechnic material (black powder) in a combustion chamber (gun chamber + barrel) has been conducted in many research centres. For example, the pressure distribution in time, measured from the moment of ignition, has been studied and is shown in Figure 1. After initialising the combustion of pyrotechnical material (powder), a pressure surge of approximately 276 MPa can be witnessed in a time shorter than $0.5 \cdot 10^{-3}$ seconds. After this the pressure in the barrel lowers due to the expansion of the combustion products caused by the movement of the bullet in the barrel.

In this paper the authors used black powder consisting only of two components – sulphur nitrate, which is an easily accessible cheap material because it is used as soil fertiliser in agriculture, and charcoal, commonly used in households for food grilling. The black powder components were mixed after they had been ground mechanically in suitable stoichiometric proportions in order to obtain the course of reaction presented below (Błasiak, 1956; McLean, 1992):

$$4KNO_3 + 5C \rightarrow 2K_2CO_3 + 2N_2 + 3CO_2 \quad (2)$$

The authors are aware that the above reaction (2) is a very simplified description of the combustion of black powder. The authors emphasize the importance

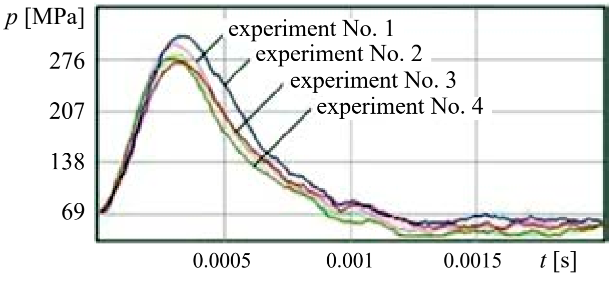

Figure 1. Pressure distribution in time in the combustion chamber (Recreational Software, 2016)

of the controlled (deflagration) pyrotechnic reaction, in which the main gaseous products would be CO_2 and N_2. Our analysis shows that the most favourable response that meets our expectations is that which occurs according to the diagram (2).

Sulphur was purposely excluded in order to avoid the enhancement of the explosive properties of the powder mixture. The problem of CO production during the explosion and its potentially harmful influence on the researchers was neutralised due to the fact that the experiment was conducted in an open space. Besides, the lack of sulphur in the powder mixture facilitates the control over the pyrotechnic reaction and prevents the emergence of harmful products of combustion (sulphur compounds). By eliminating sulphur we can obtain fewer reaction products, which would otherwise have to be taken into consideration in the reaction control process.

Experimental research of pyrotechnical reaction with "geometric" attenuation

In order to determine the intended use of pyrotechnical materials for transport in the water environment, a special research unit was constructed (Figure 2). It consists of a combustion chamber (1) with pyrotechnical material (2). The chamber's ignition is radio-controlled (3). The chamber is connected with a main body (4), which is the area where gases expand and from which they emerge as explosion products. The main body is connected to a manometer (5), thermometer (6) and check valve (7) used for filling in the installation and for controlling tightness. At the end of the main body there is a valve (8) that remains closed during the experiment or tightness testing. When the experiment is finished, the valve is opened to release the reaction product gases.

The experiment was begun with a measurement of the air inside the system equipped with the thermometer (6) and by loading the pyrotechnic material (2). Then the chamber (1) was connected to the main body (4) and the connection (9) was tightened, after which the tightness test was conducted. A pump was plugged to the valve (7) and the pressure was increased to 0.59 MPa. The pressure increase is obviously – in accordance with the principles of thermodynamics – connected with the increase in the temperature of the gas. This phenomenon was observed on the thermometer (6). During the time in which the temperature was decreasing to its initial value, the pressure within the measurement system was still diminishing and the tightness test could not be performed. It is therefore not known whether the pressure drop is only due to a decrease in temperature or to a leakage of the measuring system. Therefore, we considered the measurement system to be tight if, after about one hour from the point when the initial temperature was reached, the pressure remained unchanged. If the test proved unit tightness, the pressure was lowered to the value of 0.1 MPa, the initial pressure value for the conducted experiments. The explosion was then radio-activated. Pressure changes on the meter (5) were recorded with a camera at a frame rate of 25 fps. At this stage of the experiment the thermometer (6) was only used as a controller. If the temperature exceeded 100°C, it would be highly likely that connection tightness would be lost for technical reasons (9). Having conducted the experiment, the valve (8) was opened to

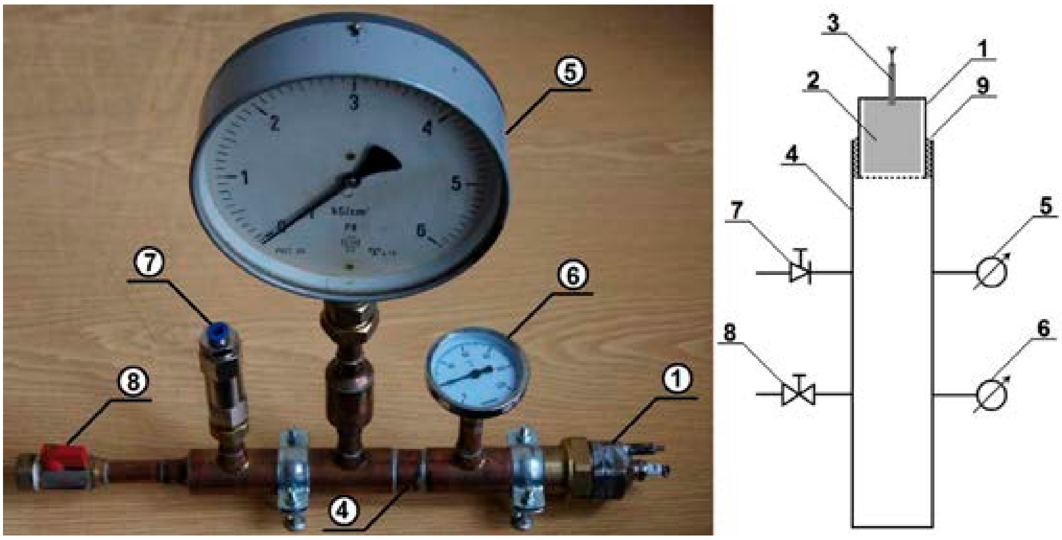

Figure 2. Research unit for research of pyrotechnical reaction with "geometric" attenuation

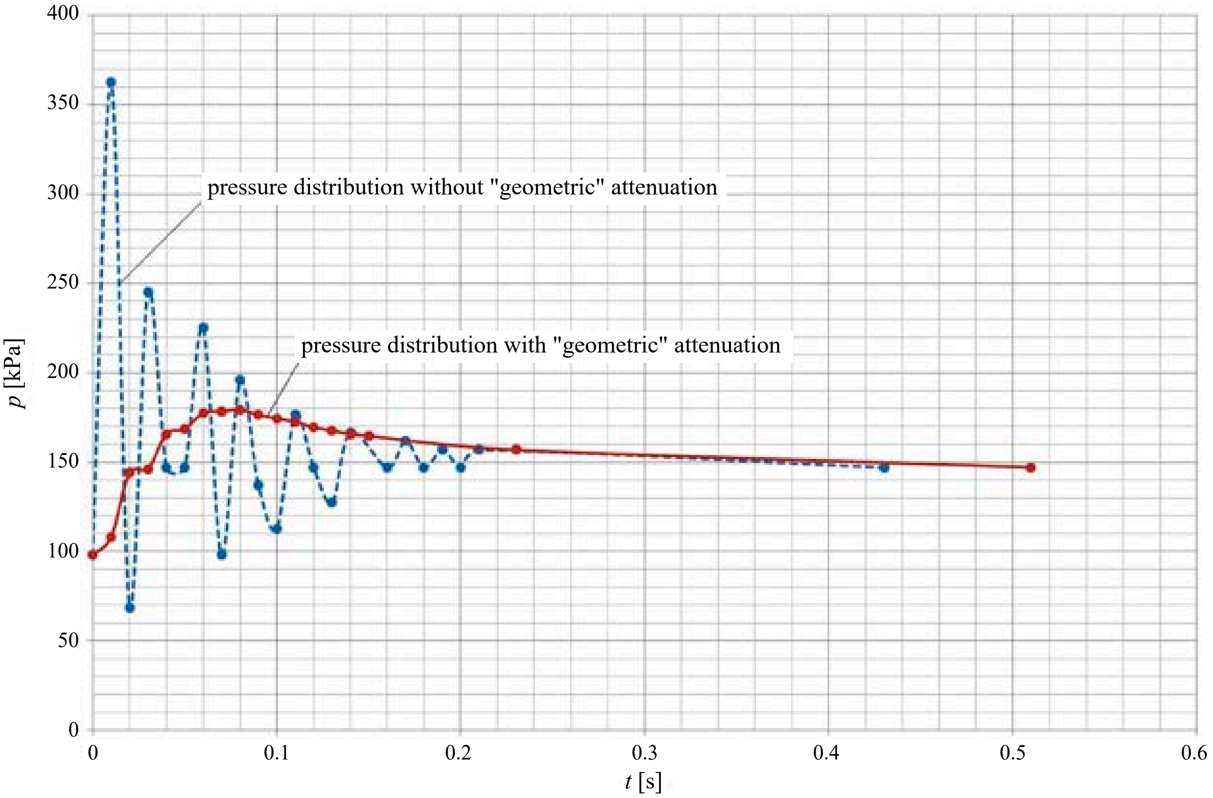

Figure 3. Comparison of pressure distribution during pyrotechnical reaction without and with attenuation

release the gaseous reaction products from the inside of the installation. All the experiments were conducted in an open space. The volume of the main body (4), in which the gas was expanding, was about $0.3 \cdot 10^{-3} \pm 0.01 \cdot 10^{-3}$ m^3. The volume was not determined precisely because the experiments aimed at a qualitative determination of the pressure distribution during time. The main body volume (4), however, was experimentally selected to prevent a temperature increase inside the tank over 100°C. Work on the quantitative analysis of the combustion products are underway.

In Figure 3 the broken line shows a single registered pressure distribution (one – selected from many instances) during the experiment. As it can be seen, the pressure distribution takes the shape of a harmonious oscillator with amplitude attenuation. The result obtained by the researchers is qualitatively similar to the results obtained by other researchers. Similar distributions of pressure in time were obtained in observation of underwater explosions that were specifically described in literature (Snay, 1956; Le Méhauté & Wang, 1995; Klaseboer et al., 2005), where the reason for the emergence of oscillation was also explained.

The wave of expanding reaction products of pyrotechnical combustion spreads in accordance with the distribution shown in Figure 1 only when there are no local obstacles on its way. If during its expansion the wave meets an obstacle (e.g. residual powder in the barrel), the distribution in time takes the shape shown in Figure 4, where it is clearly visible that any resistance in the expansion area causes a reflected wave. This course of action is unfavourable from the perspective of transport from sea floor and prospective exploration of the device, which is based on this method, due to the local sharp changes in construction stress in in the space of a few milliseconds.

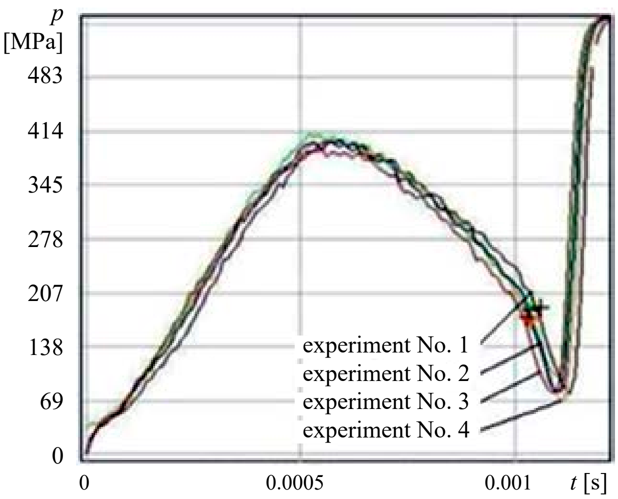

Figure 4. Pressure distribution obtained in combustion chamber (Recreational Software, 2016)

In order to improve the pressure distribution in time and attenuate the oscillation, the authors decided to introduce a minor reconstruction inside the combustion chamber (1) of the laboratory unit shown in Figure 2. The obtained effect of attenuation was marked with a solid line (Figure 3). The presented pressure distribution was obtained for exactly the same amount of pyrotechnical material ($0.5 \cdot 10^{-6}$ m^3) as for the distribution marked with the broken line.

Having prepared the method of "geometric" attenuation (appropriate geometry of combustion chamber), experiments were conducted with a gradual increase of mass (volume) of the explosive material. The pressure distribution was recorded to verify the accuracy of the assumed concept of attenuation.

Figure 5 presents the recorded results of pressure distribution in time (during the experiment with "geometric" attenuation) for a load four times bigger than the one applied in the experiments described in Figure 3. For clarity and comprehensibility of the figure, the authors used a logarithmic scale of the time axis. It can be seen that it is possible to attenuate the harmonics through reflections against the walls, obtaining a relatively "even" pressure distribution. The interval in measurements in the range 100–300 ms is caused by values exceeding the measurement range of the instrument.

Despite the perceptible "evenness" of the distribution, the authors claim that the researched method of "geometric" attenuation of harmonics is not entirely satisfying due to the fact that the gradient of the pressure in time is still too big, which may lead to the damage of the transport equipment structure.

Method of eliminating adverse phenomena through the control of chemical reaction

Since the method described above does not meet expectations, the authors proposed a different method involving elimination of the adverse phenomena presented above. They decided to lower the speed of pressure growth through the control of the chemical reaction. This method directly results from the II principle of dynamics by Newton (Jeżewski, 1964, p. 86) formulated as "*the change of momentum of a body* Δ*p is proportional to the impulse impressed on the body Ft*" (3) and is determined by the formula:

$$\Delta p = m \cdot \Delta v = F \cdot t \qquad (3)$$

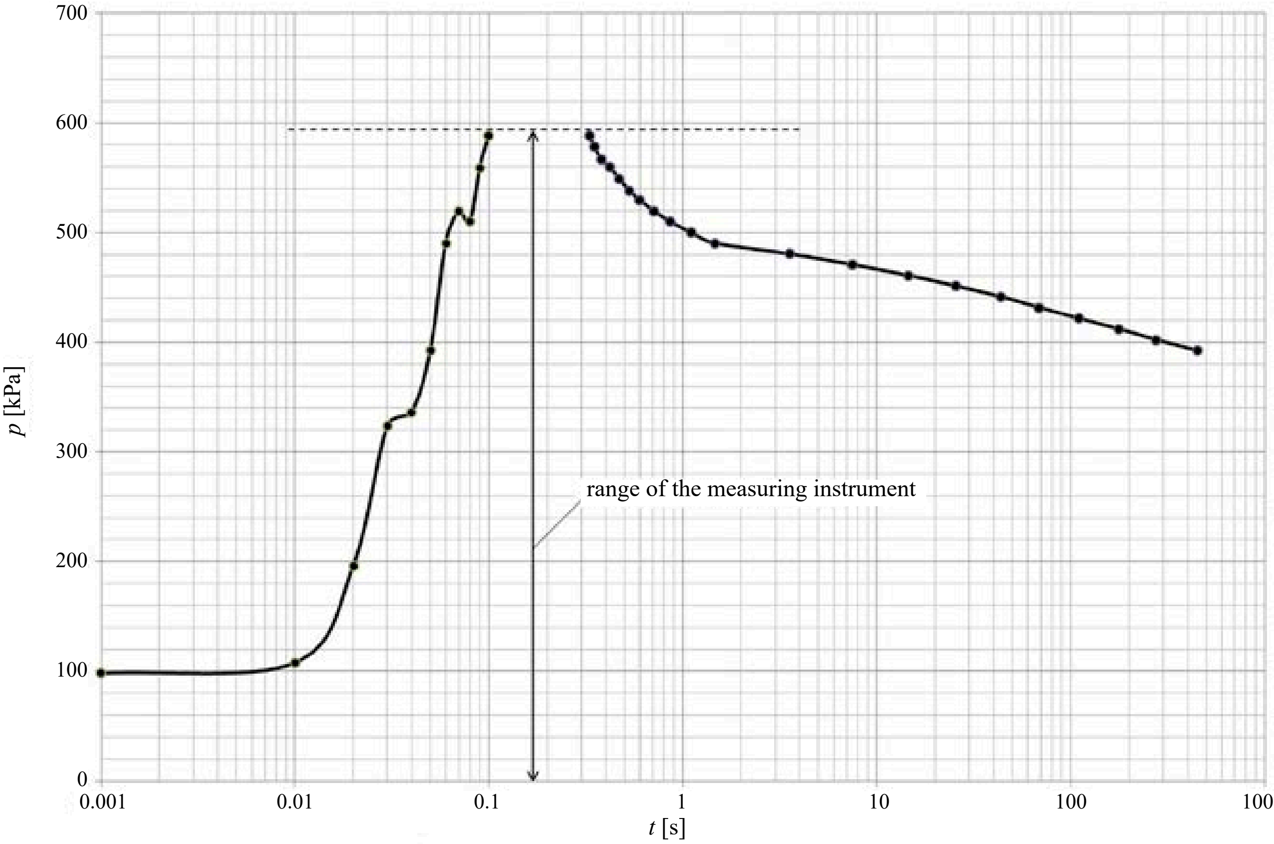

Figure 5. Pressure distribution during pyrotechnical reaction with attenuation for an increased load

Assuming the common relationship between the energy change ΔE with the momentum change, determined by formula (4):

$$\Delta E = \frac{\Delta p^2}{2m} \tag{4}$$

we obtain (5) by substituting (4) into (3):

$$F = \sqrt{\frac{2\Delta E \cdot m}{t^2}} \tag{5}$$

Bearing in mind the fact that pressure, by definition, equals the force *F* affecting a given surface, we get a direct result from formula (5) that, in order to decrease an abrupt growth of pressure in time, *t,* we have to prolong in time the reaction that causes the emergence of the pressure.

In order to verify the new concept, a new research unit was built (Figure 6).

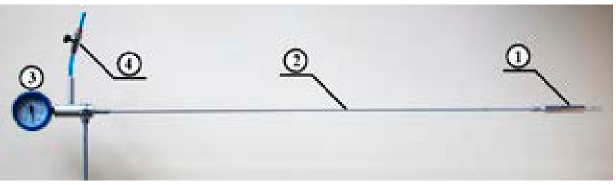

Figure 6. Laboratory unit for the research on reaction control

The combustion chamber (reactor) (1) is connected to a manometer (3) with a small pipe (2), the role of which is to cool down the gases emerging from the reaction in order to prevent damage to the manometer (3). Moreover, the pipe (2) serves as the expansion chamber. The valve (4) is used for tightness tests and facilitates gas release when the experiment is finished.

The experiment was commenced by loading the chamber (1) and changing installation tightness at 5 bar. The valve (4) was opened in order to adjust the pressure inside to atmospheric pressure. It was then closed and the reaction was initialised.

Figure 7 presents the obtained result of pressure growth in time from the moment of reaction initialisation.

The experiment took ca. 39000 s (ca. 11 hours). In that time a monotonic pressure growth was observed from 0 to 0.7 Mpa, and from 0.45 MPa a linear relationship between pressure and time was observed (broken line shows linear regression). From the analysis of linear regression the following relationship was obtained: $p(t) = 0.0137t + 182.29$, where pressure was expressed in bars and time in minutes. The correlation coefficient amounted to $R^2 = 0.9996$.

Conclusions

The authors of this paper presented two methods for the attenuation of adverse phenomena connected with abrupt pressure growth during an explosion of pyrotechnical material. The result of the first method, involving “geometrical” profiling of the combustion

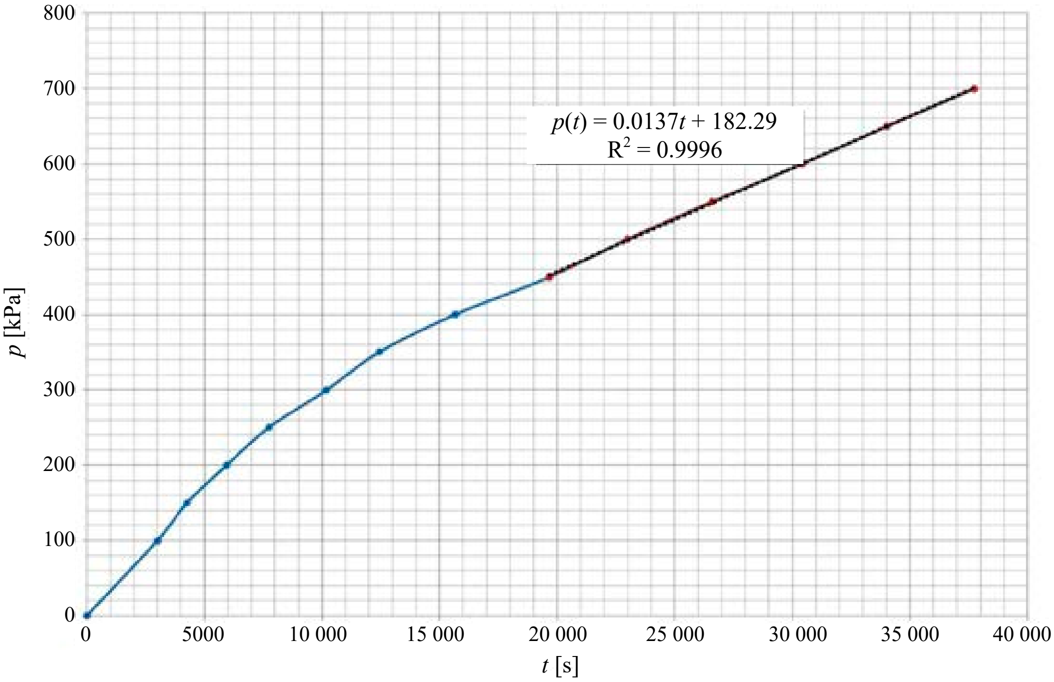

Figure 7. Pressure distribution during pyrotechnical reaction with reaction control

chamber, shows clear improvement of pressure distribution in time but it is not sufficiently satisfying, according to the authors, as the pressure gradient is still too high. Moreover, this method involves far greater complexity of the structure and thus material consumption.

The second method used by the authors facilitates the achievement of a monotonic pressure growth in time without extremes of pressure distribution in time. Therefore, the most adverse feature of pyrotechnical explosion – from the authors' perspective – was avoided. As it can be seen the obtained results qualify this concept of control in time of the pyrotechnical reaction during its use in the transport from the sea floor.

The authors claim that it is possible to use a wider range of pyrotechnical materials (explosives) sharing the common feature that the process runs as the deflagration of the explosive and not detonation. However, they do not also exclude devising methods implementing crushing-detonating materials. On the other hand, the cost of use of such materials will be higher than the use of the simplest and cheapest pyrotechnical materials.

Acknowledgments

This article was written within Statutes Research AGH, No. 11.11.100.005.

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