This article is available in PDF-format, in colour, at:
https://wydawnictwa.ipo.lukasiewicz.gov.pl/hig-en-mat-vol/vol-15/?lang=en

Materiały Wysokoenergetyczne / High Energy Materials, **2023**, *15*: 24 − 35; DOI 10.22211/matwys/0235
ISSN 2083-0165

Research paper / Praca doświadczalna

The influence of the sensor mounting method on determining the quasi-static pressure in an explosion chamber
Wpływ sposobu mocowania czujników na wyznaczenie ciśnienia quasistatycznego w komorze wybuchowej

Józef Paszula

Military University of Technology, Faculty of Advanced Technologies and Chemistry, 2 gen. Kaliskiego St., 00-908 Warszawa, Poland
** E-mail:* jozef.paszula@wat.edu.pl

ORCID Information:
Paszula J.: 0000-0003-1908-6804

Abstract: *The study investigated the influence of the diameter of the opening in the membrane separating the explosion chamber from the measurement chamber, on the determined quasi-static pressure. Pressure measurement in the closed vessel is performed using piezoelectric sensors placed on the chamber walls. The wave incident to the rigid partition wall is reflected and reinforced. Dynamic effects of reflected strong shockwaves distort the observation of the influence of detonation products afterburning effects on the pressure in the chamber. To minimise this influence, the study investigated the effects of introducing a membrane to separate the explosion chamber from the measurement chamber.*

Streszczenie: *W pracy zbadano wpływ średnicy otworu membrany separującej komorę wybuchową od komory pomiarowej ciśnienia quasistatycznego. Pomiar ciśnienia w zamkniętej objętości realizowany jest za pomocą czujników piezoelektrycznych umieszczonych na ściankach komory. Padająca fala na sztywną ściankę przegrody odbija się i ulega wzmocnieniu. Efekty dynamiczne odbić silnych fal uderzeniowych zaburzają obserwacje wpływu efektów dopalania produktów wybuchu na ciśnienie w komorze. W celu zminimalizowania tego wpływu, w pracy przeprowadzono badania efektów wprowadzenia membrany separującej komorę wybuchową od komory pomiarowej.*

Keywords: *quasi-static pressure, detonation products afterburning, explosion in closed vessel*
Słowa kluczowe: *ciśnienie quasistatyczne, dopalanie produktów wybuchu, wybuch w zamkniętej objętości*

1. Introduction

The processes following an explosion in a closed vessel have been the subject of wide research over the last 25 years. The afterburning processes of the detonation products are of particular interest, of both the decomposition products of individual partially oxidised explosives (e.g. C, CO) and those of different types of added metal powders (e.g. Al, Mg).

Closed vessel conditions are particularly favourable for the full oxidation of decomposition products of individual explosives. Due to the presence of oxygen in the closed vessel, the volume of gaseous detonation products increases significantly (carbon gasification occurs) and more thermal energy is released, which leads to a significant increase in overpressure values in the closed vessel [1, 2]. As an example, the heat released during the detonation of TNT, is approx. 4600 kJ/kg, however, with oxidation of the solid carbon, carbon monoxide and hydrogen present in the detonation products, an additional 10450 kJ/kg may be released. This may increase the temperature by 2.5 times and the final pressure of the reaction products in the closed vessel by almost 3.5 times.

The measurement of pressure in a closed vessel after detonation of investigated explosives enables the reaction degree of detonation products in inert gas or air atmosphere to be estimated. A comprehensive analysis of the discussed processes is presented in studies [3-7]. Analysis of the thermodynamic processes occurring in closed vessel after explosive charge detonation enables the reaction degree of the excess fuel and the energy released by these processes, to be estimated. The selection of the composition of the explosive mixtures enables the effect and adjustment of the detonation products' afterburning rate, to be maximised [8-16].

To adjust the detonation products' afterburning rate, it is necessary to reduce the influence of the dynamic phenomena occurring at the initial stage of the shockwave propagation process within the chamber. Intensive shockwaves hinder the observation of afterburning effects and their influence on the pressure in the chamber.

2. Experimental part

2.1. Explosive

For the test, the study used pressed TNT charges with a mass of 35 g, an outside diameter of 25 mm and a density of 1.59 g/cm^3. To initiate the charges, detonators made of pressed phlegmatised RDX with a mass of 5 g, an outside diameter of 16 mm and a density of 1.66 g/cm^3, were used. The detonation process was initiated using an ERG electric igniter.

2.2. Test methods

2.2.1. Explosion chamber

The overpressure phase generated by the detonation of the explosive in a closed vessel was measured in the KWK-0,2 explosion chamber with a capacity of 150 dcm^3. The technical parameters of the chambers are:

– inside diameter of the cylindrical part: 580 mm,
– height of the cylindrical part: 180 mm,
– inside diameter of lower and upper bowl: 580 mm,
– maximum weight of detonated charge: 200 g.

Figure 1 is a diagram of the explosion chamber. The observation windows are fitted with glands which enable the installation of pressure sensors.

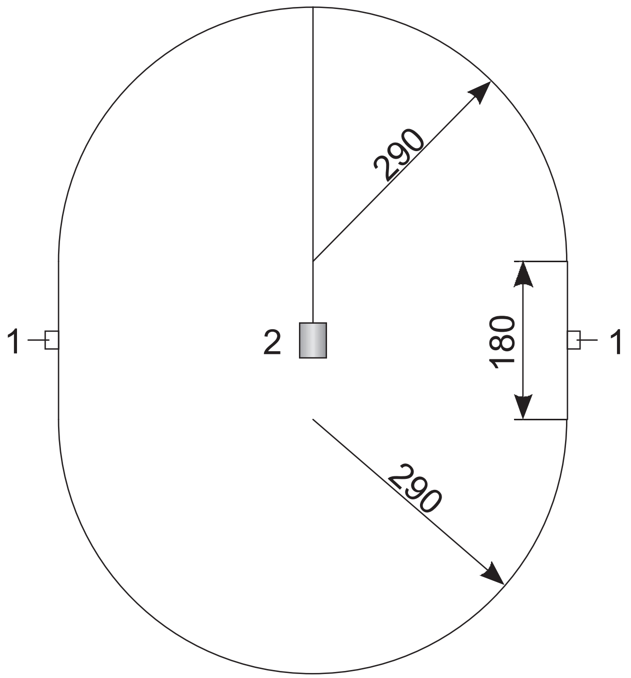


Figure 1. Diagram of the explosion chamber with installed pressure sensors and attached explosive charge: 1 – pressure sensor, 2 – explosive charge

2.2.2. Measurement system

In the tests, two pressure sensors were used, PCB Piezotronics – 113B22, with the technical specifications presented in Table 1. The signal from a F482A16 amplification system (by PCB Piezotronics) was recorded using a WaveJet 314 four-channel digital oscilloscope. Recording parameters were selected to achieve the following:

– a total recording time equal to or greater than 90 ms,
– the number of measurement points per recorded pressure oscillation period to be equal to or greater than 500.

Table 1. Technical specifications of piezoelectric sensors used for measuring pressure in the explosion chamber

Technical specifications	PCB 113B22 sensor
Measurement range [MPa]	34.5
Resolution [kPa]	0.14
Sensitivity [mV/kPa]	0.145
Enclosure material	Stainless steel 17-4
Diaphragm material	Invar

To investigate the influence of the presence of the measurement chamber connected to explosion chamber through the opening in the membrane on the quasi-static pressure measurement results, pressure sensors were fitted in two gland types. Figure 2 shows the two types of glands for pressure sensors used in the study. In the type A gland, the operating surface of the sensor is placed virtually on the inside surface of the explosion chamber. Hence the shockwaves act directly on the sensor, so in the recorded overpressure phase in the chamber, the dynamic effects are highly influenced in the initial stages. In the type B socket, the sensor is placed inside the “measurement chamber”, which is connected to the explosion chamber through the inlet duct. Such sensor placement within the chamber should reduce the influence of the dynamic effects on the measured pressure. For the type B sensor socket, the influence of the outlet duct diameter on the quasi-static pressure recording results was investigated. In the tests, steel sheet membranes with a thickness of 3 mm and openings with diameters of 1.5, 3.0 and 5.0 mm were used. Using the steel sheet membrane ensures stable measurement conditions without changing the shape and diameter of the passage duct.

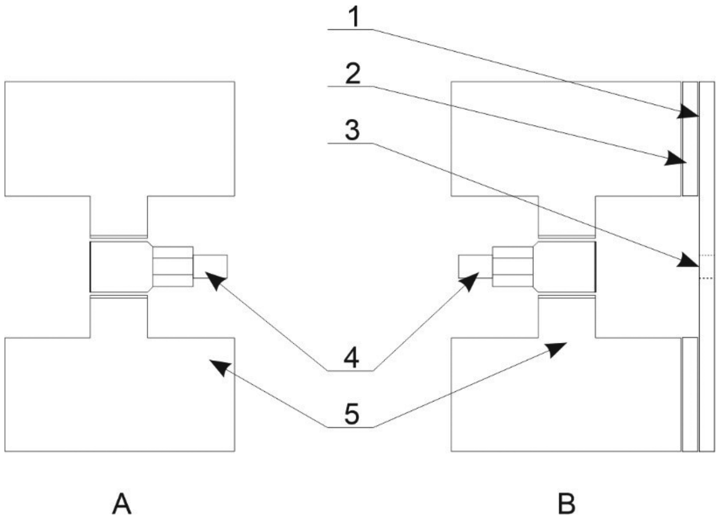


Figure 2. Diagram of two socket types prepared for fitting pressure sensors: 1 – membrane, 2 – teflon spacer, 3 – passage duct, 4 – pressure sensors, 5 – steel pressure sensor fitting sockets

2.2.3. Quasi-static pressure determination method

The overpressure in the explosion chamber was subjected to approximation using two functions. One (Equation 1) describes the pressure drop resulting from the processes of heat absorption by the walls of the chamber (which has a high thermal capacity).

$$\Delta \mathrm{p}(t) = P_{Q1} e^{-at} \tag{1}$$

where: P_{Q1} – quasi-static overpressure [Pa], α – pressure drop rate (the constant value depends on the heat exchange between the detonation products and chamber walls) [1/s], t – time [s].
The dynamic disturbances must be eliminated from the analysed recording to use Equation 1. The usual dynamic processes last for approx. 10 ms and distort the pressure change phase, which hinders the determination of the quasi-static pressure. The equation is used mainly to fit the sensor in the type A socket. Another method to describe the overpressure recorded in the explosion chamber after detonation is to use the Equation 2.

$$\Delta \mathrm{p}(t) = P_0(1 - e^{-at}) + d * e^{-bt} \tag{2}$$

where: P_0, a, d, b – approximation constants, t – time [s].
The first term of the equation describes the increase of the overpressure in the chamber at the initial stage of overpressure recording. This increase may be explained first by the gas flow resistance between the explosion chamber and the measurement chamber due to the small diameter of the opening in the membrane. Second, the overpressure increase at the initial recording stage may be caused by the detonation products

afterburning processes. The second term of the Equation 2 includes the process of the flow of heat from the products mixture to the explosion chamber walls.
Defining the approximation function constants enables the time corresponding to the maximum overpressure value and the overpressure value to be determined (Equations 3 and 4).

$$\tau_m = \ln\left(\frac{P_0 * a}{d * b}\right)\frac{1}{a-b} \tag{3}$$

$$P_{Q2} = \Delta\,\mathrm{p}(\tau_m) \tag{4}$$

For pressure measurement with a membrane with a hole, Equation was used for approximation purposes. If the pressure change phase in the chamber is analysed using this function, elimination of the initial dynamic pressure changes from the phase, is not required. The approximation function coefficients were determined using the least squares method. The approximation was conducted using the Solver function of MS Excel.

2.3. Example recording results

Figure 3 shows the overpressure recording obtained with sensors fitted to module A. Figure 4 shows the recorded results from tests with the sensors fitted in module B with different diameters of the opening in the membrane.

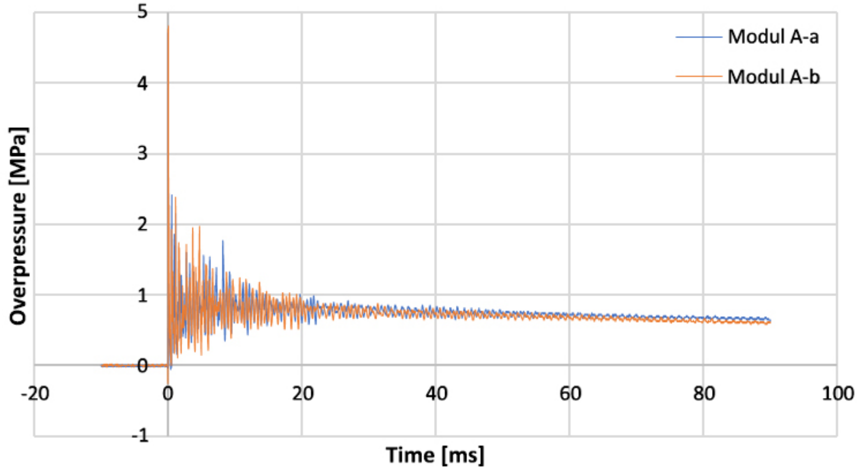
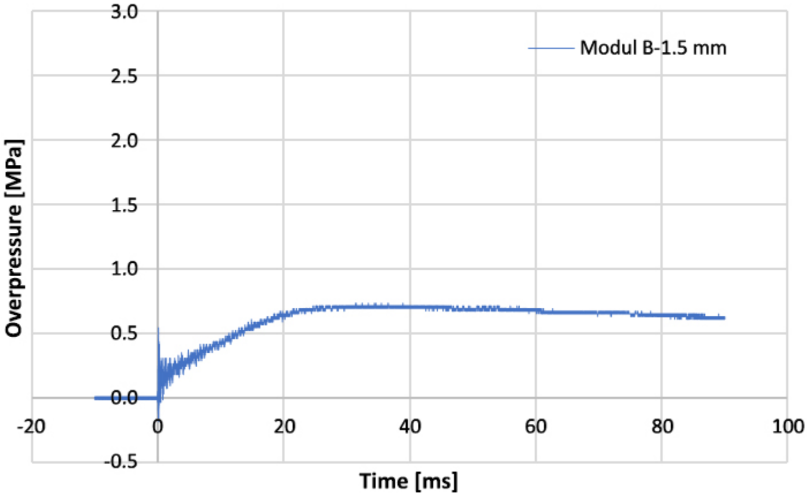
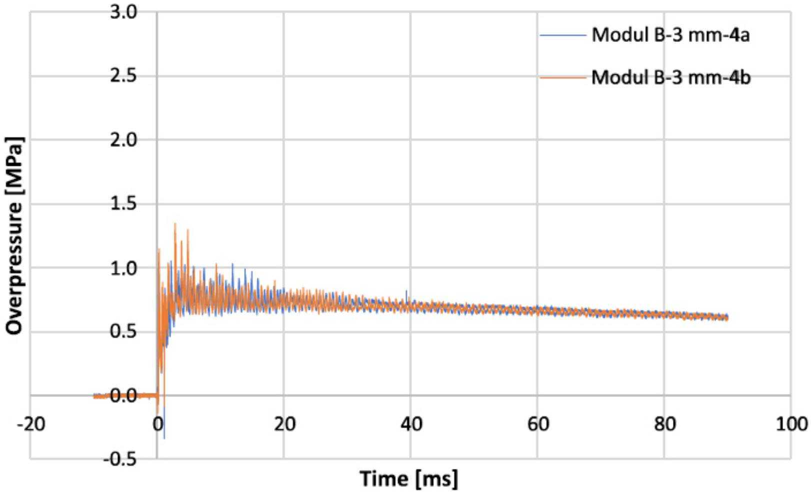


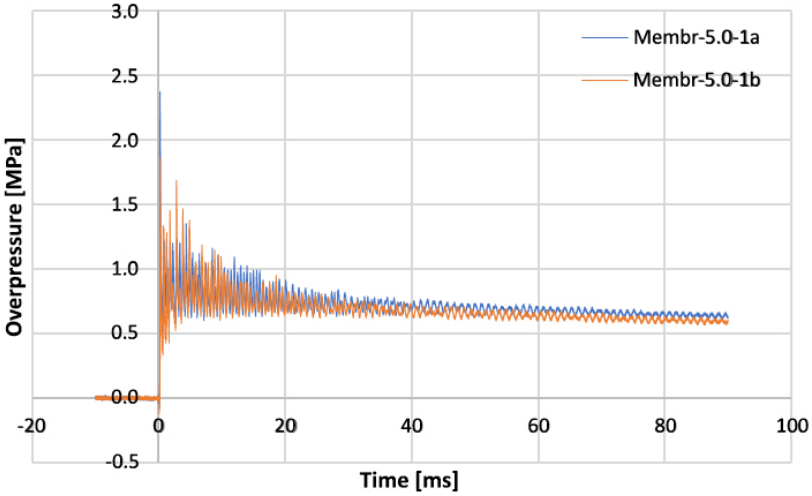
Figure 3. Recording overpressure changes in the chamber with the sensors fitted using module A


Modul B-1.5 mm
Overpressure [MPa]
Time [ms]
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
-20
0
20
40
60
80
100

(a)


Modul B-3 mm-4a
Modul B-3 mm-4b
Overpressure [MPa]
Time [ms]
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
-20
0
20
40
60
80
100

(b)



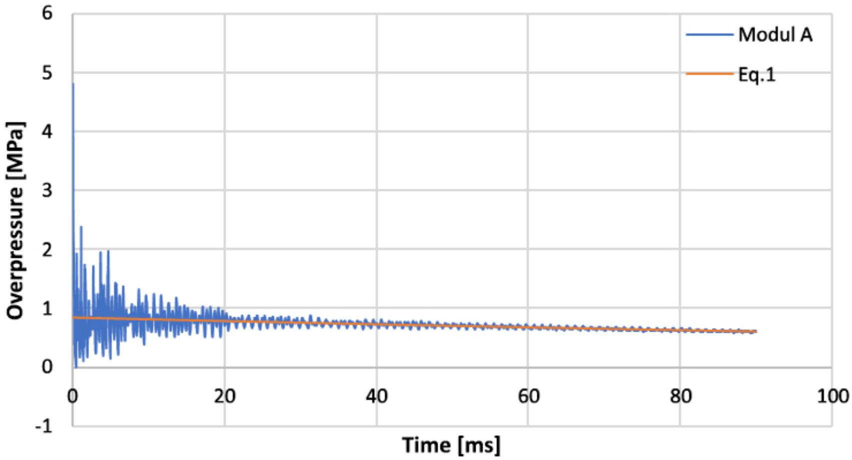
(c)

Figure 4. Recording overpressure changes in the chamber with sensors fitted using module B (diameter of the openings in the membrane: 1.5 (a), 3.0 (b) and 5.0 mm (c)

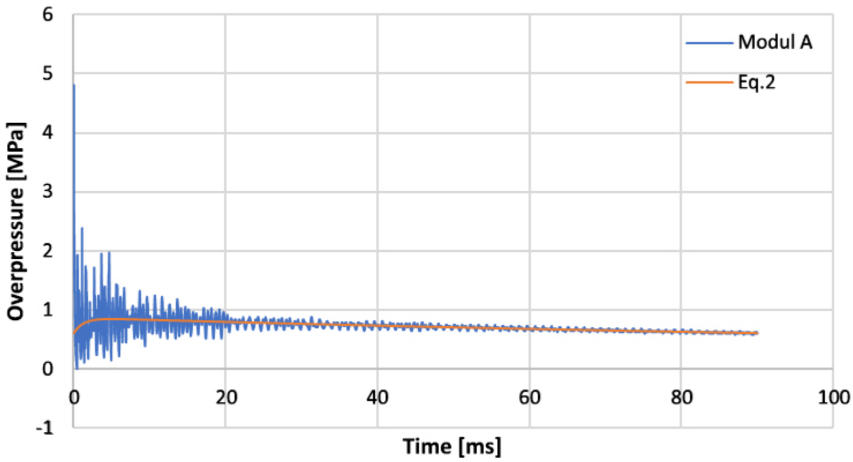
3. Measurement results and their discussion

3.1. Overpressure phase approximation results

Figure 5 shows the approximation results for typical recordings of the overpressure in the chamber using module A. Figure 6 presents the approximation of typical recordings of the overpressure in the chamber using module B at different diameters of membrane opening.

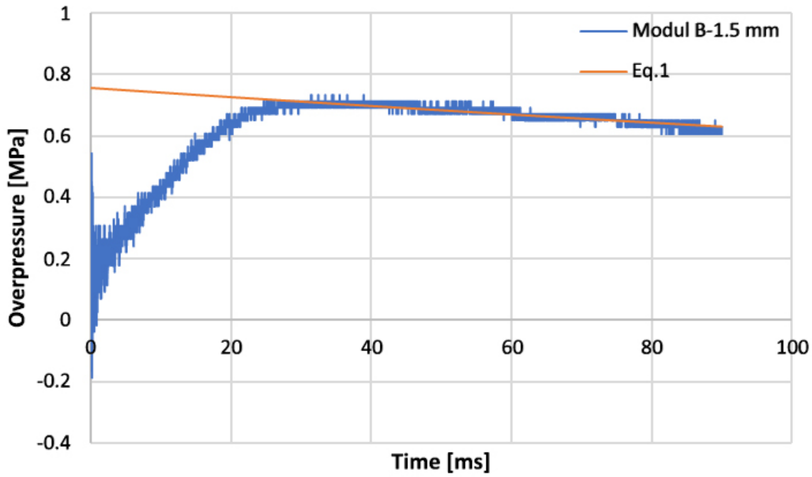


(a)

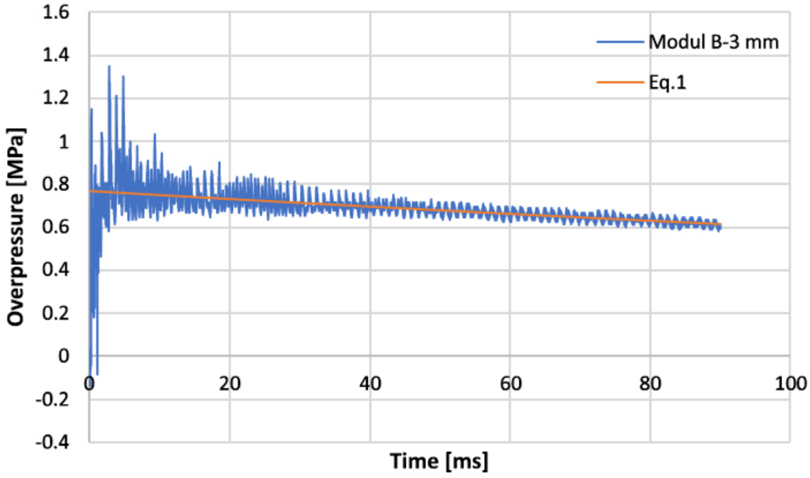


(b)

Figure 5. Typical recordings of overpressure in the chamber with sensors fitted using module A with approximated overpressure change: Equation 1 (a) and Equation 2 (b)

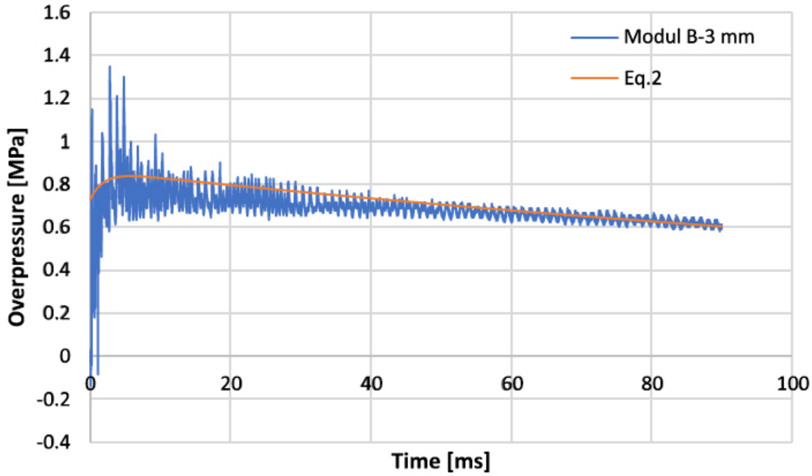


(a)



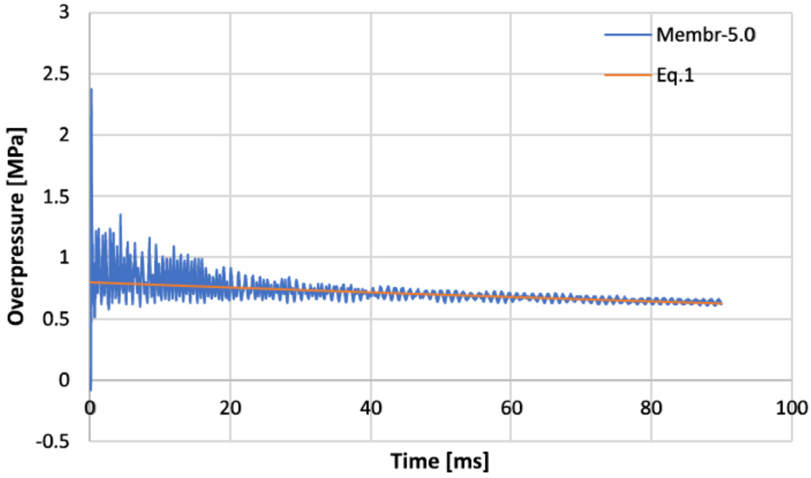
Modul B-3 mm
Eq.1
Overpressure [MPa]
Time [ms]
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
0
20
40
60
80
100

(b)

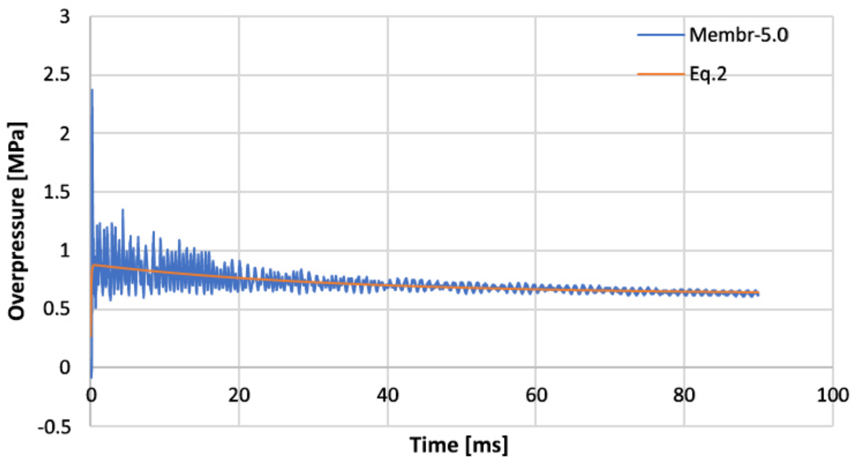


Modul B-3 mm
Eq.2
Overpressure [MPa]
Time [ms]
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
0
20
40
60
80
100

(c)



(d)



(e)

Figure 6. Typical recordings of overpressure in the chamber with sensors fitted using module B with approximated overpressure change: Equation 1 (a, b, d) and Equation 2 (c, e)

With registration being obtained using the sensors fitted using module B and a membrane with an opening diameter of 1.5 mm, a satisfactory approximation result was not obtained using the function described by Equation 2. This may be due to the fact that an insufficient opening connecting the explosion chamber and measurement chamber of module B extends the required pressure equalisation time in these areas. This time is longer than the duration of the dynamic phenomena observed during the initial shockwave reverberation period within the explosion chamber. The time observed for the measurement on the chamber wall (module A) is approx. 10 ms, however, the pressure increase time in the measurement chamber (module B) is approx. 25 ms. If the diameter of the membrane opening is increased to 3 and 5 mm, then the pressure equalisation time is comparable to the duration of the observed dynamic phenomena.

3.2. Overpressure phase approximation results

In the study, overpressure measurements were performed 2 or 3 times. In every case, the overpressure was recorded using two sensors. Approximation was performed for every phase and the results averaged. The averaged approximations enabled the quasi-static pressure of explosion in closed vessel, to be determined. Table 2 presents the averaged approximations for the tested pressure sensor fitting types and the determined overpressure values, $\boldsymbol{P_{Q1}}$ and $\boldsymbol{P_{Q2}}$.

Table 2. Averaged overpressure phase approximation results for the tested sensor fitting systems

Type Fittings Module	Approximation coefficients							
	Equation 1		Equation 2					
	P_{Q1}	A	P_0	a	b	d	τ_m	P_{Q2}
A	**0.83 ±0.02**	0.0034 ±0.0003	0.36 ±0.9	0.80 ±0.13	0.009 ±0.004	0.50 ±0.09	5.5 ±0.08	**0.84 ±0.01**
B - 1.5 mm	**0.76 ±0.02**	0.0020 ±0.0003	–	–	–	–	–	–
B - 3.0 mm	**0.77 ±0.01**	0.0025 ±0.0002	0.32 ±0.21	3.09 ±4.12	0.014 ±0.010	0.68 ±0.13	6.9 ±1.5	**0.83 ±0.01**
B - 5.0 mm	**0.78 ±0.01**	0.0029 ±0.0002	0.61 ±0.02	7.7 ±6.03	0.032 ±0.002	0.28 ±0.02	2.8 ±0.7	**0.87 ±0.01**

The approximation results show that if pressure sensors are fitted in module B, the overpressure values closest to those in the chamber from the chamber wall (module A) were obtained for a duct diameter of 3 mm. Since using the measurement chamber reduces the influence of dynamic distortions in the initial overpressure recording period, the most advantageous system (of the systems tested) is using module B to fit the sensors and the membrane having an opening diameter of 3 mm.

4. Conclusions

The study analysed the influence of the fitting method of the pressure sensors on the overpressure phases in the explosion chamber. Two sensor socket types were used to fit the sensors. The first type fitted the sensor practically on the surface of the inside wall of the explosion chamber. In contrast, the second type enabled the overpressure in the measurement chamber, connected to the explosion chamber through the opening in the membrane, to be measured. The measured overpressure results support the following conclusions:

- ♦ Measurement of explosion chamber overpressure using sensors placed on the inside surface of the chamber wall (module A) is disrupted due to the dynamic processes occurring in the initial shockwave propagation period. These processes last approx. 10-15 ms.
- ♦ Fitting the measurement chamber with a steel sheet membrane with a pass-through duct separating the explosion chamber, reduces the influence of dynamic processes.
- ♦ The opening diameter influences the pressure equalisation rate between the explosion chamber and the measurement chamber. The membrane opening with a diameter of 1.5 mm extends the equalisation time of this pressure and introduces additional measured overpressure distortions. The pressure equalisation time is 25 ms, which exceeds the duration of the dynamic processes in the initial measurement period.
- ♦ For an opening with a diameter of 3 mm, phases with a reduced influence of distortions in the initial pressure change period were obtained, which enabled the approximation of the correct phase and the determination of the quasi-static pressure.

References

[1] Wolański P., Gut Z., Trzciński W.A., Szymańczyk L., Paszula J. Visualization of Turbulent Combustion of TNT Detonation Products in a Steel Vessel. *Shock Waves* **2000**, *10*: 127-136.

[2] Trzciński W.A., Paszula J., Wolański P. Thermodynamic Analysis of Afterburning of Detonation Products in Confined Explosions. *J. Energ. Mater.* **2002**, *20*(3): 195-222; https://doi.org/10.1080/07370650208244821.

[3] Kuhl A.L, Forbes J., Chandler J., Oppenheim A.K., Spector R., Ferguson R.E. Confined Combustion of TNT Explosion Products in Air. *Proc. 8th Int. Coll. Gas Explosions*, Schaumburg, IL, September 21-25, **1998**.

[4] Oppenheim A.K. Dynamic Features of Combustion. *Phil. Trans. R. Soc. Lond. A* **1985**, *315*: 471-508.

[5] Oppenheim A.K. Quest for Controlled Combustion Engines. *SAE Int. J. Engines* **1988**, *97:* 1033-1039.

[6] Oppenheim A.K., Maxson J.A. Thermodynamics of Combustion in an Enclosure, *Progress in Astronautics and Aeronautics*. New York: American Institute of Aeronautics and Astronautics, **1991**, pp. 365-382.

[7] Oppenheim A.K., Barton J.E., Kuhl A.L., Johnson W.P. Refinement of Heat Release Analysis. *SAE Paper* **1997**, 970538; https://doi.org/10.4271/970538.

[8] Trzciński W.A., Cudziło S., Paszula J. Studies of Free Field and Confined Explosions of Aluminium Enriched RDX Compositions. *Propellants Explos. Pyrotech.* **2007**, *32*(6): 502-508; https://doi.org/10.1002/prep.200700202.

[9] Paszula J., Trzciński W.A., Sprzątczak K. Detonation Performance of Aluminium – Ammonium Nitrate Explosives. *Cent. Eur. J. Energ. Mater.* **2008**, *5*(1): 3-11.

[10] Trzciński W.A., Paszula J., Grys S. Detonation and Blast Wave Characteristics of Nitromethane Mixed with Particles of an Aluminium – Magnesium Alloy. *Propellants Explos. Pyrotech.* **2010**, *35*(2): 85-92; https://doi.org/10.1002/prep.200900041.

[11] Trzciński W.A., Barcz K., Cudziło S., Paszula J. Investigation of Confined Explosion of Layered Charges. (in Polish) *Biul. WAT* **2012**, *61*(1): 321-340.

[12] Trzciński W.A., Barcz K., Paszula J., Cudziło S. Investigation of Blast Performance and Solid Residues for Layered Thermobaric Charges. *Propellants Explos. Pyrotech.* **2014**, *39*(1): 40-50; https://doi.org/10.1002/prep.201300011.

[13] Yan Q.-L., Trzciński W.A., Cudziło S., Paszula J., Eugen T., Liviu MK., Traian R., Gozin M. Thermobaric Effects Formed by Aluminum Foils Enveloping Cylindrical Charges. *Combust. Flame* **2016**, *166*: 148-157; http://dx.doi.org/10.1016/j.combustflame.2016.01.010.

[14] Maiz L., Trzciński W.A., Szala M., Paszula J., Karczewski K. Studies of Confined Explosions of Composite Explosives and Layered Charges. *Cent. Eur. J. Energ. Mater.* **2016**, *13*(4): 957-977; https://doi.org/10.22211/cejem/65075.

[15] Maiz L., Trzciński W.A., Paszula J. Optical Spectroscopy to Study Confined and Semi-closed Explosions of Homogeneous and Composite Charges. *Opt. Lasers Eng.* **2017**, *88*: 111-119; http://dx.doi.org/10.1016/j.optlaseng.2016.08.006.

[16] Cudziło S., Trzciński W.A., Paszula J., Szala M., Chyłek Z. Performance of Magnesium, Mg-Al Alloy and Silicon in Thermobaric Explosives – A Comparison to Aluminium. *Propellants Explos. Pyrotech*. **2020**, *45*(11): 1691-1697; https://doi.org/10.1002/prep.202000103.

Received: July 20, 2023
Revised: December 19, 2023
First published on line: December 21, 2023