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Research paper / Praca doświadczalna

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The research of characteristics of combusting high-energy solid fuels and their fracturing ability to carbon cylinders
Badanie charakterystyk spalania paliw wysokoenergetycznych oraz ich zdolności do szczelinowania walców węglowych

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Abstract: *The paper presents research results of combusting high-energy solid fuels (propellants) in laboratory rocket motor specifically modified to examine the rocks . The process of combusting high-energy fuel is characterized by fast chemical reaction, which causes creation of high pressure gaseous products. The rate of pressure rise from combusting propellants can be controlled in laboratory rocket motor by an appropriate selection of mass of the fuel and the diameter of the nozzle. By selecting fuel which has bigger mass we can obtain higher rate of pressure rise as compared to smaller mass of fuel. For testing purposes the nozzle from standard laboratory rocket motor was replaced by solid coal cylinder to determine the possibility of coal fracturing by gaseous products of propellant combustion. With the use of sensors there was registered a pressure inside the combustion chamber. The aim of the paper is presentation and comparison of the pressure change graphs which were created in result of combusting high-energy materials and macroscopic determination of carbon fracturing as a result of propellant interaction.*

Streszczenie: *Artykuł przedstawia wyniki badań ze spalania wysokoenergetycznych paliw (propelantów) w specjalnie zmodyfikowanym silniku rakietowym do badań skał. Proces spalania paliw wysokoenergetycznych jest to szybka reakcja chemiczna, w wyniku której powstają produkty gazowe pod wysokim ciśnieniem. Wzrost ciśnienia powstałego w wyniku spalania propelantów można kontrolować w laboratoryjnym silniku rakietowym poprzez właściwy dobór masy paliwa oraz średnicy dyszy. Wybierając paliwo o większej masie można się spodziewać większego wzrostu ciśnienia w porównaniu do ciśnienia wytworzonego z mniejszą ilością propelantu. Na potrzeby badania dysza ze standardowego laboratoryjnego silnika rakietowego została zastąpiona walcem węglowym, aby określić możliwość zeszczelinowania węgla przez gazowe produkty spalania propelantu. Za pomocą czujnika rejestrowane było ciśnienie wewnątrz komory spalania. Celem artykułu jest (1) prezentacja oraz porównanie wykresów zmiany ciśnienia w czasie, które zostały zarejestrowane podczas spalania paliw wysokoenergetycznych (2) określenia makroskopowo zeszczelinowania węgla w wyniku oddziaływania propelantów.*

Keywords: *combustion characteristics; heterogeneous propellants; laboratory rocket motor (LRM), propellant fracturing, coal fracturing*
Słowa kluczowe: *heterogeniczne propelanty, laboratoryjny silnik rakietowy, charakterystyki spalania, szczelinowanie z wykorzystaniem propelantów, szczelinowanie węgla*

1. Introduction

An effective way to source coalbed methane (CBM) could significantly contribute to (1) improve safety of the miners, (2) improve condition of natural environment (3) and get profitable impact on energetic balance of the given country. The CBM includes unconventional hydrocarbon deposits that were not economically explored in Poland because of lack of proper technology of its extraction [1]. Currently, the most popular method of stimulating coalbeds is hydraulic fracturing [2]. However in Upper Silesian Coal Basin this treatment is very difficult to implement due to the complex geological structure of Polish coal deposits. One of the effective methods of CBM exploration may be stimulation of coalbed methane by high-energy materials (propellants) [3]. Gas fracturing with high-energy materials depends on the creation of several radial cracks in nearbore zone. Cracks are caused by the pressure generated by burning propellants that exceeds the maximum stress in the rock mass [4]. In this work series of initiation tests of propellants in specially modified laboratory rocket motor (LRM) for investigation of gas fracturing of rocks were made using coal-targets. The aim of this research was to analyze combustion characteristics of high-energy materials and the impact of combustion products on coal structure. Combustion characteristics was obtained by pressure sensor located in combustion chamber in LRM. Based on data obtained from the sensor, pressure diagrams were prepared.

2. Research method

Initiation attempts of high-energy fuels were made for a five coal-samples with using MPH fuel of different mass. MPH fuel is designed for application in wellbore in pressure generators for stimulation in oil and gas reservoirs. Before the fireground research, 5 samples of coal have been selected which were used to made a coal-targets. The initiation of propellants was performed in specially modified laboratory rocket motor (Figs. 1 and 2) - the system used for testing solid fuels [5]. For testing purposes the nozzle from standard laboratory rocket motor was replaced by solid coal cylinder to determine the possibility of coal fracturing by gaseous products from propellant combustion. The system consisted of the following elements: combustion chamber with a pressure sensor PCB M102B06 (Table 1), a coal-target of cylindrical shape; different mass of high-energy MPH fuel inhibited with heat-shrinkable polyester foil regulated the amount of gas propagation during propellants' combustion.

Figure 1. Modified laboratory rocket motor for investigation of gas fracturing of rocks

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Table 1. Pressure sensor PCB M102B06 characteristics

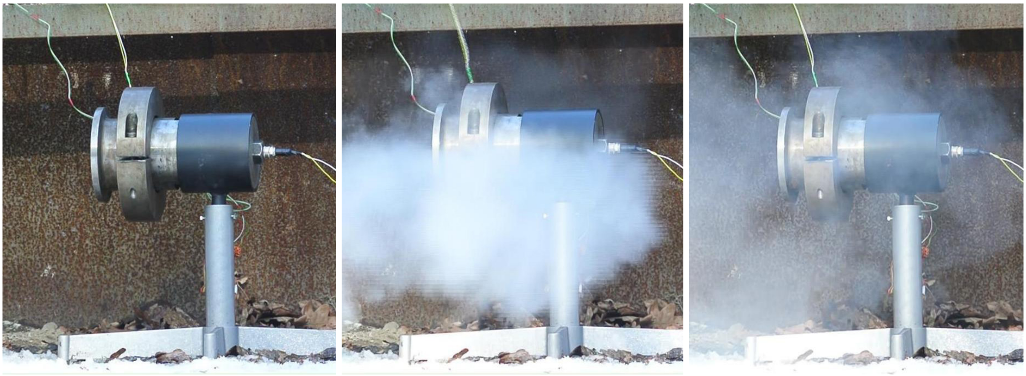
Measurement range	100 MPa
Output signal	0.5-45 V
Signal up time	≤ 1.0 ms
Nonlinearity of the signal	0.15%

3. Experimental part

An experimental part was performed on shooting fireground belonging to the Institute of Industrial Organic Chemistry in Krupski Młyn Department. Samples were characterized by parameters presented in Table 2.

Table 2. Input parameters for tests

Case no.	Fuel mass [g]	Volume of combustion chamber [cm^3]	Pseudo-density of high-energy material in combustion chamber [g/cm^3]
1	67	532	0.1
2	19	602	0.03
3	30	596	0.05
4	30,5	596	0.05
5	30,1	596	0.05



a) b) c)

Figure 2. A sequence of images presenting one of the ignition tests: a) propellant ignition; b) test system after 1 s have elapsed; c) test system after 2 s

The first attempt (Fig. 3) was initiated by m_p^1 = 67 g of high-energy fuel. After the first test it was observed that the coal cylinder was crushed into very small fragments and blown out of the test system. The reason of blowing out the carbon-cylinder was too high pressure in the combustion chamber. Based on the first test, maximum pressure at which carbon sample is destroyed in the test system was determined. On the graph of the pressure one can see that the pressure quickly grew up in the tp_{max}^1 = 0,16 s, reaching the maximum that was rated as p_{max}^1 = 42.75 MPa, and after having blown-out the carbon from the system, a very rapid pressure decrease occured. Based on the graph the impulse of blast wave was also calculated, which amounted to i_f^1 = 1.22 MPa·s. The initiation test of high-energy fuel case no. 1 lasted t_{max}^1 = 0.16 s.

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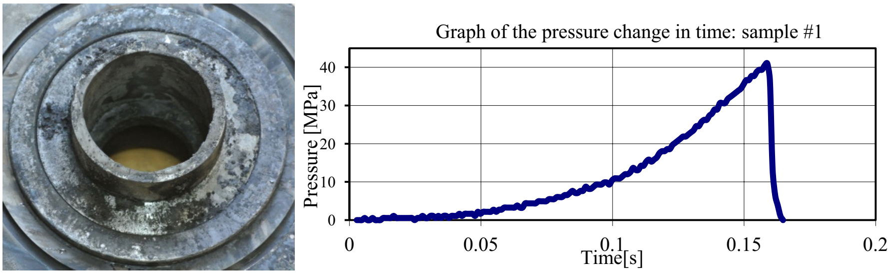

Figure 3. Experimental results after 1st test

In the second attempt (Fig. 4) of high-energy fuel initiation $m_p^2 = 19$ g of propellant was used. After attempt no. 2 there were no macroscopic sings of fracturing coal target. After initiation the fuel burned fast and after $tp_{max}^2 = 0.8$ s the pressure in combustion chamber reached a maximum value, rated at $p_{max}^2 = 14.83$ MPa. After reaching the maximum pressure in the system, there has been a slow decline that could result from fracturing of coal. Based on the graph, impulse of the blast wave was calculated, rated at $i_f^2 = 19.65$ MPa·s. The second initiation test lasted $t_{max}^2 = 6.8$ s.

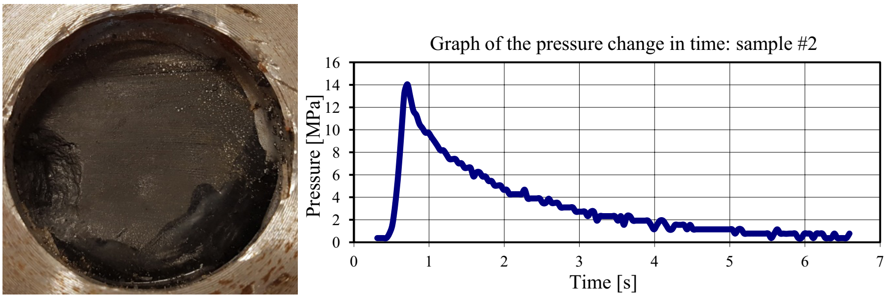

Figure 4. Experimental results after the 2nd test

In the third attempt (Fig. 5) $m_p^3 = 30$ g of high-energy fuel was used. Macroscopically we observed that the pressure blown out the part of coal from coal-target. After $tp_{max}^3 = 0.24$ s from initiation of the fuel, maximum pressure was reached, evaluated at $p_{max}^3 = 25.175$ MPa. Based on the graph the impulse of the blast wave was calculated, rated at $i_f^3 = 3.4$ MPa·s. The third initiation test lasted $t_{max}^3 = 0.42$ s.

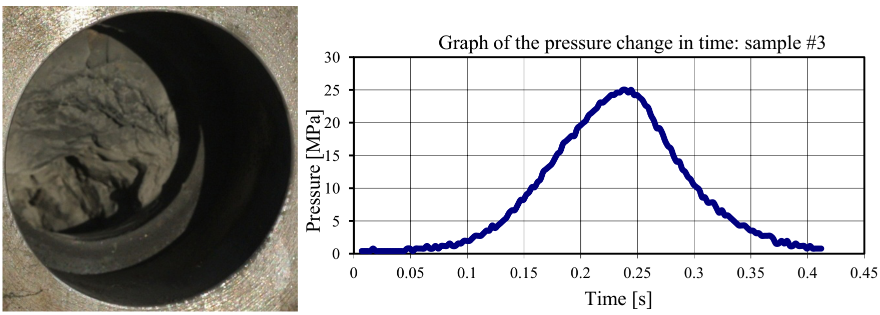

Figure 5. Experimental results after the 3rd test

In the fourth attempt (Fig. 6) $m_p^4 = 30.5$ g of propellant was used. After fireground test we observed macroscopically that the existing fractures slightly widened. The maximum pressure in combustion chamber

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achieved p^4_{max} = 28.125 MPa which was reached after tp^4_{max} = 0.9 s. Based on the graph the impulse of the blast wave it was calculated rated at i^4_f = 25.88 MPa·s. The initiation attempt No. 4 lasted t^4_{max} = 4.1 s.

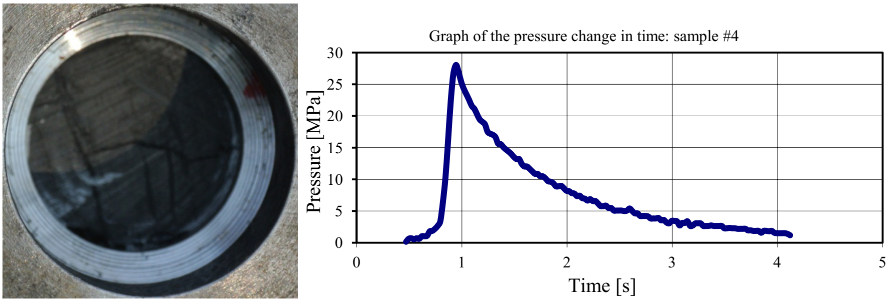

Figure 6. Experimental results after the 4th test

For the last attempt (Fig. 7) of propellant initiation m^5_p = 30.1 g of solid fuel was used. After the fifth attempt of coal sample fracturing, the pressure graph indicated that the correct combustion of fuel in the system occurred, which may develop new fractures in coal-target. Macroscopically there were created a new fractures observed in the coal sample. After tp^5_{max} = 0.75 s from initiation of the fuel, maximum pressure was reached, estimated at p^5_{max} = 25.7 MPa. Based on the graph the impulse of the blast wave was calculated, estimated at i^5_f = 24.7 MPa·s. The initiation of last attempt lasted t^5_{max} = 4.1 s.

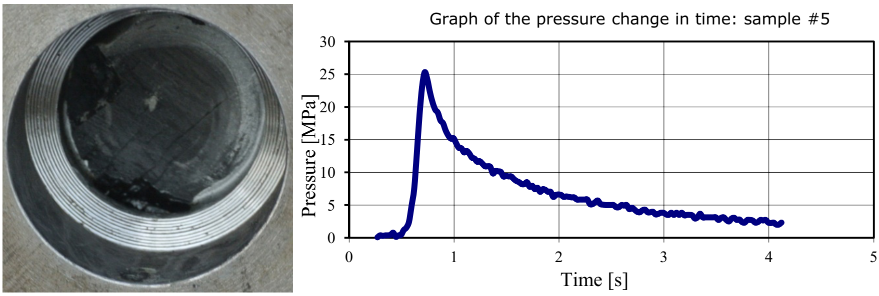

Figure 7. Experimental results after the 5th test

Table 3. Output data after all tests

Case no.	p_{max} [MPa]	tp_{max} [s]	i_f [MPa·s]	t_{max} [s]
1	42.75	0.16	1.22	0.16
2	14.83	0.8	19.65	6.8
3	25.175	0.24	3.4	0.42
4	28.125	0.9	25.88	4.1
5	25.7	0.75	24.25	4.1

Based on Table 3 it was found that the highest pressure was reached in the attempt #1 with the largest volume of fuel, this attempt was the shortest one. The highest value of the impulse of blast wave was reached in the 4th attempt which was rated at 25.88 MPa·s. The similar value of impulse of blast wave was obtained in the 5th attempt. Research of last fuel initiation was longest in the 2nd attempt and it took 6.8 s, in this attempt the smallest amount of fuel was used.

Graphs from the 1st and 3rd attempts are characterized by very rapid increase of pressure and equally rapid its decline. The pressure broke the coal, blowing out its fragments very quickly out of the research system. Another

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graphs may demonstrate fracturing nature. Pressure in these tests increased quickly, but not decreased rapidly, only slowly escaping instead from the system, possibly producing new fractures in coal samples.

4. Summary and conclusions

a) The coal samples were selected for the fireground tests of gas fracturing with the use of high-energy materials and determining the characteristics of fuel.
b) The test system was proposed and prepared, in which coal sample was pasted in the special clamping ring with drilled bore, which simulated perforation, and may be used in tests with high-energy fuel.
c) The propellant charges inhibited by heat-shrinkable polyester foil of the appropriate mass were prepared for coal fracturing.
d) The series of propellants initiation attempts were done in laboratory rocket motor.
e) After a series of tests, the possibility of gas fracturing using propellants in a modified laboratory engine found that coals were susceptible to fracturing by high-energy materials. Only the second attempt failed.
f) For the two cases: the 1st and the 3rd one, the fracture pressure was high enough to destroy a coal sample or blow out a fragments of a coal from the test system. In these cases, the tests were very short and the pressure peaks were very high and the impulse of the blast wave low as compared to another attempts.
g) For the cases: 4th and 5th we observed macroscopically increased fractures in carbon samples. The fracturing of coal took much longer time than in the 1st and the 3rd tests. The fracturing pressure for those two cases was on the similar level as in the 3rd attempt, but it didn't destroy a coal sample, it was probably due to an internal fracture system in coal samples.
h) For the 2nd case the graph from fracturing is similar to the 4th and the 5th attempts, but pressure was too low to fracture a coal sample.

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