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The study on combustion of propellants in airborne conditions

The resources of coal-bed methane in Poland, and especially in Upper-Silesian Coal Basin are estimated on tens of billions cubic meters. These are significant raw material quantities, that should take an interest in terms of acquiring them and producing in safe manner. Considering, however, very low permeability of coal-bed formations, such accumulation of hydrocarbons can be counted among unconventional deposits, requiring specific first working method. Well-known and properly mastered method of influencing the gas-rich coal-bed, consisting in reducing formation pressure by rock-mass stress relieving, effected by means of dewatering of coal beds, gives only moderate production and economical results. Despite the rock-mass pressure decreasing down to sorption isotherm value will result in process of releasing adsorbed methane, the negligible permeability of coal rock forces searching of additional, more effective methods of coal beds stimulation, facilitating flow of released methane through the formation. In opinion of the work authors, application of gas-fracturing technology using low combustion temperature propellants may contribute to effective releasing of methane and flow of the gas to producing boreholes.

Key words: gas-fracturing, combustion temperature of propellants, coal-bed methane (CBM).

Badania temperatury spalania paliw prochowych w warunkach napowietrznych

Zasoby metanu zalegającego w pokładach węgla kamiennego w Polsce, zwłaszcza w Górnośląskim Zagłębiu Węglowym, szacowane są na dziesiątki miliardów metrów sześciennych. Są to znaczne ilości surowca, którymi należy się zainteresować w kontekście pozyskania i ich bezpiecznej eksploatacji. Jednak z uwagi na bardzo niską przepuszczalność formacji węglowej taką akumulację węglowodorów możemy nazwać złożem niekonwencjonalnym, wymagającym szczególnego sposobu udostępnienia. Rozpowszechniona i dobrze opanowana metoda oddziaływania na gazonośny pokład węgla, polegająca na obniżeniu ciśnienia w złożu przez odprężenie górotworu, powodowane odwodnieniem pokładów węgla, przynosi umiarkowane rezultaty eksploatacyjne i ekonomiczne. Jakkolwiek obniżenie ciśnienia w górotworze do wartości izotermy sorpcji powoduje proces uwolnienia zaabsorbowanego metanu, to jednak znikoma przepuszczalność skały węglowej wymusza poszukiwanie dodatkowych, bardziej efektywnych metod stymulacji pokładów węgla umożliwiających przepływ uwolnionego metanu w złożu. Zdaniem autorów zastosowanie technologii szczelinowania gazowego z zastosowaniem propelantów o niskiej temperaturze spalania może przyczynić się do skutecznego uwolnienia metanu i przepływu gazu do otworów eksploatacyjnych.

Słowa kluczowe: szczelinowanie gazowe, temperatura spalania propelantów, metan z pokładów węgla (CBM).

Introduction

The initial research conducted in INiG – PIB shows that the direct translation of the propellant-based fracturing technology known from the oil industry into coal (CBM) ground seems difficult due to the high temperature of combustion of propellants [1, 3, 4]. The adaptation to the physical conditions of the deposition of hard coal requires, first of all, powder propellant whose selection – based on energy parameters – constitutes the core of this article.

The main problem addressed in the study is the choice of propellant whose combustion temperature will not exceed the value at which methane self-ignition occurs [2]. The verification of powder propellants which can be used in the process of the gas-fracturing of gas-bearing coal beds was performed through tests on a testing ground with the use of thermal imaging camera and in a laboratory engine for the analysis of solid rocket fuels (propellants).

Test method

The proposed test method is based mainly on recording with a NAC HX-7 high-speed colour camera to monitor the combustion process and determine the temperature distribution changes on the basis of the recordings and using the NAC Thermias software.

The NAC Thermias software operates based on the two-colour method. It calculates the temperature of a phenomenon on the basis of the emissivity coefficient and glowing intensity for two specific wavelengths.

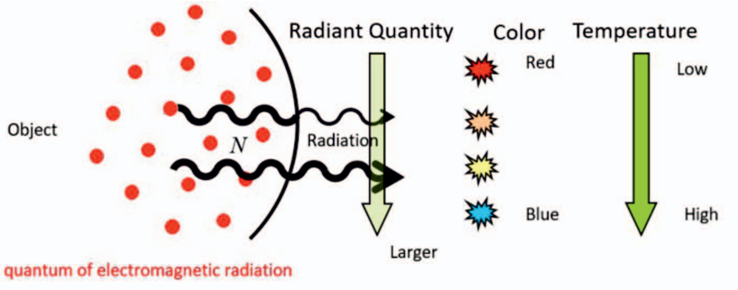

Fig. 1. Change in radiation properties depending on temperature

The temperature changes of certain phenomena, such as metal welding, gas combustion and detonation, are visible in the visible radiation range. When the temperature rises, the radiation emitted by a given object will change as follows: (a) the amount of radiation with a specific wavelength (glowing intensity) increases and (b) the radiation with an increasingly shorter wavelength is emitted. These factors are illustrated in Figure 1 below.

The temperature calculation using the two-colour method is based on Wien's displacement law and the distribution of the temperature of a black body, which is the most reliable source of radiation for a given temperature as its emissivity $\varepsilon = 1$.

A black body is an ideal object that does not exist in nature. All other phenomena have different emissivity values. When a radiation leaves an object, its intensity decreases. Emissivity is a coefficient that determines the value by which the intensity of radiation decreases after it leaves an object. For this reason, the Wien equation should be supplemented with an emissivity coefficient for real objects.

The determination of the emissivity coefficient during temperature measurements is difficult because it depends on other factors. Its value will change with the wavelength and the temperature of the object. For this reason, NAC Thermias software uses the two-wavelength method to eliminate the emissivity coefficient. In practice, the method involves recording a phenomenon in two strictly defined wavelengths and calibrating the temperature of the recorded image.

Test material

Propellants modified in several versions [1] were selected for the testing. Propellant segments (extruded shapes) modified according to proprietary technology used fuels (semi-finished products) made by the domestic manufacturer ZPS Gamrat Jasło (homogeneous fuel/gunpowder granules, such as Emerald, Sapphire, Marble, NDT3 tube powder) as the base material [5]. The additives made of potassium and ammonium perchlorates, metal powders and appropriately selected binders were used as modifiers for ring-shaped propellants [6, 7]. Comparative tests of temperature measurement were carried out using propellant ring shapes with the following composition, respectively: (a) Sz/$KClO_4$/PAM propellant granules; (b) Sz/Szd/$KClO_4$/PAM propellant granules; (c) R/$KClO_4$/PAM tube propellant granules; (d) Coiled M type propellant ring – manufactured by ZPS Gamrat Jasło; (e) R-type tube propellant granules (unmodified).

Fig. 2. Fuel samples extruded in a ring-shaped form and prepared for shooting tests: (a) Sz/$KClO_4$/PAM propellant granules; (b) Sz/Szd/$KClO_4$/PAM propellant granules; (c) R/$KClO_4$/PAM tube propellant granules; (d) Coiled M-type propellant ring – manufactured by ZPS Gamrat Jasło; (e) R-type tube propellant granules

Testing procedure

The picture below shows a view of prepared shooting models whose non-explosive and non-combustible parts constitute pieces of a section of a perfogenerator – a tandem device combining the features of a pipe perforator and a solid fuel gas generator. The selection of such a shooting system was to bring the technical (hardware) conditions of the test closer to the actual conditions of shooting operations in coal beds.

The test system, narrowed to the size of a single shaped charge placed in an aluminium carrier pole, is intended to reflect the functioning of such a device in a methane development borehole. The shooting line is supplemented during the experiments with an electric detonator without delay which stimulates the shaped charge with a short section of the detonating cord. The figure below shows an armed shooting model ready for testing on the testing ground and a view of the model after the test.

The course of each of the five shooting tests was recorded with a high-speed camera, and then the temperature of the combustion of the propellants used in the test was determined using the Thermias software. The temperature field distribution was determined for individual moments in time on the basis of the image analysis. The figure below shows an example frame of a video recording and its corresponding thermogram for the area under analysis.

The thermograms represent the points in space that take the maximum measured temperature values at a given moment in time. The colour distribution on the thermogram indicates a wide variety of recorded temperature values, which change from point to point. In test no. 1 on the combustion of the Sz/$KClO_4$/PAM powder propellant – granules of the propellant of type Sapphire with an addition of a potassium perchlorate oxidant and aluminium powder, significant areas exceeding the temperature of 1800°C are observed.

For each of the five tests, temperature histograms of the burned propellants were generated. The x-axis indicates the value of the combustion temperature and the y-axis indicates

Fig. 3. (a) Shooting models prepared for testing on the testing ground – external view;
(b) Carrier pole together with a shaped charge of type (ŁOKT-H-Fe-39-150)

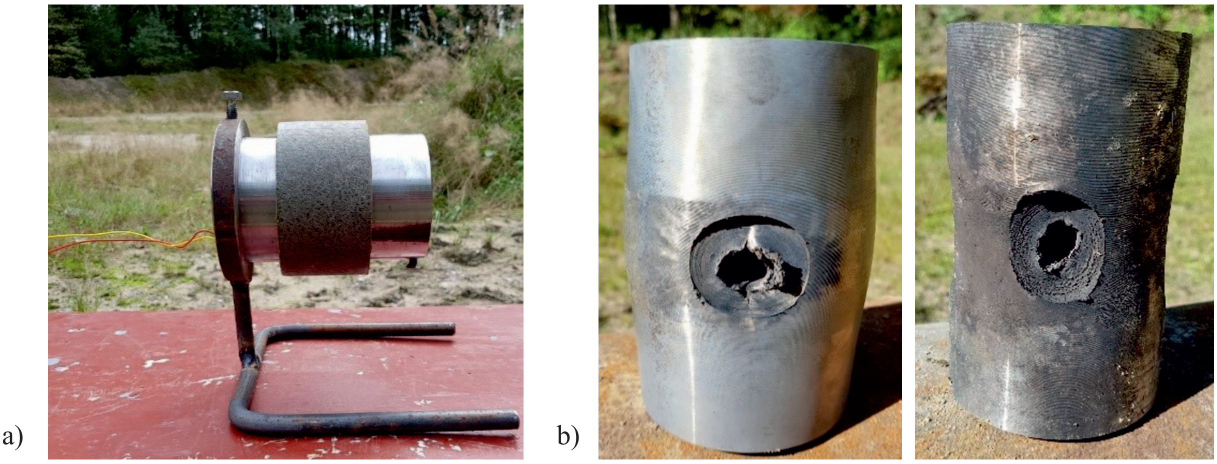

Fig. 4. (a) Example view of an armed shooting model with Sz/$KClO_4$/PAM propellant ring with a mass of 233 g;
(b) shot holes in the parts of the steel housing

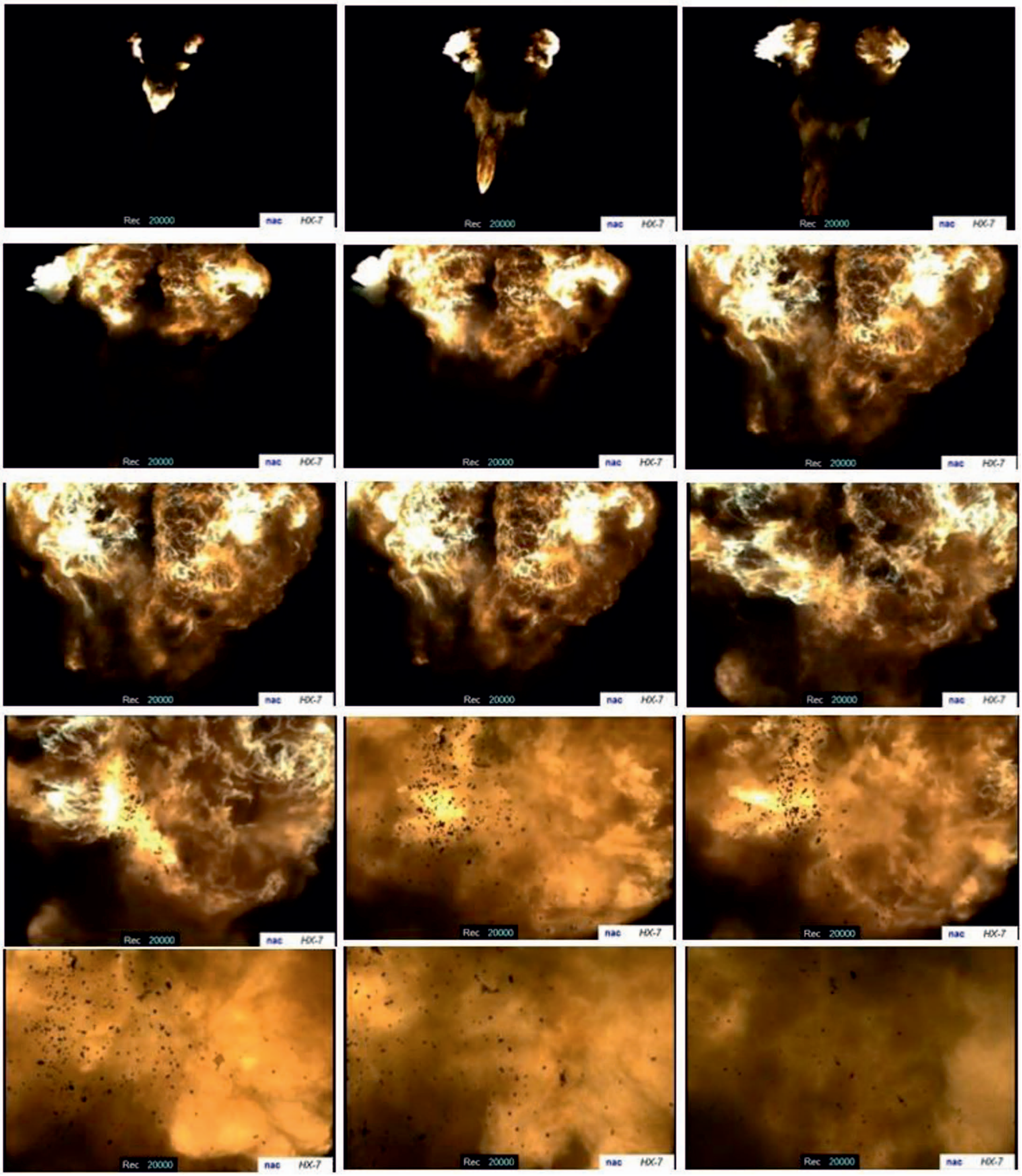

Fig. 5. A sequence of high-speed camera shots in time intervals equal to 25 μs recorded in shooting test no. 3 – the R/KClO$_4$/PAM propellant with a mass of 241 g was subjected to combustion.

the frequency of the occurrence of this temperature at a given moment in time for the area under measurement.

The analysis of the propellant combustion histograms indicates that there are significant temperature changes in the space under observation. In test no. 1, the temperatures between 1500 and 1650°C were observed at the highest frequency whereas the frequency of occurrence of lower temperatures, which ranged from 1400 to 1550°C, was observed at a very similar level at the same moment in time in test no. 4. In comparison, there is a clear difference in the occurrence of the temperatures from the upper measurement range, where the temperatures above 2200°C appear much less frequently – up to ten recordings per measurement.

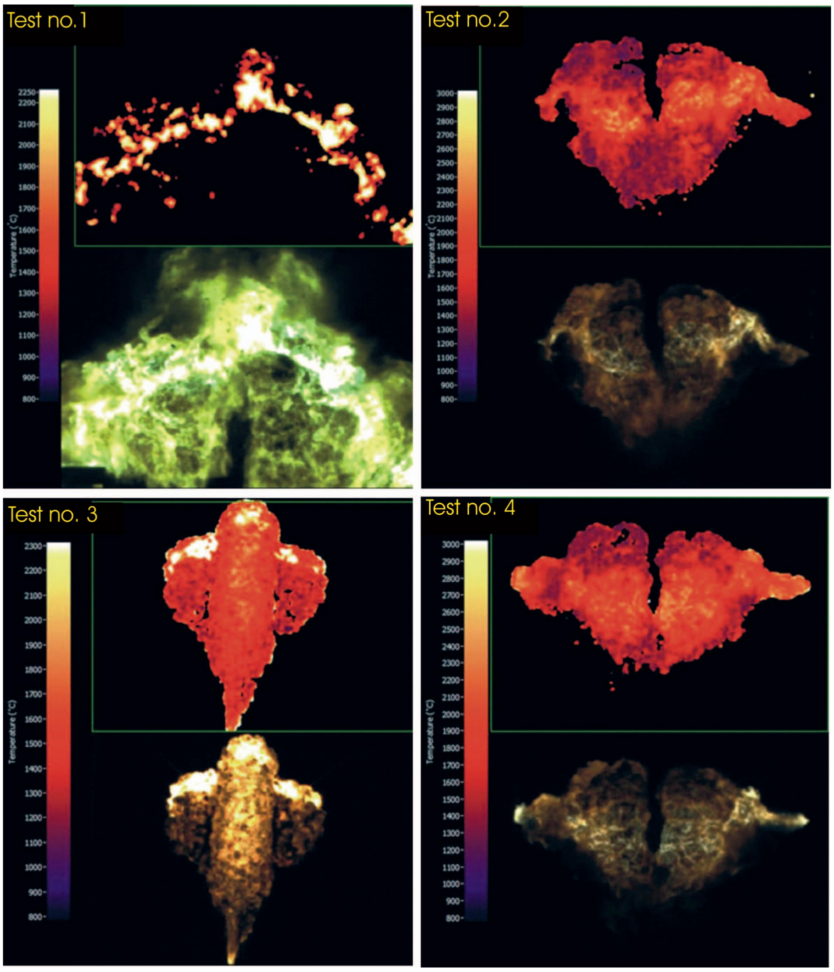

Fig. 6. Video recording frames and corresponding thermograms presented for tests no. 1, 2, 3 and 4

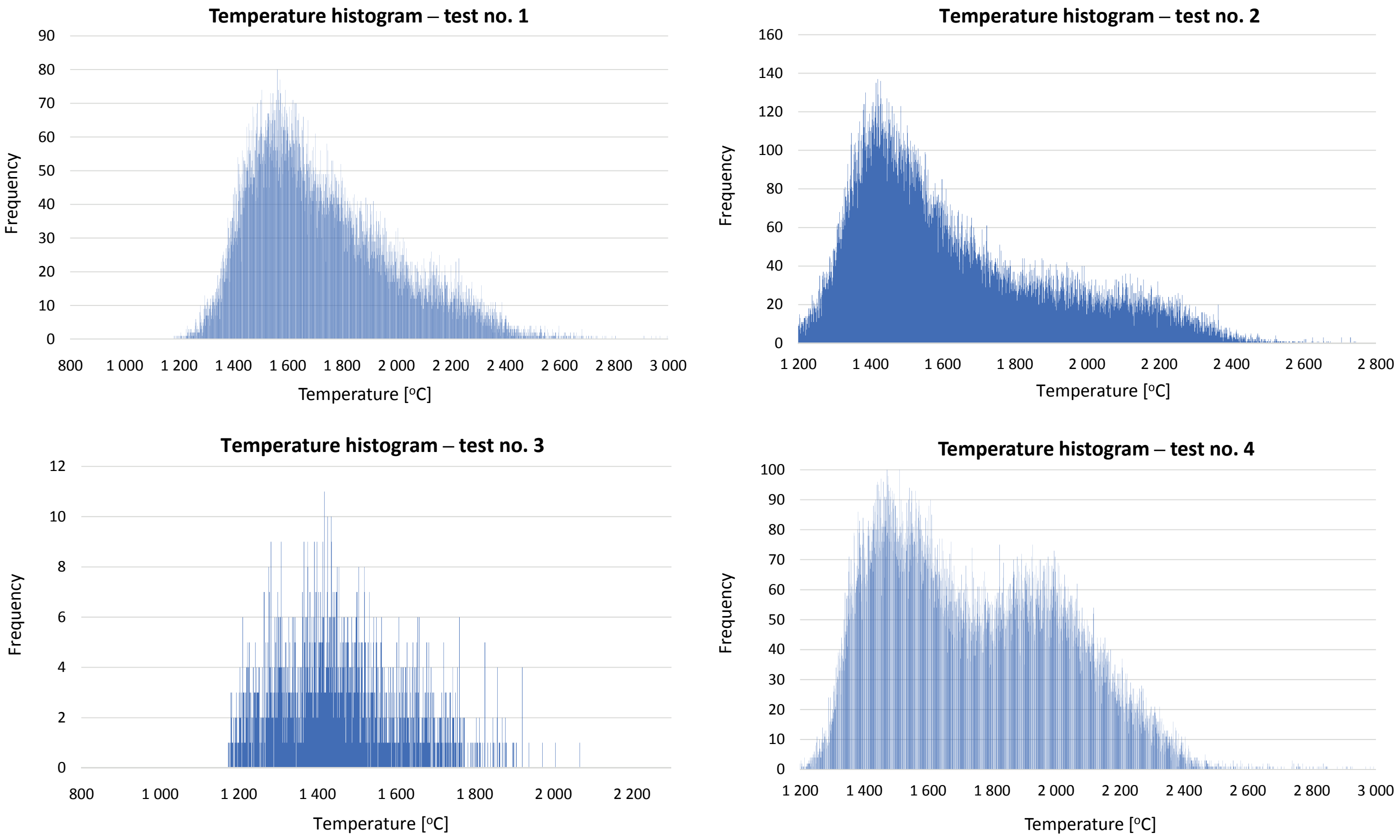

Fig. 7. The temperature distribution histograms of burned propellants for various moments in time of shooting test no. 1–4

Summary and conclusions

A tabular comparison of the results of the combustion tests of five types of propellants in airborne conditions (open testing ground) was made to summarise the results of the conducted tests. These include minimum and maximum temperatures and averaged temperature value based on the frequency of occurrence of a given value.

In the course of the testing aimed at determining the combustion temperature of selected propellants, a series of five shooting experiments was conducted, consisting in the observation of the process of combustion with a high-speed video camera and determining the temperature on the basis of the obtained images in a specialist Thermias software. Based on the temperature field distribution histogram, the average, minimum and maximum values were determined for different moments in time. In test no. 1 (1) concerning the combustion of Sz/$KClO_4$/PAM propellant, the average temperatures of 2136°C, 1760°C, 1819°C and 1224°C were obtained. In test no. 2 (2) concerning the combustion of Sz/Szd/$KClO_4$/PAM propellant, the obtained average temperature values were 1758°C, 1619°C, 1742°C and 1698°C for each moment in time, respectively. Test no 3 (3) provides information on the average combustion temperature values of R/$KClO_4$/PAM propellant, which are equal to 1714°C, 1326°C, 1196°C and 971°C, respectively. In test no. 4 (4) concerning the combustion of powder propellant of type M, the average combustion temperatures of 2084°C, 2068°C, 1983°C and 1972°C were obtained. In the last test no.5 (5), R-type propellant was burned and the average temperatures of 1714°C, 1529°C, 1217°C and 1196°C were obtained.

The completed tests make it possible to state that all the domestic propellants used for gas-fracturing operations used so far by the Department of Shooting Technology at INiG – PIB are characterized by a high combustion temperature which far exceeds the methane self-ignition temperature. However, it should be noted that the process of gas-fracturing using propellants is used almost exclusively under the tamping of the liquid column, which takes a significant portion of the thermal energy from the fuel combustion process and is conducive to lowering the temperature in the operational zone.

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