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Ignition compositions for use in ramjet engines *Mieszaniny zapłonowe do zastosowań w silnikach strumieniowych*

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Abstract: *The results of testing pyrotechnic compositions used in the ignition systems of a laboratory ramjet engine, are presented. Black powder (BP) and its formulations with a mixture of boron, potassium nitrate(V) (KNO_3) and polymer binder were used as reference compositions. To modify the combustion characteristics of these formulations, additives in the form of energetic coordination complexes were utilized. The method of synthesis and results of tests carried out on the selected compounds (including sensitivity to friction and impact) is presented. The prepared pyrotechnic compositions were tested in a targeted ignition system to examine the effect of the addition of the coordination complexes on the burning speed of the mixture. The results obtained indicate that the addition of selected complex compounds increases the pressures generated by mixtures containing KNO_3 and boron. This effect was not observed in the case of compositions based on BP.*

Streszczenie: *W pracy przedstawiono wyniki badań mieszanin pirotechnicznych wykorzystywanych w układach zapłonowych laboratoryjnego silnika strumieniowego. Jako kompozycje bazowe zastosowano proch czarny oraz jego mieszaniny z układem zawierającym bor, azotanu(V) potasu (KNO_3) i lepiszcze polimerowe. W celu modyfikacji charakterystyk spalania sporządzonych kompozycji, wprowadzono dodatki w postaci energetycznych związków kompleksowych. Zaprezentowano metodę otrzymywania zastosowanych modyfikatorów oraz wybrane wyniki badań tych związków (m.in. wrażliwość na tarcie i uderzenie). Sporządzone mieszaniny pirotechniczne badano w docelowym układzie zapłonowym w celu sprawdzenia wpływu obecności modyfikatora na prędkość spalania kompozycji. Uzyskane wyniki badań wskazują, że dodatek wybranych związków kompleksowych wpływa na zwiększenie wartości ciśnień generowanych przez mieszaniny zawierające KNO_3 i bor. Wpływu tego nie zauważono w przypadku kompozycji bazujących na prochu czarnym.*

Keywords: *ignition, pyrotechnic compositions, ramjet engine, coordination compounds, black powder, BKN*
Słowa kluczowe: *zapłon, mieszaniny pirotechniczne, silnik strumieniowy, związki kompleksowe, proch czarny, BKN*

Symbols and abbreviations:

13DCN	*Bis*(1,3-diaminopropane)copper(II) nitrate(V)
ATR	Attenuated total reflection
BKN	Pyrotechnic mixture composed of boron, potassium nitrate(V) and a binder
BP	Black powder
DTA	Differential thermal analysis
ECN	*Bis*(1,2-ethylenediamine)copper(II) nitrate(V)
FTIR	Fourier transform infrared spectroscopy
UIL	Upper insensitivity limit
$P_{\max}$	Maximum pressure recorded during the test
RDE	Rotating detonation engine
TACN	*Tetra*amminecopper(II) nitrate(V)

1. Introduction

In previous decades, black powder (BP) was mainly used as a solid ignition mixture for rocket engine igniters. However, in modern applications, its energy and performance parameters have proven to be insufficient. When applied to jet engines using the detonation process, the problem of under-performance of BP-based igniters appears even greater [1, 2].

Currently, high-energy pyrotechnic mixtures are used very frequently in rocket engine ignition systems. Such compositions are usually propellants containing amorphous boron, zirconium, magnesium powder, aluminium or their alloys [3, 4]. The oxidising function is carried out by salts of nitrate(V), chlorate(V), chlorate(VII) acid, metal oxides and halogen derivatives.

The energetic properties of pyrotechnic mixtures, such as heat, combustion velocity or temperature, are strictly dependent on the method and conditions of preparation of these mixtures. Equally important are the purity, shape and particle size of the individual components. By simply substituting charcoal with boron in a pyrotechnic mixture, a significant increase in combustion heat can be achieved. This is because the amount of heat given off when boron is burned is almost twice as high as that t generated when the same mass of charcoal is burned.

Although the demands placed on modern pyrotechnic mixtures are becoming ever higher, continuing to increase the amount of heat emitted during their combustion is no longer a simple task. According to literature, additives exhibiting catalytic activity may have some impact on this process. Such substances can include metals and metal oxides with nanometric fineness [5, 6]. Copper and chromium oxide nanocomposites can serve as an example of the positive effect of catalysts on the heat released during decomposition of pyrotechnic mixture components. It turns out that when such a nanocomposite is applied to the surface of ammonium chlorate(VII) crystals, its decomposition energy increases from 520 to 1510 J/g [7].

The present study is an attempt at an experimental evaluation of the effect of selected copper(II) compounds on the combustion process of mixtures based on amorphous boron, KNO_3 and polyester resin, hereafter abbreviated BKN. The role of combustion modifiers was taken by the complex compounds:

- *bis*(1,2-diethylenediamine)copper(II) nitrate(V) (ECN),
- *tetra*aminecopper(II) nitrate(V) (TACN), and
- *bis*(1,3-diaminopropane)copper(II) nitrate(V) (13DCN).

The choice of these additives was based on their low difficulty of synthesis, low sensitivity to mechanical stimuli and their satisfactory chemical stability. At this stage of the research, it was decided that all modified pyrotechnic mixtures tested would contain 5% of the additive. It was also important that, in their structure, the modifiers shared a common anion with the oxidiser used in the BKN mixture. It was also decided that the combustion of the mixtures tested must not generate products containing metals and their ions with potentially strong adverse effects on the human body. Therefore, salts of Pb, Ni, Co and Zr, Cr, Cd were ruled out as potential additives.

Pressure generated during the combustion of pyrotechnic mixtures is related by the Clapeyron equation, to the amount of heat generated during the combustion process. This allows the impact of modifying additives using pressure sensors to be assessed without having to measure the temperature of the process itself.

2. Experimental part

In the first part of the study, BKN- and BP-based pyrotechnic mixtures enriched with ECN, TACN and 13DCN complex compounds, were prepared. The finished compositions were used consecutively to reload igniters intended for a detonation ramjet engine. The results enabled the most promising modifiers to be selected. BP with a grain size of 0.6-1.18 mm (FFg, WANO) and pure BKN were used as reference compositions. In the next stage of the research, extensive tests were carried out involving the measurement of pressure generated as a function of time during the action of initiators in the engine. During these tests, fuel and air at a temperature of approximately 170 °C flowed through the engine at a rate of 1.3 kg/s. These initiating charges were made by pressing. At this stage, testing was also carried out using a manometric bomb, which was used to test the lower density samples.

2.1. First part of tests

2.1.1. Preparation of pyrotechnic modifiers and mixtures

Combustion modifiers in the form of copper(II) complex compounds were obtained by reacting copper(II) nitrate(V) with a ligand in a methanol environment (Diagram 1).

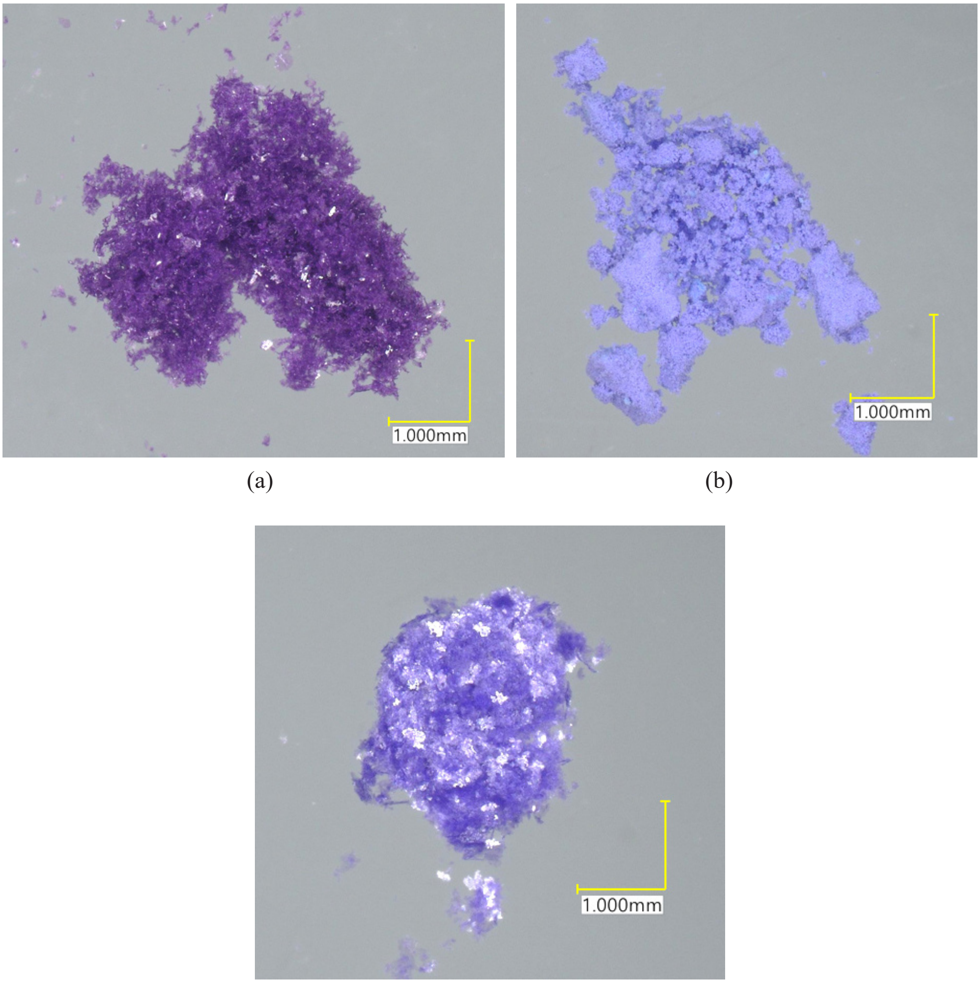
$$m\,Cu(NO_3)_2 + n\,L \xrightarrow{CH_3OH} m\,[Cu(L)_n](NO_3)_2$$

Diagram 1. Synthesis of the complex compounds

The synthesis method for the complex compounds used in the study was analogous. Copper(II) nitrate(V) trihydrate (analytical grade, Chempur) and methanol (analytical grade, Chempur) were put into a flask fitted with a magnetic stirrer. After complete dissolution of the salt, the ligand was added drop-wise as an aqueous solution of 30% ammonia (analytical grade, Chempur), 1,2-ethylenediamine (analytical grade, ≥99.5% (GC), Sigma-Aldrich) or 1,3-diaminopropane (Sigma-Aldrich, ≥99%, cat. no. D23602). After addition, mixing was continued for another 2 h at room temperature. The precipitated product was drained, washed with methanol and dried at 40 °C. The quantities of individual reagents and yields are summarised in Table 1. Photographs of the crystals of the substances obtained were taken with a Keyence VHX 7000 digital microscope and are shown in Figures 1 and 2.

Table 1. Stoichiometry and synthesis performance of combustion modifiers

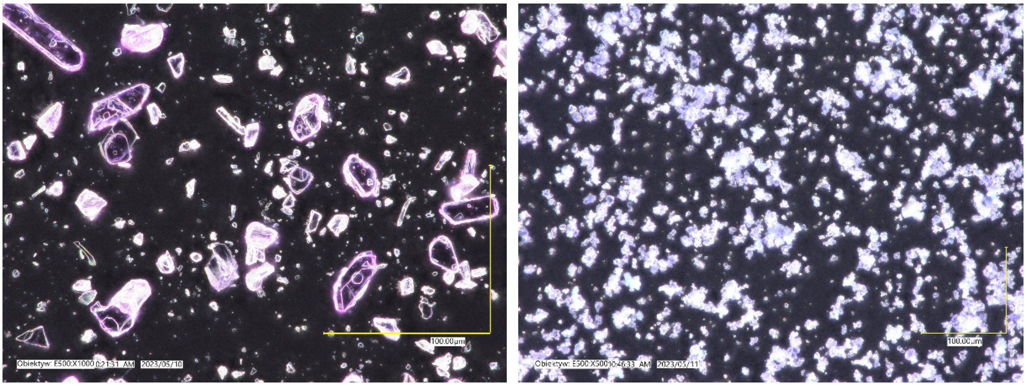
Product	Number of moles of copper(II) nitrate(V) trihydrate [mol]	Number of moles of ligand [mol]	Reaction efficiency in terms of copper salt [%]
ECN	0.013	0.026	~93
TACN	0.010	0.050	~92
13DCN	0.010	0.029	~89



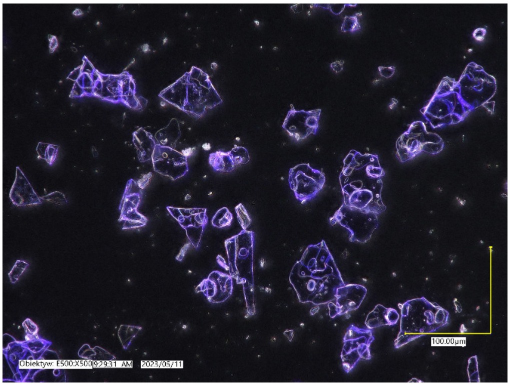
(a) (b)

(c)

Figure 1. Synthesized complex compounds: ECN (a), TACN(b) and 13DCN (c) (magnification ×20)



(a) (b)



(c)

Figure 2. Synthesised complex compounds: a) ECN (magnification ×1000), b) TACN (magnification ×500), c) 13DCN (magnification ×500)

KNO_3 (analytical grade, Chempur), amorphous boron (95-97%, Pol-Aura), polyester resin (Novol Plus 720) together with a dedicated benzoyl peroxide-based hardener (Betox 50PC) were used to prepare the BKN mixture. The oxidiser and propellant were dried at a temperature of 40 °C before use, and the oxidiser was additionally ground in a mortar. The weighed components were transferred to a porcelain vessel and moistened with a small amount of n-hexane (95%, ROTH, cat. no. 4723.1). The ingredients were then mixed using a spatula and, once a homogeneous mixture was obtained, passed through a sieve with a 1×1 mm mesh. The sieved fraction was dried at a temperature of 40 °C for at least 24 h. A photograph of the BKN mixture after granulation is shown in Figure 3.

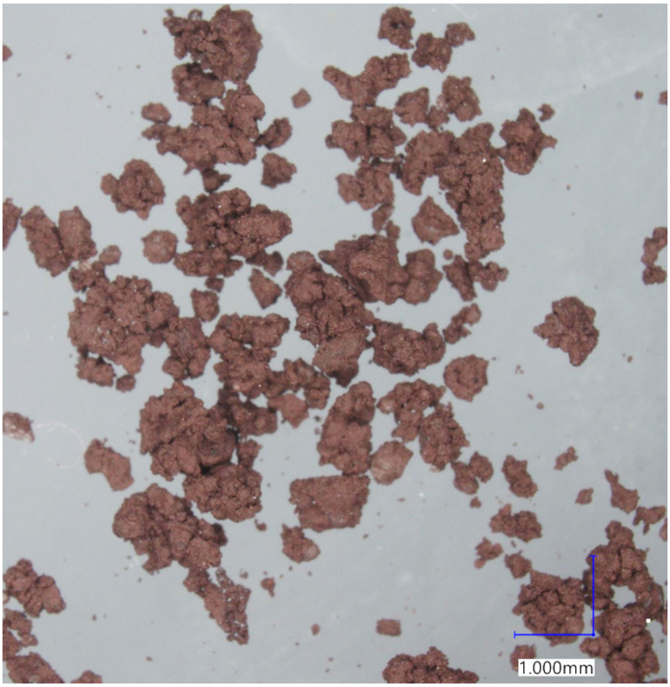


Figure 3. BKN mixture after granulation (magnification ×20)

The mixtures of BKN or BP with modifiers were obtained using previously prepared BKN and a pre-weighed amount of the complex compound. Mixing was carried out in dry conditions until the sample was visually homogeneous. The composition of pyrotechnic mixtures selected for the preliminary tests is shown in Table 2.

Table 2. Compositions of mixtures used in preliminary studies

Compositions of mixtures with BKN	Compositions of mixtures with BP
BKN 100%	BP 100%
BKN 95% ECN 5%	BP 95% ECN 5%
BKN 95% 13DCN 5%	BP 95% 13DCN 5%
BKN 95% TACN 5%	BP 95% TACN 5%

The mixtures based on BKN and modifier required for the extended tests (hereafter referred to as additional tests) in the air-breathing ramjet rotating detonation engine and the tests in the manometer bomb, were made in a slightly modified manner. The difference was that weighed-out amounts of combustion modifiers were added at the BKN composition preparation stage. The composition of the mixtures prepared for additional tests is presented later in this paper.

2.1.2. Researching the properties of modifiers and the BKN mixture

The modifiers and BKN obtained were subjected to, inter alia, mechanical stimulus sensitivity tests, thermal analysis, infrared spectroscopy analysis and heat of combustion in oxygen.

Sensitivity to mechanical stimuli was determined in accordance with standard PN-EN 13631. As a result, an upper insensitivity limit of the compounds/mixtures to friction and impact was determined. UIL was defined as the highest energy (for impact) or the highest load (for friction) at which no reaction was observed in the specimen, in at least six consecutive tests. Impact sensitivity was determined using the BFH-12A free-fall hammer, while friction sensitivity was determined using the FSA-12 friction apparatus. Both instruments were manufactured by OZM Research.

Differential thermal analysis was carried out in an analyser built at Łukasiewicz Research Network – Institute of Aviation. Measurements were carried out in an open system using glass test tubes at a heating rate of 5 °C/min. Depending on the material tested, the mass of the samples ranged from 9 to 16 mg. The reference test tube was left empty during the measurements.

The synthesised complex compounds were analysed using infrared spectroscopy utilising the attenuated total reflection (ATR) technique. The test was performed on a Thermo-Fisher Scientific Nicolet iS50 instrument equipped with an ATR attachment.

For the prepared compounds (modifiers) as well as BKN and BP, the heat of combustion was determined in a BCA 500 calorimetric bomb from OZM Research. The samples were combusted in pure oxygen at a pressure of 3 MPa in a steel bomb with an internal volume of approximately 0.28 dm^3. When it came to TACN, complete combustion of the sample posed a challenge. Therefore, measurements were repeated by combusting a 1:1 mixture of TACN and BP, from which the heat of combustion of the pure complex was calculated.

2.1.3. Preliminary tests in ramjet engine

For the preliminary tests, BP and BKN mixtures with and without the modifiers listed in Table 2, were used. The total mass of each sample was 3 g. The prepared mixtures were loaded into the electric igniter bodies shown in Figure 4. The average density of the mixtures in the igniter body was 1.3 g/cm^3. To initiate ignition of the test mixtures, an electrical resistive ignition element consisting of a 0.1 mm diameter section of Kanthal DSD resistance wire, which was coated with a layer of approximately 200 mg of fine-grained BP (0.5-0.8 mm, Vesuvit LC), was used.

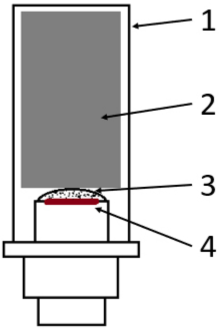


Figure 4. Igniter design for preliminary tests: 1 – body, 2 – pyrotechnic mixture, 3 – fine-grained BP, 4 – electrical resistive element

The prepared igniters were tested on detonation ramjet engine. The pressure value changes during the tests were recorded using liquid-cooled Kistler type 603B sensors, connected to a dedicated charge amplifier. Signals were recorded using an NI USB-6366 high-speed multifunction data acquisition module with a sampling rate of 1 MHz. During testing, a measuring range of 0-25 bar was set. Measurement cards from National Instruments with a USB 6259 measurement/control card and an NI USB 6366 card for recording rapid pressure changes were used to operate the station and acquire data. Oxidiser (air) was fed to the station in a time loop, where it took approximately 700 ms to stabilise the feed conditions. A time delay was needed for the individual elements of the station to heat up. After this time, an electrical pulse was applied to the igniter with the test mixture.

2.2. Second part of tests

Based on the results obtained in the first part of the research, only mixtures containing TACN and ECN were selected for subsequent tests. These compounds were determined to be the most promising and to have the greatest noticeable effect on the nature of the combustion process. The reference mixes remained BKN and BP without admixtures. The compositions of the mixtures used in the second part of the research are shown in Table 3.

Table 3. Compositions of mixtures selected for additional testing

Mixtures for additional test
BP 100% (reference)
BKN 100% (reference)
BKN 95% ECN 5%
BKN 95% TACN 5%

2.2.1. Manometric bomb tests

The tests were carried out in a closed system, allowing changes in pressure generated during the combustion of a material with a mass of 3 g and density of approximately 1.3 g/cm^3, to be recorded. The closed measuring chamber had a capacity of 370 cm^3 and was equipped with a type CL1 pressure sensor manufactured by ZEPWN sp. z o.o. sp. k. (Poland). The sensor's measuring range allowed relative pressure to be recorded from 0 to 24 MPa. A CL11D data logger, working with dedicated software enabling data recording at 32 kHz, was responsible for archiving the measurement data. ZEPWN sp. z o.o. sp. k. was also the manufacturer of this part of the measurement system. A photograph of the test chamber is shown in Figure 5.

Figure 5. Manometric bomb with test igniter

2.3. Additional tests in ramjet engine

The pyrotechnic mixture charges prepared for additional tests in the detonation ramjet engine were in the form of cylindrical pellets. Charge ignition was facilitated by cross cuts on the face surfaces (Figure 6). In order to achieve appropriate stability of the pellets, approximately 2% of Dragon's universal polymer adhesive was added to the pyrotechnic mixtures, wetted with n-hexane before pressing. The parameters of the prepared charges are shown in Table 4.

Table 4. Parameters of pyrotechnic charges used in additional tests in the engine

Mixture	Pellet diameter [mm]	Pellet height [mm]	Charge mass [g]	Density [g/cm^3]
BP	17.06	13.16	4.957	1.649
	17.28	13.91	4.936	1.514
	17.09	14.03	4.994	1.553
BKN	17.00	12.79	4.977	1.715
	17.01	12.77	4.978	1.716
BKN 95% ECN 5%	17.00	12.97	5.027	1.708
	16.98	12.81	4.996	1.723
BKN 95% TACN 5%	16.96	12.66	5.030	1.760
	16.96	12.53	5.001	1.768

Figure 6. Mouldings prepared for testing (example)

To achieve proper ignition of the pyrotechnic mixture mouldings, a 1.5 g BP pad was used. Powder ignition was initiated using an electrical method. During the tests, the measuring apparatus used was identical to that used during the preliminary tests in the detonation ramjet engine. The main difference was that, during the tests, the engine was fed with fuel (Jet-A1) and air (oxidiser) at 170 °C at approximately 1.3 kg/s. The airflow was activated 100 ms before the igniter was triggered.

3. Results and discussion

Satisfactory yields were obtained for all of the complex compounds tested. Due to the simple and reproducible synthesis process and the available literature on TACN and ECN, the structures of these compounds have not been extensively studied.

The results of the mechanical stimulus sensitivity testing are presented in Table 5. Of the complex compounds tested, 13DCN has the highest friction and impact sensitivity. Both ECN and TACN have the same sensitivity to friction, and similar sensitivity to impact. For BKN, the exact impact sensitivity was not determined, as the tests were discontinued after a positive result was obtained when an energy of 2 J was supplied. Its sensitivity to friction is low.

Table 5. Sensitivity to friction and impact

Compound/mixture	Upper limit of impact insensitivity [J]	Upper limit of friction insensitivity [N]
ECN	7.5	108
TACN	10	108
13DCN	5	84
BKN	<2	324

The thermal analysis thermograms heating rate 5 °C/min are shown in Figures 7-10. The thermal analysis showed that all the modifiers obtained decompose at temperatures equal to or higher than 190 °C. When it comes to ECN, decomposition starts around 245 °C and takes place in at least two stages. A similar result for this compound was presented in [8], however, several levels of decomposition were already observed at a temperature of 230 °C, which may have been due to a different heating rate in the quoted work (0.5 °C/min). In the TACN thermogram, an endothermic transformation can be observed at around 230 °C, followed by exothermic decomposition of the complex at 250-290 °C. Similar thermal analysis results were presented in [8-10]. The thermogram obtained for 13DCN shows two exoenergetic transformations taking place (two-step decomposition). Within the range 190-220 °C the first signal appears, which is immediately followed by another, but with a more steeper temperature rise in the sample. The BKN thermogram shows three characteristic peaks of this mixture [11, 12]. The endothermic peak occurring at around 138 °C corresponds to a polymorphic transformation of KNO_3. The next peak at 342 °C is due to the melting of the oxidiser. The last, observed at 552 °C (start of transformation) – 560 °C (end of transformation) is due to the exo-energetic decomposition of the sample.

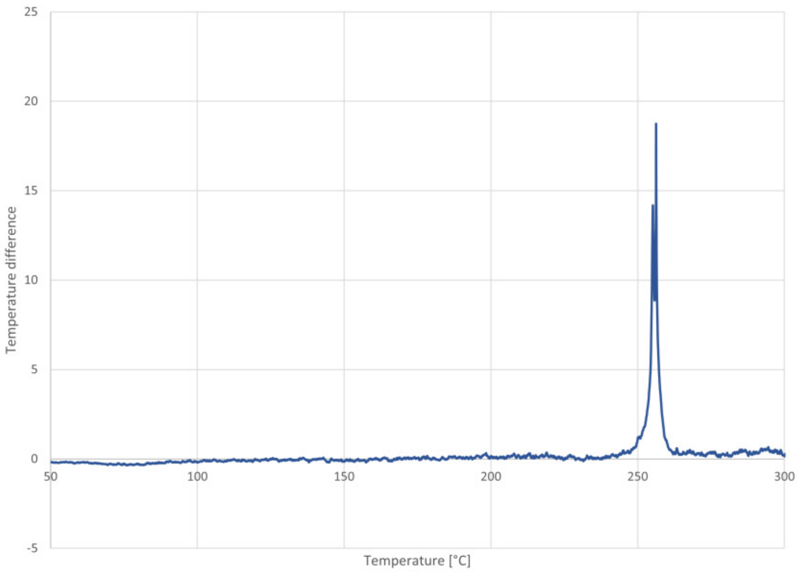


Figure 7. DTA thermogram of the ECN compound (sample mass 9.0 mg)

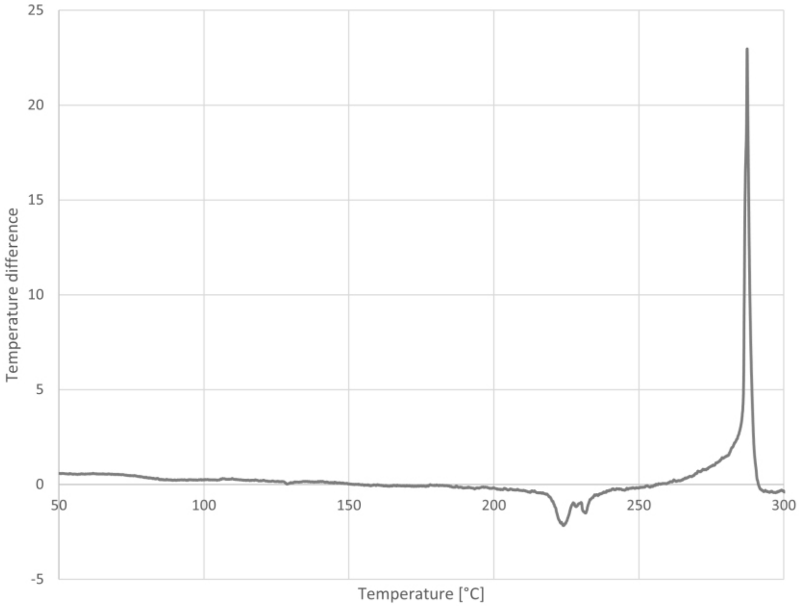


Figure 8. DTA thermogram of the TACN compound (sample mass 16.0 mg)

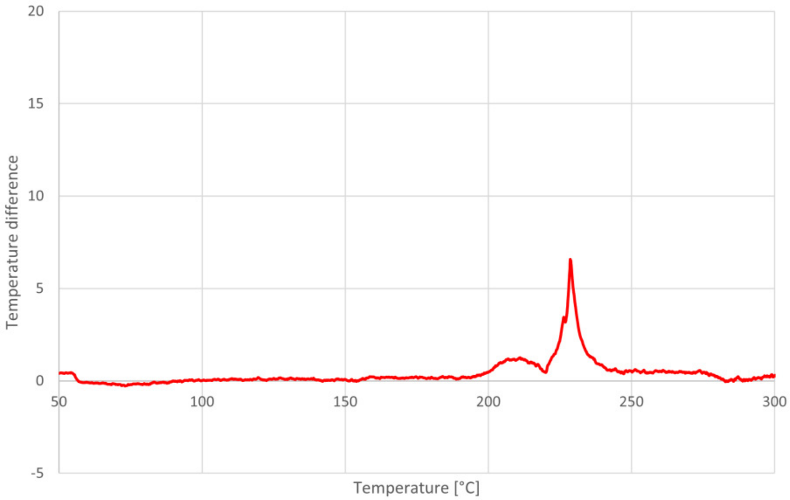


Figure 9. DTA thermogram of the 13DCN compound (sample mass 9.7 mg)

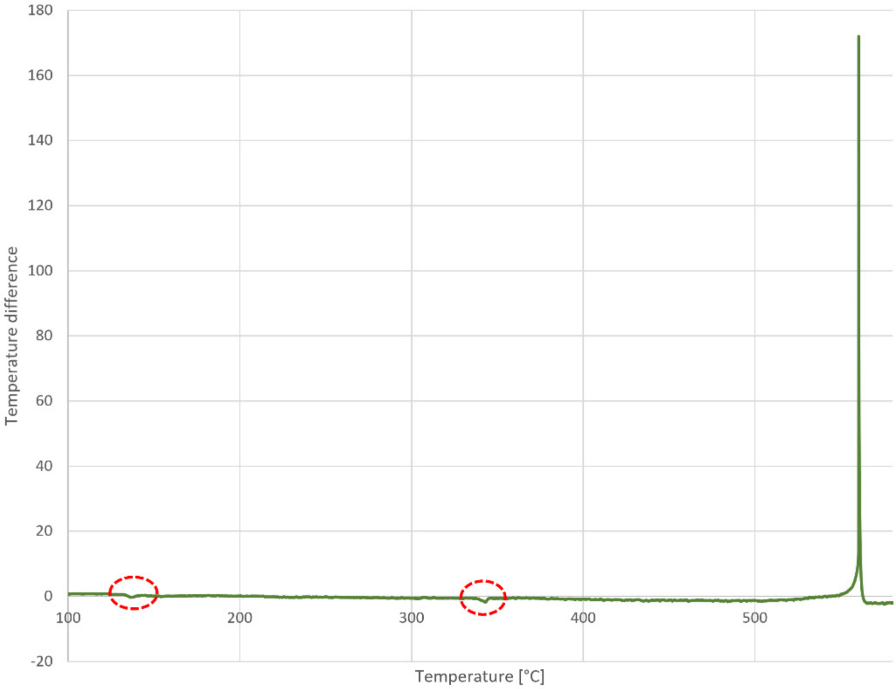


Figure 10. DTA thermogram of the BKN mixtures (sample mass 10.2 mg)

The infrared spectra obtained using ATR are shown sequentially in Figures 11-13. The spectra of all three complex compounds show absorption bands around 3200 cm^{-1} associated with N–H bond stretching vibrations and bands around 1600 cm^{-1} probably associated with N–H bond bending vibrations. The bands around 1600 cm^{-1} may also be related to the presence of N–O bonds in the studied compounds. Signals appearing in the 2850-3000 cm^{-1} region on the ECN and 13DCN spectra correspond to absorption due to the presence of C–H bonds and the stretching vibrations of this bond, characteristic of alkenes.

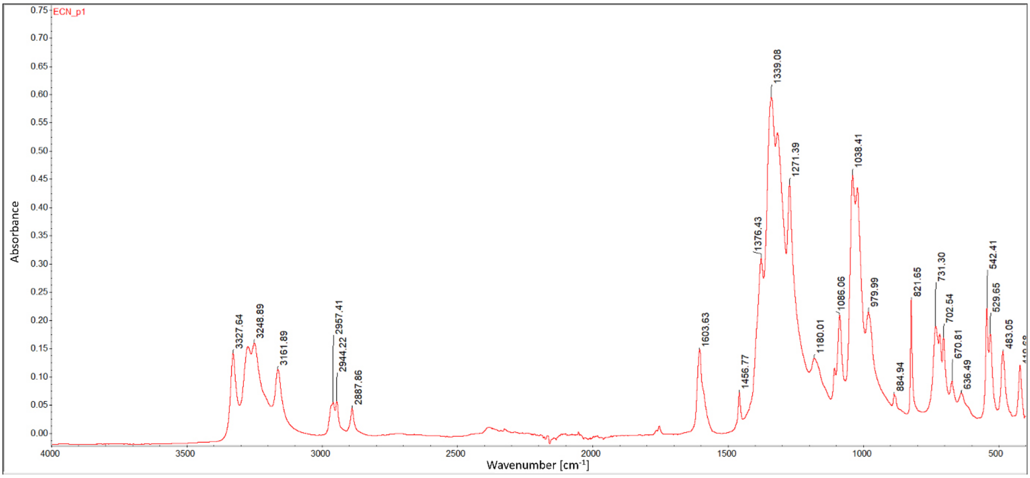


Figure 11. IR spectrum of the obtained ECN compound

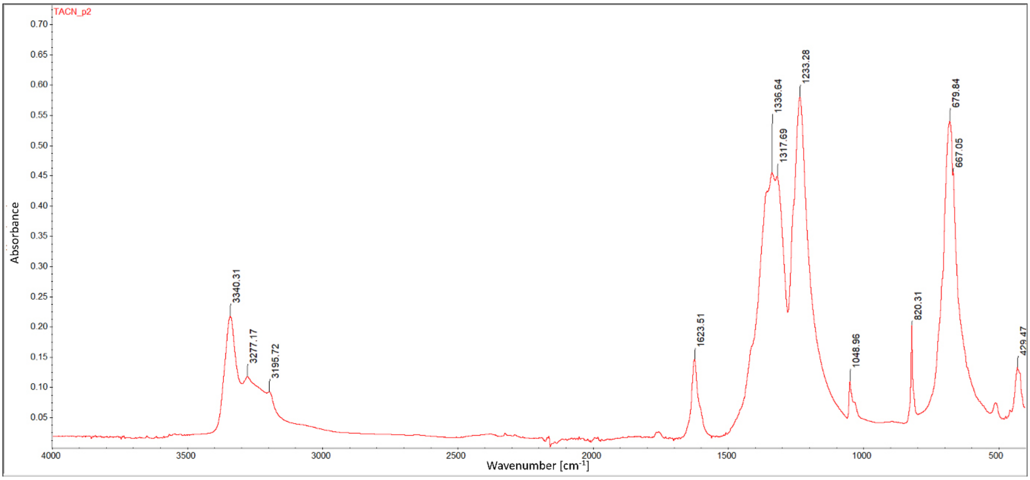


Figure 12. IR spectrum of the obtained TACN compound

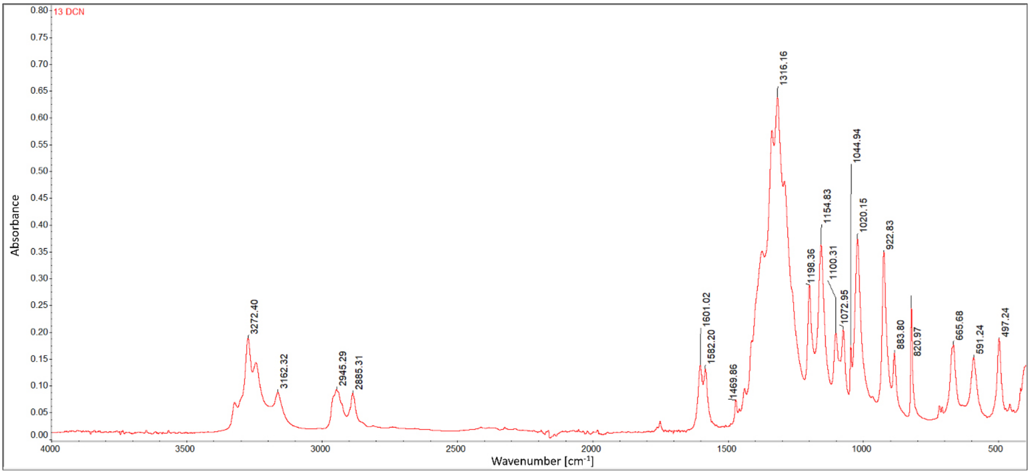


Figure 13. IR spectrum of the obtained 13DCN compound

The IR spectrum obtained for TACN concurs with the results obtained and presented in [9], allowing us to conclude that the same compound was obtained. When it comes to ECN and 13DCN, the authors were unable to access literature data with which the obtained results could be compared.

The results of the determined heat of combustion in oxygen were collected and presented in Table 6. The lowest heat of combustion value was obtained for TACN and is lower than the heat determined in [9] (4080 J/g). 13DCN features the highest heat of combustion.

Table 6. Heat of combustion in oxygen of tested compounds

Compound/mixture	Heat of combustion [J/g]
ECN	10346
TACN	3716
13DCN	14316
BKN	7545
BP	5634

The results of the preliminary tests given as the maximum ignition pressure in the detonation jet engine are shown in Figures 14 and 15. For BP (Figure 14), the use of modifiers in the form of TACN and ECN did not result in significant differences in the recorded P_{max} values, which ranged from 4.3 to 4.5 bar. However, the addition of 13DCN, resulted in a significant drop in the recorded pressure of approximately 39% relative to pure BP. Igniters reloaded with BKN (Figure 15) gave a higher pressure increase than igniters containing BP. The difference between these pyrotechnic mixtures was up to 53%. In contrast, all modified boron-based mixtures resulted in a higher pressure than pure BKN. The increase was about 8.8% for a mixture containing 13DCN and 14% when ECN was the modifier, with respect to pure BKN. The largest increase, of just under 18%, was observed when TACN was added to BKN.

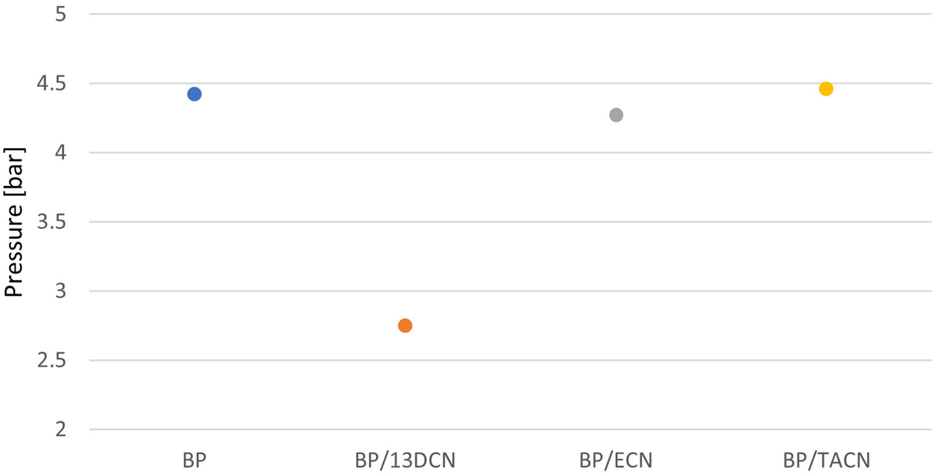


Figure 14. Summary of ramjet engine preliminary test results for compositions containing 95% BP and 5% modifier and pure BP

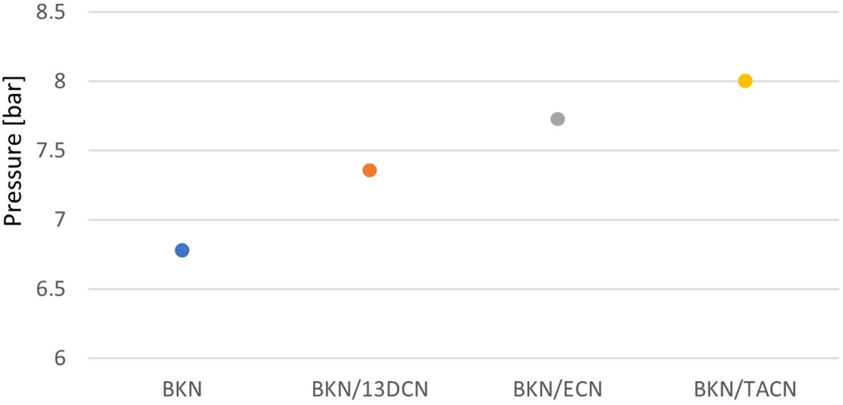


Figure 15. Summary of jet engine preliminary test results obtained for compositions containing 95% BKN and 5% modifier

Results of the tests carried out in the manometric bomb (shown in Figure 16), indicate that the maximum pressure generated during combustion of a BP charge can reach no more than 17.4 bar. It can also be observed that the gas generation process features the smoothest waveform in this instance, with the pressure staying at around 59% of the maximum value 0.4 s after the sample is ignited. In the case of BKN, a maximum pressure of 31.8 bar was obtained, which decreased in value to about 45% after 0.4 s. The waveforms recorded during testing of BKN samples admixed with complex compounds have a very similar shape. The addition of 5% TACN increased the pressure to around 38.9 bar, while the addition of 5% ECN in BKN – to 42.0 bar. In this case, after 0.4 s, the pressure values were 4.4 bar and 6.5 bar respectively, representing 11% and 15% of the initial values. The small peaks visible 1 s after the start of recording result from interference generated by the electrical system powering the igniter. The speed of operation of igniters containing pure and admixed BKN oscillate around 25 ms. The ignition delay time of the igniter containing BP has value approximately 32 ms.

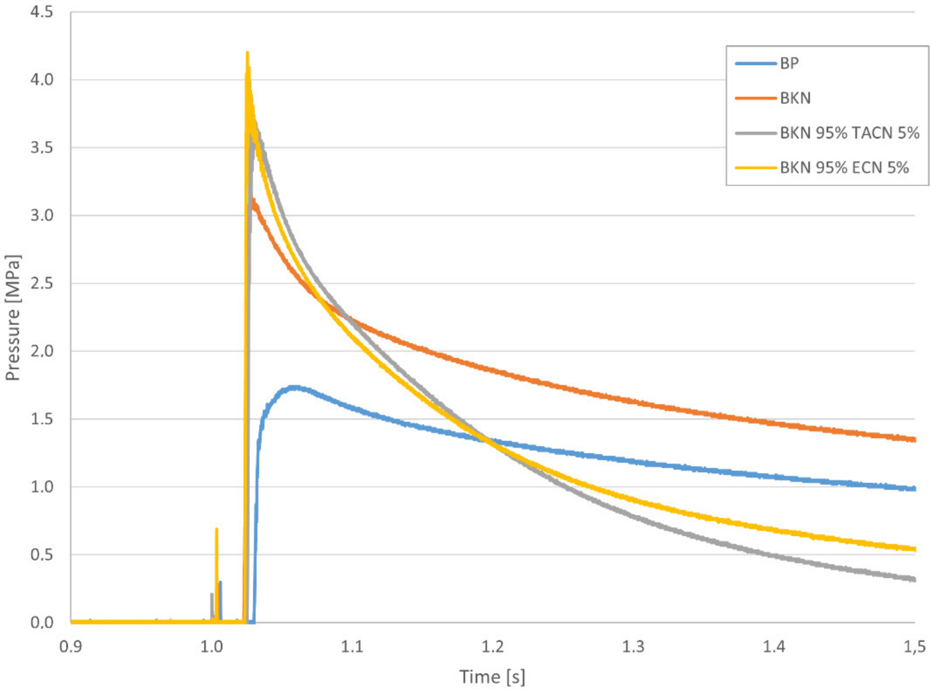


Figure 16. Results of pressure measurements for gases formed during the combustion of mixtures in the manometric bomb

Test results obtained using the detonation ramjet engine through which fuel and hot air were flowing are presented in Figure 17. The recorded maximum pressure values for the igniter containing BP differ considerably from the pressure values generated by the other igniters. Some correlation with the results obtained in the manometric bomb (Figure 16) is observed by analysing the integrated area under the graphs in Figure 18. To determine the value of the pressure impulse, integration was performed over a time interval of 0 to 5 ms.

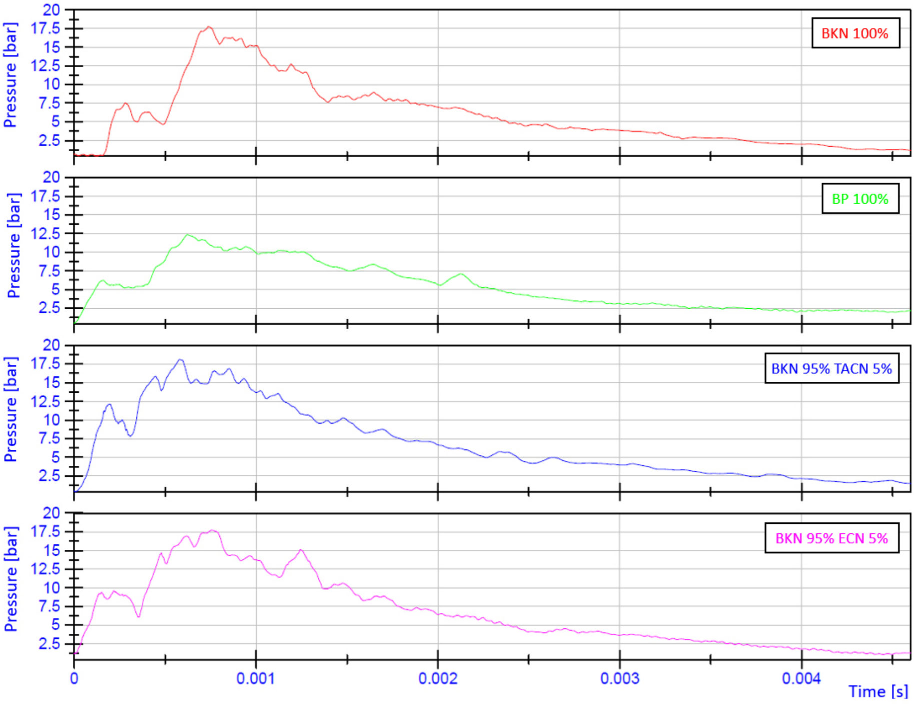


Figure 17. Results from additional tests from the airbreathing engine

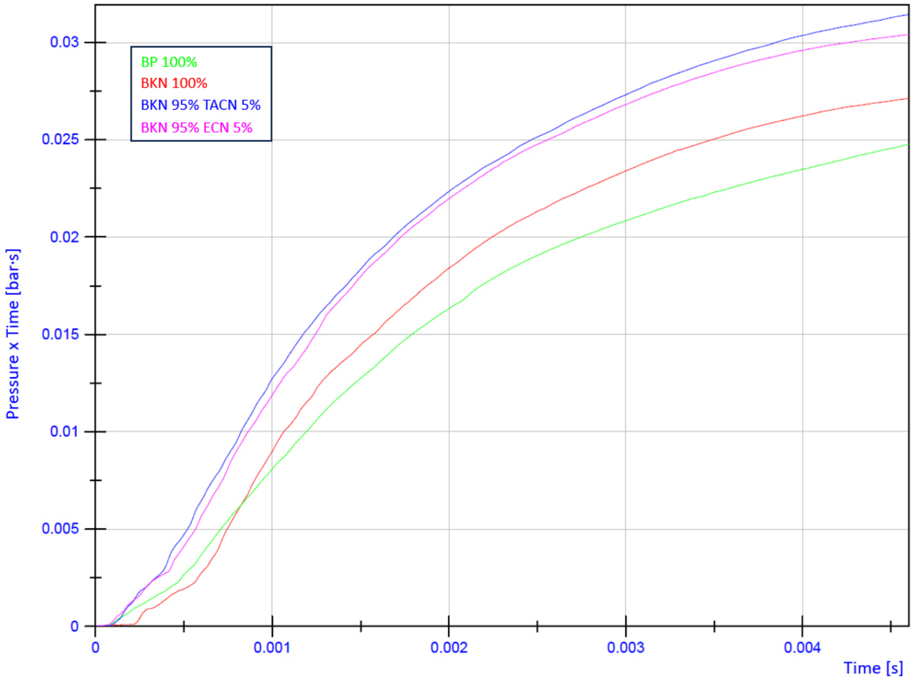


Figure 18. Integral of area of the graphs in Figure 17

Larger peak areas are indicative of the fact that increased pressure in the engine compartment lasts longer. In this situation, mixtures of TACN and ECN with BKN showed the most beneficial effect. The smallest pressure impulse value was recorded when the igniter loaded with BP was tested.

4. Summary and conclusions

- ♦ The syntheses planned and carried out during the course of the work produced complex compounds with a yield no worse than 89%. The compounds showed resistance to temperature rises to at least 190 °C. The structure of these compounds is confirmed by the IR spectra obtained. It is also noticeable that the thermograms obtained are consistent with those cited in literature. TACN and ECN also showed an acceptable level of sensitivity to mechanical stimuli. The thermal analyses confirm that none of the modifiers in milligram quantities show the decomposition characteristics of an initiating explosive. The high heat of combustion in oxygen obtained for 13DCN and ECN is due to the presence of carbon-rich ligands in the coordination spheres of these substances.
- ♦ Tests of modified BP charges, carried out in the first part of this work, indicate that additives such as ECN and TACN have no effect on the pressure values generated in a jet detonation engine. When an additive of 5% 13DCN was used as a modifier, the pressure values recorded were even lower than with non-admixed BP. For this reason, and because the sensitivity of 13DCN to mechanical stimuli is similar to that of PETN, it was abandoned for use in further studies. Due to the lack of positive effects of the modifiers on the properties of BP charges, only the BKN-based mixture was investigated further.
- ♦ When BKN was the main component of the mixtures and 5% ECN or TACN was the additive, an increase in detonation jet engine ignition pressures of 14% and 18%, respectively, was observed compared to pure BKN. This situation was repeated during additional tests in the manometric bomb. In this case, the combustion of mixtures containing ECN was accompanied by a pressure 32% higher than that of the combustion of BKN without modifiers. Regarding mixtures with TACN, an increase of approximately 22% was achieved. When testing igniters containing 5 g of pressed pyrotechnic mixture, the situation was repeated. Measurements carried out in the detonation jet engine showed that mixtures containing added complex compounds also had higher pressure impulse values. Despite the very different heat of combustion in oxygen obtained for ECN and TACN, the different oxygen balance values of these compounds, as well as the different structures of individual ligands, both modifiers change the properties of mixtures with BKN in a similar manner. This phenomenon may be indicative of the dominating influence of copper ions on the BKN combustion process over the influence resulting from the heat of decomposition of the modifiers themselves.
- ♦ The results obtained suggest that mixtures consisting of BKN and modifiers in the form of a 5% addition of ECN or TACN, can act as ignition mixtures with enhanced performance. To take full advantage of this feature, further optimisation of the geometry and density of the charge made from such a mixture is required. For safety reasons, however, it should be borne in mind that the main component of these mixtures, i.e. BKN, is an impact-sensitive composition. In order to develop mixtures featuring an even higher ignition pressure impulse, further optimisation work is required in terms of the quantities of modifying additives used.

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