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Development of a Solid, Low-Smoke Rocket Propellant – Smoke Generation Intensity Tests Using a Laser and Photodiode Setup

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Abstract. The work completed and discussed in this paper was to determine the level of smoke generation intensity in a selection of solid rocket propellants developed to minimise the level of generated smoke. This is an important issue for the application of the developed low-smoke propellant in, for example, the sustainer motor of a rocket missile. Reduced smoke generation levels can help to significantly reduce the feasibility of enemy detecting rocket munition launch sites. The authors of this paper developed a test stand that quantified the smoke generation intensity in rocket propellants. The test stand setup, based on the scatter of a laser beam by smoke, measured the smoke generation intensity, including during the operation of a rocket motor. A rocket micromotor was used along with a test chamber to measure the intensity of the smoke generated. It was located directly behind the motor exhaust and provided three laser-photodiode measurement channels. Tests of the smoke generated during the combustion of black powder and a standard mixture of HTPB and AP at a ratio of 20:80 provided reference baselines for the smoke generation intensity tests on the developed rocket propellants. The authors determined the smoke generation intensity of the propellants based on ADN, HTPB, and GAP with various additives. The results produced made it possible to compare the tested materials and select the most preferable materials as measured by their low smoke generation intensity.
Keywords: rocket motor, solid propellant, combustion, smoke generation, laser

1. INTRODUCTION

Solid rocket propellants are commonplace in driving motors and control thrusters in many rocket missiles. Determining the smoke generation intensity from the combustion of solid rocket propellants is an important issue for the development of low-smoke propellants. Reduced emissions of the combustion gases that generate the streak of smoke behind the rocket motor's exhaust can significantly reduce the feasibility of the enemy detecting rocket munition launch sites.

A part of the ongoing research work into solid heterogeneous rocket propellants (SHRP) is focused on reducing the smoke generated during combustion [1–5]. The commonly used SHRP compositions are based on hydroxyl-terminated polybutadiene (HTPB) groups as the binder with ammonium perchlorate (AP) as the oxidiser, aluminium (Al) dust as an energy additive [6, 7] and various chemicals which act as modifiers of the combustion rate [8–10]. A major deficiency of these components is the very high levels of smoke generated during combustion.

The sources of smoke can be divided into primary and secondary [11]. Primary smoking depends on the composition of the propellant. Components of exhaust gases that include metal particulates, metal oxides and carbon black significantly increase the amount of smoke generated. Secondary smoking depends largely on the composition of the ambient atmosphere, primarily the relative humidity level. Secondary smoke is generated by condensation of water vapour and acids, such as hydrogen chloride (HCl), which are present in the exhaust gas.

Many methods exist to reduce the intensity of the smoke generated, including reducing the percentage share of aluminium dust in the propellant, or using an alternative energy additive, such as magnesium [12]. Another relevant factor is the reduced quantity (or complete absence) of ammonium perchlorate [3, 13, 14] the combustion of which releases hydrogen chloride, a chemical which significantly intensifies the smoke generation and is harmful to the environment [15]. An alternative to ammonium perchlorate is an oxidiser which features no chlorine in the makeup, such as ammonium nitrate (AN) [16, 17] or ammonium dinitramide (ADN) [18, 19]. Yet another method to avoid chlorine in the combustion products is to apply HMX (octogen) which, when added at 10% to 20% w/w to a standard AP/HTPB composition, reduces the hydrogen chloride level in the combustion gas by 20% to 30%, while boosting the specific impulse [4]. Apart from completely eliminating hydrogen chloride from rocket propellant combustion products, the compound can be neutralised by applying certain chemicals, such as nitrates of sodium, lithium, potassium, strontium, or barium, as well as lithium or sodium carbonate [3, 14].

The smoke generation intensity can be evaluated with several measurement techniques. The works by Terry et al. [3] Gilla et al. [19] and Toscano et al. [20] present one such technique, being an application of Fourier-transform infrared spectroscopy (FTIR), which first enabled analysis of the quantitative composition of combustion gases and determination of each of the components in the hot jet of combustion gases (along with a variety of solids, such as carbon black or metallic particulates) generated by the combustion of solid propellant samples. Vilmart et al. [22] discussed the feasibility of applying planar laser-induced fluorescence (PLIF) imaging. The method was used to study the behaviour of aluminium particulates during the combustion of a solid rocket propellant. Another concept for measuring the intensity of the smoke generated assumed the application of a particulate filter with a combustion gas analyser [4], which made it possible to determine the quantitative results. The particulate filter applied was largely used to measure the primary smoke, while the combustion gas analysed was used to determine the level of hydrogen chloride, a significant contributor to the generation of secondary smoke. Another widely used method for determining the intensity of the smoke generation [23] is based on the results of thermodynamic calculations driven by the chemical balance of the combustion process and a standardised classification termed AGARD, which describes the measure of primary smoke and secondary smoke levels in tested samples of solid propellants. The report referenced here defined smoking classes of A, B and C for primary and secondary smoke. The outcome of the calculations is a determination of the intensity of smoke generation in the tested solid propellant, divided into several categories, such as AA for smokeless (or near-smokeless) materials, applied to primary and secondary smoke, through CC for high (primary and secondary) smoke materials. The method requires thermodynamic calculations and certain simplifying assumptions.

The scientific papers and research referred to above determine the smoke generation intensity of solid rocket propellants based on the chemical composition of their combustion products. The authors of this work, however, propose a direct method of determining the smoke generation intensity based on the scattering of a laser beam in solid propellant combustion products, while defining a smoke intensity coefficient (SIC) which is based on the change of intensity of the laser beam crossing the smoke.

2. EXPERIMENTAL TESTING

2.1. Measurement concept

The developed test method provides an experimental measurement of the intensity of smoke generation in solid rocket propellants during their combustion in a rocket motor at different relative humidity (RH) levels in an ambient atmosphere.

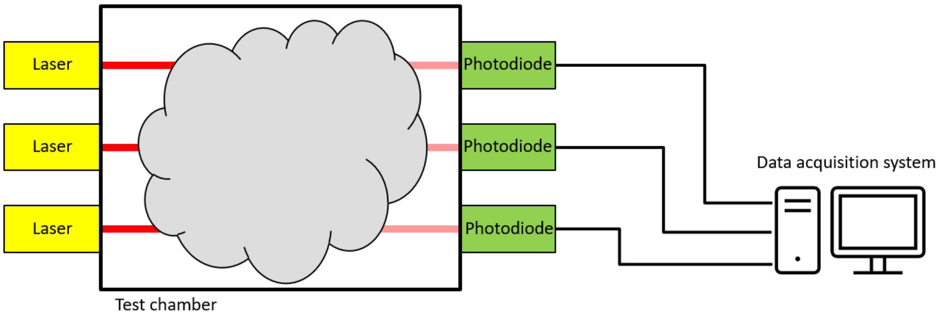

Fig. 1. Diagram of smoke generation intensity by laser beam scattering in smoke

The test system (Fig. 1) was based on the scattering and absorption of a laser beam by smoke. The test system made it possible to measure the intensity of the generated smoke via the reduction of the voltage across a photodiode which picked up the incident beam of laser light at a visible light wavelength of 650 nm. The voltage drop picked up on the photodiode was standardised by referencing the measured values to a baseline signal generated during the same measurement run prior to smoke emission into the test chamber. The acquired values could be compared to test results produced with reference materials, such as black powder or an 80:20 mixture of AP and HTPB.

2.2. Overview of the test stand

The test system formed by the test stand comprises a laser module and a photodiode module, which formed a single measurement channel. The test stand also featured a hygrometer module, a power and control system for all three modules, and a test chamber in the form of a straight-through, open-ended pipe through which smoke would pass during combustion of the propellant. The laser module emitted a 650 nm laser beam at a constant, preset power output of 1 mW which crossed the smoke, in which the beam was attenuated and incident to the photodiode installed in the photodiode module. The photodiode generated a voltage output with a level proportional to the intensity of the incident laser beam. The hygrometer module monitored the temperature and RH of the ambient atmosphere, with the latter parameter being a considerable contributor to the smoke generation intensity.

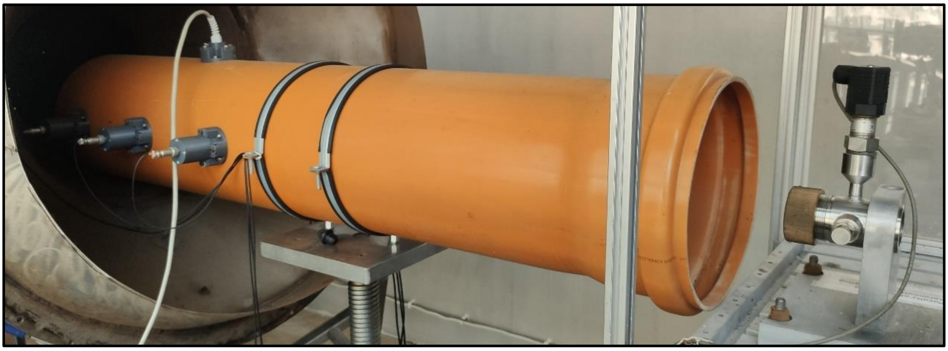

Fig. 2. Test stand: the test chamber with a laboratory rocket micromotor

The test chamber in the form of a pipe made it possible to test the smoke generated from a running laboratory rocket micromotor (Fig. 2). The pipe was a PVC duct with a diameter of 250 mm, positioned inline and downstream of the exhaust of the laboratory rocket micromotor. The test chamber featured three measurement circuits (laser-photodiode pairs) installed 750 mm, 950 mm, and 1150 mm from the test chamber pipe inlet. A constant air flow through the pipe was provided by an extraction fan, aspirating air from the pipe interior by the phenomenon of ejection.

Each test (measurement) was set up by charging the rocket micromotor with a grain of the test propellant. Next, the lasers and photodiodes were turned on, followed by the test run, while the hygrometer and an ultrasonic steam generator were used to condition the RH inside the test chamber. When the required parameters of the atmosphere flowing through the pipe were established, the rocket micromotor was fired and the motor burn generated smoke and exhaust gases, directly entering the test chamber tube with the laser-photodiode pairs installed.

The tests were run in non-steady state conditions that occur in a real-life operating environment of rocket missile motors. The test run duration depended on the burn (combustion) time of the solid propellant specimen in the rocket micromotor.

2.3. Normalisation

The indicator of smoke generation intensity for the propellant tested in this work was the loss of laser beam light intensity caused by the beam crossing the medium filled with smoke and referenced to the baseline intensity of the non-scattered laser beam. This is why the trends of the photodiode voltage output signal produced during the experimental tests and proportional to the intensity of the laser beam light incident to the photodiodes required normalisation. The normalisation was done by running a measurement in the test chamber without any smoke to determine the baseline voltage levels for a certain time each time before igniting and burning the test propellant. The voltage output normalisation followed the equation:

$$SIC(t) = 1 - \frac{U(t)}{U_0} \tag{1}$$

with $SIC(t)$ being a standardised trend representative of the SIC (smoke intensity coefficient), $U(t)$ being the photodiode voltage output trend picked up, and U_0 being the baseline voltage level. Normalisation was shown in Fig. 3.

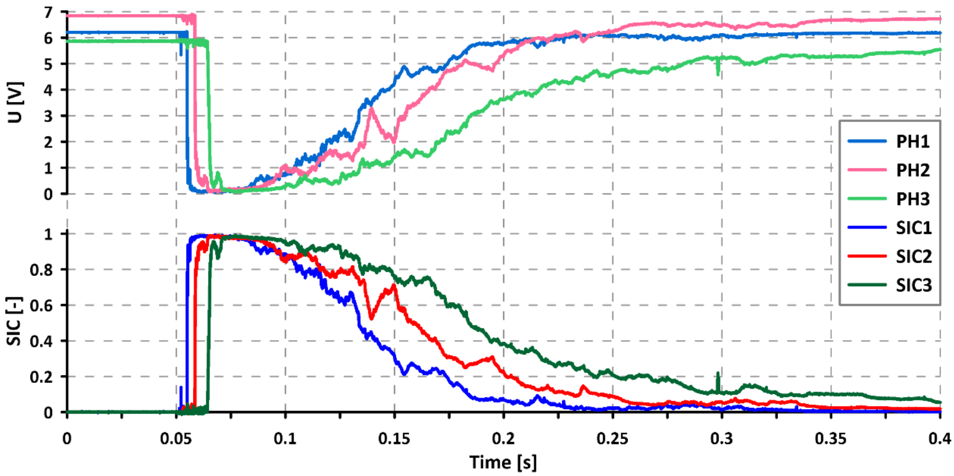

Fig. 3. Examples of photodiode voltage output trends and standardised outputs which determined SIC (smoke intensity coefficient)

Note that the photodiode voltage output trend was proportional to the light intensity of the laser beam incident to the photodiode, which made the ratio of the voltage output trend to the baseline voltage level $U(t)/U_0$ identical to the ratio of the laser beam intensity to the baseline light intensity level $I(t)/I_0$, whereas Eq. (1) $SIC(t) = 1 - U(t)/U_0$ was identical to the ratio of the laser beam intensity reduction across the smoke to the baseline light intensity $\Delta I(t)/I_0$.

2.4. Test propellants

Initially, the experimental tests were done on black powder and an AP/HTPB mixture at a ratio of 80 to 20, which were the reference materials for the novel propellant compositions. This was followed by testing the solid propellants made for this research project and based on an application of ammonium dinitramide (ADN), hydroxyl-terminated polybutadiene (HTPB) or glycidyl azide polymer (glycidyl polyazide, GAP) and a number of additives. The simplified compositions are listed in Table **1** and given that the compositions of the specific propellant materials are legally protected, the authors did not specify the exact percentage ratios of the components at this stage.

Table 1. Summary of test solid propellant compositions

Propellant	Oxidiser	Binder (fuel)	Additives
P1	AP	HTPB	HMX (Class 5)

P2	AP	HTPB	HMX (Class 3)
P3	AP	HTPB	HMX (Class 1)
P4	AP	GAP	Al, CL-20
P5	ADN	GAP	HMX (Class 3)

3. TEST RESULTS

The presented experiments were preliminary intended to test the test stand and demonstrate the capabilities of the proposed test method. The first materials tested, with a known smoke generation intensity determined with the standardised AGARD classification (CA from black powder and AC for the 80/20 AP/HTPB mix), were adopted as reference materials. Three basic propellant compositions were selected for subsequent tests: AP/HTPB/HMX, AP/GAP/Al and ADN/GAP/HMX. The experimental tests were run in the test setup with the straight-through pipe of the test stand, with its outlet placed directly at a fume hood, by which the smoke generated by combustion of the test materials was within the measurement field for a short time only, dictated by the burn time of the propellant and the flow rate through the test chamber.

The smoke intensity coefficient (SIC) for each test propellant was determined using the standardised voltage output trends discussed earlier in this work and defined as an averaged reading of the standardised voltage output within the quasi-steady smoke generation area. The SIC values produced in this way, for each measurement channel, were averaged to a single SIC value. An example of a standardises readout trend from a single photodiode is shown in Fig. 4.

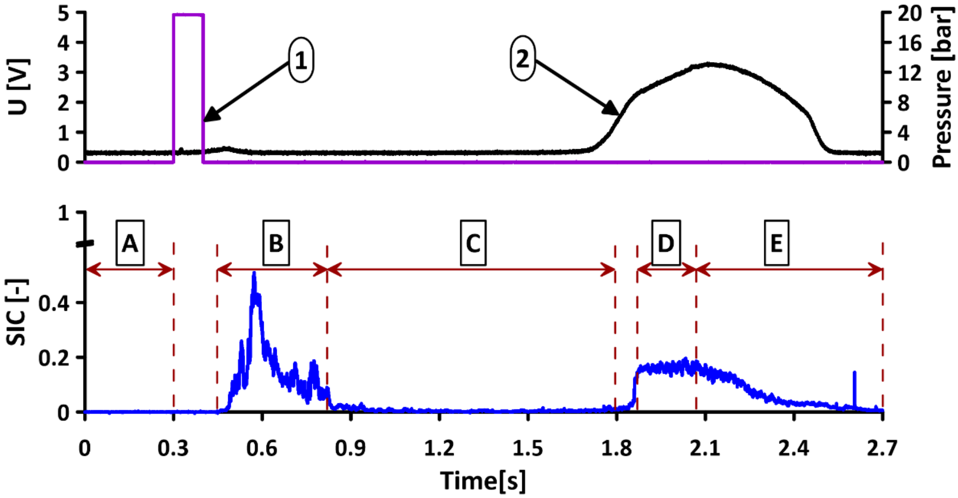

Fig. 4. Example trends of pressure, ignition unit trigger, and SIC (1 – primer trigger current pulse; 2 – pressure trend, a result of the test propellant combustion)

The chart above shows the trigger current pulse initiating the ignition unit charge labelled (1), whereas a portion of the pressure trend curve related to a pressure increase from the primer combustion is labelled (2). The trend of the SIC was divided into five characteristic intervals: A – baseline period; B – ignition unit charge combustion (primer and low-explosive charge); C – initial period of propellant combustion; D – propellant combustion with the quasi-steady smoke generation intensity; E – final burn. No nozzle plug was used in the tests, which could have considerably prolonged interval C. For propellants with a high ignition rate, the ignition time was markedly reduced or completely non-existent.

3.1. Reference propellants

First, the experimental tests focused on the SIC of the selected reference propellants, meaning black powder and the AP/HTPB 80:20 mix. The acquired SIC values are summarised in Table 2, while the chart shows a selection of trends at an approximate RH of 50%.

The very high SIC levels acquired in the black powder combustion tests and the low SIC levels in the AP/HTPB 80:20 mix combustion tests may indicate that primary smoke was measured first during the tests. Exemplary experimental results sequentially for AP/HTPB and black powder were shown in Fig. 5 and Fig. 6.

Table 2. Summary of the applied reference propellant data: RH, maximum combustion chamber pressure, specimen mass, smoke intensity coefficient (SIC)

Reference propellant	**RH [%]**	P_{max} **[bar]**	**Propellant charge [g]**	**Photodiodes**			**SIC [-]**
				SIC$_1$ **[-]**	**SIC**$_2$ **[-]**	**SIC**$_3$ **[-]**	
80:20 AP/HTPB	49.3	8.0	4.66	0.170	0.196	0.211	0.192
	50.6	5.7	4.58	0.135	0.170	0.178	0.161
	75.0	6.2	4.11	0.142	0.156	0.155	0.151
Black powder	20.8	32.0	2.76*	0.925	0.914	0.897	0.912
	43.0	47.0	2.93*	0.968	0.975	0.975	0.973
	68.2	40.0	3.05*	0.958	0.965	0.965	0.962
	50.4	143.0	2.41*	0.961	0.966	0.972	0.966
	78.8	128.0	2.44*	0.969	0.977	0.966	0.971

** The mass did not include the black powder charge in the ignition unit.*

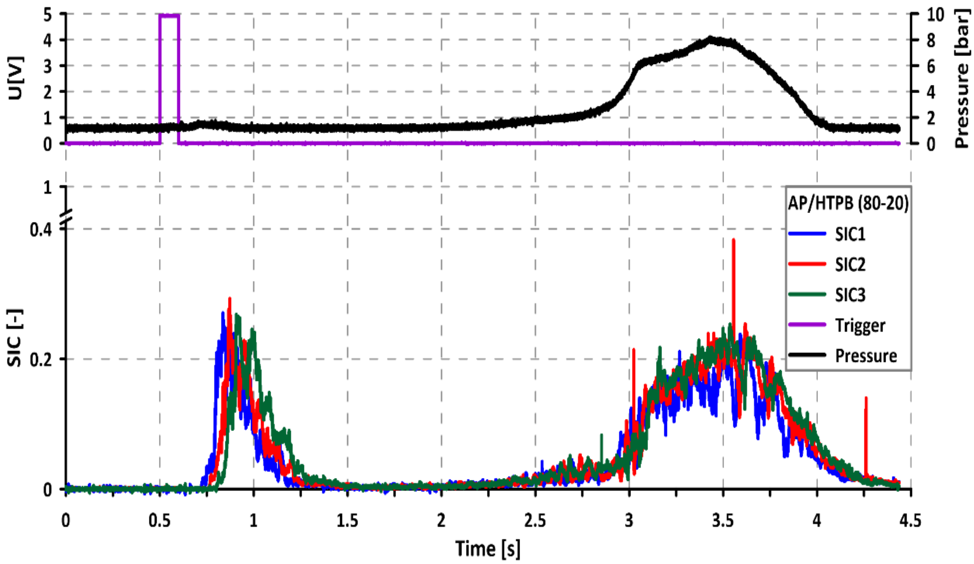

Fig. 5. Example trends of pressure, ignition unit trigger, and SIC acquired during combustion of the reference propellant, AP/HTPB 80:20 in the rocket micromotor at 49.3% RH

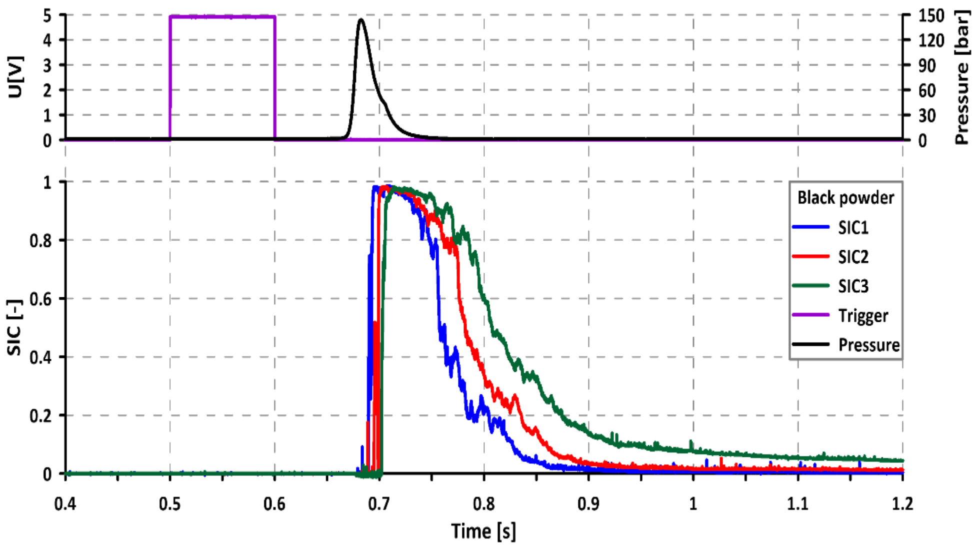

Fig. 6. Example trends of pressure, ignition unit trigger, and SIC acquired during combustion of the black powder in the rocket micromotor at 50.4% RH

3.2. Test propellants

The test bed discussed here was intended to determine the SIC (smoke intensity coefficient) for novel solid rocket propellants. Three different classes of AP/HTPB/HMX propellants (labelled P1, P2, P3), one AP/GAP/Al propellant (P4) with the addition of aluminium dust, and one ADN/GAP/HMX propellant (P5), in which AP (ammonium perchlorate) was replaced with ammonium dinitramide (ADN) were tested. In Table 3 is a summary of the SIC levels acquired in each test.

The primary contributor which modified the SIC trends was the combustion rate and ignition time of each propellant tested. For high combustion rate propellants, the smoke generated by burning the black powder charge in the ignition unit primer was mixed with the propellant combustion smoke (Fig. 7). For P4, which had a relatively high SIC due to the aluminium dust additive, it was not possible to distinguish between these two sources of smoking (Fig. 8).

Table 3. Summary of the test propellant data: RH, maximum combustion chamber pressure, specimen mass, smoke intensity coefficient (SIC)

Propellant	**RH [%]**	**P_{max} [bar]**	**Propellant charge [g]**	**Photodiodes**			**SIC [-]**
				SIC_1 [-]	**SIC_2 [-]**	**SIC_3 [-]**	
P1	50.0	14.0	4.35	0.162	0.167	0.177	0.168
	49.5	18.0	4.77	0.129	0.129	0.130	0.129
	49.1	40.0	5.21	0.159	0.172	0.174	0.168
	30.4	30.0	4.94	0.135	0.143	0.155	0.144
P2	51.9	11.0	4.39	0.072	0.080	0.088	0.080
	49.9	17.0	4.06	0.147	0.148	0.143	0.146
	49.6	38.0	4.13	0.142	0.161	0.175	0.159
P3	81.8	10.0	5.47	0.044	0.043	0.042	0.042
	73.6	13.5	4.82	0.070	0.075	0.077	0.074
P4	45.7	160.0	7.95	0.689	0.757	0.756	0.734
	42.0	170.0	8.14	0.766	0.799	0.793	0.786

	39.6	210.0	7.93	0.718	0.796	0.803	0.772
	42.3	320.0	7.71	0.730	0.821	0.822	0.791
	48.2	9.8	4.18	0.024	0.032	0.039	0.031
P5	46.6	9.5	4.29	0.023	0.027	0.034	0.028
	46.6	11.0	4.53	0.089	0.085	0.081	0.085

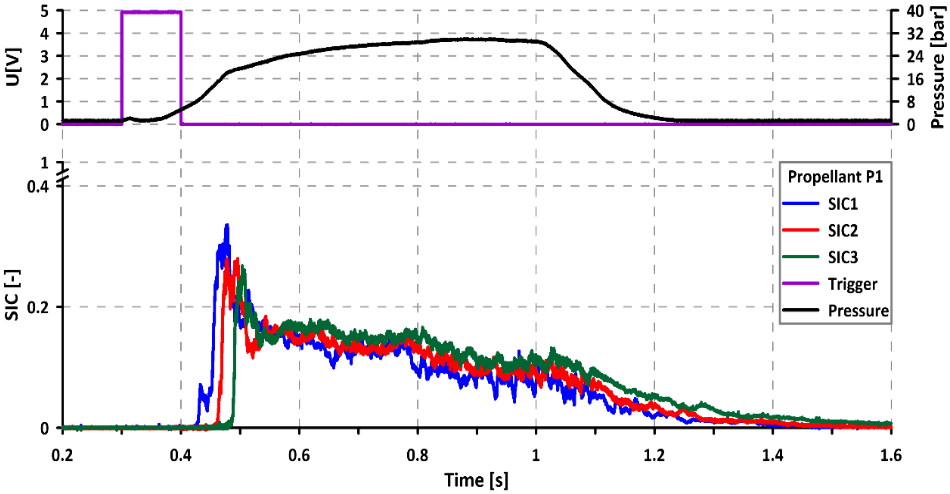

Fig. 7. Example trends of pressure, ignition unit trigger, and SIC acquired during combustion of test propellant P1 in the rocket micromotor at 30.4% RH

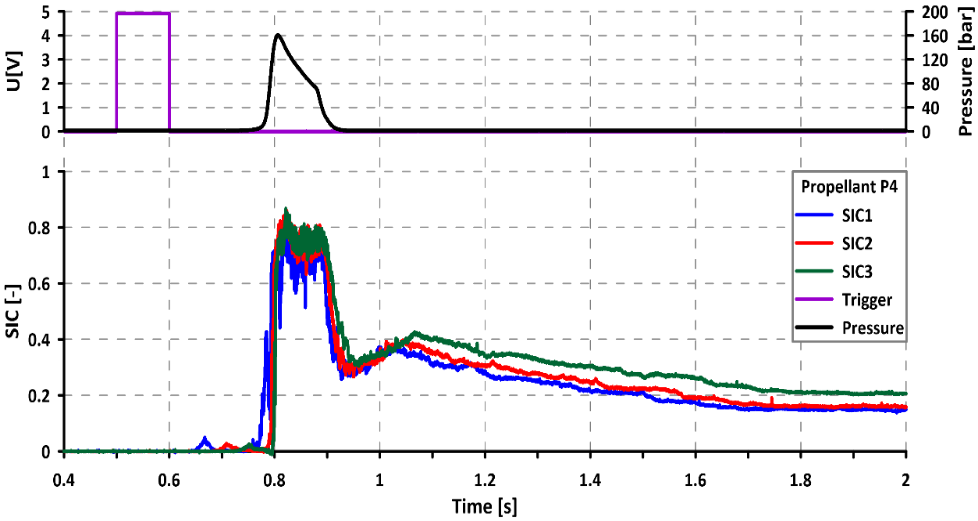

Fig. 8. Example trends of pressure, ignition unit trigger, and SIC acquired during combustion of test propellant P4 in the rocket micromotor at 45.7% RH

4. ANALYSIS OF EXPERIMENTAL TEST RESULTS

The experiments completed allowed a preliminary comparison of the SIC levels produced from the reference propellants and the novel propellant compositions under the qualification of low-smoke propellants. The SIC levels relative to RH for all tested propellants were shown in Fig. 9. The experiments done on black powder and the 80:20 AP/HTPB mix made it reasonable to conclude that the designed test stand enabled measurements of primary smoke levels, for the most part. The SIC levels acquired for both these reference propellants corresponded to the primary smoke classes calculated with reference to the AGARD report. The tests provided experimental proof that propellants with aluminium dust additives have high SIC levels. Propellant P4 (AP/GAP/Al) had a SIC only 20–30% lower than the SIC of black powder. A low SIC was demonstrated by propellant P5, where ammonium perchlorate (AP) was replaced with ammonium dinitramide (ADN).

There was no observable significant effect of the RH levels on the acquired SIC levels, even in the propellants with components that had a high condensation potential. A potential cause of there being no such relation could be local wetting (confined to the test chamber); the test stand will be modified in future work to achieve the expected RH level in the entire test room.

Propellant P2 produced wildly different SIC levels. The SIC levels in subsequent test runs were 0.080, 0.146, and 0.159. The authors suspect that the SIC measurement values were conditioned by a unique course of the propellant combustion process. The experimental tests on propellant P2 provided large disparities in the combustion chamber pressure trends.

Note the unique nature of propellant charge mass values and the maximum combustion chamber pressure levels; these could have had an effect on the measured SIC levels. The tests were performed on cuboid specimens prepared by cutting under laboratory conditions and inhibited along four lateral faces in a manual process. This propellant grain preparation drove the difference in the mass and the combustion surface areas in each test specimen. The planned ultimate tests will be done on an axially symmetrical, non-inhibited propellant grain to enable repeatability of the test propellant's specimen mass. Given the preliminary nature of the tests in the examples discussed here, only one experimental test run was performed for each of the different exhaust nozzle critical diameters, which resulted in varying levels of maximum pressure. The planned ultimate tests will feature experimental runs on the same critical diameter of the exhaust nozzle, to determine the repeatability of the combustion chamber pressure.

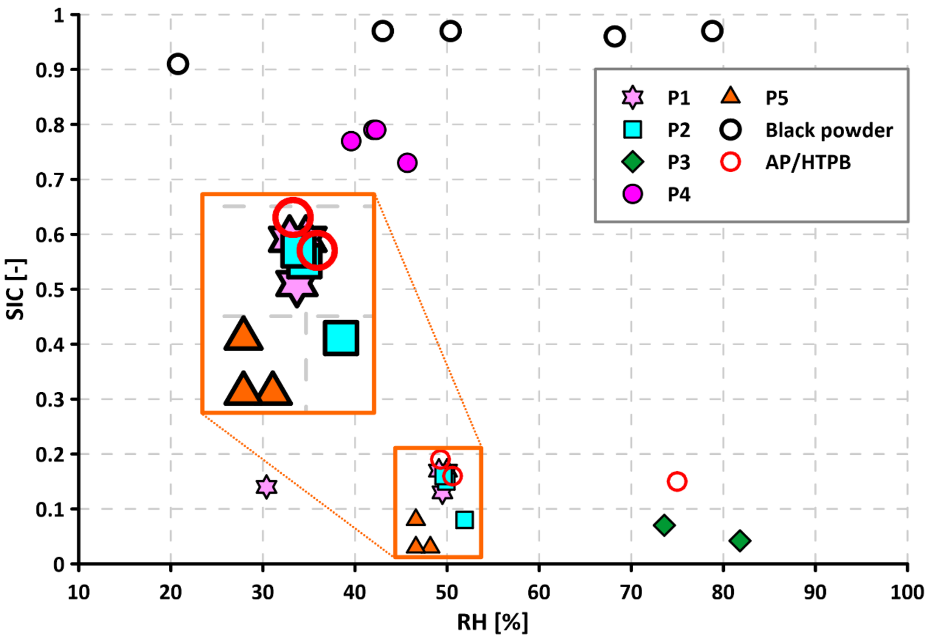

Fig. 9. SIC levels of the test propellants vs. RH

Each experimental burn was initiated with a black powder-charged ignition unit, which featured a high SIC. For the propellants with a short ignition time, the generated smoke passed through the measurement field before the smoke from the ignition unit cleared the field; this made interpreting the results difficult. The future solutions will focus on a different design of the ignition unit.

5. CONCLUSIONS

The tests completed made it possible to determine the SIC (smoke intensity coefficient) of a selection of propellants using a measurement method based on the scatter of a laser beam light by the combustion products.

The authors developed a dedicated test stand based on a laser-photodiode system that also featured RH monitoring and control. During the experiments, the SIC levels of two reference propellants were determined, black powder and an 80:20 AP/HTPB mix, along with five novel propellants based on compositions of AP/HTPB/HMX, AP/GAP/Al and ADN/GAP/HMX. The test results produced with the reference propellants proved that the SIC determined in the test method presented in this work largely described the primary smoke intensity level. The experiments on the test propellants allowed a preliminary determination of the impact of specific propellant components on the intensity of smoke generation (SIC). The future development of the test stand will feature tests using a different design of the propellant ignition unit, whereas RH will be conditioned throughout the entire room housing the test stand, and not only within the test chamber. The propellant specimens will be prepared in the form of an axially symmetrical, non-inhibited grain to achieve high repeatability of mass and combustion surface area. These changes to the test method should provide a more consistent burn in the rocket motor combustion chamber, which means a higher suitability of the SIC measurements using a laser-photodiode system for comparisons of the SIC between solid propellants.

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Opracowanie stałego rakietowego materiału pędnego o zmniejszonym dymieniu – badania intensywności dymienia z wykorzystaniem układu laser-fotodioda

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Streszczenie. Przeprowadzone prace miały na celu określenie poziomu intensywności dymienia wybranych stałych, rakietowych materiałów pędnych, opracowanych przy założeniu minimalizacji generowanego przez nie dymu. Stanowi to istotne zagadnienie w kontekście zastosowania opracowanego materiału pędnego o zmniejszonym dymieniu, np. w silniku marszowym pocisku rakietowego. Ograniczenie wytwarzania dymu może znacząco zmniejszyć możliwości wykrycia miejsca startu środków bojowych przez przeciwnika. Autorzy artykułu opracowali stanowisko badawcze umożliwiające otrzymanie wskazań intensywności dymienia rakietowych materiałów pędnych. Przygotowany system, oparty na rozpraszaniu wiązki światła laserowego w dymie, umożliwia pomiar intensywności dymienia m.in. w warunkach pracy silnika rakietowego. Zastosowano mikrosilnik rakietowy wraz z komorą badawczą układu pomiaru dymienia, umieszczoną tuż za wylotem z mikrosilnika, wyposażoną w trzy tory pomiarowe laser-fotodioda. Pomiary generowanego dymu podczas spalania prochu czarnego oraz standardowej mieszaniny HTPB z AP w stosunku 20-80 stanowiły poziomy odniesienia do porównania intensywności dymienia opracowanych materiałów pędnych. Autorzy określili intensywność dymienia materiałów pędnych opartych na zastosowaniu ADN, HTPB lub GAP oraz różnych dodatków. Otrzymane rezultaty pozwalają na porównywanie przebadanych materiałów oraz wyselekcjonowanie najlepszych pod kątem niskiej intensywności dymienia.
Słowa kluczowe: silnik rakietowy, stały materiał pędny, spalanie, dymienie, laser