Materiały Wysokoenergetyczne / High Energy Materials, **2024**, *16*: 55 − 64; DOI 10.22211/matwys/0251
ISSN 2083-0165

Research paper / Praca doświadczalna

The effect of using additive manufactured nozzle plugs on the ignition process
Wpływ zastosowania zatyczek dyszowych wykonanych w technologii addytywnej na proces zapłonu

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Abstract: *The selection of the nozzle plug and the appropriate quantity of an incendiary composition is an important step in modelling the ignition process of a solid propellant motor. The aim of the research discussed in this paper was to develop a nozzle plug which promotes adequate pressure in the combustor, while ensuring safety and simplicity of installation on the nozzle. The widespread availability of 3D printing technology has significantly simplified and reduced the cost of fabricating complex geometries. The authors designed and tested more than a dozen different snap-on nozzle plugs in order to investigate the effects of the material, the direction of printing, the shape and number of snaps, the smoothness of the printed surface, the composition of the incendiary composition and the use of an additional hold-down feature. Tests were carried out on two test rigs equipped with features imitating a rocket motor nozzle, pressure measurement, temperature measurement, and a propellant fixture. The tests showed that the printed nozzle plugs only allow effective ignition of the solid propellant with additional attachment features applied and an incendiary composition in the form of a mixture of black powder and smokeless powder. The research used a low-smoke propellant based on poly(glycidyl azide) for fuel and ammonium perchlorate as the oxidizer with the addition of octogen.*

Streszczenie: *Dobór zatyczki dyszowej oraz odpowiedniej ilości masy zapalającej stanowi istotny etap modelowania procesu zapłonu silnika na stały materiał pędny. Cel badań stanowiło opracowanie zatyczki pozwalającej na uzyskanie odpowiedniego ciśnienia w komorze spalania oraz zapewniającej bezpieczeństwo i prostotę montażu na dyszy. Szeroka dostępność technologii druku 3D znacząco uprościła i obniżyła koszty wykonywania nawet bardzo skomplikowanych* *geometrii. Autorzy pracy zaprojektowali i przetestowali kilkanaście różnych zatrzaskowych zatyczek dyszowych, badając wpływ materiału, kierunku druku, kształtu i liczby zatrzasków, stopnia wygładzenia powierzchni wydruku, składu masy zapalczej oraz zastosowania dodatkowego elementu dociskowego. Badania przeprowadzono na dwóch stanowiskach wyposażonych w element imitujący dyszę silnika, pomiar ciśnienia, pomiar temperatury i mocowanie materiału pędnego. Testy wykazały, że zatyczki drukowane pozwalają na skuteczny zapłon stałego materiały pędnego dopiero po zastosowaniu dodatkowych elementów dociskowych oraz masy zapalczej w postaci mieszaniny prochu czarnego z prochem bezdymnym. Do badań wykorzystano materiał pędny o zmniejszonej intensywności dymienia oparty na paliwie w postaci poli(azdyku glicydylu), utleniaczu chloranie(VII) amonu z dodatkiem oktogenu.*

Keywords: *rocket motor, solid propellant, nozzle plug*
Słowa kluczowe: *silnik rakietowy, stały materiał pędny, zatyczka dyszowa*

1. Introduction

Solid propellant rocket motors are a type of jet engine in which both the fuel and the oxidizer are in the solid phase and located directly in the combustor [1]. Due to the lack of moving parts, this design is characterized by simplicity, relatively low price, the longest possible storage time, and combat readiness, which means a short time between the decision to use a rocket motor propelled weapon and actual motor ignition [2]. All these characteristics make solid propellant rocket motors readily used in missiles for military applications [3]. Solid propellant motors do not require fuelling prior to launch, which significantly improves their combat capability, yet necessitates additional safeguards to prevent accidental launch during all logistical processes; in practice, this is achieved by arming the solid propellant missile as late as possible. A popular solution is to manage the combustion process so that the ignition starts from the nozzle, with the igniter itself being integrated into the rocket motor only at the last moment, before launch [4]. Depending on the type of nozzle plug used, the igniter can be integrated with or placed directly in the critical throat section of the jet nozzle.

The shape and installation method of the nozzle plug and its possible integration into the igniter depends on the motor size, manufacturing technology, the material of the nozzle plug, and the requirements for the combustion chamber's internal conditions during the ignition process [5]. The nozzle plug fulfills two fundamental functions: to protect the propellant grain from contaminants and external moisture during transport and storage and to provide a sufficiently high pressure over time to initiate fuel combustion with its oxidizer [6]. A very important parameter of nozzle plugs is their mechanical strength, which should be high enough to hold the pressure generated by the igniter but low enough to fail or be expelled once the rocket motor starts. Depending on the design of the motor, nozzle plugs can be screwed in, screwed on, pressed in, glued in, or held pressed by another component, while their separation from the motor can be achieved by bursting, pushing, or breaking the bond or joint [7, 8]. Controlled failure can occur to both the nozzle plug itself, and the motor jet nozzle, and it is important that this s occurs in a planned and reproducible manner. The authors considered it possible to use 3D printed components for nozzle plugs integrated with the igniter. The effects of 3D printing direction, surface smoothness, installation method, and ignition process sealing were studied experimentally. The context for the studies conducted was the research design of the Artemida generic rocket motor. The experiments were performed in the Department of Aircraft Engines laboratory at the Warsaw University of Technology, and the test rigs were designed so that the volume of the test combustion chamber corresponded to that of the test motor.

2. Research methodology and test rigs

To justify the considerations, it was necessary to determine the answers to the three main research questions:
1) Will a nozzle plug made by 3D printing fail reproducibly (at a comparable pressure of several bars)?
2) Will using an acrylonitrile-butadiene-styrene copolymer (ABS) component withstand the ignition process of the low explosive powder in the igniter (the component will not suffer from incineration)?
3) Will the designed component hold pressure in the test chamber long enough for the propellant to ignite?

To answer these questions, an experiment was planned in which a nozzle plug was installed on a component imitating a rocket motor nozzle. The resulting assembly was fitted into a steel combustion chamber with a volume equivalent to the dead volume of the Artemida missile motor. The test chamber was instrumented with a pressure sensor from Keller, type PAA-23, with a measuring range 0 to 200 bar.

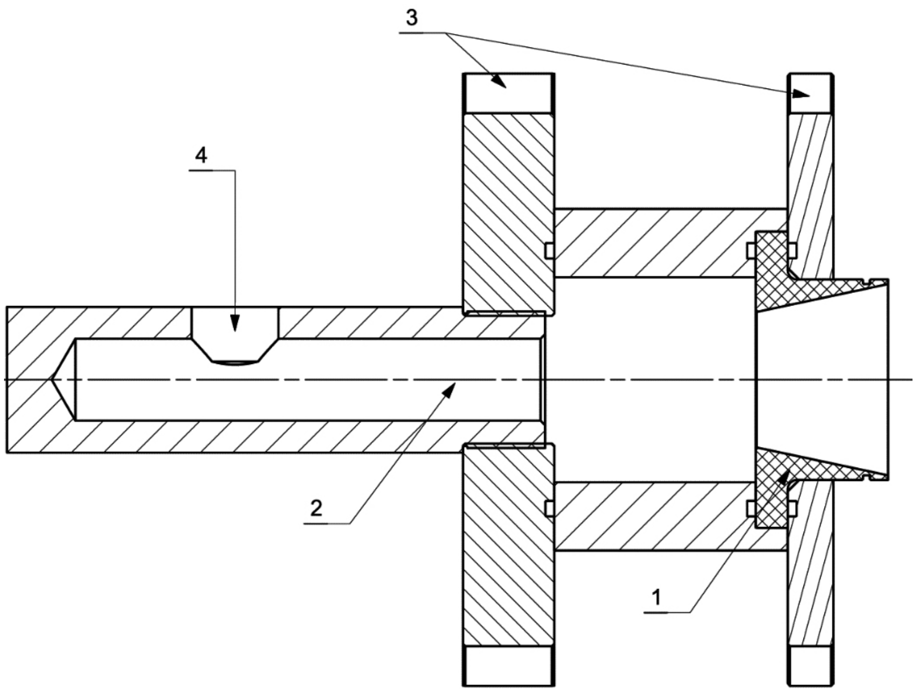


Figure 1. First test rig for pre-testing: 1 – mock-up nozzle, 2 – combustion chamber, 3 – restraints and 4 – pressure sensor connection

Due to safety concerns, it was decided that only the first two questions would be tackled initially (on test rig 1, see Figure 1), and only in further tests would a sample of the propellant be placed in the test combustion chamber (test rig 2, see Figure 2). To this end, the chamber was modified so that, in addition to the dead volume, it also corresponded in length to the motor of the Artemida missile. A cage, with space to accommodate the propellant, was provided at the end of the chamber. The test rig was also instrumented with three thermocouples, spaced equidistantly along the length of the chamber to monitor the reach of the flame by measuring the temperature.

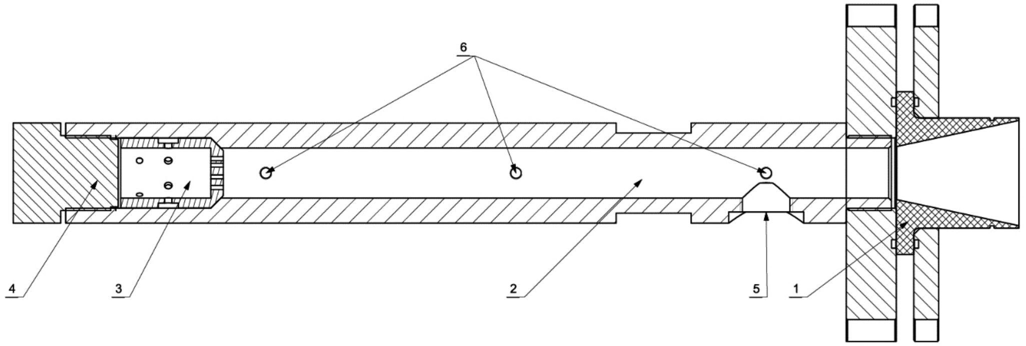


Figure 2. Second test rig for propellant tests: 1 – mock-up nozzle, 2 – combustion chamber, 3 – propellant cage, 4 – combustor plug, 5 – pressure sensor connection, and 6 – thermocouple connections

Initially, the mock-up nozzle was made of a material corresponding to the actual component, namely cotton-phenolic laminate (textolite). Initial tests revealed that the snap-in component failed much more quickly, so to increase the number of tests per nozzle, the textile component was replaced with an aluminum equivalent. In addition to the prepared chamber, the test rig included an exhaust hood, a National Instruments USB 6259 measurement interface card, a computer for data acquisition and preliminary analysis of results, and a Photron SA 1 high-speed camera recording the progress of the experiment at 2,000 frames per second (fps).

3. Nozzle plug versions tested

To decouple the strength of the nozzle plug from the unique adhesively bonded joints, it was decided that the installation would be retained by snap fasteners. A small groove was fabricated on the nozzle component, and the nozzle plug was fitted with snap locks, which facilitated the simple pushing of the plug into its seating. An integral part of the nozzle plug was the igniter, a powder chamber with holes to allow the wires from the primer (Figure 3).

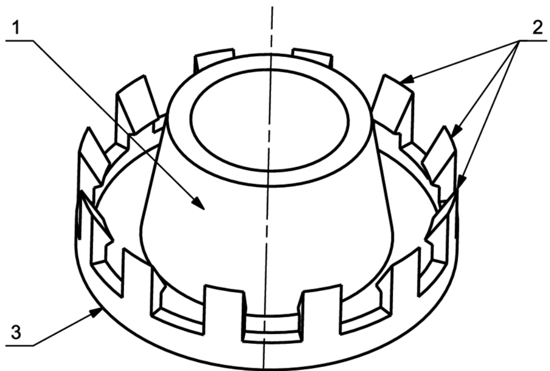
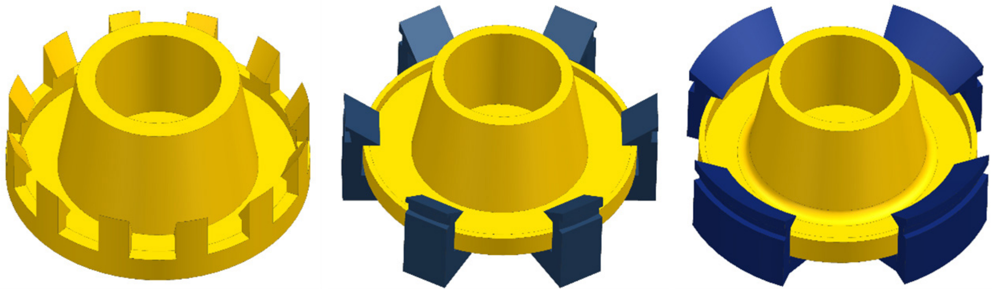


Figure 3. Components of a nozzle plug fabricated by 3D printing: 1 – low-explosive powder chamber, 2 – snap locks on the nozzle, and 3 – nozzle plug bottom

Initially, it was assumed that the nozzle plug, together with the snap locks and low-explosive powder chamber, would be fabricated as a single component; however, the first tests highlighted a difference in the strength of the 3D-printed components, which depended on the direction of printing. Thus, it was decided to split the component into a separately printed nozzle plug which featured a chamber and pairs of snap locks (Figure 4).



(a) (b) (c)

Figure 4. The three main versions of the nozzle plug fabricated by 3D printing: version 1: one-piece nozzle plug (a), version 2: split nozzle plug with three pairs of snap locks (b) and version 3: split nozzle plug with two pairs of snap locks (c)

In addition to the three main nozzle plug versions, the effect of the following factors was investigated:

- Direction of printing: tests were carried out on version 1 nozzle plugs printed flat (on the nozzle plug bottom) or at 45° and 90°.
- 3D printed material ABS (acrylonitrile-butadiene-styrene), nylon and PETG (polyethylene terephthalate glycol, modified) enhanced with carbon fibre.
- Surface smoothing (for nozzle plugs made of ABS).
- Powder used: black or single-base, smokeless powder, designation WT 104 (in appropriate proportions).
- Snap lock shape: chamfered on one side, on both sides or without chamfering.
- Location of the nozzle groove: 4 or 10 mm from the nozzle exit.
- Thickness of the nozzle plug bottom and the snap locks.
- Sealing type: butt or piston.
- Additional restraining features: clamping ring or strap.

In the experiments, a mining primer manufactured by Nitroerg S.A. in 0.2 A or 1 A safe current versions was used to initiate the ignition of the powder igniter, while the powder chamber was sealed with 50 µm thick copper foil to prevent powder spillage during assembly.

3. Experimental tests

The first series of experimental tests was conducted for version 1 nozzle plugs, printed with ABS using Fused Deposition Modelling (FDM). Successive layers were applied with a zero printing angle, i.e. perpendicular to the nozzle plug bottom. The tests demonstrated the 3D printed structure's ability to withstand high temperatures over a short period of time. In all tests, the powder chamber was only superficially charred, but no melting was found. It was decided that the ABS structure met the basic requirements, and testing could continue. Examples of the results obtained on the first test rig are shown in Figure 5.

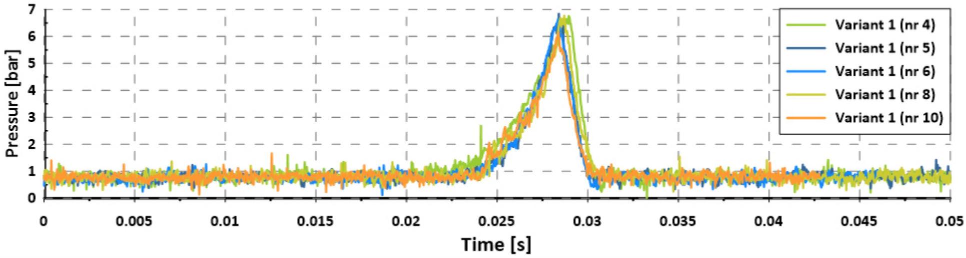


Figure 5. Repeatability tests (for 5 test runs) of pressure trends for version 1 nozzle plugs (printing angle 0°, material: ABS)

The 3D printed nozzle plug was characterized by a highly reproducible mechanical strength, not only in terms of the maximum pressure attained in the combustion chamber but also in terms of its failure mode. In each test run, this version failed by bursting at the join between successive additively deposited layers at the transition between the bottom and the snap locks (Figure 6). Moreover, the effect of smoothing on the mechanical strength was investigated on selected samples in this test series. As no correlation with mechanical strength was found, this process was abandoned.

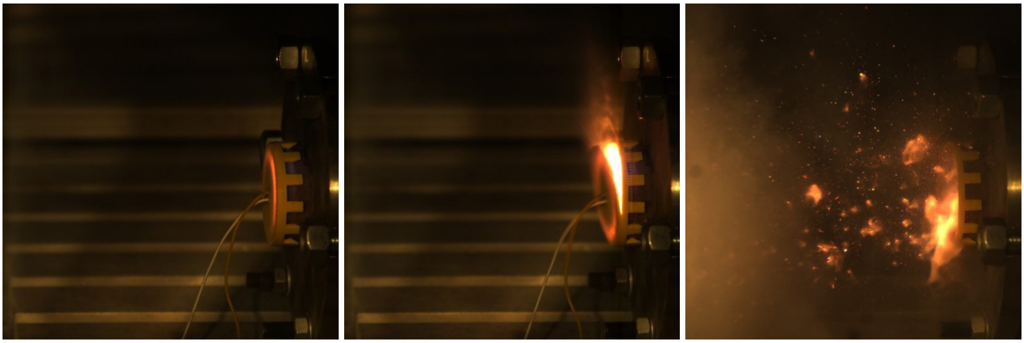


Figure 6. Consecutive still frames from the high-speed camera video recorded during experimental test #6

Increasing the thickness of the nozzle plug bottom and snap locks, further increased the nozzle plug's rigidity, becoming more brittle and more difficult to install. It was found that even the slightest misalignment of the force applied to engage the snap locks over the jet nozzle, compromises the snap lock strength. This resulted in faster breaking of the affected snap locks, followed by the nozzle plug being tilted to the side and the remaining snap locks breaking and separating at a pressure between 4 and 5 bar.

The failure mode observed prompted the authors to increase the maximum attained pressure levels; in the second test series, the 3D printing settings were modified to deposit the nozzle plug bottom at 45° to the build surface. On removal of the supports, items exhibited a much poorer quality of surface finish and structure. The concerns about the 3D print quality were confirmed in experimental tests – the nozzle plugs printed obliquely at 45° were characterized by a very large scatter in maximum chamber pressure (Figure 7).

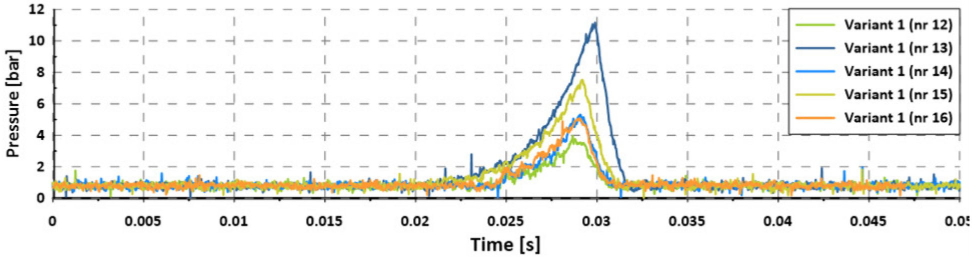


Figure 7. Pressure trend repeatability testing on version 1 nozzle plugs (printing angle 45°, material: ABS)

In the last test series of the version 1 nozzle plugs, it was decided to change the 3D print material. Prototypes were considered and fabricated from two alternative materials: (1) PETG reinforced with carbon fiber and (2) nylon. The former proved too brittle and the snap locks broke when attachment to the nozzle was attempted, so no single experiment was successfully carried out with this material. The plugs made of nylon were characterized by flexibility, which allowed the snap locks to slide free from the nozzle instead of breaking (Figure 8).

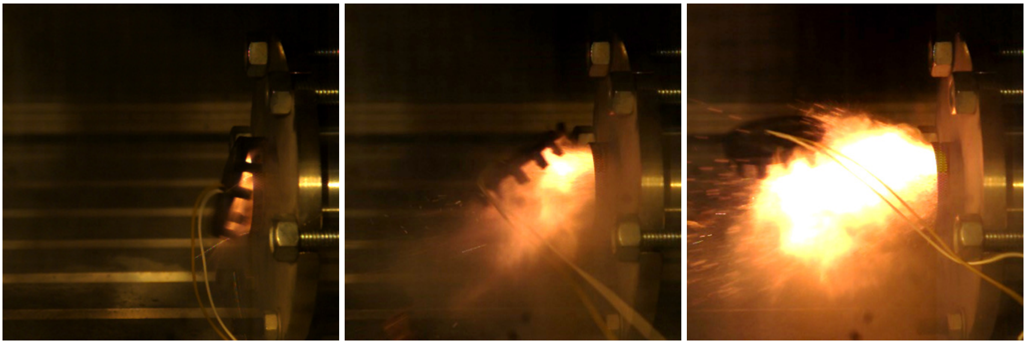


Figure 8. Consecutive still frames from the high-speed camera video recorded during experimental test #2 (version 1 nozzle plug, material: nylon)

Despite the low maximum pressure values attained (Figure 9), it was decided to continue testing nylon nozzle plugs made in other forms.

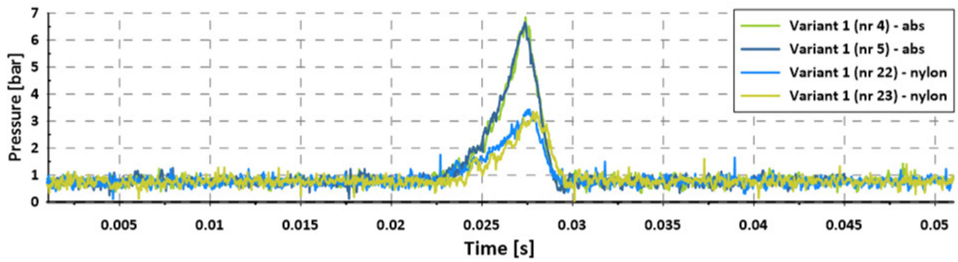


Figure 9. Comparison of pressure trends for different materials (ABS and nylon) for the version 1 nozzle plugs.

The fourth test series was per formed on version 2 nozzle plugs, which meant the plug bottom and chamber assembly printed separately to the three pairs of snap locks. The effect of an additional restraining feature and the shape of the snap lock on the maximum pressures produced in the chamber, was tested. The restraint formed by a clamping strip nearly doubled the failure strength of the plug. During the tests, the chamber opened with one pair of the snap locks breaking off, followed by detachment of the remaining pairs. In addition, the effect of changing the shape of the snap lock on its strength was tested with version 2 plugs. The absence of a chamfer on the snap lock engaging the nozzle groove made installation more difficult while forcing the pair of snap locks to be bent away more severely, resulting in micro-damage and a reduction in mechanical strength (Figure 10) Only plugs printed from nylon were tested in this series.

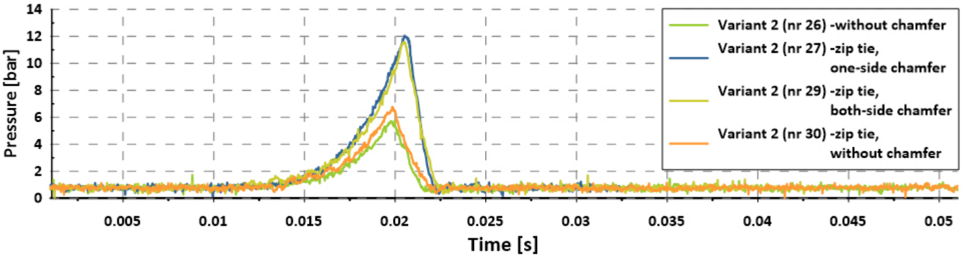


Figure 10. Comparison of pressure trends for different shapes of the snap locks and the application of a hold-down feature in version 2 nozzle plugs

Version 2 of the plugs with the additional restraining feature met the minimum requirements for mechanical strength and repeatability, yet because of the large number of components, it was decided to reduce the number of snap lock pairs from three to two in further tests (performed on version 3). This allowed the width of individual snap locks to be increased. The fifth test series was performed on the second test rig where, in addition to the pressure trends, the firing efficiency of the igniter composition placed in the combustor was tested. This was a low-smoke propellant based on poly(glycidyl azide) for fuel and ammonium perchlorate as the oxidizer with added octogen. Due to the lack of ignition in the first tests, the igniter composition was changed. A total of five versions were tested: black powder, WT 104 smokeless powder, and a mixture of both in the following proportions: 1:1, 2:3, and 1:4 (Figure 11). The propellant was ignited using a mixture of the low explosive powders (Figure 12).

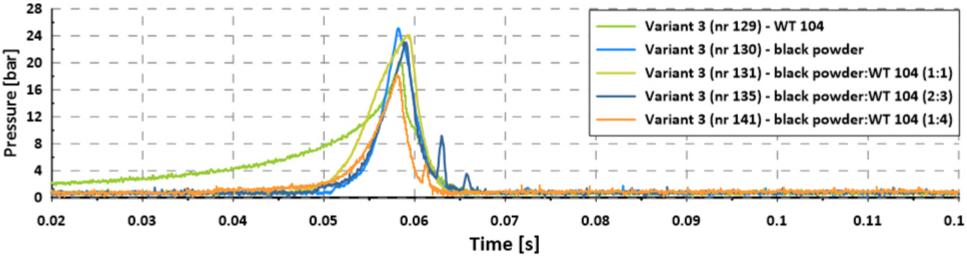


Figure 11. Comparison of pressure trends for different LE powder mixtures in version 3 nozzle plugs

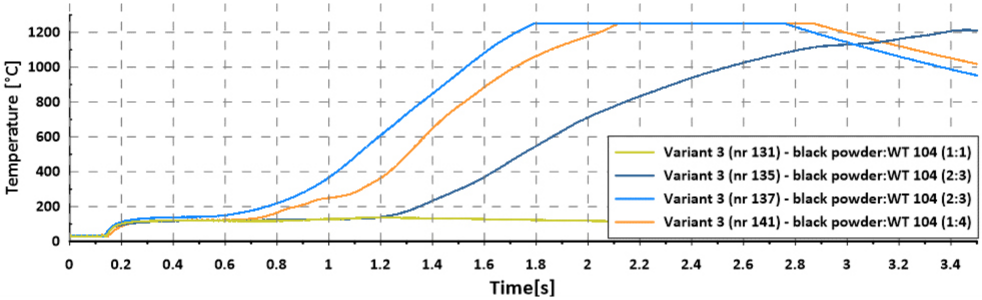


Figure 12. Comparison of temperature trends for different LE powder mixtures in version 3 nozzle plugs

4. Conclusions

- The study conducted aimed to develop a nozzle plug integrated into the igniter for the Artemida test platform rocket motor. It was accepted that these plugs would be made by 3D printing, with ABS, carbon fiber-reinforced PETG, and nylon as potential materials. From the outset, the fastening method was determined as a snap lock engaging a dedicated groove on the nozzle component. Modifications were made to the shape and number of snap locks, the direction of printing, and the thickness of the individual components.
- An important part of the work was selecting the low explosive igniter mixture, i.e. the correct proportions of black powder to smokeless powder. A dozen different nozzle plugs and six powder mixtures were tested, and two test rigs were built. The first few dozen experimental tests were performed on a simplified test rig, instrumented only with a chamber pressure gauge, to determine the maximum strength of the 3D printed plugs and the results' reproducibility. The final series of tests were performed on a modified test rig whose length corresponded to that of the Artemida rocket motor. The modified test rig was instrumented with pressure sensors and a propellant cage.
- The research identified the most important parameters affecting the strength of 3D printed components. It was found that the best strength of FDM components was achieved along the composite layers, meaning it is optimal to print the powder chamber nozzle plug (with the bottom parallel to the build surface) separately from the snap locks (printed perpendicular to the build surface). Not much difference in strength was noted between the three pairs of smaller snap locks and two pairs of wider ones, so for ergonomic reasons (fewer fasteners) the second solution with two pairs was chosen. Other parameters that had a significant impact on the installation possibilities were the thickness (optimally 2 mm) and the shape of the snap locks: a single-sided chamfer that allowed easy sliding for engagement and made it difficult for the snap locks to separate from the groove, proved to be the best. Two of the three materials tested, nylon and ABS, can be successfully used as the material for 3D printed nozzle plugs. Regardless of the material used, an additional restraining feature significantly improved the strength of the structure. However, no effect of the surface smoothing or sealing method was observed on the nozzle plug strength. The best plug selected was the one in version 3, with two pairs of snap locks 1/8 of a circle wide, or about 20 mm, with a seating groove 10 mm from the nozzle exit. For the selected geometry, a pressure of approximately 20 bar was achieved in the combustion chamber.
- From the point of view of mechanical strength, snap-in nozzle plugs made by 3D printing can provide an alternative to classic threaded solutions. Their disadvantage, however, is the large number of components, which makes assembly difficult. In further developing this solution, it is necessary to consider the speed of integration into the missile, for example, by using an adhesively bonded connection of separately 3D printed components.

Acknowledgments

The research was funded by the National Centre for Research and Development (NCBiR) under the SZAFIR 1 Program, "Development of a rocket motor based on unconventional fuel with reduced smoke and high specific thrust", Contract No. DOB-SZAFIR/03/B/001/01/2021.

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Received: October 24, 2024
Revised: December 16, 2024
First published on line: December 20, 2024