ADVANCED TECHNOLOGIES AND MATERIALS VOL. 51, NO.1 (2026), 19 - 23
DOI: 10.24867/ATM-2026-1-003

1. Received: 03 April 2026
2. Revised: 22 April 2026
3. Accepted: 17 May 2026

Advanced Technologies & Materials

http://journal-atm.org
ISSN: 2620-0325 (print), ISSN: 2620-147X (online)

Original research article

Modeling and Additive Manufacturing of a Rocket Engine Nozzle for Micro-rocket Applications

Tomasz Dziubek,[*] , Grzegorz Budzik, , Bartłomiej Sobolewski , Łukasz Kochmański

Rzeszow University Of Technology, Faculty of Mechanical Engineering and Aeronautics, Al. Powstańców Warszawy 12, 35-959 Rzeszów, Poland

ABSTRACT

The paper presents the process of modeling a rocket engine nozzle and the manufacturing method of a nozzle intended for use in micro-rocket propulsion systems. The proposed design–technological solution enables the fabrication of a rocket engine component with reduced mass through the application of a structure that allows optimization of the cooling process during flight. Designs incorporating conformal cooling channels make it possible to reduce weight while maintaining high performance, equal to or at least comparable with that of conventionally used designs manufactured using traditional subtractive methods. The presented solution is based on additive manufacturing technologies.

Key words: *3D-CAD modeling, additive manufacturing, rocket engine nozzle, conformal cooling, micro-rockets*

1. INTRODUCTION

The current geopolitical situation, both in Europe and worldwide, highlights the need to seek new and cost-effective design and technological solutions. This is particularly relevant to the manufacturing of components for micro-rocket engines. The development of such solutions and their implementation in counter-drone systems—currently posing a significant threat—is economically justified. The production of more affordable alternatives, as compared to complex missile systems, may enhance defense capabilities while minimizing expenditures on armaments. Micro-rockets, as an alternative means of anti-drone defense, may operate either through direct impact on aerial targets or in the form of decoys. Regardless of the application, it is essential to develop an engine design that ensures both reliability and the required flight performance parameters. One of the key components of such an engine is the nozzle. Therefore, minimizing the thermal impact on the applied components, as well as reducing the mass of the propulsion system, is of critical importance [1]. The use of advanced CAD modeling systems in combination with additive manufacturing technologies provides such opportunities [2, 3]. This synergy enables the production of engine components with reduced reliance on complex and costly tooling, as well as a minimized number of manufacturing operations. At the same time, the limitations associated with geometric complexity are significantly reduced, which, in the case of conventional subtractive manufacturing methods, impose considerable technological constraints.

This article presents the possibilities of modeling and manufacturing the geometry of a micro-rocket engine nozzle demonstrator equipped with cooling channels. The developed variants include both closed-loop and open-loop cooling systems.

The conducted study includes an analysis of the feasibility of manufacturing complex geometries of the test model using PolyJet additive manufacturing technology. The evaluation and interpretation of the obtained results focus not only on the influence of the developed geometry on

* *Corresponding author's.e-mail: tdziubek@prz.edu.pl*
Published by the University of Novi Sad, Faculty of Technical Sciences, Novi Sad, Serbia.

manufacturability, but also demonstrate the potential applicability of such solutions, particularly in the defense industry. The performed tests, based on the developed geometry, provide a foundation for further research on the feasibility of manufacturing such components using additive techniques, for example those based on selective metal powder sintering [4–7].

2. RESEARCH PROBLEM

The subject of this study is a micro-rocket engine nozzle and its manufacturing method for application in micro-rockets [1]. The proposed solution constitutes a design and technological approach enabling the production of a rocket engine component with reduced mass through the application of a structure that optimizes the cooling process during flight. A design incorporating conformal channels allows for weight reduction while maintaining high—or at least comparable—dimensional and geometric accuracy relative to conventionally used designs and traditional subtractive manufacturing methods (Fig. 1). The presented solution is based on additive manufacturing technologies and was fabricated using the PolyJet method with RGD720 photopolymer resin as a demonstrator material. Future work includes attempts to implement the manufacturing process using selective metal powder sintering or other additive manufacturing methods and materials [2, 8–10].
The primary objective of this study was to assess the manufacturability of the developed nozzle geometry using the selected fabrication technology. In addition, the study includes:

- defining the geometric assumptions of the nozzle and performing the modeling process in two variants,
- developing the nozzle demonstrator geometry in a manner that enables visualization of the interior of conformal channels,
- preparing and executing the manufacturing process.

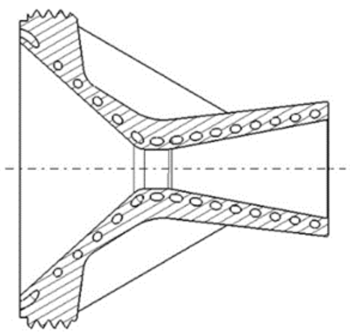

Fig. 1 *Rocket engine nozzle with cooling channels*

The application of additive manufacturing enables the production of complex nozzle geometries (Fig. 2), incorporating cooling channels (Ø1.6 mm) in two variants (closed-loop and open-loop systems), as well as threaded mounting geometry (Fig. 3), within a single manufacturing operation while maintaining high dimensional and geometric accuracy resulting from the adopted method [11]. For such components, it is possible to achieve the required dimensional accuracy [5, 12] and to manufacture finished parts without the need for additional machining or with its significant reduction.
When using conventional manufacturing methods for rocket engine nozzles, limitations arise from subtractive processes due to the inability to introduce tools into the internal walls of the nozzle geometry in order to create complex cooling channels and remove excess material. Classical approaches require the use of complex casting molds and technologically demanding casting processes. In the proposed method, this problem is addressed by incorporating openings sized to enable the removal of unbonded material from the nozzle walls. The material removal process may be carried out either by gravity or using a pressurized medium.

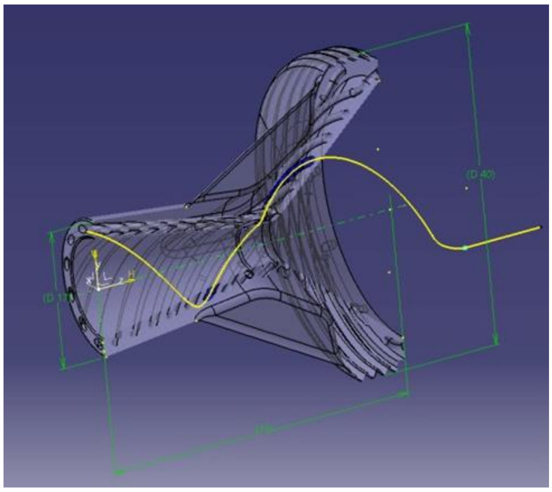

Fig. 2 *Basic dimensional data*

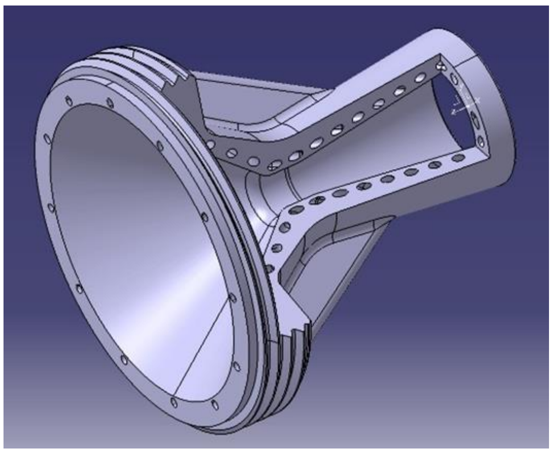

Fig. 3 *Nozzle geometry illustrating mass reduction, cooling capability, and connection to the engine body*

3. CHARACTERISTICS OF THE DESIGN AND TECHNOLOGICAL SOLUTION

In conventional design and manufacturing approaches, cooling channels and mass reduction are achieved by removing material from the nozzle wall using complex casting molds, typically produced as a monolithic structure together with the engine body. This process requires additional operations related to mold removal and finishing. Moreover, it limits the possibility of implementing more complex cooling channel geometries, which could significantly improve cooling efficiency. Conventional manufacturing methods are therefore constrained by the inability to remove material from within the nozzle walls while maintaining dimensional and geometric accuracy without resorting to complex manufacturing processes. In the proposed solution, two types of cooling systems were adopted: open-loop (Fig. 4) and closed-loop (Fig. 5).

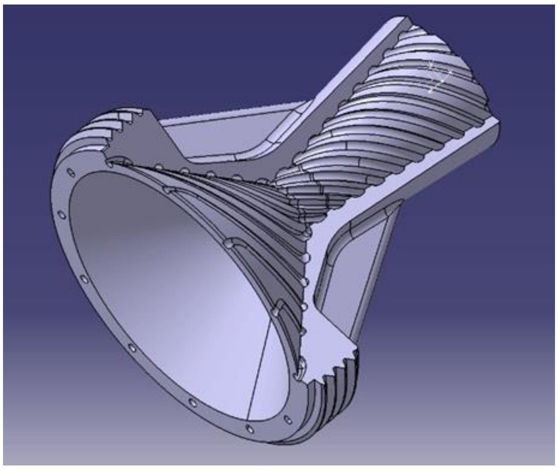

Fig. 4 *Cooling channels in an open-loop system*

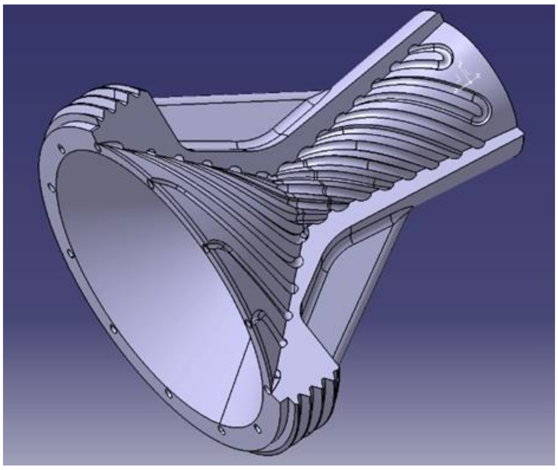

Fig. 5 *Cooling channels in a closed-loop system*

To enable the removal of excess powder from the interior of the cooling channels—thereby reducing mass while improving thermal performance—the geometry was designed to allow powder evacuation through channels integrated into the nozzle walls. Additive manufacturing technologies inherently support such capabilities, both for powder-based processes and for techniques such as FDM and PolyJet, through the removal of support material [8]. Additionally, the nozzle geometry incorporates structural reinforcement in the form of ribs, increasing stiffness and enabling a reduction in wall thickness. Compared to commonly used solutions, this allows for mass reduction while maintaining stiffness and dimensional accuracy (Figs. 4 and 6). At the current stage, topological optimization has not been performed but is planned as part of future work.

Subtractive manufacturing methods allow for a certain degree of mass reduction and the creation of relatively simple conformal channels; however, compared to the proposed geometry (Figs. 6 and 7), they result in thicker walls and lower cooling efficiency. In the case of an open-loop cooling system (Fig. 6), it is possible to induce autorotation of the rocket, thereby stabilizing its flight trajectory. This effect can be achieved through appropriately designed conformal channel geometry.

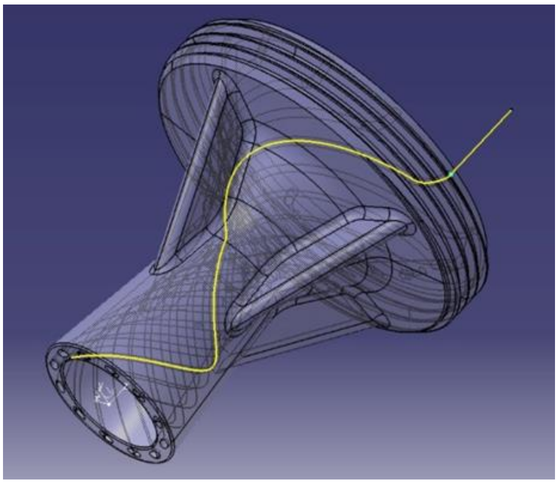

Fig. 6 *Geometry of conformal channels (open-loop) and structural reinforcement elements*

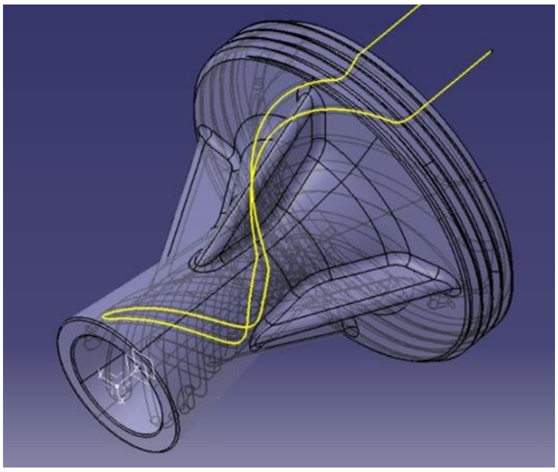

Fig. 7 *Geometry of conformal channels (closed-loop) and structural reinforcement elements*

An additional advantage of the proposed solution is the possibility of manufacturing threaded connections between the nozzle and the engine body using additive techniques, eliminating or significantly reducing the need for subtractive machining. This enables precise alignment of cooling channels between the nozzle and the engine body without requiring monolithic fabrication, thereby ensuring continuity of coolant flow.

4. FABRICATION OF TEST MODELS

To evaluate the manufacturability of the developed nozzle geometry, test models were fabricated using additive manufacturing. Prior to fabrication, the models were converted into STL format with a tessellation accuracy of 0.005 mm [13, 14]. An example of the generated STL model is shown in Fig. 8. The demonstrator models were manufactured using the PolyJet process, a layer-by-layer photopolymer jetting technology.

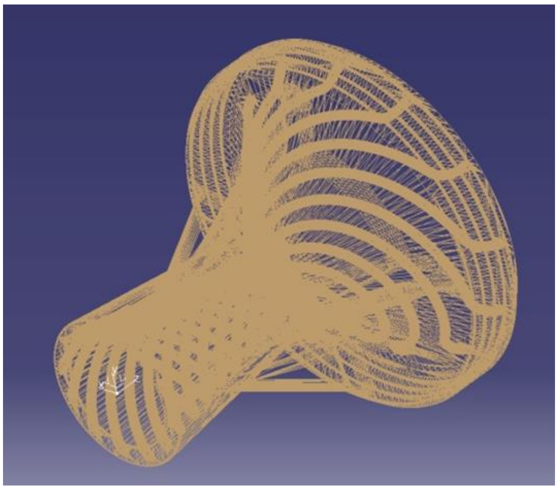

Fig. 8 *Example of the nozzle geometry after STL tessellation*

The process was carried out using an EDEN 260V printer (Objet), with a native resolution of 600 dpi in the X and Y axes and 1600 dpi in the Z axis [16]. Process preparation included importing the model geometry and performing standard setup procedures (Fig. 9). The demonstrator models were fabricated using a layer thickness of 16 µm and RGD720 photopolymer resin as the printing material [17]. The manufacturer's material data are presented in Fig. 10, while the manufacturing process is illustrated in Fig. 11

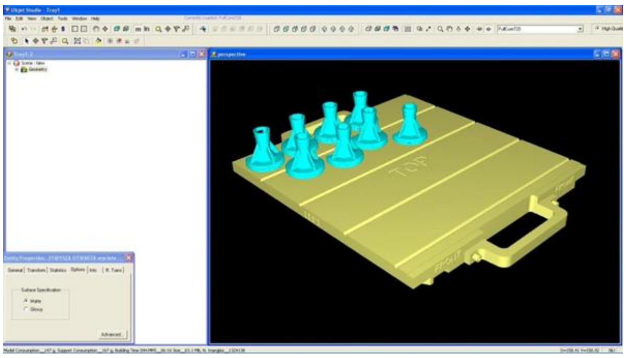

Fig. 9 *Import of the STL model and process setup*

After fabrication, the models underwent post-processing involving the removal of support material. This step consisted of standard cleaning procedures, primarily using a pressurized water jet. The key objective was to verify the feasibility of removing support material from the conformal channels. Mechanical assistance was also applied using flexible fiberglass wires with diameters of Ø0.8 mm and Ø1 mm.

The results confirmed that the adopted process assumptions are feasible. Despite the complexity of the cooling channel geometry, effective cleaning was achieved. The final results are shown in Fig. 12.

PRIMARY MATERIAL: RGD720 (Transparent)
SECONDARY MATERIAL: TangoBlack™ (FLX973)

Property	ASTM	Units	RGD7210-DM	RGD7220-DM	RGD7230-DM
Tensile strength	D-638-03	MPa	50-55	50-55	45-50
Elongation at break	D-638-05	%	15-25	15-25	15-25
Modulus of elasticity	D-638-04	MPa	2200-2500	2000-2300	1700-2000
Flexural strength	D-790-03	MPa	80-90	75-85	70-80
Flexural modulus	D-790-04	MPa	2300-2700	2200-2600	2100-2400
HDT, oC @ 0.45MPa	D-648-06	°C	45-50	45-50	45-50
Izod notched impact	D-256-06	J/m	20-30	20-30	20-30

***Fig. 10** Material data for RGD720 [17]*

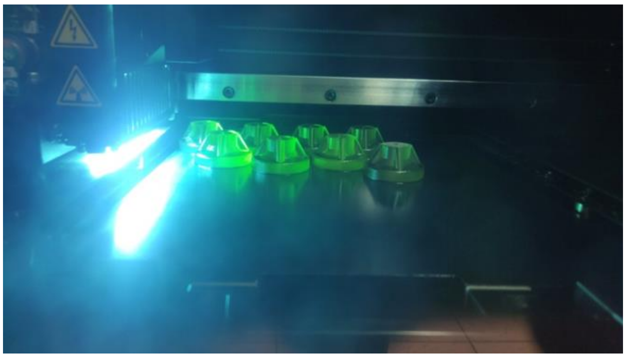

***Fig. 11** Fabrication of the nozzle demonstrators*

***Fig. 12** Fabricated nozzle demonstrators after support material removal*

5. CONCLUSIONS

The methodology presented in this study demonstrates that the proposed solution enables the fabrication of the nozzle as a separate component, unlike conventional additive manufacturing approaches in which it is produced integrally with the engine body. This allows for the use of different materials for the nozzle, engine body, and other components, thereby enabling the testing of hybrid material solutions.

The proposed approach may positively influence the thermal performance of the rocket engine and improve its operational durability by enabling more advanced cooling channel geometries. The solution incorporates spiral channels in both open-loop and closed-loop cooling systems. A key advantage is the feasibility of manufacturing closed-loop cooling systems, which are difficult to achieve using conventional technologies.

The integration of additive manufacturing with parametric CAD modeling enables rapid modification of geometry without the need for producing costly and complex casting molds. This significantly broadens the scope for design optimization and facilitates the development of highly efficient structural solutions.

An additional advantage of the open-loop cooling system is the possibility of inducing autorotation in the micro-rocket through the ejection of the cooling medium. This effect, achieved through spiral conformal channel geometry, may contribute to stabilizing the flight trajectory and improving accuracy.

The conducted research confirms the validity of the proposed design and technological assumptions and provides a basis for further research and development. Future work will include topological optimization and verification of dimensional and geometric accuracy.

REFERENCES

[1] Torecki, S. (1984), Silniki rakietowe, Wydawnictwa Komunikacji i Łączności, Warszawa.

[2] Kozik, B., Budzik, G., Dziubek, T., Bernaczek, J., Przeszłowski, Ł., Markowska, O., Rzucidło, A., Rokicki, P. (2016). Manufacturing of aircraft engine transmission gear with SLS (DMLS) method. *Aircraft Engineering and Aerospace Technology: An International Journal*, 88 (3), 397 - 403.

[3] Turek, P., Bazan, A., Budzik, G., Dziubek, T., Przeszlowski, L. (2024). Evaluation of Macro- and Micro-Geometry of Models Made of Photopolymer Resins Using the PolyJet Method. *Materials*, 17, 4315.

[4] Zafar, M.Q.; Sajjad, R.; Anwar, M.T.; Mustafa, M.S.; Husnain, N.; Aqeel, A.B.; Khan, M.B. (2025). A review on metal additive manufacturing-types, applications and future trends. *Recent Progress in Materials*, 7, 1–24.

[5] Budzik, G., Woźniak, J., Paszkiewicz, A., Przeszłowski, Ł., Dziubek, T., Dębski, M. (2021). Methodology for the quality control process of additive manufacturing products made of polymer materials. *Materials*, 14. https://doi.org/10.3390/ma14092202.

[6] Gibson, I., Rosen, D., Stucker, B., Khorasani, M. (2021). *Materials for additive manufacturing.* In Additive Manufacturing Technologies; Springer: Cham, Switzerland, 379–428. https://doi.org/10.1007/978-3-030-56127-7_14.

[7] Yehia, H.M., Hamada, A., Sebaey, T.A., Abd-Elaziem, W. (2024). Selective laser sintering of polymers: Process parameters, machine learning approaches, and future directions. *Journal of Manufacturing and Materials Processing*, 8, 197.

[8] Budzik, G., Dziubek, T., Przeszłowski, Ł.P., Sobolewski, B., Dębski, M., Gontarz, M.E. (2022). Study of unidirectional torsion of samples with different internal structures manufactured in the MEX process. *Rapid Prototyping Journal*, 29 (8), 1604-1619. https://doi.org/10.1108/RPJ-09-2022-0332.

[9] Fuwen, H., Mikolajczyk, T., Pimenov, D.Y., Gupta, M.K. (2021). Extrusion-based 3D printing of ceramic pastes: Mathematical modelling and in situ shaping retention approach. *Materials*, 14, 1137. https://doi.org/10.3390/MA14051137.

[10] ISO/ASTM 52921-13 (2019). *Standard Terminology for Additive Manufacturing-Coordinate Systems and Test Methodologies*.

[11] Dziubek, T., Budzik, G., Kawalec, A., Dębski, M., Turek, P., Oleksy, M., Paszkiewicz, A., Poliński, P., Kochmański, Ł., Kiełbicki, M., Józwik, J., Kuric, I., Cebulski, J. (2020). Strength of threaded connections additively produced from polymeric materials. *Polimery*, 67(6), 261-270. https://doi.org/10.14314/polimery.2022.6.4.

[12] Turner, B.N., Gold, S.A. (2015). Are view of melt extrusion additive manufacturing processes: II. Materials, dimensional accuracy, and surface roughness. *Rapid Prototyping Journal*, 21, 250–261. https://doi.org/10.1108/RPJ-02-2013-0017.

[13] ISO/ASTM 52900:2021: *Additive Manufacturing—General Principles—Fundamentals and Vocabulary*, ISO: Geneva, Switzerland.

[14] ISO/ASTM 52910:2018: *Additive Manufacturing—Design—Requirements, Guidelines and Recommendations*, ISO: Geneva, Switzerland.

[15] Wohlers, T. (2025). *Wohlers Report 2025: 3D Printing and Additive Manufacturing Global State of the Industry*, Wohlers Associates: Fort Collins, CO, USA.

[16] https://support.stratasys.com/en/Printers/PolyJet-Legacy/Eden260V-VS (accessed on 25 March 2026).

[17] https://www.stratasys.com/en/materials/materials-catalog/polyjet-materials/rgd720/ (accessed on 25 March 2026).