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Multi-Stream Nozzle Apparatus for Advanced Energy-Efficient Jet Devices and Systems

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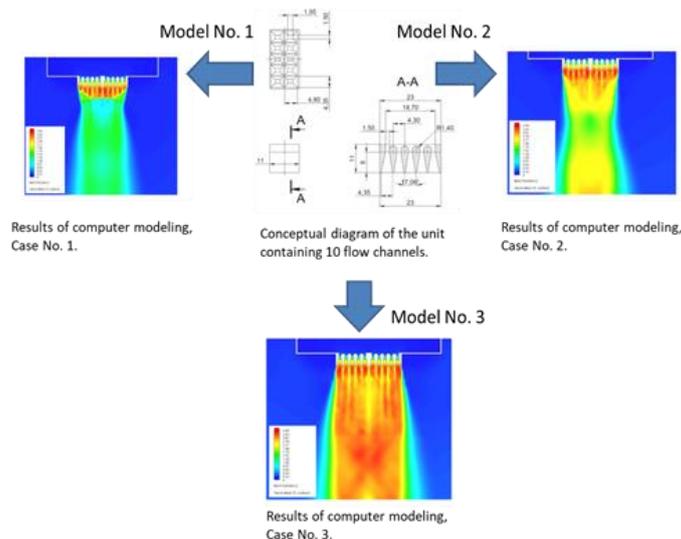[b] Empress Catherine II St. Petersburg Mining University, Saint Petersburg, Russia

A B S T R A C T

This paper aims to carry out interdisciplinary research within an emerging scientific field focused on thrust vector control over a full spherical geometry, where the thrust vector can be deflected continuously through a complete angular range of ±180° in all spatial directions. A patented variant of a multi-stream nozzle apparatus is analyzed. The distribution of energy of the working gas is analyzed for cases with different working pressures. A critical cross-section of rectangular geometry has been examined. The article presents 3 simulation results with a range of values for gas mass flow rate from 0.296 kg/s to 1.173 kg/s and for thrust from 396.53 N to 2140.15 N. Prospects for the practical application of the obtained results are discussed, including the creation of digital twins for use in the educational process in training engineers. For conceptual design, Euler's methodology in combination with CFD technologies is proposed, consistent with contemporary approaches to handling large datasets. A scientific foundation has been established for the development of lattice-type multistream jet systems based on Euler's methodology.Three main directions for further scientific research are identified: energy-efficient power systems; effective development of oil and gas fields; and transport robotic systems for operation on land, at sea, and in the air.

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Graphical Abstract

Model No. 1 — Results of computer modeling, Case No. 1.
Conceptual diagram of the unit containing 10 flow channels.
Model No. 2 — Results of computer modeling, Case No. 2.
Model No. 3 — Results of computer modeling, Case No. 3.

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1. INTRODUCTION

To tackle the existing challenges in lowering energy costs in technological processes, it is essential to explore new directions of technological development, including those related to the extraction and processing of liquid and gaseous hydrocarbons.

Contemporary CFD technologies provide unique opportunities for studying complex gas-dynamic and hydrodynamic phenomena occurring within the channels of multiphase ejectors. Drawing upon Euler's foundational concepts, the authors have formulated an innovative scientific methodology in the field of jet propulsion systems through fundamental theoretical and experimental research. The proposed systems facilitate thrust vector control over the entire geometric sphere, enabling vector deflection angles spanning ±180 degrees in all spatial orientations (1-3). Several technical solutions have been patented, including a novel class of mesh turbomachinery equipped with mesh-based jet control systems. Prospective areas of application for the results of these studies include energy, hydrocarbon production, transportation, and robotics. This article serves as a logical continuation of a series of scientific papers published in international peer-reviewed journals for the years 2020 and 2025.

In this context, a comprehensive analysis of scientific and technical information was conducted taking into account the well-established big data fusion technology "MSIF," which integrates inputs from numerous heterogeneous sources (4-6). In this case, the conditions in the energy resource market (7-9), as well as various difficulties in oil and gas production (10-12) have been taken into account. By analogy with reversible turbomachinery (13), reversible jet pumps and ejectors (1-3) are considered and studied. New possibilities of flow control in the main and additional channels of hydraulic machines are being studied (14-16). More complex hybrid systems are being increasingly considered (17, 18). Issues related to the optimization of nozzle assembly design are being addressed (19-22). Electronic systems for controlling the ejector nozzle are being considered in the field of hydrogen energy (23-26). Ejectors with annular mixing chambers are being considered separately (27-29). In aviation technologies, ejectors for enhancing engine thrust are being actively studied (30, 31). Jet control systems are recognized as revolutionary advancements in the aviation industry and are viewed as one of the most promising fields of development, particularly in the research carried out by DARPA and Boeing (32-34). Utilizing jet control and monitoring systems can notably enhance the maneuverability of aircraft and optimize their energy consumption, reduce their radar visibility, and make them less detectable. However, it should be noted that there is not enough information about such technologies

in scientific publications, which underlines the importance of conducting scientific research and creating new technical concepts in the field of jet technology. The potential to expand the range of ejector applications through the use of curved mixing chambers are currently being studied (35-37). When developing ejectors featuring a curved mixing chamber, the results from studies on S-shaped channels are taken into account (38-40) and related systems (41-43) should be considered.

In summary, it is worth noting that modern scientific and technical progress is largely driven by a set of interrelated areas and technologies. These include automation, artificial intelligence technologies, shape modification systems, as well as groups of autonomous vehicles or robotic devices. The advancement of energy-efficient and environmentally safe industrial technologies relies heavily on interdisciplinary research efforts, which are essential for addressing complex engineering and sustainability challenges.

This research focuses on the computational modeling and performance analysis of a multiphase nozzle system intended for use in energy-efficient jet technologies. The broader aim is to enable the development of adaptive jet control systems characterized by high responsiveness, structural simplicity, and broad applicability. In parallel, the study includes the development of digital twin models to aid in the training and professional growth of design engineers, based on methodological principles derived from Eulerian mechanics (1, 2). The switching time between nozzle operating modes can be reduced by employing a multi-stream nozzle, where a single large nozzle is replaced by a cluster of smaller, geometrically similar ones.

2. MATERIALS AND METHODS

To provide a clear representation of the research methodology employed, a flowchart has been constructed and is presented in Figure 1. This methodology encompasses the full scope of activities contributing to the development of new technological solutions in the field of energy-efficient jet installations. First of all, it is necessary to prepare theoretical hypotheses which are then translated into schematic representations of various devices through comprehensive analysis of scientific and technical literature. Based on these schematics, computer modeling is carried out using CFD technology. Following the analysis of modeling results, three-dimensional prototypes are created using 3D printing. The subsequent stages include assessing the potential for publishing scientific papers and patents, as well as incorporating the obtained research data into a unified database to support further fundamental and applied studies. The outcomes of this work contribute to educating students and training

intelligent systems in new developments and recommendations within the research domain.

The formulation of hypotheses is carried out within the framework of multiparametric (multidimensional) problems, drawing on Euler's ideas. Consideration is also given to the prospect of more active practical application of artificial intelligence tools. A fundamental research direction has been selected, focused on the study of gas-dynamic and hydrodynamic processes in thrust vector control under extreme conditions, thereby opening new opportunities to transcend established boundaries and expand the existing body of knowledge (1, 2).
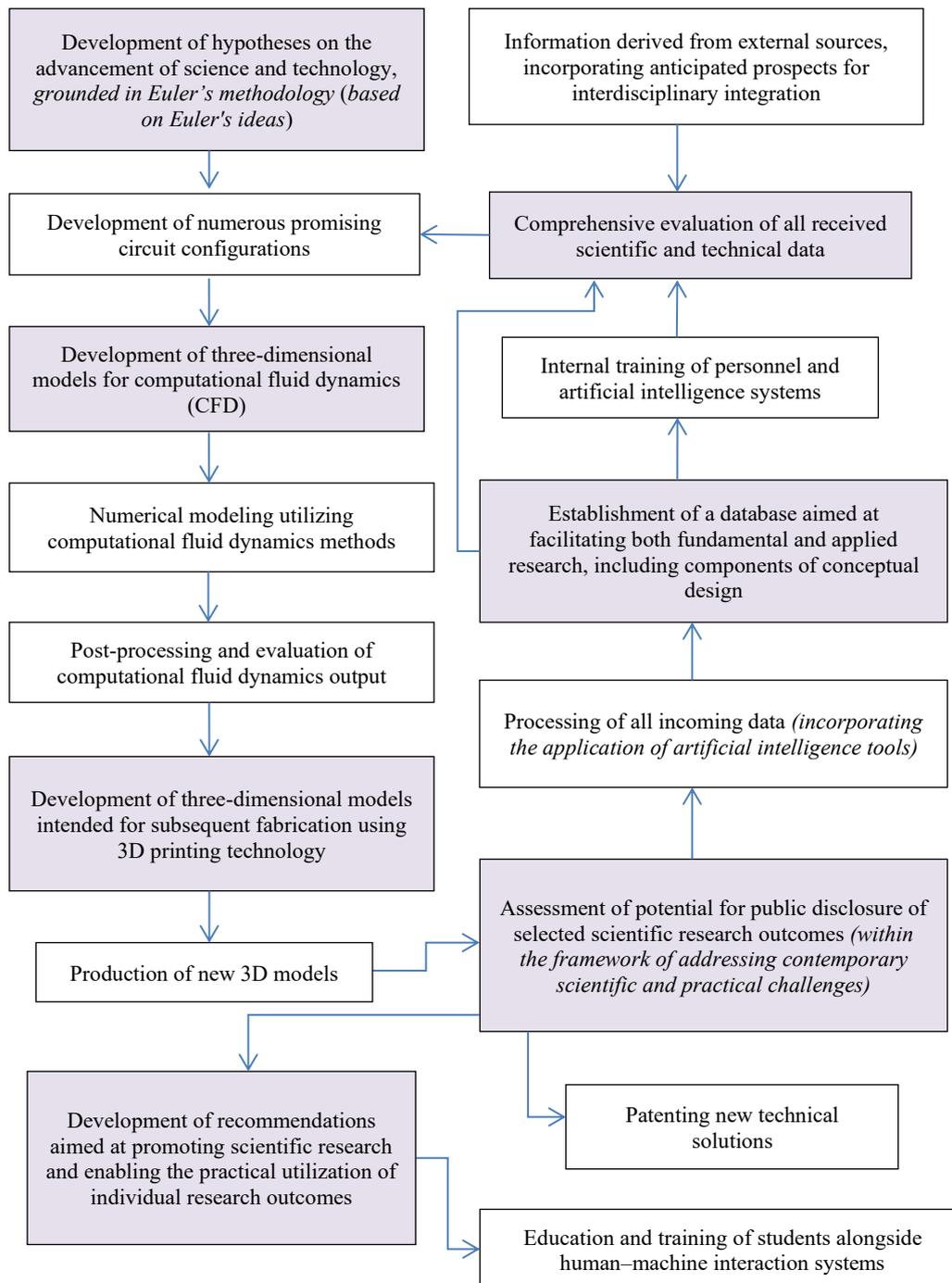

Figure 1. Block diagram of the methodology employed in the course of scientific research

Within fundamental research, the objective is to broaden the range of possibilities for achieving competitive advantages in the advancement of science and technology. Within applied research, the objective is to develop recommendations for the practical implementation of new competitive advantages from the aforementioned set of possibilities.

The scientific and engineering research was carried out with reference to the theoretical works of Euler. As demonstrated by the results obtained, Euler's legacy has not yet been fully explored. Many of his ideas were far ahead of their time and, in fact, continue to surpass our present understanding. It is appropriate here to recall the remark made by Feyerabend (44): "There is no idea, however ancient or absurd, that is not capable of improving our knowledge. The whole history of thought is condensed in science and is used for the improvement of every single theory. No idea has ever been studied in all its implications, and no concept has ever been given all the chances it deserves to succeed. Theories are eliminated and replaced by more fashionable ones long before they have had the opportunity to display their full worth." One of Euler's fundamental works, originally written in 1754, was reintroduced by modern historians in digital format in 2021 (45). In this work, Euler described his new turbine and presented a mathematical model for calculating the Segner turbine. Building on this foundation, it remains possible today to formulate new directions for the advancement of science and engineering.

According to Euler's methodology, scientific, inventive, and engineering tasks should be addressed as part of an integrated whole within the framework of interdisciplinary studies. In such interdisciplinary research, mathematics and computer technologies (CFD) currently serve as the principal unifying elements.

3. RESULTS

3. 1. Development of a conceptual design of a Multi-stream Nozzle Apparatus
Building upon Euler's work (45), the present study extends the investigation to a variant of the patented technical solution (1-3). Figure 2 presents a schematic diagram of a jet device enabling angular displacement of the nozzle 1.

In the general case, when Euler's work is interpreted more broadly, various modes of fluid flow through the nozzle 1 can be considered. These may involve a liquid, a gas, or a multiphase multicomponent medium. The flow velocity at the nozzle exit is denoted by v_c. The nozzle may move with velocity v_r or remain stationary, depending on the boundary conditions of the problem. The flow direction can be varied by controlling the thrust
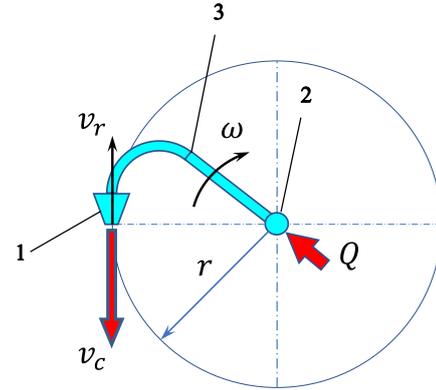

Figure 2. Schematic of the jet device variant (1-3): 1 – nozzle, 2 – energy supply point, 3 – energy transmission channel

vector within the limits of a complete geometric sphere, with thrust vector control considered in terms of its magnitude, direction, and point of application.

In a specific case, Euler employed this schematic when developing the theoretical model for calculating the Segner turbine (45). It is therefore reasonable to reproduce Euler's mathematical reasoning. The reactive force (thrust) F generated by the flow of a fluid with density ρ and volumetric flow rate Q is expressed as:

$$F = Q\rho(v_c - v_r) \tag{1}$$

$$v_r = \omega r \tag{2}$$

where r is the radius of the rotor in the Segner turbine, and ω is the angular velocity of the rotor.

Torque of the rotor:

$$M = Fr \tag{3}$$

Effective power of the turbine:

$$N_i = M\omega = Fr * \frac{v_r}{r} = Fv_r = Q\rho(v_c - v_r)v_r \tag{4}$$

The power of the flow at the turbine inlet, given the inlet pressure P_0, and the outlet pressure P_r, is expressed as:

$$N_0 = Q(P_0 - P_r) = Q\rho * \frac{v_0^2}{2} \tag{5}$$

The efficiency of the turbine (for the idealized turbine model) is given by:

$$\eta = \frac{N_i}{N_0} = \frac{2(v_c - v_r)v_r}{v_0^2} \tag{6}$$

$$\frac{v_c^2}{2}\rho = \left(P_0 + \frac{v_r^2}{2}\rho\right) - P_r = \frac{v_r^2}{2}\rho + \frac{v_0^2}{2}\rho \tag{7}$$

$$v_c = \sqrt{v_r^2 + v_0^2} \tag{8}$$

Relative velocity:

$$v = \frac{v_r}{v_0} \qquad (9)$$

$$\eta = \frac{2\left(\sqrt{v_r^2 + v_0^2} - v_r\right)v_r}{v_0^2} \qquad (10)$$

A representation of Euler's formula for the idealized Segner turbine (45) is given as:

$$\eta = 2\left(\sqrt{v^2 + 1} - v\right)v \qquad (11)$$

An alternative formulation of Euler's equation – adapted for the actual Segner turbine and its possible modifications, and incorporating the nozzle discharge coefficient $\mu = \varepsilon\varphi$, where ε is the jet (flow) contraction coefficient and φ is the velocity coefficient of the nozzle assembly and the flow passages as a whole, introduced to account for hydraulic losses – is given as:

$$\eta = 2\left(\mu\sqrt{v^2 + 1} - v\right)v \qquad (12)$$

Base on Bistafa (45) and Equations 1-11 partially reflect the scientific foundation laid by Euler for the development of modern turbomachinery and jet technology as a whole. The potential of Euler's ideas has not yet been fully revealed, and future generations of researchers will need to continue advancing this line of inquiry.

Based on Euler's Formulas 1-11, the parameters of a reactive jet with cross-sectional area f can be separately described for the case when $\omega = 0$. In this case, the thrust of a stationary reactive nozzle, F_0, can be defined as follows:

$$F_0 = Q\rho v_c = Q\rho v_0 = f\rho v_0^2 = f\rho \left(2\frac{N_0}{F_0}\right)^2 \qquad (13)$$

According to Euler's static theory, the principal parameters of an ideal jet are related by the following expression:

$$4\rho f \frac{N_0^2}{F_0^3} = 1 \qquad (14)$$

This form of Euler's Equation 14 is applicable to the calculation of jet systems with arbitrary cross-sectional shapes for an idealized jet. In the specific case of a jet with a circular cross section – for instance, the jet at the exit of an air propeller of diameter D, Equation 14 can be transformed almost entirely into the Wellner–Zhukovsky equation (46), where the jet power N_0 (in watts) is expressed as the product of the input power supplied to the air propeller and its efficiency (units of measure: thrust F_0 in newtons; propeller diameter D in meters).

$$F_0{}^3 = (1{,}39 * D * N_0)^2 = (1{,}39 * D * N_D * \eta_D)^2 \qquad (15)$$

In the Wellner–Zhukovsky equation (46), the coefficient takes a value of 1.37. As shown by the derived formula based on Euler's theory 15, a discrepancy arises in the third significant digit of this coefficient. However, given the universality of Equation 14, it can be applied to a broad range of nozzle configurations and jet geometries

– circular, rectangular, triangular, annular, and others, as well as to media of different densities, thereby enabling adaptation to varying flight altitudes in aeronautical applications.

Summarizing the intermediate results, the following conclusions can be drawn: 1 – one of the patented variants of a jet apparatus with distributed energy supply has been analyzed within the framework of Euler's theory (1-3), demonstrating the capability for thrust vector control across the entire geometric sphere; 2 – numerical experiments have confirmed the operability of a multi-stream jet apparatus with distributed energy supply, intended for the development of compact, high-response, and ergonomically efficient control systems capable of addressing a wide range of applied engineering tasks; 3 – based on the obtained results, a preliminary conclusion can be drawn regarding the applicability of such jet systems for processes involving the transfer of gases, liquids, and gas–liquid mixtures.

Figure 3 presents the conceptual design developed in the course of investigating advanced jet systems (1, 2). These systems are intended to address a range of practical tasks, including hydrocarbon extraction and processing, as well as thrust vector control within the limits of a complete geometric sphere.

The block shown contains flow channels. At the critical cross-section, the channel is rectangular, measuring 1.5 mm by 1.95 mm. The block height is 11 mm.

The nozzle apparatus shown in Figure 3 is assembled from 8 units. The height of the nozzle device can be decreased by an order of magnitude through the parallel integration of 80 channels. A geometrically similar nozzle apparatus with only a single flow channel would have a height of 110 mm instead of 11 mm.
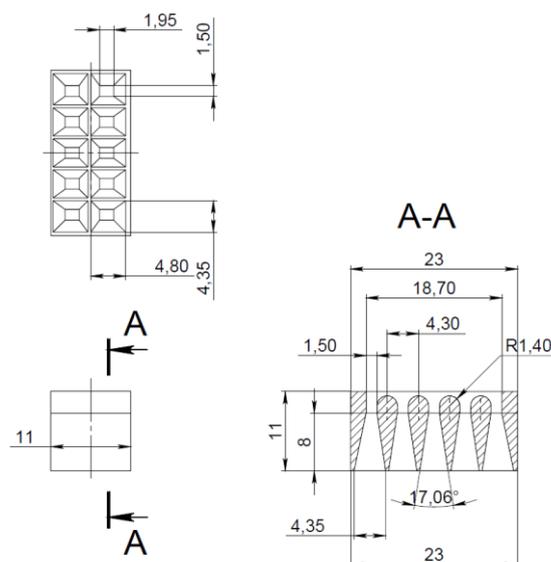

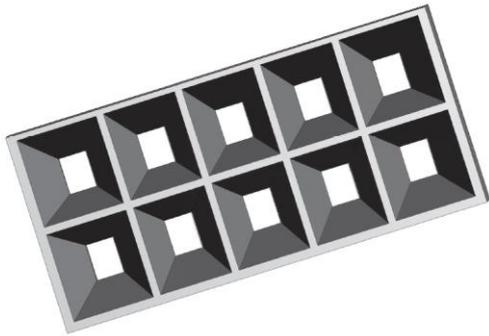**Figure 3.** Conceptual diagram of the unit containing 10 flow channels

Figure 4 (a). Three-dimensional computer model of the nozzle apparatus, which includes 10 flow channels, was created for numerical experiments
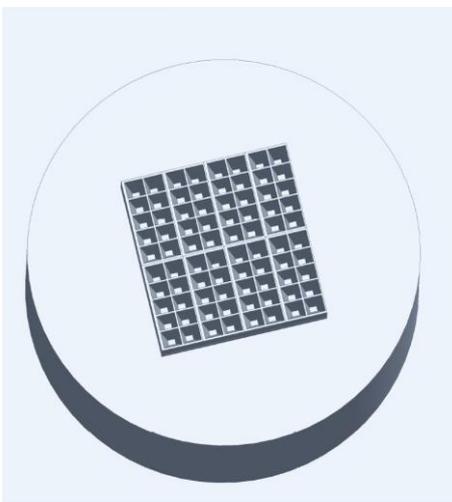

Figure 4 (b). Three-dimensional computer model of the nozzle apparatus, which includes 8 units and a total of 80 flow channels, was created for numerical experiments
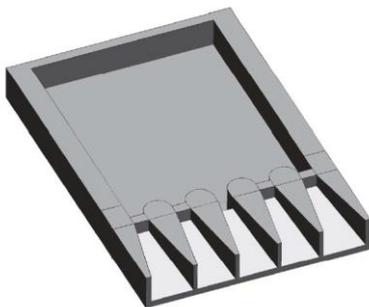

Figure 4 (c). A three-dimensional computational model of the nozzle apparatus was developed to perform numerical experiments. The model represents a block comprising five adjustable flow channels, configured with one open central channel and four closed peripheral channels

3. 2. Results of Computer Modeling   In the numerical experiments, air served as the model working medium. The baseline parameters used for the calculations in this case study included gas inlet

pressures of 1.5 MPa (Case No. 1), 3 MPa (Case No. 2), and 6 MPa (Case No. 3). The temperature of the gas entering the nozzle was maintained at 2000 °C.

Gas pressure at the nozzle inlet: $P=3$ MPa (Cases No. 4 and No. 5). Gas temperature at the nozzle inlet: 1000 ºC.

The outlet pressure was set to atmospheric conditions, specifically 101,325 Pa, while the surrounding ambient temperature was 20 °C.

- Computer parameters used for CFD:
- Software Product (SW for calculations): Flow Simulation 2018 SP5.0
- CPU type (processor): Intel(R) Core (TM) i5-6200U CPU @ 2.30GHz
- CPU speed: 2401 MHz
- RAM: 8065 MB
- Operating system: Windows 10

The k–ε turbulence model was used; the computational mesh was generated automatically, A grid consisting of more than 700,000 cells was employed, with the solver performing 1,500 iterations.

In agreement with the client, the parameters of the computer system used for performing CFD simulations were determined at the conceptual design stage. According to the current state of the art, similar simulation conditions are commonly applied in the study of nozzle devices for aerospace and rocket applications. However, based on expert recommendations, more precise and higher-performance computational equipment and technologies will be required to conduct CFD analyses during the transition to optimization tasks aimed at the development of specific products and production series.

Figures 5 through 9 offer a detailed graphical representation of specific results obtained from the computational modeling process, highlighting significant trends and observations.

In Case No. 1, the following data were obtained: mass flow rate of gas – 0.296 kg/s; thrust – 396.53 N. Within
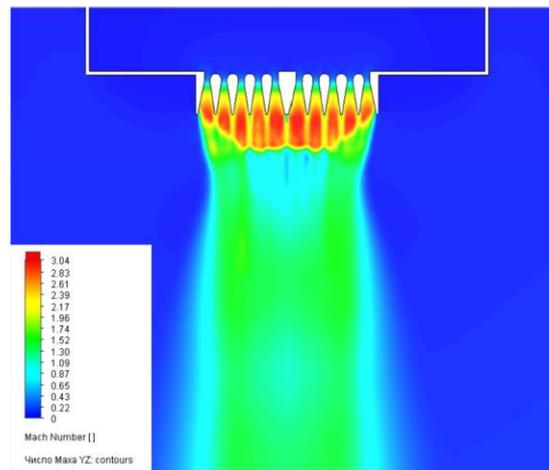

Figure 5. Results of computer modeling, Case No. 1

the framework of digital twin development, additional rapid calculations were also performed using the methodology described in (43). The results were as follows: mass flow rate of gas – 0.302 kg/s; thrust – 472.90 N.

In Case No. 2, the following data were obtained: mass flow rate of gas – 0.578 kg/s; thrust – 950.42 N. Using the methodology described in (43), the corresponding results were: mass flow rate of gas – 0.603 kg/s; thrust – 1,015.95 N.

In Case No. 3, the following data were obtained: mass flow rate of gas – 1.173 kg/s; thrust – 2,144.04 N. Using the methodology described in (43), the corresponding results were: mass flow rate of gas – 1.206 kg/s; thrust – 2,140.15 N.

In Case No. 4, the following data were obtained at a working gas temperature of 1000 ºC: gas mass flow rate: 0.00905 kg/s; thrust: 11.20 N. Specific thrust (defined as the ratio of thrust to gas mass flow rate): 1237.7 N/(kg/s).
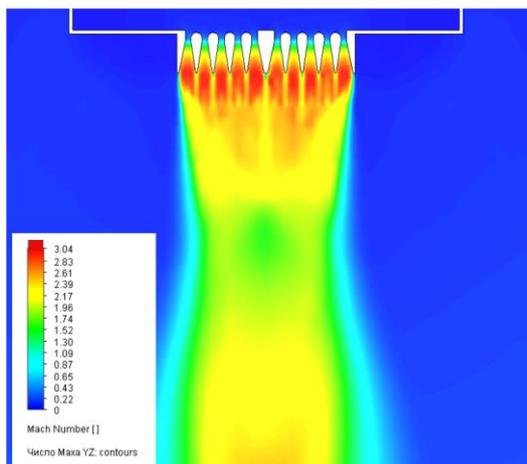
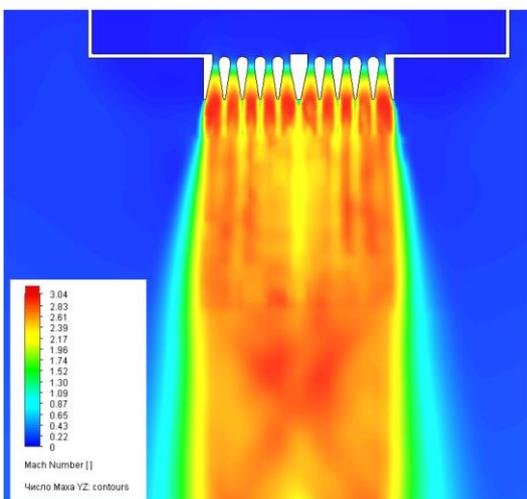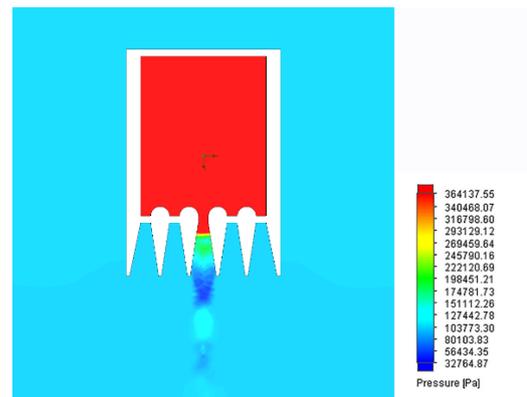

Figure 6. Results of computer modeling, Case No. 2
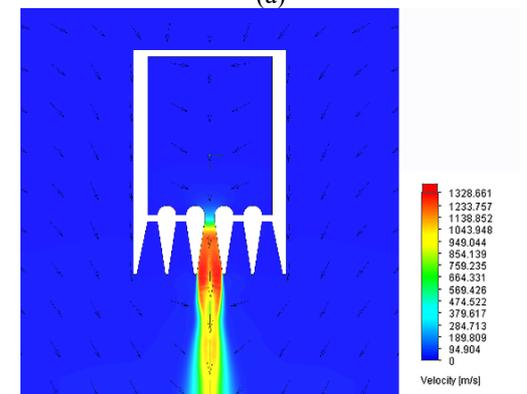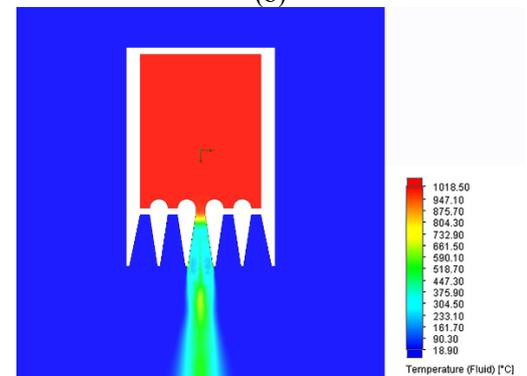

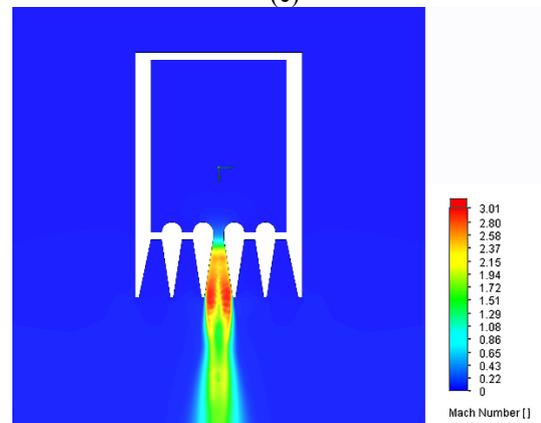**Figure 7.** Results of computer modeling, Case No. 3

(a)

(b)

(c)

(d)

Figure 8. Results of computer simulation, Case No. 4

As part of the development of digital twins for rapid computational analysis, additional calculations were carried out using the methodology described by Sokolov and Singer (43). The corresponding results were as follows: gas mass flow rate: 0.01007 kg/s; thrust: 12.70 N. Specific thrust (the ratio of thrust to gas mass flow rate): 1260.8 N/(kg/s).

In Case No. 5, the following data were obtained at a working gas temperature of 1000 ºC: gas mass flow rate: 0.04807 kg/s; thrust: 60.125 N. Specific thrust (defined as the ratio of thrust to gas mass flow rate): 1250.7 N/(kg/s).
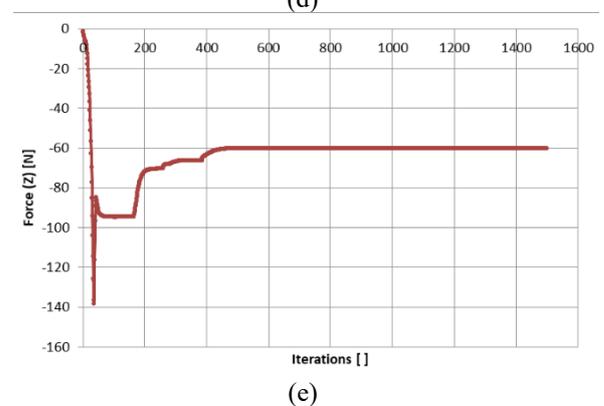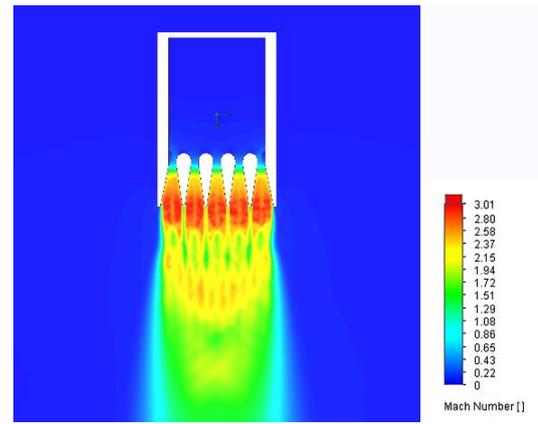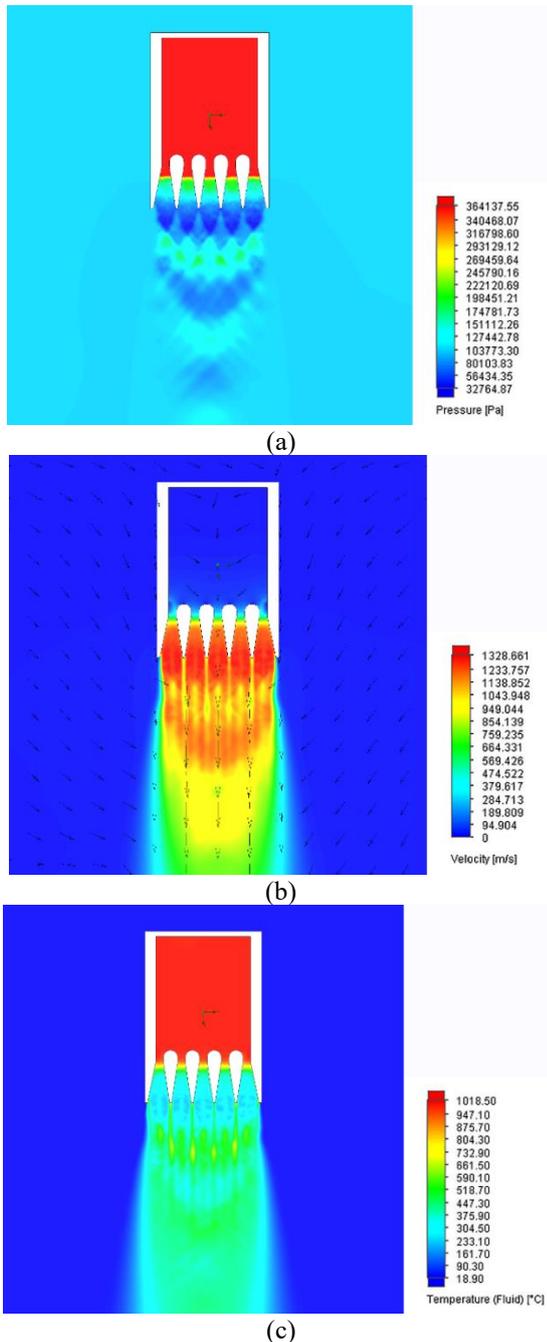

(a)

(b)

(c)

(d)

(e)

Figure 9. Results of computer simulation, Case No. 5: assessment of convergence in nozzle thrust calculation

As part of the development of digital twins for rapid computational analysis, additional calculations were carried out using the methodology described by Sokolov and Singer (43). The corresponding results were as follows: gas mass flow rate: 0.0504 kg/s; thrust: 63.50 N. Specific thrust (the ratio of thrust to gas mass flow rate): 1260.8 N/(kg/s).

Similar calculations were carried out for the operating conditions of the nozzle apparatus in a cold-gas environment and in liquid. In all cases, the operability of the new multi-stream nozzle apparatus was confirmed. The results of the research will be used in creating advanced energy-efficient jet devices and systems.

4. DISCUSSION

Within the framework of conceptual design, digital twins are required that provide capabilities for rapid calculations and for verifying the operability of new technical solutions. In regions of high velocities and supersonic flows, such tasks are particularly challenging. Modern CFD technologies provide unique opportunities to investigate complex gas-dynamic and hydrodynamic processes within the channels of multi-stream ejectors and nozzle apparatuses.

The jet system shown in Figure 2, under conditions where $\omega = 0$, allows the nozzle 1 to be oriented in a specified direction by means of angular displacement. Once positioned, the nozzle 1 can be fixed in place to provide the required thrust vector, enabling control over its direction. Thrust vector control by absolute value can be achieved by regulating the mass flow rate of the working medium at the nozzle 1 outlet. This simple configuration, originally presented in Euler's work (45), can be – and already is – applied in the development of more advanced and sophisticated systems for thrust vector control with respect to absolute value, direction, and the spatial coordinates of the point of force application.

For Cases No. 4 and No. 5, the gas temperature used in the calculations was 1000 ºC, which corresponds to the current state of the art in material selection. For Cases No. 1, No. 2, and No. 3, the gas temperature was set to 2000 ºC, representing near-term technological prospects achievable through the use of advanced materials.

Euler's mathematical model, originally developed for the Segner turbine, together with formulas 11-15, can be applied to describe jet systems designed for thrust vector control (1-3). In the particular case of a static propeller, the Wellner–Zhukovsky equation (46) can be directly derived from Euler's theory. It is therefore appropriate to extend the analysis of Euler's seminal work (45) with the goal of developing new computational algorithms and digital twin models for the design of jet propulsion systems – both for applied engineering applications and for educational purposes in the training of design engineers.

Summarizing the intermediate results, the following conclusions can be drawn:

One of the patented variants of the jet system (3), designed for energy distribution with the capability of thrust vector control within the limits of a complete geometric sphere, has been investigated.

Numerical experiments confirmed the operability of the multi-stream lattice-type nozzle apparatus, also oriented toward the development of compact, high-speed, and ergonomic control systems for a wide range of applied tasks.

Based on the results of computer modeling, a preliminary conclusion can be made regarding the suitability of such lattice-type jet systems for operation under conditions of liquid pumping and gas–liquid mixture handling, including applications with hybrid blade machines.

The materials presented in this article constitute a logical continuation of a series of fifteen publications in international scientific journals prepared by the authors between 2020 and 2025 (including journals ranked in Q1-2). The scientific novelty of the developed technological solutions is confirmed by a number of Russian patents for inventions: Nos. 2847614, 2847612, 2839870, 2819487, 2813562, 2802351, 2781534, 2781455, 2778961, 2750833, 2726511, 2714989.

Figure 10 shows photographs of the fabricated micromodel of the multi-stream nozzle.
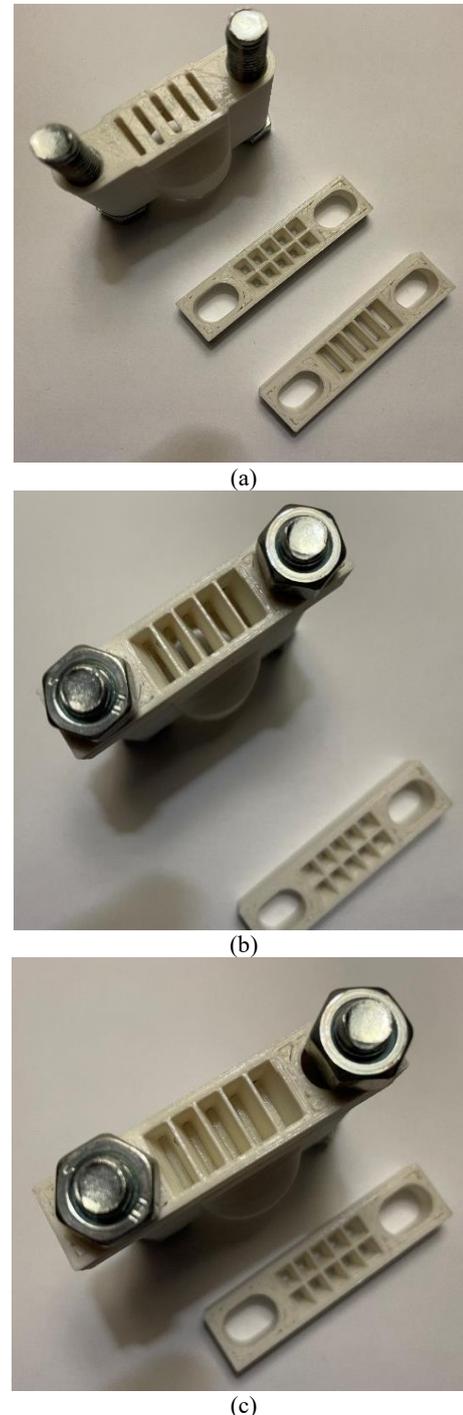
(a)

(b)

(c)

Figure 10. Micromodel of the multistream nozzle: a) Nozzle body and two movable blocks with diffusers (variants); b) Configuration with open nozzle flow channels; c) Configuration with closed nozzle flow channels

The micromodel shown in Figure 10 was fabricated according to the schematic presented in Figure 3. The design allows the diffuser block to shift in a plane perpendicular to the working medium flow passing through the multi-stream nozzle. Two operational positions are illustrated in Figure 10: 1 – nozzle open, 2 – nozzle closed. Intermediate positions of the diffuser block are also possible, resulting in a partially open critical section of the nozzle. Additional nozzle adjustment can be achieved via a movable perforated diaphragm placed between the converging section and the diffuser section. In this configuration, the diffuser block can be rigidly attached to the nozzle body, representing one of many possible arrangements. One such configuration is illustrated in Figures 4 and 8 for Case No. 4, where the central channel remains open while the four peripheral channels are closed using diaphragms at the critical cross-sections.

A lightweight movable perforated diaphragm can serve as a shut-off regulating device capable of simultaneously closing the critical sections of all channels in the multi-stream nozzle (Figure 4b). In the cases corresponding to Figures 3 and 4b, a diaphragm displacement of 1.5 mm is sufficient for complete nozzle closure. By comparison, a conventional nozzle of equivalent design speed would require a diaphragm displacement of approximately 15 mm at the critical section, assuming equal diaphragm movement speed.

Calculations confirm that the time required to switch the nozzle operating mode can be significantly reduced through the use of a multi-stream nozzle, where a single large nozzle is replaced by a group of smaller, geometrically similar nozzles. Examples demonstrate that, using this technology, actuation time can be reduced by nearly a factor of ten.

Further research into multi-stream nozzle apparatuses is warranted. These nozzles are more compact and can be adapted to complex fuselage contours of aircraft. Linear channel arrangements (Cases No. 4 and No. 5) are preferable, as they maintain specific thrust comparable to that of a single conventional nozzle. Grouping multiple channels into a single block (Case No. 3) is estimated to reduce specific thrust by approximately 15% relative to a single conventional nozzle.

A patented modification of a multi-flow nozzle assembly (3) has been developed and tested, allowing for energy distribution during thrust vector control within a full geometric sphere. This aspect was partially addressed in works (1, 2). Calculations confirm the possibility of reducing the time required to switch the nozzle operating mode, which is achieved by using a multi-stream nozzle, where a single large nozzle is replaced by a group of smaller, geometrically similar nozzles. Examples demonstrate that, using this technology, the actuation time can be reduced by nearly a factor of ten.

New methodological approaches for the design of complex jet systems with the ability to work with supersonic flows are proposed as a continuation of previously published works (1, 2).

New possibilities for the control of extreme gas flows are proposed. The findings of this study have potential applications across energy sectors, oil and gas extraction, and multiple domains within robotics. Additionally, an extension of Euler's methodological framework is proposed, aimed at addressing practical challenges in higher education and enhancing the training process for contemporary design engineers.

Computer modeling was conducted, yielding the following data:

1. In example No. 1: gas mass flow rate is 0.296 kg/s; thrust is 396.53 N. As part of the creation of digital twins, for fast calculations, calculations were also performed using the method (43), respectively, the gas mass flow rate is 0.302 kg/s; thrust is 472.90 N.
2. In example No. 2: gas mass flow rate 0.578 kg/s; thrust 950.42 N. Using the method (43), the following values were obtained: gas mass flow rate 0.603 kg/s; thrust 1015.95 N.
3. In example No. 3: gas mass flow rate 1.173 kg/s; thrust 2144.04 N. Using the method (43), the following values were obtained: gas mass flow rate 1.206 kg/s; thrust 2140.15 N.

What makes this device suitable for effective use in pumping and compressor units within the oil and gas industry.

5. CONCLUSIONS

The application of artificial intelligence to solving scientific and inventive problems with multiple parameters remains a major and unresolved challenge. A clear interpretation of the results of artificial intelligence work is still lacking. Scientific groundwork has been laid for addressing extreme maneuvering problems with thrust vector control within a full geometric sphere. When summarizing the intermediate results (for the period 2020–2025), it should be noted that with the transition from the conceptual design stage to the preliminary design stage, including prototype development, a significant increase in funding will be required to carry out more precise and higher-cost computational and design work, including CFD simulations and additive manufacturing technologies.

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Ethics Approval and Consent to Participate

This study did not involve human participants or animals. Therefore, ethical approval and informed consent were not required.

Competing Interests

The authors declare that they have no known financial or organizational conflicts of interest that could have influenced the work reported in this paper.

Data Availability

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Declaration of Generative AI and AI-Assisted Technologies in the Writing Process

The authors used artificial intelligence–based tools to assist with the accurate scientific translation of selected phrases from Russian into English. All translated content was carefully reviewed, edited, and validated by the authors, who take full responsibility for the integrity, originality, and accuracy of the final manuscript.

REFERENCES

1. Sazonov YA, Mokhov MA, Bondarenko AV, Voronova VV, Tumanyan KA, Konyushkov EI. Investigation of a multiflow ejector equipped with variable-length links for thrust vector control using Euler's methodology. Engineering. 2024;5(4):2999-3022. https://doi.org/10.3390/eng5040156

2. Sazonov YA, Mokhov MA, Bondarenko AV, Voronova VV, Tumanyan KA, Konyushkov EI. Study of reversible nozzle apparatuses using Euler methodology and CFD technologies. Civil Engineering Journal. 2024;10(11):3640-71. https://doi.org/10.28991/CEJ-2024-010-11-013

3. Sazonov YA, Mokhov MA, Bondarenko AV, Voronova VV, Tumanyan KA, Konyushkov EI. Jet apparatus. Russian Federation Patent 2839870 C1. 2025.

4. Li X, Dunkin F, Dezert J. Multi-source information fusion: Progress and future. Chinese Journal of Aeronautics. 2024;37(7):24-58. https://doi.org/10.1016/j.cja.2023.12.009

5. Schafer Y, Stossel M, Barnique A, Kozulovic D. Effects of tip injection on a turbofan engine with non-invasive high-speed actuators. International Journal of Turbomachinery, Propulsion and Power. 2025;10(2):9. https://doi.org/10.3390/ijtpp10020009

6. Luo Y, Wu Z, Li Z, Cheng L, Qi P, Mou J. Design of a novel pump cavitation valve and study of its cavitation characteristics. Water. 2025;17:1503. https://doi.org/10.3390/w17101503

7. Ulger Danaci O. The effect of renewable and non-renewable energy on economic growth: A panel cointegration analysis for the top renewable energy consumers (1970-2023). Energies. 2025;18:4745. https://doi.org/10.3390/en18174745

8. Hesami A, Kazempoor P, Acacio VJ, Van Dam JD. Systems and methods for gas pulse jet pump. United States Patent 10837463. 2020.

9. Teneva EV. Emotionalization of the 2021-2022 global energy crisis coverage: Analyzing the rhetorical appeals as manipulation means in the mainstream media. Journalism and Mass Media. 2025;6(1):14. https://doi.org/10.3390/journalism6010014

10. Legrand B, Gaillard A, Bouquain D. Comparative study of hybrid electric distributed propulsion aircraft through multiple powertrain component modeling approaches. Aerospace. 2025;12:732. https://doi.org/10.3390/aerospace12080732

11. Verbitsky VS, Dengaev AV, Safiullina EU, et al. Analyzing efficiency of joint operation of gas separator and screw pump on high-viscosity gas-liquid mixture. International Journal of Engineering, Transactions A: Basics. 2024;37(10):1901-13. https://doi.org/10.5829/ije.2024.37.10a.04

12. Sazonov YA, Mokhov MA, Gryaznova IV, et al. Development of a scientific approach to the advancement of multi-stream jet systems based on Euler's methodology. Neftyanoye Khozyaystvo. 2025;(9):30-35. https://doi.org/10.24887/0028-2448-2025-9-30-35

13. Rubison WC. Reversible flow centrifugal pump. United States Patent 2442512. 1948.

14. Hou Y, Xue R. Hydraulic performance and flow characteristics of a high-speed centrifugal pump based on multi-objective optimization. Fluids. 2025;10:174. https://doi.org/10.3390/fluids10070174

15. Shim HS. Influence of impeller-diffuser side-gap flow with a simplified leakage model on the performance and internal flow of a centrifugal pump. Energies. 2025;18:1278. https://doi.org/10.3390/en18051278

16. Koteleva N, Buslaev G, Valnev V, Kunshin A. Augmented reality system and maintenance of oil pumps. International Journal of Engineering, Transactions B: Applications. 2020;33(8):1620-28. https://doi.org/10.5829/ije.2020.33.08b.20

17. Zhang L, Li Y, Ma M, Kong L, Huang Z, Xu L, Wang B. Numerical investigation of clocking effects on the hydraulic performance of pump-turbine in pump mode. Energies. 2025;18:4317. https://doi.org/10.3390/en18164317

18. Tsentis SE, Gkoutzamanis VG, Gaitanis AD, Kalfas AI. Multi-platform app-embedded model for hybrid air-breathing rocket-cycle engine in hypersonic atmospheric ascent. Aeronautical Journal. 2021;125(1291):1631-53. https://doi.org/10.1017/aer.2021.3

19. Cardenas IR, Lain S, Lopez OD. A review of aerospike nozzles: Current trends in aerospace applications. Aerospace. 2025;12:519. https://doi.org/10.3390/aerospace12060519

20. Gonzalez-Viana A, Sastre F, Martin E, Velazquez A. Multi-objective optimization of rocket-type pulse detonation engine nozzles. Aerospace. 2025;12:502. https://doi.org/10.3390/aerospace12060502

21. Shumeiko A, Telekh V, Ryzhkov S. Thrust-vectoring schemes for electric propulsion systems: A review. Chinese Journal of Aeronautics. 2025;38(6):103401. https://doi.org/10.1016/j.cja.2025.103401

22. Cheng Z, Yang W, Zeng L, Wu L. Pressure characteristics analysis of the deflector jet pilot stage under dynamic skewed velocity distribution. Aerospace. 2025;12:638. https://doi.org/10.3390/aerospace12070638

23. Xu Z, Liu B, Tong Y, Dong Z, Feng Y. Modeling and control of ejector-based hydrogen circulation system for proton exchange

membrane fuel cell systems. Energies. 2024;17:2460. https://doi.org/10.3390/en17112460

24. Li J, Wu T, Cheng C, Li J, Zhou K. A review of the research progress and application of key components in the hydrogen fuel cell system. Processes. 2024;12:249. https://doi.org/10.3390/pr12020249

25. Li C, Sun B, Bao L. Coupling global parameters and local flow optimization of a pulsed ejector for proton exchange membrane fuel cells. Sustainability. 2024;16:4170. https://doi.org/10.3390/su16104170

26. Brunner DA, Marcks S, Bajpai M, Prasad AK, Advani SG. Design and characterization of an electronically controlled variable flow rate ejector for fuel cell applications. International Journal of Hydrogen Energy. 2012;37(5):4457-66. https://doi.org/10.1016/j.ijhydene.2011.11.116

27. Lysak IA, Lysak GV, Konyukhov VY, Stupina AA, Gozbenko VE, Yamshchikov AS. Efficiency optimization of an annular-nozzle air ejector under the influence of structural and operating parameters. Mathematics. 2023;11:3039. https://doi.org/10.3390/math11143039

28. Gu R, Sun M, Cai Z, Chen J, Li P, Dong Z, Huang Y. Experimental study on the rocket-ejector system with a throat in the secondary stream. Aerospace Science and Technology. 2021;113:106697. https://doi.org/10.1016/j.ast.2021.106697

29. Riaz S, Aaltonen J, Pinkse T, Koskinen K. Numerical investigation and validation of multiphase flow in annular jet pump: A mixture model approach. Engineering Science and Technology, an International Journal. 2025;69:102100. https://doi.org/10.1016/j.jestch.2025.102100

30. Cican G, Frigioescu TF, Crunteanu DE, Cristea L. Micro turbojet engine nozzle ejector impact on acoustic emission, thrust force and fuel consumption analysis. Aerospace. 2023;10:162. https://doi.org/10.3390/aerospace10020162

31. Kim SW. Traction booster. Japanese Patent JP2024516044. 2024.

32. Wlezien R. Control of revolutionary aircraft with novel effectors (CRANE). Defense Advanced Research Projects Agency. 2023.

33. Smith C. Aurora begins building full-scale active flow control X-plane. Aurora Flight Sciences. 2024.

34. Xu B, Feng L. Experimental research on three-axis control of flying-wing aircraft based on active flow control. Chinese Journal of Aeronautics. 2025;38(8):103443. https://doi.org/10.1016/j.cja.2025.103443

35. Suction jet pump. United States Patent 10072674. 2018.

36. Bolobov V, Martynenko YV, Voronov V, Latipov I, Popov G. Improvement of the liquefied natural gas vapor utilization system using a gas ejector. Inventions. 2022;7(1):14. https://doi.org/10.3390/inventions7010014

37. Korshak AA, Pshenin VV. Determination of parameters of non-pump ejector gasoline vapor recovery unit. Science and Technologies: Oil and Oil Products Pipeline Transportation. 2023;13(1):25-31. https://doi.org/10.28999/2541-9595-2023-13-1-25-31

38. Wang C, Lu H, Kong X, Wang S, Ren D, Huang T. Effects of pulsed jet intensities on the performance of the S-duct. Aerospace. 2023;10:184. https://doi.org/10.3390/aerospace10020184

39. Ahmed F, Eames I, Moeendarbary E, Azarbadegan A. High-Strouhal-number pulsatile flow in a curved pipe. Journal of Fluid Mechanics. 2021;923:A15. https://doi.org/10.1017/jfm.2021.553

40. Brethouwer G. Turbulent flow in curved channels. Journal of Fluid Mechanics. 2022;931:A21. https://doi.org/10.1017/jfm.2021.953

41. Zhang X, Shan Y, Zhang J. Influence of vertical/spanwise offsets on aerodynamic performance of double serpentine nozzles. Aerospace. 2025;12:171. https://doi.org/10.3390/aerospace12030171

42. Liu J, Wang D, Huang X. Design methodology for fishtailed pipe diffusers and its application to a high-pressure ratio centrifugal compressor. Aerospace. 2025;12:746. https://doi.org/10.3390/aerospace12080746

43. Sokolov EYa, Singer NM. Jet devices. Moscow: Energoatomizdat; 1989.

44. Feyerabend PK. Against method: Outline of an anarchistic theory of knowledge. London; 1975.

45. Bistafa SR. Investigation of a water turbine built according to Euler's proposals (1754). arXiv. 2021. https://arxiv.org/abs/2108.12048

46. Redkin AV, Yaloza YA, Kovalev IE. Reliability assessment of a convertible aircraft with a hybrid powerplant and a multi-rotor lifting system. Scientific Bulletin of MSTU GA. 2020;23(5):76-96. https://doi.org/10.26467/2079-0619-2020-23-5-76-96

Persian Abstract

چکیده

هدف این مقاله انجام تحقیقات میان‌رشته‌ای در یک حوزه علمی نوظهور است که بر کنترل بردار رانش بر روی یک هندسه کروی کامل متمرکز است، که در آن بردار رانش می‌تواند به طور مداوم در یک محدوده زاویه‌ای کامل ۱۸۰± درجه در تمام جهات فضایی منحرف شود. یک نوع ثبت اختراع شده از دستگاه نازل چند جریانی مورد تجزیه و تحلیل قرار می‌گیرد. توزیع انرژی گاز عامل برای مواردی با فشارهای کاری مختلف تجزیه و تحلیل می‌شود. یک مقطع بحرانی از هندسه مستطیلی بررسی شده است. این مقاله ۳ نتیجه شبیه‌سازی را با طیف وسیعی از مقادیر برای نرخ جریان جرمی گاز از ۰.۲۹۶ کیلوگرم بر ثانیه تا ۱.۱۷۳ کیلوگرم بر ثانیه و برای رانش از ۳۹۶.۵۳ نیوتن تا ۲۱۴۰.۱۵ نیوتن ارائه می‌دهد. چشم‌اندازهای کاربرد عملی نتایج به‌دست‌آمده، از جمله ایجاد دوقلوهای دیجیتالی برای استفاده در فرآیند آموزشی در آموزش مهندسان، مورد بحث قرار گرفته است. برای طراحی مفهومی، روش اویلر در ترکیب با فناوری‌های CFD پیشنهاد شده است که با رویکردهای معاصر برای مدیریت مجموعه داده‌های بزرگ سازگار است. یک پایه علمی برای توسعه سیستم‌های جت چندجریانی از نوع شبکه‌ای بر اساس روش اویلر ایجاد شده است. سه جهت اصلی برای تحقیقات علمی بیشتر شناسایی شده است: سیستم‌های قدرت با بهره‌وری انرژی؛ توسعه مؤثر میدان‌های نفت و گاز؛ و سیستم‌های رباتیک حمل و نقل برای عملیات در زمین، دریا و هوا.