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Solving Innovative Problems of Thrust Vector Control Based on Euler's Scientific Legacy

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Abstract

This study aims to develop an interdisciplinary approach to solving innovative thrust vector control problems. The methodology involves the development of a working hypothesis about the ejection process when using a controlled nozzle to deflect the thrust vector (velocity vector) in any direction within a complete geometric sphere. When developing the working hypothesis, a multilateral analysis of individual facts and scientific and technical information is performed using tools in the "big data" area, assessing opportunities to apply the "Foresight" methodology for predicting the development of fluidics. The authors propose new mathematical models to describe the thrust vector in the distribution of the mass flow rate of the fluid medium between flow channels. Patents for inventions support the novelty of scientific results that reveal new opportunities for more active development of fluidics as applied to simple and complex jet systems with low and extremely high energy density in flows. The proposed methodology rests on a modern computer base and is a logical continuation and development of well-known Euler's works. The computer simulation of multiflow jet devices mainly focuses on power engineering, production, and processing of hydrocarbons. Some results of this research work, including patented design developments and calculation methods, also apply to developing robotics, unmanned vehicles, and programable jet systems. The authors attribute further development of the interdisciplinary approach for solving inventive problems to the use of different AI options.

Keywords: Fluid Dynamics; Interdisciplinary Research; Ejector; CFD; Nozzle Apparatus; Thrust Vector.

1. Introduction

Today, one of the most urgent problems at the global level is reducing energy costs in production processes, including hydrocarbon production. Scientists from the Gubkin Russian State University of Oil and Gas conduct scientific research aimed at creating promising jet devices and turbomachines [1, 2], in which the flow channels have a mesh structure. In conventional understanding, a mesh represents a larger geometric area with smaller discrete cells. In the jet device, a mixing chamber of large dimensions is replaced by a set of smaller mixing chambers interconnected to form flow channels in a mesh structure. The works of Stephen Hall [3, 4] influenced the creative design approach [3, 4]. For the first time, extreme conditions of liquid and gas flow through a nozzle equipped with a control system for the velocity vector (thrust vector) were considered in the control range for the velocity vector angle (thrust vector) from $+180^{o}$ to -180^{o} within the geometric sphere [1, 2, 5]. Along with this, the question arose about the need to train designers with the choice of scientific directions for further development of applied research with the development of advanced technology. In general, this shows the prospect for further expansion of the "information universe," where people will have to use all possible tools for research work, including tools in the "big data" area [6, 7].

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As known, production systems for oil and gas extraction, transportation, and refining actively use advanced scientific developments from other industries, including aviation technologies and modified aircraft engines. In this regard, the system analysis of designs and generalization of experience in machine design are not limited to the framework of any branch, considering issues from the general positions of machine science, including the use of interdisciplinary and transdisciplinary approaches to organizing research. When performing fundamental scientific research, gas dynamics and hydrodynamics are used to investigate the interaction of a fluid medium with a solid wall. Gas dynamics and hydrodynamics also consider some complex jet systems to solve real practical problems during applied scientific research, paying specific attention to transformable systems that can overcome historically existing technical limitations and expand the practical use of such systems. From the same positions, researchers propose considering algorithms (including hybrid algorithms [8]) for solving inventive problems to shape science and technology in the near future.

The mesh structure of solid walls makes it possible to solve many essential technical problems. Thus, Morozov et al. [9], Yao et al. [10] studied the features of gas-dynamic processes in aircraft design, in which the mechanized wing adapted to a controlled change in its geometric shape. The transformable wing design covers most changes in flight conditions and can appropriately react to them [11, 12]. There are known jet devices with nozzles located in a fixed [13] or rotating disk support [14].

Supersonic ejectors and nozzle apparatuses for various purposes have been investigated [15, 16]. Today, comprehensive studies focus on the relationship between the dimensional design parameters, the ones of the working body state, and the ejector performance [17–19]. Aidoun et al. [20] and Koirala et al. [21] proposed detailed reviews of recent numerical and experimental investigations of the ejector and its applications. Koirala et al. [21] and Shank and Tiari [22] considered the current state of operation and measures to modify the design of ejectors for various applications. High-speed flows cover a wide range of modern directions of experimental and numerical studies, both in fundamental scientific problems of internal and external gas dynamics and in some new practical problems [23]. Such high-speed gas flows occur during the motion of aircraft (airplanes, rockets, and landers) and in many other technical devices, including detonation engines [24–26]. The development of hypersonic aircraft will require the simulation of hypersonic flows using new computational methods. Currently, non-mechanical control of high-speed flows is a widely studied topic of scientific research [23]. Injection of secondary airflow near the nozzle exit creates asymmetry in the wall pressure distribution and lateral loads on the nozzle, which are also lateral components of the thrust vector [27]. To change the thrust vector, several methods are sometimes used in combination [28]: (1) application of differential throttling when using several combustion chambers; and (2) an alternative solution that requires injection of secondary flow from the slot (hydrodynamic thrust vector control).

There are known variants of mesh nozzles for ejectors [29–31]. Ejector designs with curved mixing chambers are known but poorly studied [32, 33]. The adjustable nozzle can take the form of a diaphragm [34, 35]. For known thrust vector (velocity vector) control systems, the maximum flow deflection angle (at the nozzle exit) can vary in the range from $+20^o$ to -20^o [36, 37]. Adjustable nozzles can have a conical central body that can move in the axial [38] or radial directions [39]. Research continues on nozzles with deflectors of various shapes [40], including a cross-shaped nozzle exit channel [41]. Different aircraft jet systems for thrust enhancement [42], including hybrid systems [43, 44], are under consideration. Cican et al. [42] observed that the thrust in each mode increased with the use of the ejector, monitored acoustic noise, and found that it decreased using the ejector [42]. Zhang et al. [45] investigated various methods to predict aircraft noise from the complex effects of mixed acoustic sources in flight, primarily the airfoil, air intake, and tail nozzle jet. Radio-locating technologies for drone detection and identification of drone types using radar are being improved [46], which can also recognize the types of airscrews (pulling propellers or pushing propellers). Among several mechanisms for generating intrinsic airfoil noise, trailing edge blunting noise is an essential cause of vortex separation at blunt trailing edges. Xing et al. [47] performed a numerical study of controlling noise due to airfoil blunting at the trailing edge using wavy edges inspired by nature and biotechnology. Aircraft use an integrated ejector that acts as an infrared suppressor to reduce the infrared signal with radar-acoustic stealth [48].

When studying an ejector with a curved mixing chamber, it is necessary to consider the study results of S-shaped ducts. The large curvature of modern S-shaped ducts causes a strong secondary flow, which strongly affects flow uniformity [49–51]. Fully developed turbulent flow in ducts with weak and strong longitudinal curvature is studied by direct numerical simulation [51].

Many significant interdisciplinary technological advances are now visible in aerospace and energy engineering [52]. These encompass the increased use of computers at every stage of product design, various modeling, computation, optimization, and artificial intelligence (AI) techniques, as well as significant breakthroughs in materials science, including high-precision and additive manufacturing methods, options for electrification of flow machines together with the use of unconventional fuels. Svorcan et al. [52], Abu Salem et al. [53], and Peciak et al. [54] explored various methods for flow control (passive and active control, both in low- and high-speed flows) to improve efficiency, aerodynamic quality, boundary layer stabilization, and aircraft control.

The significant growth of AI methods in machine learning has opened additional opportunities for fluid dynamics and its applications in science and engineering. However, experts note that AI methods should be deeply immersed in interpretability, with detailed explanations of cause-and-effect relationships [55]. The potential impact of AI will be high only if the output obeys physical laws. Research in AI is advancing rapidly, and fluid dynamics will benefit from it. Nevertheless, its applicability should be thoroughly tested and verified. In addition, researchers should be allowed to publish not only their successes but also their unsuccessful attempts at using AI [55].

Publications provide a thorough analysis of fixed-wing unmanned aerial vehicles (UAVs or drones) and statistical analysis of key parameters of such aircraft designs [56]. Deploying a swarm of robots or a group of intelligent robots in a real-world scenario that can collectively perform a task or solve a problem remains a main research challenge [57–59]. These survey publications illustrate the basics of swarm systems and make predictions for the future based on their history [57–59].

The authors consider the listed publications, research, and design developments in the framework of collecting, analyzing, and summarizing information, with possibilities for its use in the educational process to train modern designers. The information analysis shows that studies mainly aim to solve applied scientific problems using known schematic diagrams or technical solutions. According to the authors, not enough attention is paid to fundamental scientific research related to the initial formation of new schematic diagrams of inventive level, which can predict, shape, and create the future in the chosen field of science and technology. The most striking example, in our opinion, relates to the justified long-term forecasts of Euler in developing hydrodynamics and gas dynamics in general and fluidics in particular. Creating the future seems to be through further development of Euler's innovative school, but with a new reading of his old works and considering the possibilities for helpful application of variations from the emerging AI. The main objectives of this paper are to identify promising directions of science, technology, and engineering development using jet devices and complex jet systems, as well as new opportunities for improving their design methodology while training modern designers-inventors.

2. Research Methodology

Figure 1 presents a flowchart explaining the research methodology.

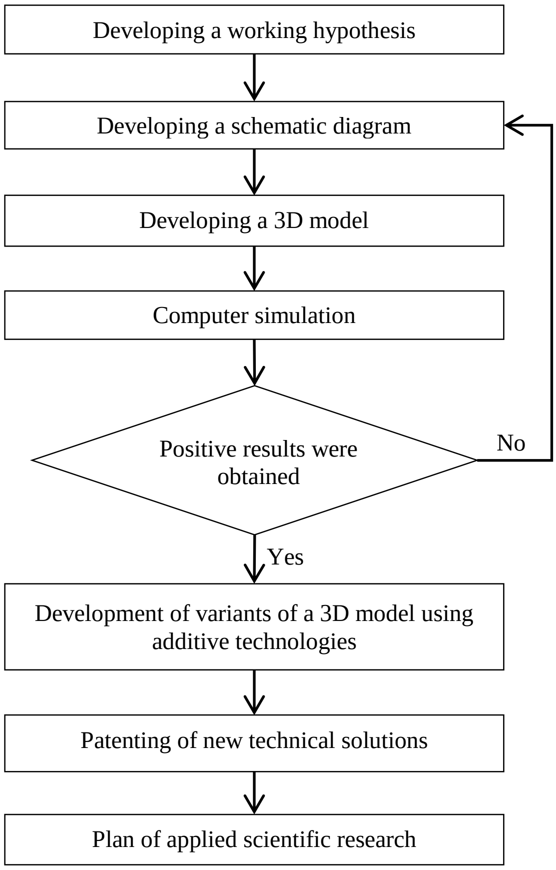


Figure 1. Flowchart explaining the research methodology

According to the flowchart (Figure 1), the methodology involves developing a working hypothesis about the ejection process when using a controlled nozzle to deflect the thrust vector (velocity vector) in any direction within a complete geometric sphere. The primary concept relates to studying gas-dynamic and hydrodynamic processes in nozzle and jet system channels. Developing the working hypothesis involves the analysis of individual facts, performing their synthesis and generalization within the framework of Euler's ideas development, and reviewing scientific and technical information. Further, the working hypothesis suggests the possibility of creating a new jet system and includes developing a schematic diagram and 3D models for jet systems equipped with control systems. Next, computer simulation uses these 3D models. After analyzing its results, the work, if necessary, returns to developing the flowchart to improve it. In case of obtaining positive results, after computer simulation, the work proceeds to create a series of 3D models to assess the practical application of the research results. The following steps include patenting new technical solutions designed to solve actual production and scientific problems and developing plans for applied research and R&D.

The authors used the well-known methodology [60] with an interdisciplinary approach in research and design [1, 2, 5], always considering a set of many processes and conditions:

- Vane and vortex workflows;
- Pumping (compressor) and turbine workflows;
- Processes of coalescence and dispersion, cavitation in liquid and gas–liquid mixture, and separation in multiphase media;
- Workflows in the presence of solids in the fluid flow, point or distributed energy supply, series and parallel connection of machines, single-stage or multi-stage machines;
- Flow processes considering hydraulic friction and impact losses with partial pressure recovery at constant and variable resistance coefficients;
- Development or attenuation of individual hydrodynamic (gas-dynamic) processes at different points of the machine working chamber with changing working body parameters;
- Features of changes in the physical properties of the liquid or gas–liquid mixture at various points in the flow part of the machine;
- Conditions for the presence (or absence) of axial symmetry for solid walls in the flow channels (and for the flow of fluid medium);
- Conditions and methods used to regulate the machine;
- Conditions for ensuring steady (or pulsed) flow regimes in individual zones and channels.

The ongoing studies include developing technical proposals for solving practical problems, including creating energy-saving technologies. The project involves new approaches to implementing energy transformations in technological and technical systems during the production and processing of hydrocarbons using computerized ejection processes while organizing interdisciplinary scientific research to develop special-purpose technologies for promising technologies. There are also plans to transition to advanced digital, intelligent manufacturing technologies, robotic systems, new materials and design methods, and the creation of systems for processing big data using machine learning and AI. The project contributes to the widespread introduction of ejection robotic systems in the energy sector and other industries, including digital jet control systems for compressors, pumps, and turbine units and ejection augmenters and control systems for drones for various purposes.

The presented paper aims to discuss the issues of variants of fluidics development, including within the framework of Euler's ideas. The authors plan to use their scientific background [1, 2, 5] to achieve this goal. When considering the methodology, it is possible to assume the necessity of using an additional tool in the form of a transdisciplinary approach, which complements disciplinary and interdisciplinary approaches. This study analyzes scientific and technical information in the framework of deductive logic, with the transition from the general to the particular in the reasoning process. Inductive logic presents individual reasoning and hypotheses, builds a general conclusion on the basis of particular premises, and derives a generalizing statement comparing facts. Some arguments use the well-known reduction principle, which is the reduction of the complex to the simple, the highest to the lowest, the whole to the properties of parts, and parts to the specificity of the whole.

The methodology of this study also relies on the philosophy of technology [61] and the theory of inventive problem-solving [62]. In addition, this paper considers some possibilities for the practical use of holistic forecasting results. As it is well known, holism in the broad sense is a position in philosophy and science on the problem of the relationship between the part and the whole, coming out of the qualitative uniqueness and priority of the whole over its parts. Specialists have described the features of future-oriented thinking [63] as follows:

- Consideration of multiple possibilities of future development, alternative futures, or, more precisely, alternative perspectives;
- Orientation not only toward a desirable future but also toward an achievable future;

- Understanding the horizon of our vision of the future;
- Developing holistic thinking, understanding the broad or even global context of any problem under study, and understanding the general laws of integration and mutually agreed sustainable development of various complex structures worldwide.

The assumption is that only the present is more or less accessible to us, and the future is achievable only through the difficult work of prediction and construction. Meanwhile, the past is attainable through the labor-intensive work of reconstruction and description [63]. Both are inevitably due to inaccuracies in our interpretations.

Experts call foresight research one of the methods of holistic forecasting. Foresight is a technology and communication format that allows participants to agree on images of the future and, having defined the desired image, and to coordinate actions in its context. Foresight is also defined as active forecasting, predicting the development of the future situation in the economy, science, business, and other spheres. According to experts, foresight can mean a way of thinking (from the future to the present), a way of organizing activities (building projects of changes), a method of organizing group work, and a specific product (forecast, roadmap, handbook).

3. Results

3.1. Development of Schematic Diagrams for Promising Fluidics

The ongoing studies consider new approaches to the development of fluidics. Prepared for patenting, the technical solution under development relates to fluidics, including jet pumps and compressors, jet amplifiers with control systems, and jet propulsion systems for dynamic positioning systems with thrust vector control. It is particularly applicable in the oil and gas industry to improve the efficiency of hydrocarbon production and processing, including offshore development with underwater equipment.

From known technical solutions, the closest to the proposed solution is a jet pump unit containing a source of the working medium, working chamber, nozzle, and diaphragm placed between the nozzle and working chamber (patent RU 2100659, 1997). The disadvantage of known technical solutions is a relatively narrow range of regulation of flow operating parameters at the nozzle outlet, which limits the scope of application of the pumping unit in creating energy-saving technologies. The range limitation is due to the energy conversion in one working chamber rigidly connected with one energy consumer. The technical problem that this invention aims to solve is to extend the range of flow operating parameters at the nozzle outlet. The jet device contains at least two working chambers, a nozzle with inlet and outlet channels, and a diaphragm placed between them. The diaphragm has a rod mounted on it that is adapted to reciprocating or angular movement of the diaphragm relative to the outlet channel of the nozzle to ensure the adjustable direction of the working medium flow into one of the working chambers.

Preferably, the diaphragm comprises a disk with an arched canopy and a rod mounted on it. The achievable technical result is to provide a controlled redistribution of energy flow for the individual working chambers by regulating the momentum parameters of flows in the cross-section at the nozzle outlet and separate working chambers and the possibility of complete disconnection of one or more of them in emergencies, particularly in the case of a blackout. The developed technical solution was patented, the application for invention No. 2022129561, the obtained decision to grant a patent of the Russian Federation of 19.06.2023.

The following figures explain the essence of the described invention. Figure 2 shows a diagram of the jet pump unit.

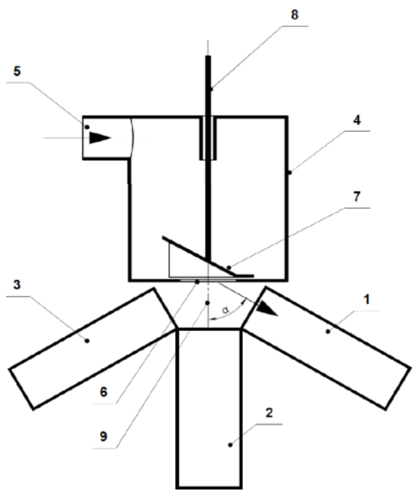


Figure 2. A diagram of the jet pump unit

Figure 3 shows the diagram of the jet pump unit (after rotating diaphragm 7 by 180° relative to axis 9).

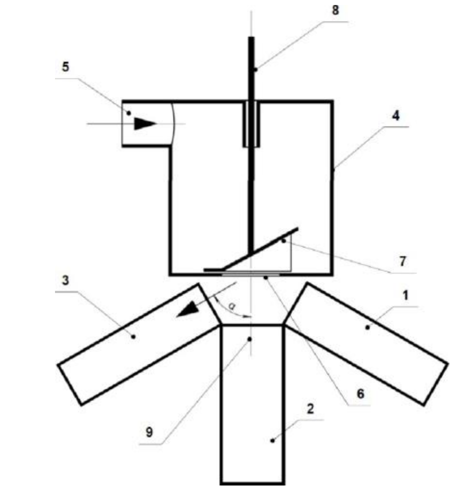


Figure 3. A diagram of the jet pump unit (after rotating diaphragm 7 by 180 degrees relative to axis 9)

Figure 4 shows a diagram of the jet pump unit (after linear displacement of diaphragm 7).

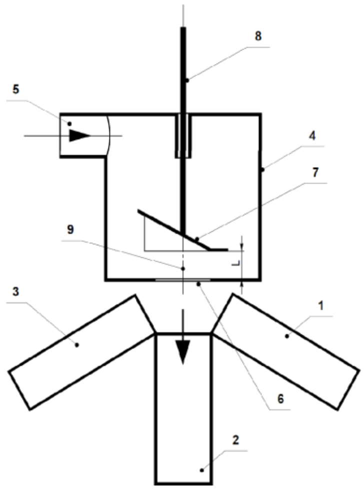


Figure 4. A diagram of the jet pump unit (after linear displacement of diaphragm 7)

Figure 5 shows a 3D model of the diaphragm (embodiment) with a view of the top surface of disk 10.

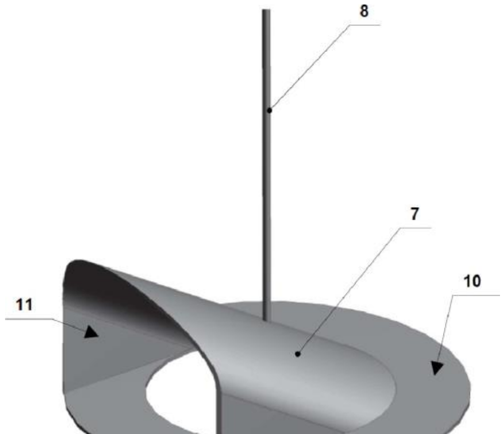


Figure 5. 3D model of the diaphragm (embodiment) with a view of the top surface of disk 10

Figure 6 shows a 3D model of the diaphragm with a view of the bottom surface of disk 10.

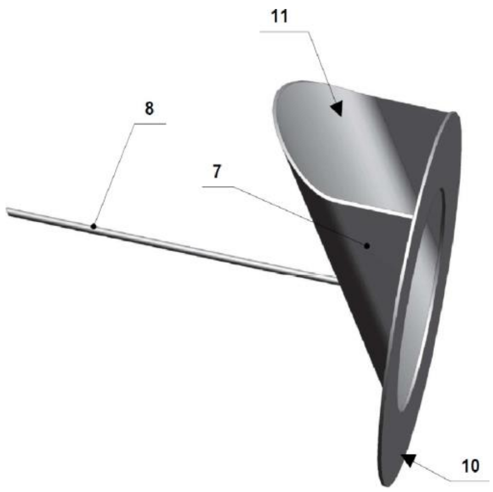


Figure 6. 3D model of the diaphragm with a view of the bottom surface of disk 10

Figure 7 shows one of the examples for a graphical representation of the dependence of the flow deflection angle $\propto$ on the linear displacement of the diaphragm $l = \frac{L}{d}$ (where L is the linear displacement [m], d is the diameter of the nozzle outlet channel [m]; the dependence $\propto (l)$ was obtained based on the results of computer simulation).

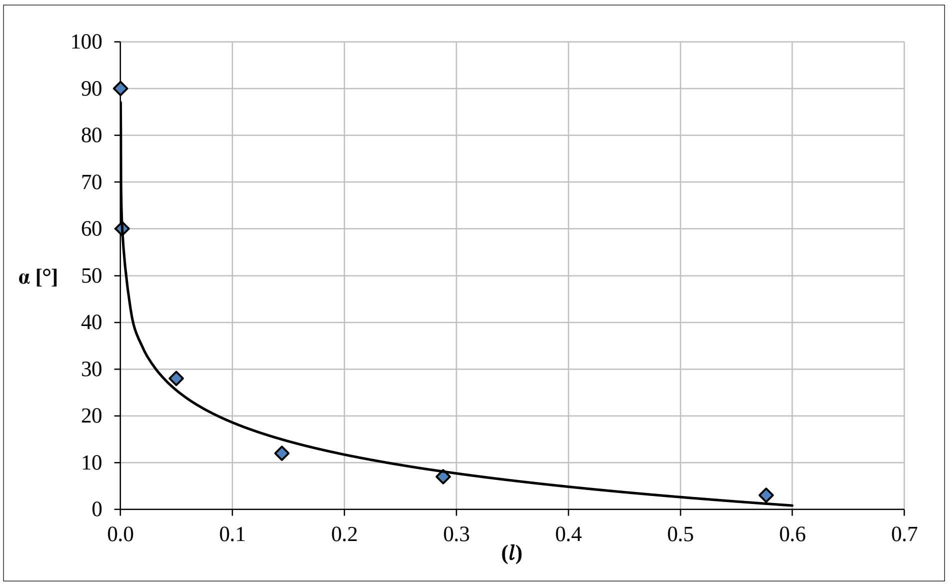


Figure 7. Graph of dependence of the flow deflection angle $\propto$ on the linear displacement of the diaphragm

The proposed jet device contains at least two working chambers 1 and 2 (the considered example shows the embodiment with three working chambers 1, 2, and 3), nozzle 4 with inlet 5 and outlet 6 channels, diaphragm 7 with rod 8 mounted on it adapted to reciprocating or angular movement of diaphragm 7 relative to outlet channel 6 of nozzle 4.

Outlet channel 6 of nozzle 4 has a hydraulic connection with working chamber 1 or working chambers 2 and 3. The number of working chambers may be greater, and they, with flow channels, may form a mesh structure. Diaphragm 7 is between inlet 5 and outlet 6 channels of nozzle 4 adapted to linear and angular displacements relative to outlet channel 6 of nozzle 4 for controlled change of flow direction in it. Angular displacement (rotation) of diaphragm 7 around axis 9 is possible from +180° to -180°. Diaphragm 7 may have various embodiments and aperture configurations. In the example shown, diaphragm 7 is in the form of disk 10 with an arched canopy 11. Other geometric shapes for making the aperture in diaphragm 7 are also possible, including polygonal variants (pentagon or others). Diaphragm 7 itself may have various embodiments and shapes, including variable geometry. It is also possible to rotate diaphragm 7, for example, around axis 9, at a constant or variable angular velocity. Various known drive systems, such as electromagnetic or hydraulic actuators (not shown in the figures), are possible for the linear and angular displacement of diaphragm 7. For example, the kinematic connection between diaphragm 7 and the mentioned drive system may use rod 8.

Figures 5 and 6 show an embodiment of the diaphragm comprising disk 10 with an arched canopy 11 and rod 8 mounted on it.

3.2. Description of the Operating Principle of the Jet Unit

The jet unit operates as follows: a working medium (liquid, gas, or gas-liquid mixture) enters nozzle 4 through inlet channel 5. Figures do not show the source of the working medium.

The working medium flow passes through the aperture of diaphragm 7 and outlet channel 6 of nozzle 4. From nozzle 4, the working medium flow goes to working chamber 1. Arrows in the figures show the flow direction. In working chamber 1, the working medium mixes with the pumped medium, implementing the ejection workflow, in which part of the energy from the working medium flow passes to the pumped medium flow. After passing through working chamber 1, the mixture of working and pumped medium goes further to the technological system, not shown in the figures.

Diaphragm 7 is between inlet 5 and outlet 6 channels of nozzle 4 adapted to linear and angular displacements relative to outlet channel 6 of nozzle 4 for controlled change of flow direction in it. By turning rod 8 and diaphragm 7, the working medium flow can go into working chamber 2 or 3, depending on the solved technological task (Figure 3 and 4).

At linear displacement L of diaphragm 7, the flow direction in outlet channel 6 of nozzle 4 changes with the flow deflection angle a (Figure 4). The combined linear and angular displacement of diaphragm 7 relative to outlet channel 6 of nozzle 4 allows flexible regulation of the working medium flow direction within the lower geometrical hemisphere (Figures 4 and 7): it can go into one, two, or three working chambers. The distribution of the working medium over working chambers 1, 2, and 3 can be uniform or non-uniform, depending on the solved technological task. Thus, the above regulates the momentum parameters of flows in the cross-section at the nozzle outlet and separate working chambers, defined as the product of the mass flow rate by the flow velocity. It is possible to rotate diaphragm 7, for example, around axis 9 to realize a pulse (unsteady) flow mode through working chambers 1, 2, and 3, while possibly maintaining a stationary flow regime in the channels of nozzle 4 and diaphragm 7.

The graph shown in Figure 7 illustrates one example of a graphical representation of the dependence of the flow deflection angle $\propto$ on the linear displacement of the diaphragm $l = \frac{L}{q}$. Other embodiments of the jet device are also possible, for which the maximum flow deflection angle $\propto$ takes the value of 90°. In this case, it is possible to adjust the direction of the working medium flow within the lower geometric hemisphere, considering that the angular displacement (turn) of the diaphragm 7 around axis 9 is possible in the entire range from +180° to -180°.

The nozzle may have two apertures 6 pointing in opposite directions. Each can be supplemented with its diaphragm 7 using an independent control system. Such a tandem will make it possible to control the thrust vector (velocity vector) within a complete geometric sphere. The jet unit may have a plurality of diaphragms 7 with a plurality of apertures 6 simultaneously in one technical system for solving specific technological problems. The description of the invention provides only an example of an implementation of the claims of this invention, and this description is not a limitation on the broad possibilities or variants for the practical use of the claims themselves.

Thus, the proposed invention solves the problem of increasing the control of energy distribution in the flow over the area of the nozzle outlet channel to ensure controlled redistribution of flow energy over separate working chambers and adapted to regulating the momentum parameters in the cross-section at the nozzle outlet and separate working chambers, respectively.

3.3. Developing a Simplified Mathematical Model

Figure 8 shows a diagram of the jet device with two working chambers. In this example, one working chamber is straight and the other is curved. The nozzle makes it possible to change the direction of the working medium flow by changing the mass flow rate of the working medium in each of the working chambers.

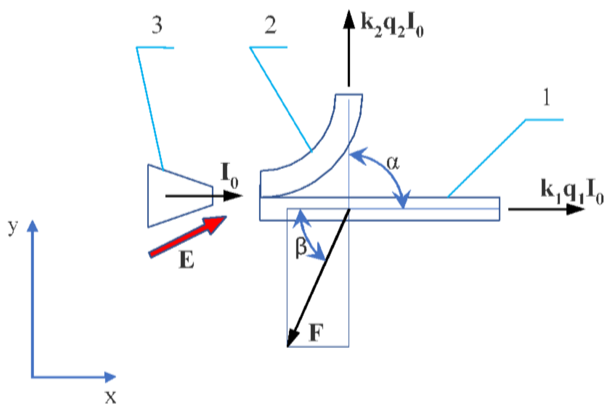


Figure 8. Diagram of a jet device with two working chambers: 1 – straight working chamber; 2 – curved working chamber; 3 – nozzle

We consider the simplest training example when the ambient pressure does not change and remains constant at the inlet and outlet for each working chamber 1 and 2. For example, this jet device (as part of the propulsion device) can operate in atmospheric air or underwater. In the patent phase of a new technical solution, as a rule, calculations confirm the operability of this technical solution. In this case, we can limit ourselves to a simplified mathematical model. Here, the mass flow rate of the working medium at the nozzle outlet is Q_0. The momentum parameter for the flow at the nozzle outlet is $I_0 = Q_0 v$, where v is the working medium flow velocity. In this example, the fluid flow is divided into two streams:

$$Q_0 = Q_{01} + Q_{02} \tag{1}$$

where Q_{01} is mass flow rate of the working medium through the first working chamber, Q_{02} is mass flow rate of the working medium through the second working chamber.

$$q_1 = \frac{Q_{01}}{Q_0} = \frac{Q_{01} v}{Q_0 v} = \frac{I_{01}}{I_0} \tag{2}$$

$$q_2 = \frac{Q_{02}}{Q_0} = \frac{Q_{02} v}{Q_0 v} = \frac{I_{02}}{I_0} \tag{3}$$

where q_1 is the relative flow rate of the working medium through the first working chamber, q_2 is the relative flow rate of the working medium through the second working chamber, I_{01} is the momentum at the inlet to the first working chamber, I_{02} is the momentum at the inlet to the second working chamber.

In this case,

$$I_0 = Q_0 v = Q_{01} v + Q_{02} v = I_{01} + I_{02} \tag{4}$$

The momentum parameters at the inlet of the first working chamber I_{01} and its outlet I_1 may differ. The momentum parameters at the inlet of the second working chamber I_{02} and its outlet I_2 may also differ. In this connection, let us introduce the coefficients of the momentum change for the first working chamber k_1 and the second one k_2:

$$\frac{I_1}{I_{01}} = k_1 = \frac{I_1}{q_1 I_0} \tag{5}$$

$$\frac{I_2}{I_{02}} = k_2 = \frac{I_2}{q_2 I_0} \tag{6}$$

$$I_1 = k_1 q_1 I_0 = k_1 I_{01} \tag{7}$$

$$I_2 = k_2 q_2 I_0 = k_2 I_{02} \tag{8}$$

We can assume for a simplified mathematical model the equality of modulo for the nozzle reactive force (propulsive thrust) F_0 and the momentum I_0.

$$|F_0| = |I_0| \tag{9}$$

Projections of the resulting reactive force F on the axes in the adopted coordinate system are as follows:

$$F_x = k_1 Q_{01} v + k_2 Q_{02} v \cos\alpha \tag{10}$$

$$\frac{F_x}{F_0} = k_1 q_1 + k_2 (1 - q_1) \cos\alpha = k_1 q_1 + k_2 q_2 \cos\alpha \tag{11}$$

$$F_y = Q_{02} v \sin\alpha = k_2 q_2 I_0 \sin\alpha \tag{12}$$

$$\frac{F_y}{F_0} = k_2 q_2 \sin\alpha = k_2 (1 - q_1) \sin\alpha \tag{13}$$

$$F = \sqrt{F_x^2 + F_y^2} \tag{14}$$

The coefficient of thrust variation k_F when using two working chambers is given by:

$$k_F = \frac{F}{F_0} \tag{15}$$

To determine the angle β, in this case, we can use the following relations:

$$\beta = \arctan\left(\frac{F_y}{F_x}\right) = \arctan\left(\frac{k_2 (1-q_1) \sin\alpha}{k_1 q_1 + k_2 (1-q_1) \cos\alpha}\right) \tag{16}$$

$$\beta = \arctan\left(\frac{k_2 q_2 \sin\alpha}{k_1(1-q_2)+k_2 q_2 \cos\alpha}\right) \tag{17}$$

In this example (in the patent phase of a new technical solution), $k_1 = 1$. To reflect the dependence of k_2 on the angle α, we used the following empirical formula:

$$k_2 = 1 - (A_2\alpha^2 - B_2\alpha) = 1 - (0.0304\alpha^2 - 0.0159\alpha) \tag{18}$$

Here A_2, B_2 are empirical coefficients that will be refined as scientific information accumulates.

Additional energy E can be supplied at the inlet to working chambers 1 and 2 (Figure 8). Here, coefficients k_1, k_2 can be slightly increased, but we plan to consider these workflow features later while developing scientific research.

4. Discussion

4.1. Discussion of Different Versions of the Jet Device

The developed mathematical model (Equations 1 to18) allows us to quantitatively evaluate the relationship between some geometric and gas-dynamic (hydrodynamic) parameters when controlling the thrust vector. Tables 1 to 3 present the calculation results for the three variants: $\alpha = 30°$; $\alpha = 60°$; $\alpha = 90°$.

Table 1. Calculation results for variant α=30°

q1	q2	Fx/F0	Fy/F0	KF(α=30°) KF	rad β	β(α=30°) degrees β
0.00	1.00	0.87	0.50	1.00	0.52	30.00
0.10	0.90	0.88	0.45	0.99	0.47	27.10
0.20	0.80	0.89	0.40	0.98	0.42	24.13
0.30	0.70	0.91	0.35	0.97	0.37	21.12
0.40	0.60	0.92	0.30	0.97	0.32	18.07
0.50	0.50	0.93	0.25	0.97	0.26	15.00
0.60	0.40	0.95	0.20	0.97	0.21	11.93
0.70	0.30	0.96	0.15	0.97	0.16	8.88
0.80	0.20	0.97	0.10	0.98	0.10	5.87
0.90	0.10	0.99	0.05	0.99	0.05	2.90
1.00	0.00	1.00	0.00	1.00	0.00	0.00

Table 2. Calculation results for variant α=60°

q1	q2	Fx/F0	Fy/F0	KF(α=60°) KF	rad β	β(α=60°) degreesβ
0.00	1.00	0.49	0.85	0.98	1.05	60.00
0.10	0.90	0.54	0.77	0.94	0.95	54.71
0.20	0.80	0.59	0.68	0.90	0.85	48.95
0.30	0.70	0.64	0.60	0.88	0.75	42.78
0.40	0.60	0.69	0.51	0.86	0.63	36.32
0.50	0.50	0.75	0.43	0.86	0.52	29.72
0.60	0.40	0.80	0.34	0.87	0.40	23.15
0.70	0.30	0.85	0.26	0.89	0.29	16.78
0.80	0.20	0.90	0.17	0.91	0.19	10.74
0.90	0.10	0.95	0.09	0.95	0.09	5.13
1.00	0.00	1.00	0.00	1.00	0.00	0.00

Table 3. Calculation results for variant α=90°

q1	q2	Fx/F0	Fy/F0	KF(α=90°) KF	rad β	β(α=90°) degrees β
0.00	1.00	0.00	0.95	0.95	1.57	90.00
0.10	0.90	0.10	0.85	0.86	1.45	83.33
0.20	0.80	0.20	0.76	0.79	1.31	75.26
0.30	0.70	0.30	0.66	0.73	1.15	65.72
0.40	0.60	0.40	0.57	0.70	0.96	54.94
0.50	0.50	0.50	0.47	0.69	0.76	43.53
0.60	0.40	0.60	0.38	0.71	0.56	32.35
0.70	0.30	0.70	0.28	0.76	0.39	22.15
0.80	0.20	0.80	0.19	0.82	0.23	13.36
0.90	0.10	0.90	0.09	0.90	0.11	6.03
1.00	0.00	1.00	0.00	1.00	0.00	0.00

Figures 9 to 11 graphically present the calculation results for the three variants: $\alpha = 30°; \alpha = 60°; \alpha = 90°$.

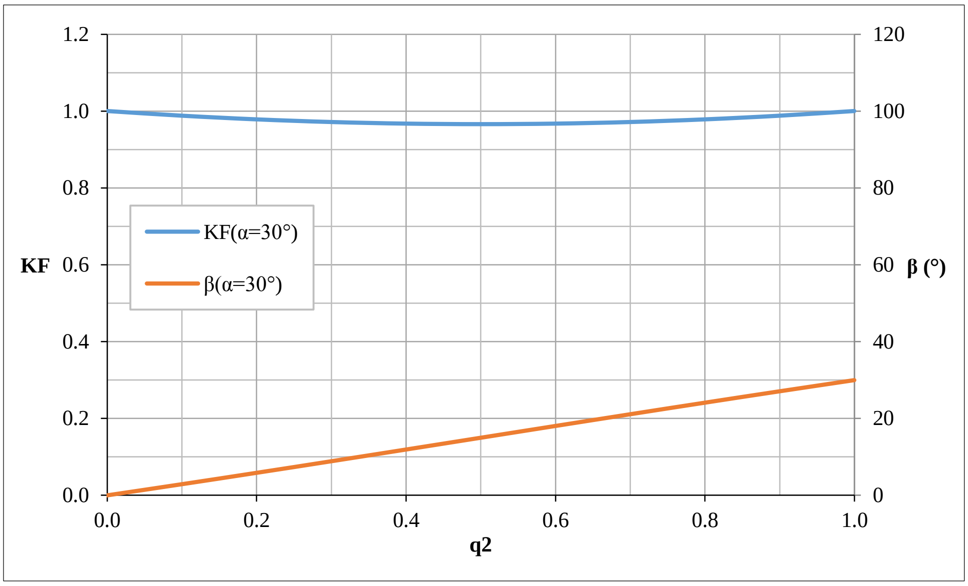


Figure 9. Calculation results for variant α=30° Source: developed by the authors of the paper

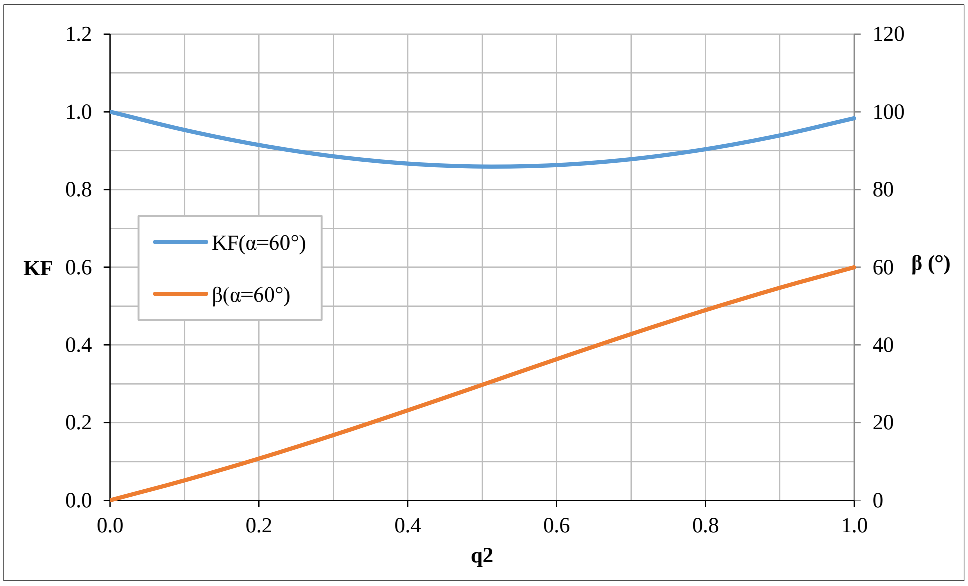


Figure 10. Calculation results for variant α=60° Source: developed by the authors of the paper

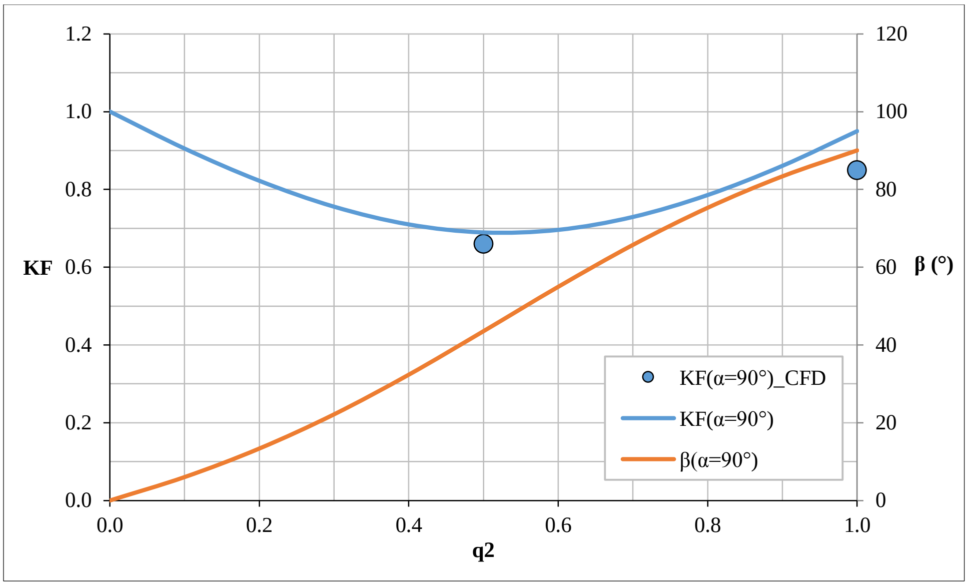


Figure 11. Calculation results for variant α=90° Source: developed by the authors of the paper

Figures 12 and 13 show a 3D model of the block of working chambers (variant according to the RF invention application No. 2022129561). Figure 13 shows all dimensions in millimeters.

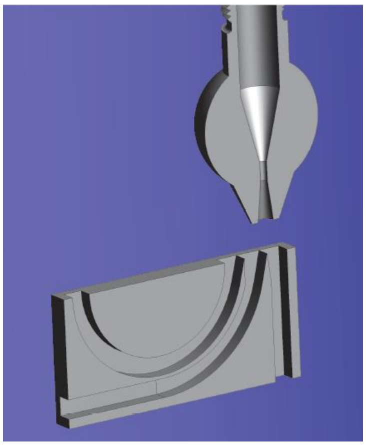


Figure 12. 3D model of the block of working chambers (variant according to the RF invention application No. 2022129561)

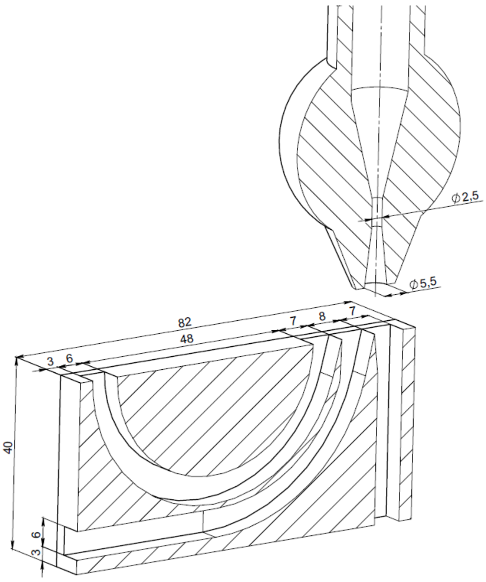


Figure 13. Calculation diagram of the block of working chambers (variant according to the RF invention application No. 2022129561)

In the presented embodiment, the linear movement of the nozzle distributes the working medium flow.

In the patent phase of a new technical solution, computational fluid dynamics (CFD) computer simulations aimed only to confirm the performance of the developed design and its elements. More detailed calculations and solutions of optimization problems will be performed later, at the stage of preliminary design. Computer simulation and computational study (CFD) used the FlowSimulation (*FloEFD*) software package. 3D modeling used the CAD SolidWorks system. In the simulation process, the full system of Navier–Stokes equations described by mathematical expressions of the laws of conservation of mass, energy, and momentum was solved with the turbulence parameters set automatically by default. A "k-ε" turbulent viscosity model was used to calculate the turbulence parameters for the closure of the Navier–Stokes equation system. The computer used had the following parameters: CPU type: Intel(R) Core (TM) i5-6200UCPU @ 2.30GHz; CPU speed: 2401 MHz; RAM: 8065 MB; Operating system: Windows 10.

Figure 14 graphically shows the separate results of the computer simulation. After dividing the working gas flow into two flows, one flow goes into the straight working chamber, and the second goes into the curved chamber with the flow turning by 90º. The calculation conditions were as follows: gas (air) pressure at the nozzle inlet was equal to 1519875 Pa at a gas temperature of 2000℃. The ambient gas (air) pressure was 101325 Pa, temperature – 20℃. The total number of cells was 580945. The calculation time was 15085 s. The number of iterations was 1500.

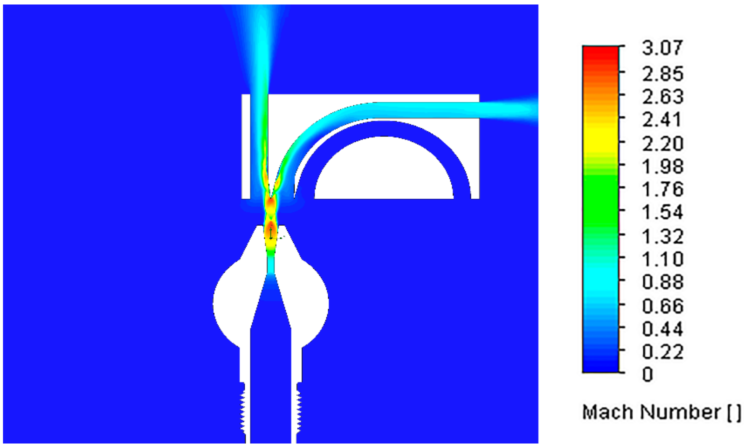


Figure 14. Example with computer simulation results (CFD): velocity palette (Mach number) when the second flow turns by 90º ($q_2 = 0.5$)

In the training example shown in Figure 14, the value of the coefficient $k_F = 0.66$ is obtained under the assumption that $q_2 = 0.5$ with flow division at the nozzle outlet. This result is marked in Figure 11 under the legend KF(α = 90°)_CFD. Comparing this result with the data in Figure 11, we can draw an intermediate conclusion about the suitability of the developed mathematical model for training purposes and for performing preliminary calculations.

Figure 15 graphically presents the separate results of the computer simulation. The working gas goes into a curved working chamber with the flow turning by 90º. The calculation conditions were as follows: gas (air) pressure at the nozzle inlet was equal to 1519875 Pa at a gas temperature of 2000℃. The ambient gas (air) pressure was 101325 Pa, temperature – 20℃. The total number of cells was 517139. The calculation time was 13562 s. The number of iterations was 1500.

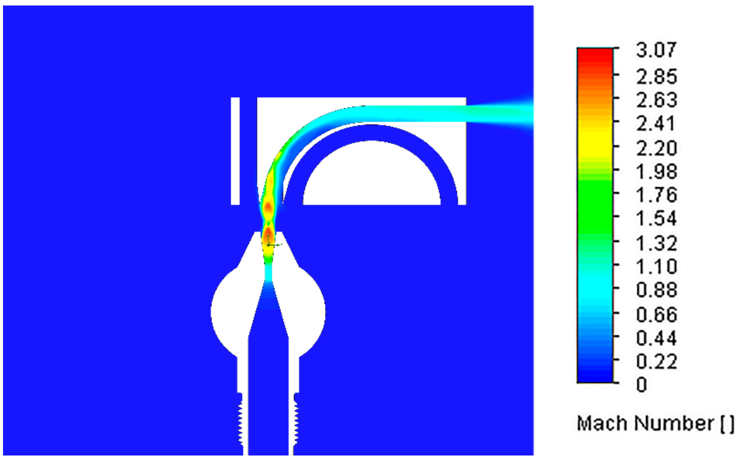


Figure 15. Example with computer simulation results (CFD): velocity palette (Mach number) when the flow turns by 90º ($q_2 = 1$)

In the training example in Figure 15, the value of the coefficient $k_F = 0.85$ is obtained when the flow turns by 90° ($q_2 = 1$). This result is marked in Figure 11 under the legend KF(α = 90°)_CFD. Comparing this result with the data in Figure 11, we can make an intermediate conclusion about the suitability of the developed mathematical model for training purposes and for performing preliminary calculations.

Figure 16 graphically presents the separate results of the computer simulation. After dividing the working gas flow into two flows, one flow goes into the curved working chamber with the flow turning by 90°, and the second goes into the curved chamber with the flow turning by 180°. The calculation conditions were as follows: gas (air) pressure at the nozzle inlet was equal to 1519875 Pa at a gas temperature of 2000℃. The ambient gas (air) pressure was 101325 Pa, temperature – 20℃. The total number of cells was 711568. The calculation time was 18262 s. The number of iterations was 1500.

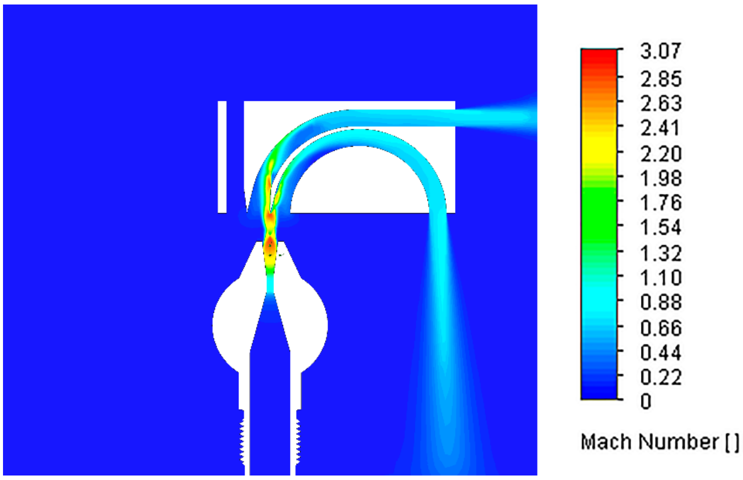


Figure 16. Example with computer simulation results (CFD): velocity palette (Mach number) when two flows turn by 90° and 180°

Figure 17 graphically presents the separate results of the computer simulation. The working gas flow goes into the curved working chamber with the flow turning by 180°. The calculation conditions were as follows: gas (air) pressure at the nozzle inlet was equal to 1519875 Pa at a gas temperature of 2000℃. The ambient gas (air) pressure was 101325 Pa, temperature – 20℃. The total number of cells was 598768. The calculation time was 15316 s. The number of iterations was 1500.

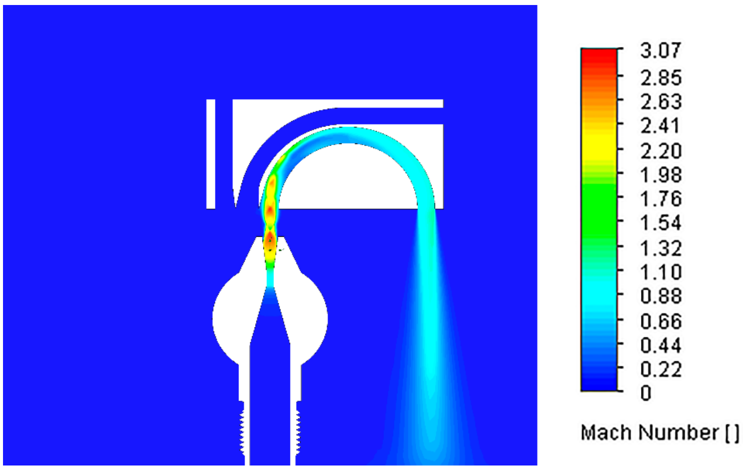


Figure 17. Example with computer simulation results (CFD): velocity palette (Mach number) when the flow turns by 180°

In the training example in Figure 17, the value of the coefficient $k_F = 0.83$ is obtained when the flow turns by 180° ($q_2 = 1$). Based on this result, we can make an intermediate conclusion about the suitability of curved S-shaped Euler tubes for creating various technical devices and jet systems to control the thrust vector, with the flow reversal at an angle of up to 180°

Figures 18 and 19 show a 3D model of the nozzle apparatus (variant according to the RF invention application No. 2022129561). The presented variant considers only the nozzle apparatus without working chambers. Figure 19 shows all dimensions in millimeters.

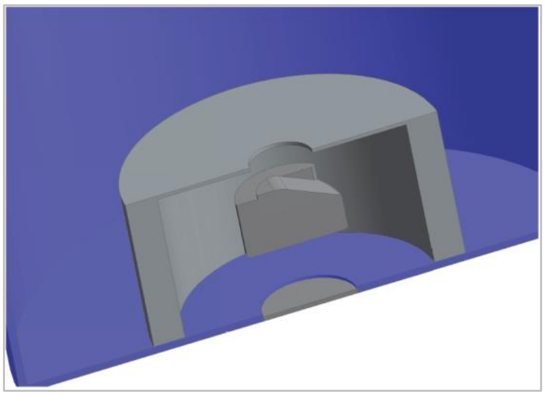


Figure 18. 3D model (variant) of the nozzle apparatus (according to the RF invention application No. 2022129561) *Source*: developed by the authors of the paper

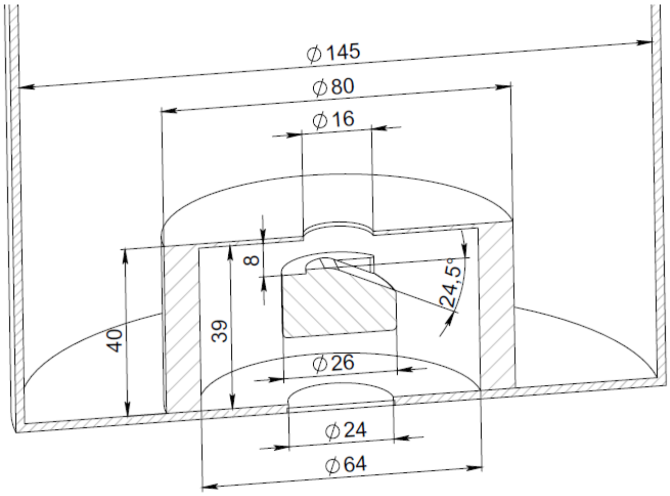


Figure 19. Calculation diagram of the nozzle apparatus (according to the RF invention application No. 2022129561)

Figure 20 graphically presents the separate results of the computer simulation. The working gas flows along the longitudinal axis of the nozzle. The calculation conditions were as follows: gas (air) pressure at the nozzle inlet was equal to 121325 Pa at a gas temperature of 20℃. The ambient gas (air) pressure was 101325 Pa, temperature – 20℃. The total number of cells was 659318. The calculation time was 17904 s. The number of iterations was 1500.

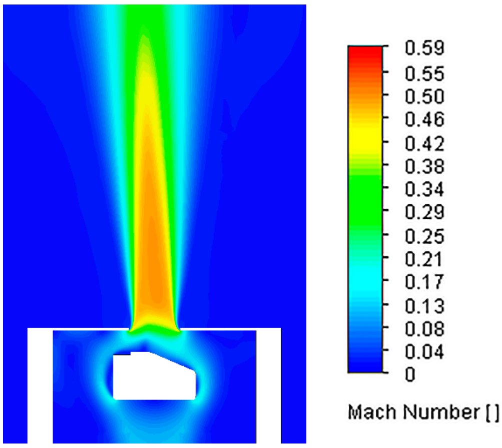


Figure 20. Results of computer modeling of the nozzle apparatus (according to the RF invention application No. 2022129561), variant at axial displacement L=8 mm

Figure 21 graphically presents the separate results of the computer simulation. The working gas flow deflects from the nozzle longitudinal axis by 90°. The calculation conditions were as follows: gas (air) pressure at the nozzle inlet was equal to 121325 Pa at a gas temperature of 20℃. The ambient gas (air) pressure was 101325 Pa, temperature – 20℃. The total number of cells was 665726. The calculation time was 18121 s. The number of iterations was 1428.

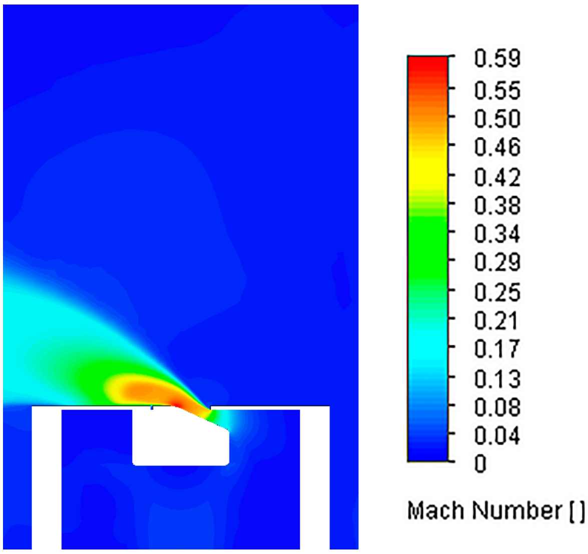


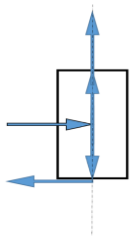
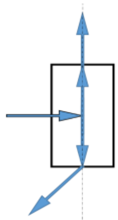
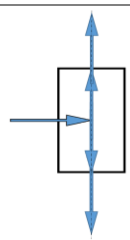
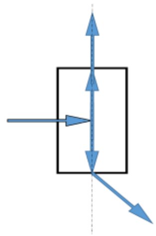
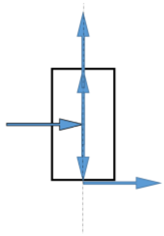
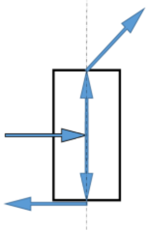
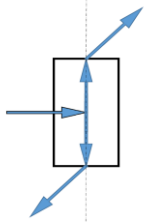
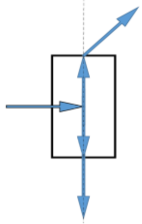
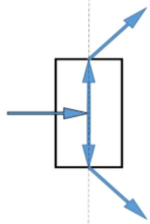
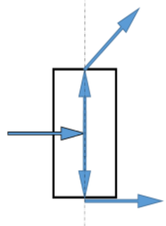
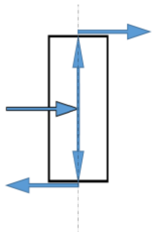
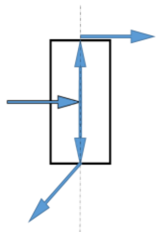
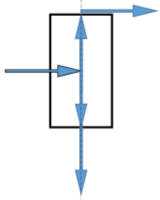
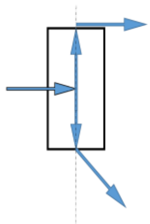
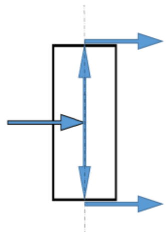
Figure 21. Results of computer modeling of the nozzle apparatus (according to the RF invention application No. 2022129561), variant of thrust vector control at axial displacement L=0 mm

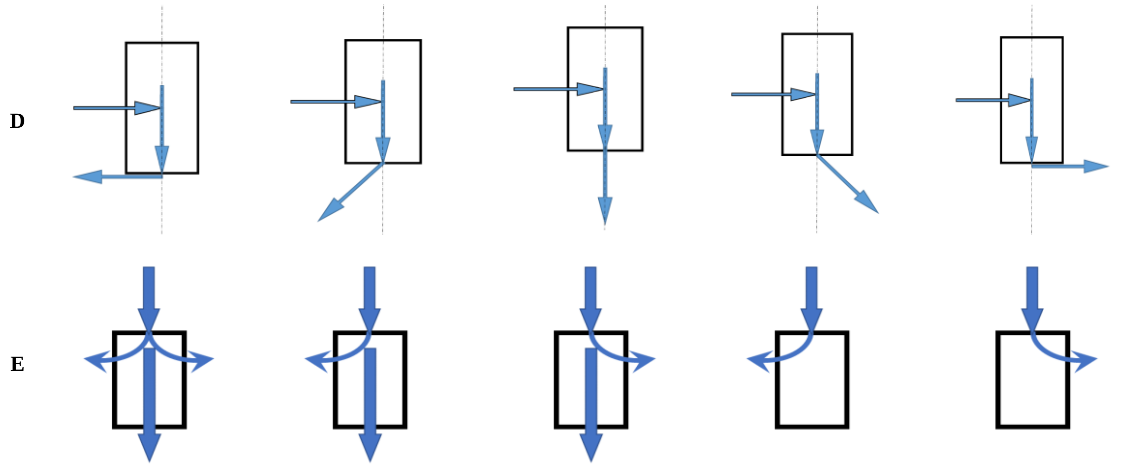
Thus, in the patent phase of the invention, the computer simulation results confirmed the performance of the new technical solution and its components.

4.2. Extending the List of Nozzle Apparatuses for Thrust Vector Control within a Complete Geometric Sphere

Table 4 schematically shows the basic modes of operation (variants) for the nozzle apparatus capable of controlling the thrust vector within the complete geometric sphere. The variants in rows A, B, C, and D were previously presented by the authors in their scientific groundwork [1]. In Table 4, the arrows in the diagrams show the flow directions (basic variants in continuation of [1]). Given the new patented technical solution (the RF invention application No. 2022129561), we have added line E to Table 4. The nozzle operation mode in Figure 14 corresponds to variants E2 and E3 (in the notation of the operation mode, the letter corresponds to the row, and the subsequent digit corresponds to the column number from the table). The nozzle operation mode in Figure 15 corresponds to variants E4 and E5; Figure 20 corresponds to variant D3; and Figure 21 corresponds to variants D1 and D5.

Table 4. Operating modes of the distributor (nozzle apparatus)

	1	2	3	4	5
A					
B					
C					



With the development of new technical solutions, Table 4 will be gradually updated with new data.

4.3. Laboratory Tests of the Nozzle Apparatus Micromodels for Thrust Vector Control within a Complete Geometric Sphere

Micromodels of the nozzle apparatus, adapted for thrust vector control within a complete geometric sphere, have been fabricated using additive technologies. Figures 22 and 23 show one of the nozzle apparatus variants and its main parts.

Figure 22. Micromodel (variant) of the nozzle apparatus (according to the RF invention application No. 2022129561)

Figure 23. Parts (variant) of the nozzle apparatus (according to the RF invention application No. 2022129561)

Figures 24 to 27 show photos of the nozzle apparatus micromodel (according to the RF invention application No. 2022129561) demonstrating thrust vector control variants when performing laboratory tests in the educational process. During the tests, water and air were the working media. This paper presents the results of hydraulic tests with a more informative visualization of the workflow in the print edition.

Figure 24. Photo of the nozzle apparatus micromodel (according to the RF invention application No. 2022129561) with a demonstration of thrust vector control, operating mode D3 (Table 4)

Figure 25. Photo of the nozzle apparatus micromodel (according to the RF invention application No. 2022129561), thrust vector control variant at axial displacement L=0 mm, operating mode D1 (Table 4)

Figure 26. Photo of the nozzle apparatus micromodel (according to the RF invention application No. 2022129561), thrust vector control variant within the complete geometric sphere, and operating mode C1 (Table 4)

Figure 27. Photo of the nozzle apparatus micromodel (according to the RF invention application No. 2022129561), thrust vector control variant at axial displacement L=0 mm, operating mode D5 (Table 4)

Thus, in the patent phase of the invention, the results of laboratory physical tests of micromodels confirmed the performance of the new technical solution and its components. The results of the numerical and physical experiments also show promise for developing scientific research in power jet automation by creating new jet logic elements and programable technical systems compatible with computer technologies.

4.4. Extending the List of Questions for a Design System of Jet Devices To Control The Thrust Vector Within A Complete Geometric Sphere

The diaphragm (or movable solid wall) may be inside the nozzle apparatus, at its outlet, or placed and used otherwise. For training and retraining of designers, a basic list of training questions was prepared, as shown in Tables 5 to 7 at the end of the paper in the Appendix section. This list can change according to the assigned training or production task.

Table 5. List of questions about the diaphragm design- *Source*: developed by the authors of the paper

No.	Questions	The answer option "Yes"	The answer option "No"
1	Diaphragm with a central body. The center body is placed inside the nozzle	Yes	No
2	Diaphragm with center body. The center body is placed outside the nozzle	Yes	No
3	Diaphragm with center body. The center body is movable relative to the nozzle exit	Yes	No
4	The diaphragm with a central body. The center body is capable of turn motion and rotation	Yes	No
5	Diaphragm with a central body. The central body is capable of linear movement	Yes	No
6	Diaphragm with a central body. Several central bodies (including different designs) are used	Yes	No
7	Diaphragm with a central body. The central body has one or more apertures (flow channels).	Yes	No
8	Diaphragm with a central body. The central body has flat surfaces	Yes	No
9	Diaphragm with a central body. The central body has curved surfaces (cylinder, cone, sphere or combined more complex surfaces)	Yes	No
10	The diaphragm is placed inside the nozzle	Yes	No
11	The diaphragm is placed outside the nozzle	Yes	No
12	The diaphragm is movable relative to the nozzle exit	Yes	No
13	The diaphragm is capable of turn motion and rotation	Yes	No
14	The diaphragm is capable of linear movement	Yes	No
15	Several diaphragms are used (including different modifications)	Yes	No
16	The diaphragm has one or more apertures (flow channels)	Yes	No
17	The diaphragm has flat surfaces	Yes	No
18	The diaphragm has curved surfaces (cylinder, cone, sphere or combined more complex surfaces)	Yes	No
19	A diaphragm fragment is used	Yes	No
20	Combined systems with center bodies and diaphragms are used	Yes	No
21	The diaphragm makes it possible to divide the flow into two flows (including different flow directions at the nozzle outlet, following the ideas of Euler, Segner, and Geron)	Yes	No
22	The diaphragm makes it possible to divide the flow into three or more flows (including different flow directions at the nozzle outlet)	Yes	No
23	A multi-flow ejector system for thrust vector control is used	Yes	No
24	Ejector features are utilized for thrust vector control	Yes	No
25	Combination of rotation with thrust vector control	Yes	No
26	Partial utilization of jet kinetic energy for energy conversion (redistribution) (including thrust increase)	Yes	No
27	Creating conditions for thrust reduction and zeroing (without disconnecting from the energy source, among other things)	Yes	No
28	Reverse flows occur in the ejector chambers or the jet system chambers	Yes	No
29	Pulsed flows occur in the ejector chambers or the jet system chambers	Yes	No
30	The diaphragm is equipped with a system for transforming the shape and dimensions of the flow channels	Yes	No
31	A fast thrust vector (velocity vector) control system is used	Yes	No
32	The thrust vector angle ranges from +180o to -180o within the geometric sphere	Yes	No
33	Ergonomics and simplicity of the control system (for example, one common control system for vertical takeoff/landing and horizontal flight)	Yes	No

Table 6. List of questions about the design of the nozzle apparatus

No.	Questions	The answer option "Yes"	The answer option "No"
1	The nozzle has a traditional shape	Yes	No
2	Nozzle with a central body	Yes	No
3	Nozzle with axisymmetric channel shape	Yes	No
4	The cross-sectional area of the outlet channel is adjustable	Yes	No
5	The shape of the outlet channel is adjustable	Yes	No
6	Gas (fluid) temperature constant at points in the outlet section	Yes	No
7	Gas (fluid) velocity constant at points in the outlet section	Yes	No
8	Gas (fluid) density constant at points in the outlet section	Yes	No
9	More than one input channel	Yes	No
10	More than one outlet channel	Yes	No
11	More than one working body (gas, liquid, or other fluid)	Yes	No
12	The nozzle has moving (including rotating) parts	Yes	No
13	The flow regime is unsteady (gas, liquid, or other fluid)	Yes	No
14	Phase transitions occur (gas, liquid, or other fluid)	Yes	No
15	Chemical reactions occur (gas, liquid, or other fluid)	Yes	No
16	The working body interacts with the environment (gas, liquid, or other fluid medium)	Yes	No
17	The properties of the environment change (including temperature, pressure, and density)	Yes	No
18	Nozzle solid walls are washed by ambient flow	Yes	No
19	Nozzle solid walls are placed inside the product body	Yes	No
20	The nozzle is equipped with a thrust vector (velocity vector) control system	Yes	No
21	A fast thrust vector (velocity vector) control system is used	Yes	No
22	The thrust vector angle is from +180o to -180o within the geometric sphere.	Yes	No
23	Supersonic flow velocity at the nozzle exit	Yes	No
24	There are restrictions on the flow velocity at the nozzle outlet	Yes	No
25	There are restrictions on the flow temperature at the nozzle outlet	Yes	No
26	There are restrictions on the noise level for the flow at the nozzle outlet	Yes	No
27	There are restrictions on nozzle weight and dimensions	Yes	No
28	There are restrictions on the properties of structural materials for manufacturing the nozzle (and its components)	Yes	No
29	There are restrictions on nozzle operation time	Yes	No
30	There are additional requirements for assessing nozzle performance	Yes	No
31	There are additional requirements for assessing nozzle performance in terms of the "efficiency-price" criterion	Yes	No
32	Stationary operating mode for the working body source (fluid medium or working media)	Yes	No
33	The nozzle is used as part of the turbomachine - an "engine machine"	Yes	No
34	The nozzle is used as part of the turbomachine - "executing machine"	Yes	No
35	The nozzle is used as part of the turbomachine - "propulsion device"	Yes	No
36	The nozzle is used as part of the turbomachine - "gas generator machine"	Yes	No
37	The nozzle is used as part of the turbomachine - "heat exchanger machine"	Yes	No
38	The nozzle is used as part of the turbomachine - "mixer machine"	Yes	No
39	The nozzle is used as part of the turbomachine - "separator machine"	Yes	No
40	The nozzle is used as part of the hybrid machine (or system)	Yes	No
41	The nozzle is used as part of the jet device (or jet system)	Yes	No
42	Multicomponent multiphase medium is in the nozzle channels	Yes	No
43	The opportunity to choose and switch modes of operation in response to changes in the technical task (e.g., for the UAV with vertical takeoff and landing)	Yes	No
44	The parallel connection of individual jet devices (or elements) for thrust vector control is used	Yes	No
45	The series connection of separate jets (or elements) for thrust vector control is used	Yes	No
46	The opportunity of the special nozzle operation in combination with an airscrew, fan, compressor, gas turbine engine, rocket engine, direct-flow engine, or hybrid engine (provided that the thrust vector angle is in the range from +180o to -180o within the geometric sphere). Relevant implementation options	Yes	No

47	The opportunity of the special nozzle operation in combination with a propeller, axial pump, centrifugal pump, underwater rocket engine, or hybrid engine (provided that the thrust vector angle is in the range from +180o to -180o within the geometric sphere). Relevant implementation options	Yes	No
48	The pulse mode of flow of gases (liquids or multiphase media) in the control system elements is used	Yes	No
49	There is a requirement to minimize the number of moving parts in the control system	Yes	No
50	The nozzle is equipped with a specific system for transforming the shape and size of the flow channels	Yes	No
51	Adaptability of the control system shape and size to the shape and size of the aircraft or other product	Yes	No
52	Ergonomics and simplicity of the control system (for example, one common control system for vertical takeoff/landing and horizontal flight)	Yes	No
53	The opportunity to automatically perform a series of consecutive maneuvers within special programs	Yes	No
54	There is a synergistic effect of using combinations of several workflows for thrust vector control and solving additional tasks	Yes	No
55	There is a synergistic effect of using combinations of several thrust vector control methods	Yes	No
56	Fast and cheap training and retraining system for operators (or customers)	Yes	No

Table 7. List of questions about the design of the mixing chamber (working chamber)

No.	Questions	The answer option "Yes"	The answer option "No"
1	The mixing chamber has a traditional shape	Yes	No
2	The mixing chamber with central body	Yes	No
3	The mixing chamber with an axisymmetric form of channels	Yes	No
4	The cross-sectional area of the output channel is adjustable	Yes	No
5	The shape of the outlet channel is adjustable	Yes	No
6	Gas (fluid) temperature is constant at points in the outlet section	Yes	No
7	Gas (fluid) velocity is constant at points in the outlet section	Yes	No
8	Gas (fluid) density is constant at points in the outlet section	Yes	No
9	More than one inlet channel	Yes	No
10	More than one outlet channel	Yes	No
11	More than one working body (gas, liquid, or other fluid)	Yes	No
12	The mixing chamber has moving (including rotating) parts	Yes	No
13	The flow mode is unsteady (gas, liquid, or other fluid)	Yes	No
14	Phase transitions occur (gas, liquid, or other fluid)	Yes	No
15	Chemical reactions occur (gas, liquid, or other fluid)	Yes	No
16	The working body interacts with the environment (gas, liquid, or other fluid)	Yes	No
17	The properties of the environment change (including temperature, pressure, and density)	Yes	No
18	The solid walls of the mixing chamber are washed by the flow of the environment	Yes	No
19	The solid walls of the mixing chamber are placed inside the product body	Yes	No
20	The mixing chamber is equipped with a thrust vector (velocity vector) control system	Yes	No
21	A fast-acting thrust vector (velocity vector) control system is used	Yes	No
22	The thrust vector angle ranges from +180o to -180o within the geometric sphere	Yes	No
23	Supersonic flow velocity at the mixing chamber outlet	Yes	No
24	There are restrictions on the flow velocity at the outlet of the mixing chamber	Yes	No
25	There are restrictions on the temperature of the flow at the outlet of the mixing chamber	Yes	No
26	There are restrictions on the noise level of the mixing chamber outlet flow	Yes	No
27	There are restrictions on the mass and dimensions of the mixing chamber	Yes	No
28	There are restrictions on the properties of construction materials for the mixing chamber (and its components)	Yes	No
29	There are restrictions on the operating time of the mixing chamber	Yes	No
30	There are additional requirements for evaluating the mixing chamber performance	Yes	No
31	There are additional requirements for evaluating the mixing chamber performance in terms of the "efficiency-price" criterion	Yes	No
32	Stationary operating mode for the working body source (working medium or media)	Yes	No
33	The mixing chamber is used as part of the turbomachine - an "engine machine"	Yes	No
34	The mixing chamber is used as part of the turbomachine - "executing machine"	Yes	No

35	The mixing chamber is used as part of the turbomachine "propulsion device"	Yes	No
36	The mixing chamber is used as part of the turbomachine "gas generator machine"	Yes	No
37	The mixing chamber is used as part of the turbomachine - "heat exchanger machine"	Yes	No
38	The mixing chamber is used as part of the turbomachine - "mixer machine"	Yes	No
39	The mixing chamber is used as part of the turbomachine - "separator machine"	Yes	No
40	The mixing chamber is used as part of the hybrid machine (or system)	Yes	No
41	The mixing chamber is used as part of the jet device (or jet system)	Yes	No
42	Multicomponent multiphase medium is in the channels of the mixing chamber	Yes	No
43	The opportunity to choose and switch modes of operation in response to changes in the technical or tactical task (e.g., for the UAV with vertical takeoff and landing)	Yes	No
44	The mixing chamber is equipped with a specific system for transforming the shape and dimensions of the flow channels	Yes	No
45	The flow channels of the mixing chamber are formed using curved pipes	Yes	No
46	The flow channels of the mixing chamber are formed using straight pipes	Yes	No
47	Several mixing chambers are connected in series	Yes	No
48	Several mixing chambers are connected in parallel	Yes	No
49	Passive flow is adjustable	Yes	No
50	Active flow is adjustable	Yes	No
51	There are additional requirements for the properties of the working medium (gas, liquid, or other fluid) at the inlet of the mixing chamber	Yes	No
52	There are additional requirements for the properties of the working medium at the outlet of the mixing chamber	Yes	No
53	There are additional requirements for the process of energy supply in the channels of the mixing chamber	Yes	No
54	There are additional requirements for the process of energy redistribution in the channels of the mixing chamber	Yes	No
55	There are additional requirements for the process of energy removal from the channels of the mixing chamber	Yes	No
56	There are additional requirements for the simultaneous implementation of several workflows in the mixing chamber channel (including operation on new physical principles)	Yes	No

The presented questions aim at a deeper study of fluidics and improving the quality of education of students and specialists capable of solving non-standard tasks and inventive problems. It will not be an exaggeration to say that for each of the listed questions (for example, within the framework of the educational process), it is possible to prepare a dozen new technical solutions. Many new hybrid solutions can occur based on these solutions, and over the years, this number will tend to infinity. The selection of specific solutions (for solving practical human problems) involves financial costs and risk assessment. However, in terms of developing technical information and preparing scientific groundwork, there are now relatively inexpensive tools in the form of computer technologies (including AI). It is essential to have more high-quality scientific information in this scientific groundwork and to work out how to develop industrial production and transition ideas and inventions from the virtual to the real world in advance. It seems that this kind of scientific groundwork will determine the conditions of a competitive struggle shortly when the abilities of one person or hundreds of thousands of people together, even if all these people are super-geniuses, become insufficient to generalize cumbersome multidimensional scientific information. Thus, the role of computer technologies and AI will significantly increase in the scientific and technical fields.

As part of the history of turbomachinery development, it is possible to revisit the preserved materials of Leonhard Euler's correspondence with Janos-Andros Segner. As known, Leonard Euler proposed to consider the rotating (turbine rotor) and the stationary parts (turbine nozzle apparatus) jointly at the system level [64, 65] and to use curved S-shaped pipes to form the flow path of a hydraulic machine (the noted important historical documents should be considered together with modern publications to study and trace the trends in developing hydrodynamics and gas dynamics in general and fluidics in particular). In this correspondence [64], it is possible to see most of the essential recommendations suitable for designing modern vane machines. Euler's ideas and theory have been used before and continue to be actively applied nowadays in creating various jet devices and turbomachines. It is possible to say that Euler, in his lifetime, predicted the future for many centuries ahead and built a scientific base for this future, doing it in the spirit of holistic forecasting and "foresight" research [66]: "the best way to predict the future is to create it".

We see the following processes in Euler's diagrams and correspondence [64]. The fluid medium flow divides into several flows or several flows combine into one. The jet of liquid (or other working body) changes its direction after flowing out of the nozzle, which may be due to gravity, but other mechanisms may influence the flow. One of the diagrams shows a curved pipe at the nozzle outlet to provide a 90º flow turn (in a particular case) but generally, the angle of turn itself, as a parameter, can take other values. The mass flow rate of the working body (working gas or working fluid) is usually distributed uniformly throughout all channels of the rotor; however, this distribution may be non-uniform in general.

4.5. Discussion of Issues Related to Solving Innovative (Inventive) Problems

The development of interdisciplinary research [60] in fluidics today can be closely connected with computer simulation (CFD) and additive technologies. This implies the consideration of increasingly complex systems, including the use of AI. Generally, gas dynamics and hydrodynamics consider and study the interaction of a fluid medium with a solid wall. Scientific research and design here usually solve direct and inverse problems by considering many parameters. Here, multifactorial numerical experiments are planned and executed, in fact, with research and computational work in multidimensional space.

As part of the educational process (for example, in teaching constructors), in tasks with parameters, it is possible to divide all parameters into several sets (A, B, C, D). The solution to a similar problem with parameters can be represented as a function Y:

$$Y = f_Y(A, B, C, D) \tag{19}$$

where:

A – A set of geometrical parameters (for example, $a_1, a_2, a_3, ...$) that makes it possible to describe and form a 3D model of a solid wall with which the fluid medium interacts (it can be a 3D model of a separate flow channel or a whole complex hydraulic machine);

B – A set of gas-dynamic and hydrodynamic parameters (for example, $b_1, b_2, b_3, ...$) that makes it possible to describe the properties of the fluid medium at its interaction with a solid wall, considering the shape and dimensions of all elements of the solid wall and all elements as a part of a complex 3D model;

C – A set of parameters characterizing the properties of structural materials (for example, $c_1, c_2, c_3, ...$) used to form a solid wall with which the fluid medium interacts;

D – A set of economic parameters (for example, $d_1, d_2, d_3, ...$) characterizing the commercial attractiveness and practical value of the considered complex system, which realizes the fluid medium interaction with a solid wall.

Each of the noted sets has a limited number of parameters, which, to some extent, reflect the level of development of science and technology at a given point in time.

$$\begin{cases} A = \{a_1, a_2, a_3, ... a_{i_a} ... a_{t_a}\} \\ B = \{b_1, b_2, b_3, ... b_{i_b} ... b_{t_b}\} \\ C = \{c_1, c_2, c_3, ... c_{i_c} ... c_{t_c}\} \\ D = \{d_1, d_2, d_3, ... d_{i_d} ... d_{t_d}\} \end{cases} \tag{20}$$

$$\begin{cases} 1 \le i_a \le t_a \\ 1 \le i_b \le t_b \\ 1 \le i_c \le t_c \\ 1 \le i_d \le t_d \end{cases} \tag{21}$$

In general (when solving an optimization problem), the chosen optimization criterion η_i, or a set of similar criteria, depends functionally on the base sets (*A, B, C, D*):

$$\eta_i = f_{\eta_i}(A, B, C, D) \tag{22}$$

To predict the further development of science and technology, we propose the following expressions to illustrate that the total number of parameters will always increase with the accumulation of scientific and technical information:

$$\begin{cases} A_\infty = \{a_1, a_2, a_3, ... a_{i_a} ... a_{t_a}, a_{(t_a+1)}, ... a_\infty\} \\ B_\infty = \{b_1, b_2, b_3, ... b_{i_b} ... b_{t_b}, b_{(t_b+1)}, ... b_\infty\} \\ C_\infty = \{c_1, c_2, c_3, ... c_{i_c} ... c_{t_c}, c_{(t_c+1)}, ... c_\infty\} \\ D_\infty = \{d_1, d_2, d_3, ... d_{i_d} ... d_{t_d}, d_{(t_d+1)}, ... d_\infty\} \end{cases} \tag{23}$$

$$\begin{cases} 1 \le i_a < \infty \\ 1 \le i_b < \infty \\ 1 \le i_c < \infty \\ 1 \le i_d < \infty \end{cases} \tag{24}$$

In the context of historical development, the following relation $1 \le i_a \le t_{a_}$a is correct at a given moment (t). Accordingly, the parameter $a_{(t_a+1)}$ has not been invented yet; it does not exist, and specialists do not use it. On the other hand, we can say that this parameter already exists, but it is simply unnoticeable and invisible because it is the "invisible parameter" that has a zero numerical value $a_{(t_a+1)} = 0$. It will take some time for a human (or AI) to see this parameter, and the practical benefit is that this parameter can also have non-zero values $a_{(t_a+1)} \neq 0$. In this case, all such "invisible" parameters will become tangible objects suitable for scientific discussion and solving scientific and practical problems. Accordingly, the total number of analyzed parameters constantly increases over time within each set:

$$\begin{aligned} &a_{i_a} \in A_\infty \\ &b_{i_b} \in B_\infty \\ &c_{i_c} \in C_\infty \\ &d_{i_d} \in D_\infty \end{aligned} \tag{25}$$

$$\begin{aligned} &A \subset A_\infty \\ &B \subset B_\infty \\ &C \subset C_\infty \\ &D \subset D_\infty \end{aligned} \tag{26}$$

Such a scheme for predicting scientific development can be associated with the eternal movement "from knowledge to absolute knowledge."

If we argue in the context of the historical development of science and technology, we can also conduct a mental experiment in which we will move backward in time. In this case, the logical statement will be that the number of parameters with a non-zero value will decrease, and the number of parameters with a zero value will increase because we consider the movement variant according to the scheme "from knowledge to ignorance." As a result (with such a backward movement in time), we can come to the moment when all parameters take zero values. This moment corresponds to the level of “absolute ignorance” or “the level of knowledge of an infant” – we can also find such formulation in the philosophy of technology or the study of human cognitive abilities.

The content of all sets in Equations 20-22 is very individual, and to some extent, this content characterizes the readiness of a specialist (or a company) to conduct multifactor numerical experiments (or to solve optimization problems) in the presence of appropriate calculation methods and computer programs. The content of all sets, according to Equations 20-22, also characterizes the readiness of a specialist (or a company) to search for new patentable technical solutions, which itself relates to the accuracy of forecasting the future in general and separate innovations in particular (in terms of the development of science, engineering, and technology).

The specific theory for solving inventive problems can use the above considerations regarding the set of parameters. Here, it is essential to say that these problems are closely related to scientific, design, and engineering problems, although we can recognize that in modern conditions, the boundaries between all these tasks are becoming very blurred. With some simplifications, we can say that the inventive problem is reduced to the search for an unknown "invisible parameter" from the sets (A, B, C, D) with the assessment of real possibilities to give this parameter a non-zero value, for example, $a_{(t_a+1)} \neq 0$. Once this new parameter appears in a new mathematical formula, in a schematic diagram, or in a part or an assembly drawing, it will be possible to speak about the appearance of a new technical solution suitable for evaluating its inventive level and practical value. In this paper, we can distinguish the parameter $q_2 \neq 0$ as a candidate for the title of "invisible parameter."

During initial training or retraining of a designer, it is advisable to use a systematic approach aimed at solving non-standard and prospective tasks. Here, the solution of standard tasks should be oriented toward improving the quality of work results and reducing the expenditure of time and material resources.

As mentioned above, scientific research and design work in fluidics usually solve direct and inverse problems. In addition to these two types, Sazonov [60] proposed a third type of problem that refers to inventive problems in developing initial primary schematic diagrams. Only its development makes it possible to create a digital solid-state 3D model. Further, calculations and computer simulation (CFD) use this 3D model to solve direct and inverse problems. Thus, it is possible to accept the working hypothesis that the third type of problem is primarily relative to the direct or inverse ones. If we evaluate the above philosophically (in terms of the philosophy of technology, for example), then the schematic diagram reflects the general, and the 3D model reflects the particular.

4.6. Some Generalizations

The scientific research performed in 2021 and 2022 [1, 2, 5] prepared the scientific groundwork for fluidics. This scientific groundwork, in 2023, made it possible to raise the question of the possibility of forming a new scientific direction related to the use of ejection processes along with thrust vector control systems in extreme operating conditions within the complete geometric sphere (when the thrust vector can deflect by an angle from +180º to -180º). This groundwork showed the possibilities of creating a scientific and design school based on the Leonard Euler legacy within the emerging scientific direction (new design developments are also reflected in RF patents for inventions nos. 2778961 and 2781455 and the RF patent for utility model No. 214452).

Sazonov [60] considered the methodological issues in the design of various jet systems to implement ejection processes. Generally, such a jet system includes the following main components: nozzle apparatus, working chamber, and working medium source. Within the further development of the known methodology of jet system design, Sazonov [60] proposed in a more general case to consider nozzle apparatuses that provide thrust vector control within the complete geometric sphere (when for the thrust vector, the range of rotation angle variation is ±180° in any direction [1, 2, 5]. For such thrust vector control, it is possible to use movable elements (diaphragms) at the nozzle apparatus outlet [1, 5]. Here, we present variants of the diaphragms inside the nozzle apparatus. Further development of such nozzle apparatus diaphragms relates to the use of other technical and technological approaches, including many hybrid systems (philosophically, we can talk about an infinite number of variants). In the general case, we also proposed the use of multi-flow mesh structures to form channels in nozzle apparatuses and working chambers [1, 2, 5]. Generally, when considering the source of the working medium, we proposed to rely on the scientific groundwork prepared by Leonard Euler in the field of gas dynamics and hydrodynamics [64, 65]. In a particular case, the working medium source can be a pump, compressor, gas generator, or another source, for example, hybrid. Leonard Euler laid the scientific foundation and correctly predicted the development of fluidics and turbomachinery in general. Even today, it is hard to find examples in this field that do not use Euler's inventions and equations.

The scientific results obtained by the authors of this paper reveal new opportunities for more active development of jet (reactive) technology with the solution of interdisciplinary problems as applied to simple and complex jet systems, with low and extremely high energy density in the flows, with opportunities for predicting innovations since the proposed methodology is a logical continuation of Euler's time-tested works, but the continuation is based on a modern computerized science in the intersection of several (many) research disciplines.

Further development of the well-known methodology of jet system design [60] is related to the continuous updating of the curriculum in the training of modern designers. In contemporary conditions, this educational process should be more actively connected with computer modeling and additive technologies, solving inventive problems on this technological basis with a priority to those of the third type, not limiting itself to solving only direct and inverse problems. Developing the mathematical basis for the theory of inventive problem solving can use AI, and today, it is difficult to say anything about the "speed of development" of this theory when combined with mathematics, computer technologies, and AI. However, we cannot exclude the possibility that this "speed of development" may be dangerously high. In this connection, when solving applied practical problems, as everywhere accepted, special attention should be paid to the safety rules of design, construction, and production.

The main fields of application of the obtained scientific results include power engineering, production, and processing of oil and gas. Some results are applicable to aviation and marine transportation systems. The project solved its main objectives within the presented scientific paper:

1. Revealed promising directions for developing fluidics and jet systems for thrust vector control;
2. Identified new opportunities for improving the methodology of design of jet and ejection systems within the training of modern designers because proposed a new direction of work for the development of Euler's ideas;
3. Developed separate methodological approaches for solving inventive problems using CFD technologies based on Leonard Euler's scientific legacy in gas dynamics and hydrodynamics.

5. Conclusion

Technical solutions allowing thrust vector control within the complete geometrical sphere using movable diaphragms at their angular and axial displacements have been developed and patented by studying the working process features of thrust vector control using mesh S-shaped channels as part of the jet device. The authors of this paper propose a new mathematical model to describe the thrust vector (in modulus and direction) in the distribution of the mass flow rate of a fluid medium between flow channels connected in parallel. Based on the scientific groundwork prepared by Leonard Euler, this paper proposes a new direction for the development of the theory of ejectors and fluidics in general, using S-shaped channels and nozzle apparatuses to control the thrust vector within a complete geometric sphere. This paper also proposes a new direction for the development of the theory of inventive problem solving, using set theory and an interdisciplinary research approach (including the use of different variants of AI). The field of application of the obtained results includes power engineering, production, and processing of oil and gas, with some results applicable to aviation and marine thrust vector control systems or dynamic positioning systems for drones. Research limitations relate to the multidimensionality of the studied jet systems and the complexity of the interaction of fluid media with solid walls (attention is also drawn to the complexity of solving optimization problems with a systematic consideration of several sets of parameters characterizing gas dynamic conditions, geometric shapes of solid walls, and properties of structural materials with simultaneous economic evaluation of all work stages). Research development may be due to new tools in computer modeling and additive technologies.

6. Declarations

6.1. Author Contributions

Conceptualization, Y.A.S.; methodology, M.A.M.; software, E.I.K.; validation, K.A.T.; formal analysis, V.V.V.; investigation, K.A.T.; resources, Y.A.S.; data curation, I.V.G.; writing—original draft preparation, K.A.T.; writing—review and editing, Y.A.S.; visualization, E.I.K.; supervision, M.A.M.; project administration, M.A.M.; funding acquisition, Y.A.S. All authors have read and agreed to the published version of the manuscript.

6.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

6.3. Funding

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6.4. Conflicts of Interest

The authors declare no conflict of interest.

7. References

[1] Sazonov, Y. A., Mokhov, M. A., Gryaznova, I. V., Voronova, V. V., Tumanyan, K. A., Frankov, M. A., & Balaka, N. N. (2021). Development and prototyping of jet systems for advanced turbomachinery with mesh rotor. Emerging Science Journal, 5(5), 775–801. doi:10.28991/esj-2021-01311.

[2] Sazonov, Y. A., Mokhov, M. A., Gryaznova, I. V., Voronova, V. V., Tumanyan, K. A., Frankov, M. A., & Balaka, N. N. (2022). Designing Mesh Turbomachinery with the Development of Euler's Ideas and Investigating Flow Distribution Characteristics. Civil Engineering Journal (Iran), 8(11), 2598–2627. doi:10.28991/CEJ-2022-08-11-017.

[3] Holl, S. (2000). Parallax. Princeton Architectural Press, New York, United States.

[4] Holl, S. (2020). Steven Holl: Inspiration and process in architecture. Princeton Architectural Press, New York, United States.

[5] Sazonov, Y. A., Mokhov, M. A., Tumanyan, K. A., Frankov, M. A., & Balaka, N. N. (2020). Prototyping mesh turbine with the jet control system. Periódico Tchê Química, 17, 1160-1175. doi:10.52571/ptq.v17.n36.2020.1176_periodico36_pgs_1161_1175.pdf.

[6] Dehghani, M., & Yazdanparast, Z. (2023). From distributed machine to distributed deep learning: a comprehensive survey. Journal of Big Data, 10(1), 158. doi:10.1186/s40537-023-00829-x.

[7] Du, H., Thudumu, S., Giardina, A., Vasa, R., Mouzakis, K., Jiang, L., Chisholm, J., & Bista, S. (2023). Contextual topic discovery using unsupervised keyphrase extraction and hierarchical semantic graph model. Journal of Big Data, 10(1), 156. doi:10.1186/s40537-023-00833-1.

[8] Darvishpoor, S., Darvishpour, A., Escarcega, M., & Hassanalian, M. (2023). Nature-Inspired Algorithms from Oceans to Space: A Comprehensive Review of Heuristic and Meta-Heuristic Optimization Algorithms and Their Potential Applications in Drones. Drones, 7(7), 427. doi:10.3390/drones7070427.

[9] Morozov, A. V., Nazarov, E. A., & Pokotilo, S. A. (2022). The patent for invention No. 2777459 of the Russian Federation. Method of creating aerodynamic forces on an aircraft wing and a device for its implementation. Moscow, Russia.

[10] Yao, Z., Kan, Z., & Li, D. (2023). Gust Response of Spanwise Morphing Wing by Simulation and Wind Tunnel Testing. Aerospace, 10(4), 328. doi:10.3390/aerospace10040328.

[11] Rodríguez-Sevillano, Á. A., Casati-Calzada, M. J., Bardera-Mora, R., Nieto-Centenero, J., Matías-García, J. C., & Barroso-Barderas, E. (2023). Rapid Parametric CAx Tools for Modelling Morphing Wings of Micro Air Vehicles (MAVs). Aerospace, 10(5), 467. doi:10.3390/aerospace10050467.

[12] Mahmood, F., Hashemi, S. M., & Alighanbari, H. (2023). Structural Dynamic Characterization of a Modular Morphing Wing Exploiting Finite Elements and Taguchi Methodology. Aerospace, 10(4), 376. doi:10.3390/aerospace10040376.

[13] Friedmann, G. (1952). US Patent 2623474. Injection mixer. United States Patent Office, Alexandria, United States.

[14] Wheatley, M. J. (1997). Apparatus for energy transfer. UK Patent Application, GB No: 2310005, London, United Kingdom.

[15] Ringstad, K. E., Banasiak, K., Ervik, Å., & Hafner, A. (2022). Swirl-Bypass Nozzle for CO2 Two-Phase Ejectors: Numerical Design Exploration. Energies, 15(18), 6765. doi:10.3390/en15186765.

[16] Jia, F., Yang, D., & Xie, J. (2021). Numerical investigation on the performance of two-throat nozzle ejectors with different mixing chamber structural parameters. Energies, 14(21), 6900. doi:10.3390/en14216900.

[17] Jing, Q., Xu, W., Ye, W., & Li, Z. (2022). The Relationship between Contraction of the Ejector Mixing Chamber and Supersonic Jet Mixing Layer Development. Aerospace, 9(9), 469. doi:10.3390/aerospace9090469.

[18] Zhang, Y., Dong, J., Song, S., Pan, X., He, N., & Lu, M. (2023). Numerical Investigation on the Effect of Section Width on the Performance of Air Ejector with Rectangular Section. Entropy, 25(1), 179. doi:10.3390/e25010179.

[19] Yan, J., Shu, Y., Jiang, J., & Wen, H. (2023). Optimization of Two-Phase Ejector Mixing Chamber Length under Varied Liquid Volume Fraction. Entropy, 25(1), 7. doi:10.3390/e25010007.

[20] Aidoun, Z., Ameur, K., Falsafioon, M., & Badache, M. (2019). Current advances in ejector modeling, experimentation and applications for refrigeration and heat pumps. Part 1: Single-phase ejectors. Inventions, 4(1), 15. doi:10.3390/inventions4010015.

[21] Koirala, R., Ve, Q. L., Zhu, B., Inthavong, K., & Date, A. (2021). A review on process and practices in operation and design modification of ejectors. Fluids, 6(11), 409. doi:10.3390/fluids6110409.

[22] Shank, K., & Tiari, S. (2023). A Review on Active Heat Transfer Enhancement Techniques within Latent Heat Thermal Energy Storage Systems. Energies, 16(10), 4165. doi:10.3390/en16104165.

[23] Azarova, O. A. (2023). High Speed Flows. Fluids, 8(4), 109. doi:10.3390/fluids8040109.

[24] Lee, J. H., Ryu, J. H., Lee, E. S., Han, H. S., & Choi, J. Y. (2023). Experimental Proof of Concept of a Noncircular Rotating Detonation Engine (RDE) for Propulsion Applications. Aerospace, 10(1), 27. doi:10.3390/aerospace10010027.

[25] Wang, Y., & Wang, N. (2023). Influence of the Projectile Rotation on the Supersonic Fluidic Element. Aerospace, 10(1), 35. doi:10.3390/aerospace10010035.

[26] Li, M., Lei, Z., Deng, H., Ouyang, X., Zhang, Y., Lu, X., Xu, G., & Zhu, J. (2023). Numerical Research on the Jet-Mixing Mechanism of Convergent Nozzle Excited by a Fluidic Oscillator and an Air Tab. Energies, 16(3), 1412. doi:10.3390/en16031412.

[27] Resta, E., Marsilio, R., & Ferlauto, M. (2021). Thrust vectoring of a fixed axisymmetric supersonic nozzle using the shock-vector control method. Fluids, 6(12), 441. doi:10.3390/fluids6120441.

[28] Ferlauto, M., Ferrero, A., Marsicovetere, M., & Marsilio, R. (2021). Differential throttling and fluidic thrust vectoring in a linear aerospike. International Journal of Turbomachinery, Propulsion and Power, 6(2), 8. doi:10.3390/ijtpp6020008.

[29] Skaggs, B. D. (2000). US Patent #6,017,195. Fluid jet ejector and ejection method. United States Patent Office, Alexandria, United States.

[30] Dodge, A. Y. (1995). U.S. Patent No. 3,188,976. Jet pump. United States Patent Office, Alexandria, United States.

[31] Samuel, L. (1968). U.S. Patent No. 3,385,030. Process for scrubbing a gas stream containing particulate material. United States Patent Office, Alexandria, United States.

[32] Bayles, W. H., & Nash, B. C. (1962). U.S. Patent No. 3,064,878: Method and apparatus for high performance evacuation system. United States Patent Office, Alexandria, United States.

[33] Volker, M., & Sausner, A. (2018). U.S. Patent No. 10,072,674: Suction jet pump. United States Patent Office, Alexandria, United States.

[34] Chanut, P. L. J. (1961). US Patent # 3013494. Guided missile. United States Patent Office, Alexandria, United States.

[35] Sota Jr., C. G., Callis, G. J., & Masse, R. K. (2007). United States Patent 7155898. Thrust vector control system for a plug nozzle rocket engine. United States Patent Office, Alexandria, United States.

[36] Aerospaceweb.org (2018). Missile Control Systems. Available online: http://www.aerospaceweb.org/question/weapons/q0158.shtml (accessed on October 2023).

[37] Sahbon, N., Jacewicz, M., Lichota, P., & Strzelecka, K. (2023). Path-Following Control for Thrust-Vectored Hypersonic Aircraft. Energies, 16(5), 2501. doi:10.3390/en16052501.

[38] Bailey,J. M. (1982). US Patent #4355949. Control system and nozzle for impulse turbines. United States Patent Office, Alexandria, United States.

[39] Hickerson, F. R. (1965). United States Patent 3192714. Variable thrust rocket engine incorporating thrust vector control. United States Patent Office, Alexandria, United States.

[40] Kinsey, L. E., & Cavalleri, R. J. (2013). United States Patent 8387360. Integral thrust vector and roll control system. United States Patent Office, Alexandria, United States.

[41] Plumpe Jr., W. H. (2003). United States Patent 6622472. Apparatus and method for thrust vector control. United States Patent Office, Alexandria, United States.

[42] Cican, G., Frigioescu, T. F., Crunteanu, D. E., & Cristea, L. (2023). Micro Turbojet Engine Nozzle Ejector Impact on the Acoustic Emission, Thrust Force and Fuel Consumption Analysis. Aerospace, 10(2), 162. doi:10.3390/aerospace10020162.

[43] Bhadran, A., Manathara, J. G., & Ramakrishna, P. A. (2022). Thrust Control of Lab-Scale Hybrid Rocket Motor with Wax-Aluminum Fuel and Air as Oxidizer. Aerospace, 9(9), 474. doi:10.3390/aerospace9090474.

[44] Liu, B., Gao, Y., Gao, L., Zhang, J., Zhu, Y., Zang, X., & Zhao, J. (2022). Design and Experimental Study of a Turbojet VTOL Aircraft with One-Dimensional Thrust Vectoring Nozzles. Aerospace, 9(11), 678. doi:10.3390/aerospace9110678.

[45] Zhang, X., Dang, H., & Li, B. (2023). Prediction of Aircraft Surface Noise in Supersonic Cruise State. Aerospace, 10(5), 439. doi:10.3390/aerospace10050439.

[46] Yan, J., Hu, H., Gong, J., Kong, D., & Li, D. (2023). Exploring Radar Micro-Doppler Signatures for Recognition of Drone Types. Drones, 7(4), 280. doi:10.3390/drones7040280.

[47] Xing, Y., Chen, W., Wang, X., Tong, F., & Qiao, W. (2023). Effect of Wavy Leading Edges on Airfoil Trailing-Edge Bluntness Noise. Aerospace, 10(4), 353. doi:10.3390/aerospace10040353.

[48] Yang, Z., Zhang, J., & Shan, Y. (2023). Research on the Infrared Radiation Suppression of the High-Temperature Components of the Helicopter with an Integrated Infrared Suppressor. Aerospace, 10(4), 351. doi:10.3390/aerospace10040351.

[49] Wang, C., Lu, H., Kong, X., Wang, S., Ren, D., & Huang, T. (2023). Effects of Pulsed Jet Intensities on the Performance of the S-Duct. Aerospace, 10(2), 184. doi:10.3390/aerospace10020184.

[50] Ualiyeva, R. M., Kaverina, M. M., Ivanko, L. N., & Zhangazin, S. B. (2023). Assessment of Spring Wheat Varieties for Pest Resistance. OnLine Journal of Biological Sciences, 23(4), 489–503. doi:10.3844/ojbsci.2023.489.503.

[51] Brethouwer, G. (2022). Turbulent flow in curved channels. Journal of Fluid Mechanics, 931, 21. doi:10.1017/jfm.2021.953.

[52] Svorcan, J., Andrić, J., Čantrak, Đ., & Ivanov, T. (2022). Special Collection on advanced practices in aerospace and energy engineering. Advances in Mechanical Engineering, 14(10), 10. doi:10.1177/16878132221125578.

[53] Abu Salem, K., Palaia, G., Chiarelli, M. R., & Bianchi, M. (2023). A Simulation Framework for Aircraft Take-Off Considering Ground Effect Aerodynamics in Conceptual Design. Aerospace, 10(5), 459. doi:10.3390/aerospace10050459.

[54] Peciak, M., Skarka, W., Mateja, K., & Gude, M. (2023). Impact Analysis of Solar Cells on Vertical Take-Off and Landing (VTOL) Fixed-Wing UAV. Aerospace, 10(3), 247. doi:10.3390/aerospace10030247.

[55] Drikakis, D., & Sofos, F. (2023). Can Artificial Intelligence Accelerate Fluid Mechanics Research? Fluids, 8(7), 212. doi:10.3390/fluids8070212.

[56] Mitridis, D., Kapsalis, S., Terzis, D., & Panagiotou, P. (2023). An Evaluation of Fixed-Wing Unmanned Aerial Vehicle Trends and Correlations with Respect to NATO Classification, Region, EIS Date and Operational Specifications. Aerospace, 10(4), 382. doi:10.3390/aerospace10040382.

[57] Shahzad, M. M., Saeed, Z., Akhtar, A., Munawar, H., Yousaf, M. H., Baloach, N. K., & Hussain, F. (2023). A Review of Swarm Robotics in a NutShell. Drones, 7(4), 269. doi:10.3390/drones7040269.

[58] Pesci, A., Teza, G., & Fabris, M. (2023). Editorial of Special Issue "Unconventional Drone-Based Surveying." Drones, 7(3), 175. doi:10.3390/drones7030175.

[59] Dinelli, C., Racette, J., Escarcega, M., Lotero, S., Gordon, J., Montoya, J., Dunaway, C., Androulakis, V., Khaniani, H., Shao, S., Roghanchi, P., & Hassanalian, M. (2023). Configurations and Applications of Multi-Agent Hybrid Drone/Unmanned Ground Vehicle for Underground Environments: A Review. Drones, 7(2), 136. doi:10.3390/drones7020136.

[60] Sazonov, Y. A. (2012). Fundamentals of calculation and design of pump-ejector installations. SUE "Oil and Gas Publishing House" of Gubkin University: Moscow, Russia.

[61] Petrovich, G. P. (2002). Philosophy of technology and creativity of P. K. Engelmeyer: Historical and philosophical analysis. PhD Thesis, Ural State Economic University Press, Yekaterinburg, Russia.

[62] Altshuller, G. S. (2011). To find an idea: An introduction to TRIZ - the theory of inventive problem solving. Alpina Publisher, Moscow, Russia.

[63] Kurdyumov, S. P., & Knyazeva, E. N. (2021). Future and its horizons: synergetic methodology in forecasting. Synergetics and Scientific Forecasting, Moscow, Russia. (In Russian).

[64] Raskin, N.M. (1958). Euler's Questions of Technique. Leonhard Euler. Collection of articles in honor of the 250th anniversary of the birth, presented to the Academy of Sciences of the USSR, 499–556, Publishing House of the Academy of Sciences of the USSR, Moscow, Russia.

[65] Ackeret, J. (1944). Investigation of a water turbine built according to Euler's proposals (1754). Swiss Construction Newspaper, 123/124. Available online: https://arxiv.org/ftp/arxiv/papers/2108/2108.12048.pdf (accessed on July 2023).

[66] Izadi, M., Seiti, H., & Jafarian, M. (2022). Foresight: a new approach based on the Z-number cognitive map. European Journal of Futures Research, 10(1), 1-14. doi:10.1186/s40309-022-00188-5.