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Computational Fluid Dynamics (CFD) Simulation of Mesh Jet Devices for Promising Energy-Saving Technologies

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Abstract

This paper discusses the development of mesh jet devices for hybrid turbines, including developing Euler's ideas, and considers a new patented version of a mesh jet device designed to create guiding devices for turbines. The research methods are based on simulations using CFD and additive technologies. An intermediate conclusion is that a new scientific direction for the study and creation of mesh jet control systems has been formed as part of developing Euler's ideas. Calculation methods showed possible improvements in the performance of jet devices, including the use of curved tubes proposed by Euler to create turbines. This study shows that at the nozzle or mixing chamber outlet, the jet can deflect by an angle from +180° to -180° within the geometric sphere. This study also shows that the scientific groundwork prepared by Euler is not yet fully understood. The ongoing research mainly focuses on creating multi-mode jet devices designed for control systems for mesh turbomachines. Here, power consumption from an external source can be reduced to save energy. Some results of ongoing studies can also be applied in other industries (for example, when creating hybrid propulsion systems or propulsors). The scientific novelty of this work consists of improving the design methodology of jet machinery and turbomachines.

Keywords: CFD; Energy Saving; Jet Device; Nozzle; Mixing Chamber; Turbomachine; Fluid Dynamics.

1. Introduction

In current conditions, there is a need to solve the urgent problem of energy savings in the implementation of production processes, including developing oil and gas fields. The laboratories at Gubkin University solve this problem through a series of research studies on developing promising jet devices and turbomachines [1–6]. Their flow channels have a mesh structure. In common understanding, a mesh represents a larger geometric area by having smaller discrete cells. In a jet device, a set of smaller interconnected mixing chambers replaces a mixing chamber of larger size with the formation of flow channels in the form of a mesh structure. The novelty of this scientific development lies in the creation of special jet devices to control the velocity vector in an extremely wide range. During physical and numerical experiments, the extreme conditions of fluid and gas flow through a nozzle equipped with a velocity vector (or thrust vector, according to aviation terminology) control system in the control range for the angle of the velocity vector

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deviation from $+180°$ to $-180°$ within the geometric sphere were considered for the first time [1, 5]. Simultaneously, the question arose about the necessity of selecting scientific directions for further applied research to develop promising mesh jet devices for control systems for mesh turbomachines. The authors of this paper developed and published the following hypothesis [1–6]: it is reasonable to develop energy-saving technologies and techniques at the junction of two scientific and technical directions; the first direction relates to the area of mesh hybrid turbomachines, the second – to jet control systems to control the velocity vector (thrust vector). The mesh structure of the turbomachine flow path provides strength and rigidity of the rotor structure at low weight. The jet control system has high reliability (due to the small number of moving parts) with the low weight of the entire system.

Jet devices perform the injection process [7] – kinetic energy is transferred from one flow to another by direct contact (mixing). The main elements of the jet device are the working nozzle, receiving chamber, mixing chamber, and diffuser. The pressure increase in the injected flow without direct mechanical energy consumption is a primary, fundamental quality of jet devices. The paper considers the following variants of jet devices – a mixer, propulsor, gas generator, and heat exchanger. The mixer is usually a technical device designed to prepare mixtures from initial components in the same or different aggregate state. The propulsor is commonly a device that converts the engine energy into network output for moving the vehicle through interaction with the environment. The gas generator usually converts solid or liquid fuel into a gaseous form when implementing the gasification process. The heat exchanger is a technical device for the heat exchange between two media with different temperatures. In regenerative heat exchangers, hot and cold heat carriers contact the same surface alternately. The heat accumulates in the wall during contact with the hot heat carrier and goes away during contact with the cold heat carrier.

2. Literature Survey

It is well-known that production systems for oil and gas production, transportation, and refining actively use advanced scientific developments from other industries, including aviation technologies and modified aircraft engines. Therefore, conducting a system analysis of structures and generalization of experience in machine design is not confined to any one branch but considers the issues from the general positions of machine science, using interdisciplinary and even transdisciplinary approaches to organize research. It is well-known that the mesh structure of solid walls makes it possible to solve many essential technical problems. Thus, the peculiarities of gas-dynamic processes in developing lattice wings [8, 9] and aircraft [10-12] have been studied.

Patent materials describe jet devices, including electors with nozzles placed in stationary disk supports [13, 14] or rotating disk supports [15]. Supersonic electors for various purposes have been actively studied [16–22]. Examples of mesh nozzles used in designing electors are known [23–25]. Ejector structures with cylindrical or conical mixing chambers are known [26]; however, ejector structures with curved mixing chambers are less known [27, 28]. Recently, the Coandă effect has been actively studied in aircraft technologies intended for thrust vector control [29, 30].

The adjustable nozzle structure using a deflector made in the form of a diaphragm is known [31-33]. For the known control systems of the thrust vector (velocity vector), the highest deflection angle of the flow, at the exit from the nozzle, can vary in the range from $+20°$ to $-20°$ [34-36]. The adjustable nozzle can have a conical central body, which can move in the axial direction [37, 38], or the radial direction [39]. Studies continue on nozzle variants with deflectors of various shapes [40], including a cross-shaped nozzle exit channel [41], where the deflectors move independently to transmit the directional force to conventional aircraft (roll, pitch, and yaw) and vertical take-off and landing aircraft [42]. The variants of aircraft jet systems for performing thrust reverse [43] and thrust enhancement [44, 45] are considered separately. Work on creating hybrid aircraft engines and jet vehicles is intensifying [9, 11, 46]. Analyzing the published data, one can notice that different methods for controlling the velocity vector (thrust vector) have been developed and patented today. Simultaneously, it is possible to note that there is little coverage in the literature about the synergistic effect of the simultaneous use of two (or more) different control methods. Investigating synergistic effects in jet devices can help solve the urgent problem of energy saving in production processes, including developing oil and gas fields.

The mention publications, scientific developments, and achievements are now considered for their applicability in developing promising jet devices and systems. The main project objectives, within the framework of this scientific paper, are to identify promising development directions of technologies and techniques using mesh jet devices and jet systems and new opportunities for improving the design methodology of mesh jet devices and jet systems as part of the training of modern designers.

The ongoing studies mainly focus on developing multi-mode jet devices and systems operating in complicated conditions, including conditions of offshore oil and gas fields. Thus, at the late stage of gas field development, the relevant problem has not yet been fully solved, associated with operating booster compressors at the inlet pressure of $P_1 \leqslant 0.5$ MPa. Under these conditions, it is difficult to provide cost-effective operation of expensive compressors at a rapid change (decrease) in formation pressure at the producing wells. However, gas energy loses and dissipates in the choke at the mouth of each well with high-reservoir pressure. Eco-friendly gas energy from wells with high reservoir pressure can be applied to operate a booster compressor station and reduce power consumption from an external source. In this regard, to solve the problem of energy saving, scientific studies are developing new mesh jet machines and hybrid mesh turbomachinery.

Some research results can solve practical tasks in other industries, including increasing the efficiency of energy conversion processes, electric power generation, transport systems of aviation and maritime profiles, and actively using interdisciplinary and transdisciplinary approaches to research and design works.

3. Research Methodology

These fundamental and applied scientific studies use the well-known methodology [47] with an interdisciplinary approach, always considering a set of the following processes and conditions:

- Blade and vortex, pump (or compressor), and turbine workflows;
- Coalescence and dispersion processes, cavitation in liquid and gas-liquid mixtures, separation in multiphase media;
- Workflows in the presence of solid particles in a fluid flow, at a point or distributed power input, at series and parallel connection of machines, in one-stage or multistage machinery, flow processes considering hydraulic friction and impact losses with partial pressure recovery at constant and variable resistance coefficients;
- The development or attenuation of individual hydrodynamic (gas-dynamic) processes in different points of the engine working chamber when changing the parameters of the working fluid;
- The features of changes in the physical properties of the liquid or gas-liquid mixture at different points in the machine flow path;
- Conditions of presence (or absence) of axial symmetry for solid walls in flow channels (and for the fluid flow);
- Conditions and methods used for machine regulation;
- Conditions for a steady (or impulse) flow regime in individual zones and flow channels.

Figure 1 shows a flowchart to explain the research methodology.

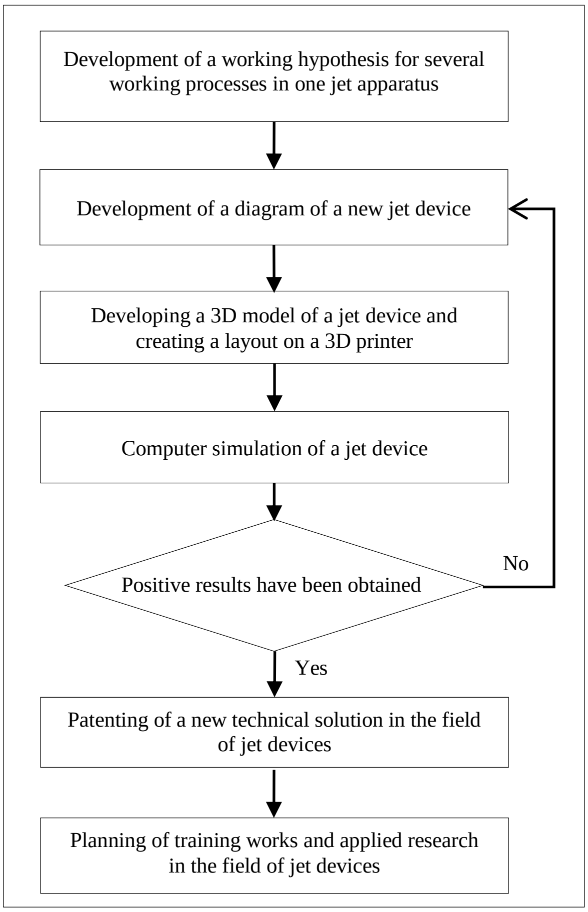


Figure 1. Flowchart to explain the research methodology

This paper presents the results of calculations and computer simulation. As part of the ongoing research, laboratory tests of micromodels on bench installations were conducted in 2020–2021 and published earlier [1–5]. Such physical laboratory experiments test individual scientific principles and the performance of nodes and elements. The study object is a set of gas-dynamic and hydrodynamic processes under the stationary and non-stationary regimes of flow through rotating and fixed channels with a mesh structure.

This study discusses the development of mesh-jet devices, including advancing Euler's ideas and proposed as a continuation to the already published materials [1–6]. The research results are used to develop new models and prototypes. Individual developments are patented, and inventions are prepared and formalized within the philosophy of technology. The research results are the basis for future applied R&D works. It is also possible to assume the need for an additional tool in the form of a transdisciplinary approach. It is well-known that transdisciplinarity complements disciplinary and interdisciplinary approaches. Here, we are talking about only one form of transdisciplinarity called "experimental transdisciplinarity," using a well-defined procedure that has an acceptable (for the scientific community) level of reproduction, including its results.

The analysis of scientific and technical information was carried out within the framework of deductive logic, building a logical and methodological procedure for the transition from the general to the particulars during the reasoning process. Individual arguments and hypotheses are presented within the framework of inductive logic, with a general conclusion drawn based on particular premises. In the common understanding, induction is a cognitive procedure with a generalizing statement deduced from a comparison of the available facts. Some reasoning use the reduction principle – reducing complex to simple, higher to lower, the whole to the properties of parts, and the parts to the specifics of the whole. In the conventional sense, the reduction is a logical and methodological procedure of presenting a complex object as a sum of simple elements that makes it available for analysis.

4. Results and Discussion

4.1. Development of Schematics for Promising Jet Devices

During the ongoing research, the utility model application No. 2022123131 was prepared [48]. It refers to the production and design of jet technology in various industries. In particular, the claimed technical solution can be applied to developing jet control systems for energy-saving technologies in the oil and gas fields.

The technical problem, which the claimed utility model addresses is to expand the regulation range of operating parameters. To solve the above technical problem, the jet device contains sources of working and pumped media, a nozzle diaphragm, and a working chamber with an annular channel with guide blades placed with the formation of flow channels between the blades, isolated from each other. According to the utility model, the jet device has a control unit for turning the nozzle diaphragm to change the flow direction of the mixture of the working and pumped media. The outlet of the working chamber with the annular channel has a system of multi-directional nozzles, forming a multi-channel system of flow channels between the guide blades to feed the mixture of working and pumped media from the nozzle diaphragm through the annular channel of the working chamber.

In some specific cases of the device, the control unit for turning the nozzle diaphragm to change the flow direction of the working medium is made in the form of a spherical joint, and the annular channel of the working chamber has a conical deflector with the ability to move in the vertical direction. The achievable technical results are to provide changes in the flow direction of the working and pumped media mixture and unequal distribution of gas (or liquid) along the flow channels at different gas or liquid mass flow rates in each of these channels. The flexible control system makes it possible to expand the scope of the proposed jet device because, besides the pressure and mass flow rate, it is also possible to regulate the direction of flows in a wide range within the geometric sphere. Figure 2 shows the scheme of the developed jet device with a longitudinal section (the conical deflector is in the upper position). Figure 3 shows the isometric scheme of the jet device. Figure 4 shows the scheme of the jet device with a longitudinal section (the conical deflector is in the lower position when turning the outlet channel of the nozzle diaphragm at a certain preset angle).

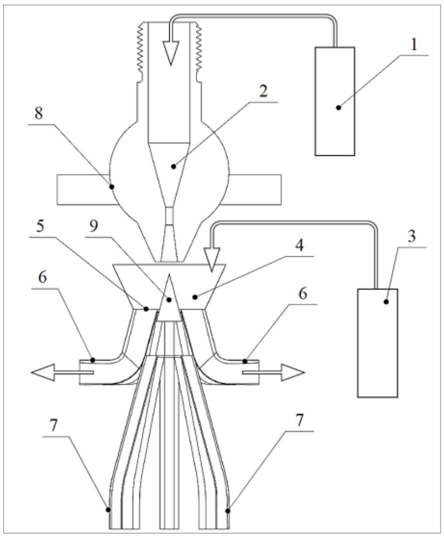


Figure 2. Scheme of the developed jet device according to the application for utility model of the Russian Federation No. 2022123131 (the conic deflector is in the upper position): 1 – working medium source; 2 – nozzle diaphragm; 3 – pumped medium source; 4 – working chamber; 5 – guide blades; 6 –nozzle system; 7 –nozzle system; 8 – control node for deflection and change of the working medium flow direction; 9 – conic deflector.

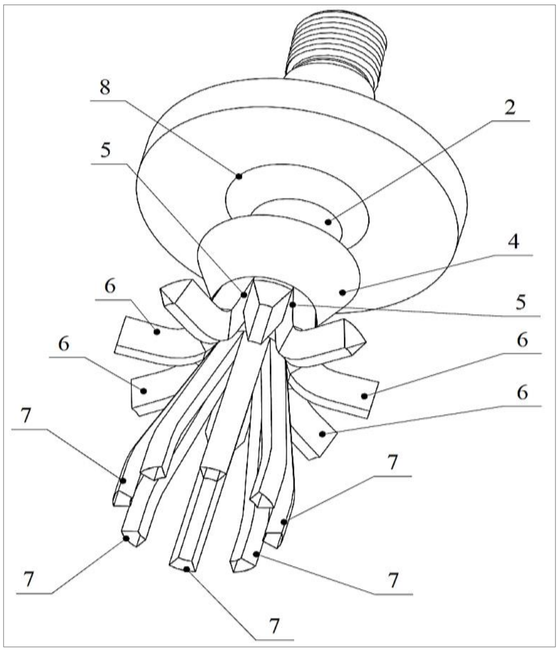


Figure 3. Isometric scheme of the developed jet device by the application for utility model of the Russian Federation No. 2022123131

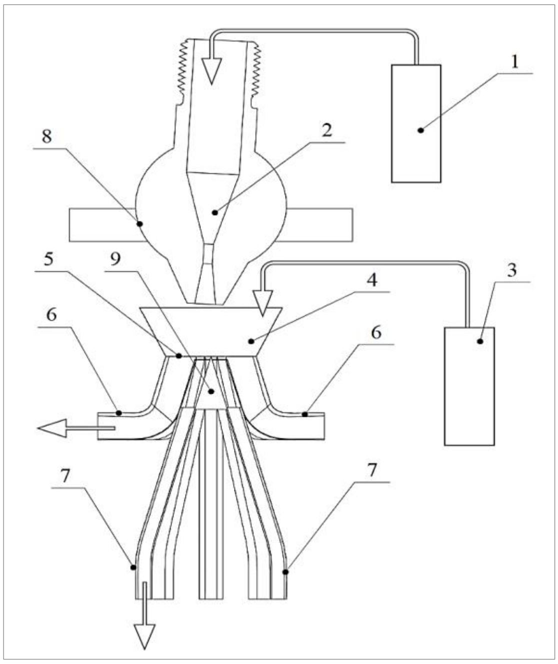


Figure 4. Scheme of the jet device by the application for utility model of the Russian Federation No. 2022123131 (the conic deflector is in the lower position)

The jet device works as follows:

The working medium source 1 supplies the working medium to the nozzle diaphragm 2. After forming in the nozzle diaphragm 2, the working jet enters the annular channel of the working chamber 4. The pumped medium from source 3 flows to the working medium jet, passing through the annular channel of working chamber 4. Control node 8 provides deflection and directional change of the working medium flow considering the current technological problem.

Then the pumped medium, mixed with the flow of the working medium, goes to the flow channels of the nozzle system 6 and/or 7, depending on the current technological task. The working and pumped medium can be liquids, gases, or gas-liquid mixtures with different ratios of components. The flow regime of the working medium through the nozzle diaphragm 2 can be steady-state or unsteady (for example, pulse regime, according to a specified law of change in gas-dynamic parameters, considering the conditions of the current technological problem). From the outlets of the flow channels of the nozzle systems 6 and 7, the mixture of the working and pumped media flows further into the process line (not shown in the figures) to the reception of the consumer or several consumers (not shown in the figures).

Nozzle diaphragm 2 and control node 8 provide an opportunity to supply the working and pumped media in different directions within a geometrical sphere, depending on the shape and number of nozzles 6 and 7, forming a multi-channel working chamber with a mesh structure of channels. Depending on the spatial position of nozzle diaphragm 2 and conical deflector 9 (and considering their geometrical dimensions), the working medium flow conditions and mixing conditions of working and pumped media flows in the flowing channels of nozzles 6 and 7 change. During this, values of mass flow rates, pressures, temperature, Coriolis and Boussinesq coefficients, and other gas-dynamic (hydrodynamic) parameter change in the mentioned channels. Accordingly, the parameters of momentum (power impulse) of working and mixed flows and velocity profiles in the cross-section of each channel change.

Figure 2 shows a scheme of the jet device with a longitudinal section when the conical deflector 9 is in the upper position. The outlet sections of the flow channels of the nozzle system 6 can be located in a plane perpendicular to the flow direction from the nozzle diaphragm 2, as shown in Figure 2. Here, the mixed flow of the working and pumped media can be evenly distributed along the specified flow channels (if the mass flow rate of gas or liquid in each channel is equal). Turning the nozzle diaphragm 2 provides a non-uniform distribution of gas or liquid through flow channels (at different values of the mass flow rate of gas or liquid in each channel, with a possibility to direct the entire working flow into one of the flow channels).

Figure 4 shows a scheme of the jet device with a longitudinal section when the conical deflector 9 is in the lower position. The outlet sections of the flow channels of the nozzle system 7 can be arranged in parallel, as shown in the figures. Here, the mixed flow of the working and pumped media can be evenly distributed along the flow channels (if the mass flow rates of the gas or liquid in each channel are equal). Turning the nozzle diaphragm 2 provides a non-uniform distribution of gas or liquid through flow channels (at different values of the mass flow rate of gas or liquid in each channel, with a possibility to direct the entire working flow into one of the flow channels).

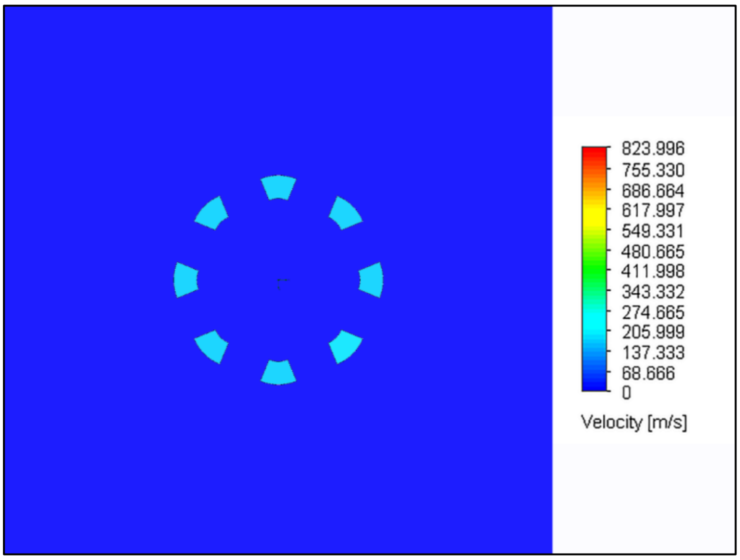
Other variants of gas (liquid) flow distribution in flow channels of nozzles 6 and 7 are also possible. In the general case, flow channels, which form a mesh structure, provide an opportunity for supply working and pumped media in different directions within the geometrical sphere due to the shape of these flow channels and control node 8.

With control node 8, by directing the fluid flow into one or more flow channels, it is possible to control the operation of the jet device, using it to solve many technical and technological problems in various industries. Thus, the proposed jet device provides a flexible control system that makes it possible, in addition to pressure and mass flow rate, to change the direction of flows in a wide range within the geometric sphere, expanding the scope of the proposed jet device. Figure 5 shows a picture of the micromodel, which is a prototype of the jet device according to the application for utility model of the Russian Federation No. 2022123131.

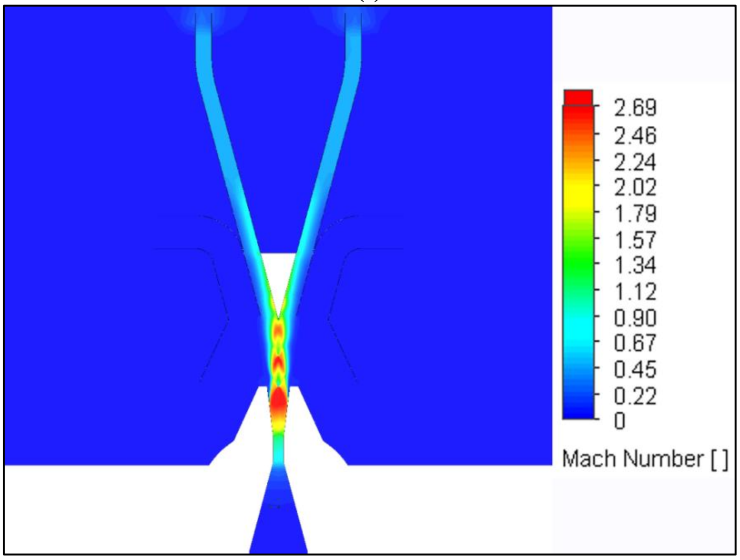
Figure 5. Picture of the micromodel (a prototype of the jet device) according to the application for utility model of the Russian Federation No. 2022123131

This research included a computer simulation of the developed jet system for the following conditions: working air – air; the gas temperature at the nozzle inlet 191°C, ambient space – 20°C; gas pressure at the nozzle inlet – 1519875 Pa, ambient space – 101325 Pa; nozzle outlet diameter – 5.5 mm, using FloEFD (Flow Simulation) software package for computer simulation and computational study. The 3D model was built using the SolidWorks CAD system. During modeling, the complete system of Navier-Stokes equations, described by mathematical expressions of the laws of mass, energy, and momentum conservation, was solved with the automatic setting of the turbulence parameters by default. The turbulent viscosity model "k-ε" was used to calculate the turbulence parameters for the closure of the system of Navier-Stokes equations. The computer 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.

Figures 6 to 8 show the individual results of the computer simulation. This version of the jet device should be considered concerning three-dimensional space, and this version corresponds to the three-dimensional model presented in Figures 2–4. The total number of cells was 490065 to 495756, the computation time was 17090 to 17722 s, and the number of iterations was 1500. In the patenting stage of the developed technical solution, the computer simulation included checking the jet system performance.



(a)



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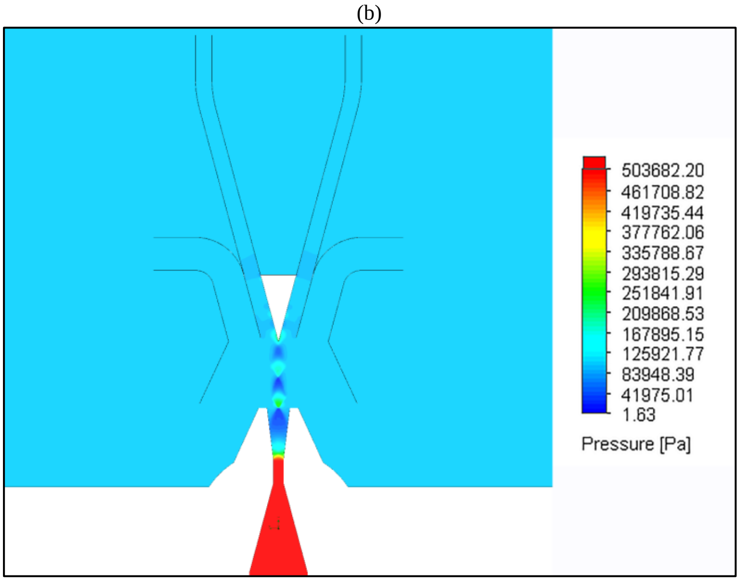
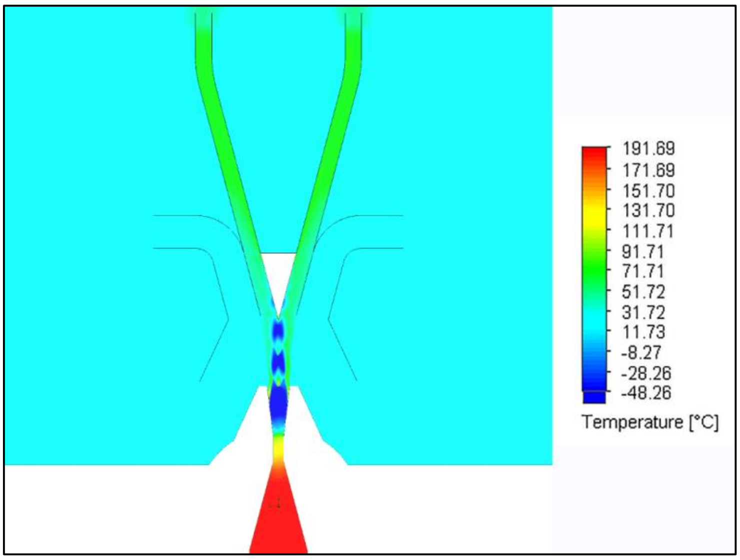


(c)

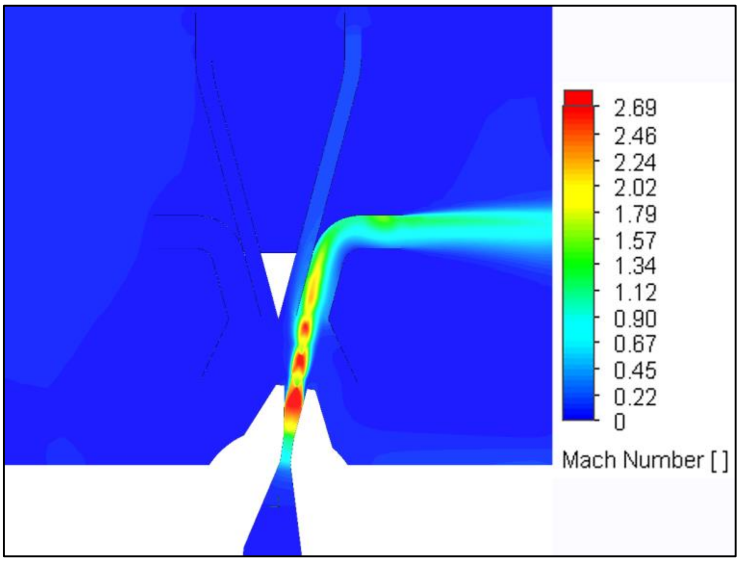


(d)

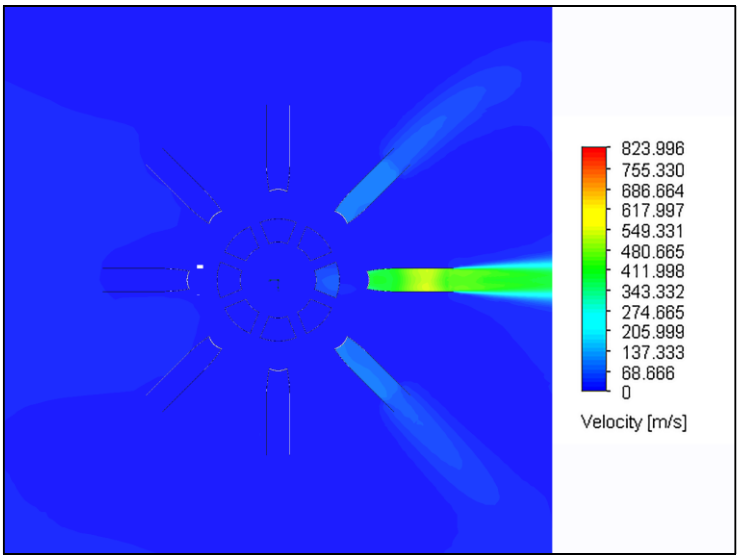
Figure 6. Computer simulation results with the centered nozzle position with the exit of the flows through the axial channels a) - Mach number (in the longitudinal section); b) - velocity (in the cross-section); c) - pressure (in the longitudinal section); d) - temperature (in the longitudinal section).

In this example (Figure 6), one flow from the nozzle is divided into three-dimensional space into eight channels. When turning the nozzle, the mass flow rate of the working gas can be unevenly distributed along these eight channels. In a particular case, it is possible to direct the entire flow of the working gas into one of these eight channels.

Turning the nozzle by 10° (Figure 7) makes it possible to direct the working gas flow through the radial channel. Here, the final deflection angle of the flow is 90°. Accordingly, the deflection angle of the velocity vector (thrust vector) is 90°. This example demonstrates the simultaneous use of two different methods designed to control the velocity vector (thrust vector). The first method uses a rotating nozzle, and the second method uses a deflector made as a curved tube with a radial exit channel. The simultaneous use of two different control methods gives a synergistic effect. If we denote the angular displacement velocity of the nozzle as υ_ω and the angular displacement velocity of the velocity vector as, Υ_ω it is possible to write the relation $\Upsilon_\omega > \upsilon_\omega$. If only one control method with a rotating nozzle was used, then $\Upsilon_\omega = \upsilon_\omega$. With such equality of velocities, it would take nine times longer to turn the velocity vector (thrust vector) by 90°. A deflector made in the form of a curvilinear tube with flow reversal by 180° can reduce the time spent on flow switching by 18 times. Thus, the synergistic effect of the simultaneous use of two different control methods will increase the speed of the jet control system, which will positively impact improving the safety and reliability of equipment (technology) as a whole (Figure 8).



(a)



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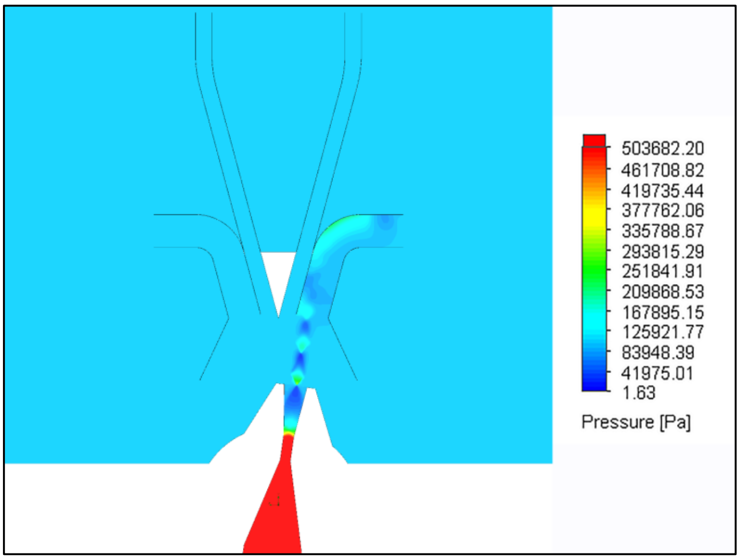

(c)

Figure 7. Computer simulation results with flow exit through the radial channel: a) - Mach number (in the longitudinal section); b) - velocity (in the cross-section); c) - pressure (in the longitudinal section

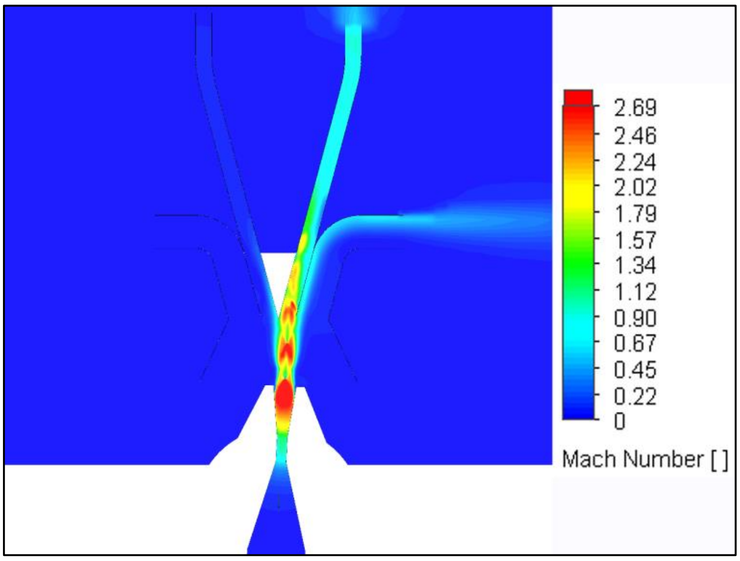

Figure 8. Computer simulation results with flow exit through the axial channel and radial channel (Mach number)

Figure 9 shows a prototype of a similar jet control system but with five output channels. Four channels are in a plane perpendicular to the main flow direction coming out of the nozzle, and one is coaxial to the nozzle.

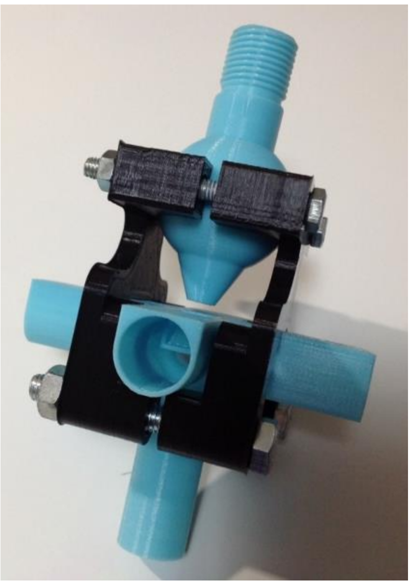

Figure 9. Prototype of the jet control system with five output channels (variant)

4.2. Discussion of Schematics of Jet Devices within Advancing Euler's Ideas

Note that different structures of jet devices have been developed. Each such original structure can be considered an integral part of the general group of jet devices. Thus, it is well-known that the individual elements of the jet device can be on a swivelling carriage or the rotating rotor as part of a turbomachine. The flow direction of the working medium can change over time. From the science of pneumonic, jet devices with several mixing chambers with nozzle diaphragms equipped with a control system to change the flow direction of the working medium are known. The working medium flows to one or the other mixing chamber, depending on the current technical problem. Recently, new technological solutions have been developed and patented for jet devices with a mesh structure of flow channels in nozzles and mixing chambers. Using parallel or sequential connections of jet devices (or their separate parts and units) is well-known. Several different workflows can be in the jet device. Multi-flow jet devices with several working media and various pumped media used simultaneously are known. Here, the flow regime through the nozzle diaphragm can be stationary or non-stationary. The flow regime through the mixing chamber can also be stationary or non-stationary. If the nozzle operation in the mixing chamber is stationary, the flow regime may be non-stationary. The jet device can be stationary or moving in three-dimensional space. The ejection regime can also be implemented in rotor channels of the turbomachine, advancing Euler's ideas. The history of turbines partially preserved materials of correspondence between Leonhard Euler and Janosz-Androsz Segner [49]. As is known, Leonhard Euler proposed considering the rotating part (turbine rotor) and the stationary part (turbine guide apparatus) together at the system level [49, 50]. Leonhard Euler also proposed using curvilinear pipes to form the flow path of a hydraulic machine, both in designing the rotor and guiding apparatus (stator or nozzle diaphragm). This correspondence with Segner on the design of hydraulic machines reflects many of Euler's ideas, whose relevance has survived to this day. Euler's idea of combining several curvilinear pipes into a single unit can be applied in developing promising multi-stream and mesh jet devices.

Within the philosophy of technology, we can ask the following question. If all known jet devices are a set of facts and particular cases, as a set of parts from the whole, then how should we characterize this whole or general? At least for educational purposes, such a question is worth considering. We can try deriving a generalizing statement by comparing the available facts within inductive logic. Generally, a jet device is a system that contains the following subsystems: a multi-flow nozzle diaphragm with a velocity vector (thrust vector) control system, a multi-flow receiving chamber with the control system, a multi-flow mixing chamber with a control system, and multi-flow diffuser with a control system. Here, the listed subsystems can change their position in three-dimensional space (including participation in rotational motion) and the shape and size of individual channels. In a particular case (and in the simplest one), a jet device contains the following elements: a working nozzle, a receiving chamber, a mixing chamber, and a diffuser. This simplified specified case is suitable for popularizing jet technology in stationary operating regimes, but more complex practical problems will also require a more complex diagram for developing cost-effective jet devices. In this regard, for educational purposes, it is possible to consider questions about the classification of jet devices as philosophical questions about the relationship of general and particular, complex and simple, with consideration of system and subsystems, class of jet devices, and separate subclasses included in this class. Figure 10 shows one of the possible variants – a multi-flow mesh jet device.

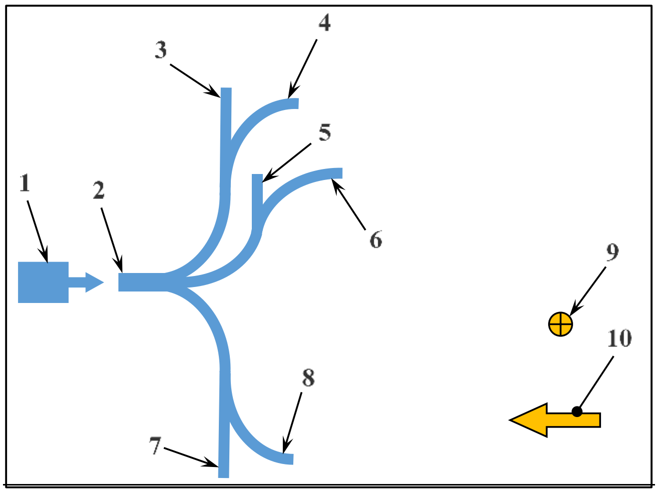

Figure 10. Scheme of the mesh jet device (variant): 1 – nozzle diaphragm with control system; 2 – inlet to multi-flow mixing chamber; 3–8 – outputs from multi-flow mixing chamber; 9 – characteristic point; 10 – external force vector

This variant of the jet device should be considered concerning three-dimensional space, and it partially corresponds to the model presented in Figures 2 to 4. In this example, channels 4, 6, and 8 direct the flows mainly along a cylindrical surface, and channels 3, 5, and 7 direct the flows predominantly along a single flat surface. Through inlet 2, the mixing chamber can receive media from the ambient space. Here, several basic operating regimes are possible when the working medium flow from nozzle diaphragm 1 can be:

- Distributed (evenly or unevenly) over outlet channels 3–8;
- Distributed (evenly or unevenly) only over outlet channels 3, 5, and 7;
- Distributed (evenly or unevenly) only through outlet channels 4, 6, and 8;
- Directed to one of the outlet channels 3–8.

The external force 10 can impact the jet device elements. Characteristic point 9 can occupy different positions relative to the jet device, considering the current technical problem. For the movable jet devices, characteristic point 9 may be the center of mass of the jet device or the product as a whole. When using rotating elements, the characteristic point 9 may be a point on the axis of rotation. It can be assumed that such a jet device (Figure 10) can be applied to various practical tasks (in addition to the well-known pumping and compressor technologies). It is possible to show some guidelines (directions) for developing scientific research in the field of mesh jet devices beforehand:

- A jet device – mixer. Using the proposed mesh jet systems, methods of efficient mixing fuel gas with steam and air to form a multicomponent homogeneous mixture can be developed, including ejector schemes combined with a mesh turbomachine (including for energy saving);
- A jet device – propulsor. At all times, the following problems in the field of propulsors remain relevant: increasing the efficiency of workflows and developing new ergonomic man-machine control systems of vehicles for three-dimensional space. Technologies for controlling high-temperature gas jets using low-temperature or cold actuators may be of particular scientific and practical interest. When developing offshore oil and gas fields, work on energy saving and developing effective systems of dynamic positioning for drilling and transport vessels and submarines are very relevant.
- A jet device – gas generator. It is well-known that gasification makes the use of solid and liquid fuel more convenient and more efficient for energy saving.
- A jet device – heat exchanger. This direction of work on energy saving could be developed using mesh jet devices and hybrid turbomachines.

Also, a variant of "A jet device – turbomachine" can be considered [1–6, 51]. A brief discussion of the turbine mathematical model uses the following symbols: the absolute gas temperature at the turbine inlet is T_0, the adiabatic exponent is k_0, the gas constant is, R_0 the average isobaric heat capacity is c_{p0} for the flow through the turbine, the efficiency factor for the turbine is, η_0 the mass flow of gas through the turbine is $\dot{Q}_0$., the gas pressure at the turbine inlet is P_0 and at the outlet is P_2.

When discussing a given topic, it is possible to use well-known mathematical dependencies usually used when discussing various heat machines and turbojet engines [52]. The degree of pressure reduction in a turbine:

$$\pi_0 = \frac{P_0}{P_2} \tag{1}$$

Specific turbine work:

$$L_0 = \frac{k_0}{k_0 - 1} R_0 T_0 \left(1 - \pi_0^{\frac{1-k_0}{k_0}}\right) \eta_0 \tag{2}$$

Gas temperature after the turbine:

$$T_{20} = T_0 \left(1 - \left(1 - \pi_0^{\frac{1-k_0}{k_0}}\right) \eta_0\right) \tag{3}$$

The patenting stage of the technical solution included calculations confirming the performance of the proposed jet system coupled with turbomachine. In calculations, the working gas is methane (such as gas from a gas well with high reservoir pressure). The pumped gas (methane) temperature T_0at the turbine inlet changes from 270 K to 600 K, the gas constant $R_0 = 523$ J/(kg*K), and the adiabatic exponent $k_0 = 1.31$. In some variants, $P_0 = 10$, MPa, $P_2 = 0.6$ MPa, and the efficiency factor for the turbine η_0 takes values from 0.5 to 0.9. Table 1 and Figure 11 partially present the information on calculations.

Table 1. Calculation results

T_0	L	η_0
K	MJ/kg	/
270	0.15	0.50
400	0.21	0.50
500	0.27	0.50
600	0.32	0.50
270	0.17	0.60
400	0.26	0.60
500	0.32	0.60
600	0.39	0.60
270	0.20	0.70
400	0.30	0.70
500	0.38	0.70
600	0.45	0.70
270	0.23	0.80
400	0.34	0.80
500	0.43	0.80
600	0.52	0.80
270	0.26	0.90
400	0.39	0.90
500	0.48	0.90
600	0.58	0.90

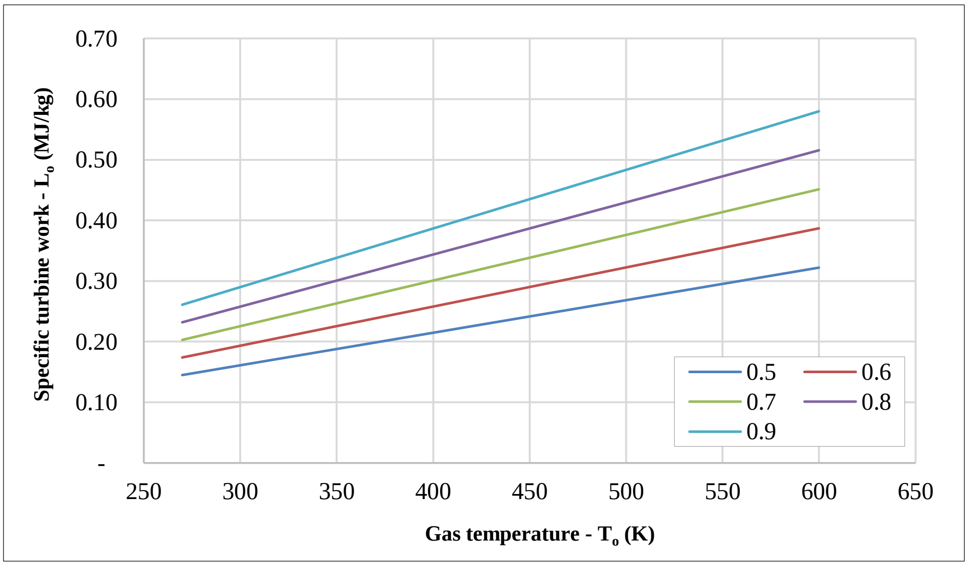

Figure 11. Calculated dependence of specific turbine work L_0 on working gas temperature T_0 at different values of turbine efficiency η_0 (in the range from 0.5 to 0.9)

The late stage of gas field development requires a solution to the urgent problem of energy saving associated with operating booster compressor stations at an inlet pressure of $P_1 \leq 0.5$ MPa. Under these conditions, it is difficult to provide cost-effective operation of expensive turbines and compressors a rapid change (decrease) in formation pressure at producing wells. However, gas energy loses and dissipates in the choke at the mouth of each well with high-reservoir pressure. Eco-friendly gas energy from wells with high reservoir pressure can be used to operate a booster compressor station and for cost-effective operation of production wells with low reservoir pressure. Here, power consumption from an external source reduces by 30...50%, considering the specifics of gas field development. Mesh turbines equipped with jet control systems will help solve the mentioned problems.

The well-known models of turbines (and turbomachines in general) mainly focus on obtaining the highest possible value for the efficiency factor. Calculations show that a high-efficiency turbine with $\eta_0 = 0.9$ can have power at the level of 3 MW at a mass flow rate of gas through the turbine $\dot{Q}_0 = 10$ kg/s. Note the following point when conducting the analysis. A less efficient turbine with $\eta_0 = 0.5$ can have this capacity at 3 MW at a mass flow rate of gas through the turbine $\dot{Q}_0 = 10$ kg/s, but it will be necessary to heat the working gas to a temperature of 550 K. The decision on the best variant in the equipment selection can be made after performing technical and economic calculations, considering the capital and operating costs and changing conditions of gas field development over time. Here, it is necessary to consider that equipment with a higher efficiency coefficient cost more, and the payback period of such equipment is longer. It is essential to be able to select the equipment on the criterion of "*efficiency-cost*". However, an additional issue may arise, and it is quite a complex issue that goes beyond the scope of one paper – a question of some mismatch of economic interests of the equipment manufacturer and the equipment buyer when discussing the above criterion.

A list of questions has been prepared to train designers reasonably to discuss the conceptual design stage and when preparing the technical assignment. For example, the list of questions for the nozzle design is shown in Table 2, and that for the mixing chamber design – in Table 3.

Table 2. Questions for the nozzle design

No.	Questions (On the nozzle or nozzle device design)	The answer is "Yes"	The answer is "No"
1	The nozzle has a traditional shape	Yes	No
2	The nozzle with the central body	Yes	No
3	The nozzle with the axisymmetric shape of channels	Yes	No
4	The outlet channel area was also adjustable	Yes	No
5	The outlet channel shape was also adjustable	Yes	No
6	Temperature is constant on points at the outlet cross-section	Yes	No
7	Velocity is constant on points at the outlet cross-section	Yes	No
8	Density is constant on points at the outlet cross-section	Yes	No
9	More than one inlet channel	Yes	No
10	More than one output channel	Yes	No
11	More than one working body	Yes	No
12	The nozzle has moved (including rotating) parts	Yes	No
13	The flow regime is unsteady	Yes	No
14	Phase transitions occur	Yes	No
15	Chemical reactions occur	Yes	No
16	The working body interacts with the environment	Yes	No
17	The properties of the environment (including temperature, pressure, and density) change	Yes	No
18	The environmental flow washes the solid walls of the nozzle	Yes	No
19	The product body contains the nozzle solid walls	Yes	No
20	The nozzle has 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 deflection angle ranges from +180 degrees to -180° within a geometric sphere	Yes	No
23	Supersonic flow velocity at the nozzle exit	Yes	No
24	restrictions on the flow velocity existing at the nozzle exit	Yes	No
25	Flow temperature limitations exist at the nozzle exit	Yes	No
26	restrictions on the flow noise level existing at the nozzle outlet	Yes	No
27	Limitations on the nozzle weight and size exist	Yes	No
28	Restrictions exist on the properties of structural materials for manufacturing the nozzle (and its elements)	Yes	No

29	Limitations exist on the nozzle operation time exist	Yes	No
30	Additional requirements for nozzle performance assessment exist	Yes	No
31	Additional requirements for nozzle performance assessment in terms of "efficiency-price" exist	Yes	No
32	Stationary operating mode for the working body source (the working medium or media)	Yes	No
33	The nozzle is used as a part of a turbomachine - "machine-engine "	Yes	No
34	The nozzle is used as a part of a turbomachine - "machine-executor"	Yes	No
35	The nozzle is used as a part of a turbomachine - "machine-propulsor"	Yes	No
36	The nozzle is used as a part of a turbomachine - "machine- gas generator"	Yes	No
37	The nozzle is used as a part of a turbomachine - "machine- heat exchanger"	Yes	No
38	The nozzle is used as a part of a turbomachine - "machine- mixer"	Yes	No
39	The nozzle is used as part of a turbomachine - "machine-separator"	Yes	No
40	The nozzle is used as part of a hybrid machine (or system)	Yes	No
41	The nozzle is used as a part of a jet device (or jet system)	Yes	No
42	Nozzle channels contain multi-component, multiphase fluid	Yes	No
43	Ability to select and switch operating modes in response to changes in the technical problem	Yes	No

Table 3. Questions for the design of the mixing chamber (MC) to the jet device

No.	Questions (On the mixing chamber design)	The answer is "Yes"	The answer is "No"
1	MC has a traditional shape	Yes	No
2	MC with the central body	Yes	No
3	MC with the axisymmetric shape of channels	Yes	No
4	The outlet channel area was also adjustable	Yes	No
5	The outlet channel shape was also adjustable	Yes	No
6	Temperature is constant on points at the outlet cross-section	Yes	No
7	Velocity is constant on points at the outlet cross-section	Yes	No
8	Density is constant on points at the outlet cross-section	Yes	No
9	More than one inlet channel	Yes	No
10	More than one output channel	Yes	No
11	More than one working body	Yes	No
12	MC has moved (including rotating) parts	Yes	No
13	The flow regime is unsteady	Yes	No
14	Phase transitions occur	Yes	No
15	Chemical reactions occur	Yes	No
16	The working body interacts with the environment	Yes	No
17	The properties of the environment (including temperature, pressure, and density) change	Yes	No
18	The environmental flow washes the solid walls of the nozzle	Yes	No
19	The product body contains the nozzle solid walls	Yes	No
20	The nozzle has 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 deflection angle ranges from +180 degrees to -180° within a geometric sphere	Yes	No
23	Supersonic flow velocity at the nozzle exit	Yes	No
24	Restrictions on the flow velocity existing at the nozzle exit	Yes	No
25	Flow temperature limitations exist at the nozzle exit	Yes	No
26	Restrictions on the flow noise level existing at the nozzle outlet	Yes	No
27	Limitations on the nozzle weight and size exist	Yes	No
28	Restrictions exist on the properties of structural materials for manufacturing the nozzle (and its elements)	Yes	No
29	Limitations exist on the nozzle operation time exist	Yes	No
30	Additional requirements for nozzle performance assessment exist	Yes	No
31	Additional requirements for nozzle performance assessment in terms of "efficiency-price" exist	Yes	No
32	Stationary operating mode for the working body source (the working medium or media)	Yes	No
33	The nozzle is used as a part of a turbomachine - "machine-engine "	Yes	No
34	The nozzle is used as a part of a turbomachine - "machine-executor"	Yes	No

35	The nozzle is used as a part of a turbomachine - "machine-propulsor"	Yes	No
36	The nozzle is used as a part of a turbomachine - "machine- gas generator"	Yes	No
37	The nozzle is used as a part of a turbomachine - "machine- heat exchanger"	Yes	No
38	The nozzle is used as a part of a turbomachine - "machine- mixer"	Yes	No
39	The nozzle is used as part of a turbomachine - "machine-separator"	Yes	No
40	The nozzle is used as part of a hybrid machine (or system)	Yes	No
41	The nozzle is used as a part of a jet device (or jet system)	Yes	No
42	Nozzle channels contain multi-component, multiphase fluid	Yes	No
43	Ability to select and switch operating modes in response to changes in the technical problem	Yes	No
44	Possibility of creating hybrid systems	Yes	No
45	The MC flow channels were shaped using curved tubes	Yes	No
46	The MC flow channels were shaped using straight tubes	Yes	No
47	Several MCs are connected in series	Yes	No
48	Several MCs are connected in parallel	Yes	No
49	The passive flow is adjustable	Yes	No
50	The active flow is adjustable	Yes	No
51	Additional requirements exist for the properties of the working body at the MC inlet	Yes	No
52	Additional requirements exist for the properties of the working body at the MC outlet	Yes	No
53	Additional requirements exist for the process of energy supply in MC channels	Yes	No
54	Additional requirements exist for the process of redistribution of energy in MC channels	Yes	No
55	Additional requirements exist for the process of energy extraction from MC channels	Yes	No
56	Additional requirements exist for the simultaneous implementation of several workflows in the MC channel (including when working on new physical principles)	Yes	No

By selecting the answer options to the questions posed, it is possible to prepare a preliminary design description for the designed product. During the design and research work, the list of questions in Tables 2 and 3 can be expanded (or shortened). The listed questions emphasize the variety of designs of jet devices that have already been created and that are to be created. It is reasonable to consider the listed questions when further improving the methodology of design of the jet devices intended for various industries.

4.3. Discussion of Individual Issues on Patenting of Scientific and Technical Developments

Continuing scientific research involves the patenting of individual developments to consolidate the results of intellectual activity. Given the experience gained, the analysis [53] advises conducting the preparation and formalization of inventions within the philosophy of technology. Note that P. K. Engelmeyer's philosophy of technology [53] succeeded as a new scientific trend comprising 1) the definition of technology in historical terms; 2) the inexhaustibility of technology possibilities; 3) the identification of fundamental features of technology, without which it is unthinkable both as a material and social phenomenon – the principle of transformation; 4) basis and methodology of technical knowledge addressed to the past, present and future.

At the stage of solving any technical or technological problem in energy saving, where various hybrid versions of jet devices are applicable, it is advisable to use additional tools from the theory of inventive problem solving [54]. In the framework of invention development and during educational work related to the training of designers, it is also advisable to advance according to the scheme "*from simple to complex*" using inductive and deductive logic with reasoning from the philosophy of technology.

4.4. Some Generalizations

A summary of the scientific research results performed in 2020 and 2022 [1–6, 55–59] makes it possible to state the following:

- As part of advancing Euler's ideas, a new scientific direction for the study of mesh turbomachines equipped with mesh jet control systems has been formed;
- For the first time, the issue of turbomachines, where the individual rotor blades alternately cyclically perform either the turbine function or the compressor (or pump) function, became subject to extensive discussion;
- For the first time, the issue of extreme working conditions of a new mesh jet control system becomes subject to extensive discussion, and for the first time, it has been shown that at the nozzle outlet, the jet can deflect an angle from $+180°$ to $-180°$within the geometric sphere.

The scope of the obtained results includes power engineering, oil and gas production and processing, and dynamic positioning systems as part of the development of offshore hydrocarbon fields. Individual results can apply to aviation and marine transportation systems.

This research paper solved the following main project tasks:

- It revealed promising directions for developing technologies and techniques using mesh jet devices;
- It revealed new opportunities for improving the methodology of designing mesh jet devices within the training of modern designers because of the proposed novel modifications of mesh jet devices and a direction of work for advancing Euler's ideas.

Within the advancement of Euler's ideas, a new scientific direction for studying and developing mesh turbomachines equipped with mesh jet control systems has been formed. It is well-known that the classification of turbomachines should reflect the level of historical development of this technique. However, it is possible to suggest the following. The classification of jet devices should also reflect plans (possible variants) for developing jet devices so that a student or graduate student could see more clearly prospects to apply his forces in science and technology and that a young scientist could also see the outlines of that "new," which is possible to create, but this "new" does not exist yet physically.

In general, the basic schematics of a multi-flow jet device can be (expediently) applied to the basic schematics of the entire class of jet devices. Based on this basic scheme, it is possible to make a logical transition to any known jet device included in the known subclass or a new (not yet created) subclass of jet devices. Within the framework of philosophical reasoning, this paper raises the question of the possibility of forming additional subclasses (subsystems). For educational purposes and within the framework of the philosophy of technology (for the training of designers), this paper proposes to consider the following additional subclasses of jet devices: "Jet device – mixer," "Jet device – propulsor," "Jet device – gas generator," "Jet device – heat exchanger," and "Jet device – turbomachine." It is also possible to consider the main workflow or several main workflows in a hybrid jet machine. It is possible to consider one or more energy sources in a hybrid jet device, including sources operating on different physical principles. In this regard, at the discussion stage, the authors of the paper proposed the following definition: "Generally, a jet device is a system that contains the following subsystems: a multi-flow nozzle diaphragm with a velocity vector (thrust vector) control system, a multi-flow receiving chamber with the control system, a multi-flow mixing chamber with the control system, and a multi-flow diffuser with the control system." We are talking about several workflows occurring on one jet device.

5. Conclusions

5.1. Scientific Novelty

Selected issues about the synergistic effect of the simultaneous use of two (or more) different control methods designed to control the velocity vector (thrust vector) are studied. Examples are considered where two different control methods were used simultaneously. The first method involves using a rotating nozzle, and the second one - a deflector made in the form of a curved tube with an outlet radial channel. This research showed that the synergistic effect of the simultaneous use of two different control methods would increase the speed of the jet control system by an order (and more).

5.2. The Theoretical Contribution

This paper put forward the working hypothesis: "In the general case, in the jet device, several workflows of energy transformation (or redistribution of energy) can occur in the flow of one fluid (the working body) or several flows of different fluids." This research has revealed the promising directions of theory development for creating jet devices of the new generation, including hybrid ones, and novel opportunities for the improvement of the methodology of jet device design to train designers.

5.3. Practical Significance

In the current conditions, the problem of energy savings in the implementation of production processes is the most urgent, and in this regard, the role of jet devices increases significantly. The scope of the obtained results includes power engineering, oil and gas production, and processing. Individual results can be applied to the field of aviation and marine transportation systems, including dynamic positioning systems.

5.4. Limitations and Further Research

Limitations related to the difficulty of calculating nonstationary processes within the existing gas and fluid dynamics as applied to mesh jet devices. At this research stage, the role of bench tests will be decisive in obtaining new scientific information. The research development can relate to evaluating the scientific and practical potential of hybrid mesh jet devices.

6. Declarations

6.1. Author Contributions

Conceptualization, Y.A.S.; methodology, M.A.M.; software, I.V.G.; validation, K.A.T.; formal analysis, V.V.V.; investigation, K.A.T.; resources, Y.A.S.; data curation, V.V.V.; writing—original draft preparation, N.N.B.; writing—review and editing, M.A.F.; visualization, I.V.G.; 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., Mulenko, V. V., Tumanyan, K. A., Frankov, M. A., & Balaka, N. N. (2021). Prototyping and study of mesh turbomachinery based on the Euler turbine. Energies, 14(17), 5292. doi:10.3390/en14175292.

[3] Sazonov, Y. A., Mokhov, M. A., Gryaznova, I. V., Voronova, V. V., Mulenko, V. V., Tumanyan, K. A., Frankov, M. A., & Balaka, N. N. (2021). Prototyping and study of jet systems for developing mesh turbomachines. International Review of Mechanical Engineering, 15(7), 335–345. doi:10.15866/ireme.v15i7.21163.

[4] Sazonov, Y. A., Mokhov M. A., Gryaznova, I. V., Voronova, V. V., Tumanyan, KH. A., Frankov, M. A., & Balaka, N. N. (2021). Prototyping and Research of Mesh Jet Systems. International Journal of Mechanical Engineering, 6(3), 22-42.

[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.

[6] Sazonov, Y. A., Mokhov, M. A., & Tumanyan, KH. A. (2022). Utility model Patent No. 209663 of the Russian Federation U1, IPC F03B 5/00, Moscow, Russia.

[7] Liu, Y. P., Wang, X. S., Zhu, P., Li, G. C., Ni, X. M., & Zhang, J. (2019). Experimental study on gas jet suppressed by water mist: A clean control technique in natural gas leakage incidents. Journal of Cleaner Production, 223, 163-175. doi:10.1016/j.jclepro.2019.03.107.

[8] Rendón, M. A., Assato, M., Martins, V. A., Hallak, P. H., Altgott, A. S., Graça, R., ... & Delmonte, R. G. P. (2022). Design method and performance analysis of a hybrid-electric power-train applied in a 30-passenger aircraft. Journal of Cleaner Production, 339, 130560. doi:10.1016/j.jclepro.2022.130560.

[9] Ma, T., Wang, X., Qiao, N., Zhang, Z., Fu, J., & Bao, M. (2022). A Conceptual Design and Optimization Approach for Distributed Electric Propulsion eVTOL Aircraft Based on Ducted-Fan Wing Unit. Aerospace, 9(11), 690. doi:10.3390/aerospace9110690.

[10] 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.

[11] Xia, J., & Zhou, Z. (2022). Model Predictive Control Based on ILQR for Tilt-Propulsion UAV. Aerospace, 9(11), 688. doi:10.3390/aerospace9110688.

[12] Wang, R., Zhang, G., Ying, P., & Ma, X. (2022). Effects of Key Parameters on Airfoil Aerodynamics Using Co-Flow Jet Active Flow Control. Aerospace, 9(11), 649. doi:10.3390/aerospace9110649.

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

[14] Kalachev, V. V. (2017). Jet pumps: theory, calculation and design. Omega, Moscow, Russia.

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

[16] Han, J., Feng, J., Hou, T., & Peng, X. (2021). Performance investigation of a multi-nozzle ejector for proton exchange membrane fuel cell system. International Journal of Energy Research, 45(2), 3031–3048. doi:10.1002/er.5996.

[17] Arun Kumar, R., & Rajesh, G. (2018). Physics of vacuum generation in zero-secondary flow ejectors. Physics of Fluids, 30(6), 66102. doi:10.1063/1.5030073.

[18] Chen, W., Xue, K., Chen, H., Chong, D., & Yan, J. (2018). Experimental and Numerical Analysis on the Internal Flow of Supersonic Ejector under Different Working Modes. Heat Transfer Engineering, 39(7–8), 700–710. doi:10.1080/01457632.2017.1325686.

[19] Sri Ramya, E., Lovaraju, P., Dakshina Murthy, I., Thanigaiarasu, S., & Rathakrishnan, E. (2020). Experimental and computational investigations on flow characteristics of supersonic ejector. International Review of Aerospace Engineering, 13(1), 1–9. doi:10.15866/irease.v13i1.18108.

[20] Vojta, L., & Dvorak, V. (2019). Measurement and calculating of supersonic ejectors. EPJ Web of Conferences, 213, 02097. doi:10.1051/epjconf/201921302097.

[21] Falsafioon, M., Aidoun, Z., & Ameur, K. (2019). Numerical investigation on the effects of internal flow structure on ejector performance. Journal of Applied Fluid Mechanics, 12(6), 2003–2015. doi:10.29252/JAFM.12.06.29895.

[22] Bharate, G., & Kumar R, A. (2021). Starting transients in second throat vacuum ejectors for high altitude testing facilities. Aerospace Science and Technology, 113. doi:10.1016/j.ast.2021.106687.

[23] Skaggs, B. D. (1997). U.S. Patent No. 5,628,623: Fluid ejector and ejection method. United States Patent Office, Alexandria, United States.

[24] Dodge, A. Y. (195). U.S. Patent No. 3,188,976. Jet pump. United States Patent Office, Alexandria, United States.

[25] 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.

[26] Asgarnejad, S., Kouhikamali, R., & Hassani, M. (2022). Triple-Nozzle Thermo-Compressor: Geometrical Investigation and Comparison with Single-Nozzle Thermo-Compressor. Journal of Applied Fluid Mechanics, 15(6), 1693–1702. doi:10.47176/jafm.15.06.1316.

[27] 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.

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

[29] Liu, J. F., Luo, Z. B., Deng, X., Zhao, Z. J., Li, S. Q., Liu, Q., & Zhu, Y. X. (2022). Dual Synthetic Jets Actuator and Its Applications—Part II: Novel Fluidic Thrust-Vectoring Method Based on Dual Synthetic Jets Actuator. Actuators, 11(8), 209. doi:10.3390/act11080209.

[30] Shakouchi, T., & Fukushima, S. (2022). Fluidic Thrust, Propulsion, Vector Control of Supersonic Jets by Flow Entrainment and the Coanda Effect. Energies, 15(22), 8513. doi:10.3390/en15228513.

[31] Chanut, P. L. J. (1964). U.S. Patent No. 3,013,494. Guided Missile. United States Patent Office, Alexandria, United States

[32] Sota Jr, C. G., Callis, G. J., & Masse, R. K. (2007). U.S. Patent No. 7,155,898: Thrust vector control system for a plug nozzle rocket engine. United States Patent Office, Alexandria, United States.

[33] Maré, J. C. (2021). Review and analysis of the reasons delaying the entry into service of power-by-wire actuators for high-power safety-critical applications. Actuators, 10(9), 233. doi:10.3390/act10090233.

[34] Aerospaceweb (2018). Missile Control Systems. Available online: http://www.aerospaceweb.org/question/weapons/q0158.shtml (accessed on August 2022).

[35] Abugov, D. I., & Bobylev, V. M. (1987). Theory and calculation of solid propellant rocket engines. Mechanical engineering, Moscow, Russia.

[36] 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.

[37] Bailey, J. M. (1982). U.S. Patent No. 4,355,949: Control system and nozzle for impulse turbines. United States Patent Office, Alexandria, United States.

[38] Decaix, J., & Münch-Alligné, C. (2022). Geometry, Mesh and Numerical Scheme Influencing the Simulation of a Pelton Jet with the OpenFOAM Toolbox. Energies, 15(19), 7451. doi:10.3390/en15197451.

[39] Hickerson, F. R. (1965). U.S. Patent No. 3,192,714: Variable thrust rocket engine incorporating thrust vector control. United States Patent Office, Alexandria, United States.

[40] Kinsey, L. E., & Cavalleri, R. J. (2013). U.S. Patent No. 8,387,360: Integral thrust vector and roll control system. United States Patent Office, Alexandria, United States.

[41] Plumpe Jr., William, H. (2003). U. S. Patent No. 6,622,472: Apparatus and method for thrust vector control. United States Patent Office, Alexandria, United States.

[42] 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.

[43] Dellali, R., & Kadja, M. (2019). Study of turbulent flow through a thrust reverser. International Review of Mechanical Engineering, 13(3), 173–184. doi:10.15866/ireme.v13i3.16306.

[44] 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). doi:10.3390/aerospace9090474.

[45] 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.

[46] Donateo, T., Spada Chiodo, L., Ficarella, A., & Lunaro, A. (2022). Improving the Dynamic Behavior of a Hybrid Electric Rotorcraft for Urban Air Mobility. Energies, 15(20), 7598. doi:10.3390/en15207598.

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

[48] Sazonov, Y. A., Mokhov, M. A., Tumanyan, K. A., Frankov, M. A. Voronova, V. V., & Balaka, N. N. (2022). The patent for the utility model of the Russian Federation No. 214452. Jet installation, Moscow, Russian Federation.

[49] Lavrentyev, M. A., Yushkevich, A. P., & Grigoryan, A. T. (1958). Leonhard Euler. Collection of articles in honour of the 250th anniversary of his birth presented to the Academy of Sciences of USSR, Moscow, Russia.

[50] Ackeret, J. (1944). Investigation of a water turbine built according to Euler's suggestions. Schweizerische Bauzeitung, 123(1), 2. (In German).

[51] Sazonov, Y. A., Mokhov, M. A., Tumanyan, K. A., Frankov, M. A., Voronova, V. V., & Balaka, N. N. (2022). The utility model patent of the RF No. 213280 Useful model patent of the Russian Federation No 213280. Jet Installation. Moscow, Russia.

[52] Baturin, O. V. (2011). Lecture notes on the educational discipline “Theory and calculation of blade machines”: a textbook. Samara University, Samara, Russia. (In Russian).

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

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

[55] Oz, F., & Kara, K. (2020). Jet Oscillation Frequency Characterization of a Sweeping Jet Actuator y. Fluids, 5(2), 72. doi:10.3390/fluids5020072.

[56] Portillo, D. J., Hoffman, E., Garcia, M., LaLonde, E., Combs, C., & Hood, R. L. (2022). The Effects of Compressibility on the Performance and Modal Structures of a Sweeping Jet Emitted from Various Scales of a Fluidic Oscillator. Fluids, 7(7), 251. doi:10.3390/fluids7070251.

[57] Tomac, M. (2020). Effect of the Oscillator Length on the Characteristics of a Feedback Type Fluidic Oscillator. Academic Platform Journal of Engineering and Science, 8(3), 432–438. doi:10.21541/apjes.583500.

[58] Baghaei, M., & Bergada, J. M. (2020). Fluidic oscillators, the effect of some design modifications. Applied Sciences (Switzerland), 10(6), 2105. doi:10.3390/app10062105.

[59] Hossain, M. A., Ameri, A., Gregory, J. W., & Bons, J. P. (2020). Sweeping jet film cooling at high blowing ratio on a turbine vane. Journal of Turbomachinery, 142(12), 121010. doi:10.1115/1.4047396.