

## Designing Mesh Turbomachinery with the Development of Euler's Ideas and Investigating Flow Distribution Characteristics

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Received 13 August 2022; Revised 15 October 2022; Accepted 19 October 2022; Published 01 November 2022

### Abstract

This research discusses developing an Euler turbine-based hybrid mesh turbomachinery. Within the framework of mechanical engineering science, turbomachinery classification and a novel method for mesh turbomachinery design were considered. In such a turbomachine, large blades are replaced by a set of smaller blades, which are interconnected to form flow channels in a mesh structure. Previous studies (and reasoning within the framework of inductive and deductive logic) showed that the jet mesh control system allows for operation with several flows simultaneously and provides a pulsed flow regime in flow channels. This provides new opportunities for expanding the control range and reducing the thermal load on the turbomachine blades. The novel method for performance evaluation was confirmed by the calculation: the possibility of implementing pulsed cooling of blades periodically washed by a hot working gas flow (at a temperature of 1000°C) and a cold gas flow (at a temperature of 20°C) was shown. The temperature of the blade walls remained 490–525°C. New results of ongoing research are focused on creating multi-mode turbomachinery that operates in complicated conditions, e.g., in offshore gas fields. Gas energy is lost and dissipated in the throttle at the mouth of each high-pressure well. Within the framework of ongoing research, the environmentally friendly net reservoir energy of high-pressure well gas should be rationally used for operating a booster compressor station. Here, the energy consumption from an external power source can be reduced by 50%, according to preliminary estimates.

*Keywords:* Flow; Euler Turbine; Mesh Turbomachine; Interdisciplinary Approach; Transdisciplinarity; Deductive Logic; Inductive Logic.

### 1. Introduction

Developing principles for machinery creation, conducting a systematic analysis of structures, generalizing the experience of machinery design, and searching for ways to improve the specific machinery performance with the rational use of energy are usually referred to as the general problems of mechanical engineering science [1, 2].

In modern conditions, the reduction of energy costs for implementing production processes is the most urgent problem. To solve this problem, a series of research works is being conducted in the laboratories of Gubkin University to create novel and promising turbomachinery [3–5]. In these promising machines, the flow channels have a mesh structure. In a conventional sense, a mesh is a representation of a larger geometric area in smaller discrete cells [6]. In a turbomachine, large blades are replaced with a set of smaller blades, which are interconnected to form mesh-structured flow channels. During physical and numerical experiments, for the first time, extreme conditions were considered for

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<http://dx.doi.org/10.28991/CEJ-2022-08-11-017>



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the flow of liquid and gas through a nozzle equipped with a velocity vector control system (or thrust vector, in aviation terminology), in the control range for the velocity vector deviation angle (thrust vector) from plus 180 degrees to minus 180 degrees, within the geometric sphere [3, 5]. Along with this, the question arose about the need to choose scientific directions for expanding applied research and developing promising mesh turbomachinery. This study proposes to consider a mesh turbomachine and a mesh jet control system within the framework of a single system. When studying the flow distribution processes moving in the channels of such a system, it will be necessary to consider a whole range of interrelated issues. For example, only a few from such a set of questions can be cited. A hybrid mesh turbomachine can have two (or more) input channels, and two (or more) output channels, with various geometric and gas-dynamic parameters for individual channels. The turbomachine can be connected to various energy sources, which can operate based on various physical principles. Several operational processes can occur simultaneously in a single impeller in a hybrid mesh turbomachine, such as a turbine operating process and a compressor operating process. In this case, a separate blade of such an impeller will periodically participate in both the turbine and the compressor operating processes. Variants with the implementation of chemical reactions and heat exchange processes in the mesh flow channels of the turbomachine rotor and stator are considered. It can be assumed that a set of such issues will be difficult to solve within the framework of any one discipline. Most likely, we should talk about research of an interdisciplinary nature.

Advanced scientific developments from other industries, including aviation technologies and modified aircraft engines, are actively used in production systems for producing, transporting, and processing oil and gas. In this regard, conducting a systematic analysis of structures and generalizing the machinery designing experience is not limited to any one industry, and issues are considered from the general positions of mechanical engineering science; thus, an interdisciplinary and even a transdisciplinary approach is used to organize research. As is known, the mesh structure of solid walls makes it possible to solve several important technical problems. Thus, the peculiarities of gas-dynamic processes have been studied when creating lattice wings [7] and aircraft [8, 9]. Computer simulation of gas-dynamic processes helps solve the complex problems of selecting the optimal geometric shape for solid walls in a gas flow under various flow regimes at low velocities [10] and at high velocities in the flow [11, 12], including the development of noise suppression technologies [13, 14]. At the same time, note that modern computer simulations cannot completely replace a physical experiment [15, 16]. The lattice structure of the channels significantly improves the heat dissipation characteristics of heat exchangers of various designs [17–19]. The mesh structure of the channels makes it possible to reduce the weight and overall dimensions of the heat exchanger [20–22].

Ejectors are known from patent materials, in which the nozzles are placed in a fixed disk support [23, 24] or in a rotating disk support [25, 26]. Supersonic ejectors for various purposes have been actively studied [27–29]. The peculiarities of energy exchange in the mixing chamber were investigated [30, 31]. Examples of the use of a mesh nozzle in the creation of ejectors are known [32]. Ejectors with curved-mixing chambers have not been sufficiently studied [33, 34]. An aircraft engine with an ejector reduces infrared radiation and specific fuel consumption and increases the installed engine thrust [35]. The ejector thrust booster also makes it possible to solve the problem of noise suppression during aircraft take-off and landing [36]. Ejectors are studied as part of rocket engines [37, 38]. The ejector flow part is sometimes included in the jet turbine rotor [39].

Currently, mesh structures are studied mainly to reduce the product weight while maintaining their strength characteristics [40, 41]. It can also be noted that with the use of advanced additive technologies, the maximum rigidity of the rotor design is achieved with a rotor minimum mass [42, 43]. With the use of additive technologies, it has now also become possible to create complex compositions from metal and ceramic materials [44].

Computer simulation nowadays opens up new possibilities for studying gas jets at the nozzle outlet with an unconventional shape [45, 46]. The conventional form usually includes nozzles with round or annular sections and square or rectangular sections [47]. Triangular and crescent-shaped nozzles are classified as unconventional shapes [48–50]. Novel application domains for non-traditional nozzle geometries are emerging [51–53]. Multiple nozzle systems are found in many engineering applications, including aircraft and missile propulsion. When several jets are located close to each other, the resulting aerodynamics are complicated due to the interaction of the jets [54]. The field of scientific research and practical applications of nozzle devices can be significantly expanded, regarding the expansion of the control range for the velocity vector (thrust vector) [3, 4].

Parts of contemporary turbines experience high thermal loads [55–57], which requires the search for new solutions in the design of cooled blades. The leading edge is the critical site of the blades [58, 59]. The issue of blade cooling in hybrid mesh turbomachinery can find non-standard solutions. It is noticeable that special attention is paid to studying the processes of gas jet interaction with a barrier [60] and the Coanda effect [61–63]. The use of the Coanda effect is considered a promising method for increasing aircraft lift force [64–66]. The issue of the practical use of the Coanda effect in hybrid mesh turbomachinery can find novel, non-standard solutions.

Various mechanical [67] and magnetohydrodynamic systems [68] are used to control gas flows. An adjustable nozzle design with the use of a deflector made in the form of a diaphragm is known [69, 70]. For the known thrust vector

(velocity vector) control systems, the largest flow deflection angle can vary in the range from plus 20 degrees to minus 20 degrees [71]. The nozzle can be equipped with a conical central body that can move in the axial direction [72] or in the radial direction [73]. The possibilities of thrust vector control due to liquid injection into a supersonic nozzle have been studied [74]. Research continues on nozzle options with deflectors of various shapes [75], including a cruciform nozzle outlet channel [76], to transfer directional force to the traditional aircraft, and to vertical take-off and landing aircraft. The field of scientific research and practical applications of novel nozzle devices can be significantly expanded considering the expansion of the control range for the velocity vector (thrust vector) [3, 4], from plus 180 degrees to minus 180 degrees within the geometric sphere.

Hybrid power plants containing two engines operating on different physical principles began to be actively discussed [77- 79]. The first engine is designed to take off and land the aircraft. The second engine is designed to fly at supersonic speeds. Research has intensified in the field of using hydrogen fuel [80], and detonation engines [81]. Turbine designs suitable for impulse flow [82] and energy recovery [83, 84] have been analyzed. The issue of non-stationary mixing of various fluid media is considered [85, 86]. The issue of adaptation to changing operating conditions in hybrid mesh turbomachinery can find new non-standard solutions. The mentioned publications, scientific developments, and achievements are now considered from the standpoint of their applicability when creating promising mesh turbomachinery equipped with mesh jet control systems. Within the framework of the presented article, the main objectives of the project include identifying promising areas for developing technologies and equipment using mesh turbomachinery and identifying new opportunities for improving the mesh turbomachinery design methodology as part of the training of modern designers.

The results of the ongoing research are mainly focused on the creation of multi-mode turbomachinery operating in complicated conditions, including offshore oil and gas fields. Thus, at the late stage of gas field development, an urgent problem related to the operation of booster compressors at an inlet pressure of  $P_1 \leq 0.5$  MPa has not yet been solved. Under these conditions, it is difficult to ensure the cost-effective operation of expensive compressors with a fairly rapid change (decrease) in reservoir pressure in the producing wells. At the same time, in high-pressure wells, gas energy is lost and dissipated in the throttle, at the mouth of each such well. Within the framework of ongoing research, the environmentally friendly net reservoir energy of gas from high-pressure wells should be used to operate a booster compressor station. Here, the consumption of electricity from an external source can be reduced by 50%, according to preliminary estimates. In this regard, scientific research is being carried out to create new mesh turbomachinery.

Simultaneously, individual results of research work can be used to solve practical problems in other industries, including improving the efficiency of energy conversion processes, generating electrical energy, and developing aviation and marine transport systems. In such cases, interdisciplinary and transdisciplinary approaches to research and design work are used. It is reasonable to discuss individual issues based on the philosophy of technology. Back in 1898, in the pamphlet *Technical Sum of the 19th Century*, P.K. Engelmeier formulated its tasks as follows [87]: In any human activity, in any transition from an idea to a thing, from a goal to its achievement, we must approach a certain technique. All the techniques have a lot in common. The task of the technology philosophy is precisely to determine that common.

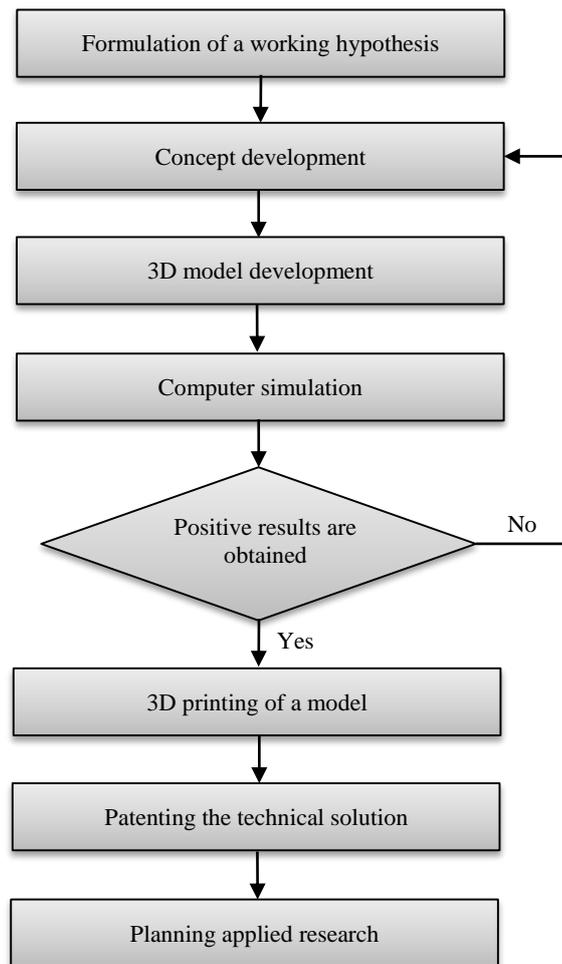
In the generally accepted understanding, a blade machine (turbomachines) is a device in the flow part of which energy is supplied or removed from a continuous flow of liquid or gas due to the aerodynamic interaction with specially profiled elements – blades [88]. Moreover, turbomachines are divided into “executor machines” and “engine machines”: “executor machines” supply energy to the flow of liquid or gas, and “engine machines” convert the flow energy into mechanical work. The operating processes of these two types of machinery obey the same physical principles, and are described by the same equations, including Newton’s second law of motion, and the Euler pump and turbine equations. The group of “executor machines” includes pumps, compressors, and fans. The group of “engine machines” includes turbines (hydraulic, gas, and steam ones).

As part of philosophical reasoning (on the question of “universals” and “particulars”) and within the existing classification, the class of turbomachinery should be taken as “universals”, and the subclasses “executor machinery” and “engine machinery” should be taken as “particulars 1” and “particulars 2”, respectively. Here, it turns out that the “universal” is “particular 1” or “particular 2”. But logically, “universals” should always be greater than any “particulars”. It is desirable to eliminate this contradiction, and in this regard, the article proposes a fragmentary discussion of the issue of the turbomachinery classification, at least for educational purposes when training of design specialists. The turbomachinery classification should reflect the level of historical development of this technique. However, it can be assumed that the turbomachinery classification should also reflect the plans (and possible options) for the turbomachinery development, so that the students or graduate students could see more clearly the prospects for the possible application of their forces in science and technology, and the young scientists could see the contours of the “innovation” that can be created, but this “innovation” does not yet exist.

Some results of ongoing research can also be used in other industries (for example, when creating hybrid power plants or propulsion systems). The scientific novelty of the article lies in the improvement of the turbomachinery design methodology, using interdisciplinary and transdisciplinary approaches to organize research and design work.

## 2. Methodology

Figure 1 provides a flowchart to explain the research methodology.



**Figure 1. A flowchart to explain the research methodology**

According to the flowchart (Figure 1), the methodology involves the formulation of a working hypothesis about the operating process in a hybrid turbomachine. The main concept is related to the study of gas-dynamic and hydrodynamic processes in the mesh structure channels. When developing a working hypothesis, individual facts are analyzed and scientific and technical information is reviewed. The facts are synthesized and generalized within the framework of the development of Euler's ideas. Next, assumptions are made about the possibility of creating a new series of hybrid turbomachinery and a diagram is developed. Three-dimensional models are developed for the study of mesh turbomachinery equipped with mesh jet control systems. Computer simulation is conducted using the developed three-dimensional models. The results of the computer simulation are analyzed, and, if necessary, a return to the stage of a diagram composing may be carried out to improve it. When positive results are obtained after computer simulation, 3D printing of micromodels is conducted. Furthermore, new technical solutions designed to solve actual production problems are patented. The development of applied scientific research and development work is planned.

This article presents the results of calculations and computer simulation. As part of the ongoing research work in 2020–2021, laboratory bench tests of micromodels have been carried out; materials on these bench tests were published earlier [3–5]. The object of this research is a combination of gas-dynamic and hydrodynamic processes in stationary and non-stationary flow modes through mesh-structured rotating and stationary channels. This goal of this article is to discuss and analyze the development of hybrid mesh turbomachinery, based on the Euler turbine. The obtained research results are used to create new models and prototypes. Individual developments are patented, the preparation and formalization of inventions is carried out within the framework of the philosophy of technology [89–91]. The research results form the basis for future applied scientific R&D work. When performing fundamental and applied scientific research, it was decided to use the well-known methodology [92] with an interdisciplinary approach, while always considering a combination of many processes, including bladed and vortex operating processes; pumping, compressor and turbine workflows; coalescence and separation processes.

It is also possible to make an assumption about the need to use an additional tool in the form of a transdisciplinary approach [93]. As is known, transdisciplinarity complements disciplinary and interdisciplinary approaches. In our case, it refers only to one of the forms of transdisciplinary, which is called “experimental transdisciplinarity”, while using a

clearly defined procedure that has an acceptable (for the scientific community) level of reproduction of the procedure itself and its results. The scientific and technical information was analyzed within the framework of deductive logic, when a logical and methodological procedure is built, through which the transition from the universals to the particulars is carried out in the process of reasoning. Some reasoning and hypotheses were presented within the framework of inductive logic, when the general conclusion is based on particular premises. In the conventional sense, induction is a cognitive procedure using which a statement generalizing existing facts is derived from their comparison.

The principle of reduction has been used in some arguments, which in general is a reduction of the complex to the simple, the higher to the lower, the whole to the properties of the parts, and the parts to the specifics of the whole. In the generally accepted sense, reduction is a logical and methodological procedure for representing a complex object as a sum of simple elements, which makes it accessible for analysis.

### 3. Research Results

#### 3.1. Development of Schematic Arrangement for Promising Hybrid Turbomachinery

As part of the ongoing research, we considered novel approaches to the creation of special turbomachinery: turbines, pumps, compressors and hybrid turbomachinery. A peculiarity of such machinery is the use of a mesh structure when profiling the rotor and stator flow parts in a dynamic machine. New possibilities for the practical use of a multi-flow ejector are also considered with regard to the rotational movement of its individual parts [3–5]. A turbomachine [80] was considered an analog. This machine uses an option of the Segner turbine. The disadvantages of such a turbine are low efficiency and high thermal loads on the blades. It was necessary to solve the technical problem of creating a simple and reliable hybrid turbomachine, providing good conditions for cooling the blades in the rotor wheel. Figure 2 shows a new scheme for describing the developed and patented turbomachine [5] according to the application for utility model RF # 2022110755, of 04/20/2022 (there is a decision to grant a patent dated 07/19/2022). This turbomachine belongs to the field of pumping and compressor equipment and is designed for pumping liquids, gases and their mixtures; it can also be used to create heat engines in the framework of interdisciplinary and transdisciplinary work [94, 95]. Figure 3 shows a schematic of the impeller.

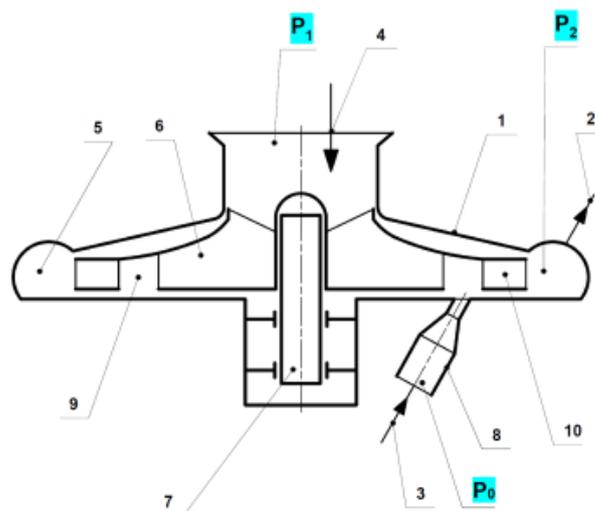


Figure 2. Scheme of the developed and patented turbomachine, according to application 2022110755: 1 – body; 2 – outlet channel (pressure  $P_2$ ); 3 – inlet channel for the working medium (pressure  $P_0$ ); 4 – inlet channel for the pumped medium (pressure  $P_1$ ); 5 – mixing chamber; 6 – impeller; 7 – shaft; 8 – nozzle apparatus; 9 – annular channel; 10 – turbine blades.

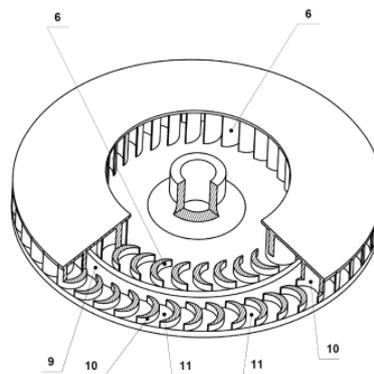
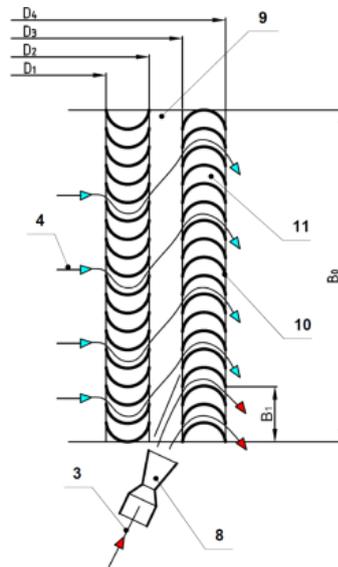


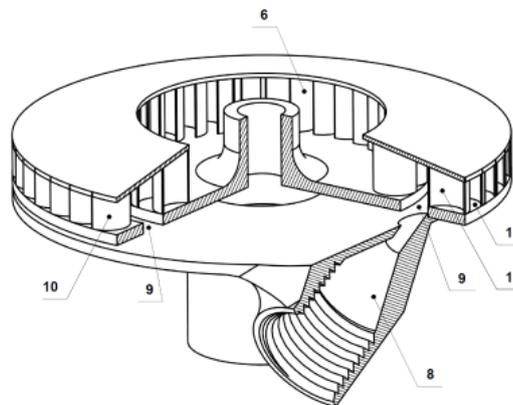
Figure 3. The impeller scheme, according to application 2022110755

Impeller 6 is equipped with a system of turbine blades 10 with flow channels 11 hydraulically connecting annular channel 9 with outlet channel 2. The flow channels in impeller 6 and in turbine blade system 10 can have a mesh structure (in the conventional sense, a mesh is a representation of a larger geometric region by smaller discrete cells). The mesh structure provides higher rigidity and strength of the structure with its low weight. Figure 4 schematically shows the development drawing of the impeller blade system.



**Figure 4. Schematic development drawing of the impeller blade system, according to application 2022110755**

The trailing edges of blades 10 are placed on a circumference with a diameter  $D_4$ . In the diagram, segment  $B_0$  corresponds to the circumference length with diameter  $D_4$ , or  $B_0 = \pi D_4$ . The flow of the working medium coming out of the nozzle 8 interacts with blades 10 when these blades, during their movement, overcome the path segment  $B_1$ . Figure 5 shows an impeller with a nozzle apparatus.



**Figure 5. Impeller with nozzle assembly (3D model – isometric projection), according to application 2022110755**

The mode of the working medium flow through nozzle apparatus 8 can be stationary or pulsed, depending on the technical problem being solved. The nozzle apparatus 8 may have several outlets directed toward turbine blades 10. To supply additional power, shaft 7 can be connected to an additional engine (with an internal combustion engine or an electric engine), depending on the technical problem being solved (interdisciplinary or transdisciplinary problem). The additional engine is not shown in the figures. To remove excess power, shaft 7 can be connected to an additional machine (an electric generator, an additional compressor or pump), depending on the technical task being solved (interdisciplinary or transdisciplinary task). The additional machine is not shown in the figures.

The turbomachine operates as follows (Figures 2 to 5). Through inlet channel 3, the working medium (liquid, gas or gas-liquid mixture, at a high temperature) is supplied under pressure to the nozzle apparatus 8. The high-temperature jet of the working medium leaving the nozzle apparatus 8 exerts a force on turbine blades 10, causing the impeller 6 to rotate. Impeller 6 has a force effect on the pumped medium. During rotation, impeller 6 creates a flow of the pumped medium (liquid, gas or gas-liquid mixture), while the temperature of the pumped medium can be significantly lower than the temperature of the working medium. The pumped medium enters through inlet channel 4, then passes through

the channels of impeller 6, flow channels 11 and is discharged through outlet channel 2. The working medium, having passed through flow channels 11, mixes with the pumped medium and is discharged through outlet channel 2.

Thus, energy is transferred from the working medium to the pumped medium by rotating impeller 6 equipped with a system of turbine blades 10. When impeller 6 and turbine blades 10 rotate, either the working medium flow or the pumped medium flow periodically passes through flow channels 11. The high-temperature working fluid flow heats turbine blades 10, while the cooler flow of the pumped medium removes heat and cools turbine blades 10.

Due to the favorable cooling conditions of turbine blades 10, it becomes possible to increase the temperature of the working medium (gas), which, as known, contributes to an increase in the efficiency of the working process in a turbomachine. For example, for a heat engine, the cold air is a pumped medium, and the hot gas from a gas generator is a working medium. Thus, a technical result achieved is improved cooling conditions of turbine blades with the possibility of increasing the working gas temperature and ensuring an increase in the efficiency of energy conversion in the flow path of the turbomachine (an interdisciplinary or transdisciplinary task).

### 3.2. Use of Additive Technologies for Micromodel Creation (Prototyping)

Figure 6 shows a photograph of the created prototype – an impeller with a nozzle assembly. The performance of the created prototype was successfully tested under laboratory conditions, and the test results were previously reflected in publications [3–5]. Air, steam and water were used for these tests. Figure 7 shows a photograph of the created turbomachine prototype, according to the schematic diagrams in Figures 2 to 5.

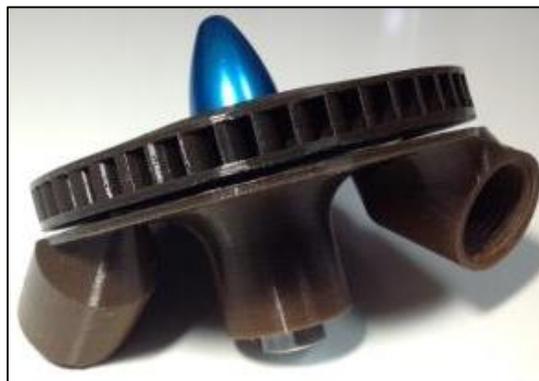


Figure 6. A photo of the created prototype – an impeller with a nozzle assembly (prototype version), according to application 2022110755



Figure 7. A photo of the created turbomachine prototype (option), according to application 2022110755

The nozzle apparatus in such a turbomachine (Figure 7) can be equipped with a velocity vector control system (thrust vector). This article does not consider such a control system, but the system was described in other publications of the authors [3–5].

### 3.3. Discussion of Approaches to the Calculation of Hybrid Machinery, Based on the Existing Theoretical Basis

As is known, after the appearance of a patentable idea, there is immediately a need to test the performance of a novel technical solution. The performance of the technical solution is verified at all stages of design, starting with the implementation of preliminary calculations. Consider a simplified diagram of a turbomachine (jet system), in which the working medium interacts with the pumped medium (Figure 8).

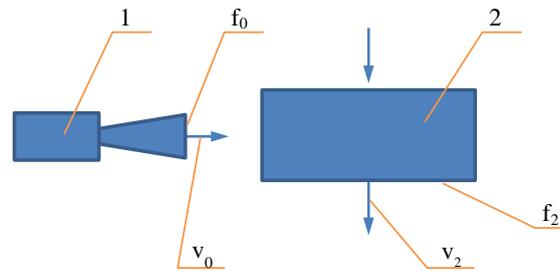


Figure 8. Scheme of the jet system for the energy converter: 1 – the working medium source; 2 – the working chamber

Consider a variant of the mathematical model for the presented idealized jet system. Working medium source (or gas generator) 1 makes it possible to form a working medium jet, at a flow rate  $v_0$  in the outlet section area  $f_0$ , with a working medium density of  $\rho_0$ . Here, the volumetric flow rate of the working medium is  $Q_0 = f_0 v_0$ , and the mass flow rate of the working medium is  $\dot{Q}_0 = Q_0 \rho_0$ . As is known, the reactive force (or thrust, according to aviation terminology) is determined at the loss of the working medium by the relationship  $F_0 = Q_0 \rho_0 v_0$ .

Energy conversion is carried out in working chamber 2, with a force effect on the pumped medium flow. An ejector or a turbofan (turbocharger), or another machine can be located in the working chamber 2. A jet is formed at the outlet of working chamber 2, at a flow rate  $v_2$  in the outlet section with an area  $f_2$ , and the pumped medium density of  $\rho_2$  (or a mixture of the pumped and working media). Here, the volumetric flow rate at the outlet of chamber 2 will be  $Q_2 = f_2 v_2$ , and the mass flow will be  $\dot{Q}_2 = Q_2 \rho_2$ , respectively.

The reactive force or thrust at the outlet of chamber 2 is determined by the relationship  $F_2 = Q_2 \rho_2 v_2$ . As is known, the kinetic energy of the working medium flow can be estimated through the power parameter:

$$N_0 = Q_0 \rho_0 \frac{v_0^2}{2} \quad (1)$$

The kinetic energy of the flow at the outlet of chamber 2 can be estimated through the power parameter:

$$N_2 = Q_2 \rho_2 \frac{v_2^2}{2} \quad (2)$$

The ratio of the volumetric flow rates has the following form:

$$q = \frac{Q_2}{Q_0} \quad (3)$$

The thrust amplification (change rate) factor is calculated as follows:

$$K_F = \frac{F_2}{F_0} \quad (4)$$

The results of laboratory tests of mesh turbomachinery micromodels were previously presented in publications [3-5, 37, 77], while the operability of novel technical solutions was confirmed (the  $K_F$  coefficient values were recorded at a level from 1.9 to 2.1 when testing micromodels in the air, in the turbofan mode). Preliminary calculations show that this  $K_F$  coefficient can reach values of 10 for a full-sized mesh turbomachine operating in the mode of the afterburner gas turbine engine, considering the restrictions on the gas temperature at the turbine inlet.

The efficiency factor for the kinetic energy conversion process is calculated as follows:

$$\eta_{20} = \frac{N_2}{N_0} \quad (5)$$

The following dependences can be obtained through the transformations:

$$q = \sqrt{K_F \frac{\rho_0 f_2}{\rho_2 f_0}} \quad (6)$$

$$f_0 = \frac{2 N_0}{v_0^3 \rho_0} \quad (7)$$

$$f_2 = \frac{2 N_0 \eta_{20}}{v_2^3 \rho_2} \quad (8)$$

$$K_F = \frac{v_0}{v_2} \times \eta_{20} \quad (9)$$

$$q = \frac{v_0^2}{v_2^2} \times \frac{\rho_0}{\rho_2} \times \eta_{20} \quad (10)$$

$$\frac{f_2}{f_0} = \frac{v_0^3}{v_2^3} \times \frac{\rho_0}{\rho_2} \times \eta_{20} \quad (11)$$

$$\frac{f_2}{f_0} = \frac{v_0}{v_2} \times q \tag{12}$$

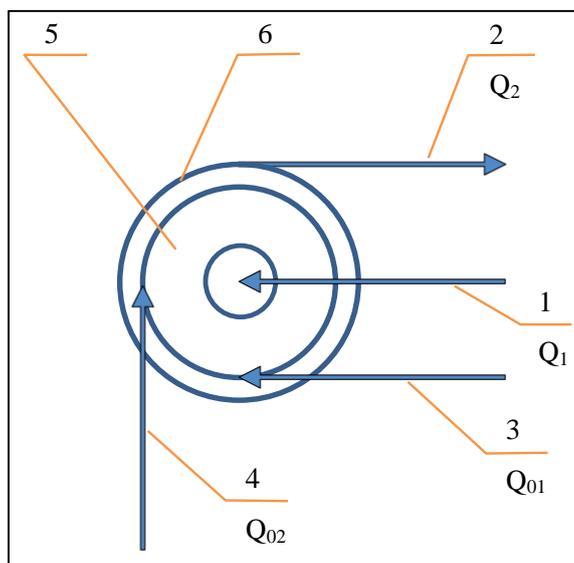
The presented dependencies are used when verifying the performance of the created mesh turbomachinery [3–5].

Figure 9 shows a photo of a jet system micromodel for energy conversion: a turbofan with a propeller. The micromodel is created in compliance with the scheme in Figure 8.



**Figure 9. A photo of a jet system micromodel for energy conversion: a turbofan with a pusher propeller placed at the bottom (prototype version)**

Figure 10 schematically shows option 1 of the turbomachine, which is shown in more detail in Figures 2 to 5. The flow from the working medium source, with a volumetric flow  $Q_{01}$ , is directed to the rotor channels. An additional source of working medium with a volume flow  $Q_{02}$  can also be used. The pumped medium, with volumetric flow  $Q_1$ , is fed into the rotor center. The mixture of the working and the pumped media, with a volume flow  $Q_2$ , is discharged through the outlet channel.



**Figure 10. A turbomachine scheme (option 1): 1 – inlet channel for the pumped medium; 2 – outlet channel for a mixture of the working and the pumped media; 3, 4 – input channels for the working medium; 5 – rotor; 6 – body**

According to the scheme in Figure 10, the flow from the working medium source 3, with a volumetric flow rate  $Q_{01}$ , is directed to the rotor channels. An additional working medium source 4, with a volumetric flow rate of  $Q_{02}$ , can also be used (a more complex interdisciplinary or transdisciplinary task can also be considered). Pumped medium 1, with a volume flow  $Q_1$ , is fed into the center of rotor 5. The mixture of the working and the pumped media, with a volumetric flow rate of  $Q_2$ , is discharged from body 6 through outlet channel 2.

A heat exchange chamber (or afterburner), with the supply of thermal energy  $L_2$ , can be installed at the turbomachine outlet (Figure 11-a – Option 2). A heat exchange chamber (heater or afterburner) with the supply of thermal energy  $L_{02}$  can also be installed at the turbomachine inlet (Figure 11-b – Option 3). It is possible to consider options with the implementation of chemical reactions releasing thermal energy in the flow channels of a turbomachine.

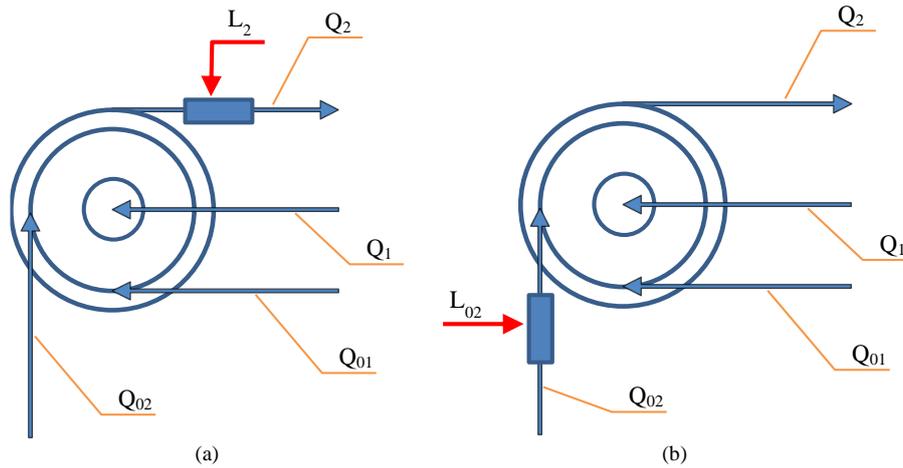


Figure 11. A turbomachine scheme: a) option 2; b) option 3

For working conditions in gaseous media, the following symbols are used: absolute gas temperatures at the inlet  $T_0$  and outlet  $T_{20}$  of the turbine, at the inlet  $T_1$  and outlet  $T_{21}$  of the compressor, at the outlet of the mixing chamber  $T_3$ ; adiabatic exponents  $k_0, k_1, k_3$ ; gas constants  $R_0, R_1, R_3$ ; average isobaric heat capacities  $c_{p0}, c_{p1}, c_{p3}$  for the flow through the turbine, the compressor and the mixing chamber, respectively; efficiency factors for the turbine and for the compressor  $\eta_0, \eta_1$ ; mass flow rate of gas through the turbine  $\dot{Q}_0$  and through the compressor  $\dot{Q}_1$ ; the power of an additional energy source, for example, an additional  $N_3$  engine (connected to the rotor shaft); the power of the additional source of thermal energy  $E_4$  (as applicable to the schemes in Figures 2 to 5, 9 to 11); gas pressure at the inlet  $P_0$  and outlet  $P_2$  of the turbine, and at the inlet  $P_1$  and outlet  $P_2$  of the compressor. The turbomachine can be connected to various energy sources that can operate based on various physical principles ( $N_3; E_4$ )

Here, turbomachinery options are mainly considered for the following conditions:

$$T_0 > T_{20} > T_1 \tag{13}$$

$$T_0 > T_{21} > T_1 \tag{14}$$

The turbine blades are intermittently directly cooled by the gas leaving the compressor at a temperature  $T_{21}$ . If we denote the total turbine operation time as  $x_0$ , and the total cooling time for these blades as  $x_2$ , we can introduce a dimensionless parameter  $X$ , characterizing the conditions for cooling turbine blades:

$$X = \frac{x_2}{x_0} \tag{15}$$

When discussing the presented topic, one can use the well-known mathematical relationships that are usually applied to discuss various heat and turbojet engines [88, 96]. The degree of pressure reduction in the turbine is calculated as follows:

$$\pi_0 = \frac{P_0}{P_2} \tag{16}$$

The compressor pressure ratio:

$$\pi_1 = \frac{P_2}{P_1} \tag{17}$$

The specific work of the turbine:

$$l_0 = \frac{k_0}{k_0 - 1} R_0 T_0 \left( 1 - \pi_0^{\frac{1 - k_0}{k_0}} \right) \eta_0 \tag{18}$$

The specific work of the compressor:

$$l_1 = \frac{k_1}{k_1 - 1} R_1 T_1 \left( \pi_1^{\frac{k_1 - 1}{k_1}} - 1 \right) \eta_1^{-1} \tag{19}$$

Mass flow ratio:

$$\dot{q} = \frac{\dot{Q}_1}{\dot{Q}_0} \tag{20}$$

The specific work of the additional engine:

$$l_3 = \frac{N_3}{\dot{Q}_0} \tag{21}$$

The specific work balance:

$$l_3 + l_0 = \dot{q}l_1 \tag{22}$$

$$\frac{N_3}{\dot{Q}_0} + \frac{k_0}{k_0-1}R_0T_0\left(1 - \pi_0^{\frac{1-k_0}{k_0}}\right)\eta_0 = \dot{q}\frac{k_1}{k_1-1}R_1T_1\left(\pi_1^{\frac{k_1-1}{k_1}} - 1\right)\eta_1^{-1} \tag{23}$$

It should be noted here that in the novel mesh turbomachine, a separate rotor blade periodically participates in the turbine workflow and in the compressor workflow. This feature of the workflow must be considered when developing new theories and novel computer programs for such mesh turbomachinery. At this stage of research, the known theories of turbines and compressors can only be used with certain reservations, only as part of confirming the operability of the discussed mesh turbomachine option.

Heat balance in the mixing chamber:

$$\dot{Q}_0c_{p0}T_{20} + \dot{Q}_1c_{p1}T_{21} + E_4 = (\dot{Q}_0 + \dot{Q}_1)c_{p3}T_3 \tag{24}$$

Gas temperature downstream of the turbine:

$$T_{20} = T_0\left(1 - \left(1 - \pi_0^{\frac{1-k_0}{k_0}}\right)\eta_0\right) \tag{25}$$

Gas temperature downstream of the compressor:

$$T_{21} = T_1\left(1 + \left(\pi_1^{\frac{k_1-1}{k_1}} - 1\right)\eta_1^{-1}\right) \tag{26}$$

As is known, there may be restrictions on the gas velocity and on the gas temperature at the outlet of the turbomachine (for example, for some aircraft with vertical takeoff and landing). In this regard, when calculating and considering mesh turbomachinery (for example, by the scheme in Figure 8), it will be necessary to choose a particular or comprehensive optimization criterion, regarding the conditions for a particular applied problem.

At the stage of the technical solution patenting, calculations were made confirming the performance of the proposed turbomachine (Figures 2 to 5, Equations 16 to 23). Information on the calculations is partially presented in Tables 1 to 3. In calculations 1 and 2, methane acts as a working gas (for example, gas from a high-pressure well), methane also acts as a pumped gas (for example, gas from a low-pressure well). The temperature of the pumped gas (methane) at the compressor inlet is  $T_1 = 300\text{ K}$ . The gas constant is  $R_0 = R_1 = 523\text{ J}/(\text{kg} * \text{K})$ . Adiabatic exponents are  $k_0 = k_1 = 1.31$ . Isobaric heat capacities are  $c_{p0} = c_{p1} = 2483\text{ J}/(\text{kg} * \text{K})$ . The range of pressure change  $0.2\text{ MPa} \leq P_1 \leq 0.5\text{ MPa}$  is considered. Here, the degree of pressure increase in the compressor is  $1.2 \leq \pi_1 \leq 3$ , where  $\pi_1 = P_2/P_1$ . The efficiency factors are taken in calculation-1 and in calculation-2:  $\eta_0 = 0.5$  for the turbine and  $\eta_1 = 0.7$ .

**Table 1. Input data and calculation results-1**

#	$T_0$	$P_0$	$P_1$	$P_2$	$P_2/P_1$	$\dot{Q}_0$	$\dot{Q}_1$	$\dot{Q}_1/\dot{Q}_0$
	K	MPa	MPa	MPa	/	kg/s	kg/s	/
1	300	10	0.20	0.60	3.00	1	0.57	0.57
2	300	10	0.25	0.60	2.40	1	0.74	0.74
3	300	10	0.30	0.60	2.00	1	0.95	0.95
4	300	10	0.35	0.60	1.71	1	1.25	1.25
5	300	10	0.40	0.60	1.50	1	1.69	1.69
6	300	10	0.45	0.60	1.33	1	2.42	2.42
7	300	10	0.50	0.60	1.20	1	3.86	3.86

**Table 2. Input data and calculation results-2**

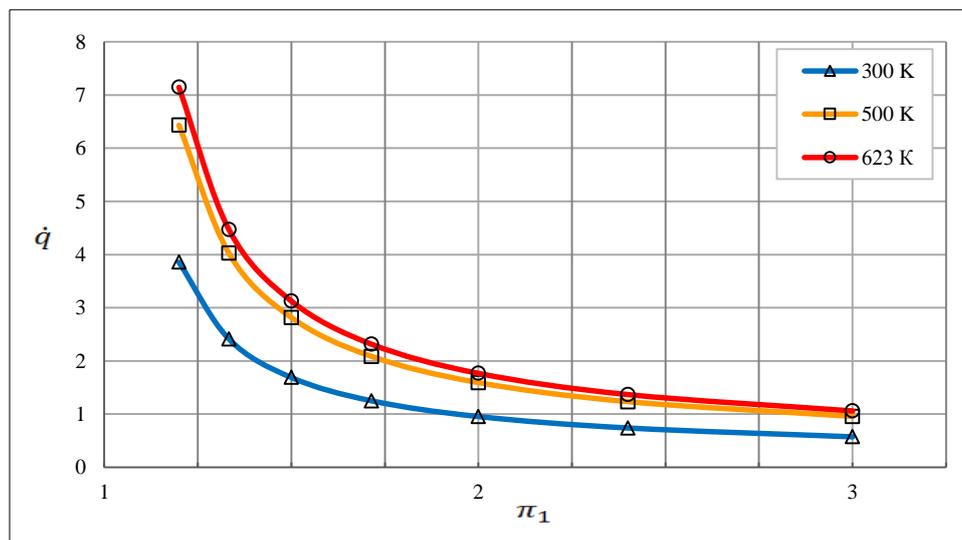
#	$T_0$	$P_0$	$P_1$	$P_2$	$P_2/P_1$	$\dot{Q}_0$	$\dot{Q}_1$	$\dot{Q}_1/\dot{Q}_0$
	K	MPa	MPa	MPa	/	kg/s	kg/s	/
1	500	10	0.20	0.60	3.00	1	0.96	0.96
2	500	10	0.25	0.60	2.40	1	1.23	1.23
3	500	10	0.30	0.60	2.00	1	1.59	1.59
4	500	10	0.35	0.60	1.71	1	2.08	2.08
5	500	10	0.40	0.60	1.50	1	2.82	2.82
6	500	10	0.45	0.60	1.33	1	4.03	4.03
7	500	10	0.50	0.60	1.20	1	6.43	6.43

**Table 3. Input data and calculation results-3**

#	$T_0$	$P_0$	$P_1$	$P_2$	$P_2/P_1$	$\dot{Q}_0$	$\dot{Q}_1$	$\dot{Q}_1/\dot{Q}_0$
	K	MPa	MPa	MPa	/	kg/s	kg/s	/
1	623	10	0.20	0.60	3.00	1	1.06	1.06
2	623	10	0.25	0.60	2.40	1	1.37	1.37
3	623	10	0.30	0.60	2.00	1	1.77	1.77
4	623	10	0.35	0.60	1.71	1	2.32	2.32
5	623	10	0.40	0.60	1.50	1	3.13	3.13
6	623	10	0.45	0.60	1.33	1	4.47	4.47
7	623	10	0.50	0.60	1.20	1	7.15	7.15

According to calculation-1, the mass flow ratio  $\dot{q} = \dot{Q}_1/\dot{Q}_0$  varies in the range from 0.57 to 3.86 (Table 1). Calculation-2 considers an option with heating of the working gas before entering the turbine. The working gas (methane) temperature at the turbine inlet is  $T_0 = 623 K$ . According to calculation-2, the mass flow ratio  $\dot{q} = \dot{Q}_1/\dot{Q}_0$  varies in the range from 0.96 to 6.43 (Table 2).

In calculation-3, superheated water vapor acts as a working gas (for example, from a steam generator), methane acts as a pumped gas (for example, gas from a low-pressure well). The working gas (superheated water vapor) temperature at the turbine inlet is  $T_0 = 623 K$ . The pumped gas (methane) temperature at the compressor inlet is  $T_1 = 300 K$ . The gas constant is  $R_0 = 463 J/(kg \cdot K)$  for superheated steam, and  $R_1 = 523 J/(kg \cdot K)$  for methane. The adiabatic exponent for superheated steam is  $k_0 = 1.3$ . At a pressure of 10 MPa, the isobaric heat capacity of superheated water vapor is  $c_{p0} = 4012 J/(kg \cdot K)$ . The range of pressure change  $0.2 MPa \leq P_1 \leq 0.5 MPa$  is considered. Here, the degree of pressure increase in the compressor is  $1.2 \leq \pi_1 \leq 3$ , where  $\pi_1 = P_2/P_1$ . The efficiency factors are taken in calculation-3 as  $\eta_0 = 0.5$  for the turbine and  $\eta_1 = 0.7$  for the compressor. According to calculation-3, the mass flow ratio  $\dot{q} = \dot{Q}_1/\dot{Q}_0$  varies in the range from 1.06 to 7.15 (Table 3). The calculated dependences of  $\dot{q}$  on  $\pi_1$  are shown in Figure 12.



**Figure 12. The calculated dependences of  $\dot{q}$  on  $\pi_1$  at different working gas temperatures: 300 K (calculation-1); 500 K (calculation-2); 623 K (calculation-3)**

At the late stage of gas field development, it is necessary to solve an urgent problem related to booster compressor stations at an inlet pressure of  $P_1 \leq 0.5$  MPa. Under these conditions, it is difficult to ensure the cost-effective operation of expensive compressors with a fairly rapid change (decrease) in reservoir pressure in the producing wells. Simultaneously, in high-pressure wells, gas energy is lost and dissipated in the throttle, at the mouth of each such well. The environmentally friendly energy of gas from high-pressure wells can be used to operate a booster compressor station and for the cost-effective operation of low-pressure production. As shown by the calculations (Figure 12), both methane and water vapor can be used as a working gas, or these two flows can be used jointly for the turbomachine operation. By controlling the water vapor parameters, it is possible to adjust the turbomachine operation mode to the conditions for changing the parameters of gas flows  $P_1$  and  $P_0$ . As is known, in turbines, the gas phase of propane or butane can also be used, in addition to water vapor; these options will expand the regulation range of turbomachinery and individual compressors.

When evaluating the turbomachine operation on gas-liquid mixtures, in some cases, an isothermal process is considered [92]. The turbomachine itself is schematically shown in Figures 2–5, and 10–12. The formulas use the following conventions: pressure at the inlet  $P_0$  and at the outlet  $P_2$  of a hydraulic turbine, at the inlet  $P_1$  and at the outlet  $P_2$  of a multiphase pump; efficiency factors for the turbine and for the pump  $\eta_0$ ,  $\eta_1$ ; additional motor power  $N_3$ ; volumetric flow rate of the fluid through the turbine  $Q_0$ ; volumetric flow rate of the fluid through the multiphase pump  $Q_{1f}$ ; volumetric flow rate of gas at the inlet of the multiphase pump  $Q_{1g}$ ; volumetric flow rate of gas at the outlet of the multiphase pump  $Q_{2g}$ ; gas content at the pump inlet  $\beta_1$  and gas content at the pump outlet  $\beta_2$ .

Hydraulic turbine power:

$$N_0 = Q_0(P_0 - P_2)\eta_0 \quad (27)$$

Multiphase pump power:

$$N_1 = (Q_{1f}(P_2 - P_1) + Q_{1g}P_1 \ln \frac{P_2}{P_1})\eta_1^{-1} \quad (28)$$

Gas content at the pump inlet:

$$\beta_1 = \frac{Q_{1g}}{Q_{1g} + Q_{1f}} \quad (29)$$

Change in the gas volumetric flow rate with pressure change:

$$Q_{2g} = Q_{1g} \frac{P_1}{P_2} \quad (30)$$

Gas content at the pump outlet:

$$\beta_2 = \frac{Q_{1g} \frac{P_1}{P_2}}{Q_{1g} \frac{P_1}{P_2} + Q_{1f}} \quad (31)$$

Gas content in the mixing chamber:

$$\beta_2 = \frac{Q_{1g} \frac{P_1}{P_2}}{Q_{1g} \frac{P_1}{P_2} + Q_{1f} + Q_0} \quad (32)$$

Power balance:

$$N_0 + N_3 = N_1 \quad (33)$$

$$Q_0(P_0 - P_2)\eta_0 + N_3 = (Q_{1f}(P_2 - P_1) + Q_{1g}P_1 \ln \frac{P_2}{P_1})\eta_1^{-1} \quad (34)$$

## 4. Discussion

### 4.1. Discussion of Schematic Diagrams of Turbomachines, As Part of Developing Euler's Ideas

In the history of turbines, materials of correspondence between Leonhard Euler and Janos AndrashSegner were partially preserved [97]. Leonhard Euler proposed jointly considering the rotating part (turbine rotor) and the fixed part (turbine guide vane) at the system level [97, 98]. Additionally, Leonhard Euler proposed using curved pipes to form the flow part of a hydraulic machine, when creating a rotor and a guide vane (stator, or nozzle apparatus).

Many of Euler's ideas are reflected in the correspondence with Segner [97] on the creation of hydraulic machines. On careful reading, the majority of the most important recommendations applicable to the design of the cutting-edge

turbines and other bladed machines can be seen in this correspondence. Euler’s ideas and his theory have been used and continue to be used when creating various turbomachines, including turbines, compressors, fans, and pumps.

Analyzing the legacy of the great scholar [97], we can consider in more detail the version of the Euler turbine, schematically presented in Figures 13 to 15. The figures schematically show only one of the numerous rotor channels, and one of the numerous guide vane channels. The rotor rotates around the vertical axis  $y$ . It is logical and understandable that with a compact arrangement of a group of channels (which is a group or a set of curved Euler tubes), it is quite possible to form flow channels similar to those of contemporary bladed machines. For clarification, the figures show some important (basic) points, with the corresponding numbers: 1 – inlet to the guide vane channel; 2 – outlet from the guide vane channel; 3 – inlet to the rotor channel; 4 – outlet from the rotor channel.

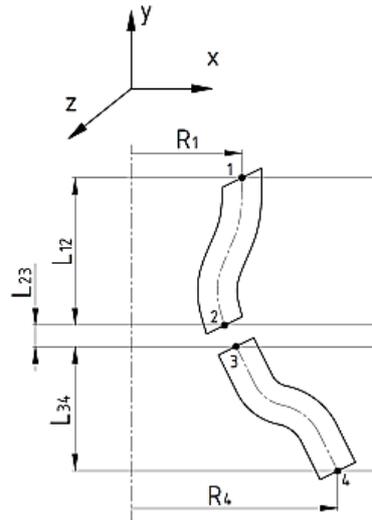


Figure 13. A scheme of the Euler turbine (basic version)

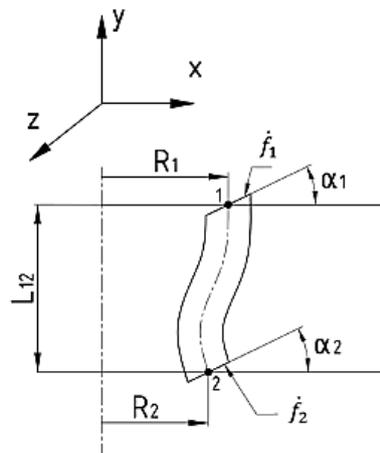


Figure 14. A scheme of the guide vane channel for the Euler turbine (basic version)

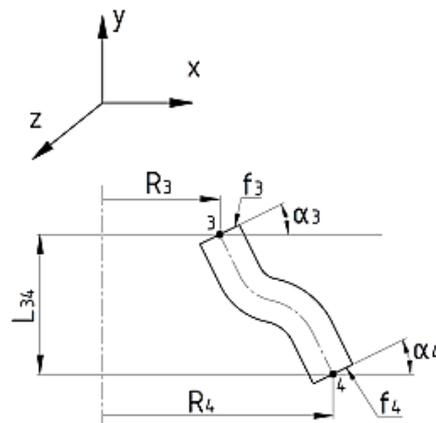


Figure 15. A scheme of the rotor for the Euler turbine (basic version)

The following conventions were adopted for basic geometric dimensions and base points (with the corresponding numbers 1-4) in Figures 13 to 15:

- The average radius at the inlet of the guide vane  $R_1$  corresponds to point 1; the average radius at the outlet of the guide vane  $R_2$  corresponds to point 2; the average radius at the rotor inlet  $R_3$  corresponds to point 3; the average radius at the rotor outlet  $R_4$  corresponds to point 4;
- Cross-sectional area of the channel at the guide vane inlet  $f_1$ ; cross-sectional area of the channel at the guide vane outlet  $f_2$ ; cross-sectional area of the channel at the rotor inlet  $f_3$ ; cross-sectional area of the channel at the rotor outlet  $f_4$ ;
- Inclination of the guide vane inlet cross-section relative to the horizontal plane  $\alpha_1$ ; inclination of the guide vane outlet cross-section relative to the horizontal plane  $\alpha_2$ ; inclination of the rotor inlet cross-section relative to the horizontal plane  $\alpha_3$ ; inclination of the rotor outlet cross-section relative to the horizontal plane  $\alpha_4$ ;
- Linear dimension of the guide vane  $L_{12}$ ; linear dimension in the gap between the guide vane and the rotor  $L_{23}$ ; linear dimension of the rotor  $L_{34}$ .

According to Figures 13 to 15, the Euler turbine can have different designs, depending on the relationship between the basic geometric parameters. In discussing Euler's legacy, one can consider some of these designs as applied to turbines, and to turbomachinery in general. For example, Figure 16 shows a variant of the Euler turbine for the case when  $R_1 < R_2 < R_3 < R_4$ . Here,  $L_{12} > 0$ . In addition,  $L_{34} > 0$ .

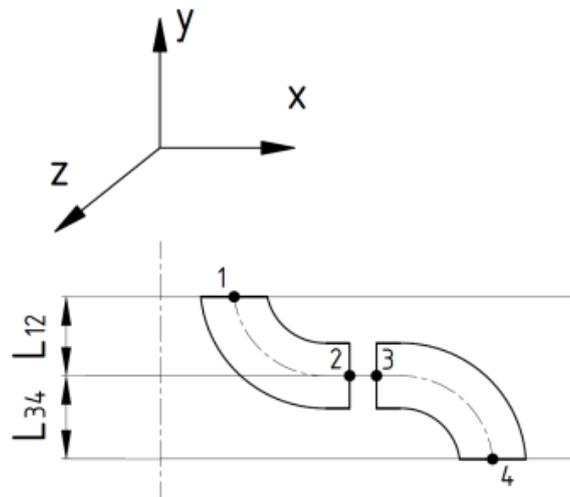


Figure 16. A scheme of the Euler turbine modification (version, when  $R_1 < R_2 < R_3 < R_4$ )

Another example of the Euler turbine is shown in Figure 17 when  $R_1 < R_2 < R_3 < R_4$ . In this case,  $L_{12} > 0$ . Angular dimensions  $\alpha_2 = \alpha_3 = 90^\circ$ . In this example,  $L_{34} = 0$ . B. Fourneyron's well-known turbine corresponds to this scheme.

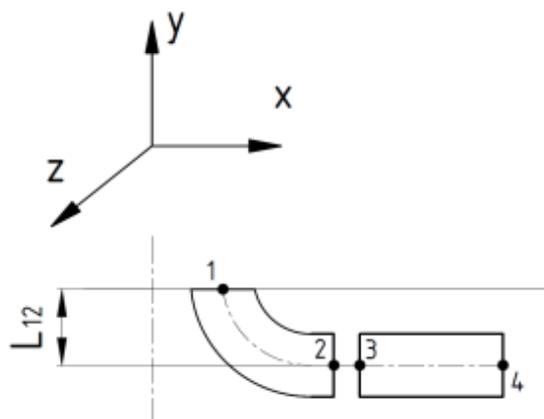


Figure 17. A scheme of the Euler turbine modification (a version, when  $R_1 < R_2 < R_3 < R_4$ ;  $\alpha_2 = \alpha_3 = 90^\circ$ )

For example, Figure 18 shows a variant of the Euler turbine for the case when  $R_1 > R_2 > R_3 > R_4$ . Here,  $L_{12} > 0$ , and  $L_{34} > 0$ . Angular dimensions  $\alpha_2 = \alpha_3 = -90^\circ$ . The famous Francis turbine corresponds to this scheme.

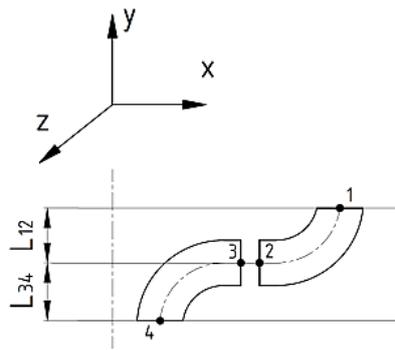


Figure 18. A scheme of the Euler turbine modification (a version, when  $R_1 > R_2 > R_3 > R_4$ ;  $\alpha_2 = \alpha_3 = -90^\circ$ )

For example, Figure 19 shows a variant of the Euler turbine for the case when  $R_1 = R_2 = R_3 = R_4$ . In this case,  $L_{12} > 0$  and  $L_{34} > 0$ . Angular dimensions  $\alpha_1 = \alpha_2 = \alpha_3 = \alpha_4 = 0^\circ$ . The famous Henschel-Jonval axial turbine corresponds to this scheme.

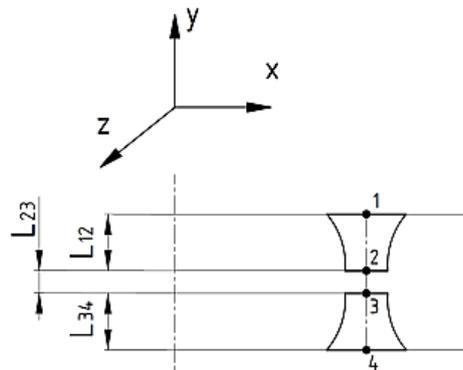


Figure 19. A scheme of the Euler turbine modification (a version, when  $R_1 = R_2 = R_3 = R_4$ ;  $\alpha_1 = \alpha_2 = \alpha_3 = \alpha_4 = 0^\circ$ )

As is known, hydraulic machines of the dynamic type are reversible: under certain conditions, the turbine is capable of performing the functions of a pump. Accordingly, all the arguments referring to Figures 13–19 from the field of turbine technology can be completely transferred to the field of pumping and compressor technology, considering the compressibility of the working medium (fluid). There is an opinion that the scientific groundwork prepared by Leonhard Euler has not yet been fully disclosed. Many scientific and technical directions for the further development of Euler’s ideas are viable.

#### 4.2. Discussion about the Development of Euler’s Ideas

Based on Euler’s ideas, it is possible to continue creating novel turbomachinery [3–5]. One of the promising areas of scientific research is related to the study and creation of mesh hybrid turbomachinery. In the hybrid turbomachine blades, the properties of the turbine and compressor (or pump) are periodically manifested (Figures 2 to 5). In this case, the working medium and the pumped medium periodically pass through the flow channels of the rotor (Figures 2 to 5). Figures 20 to 22 show the corresponding scheme and micromodel of a hybrid mesh turbomachine (an option according to application 2022110755), developed using the basic Euler turbine scheme according to Figures 13 to 15.

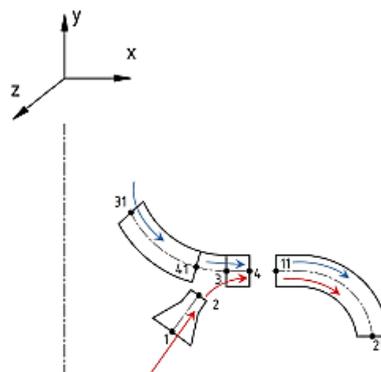


Figure 20. A scheme of mesh turbomachine (an option according to application 2022110755), developed using the basic Euler turbine scheme

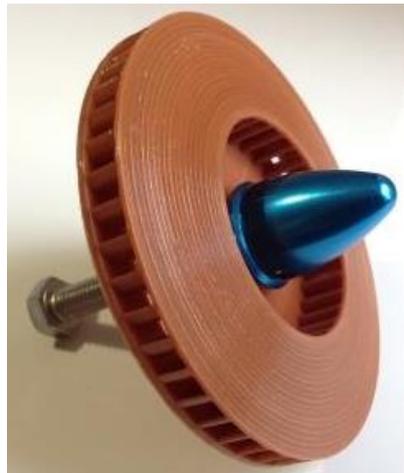


Figure 21. An impeller for a hybrid mesh turbomachine (prototype version according to application 2022110755): a photo of the micromodel – a view from the pumped medium inlet side



Figure 22. An impeller for a hybrid mesh turbomachine (prototype version according to application 2022110755): a photo of the micromodel – a view from the side of the working medium inlet into the annular channel

The arrows schematically show the direction of the moving working and pumped media (red and blue arrows, respectively). Figure 20 shows some essential (basic) points for clarification: 1 – the inlet to the guide vane (nozzle vane) channel; 2 – the outlet from the guide vane channel; 3 – the inlet to the rotor channel; 4 – the outlet from the rotor channel; 11 – the inlet to the channel of the additional guide vane; 21 – the outlet from the additional guide vane channel; 31 – the inlet to the additional channel of the rotor; 41 – the outlet from the additional channel of the rotor.

Figures 23 to 25 show another scheme of mesh turbomachine.

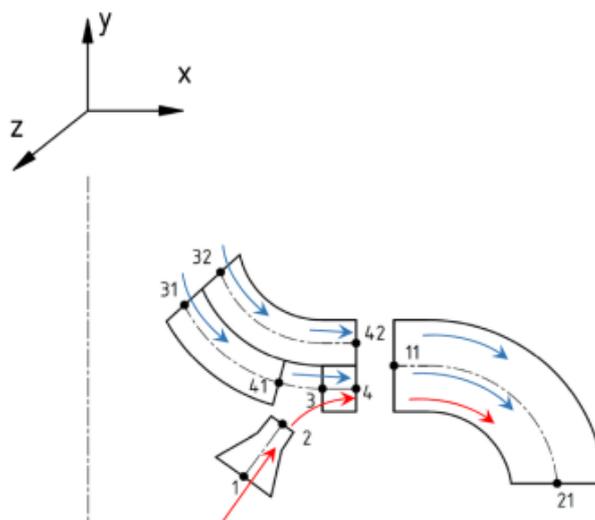
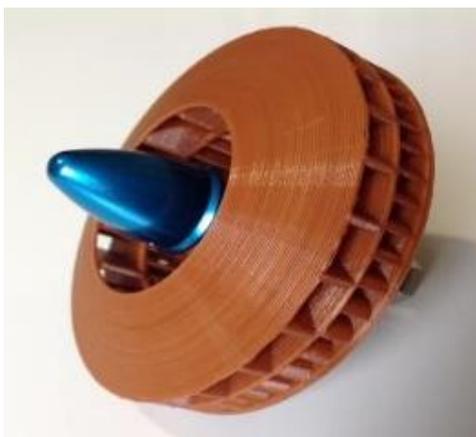


Figure 23. A scheme of a mesh turbomachine (option with two rows of blades), developed using the basic scheme of the Euler turbine



**Figure 24. An impeller for a hybrid mesh turbomachine (prototype version with two rows of blades): a photo of the micromodel – a view from the side of the pumped medium inlet**



**Figure 25. An impeller for a hybrid mesh turbomachine (prototype version with two rows of blades): a photo of the micromodel – a view from the side of the working medium inlet into the annular channel**

The arrows schematically show the direction of the moving working and pumped media (red and blue arrows, respectively). For clarification, Figure 23 indicates some essential (basic) points: 1 – the inlet to the channel of the guide vane (nozzle vane); 2 – the outlet from the guide vane channel; 3 – the inlet to the rotor channel; 4 – the outlet from the rotor channel; 11 – the inlet to the additional guide vane channel; 21 – the outlet from the additional guide vane channel; 31 – the inlet to the additional channel of the rotor; 41 – the outlet from the additional channel of the rotor; 32 – the inlet to the additional channel of the rotor, in the second row of blades; 42 – the outlet from the additional channel of the rotor, in the second row of blades.

It is possible to use several sources of working medium (Figures 2 to 7, 10 to 12, 20 to 25). Moreover, such sources of the working medium can operate on various physical principles (for example, a steam generator or a gas generator, or another technical system). The rotor shaft can be connected to another machine (for example, an electric motor, or an internal combustion engine, or a generator). For example, natural gas, gas condensate, or oil from a production well can be used as a working medium. A gas, a liquid, or a gas-liquid mixture can be the pumped medium.

#### **4.3. Discussion of Issues about the Turbomachinery Classification**

In mechanical engineering science, the term *machine* is usually used to describe a technical device that performs mechanical movements to convert energy, materials, and information.

Within the framework of the scientific topic under consideration, the following hypothesis can be proposed for discussion: in a more extended consideration of the issues of the turbomachinery classification, it is advisable to account for the presence (or appearance) of machines of the third type (Figures 2 to 7). At this stage of research, we will use the working name for machines of this third type – “engine executor machine”. In the flow channels of one impeller in machines of the third type, several workflows are periodically implemented: 1 – the process of supplying energy to the flow of liquid or gas (to the flow of the working fluid); 2 – the process of converting flow energy into mechanical energy. It would be logical to assume that several additional workflows can also be considered, which are not yet mentioned in the discussion of classical turbomachines and classical classification. In a turbomachine of the third type, it is permissible to use two or three working fluids (or more than three working fluids with different parameters). In the channels of turbomachines of the third type, a stationary flow of the working fluid and a non-stationary (pulsed) flow are observed.

In this regard, one can (hypothetically) assume that it is possible to create turbomachines of the fourth type, the fifth type, and so on. Such questions and generalizations can and should be considered within the framework of scientific induction. Incomplete induction makes it possible to reduce the scientific search and come to general provisions, revealing patterns, without waiting until all phenomena of this class are studied in detail [99]. Opinion is known that incomplete induction is the main way to obtain new knowledge.

As noted by experts, the knowledge obtained in the framework of incomplete induction is usually problematic, probabilistic, and there is an opportunity for numerous errors that are the result of hasty generalizations. The problematic nature of most inductive conclusions requires their repeated verification by practice, comparison with the experience of the consequences derived from the inductive generalization. As these consequences coincide with the experimental results, the degree of reliability of the inductive conclusion increases. In this process, the justification of knowledge obtained by induction necessarily implies the movement from inductive generalizations to one or another particular case. Such a conclusion is already a deductive reasoning. Thus, deduction supplements induction and ensures the transition from probabilistic to reliable knowledge.

The idea “if there is a particular, then there is universal” is well known. Using the inductive method of cognition, we can consider the transition from the particular to the universal. As already noted, now turbomachines are divided into “executor machines” and “engine machines”. A blade machine (turbomachine) is a device in the flow part of which energy is supplied or removed from a continuous flow of liquid or gas due to the aerodynamic interaction with specially profiled elements – blades [88]. “Executor machines” supply energy to the flow of liquid or gas. “Engine machines” convert the flow energy into mechanical work.

Thus, the generalized knowledge about turbomachinery contains particular knowledge about “executor machines” and “engine machines”. Generalized knowledge always contains massive of particular knowledge combined into a single universal knowledge, and this is the power of universal (generalized and most generalized, abstract) knowledge. In this case, “universal” is a turbomachinery class (system). Accordingly, “particular 1” is a subclass called “executor machines” (or subsystem). “Particular 2” is a subclass called “engine machines” (or subsystem). Other wording states: turbomachinery is the general name of machines in which energy is exchanged between continuously moving liquid or gas and rotating blades [96]. A separate blade (in the turbomachine rotor) is involved in the workflow and ensures conversion of the energy of the fluid into mechanical energy, or conversion of mechanical energy into the energy of the fluid (energy of the working fluid). Inductive and deductive logic both enable to continue reasoning on this issue about the “universal” and the “particular”.

The established framework of mechanical engineering science can be slightly enlarged. When the turbomachine rotor rotates, a separate blade can periodically enter the flow of one fluid medium 1 and another fluid medium 2. In this case, a separate blade (in the turbomachine rotor) periodically participates in the conversion of the energy of the fluid 1 into mechanical energy, and in the conversion of mechanical energy into the energy of the fluid medium 2 (Figures 2 to 7). Such a machine can be termed as an “engine-executor machine”, and assigned to a new subclass 3. It can be assumed (put a working hypothesis forward) that “in the general case, in a turbomachine, a separate blade can periodically participate in several energy conversion (or energy redistribution) workflows in the flow of one fluid (working fluid), or in several flows of different fluids.”

As known, a hypothesis is a form of probabilistic knowledge, the truth value of which is uncertain, and in scientific cognition, a hypothesis is considered as a method for the development of scientific knowledge, including the hypothesizing and subsequent experimental verification of assumptions or suppositions.

The analysis of scientific and technical literature allows to say that energy can be supplied to the turbine (turbomachine) impeller from several different energy sources. These energy sources can operate on various physical principles. Additionally, several fluid flows can be supplied to the turbine (turbomachine) impeller, and the operating parameters of these fluids can vary significantly.

The first section of this article has already outlined philosophizing on the issue of the “universal” and “particular”, regarding the existing turbomachinery classification. A contradiction is noted, when it is proposed to perceive the “universal” as “particular 1” or as “particular 2”. However, logically, the “universal” should always be greater than any “particular”. In this regard, at the stage of discussion, we propose the following definition to eliminate the contradiction: A turbomachine is a machine in which energy is redistributed between a rotating impeller and fluid flows with which this impeller interacts. It can be noted that we are talking about workflows occurring in one turbomachine impeller. Moreover, in the general case, several flows with different fluid properties can pass through the turbomachine impeller. But in a particular case, one flow of one fluid can pass through the turbomachine impeller, while all the impeller blades operate under the same conditions. The presented reasoning is carried out within the framework of inductive and deductive logics, enabling to eliminate the identified contradiction.

Generally, the basic Euler turbine diagram can (appropriately) be used as the basic diagram for the turbomachinery class as a whole. In the general case, several different workflows can occur simultaneously in the channels of one

turbomachine impeller, but among them the most essential workflow can be distinguished (considering the technical task or problem being solved), for example, the gasification process; or the process of heat exchange between two media; or the process of forming mixtures of various components in the same or different aggregate state; or separation process; or other processes. In this regard, a turbomachinery class (perceived as the “universal”) may contain several additional subclasses (and a subclass may be perceived as the “particular”). An approximate list of subclasses can be brought up for discussion, where hybrid subclasses 3-8 are added to the known subclasses 1 and 2:

- Subclass 1 – “executor machines”
- Subclass 2 – “engine machines”
- Subclass 3 – “engine executor machines”
- Subclass 4 – “propulsion machines”
- Subclass 5 – “gas generator machines”
- Subclass 6 – “heat-exchanger machines”
- Subclass 7 – “mixer machines”
- Subclass 8 – “separator machines”

The considered mesh turbomachines [3–5] can be used to create novel turbomachinery from subclasses 1-8.

“Propulsion machines” form an additional subclass 4. A propulsion device is commonly referred to as one that converts the engine energy into useful work to relocate the vehicle. This means, the energy conversion is carried out through interaction with the environment. At all times, the following problems in the field of propulsion devices remain relevant: increasing the workflow efficiency, and creating novel ergonomic human-machine vehicle control systems for three-dimensional space. Technologies for controlling high-temperature gas jets using low-temperature or cold actuating elements are of particular scientific and practical interest.

Subclass 5 covers “gas generator machines”. A device designed to convert a solid or liquid fuel into a gaseous form during the gasification process is usually called a gas generator. The gasification process makes the use of solid and liquid fuels more convenient and more efficient. Subclass 6 includes “heat exchanger machines”: a heat exchanger is a technical device in which heat is exchanged between two media having different temperatures. In regenerative heat exchangers, hot and cold coolants are in contact with the same surface in turn. Heat accumulates in the wall upon contact with a hot coolant and is released upon contact with a cold coolant. This article is the first to consider the issue of turbomachinery comprehensively, where separate blades of the rotor (impeller) alternately cyclically perform the functions of a turbine or the functions of a compressor, which improves the cooling conditions of the blades. Subclass 7 includes “mixing machines”: a mixer is a technical device designed to prepare mixtures from initial components that are in the same or different aggregate state. Using the proposed mesh turbomachinery [3–5], methods for efficient mixing of fuel gas with steam and air can be developed to form a multicomponent homogeneous mixture, including ejector mixer schemes, along with a mesh turbomachine. Subclass 8 refers to “separator machines”: a separator is a technical device in which a multicomponent mixture of several substances is separated into fractions with different characteristics. During the operation of any separator, there is no change in the chemical composition of the separated substances. Separators with a mesh rotor are known. This line of work can also be developed using mesh turbomachinery with mesh jet control systems [3–5].

#### 4.4. Discussion of Certain Issues in Patenting Scientific and Technical Developments

While continuing scientific research, it is planned to patent individual developments to consolidate the results of intellectual activity. Considering the accumulated experience, it is recommended to prepare and formalize inventions within the framework of the philosophy of technology [100-102]. Note that Engelmeyer’s philosophy of technology [91] succeeded as a new scientific direction, which includes: 1 – the definition of technology in historical terms; 2 – the inexhaustibility of the possibilities of technology; 3 – revealing the fundamental features of technology, without which it is not conceivable as a material or as a social phenomenon – the principle of transformation; 4 – the basis and methodology of technical knowledge, facing the past, present and future.

At the stage of solving a technological problem, where various hybrid versions of turbomachinery are possible (and where the properties of individual machines from subclasses 1-8 are manifested), it is advisable to use additional tools from the theory of inventive problem solving [101, 102]. As part of the invention development and when performing educational work related to the training of designers, it is also advisable to move along the “from-simple-to-complex” scheme, using inductive and deductive logic from reasoning from the field of philosophy of technology, and from the field of mechanical engineering science. In this regard, the simplest (training) example is considered, simulating the work of hybrid turbomachine blades (Figures 2 to 5), according to application 2022110755. The blade periodically

interacts with a hot gas flow and with a cold gas flow. For a preliminary assessment of the thermal loads acting on the plate (blade), a three-dimensional model is considered, shown schematically in Figure 26. The material of the plate is aluminum alloy (1060 Alloy). Plate dimensions are 20 mm-20 mm-1 mm. The plate is placed in a cylindrical channel – a pipe with a diameter of 25 mm. During simulation, it is necessary to obtain the calculated dependence of the temperature of the solid wall of the plate on time, with periodic blowing of this plate with hot and cold gas (at three points 1, 2, and 3 in accordance with the scheme in Figure 26).

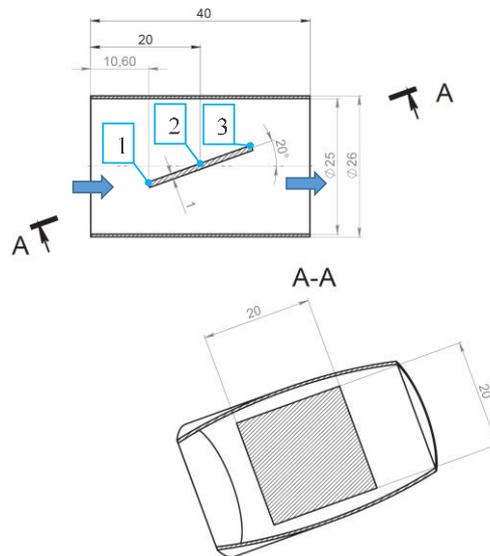


Figure 26. Calculation scheme (3D model)

The conditions for the gas (air) flow through a pipe with an outlet pressure of 0.1 MPa at a constant mass flow rate of 0.01 kg/s are considered to exemplify this option. The gas temperature at the inlet to the pipe, according to the condition of this problem, periodically changed over time, from 20 to 1000°C. For this example, the law of temperature change was set, this dependence is graphically presented in Figure 27. The initial temperature of the plate is 500°C. The working conditions of hybrid type turbomachine blades are simulated (Figures 2 to 5), according to application 2022110755, when the blade periodically interacts with a hot gas flow (with a working gas temperature of 1000°C) and with a cold gas flow (with a pumped gas temperature of 20°C).

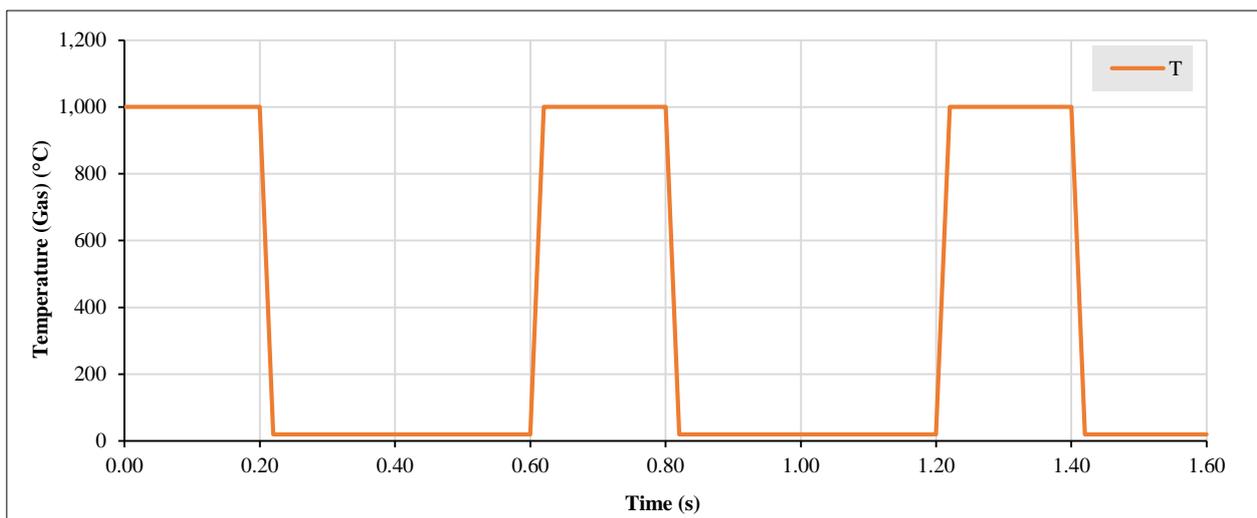


Figure 27. Changes in gas temperature over time

The Flow Simulation (*FloEFD*) software package was used to conduct computer simulation and computational studies. The 3D model was created using the SolidWorks CAD system. During the simulation process, the complete system of Navier–Stokes equations was solved, which is described by mathematical expressions for the laws of conservation of mass, energy, and momentum. By default, the turbulence parameters were set automatically. The turbulent viscosity model “k-ε” was used to calculate of turbulent parameters for the closure of the Navier–Stokes system of equations. A computer with the following parameters was used: CPU type: Intel(R) Core (TM) i5-6200U CPU @ 2.30GHz; CPU speed: 2401 MHz; RAM: 8065 MB Operating system: Windows 10.

Calculation parameters (in the presented example) are as follows: the total number of cells in the calculation grid is 72,538; calculation time takes 97 394 s; the number of iterations is 55,169. The results of computer simulation are graphically presented in Figure 28. The calculated temperature dependence of the solid wall of the plate on time is shown, with periodic blowing of this plate with hot and cold gas (at three points 1, 2, and 3 in compliance with the scheme in Figure 26).

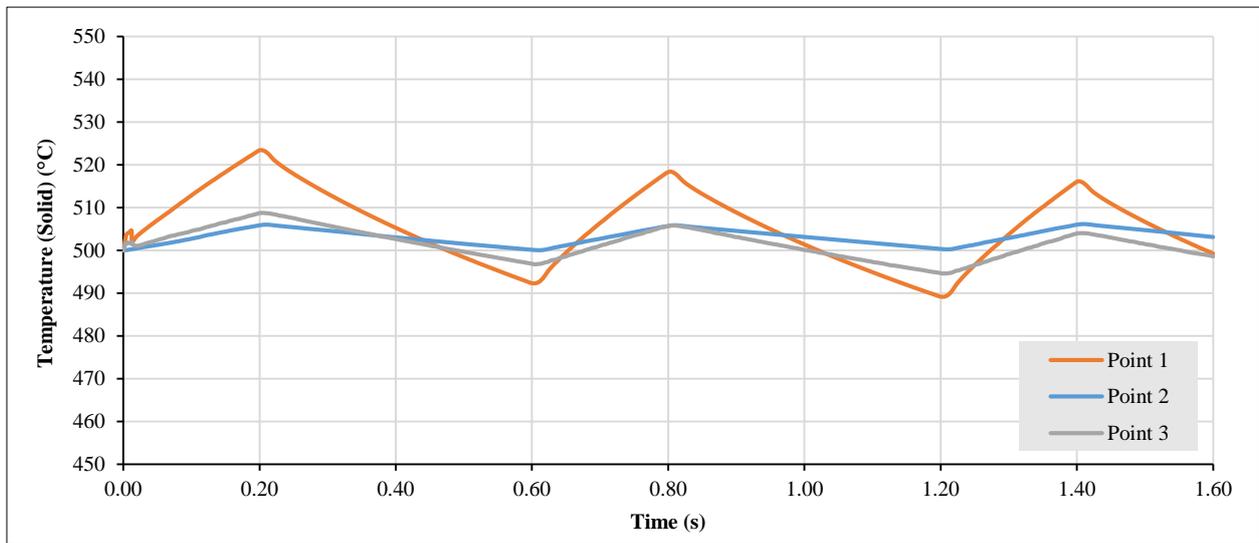


Figure 28. Calculation of time-temperature dependence for a solid wall

The results of the calculations allow to conclude that the proposed method is promising, aimed at reducing the thermal load acting on the turbomachine blades when they interact with the hot gas flow. It is planned to conduct further studies with the development of calculation methods, within the framework of applied scientific research in solving actual practical problems.

Individual results of computer simulation are graphically presented in Figures 29 and 30, where the plate is shown (in section A-A in Figure 26). The results of computer simulations make it possible to consider the temperature distribution over the plate surface at different times. Here, the plate (blade model) periodically interacts with the hot gas flow and with the cold gas flow.

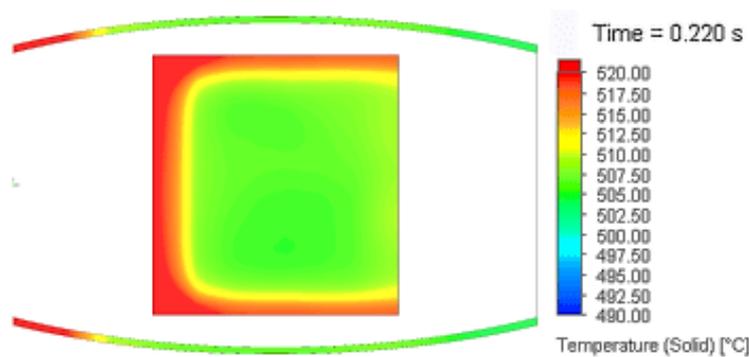


Figure 29. Temperature distribution over the plate (blade) surface at 0.220 s

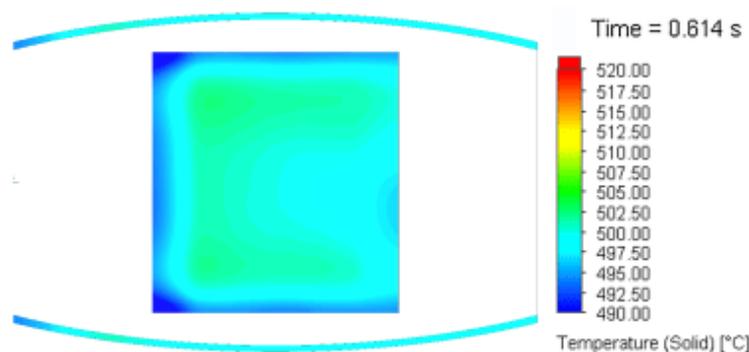


Figure 30. Temperature distribution over the plate (blade) surface at 0.614 s

The possibility of implementing pulsed cooling of blades periodically washed by a hot working gas flow (with a temperature of 1000°C) and a cold gas flow (with a temperature of 20°C) is shown. The temperature of the blade walls remained in the range from 490 to 525°C.

Figure 31 shows the gas temperature distribution for various times: 0.220 s; 0.614 s; 0.654 s.

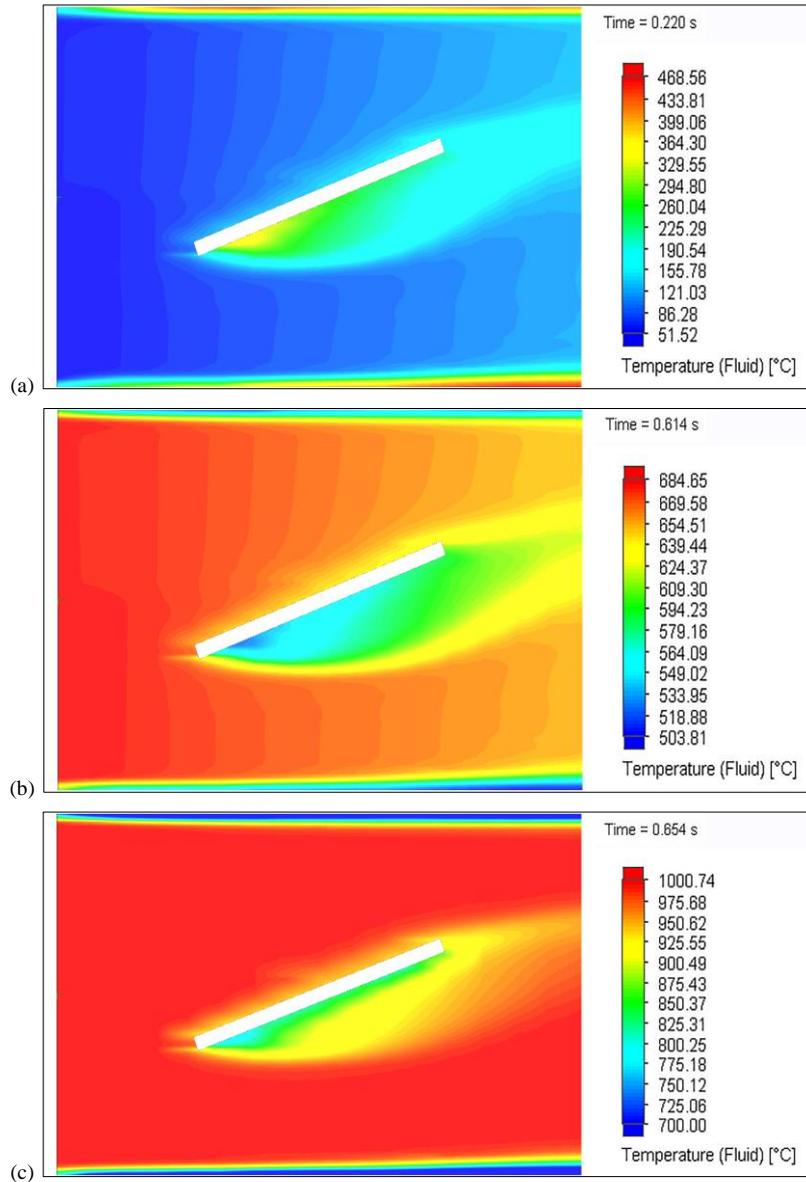
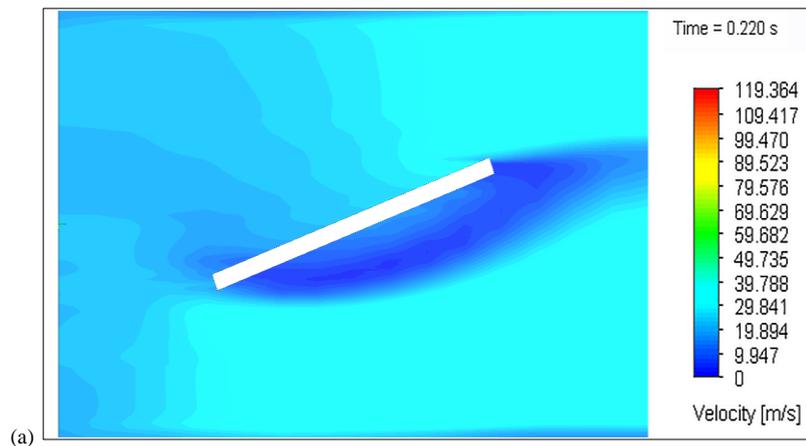


Figure 31. Distribution of gas temperature for different moments of time: a) 0.220 s; b) 0.614 s; c) 0.654 s

Figure 32 shows the gas velocity distribution for various times: 0.220 s; 0.614 s; 0.654 s.



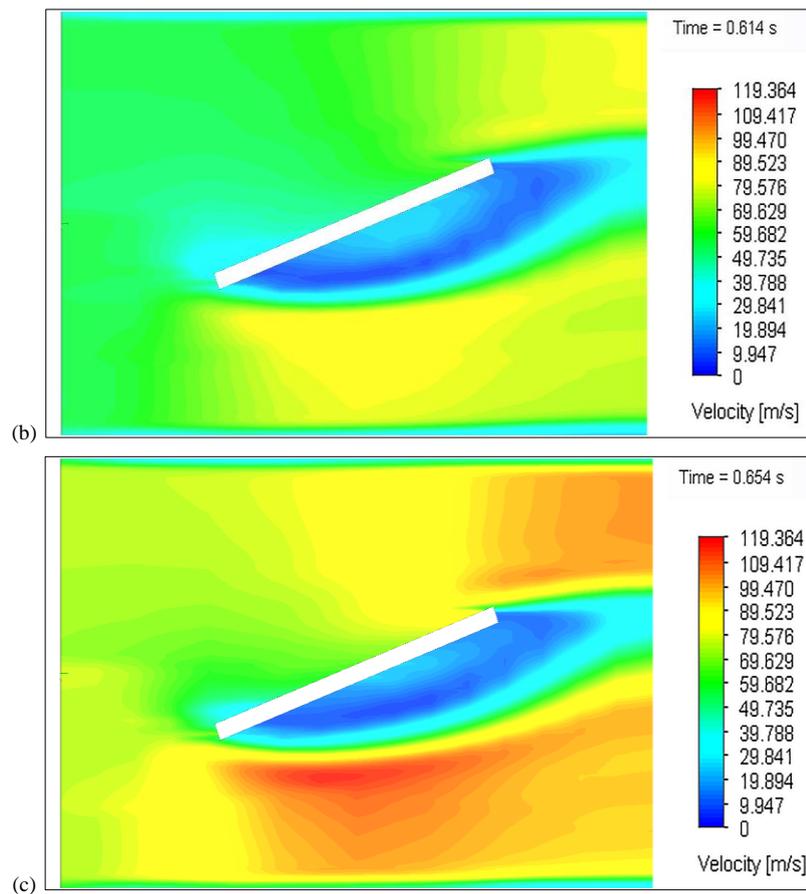


Figure 32. The distribution of gas velocity for various times: a) 0.220 s; b) 0.614 s; c) 0.654 s

This research shows that several operating processes can occur simultaneously in one impeller of a hybrid mesh turbomachine: a turbine operating process and a compressor operating process. A separate blade of such an impeller will periodically participate in both the turbine and the compressor operational processes. It is planned to organize applied scientific research to study the cooling conditions of blades in such mesh turbomachines.

#### 4.5. Some Generalizations

Summarizing the results of scientific research carried out in 2021 and 2022 [3-5], we can state the following: 1) as part of the development of Euler's ideas, a new scientific direction has been formed to study mesh turbomachinery equipped with mesh jet control systems; 2) for the first time, the issue of turbomachinery, where individual rotor blades alternately cyclically function as a turbine or a compressor (or pump), has been brought up for wide discussion; 3) for the first time, the issue of extreme operating conditions of the novel mesh jet control system was brought up for wide discussion, and for the first time it was shown that at the nozzle outlet, the jet is able to deviate by an angle from plus 180 degrees to minus 180 degrees within the full geometric sphere.

The scope of the obtained results includes energy, oil, and gas production and processing. Some results can be used for aviation and maritime transport systems. Also, the ways to create novel mesh engines have been outlined; in these engines, the combustion of the air-fuel mixture is carried out at a constant volume or at a constant pressure, using liquid, gaseous, or solid fuel.

The main tasks of the project have been solved within the framework of the presented scientific article: 1) promising directions for the development of technologies and equipment using mesh turbomachinery, which can be attributed to new generation machines; 2) new opportunities have been identified for improving the methodology for designing turbomachines as part of the training of modern designers since new turbomachinery modifications were proposed and a direction of work for developing Euler's ideas was suggested.

## 5. Conclusions

### 5.1. Scientific Novelty of the Development

Within the framework of Euler's ideas development, a new scientific direction has been formed to study mesh turbomachinery equipped with mesh jet control systems. The turbomachinery classification should reflect the level of historical development of these machines. However, it can be assumed (proposed): turbomachinery classification should also reflect the plans (possible options) for the turbomachinery development, so that the students or graduate students

could see more clearly the prospects for the possible application of their forces in science and technology, and so that the young scientists could also see the contours of that innovation that can be created, although this innovation does not yet exist.

Generally, the basic Euler turbine scheme can (appropriately) be used as the basic scheme for the class of turbomachines as a whole. Proceeding from this basic Euler scheme, it is possible to make a logical transition to any known turbomachine included in subclass 1 – “executor machines”, or in subclass 2 – “engine machines”, or included in a new (not yet created) subclass.

As part of philosophical reasoning, the question of the possibility of the existence of other subclasses (subsystems) is raised. For educational purposes and within the framework of the philosophy of technology (for the training of designers), it is proposed to consider the following additional subclasses of hybrid turbomachinery: "engine executor machines"; propulsion machines"; "gas generator machines"; "heat exchanger machines"; "mixing machines"; and "separator machines". One or several main workflows can be considered for a hybrid turbomachine. One or more energy sources can be considered for a hybrid turbomachine, including sources that operate according to various physical principles. In this regard, at the stage of discussion, the authors of the article proposed the following definition: A turbomachine is a machine in which energy is redistributed between a rotating impeller and the fluid flows with which this impeller interacts. This refers to several workflows occurring in one impeller of a turbomachine.

## 5.2. Theoretical Contribution

A working hypothesis has been put forward – “in the general case, in the turbomachine impeller, a separate blade can periodically participate in several workflows for energy conversion (or energy redistribution), in the flow of one fluid (the working fluid), or in several flows of different fluids.” A working hypothesis was developed, as customary, in stages: through the analysis of individual facts, through the synthesis of facts with their generalization, and through the formulation of an assumption. The working hypothesis was first tested in practice during laboratory tests of micromodels made using additive technologies.

Promising directions were identified for developing the theory for creating a new generation of turbomachinery, including hybrid turbomachinery. New opportunities for improving the methodology of turbomachinery design were identified as part of the designers’ training.

## 5.3. Significance of Practice

Under current conditions, the reduction of energy costs for workflow implementation is the most urgent problem, and in this regard, the role of turbomachinery is increasing significantly. The scope of the obtained results includes energy, oil, and gas production and processing. Some results can be used in the fields of aviation and maritime transport systems.

## 5.4. Limitations and Future Research

Research limitations are related to the complexity of calculating non-stationary processes in the existing framework of gas dynamics and hydrodynamics, as applicable to mesh turbomachinery. At this stage of research, the role of bench tests will be decisive for obtaining novel scientific information. The research development may be related to the assessment of the scientific and practical potential of hybrid mesh turbomachinery.

## 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

The research was financially supported by the Russian Ministry of Education and Science within the framework of the government task in scientific activity, subject number FSZE-2020-0006.

### 6.4. Conflicts of Interest

The authors declare no conflict of interest.

## 7. References

- [1] Kosov, M. E., Akhmadeev, R. G., Smirnov, D. A., Solyannikova, S. P., & Rycova, I. N. (2018). Energy industry: Effectiveness from innovations. *International Journal of Energy Economics and Policy*, 8(4), 83.
- [2] Bahrami, N., Liu, S., Ponkratov, V. V., Nguyen, P. T., Maseleno, A., & Berti, S. (2022). Novel load management for renewable generation sources/battery system through cut energy expenditure and generate revenue. *International Journal of Ambient Energy*, 43(1), 368–384. doi:10.1080/01430750.2019.1636868.
- [3] 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.
- [4] 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.
- [5] Sazonov, Y. A., Mokhov, M. A., Tumanyan, K. A., Frankov, M. A., Voronova, V. V., & Balaka, N. N. (2022). RF Utility Model Patent No. 213280. Jet installation. Published on 05.09.2022 Bulletin No. 25. Decision to grant a patent for a utility model of the Russian Federation under application No.2022110755 – 19.07.2022. Available online : <https://www1.fips.ru/ofpstorage/Doc/IZPM/RUNWU1/000/000/000/213/280/%D0%9F%D0%9C-00213280-00001/document.pdf> (accessed on May 2022).
- [6] Alayi, R., Sevbitov, A., Assad, M. E. H., Akhmadeev, R., & Kosov, M. (2022). Investigation of energy and economic parameters of photovoltaic cells in terms of different tracking technologies. *International Journal of Low-Carbon Technologies*, 17, 160–168. doi:10.1093/ijlct/ctab093.
- [7] Konovalova, N.E. (2005). Calculation of the minimum drag of lattice wings and their elements and comparison of the calculation results with experiment at  $M = 0.6 - 4.0$ . *Air Fleet Technology*, 2(673), 36–43.
- [8] Xue, Y., Wang, L., & Fu, S. (2018). Detached-eddy simulation of supersonic flow past a spike-tipped blunt nose. *Chinese Journal of Aeronautics*, 31(9), 1815–1821. doi:10.1016/j.cja.2018.06.016.
- [9] Anbu Serene Raj, C., Narasimhavaradhan, M., Vaishnavi, N., Arunvinthan, S., Al Arjani, A., & Nadaraja Pillai, S. (2020). Aerodynamics of ducted re-entry vehicles. *Chinese Journal of Aeronautics*, 33(7), 1837–1849. doi:10.1016/j.cja.2020.02.019.
- [10] Ding, X., Guo, P., Xu, K., & Yu, Y. (2019). A review of aerial manipulation of small-scale rotorcraft unmanned robotic systems. *Chinese Journal of Aeronautics*, 32(1), 200–214. doi:10.1016/j.cja.2018.05.012.
- [11] Ahmad, K., Baig, Y., Rahman, H., & Hasham, H. J. (2020). Progressive failure analysis of helicopter rotor blade under aeroelastic loading. *Aviation*, 24(1), 33–41. doi:10.3846/aviation.2020.12184.
- [12] Kim, H. I., Roh, T. S., Huh, H., & Lee, H. J. (2022). Development of Ultra-Low Specific Speed Centrifugal Pumps Design Method for Small Liquid Rocket Engines. *Aerospace*, 9(9). doi:10.3390/aerospace9090477.
- [13] Hu, H., Yang, Y., Liu, Y., Liu, X., & Wang, Y. (2021). Aerodynamic and aeroacoustic investigations of multi-copter rotors with leading edge serrations during forward flight. *Aerospace Science and Technology*, 112, 106669. doi:10.1016/j.ast.2021.106669.
- [14] Hu, Y., Qing, J. xiang, Liu, Z. H., Conrad, Z. J., Cao, J. N., & Zhang, X. P. (2021). Hovering efficiency optimization of the ducted propeller with weight penalty taken into account. *Aerospace Science and Technology*, 117, 106937. doi:10.1016/j.ast.2021.106937.
- [15] Glaznev, V.N., Zapryagaev, V.I., Uskov, V.N., Terekhova, N.M., Erofeev, V.K., Grigoriev, V.V., Kozhemyakin, A.O., Kotenok, V.A., & Omelchenko, A.V. (2000). Jet and unsteady flows in gas dynamics. SO RAN Press, Novosibirsk, Russia.
- [16] Garbaruk, A.V. (2020). Numerical simulation and stability analysis of near-wall turbulent flows. Ph.D. Thesis, Peter the Great St. Petersburg Polytechnic University, St. Petersburg, Russia.
- [17] Deng, H., Zhao, J., & Wang, C. (2021). Leaf Vein-Inspired Bionic Design Method for Heat Exchanger Infilled with Graded Lattice Structure. *Aerospace*, 8(9), 237. doi:10.3390/aerospace8090237.
- [18] Orman, L. J. (2020). Aspects of complexity of metal-fibrous microstructure for the construction of high-performance heat exchangers: Thermal properties. *Aviation*, 24(3), 99–104. doi:10.3846/aviation.2020.12086.
- [19] Giuliani, F., Stütz, M., Paulitsch, N., & Andracher, L. (2020). Forcing Pulsations by Means of a Siren for Gas Turbine Applications. *International Journal of Turbomachinery, Propulsion and Power*, 5(2), 9. doi:10.3390/ijtp5020009.
- [20] Sundermeier, S., Passmann, M., aus der Wiesche, S., & Kenig, E. Y. (2022). Flow in Pillow-Plate Channels for High-Speed Turbomachinery Heat Exchangers. *International Journal of Turbomachinery, Propulsion and Power*, 7(2), 12. doi:10.3390/ijtp7020012.
- [21] Oyewola, O. M., Awonusi, A. A., & Ismail, O. S. (2022). Performance Improvement of Air-cooled Battery Thermal Management System using Sink of Different Pin-Fin Shapes. *Emerging Science Journal*, 6(4), 851–865. doi:10.28991/ESJ-2022-06-04-013.

- [22] Alrwashdeh, S. S., Ammari, H., Madanat, M. A., & Al-Falahat, A. M. (2022). The Effect of Heat Exchanger Design on Heat transfer Rate and Temperature Distribution. *Emerging Science Journal*, 6(1), 128–137. doi:10.28991/ESJ-2022-06-01-010.
- [23] Friedmann, G. (1952). US Patent 2623474. Injection mixer. United States Patent Office, Alexandria, United States. Available online: <https://www.freepatentsonline.com/2623474.pdf> (accessed on July 2022).
- [24] Arabnejad, M. H., Svennberg, U., & Bensow, R. E. (2022). Numerical Assessment of Cavitation Erosion Risk in a Commercial Water-Jet Pump. *Journal of Fluids Engineering*, 144(5), 051201. doi:10.1115/1.4052634.
- [25] Chen, T., Zhou, Y., Wang, B., Deng, W., Song, Z., Li, W., ... & Sun, L. (2020). Investigations on combustion optimization and NOX reduction of a 600-MWe down-fired boiler: Influence of rearrangement of tertiary air and jet angle of secondary air and separated over-fire air. *Journal of Cleaner Production*, 277, 124310. doi:10.1016/j.jclepro.2020.124310
- [26] Rantererung, C. L., Soeparman, S., Soenoko, R., & Wahyudi, S. (2020). A double nozzle cross flow turbine fluid flow dynamics. *Journal of Southwest Jiaotong University*, 55(4). doi:10.35741/issn.0258-2724.55.4.49.
- [27] 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.
- [28] Arun Kumar, R., & Rajesh, G. (2018). Physics of vacuum generation in zero-secondary flow ejectors. *Physics of Fluids*, 30(6), 066102. doi:10.1063/1.5030073.
- [29] 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.
- [30] Falsafioon, M., Aidoun, Z., & Ameer, 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.
- [31] 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.
- [32] Skaggs, B. D. (2000). US Patent #6,017,195. Fluid jet ejector and ejection method. United States Patent Office, Alexandria, United States. Available online: <https://www.freepatentsonline.com/6017195.pdf>(accessed on July 2022).
- [33] Bayles, W. H., et al. (1962). US Patent #3,064,878. Method and apparatus for high performance evacuation system. United States Patent Office, Alexandria, United States. Available online: <https://www.freepatentsonline.com/3064878.pdf> (accessed on July 2022).
- [34] Voelker, M., & Sausner, A. (2018). US Patent #10,072,674. Suction jet pump. United States Patent Office, Alexandria, United States. Available online: <https://www.freepatentsonline.com/10072674.pdf> (accessed on July 2022).
- [35] Chen, H., Cai, C., Jiang, S., & Zhang, H. (2021). Numerical modeling on installed performance of turbofan engine with inlet ejector. *Aerospace Science and Technology*, 112, 106590. doi:10.1016/j.ast.2021.106590.
- [36] Monakhova, V.P. (2005). Research of ejector thrust amplifiers (ETA). PhD Thesis, Moscow Aviation Institute, Moscow, Russia.
- [37] 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). doi:10.3390/aerospace9090469.
- [38] Gu, R., Sun, M., Cai, Z., Chen, J., Li, P., Dong, Z., Wang, T., Yao, Y. Z., & Huang, Y. H. (2021). Experimental study on the rocket-ejector system with a throat in the secondary stream. *Aerospace Science and Technology*, 113. doi:10.1016/j.ast.2021.106697.
- [39] Berezhnoy, A.S. (2014). Improving the performance of a reaction-jet pneumatic unit based on the refinement of the workflow model. Ph.D. Thesis, Sumy State University, Sumy, Ukraine.
- [40] Yan, J., Zhang, C., Huo, S., Chai, X., Liu, Z., & Yan, K. (2021). Experimental and numerical simulation of bird-strike performance of lattice-material-infilled curved plate. *Chinese Journal of Aeronautics*, 34(8), 245–257. doi:10.1016/j.cja.2020.09.026.
- [41] Di Caprio, F., Acanfora, V., Franchitti, S., Sellitto, A., & Riccio, A. (2019). Hybrid Metal/Composite Lattice Structures: Design for Additive Manufacturing. *Aerospace*, 6(6), 71. doi:10.3390/aerospace6060071.
- [42] Boccini, E., Furferi, R., Governi, L., Meli, E., Ridolfi, A., Rindi, A., & Volpe, Y. (2019). Toward the integration of lattice structure-based topology optimization and additive manufacturing for the design of turbomachinery components. *Advances in Mechanical Engineering*, 11(8), 1–14. doi:10.1177/1687814019859789.
- [43] Zhang, Y., Li, F., & Jia, D. (2020). Lightweight design and static analysis of lattice compressor impeller. *Scientific Reports*, 10(1). doi:10.1038/s41598-020-75330-z.
- [44] Krasnova, E.V., & Saushkin, B.P. (2022). Additive shaping of products from metals and alloys by an electron beam. Selective melting (Part 1). *Additive Technologies*, 2, 44-57.

- [45] Bhide, K., Siddappaji, K., & Abdallah, S. (2021). Aspect ratio driven relationship between nozzle internal flow and supersonic jet mixing. *Aerospace*, 8(3), 78. doi:10.3390/aerospace8030078.
- [46] Ferlauto, M., Ferrero, A., Marsicovetere, M., & Marsilio, R. (2021). Differential throttling and fluidic thrust vectoring in a linear aerospace. *International Journal of Turbomachinery, Propulsion and Power*, 6(2). doi:10.3390/ijtp6020008.
- [47] Kovalenko, N.D., Strelnikov, G.A., & Zolotko, A.E. (2011). Gas-dynamic aspects and development of high-density rocket stage engine nozzles. *Technical Mechanics*, 3, 36–53.
- [48] Zhao, Z., Luo, Z., Deng, X., Liu, Z., & Li, S. (2021). Theoretical modeling of vectoring dual synthetic jet based on regression analysis. *Chinese Journal of Aeronautics*, 34(3), 1–12. doi:10.1016/j.cja.2020.07.020.
- [49] He, Y., Yang, Q., & Gao, X. (2021). Comprehensive optimization design of aerodynamic and electromagnetic scattering characteristics of serpentine nozzle. *Chinese Journal of Aeronautics*, 34(3), 118–128. doi:10.1016/j.cja.2020.10.010.
- [50] Bhide, K., Siddappaji, K., Abdallah, S., & Roberts, K. (2021). Improved supersonic turbulent flow characteristics using non-linear eddy viscosity relation in RANS and HPC-enabled LES. *Aerospace*, 8(11), 352. doi:10.3390/aerospace8110352.
- [51] Chen, S., Gojon, R., & Mihaescu, M. (2021). Flow and aeroacoustic attributes of highly-heated transitional rectangular supersonic jets. *Aerospace Science and Technology*, 114, 106747. doi:10.1016/j.ast.2021.106747.
- [52] Quadros, J. D., Khan, S. A., Aabid, A., Alam, M. S., & Baig, M. (2021). Machine Learning Applications in Modelling and Analysis of Base Pressure in Suddenly Expanded Flows. *Aerospace*, 8(11), 318. <https://doi.org/10.3390/aerospace8110318>.
- [53] Mirjalily, S. A. A. (2021). Lambda shock behaviors of elliptic supersonic jets; a numerical analysis with modification of RANS turbulence model. *Aerospace Science and Technology*, 112. doi:10.1016/j.ast.2021.106613.
- [54] Faheem, M., Khan, A., Kumar, R., Afghan Khan, S., Asrar, W., & Sapardi, A. M. (2021). Experimental study on the mean flow characteristics of a supersonic multiple jet configuration. *Aerospace Science and Technology*, 108. doi:10.1016/j.ast.2020.106377.
- [55] Kini, C. R., Purohit, S., Bhagat, K. K., & Shenoy B., S. (2019). Effect of helix angle and cross section of helicoidal ducts in gas turbine blade cooling. *International Review of Mechanical Engineering*, 13(2), 87–96. doi:10.15866/ireme.v13i2.14942.
- [56] Kini, C. R., Purohit, S., Bhagat, K. K., & Satish Shenoy, B. (2018). Heat transfer augmentation and cooling of a turbine blade using an innovative converging-diverging ducts - A CFD study. *International Review of Mechanical Engineering*, 12(7), 570–579. doi:10.15866/ireme.v12i7.15125.
- [57] Yeranee, K., & Rao, Y. (2021). A review of recent studies on rotating internal cooling for gas turbine blades. *Chinese Journal of Aeronautics*, 34(7), 85–113. doi:10.1016/j.cja.2020.12.035.
- [58] Deng, Q., Wang, H., He, W., & Feng, Z. (2022). Cooling Characteristic of a Wall Jet for Suppressing Cross flow Effect under Conjugate Heat Transfer Condition. *Aerospace*, 9(1), 29. doi:10.3390/aerospace9010029.
- [59] Courtis, M., Murray, A., Coulton, B., Ireland, P., & Mayo, I. (2021). Influence of spanwise and streamwise film hole spacing on adiabatic film effectiveness for effusion-cooled gas turbine blades. *International Journal of Turbomachinery, Propulsion and Power*, 6(3), 37. doi:10.3390/ijtp6030037.
- [60] Sarwar Abbasi, W., Ul Islam, S., Faiz, L., & Rahman, H. (2018). Numerical investigation of transitions in flow states and variation in aerodynamic forces for flow around square cylinders arranged inline. *Chinese Journal of Aeronautics*, 31(11), 2111–2123. doi:10.1016/j.cja.2018.08.020.
- [61] Li, Z., Zhou, K., Liu, Y., & Wen, X. (2021). Jet sweeping angle control by fluidic oscillators with master-slave designs. *Chinese Journal of Aeronautics*, 34(5), 145–162. doi:10.1016/j.cja.2020.12.013.
- [62] Sang, Y., Shan, Y., Zhang, J., Tan, X., & Lyu, Y. (2021). Numerical investigation on flow mechanism in a supersonic fluidic oscillator. *Chinese Journal of Aeronautics*, 34(5), 214–223. doi:10.1016/j.cja.2020.10.015.
- [63] Zheng, J. G., Xia, L., Hu, J., & Mao, Y. J. (2021). Numerical investigation of characteristics of fluidic oscillator operating in quiescent air and a crossflow. *Aerospace Science and Technology*, 113, 106731. doi:10.1016/j.ast.2021.106731.
- [64] Xiao, T., Zhu, Z., Deng, S., Gui, F., Li, Z., & Zhou, Z. (2021). Effects of nozzle geometry and active blowing on lift enhancement for upper surface blowing configuration. *Aerospace Science and Technology*, 111, 106536. doi:10.1016/j.ast.2021.106536.
- [65] Chen, Y., Hou, Z., Deng, X., Guo, Z., Shao, S., & Xu, B. (2021). Numerical Study of the Lift Enhancement Mechanism of Circulation Control in Transonic Flow. *Aerospace*, 8(11), 311. doi:10.3390/aerospace8110311.
- [66] Moubogha Moubogha, J., Margalida, G., Joseph, P., Roussette, O., & Dazin, A. (2022). Stall Margin Improvement in an Axial Compressor by Continuous and Pulsed Tip Injection. *International Journal of Turbomachinery, Propulsion and Power*, 7(1), 1–15. doi:10.3390/ijtp7010010.
- [67] Neigapula, S. N. V., Maddula, S. P., & Nukala, V. B. (2020). A study of high lift aerodynamic devices on commercial aircrafts. *Aviation*, 24(3), 123–136. doi:10.3846/aviation.2020.12815.

- [68] Zhao, K., Ming, M., Li, F., Lu, Y., Zhou, T., Wang, K., & Meng, N. (2020). Experimental study on plasma jet deflection and energy extraction with MHD control. *Chinese Journal of Aeronautics*, 33(6), 1602–1610. doi:10.1016/j.cja.2020.01.003.
- [69] Chanut, P. L. J. (1961). US Patent # 3013494. Guided missile. United States Patent Office, Alexandria, United States. Available online: <http://www.freepatentsonline.com/3013494.pdf> (accessed on July 2022).
- [70] 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. Available online: <https://www.freepatentsonline.com/7155898.pdf> (accessed on July 2022).
- [71] Aerospaceweb. Missile Control Systems. Available online: <http://www.aerospaceweb.org/question/weapons/q0158.shtml> (accessed on May 2022).
- [72] Bailey, J. M. (1982). US Patent #4355949. Control system and nozzle for impulse turbines. United States Patent Office, Alexandria, United States. Available online <https://www.freepatentsonline.com/4355949.pdf> (accessed on July 2022).
- [73] Hickerson, F. R. (1965). United States Patent 3192714. Variable thrust rocket engine incorporating thrust vector control. United States Patent Office, Alexandria, United States. Available online: <https://www.freepatentsonline.com/3192714.pdf> (accessed on June 2022).
- [74] Semlitsch, B., & Mihăescu, M. (2021). Evaluation of Injection Strategies in Supersonic Nozzle Flow. *Aerospace*, 8(12), 369. doi:10.3390/aerospace8120369.
- [75] 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. Available online: <https://www.freepatentsonline.com/8387360.pdf> (accessed on July 2022).
- [76] Plumpe Jr., W. H. (2003). United States Patent 6622472. Apparatus and method for thrust vector control. United States Patent Office, Alexandria, United States. Available online: <https://www.freepatentsonline.com/6622472.pdf> (accessed on July 2022).
- [77] 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.
- [78] Kopiev, V.F., Belyaev, I.V., & Dunaevsky, A.I. (2022). RF patent #2776193. Supersonic Aircraft. Bull.#20. Available online: <https://www.fips.ru/cdfi/fips.dll/ru?ty=29&docid=2776193> (accessed on August 2022).
- [79] Ji, Z., Zhang, H., & Wang, B. (2021). Thermodynamic performance analysis of the rotating detonative airbreathing combined cycle engine. *Aerospace Science and Technology*, 113, 106694. doi:10.1016/j.ast.2021.106694.
- [80] Seitz, A., Nickl, M., Troeltsch, F., & Ebner, K. (2022). Initial Assessment of a Fuel Cell—Gas Turbine Hybrid Propulsion Concept. *Aerospace*, 9(2), 68. doi:10.3390/aerospace9020068.
- [81] Zhou, S., Ma, H., Ma, Y., Zhou, C., & Hu, N. (2021). Experimental investigation on detonation wave propagation mode in the start-up process of rotating detonation turbine engine. *Aerospace Science and Technology*, 111. doi:10.1016/j.ast.2021.106559.
- [82] Hermet, F., Binder, N., Gressier, J., & Sáez-Mischlich, G. (2021). Pulsed Flow Turbine Design Recommendations. *International Journal of Turbomachinery, Propulsion and Power*, 6(3), 24. doi:10.3390/ijtp6030024.
- [83] Christodoulides, P., Agathokleous, R., Aresti, L., Kalogirou, S. A., Tassou, S. A., & Florides, G. A. (2022). Waste Heat Recovery Technologies Revisited with Emphasis on New Solutions, including Heat Pipes, and Case Studies. *Energies*, 15(1), 384. doi:10.3390/en15010384.
- [84] Danieli, P., Masi, M., Lazzaretto, A., Carraro, G., & Volpato, G. (2022). A Smart Energy Recovery System to Avoid Preheating in Gas Grid Pressure Reduction Stations. *Energies*, 15(1), 371. doi:10.3390/en15010371.
- [85] Frankiewicz, S., & Woziwodzki, S. (2022). Gas Hold-Up and Mass Transfer in a Vessel with an Unsteady Rotating Concave Blade Impeller. *Energies*, 15(1), 346. doi:10.3390/en15010346.
- [86] Khanjari, A., Kang, S., Lee, D., Jung, D. Y., & Lee, J. H. (2022). Studying Four Different Permanent Magnet Eddy Currents Heaters with Different Magnet Areas and Numbers to Produce Heat Directly from a Vertical Axis Wind Turbine. *Energies*, 15(1), 275. doi:10.3390/en15010275.
- [87] Rozin, V. M., Gorokhov, V. G., Aronson, O. V., & Alekseeva, I. Yu. (1997). Philosophy of technology: history and modernity. Part I. General foundations of the philosophy of technology. Chapter 1. Philosophizing engineers and the first philosophers of technology. Collective monograph. Institute of Philosophy of the Russian Academy of Sciences, Moscow, Russia.
- [88] Baturin, O. V. (2011). Lecture notes on the academic discipline “Theory and calculation of blade machines: textbook. SSAU Press, Samara, Russia.
- [89] Engelmeier, P.K. (1911). Creative personality and environment in the field of technical inventions. Education, Saint Petersburg, Russia.

- [90] Patnaik, J., & Tarei, P. K. (2022). Analysing appropriateness in appropriate technology for achieving sustainability: A multi-sectorial examination in a developing economy. *Journal of Cleaner Production*, 349, 131204. doi:10.1016/j.jclepro.2022.131204.
- [91] 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.
- [92] Sazonov, Y. A. (2012). *Fundamentals of calculation and design of pump-ejector installations*. SUE "Oil and Gas Publishing House" of Gubkin University: Moscow, Russia.
- [93] UNESCO (1998). *Transdisciplinarity: Stimulating synergies, integrating knowledge*. UNESCO, Division of Philosophy and Ethics, Geneva, Switzerland. Available online: <http://unesdoc.unesco.org/images/0011/001146/114694eo.pdf> (accessed on May 2022).
- [94] Sheptunov, Sergey. A., Alexandrov, I. A., Golovатов, D. A., & Glashev, R. M. (2018). Simulation of Thermoset Heat Conductivity by Means of Artificial Neural Networks. 2018 IEEE International Conference "Quality Management, Transport and Information Security, Information Technologies. doi:10.1109/itmqs.2018.8524984.
- [95] Tatarkanov, A. A. B., Alexandrov, I. A., & Olejnik, A. V. (2020). Evaluation of the contact surface parameters at knurling finned heat-exchanging surface by knurls at ring blanks. *Periodico Tche Quimica*, 17(36), 372–389.
- [96] Kalinkevich, N. V., & Melnik, I. A. (2017). *Turbomachinery. Fundamentals of theory: textbook*. Sumy State University, Sumy, Ukraine.
- [97] 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.
- [98] 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 August 2022).
- [99] *Encyclopedia of Humanities. Concepts. Concepts of scientific discourse. Concepts of methodological discourse. Induction*. Available online: <https://gtmarket.ru/concepts/7146> (accessed on August 2022). (In Russian).
- [100] Franssen, M., Lokhorst, G.-J., & van de Poel, I. (2018). *Philosophy of Technology*. *Stanford Encyclopedia of Philosophy*. Available online: <https://plato.stanford.edu/entries/technology/> (accessed on May 2022).
- [101] Sojka, V., & Lepšik, P. (2020). Use of triz, and triz with other tools for process improvement: A literature review. *Emerging Science Journal*, 4(5), 319–335. doi:10.28991/esj-2020-01234.
- [102] Altshuller, G. S. (2011). *To find an idea: An introduction to TRIZ - the theory of inventive problem solving*. Alpina Publisher, Moscow, Russia.