PERIÓDICO TCHÊ QUÍMICA
ARTIGO ORIGINAL

PROTOTIPAGEM DE TURBINA MALHA COM SISTEMA DE CONTROLE DE JATO

PROTOTYPING MESH TURBINE WITH THE JET CONTROL SYSTEM

РАЗРАБОТКА ПРОТОТИПА СЕТЧАТОЙ ТУРБИНЫ СО СТРУЙНОЙ СИСТЕМОЙ УПРАВЛЕНИЯ

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RESUMO

Nas condições de instabilidade do mercado de petróleo e gás, é necessário intensificar a pesquisa científica exploratória para o desenvolvimento de equipamentos avançados e baratos de bombeamento e compressores destinados a uma produção mais eficiente de hidrocarbonetos. O trabalho de pesquisa em andamento está sendo realizado com o objetivo de pesquisar e estudar novas oportunidades técnicas para o desenvolvimento de equipamentos avançados de bombeamento e compressores adaptados às complicadas condições de produção de óleo e gás na presença de partículas sólidas abrasivas no escoamento do meio bombeado. Uma nova tecnologia de compressão de gás foi desenvolvida e patenteada usando uma unidade de compressor a jato quando o ejetor é ligado em modo cíclico. O ciclo liga-desliga do ejetor em vez de sua operação contínua torna possível aumentar a multiplicação da razão de compressão do gás. Para aumentar a eficiência energética da unidade de compressor a jato, a tecnologia de recuperação de energia com a aplicação de uma turbina especial tendo a estrutura de malha da parte de fluxo foi proposta e patenteada. Foram realizados trabalhos de pesquisa e desenvolvimento, a caminho do desenvolvimento de turbinas inteligentes e unidades compressoras inteligentes. Modelos 3D com a aplicação do sistema CAD SOLIDWORKS 3D foram desenvolvidos. O pacote de software FloEFD de dinâmica de fluidos computacional tem sido usado para modelagem de computador. Em condições de laboratório, o desempenho do protótipo de turbina de malha equipado com o sistema de controle de jato foi testado com sucesso. O desenvolvimento de unidades compressoras eficientes e mais baratas tornará possível resolver os problemas atuais de produção ao extrair hidrocarbonetos em condições complicadas, bem como no estágio final de desenvolvimento dos campos de petróleo e gás. Certos resultados de pesquisas científicas realizadas podem ser usados em outros ramos de produção, incluindo energia, transporte e robótica.

Palavras-chave: *modelo 3D, modelagem computacional, produção de petróleo.*

ABSTRACT

The oil and gas market is unstable, which requires intensification of the exploratory research for working advanced and inexpensive pumping and compressor equipment out. Such equipment is crucial for more efficient hydrocarbon production. The ongoing research work is being undertaken to search and study new technical opportunities to develop advanced pumping and compressor equipment adapted to the complicated conditions of oil and gas production in solid abrasive particles in the flow of the pumped medium. New technology for gas compression has been evolved and further patented. The technology utilized a jet compressor unit to assist a turned on ejector while in the cyclic mode. Pulsed cycling of the ejector in contrary to continuous operation, increases the compression ratio of the multiplied gas. The energy recovery technology has been evolved, and further patented io increase the energy efficiency in the jet compressor unit. This technology applies a particular mesh turbine located at the flow part. The evolvement of smart turbines and compressor units was thoroughly researched. 3D-models have been developed in SOLIDWORKS 3D CAD system. The FloEFD software package of computational fluid dynamics has been used for computer modeling. In laboratory conditions, the performance of the mesh turbine prototype

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equipped with the jet control system has been successfully tested. Efficient and cheap compressor units solve many urgent issues in production connected with hydrocarbons extraction in harsh environments and those, which occur at the later stages of developing oil and gas fields. Specific research results can be used in other domains, including energy, transport, and robotics.

Keywords: *3D-model, computer modeling, oil production.*

АННОТАЦИЯ

Рынок нефти и газа нестабилен, что требует интенсификации поисковых исследований для отработки современного и недорогого насосного и компрессорного оборудования. Такое оборудование имеет решающее значение для более эффективной добычи углеводородов. Ведутся постоянные исследовательские работы по поиску и изучению новых технических возможностей для разработки передового насосного и компрессорного оборудования, адаптированного к сложным условиям добычи нефти и газа в виде твердых абразивных частиц в потоке перекачиваемой среды. Была разработана и запатентована новая технология сжатия газа. В технологии использовался струйный компрессор для помощи включенному эжектору в циклическом режиме. Импульсное переключение эжектора в отличие от непрерывного режима увеличивает степень сжатия попутного газа. Технология рекуперации энергии была усовершенствована и запатентована, чтобы повысить энергоэффективность струйного компрессора. В этой технологии применяется конкретная сетчатая турбина, расположенная в проточной части. Разработка интеллектуальных турбин и компрессорных агрегатов была тщательно исследована. 3D-модели разработаны в системе SOLIDWORKS 3D CAD. Программный пакет вычислительной гидродинамики FloEFD был использован для компьютерного моделирования. В лабораторных условиях успешно испытана работоспособность опытного образца сетчатой турбины с системой управления струей. Эффективные и дешевые компрессорные агрегаты решают многие актуальные производственные вопросы, связанные с добычей углеводородов в суровых климатических условиях и возникающие на поздних этапах разработки нефтяных и газовых месторождений. Конкретные результаты исследований могут быть использованы в других областях, включая энергетику, транспорт и робототехнику.

Ключевые слова: *3D-модель, компьютерное моделирование, добыча нефти.*

1. INTRODUCTION:

As reservoir pressure drops at the late stage of oil and gas field development, there is a need for additional pumping and compressor equipment. However, the well-known compressor and turbine machines do not yet fully solve such urgent tasks because the working conditions for the equipment are complicated by the presence of solid abrasive particles in the flow of the pumped media (Chen, Li, Li, and Zhao, 2015).

There are known technologies for developing oil and gas fields, where jet pumps and compressors are used for liquid and gas pumping at high mechanical impurities content, as described in papers by Brink (2014), Singh, Prasad, Singh, Jha, and Tandon (2013). Adjustable ejectors are also used, and most frequently, the adjustment is made by changing the cross-section area in the channel at the nozzle, as described in the patent (Morishima, 2008).

The information on new developments where flow direction is periodically changed in hydraulic system channels is published in our previous work (Sazonov *et al.,* 2019). Scientific research studies in this area are developing. However, the specific features of reversible pumps and reversible compressors have not yet been studied sufficiently. The technological capabilities of such machines in the area of hydrocarbon extraction under complicated conditions have not been fully realized.

Special pumps and turbines have been developed for severe operational conditions, and each such hydraulic machine is equipped with a rotor made in the form of the mesh. This rotor structure can withstand higher loads, and here the authors can refer to the experience of the development and application of grid-like wings described in by Bilotserkovskiy *et al.* (1985).

In oil and gas fields, the active application of compressor and turbine technologies is currently being hampered by rather high prices for such equipment, especially in falling oil and gas prices. In this regard, the development of new efficient and affordable pump, compressor and turbine units can be fully attributed to the relevant objectives.

The known turbine designs are not adapted to the operating conditions in the oil and gas production system. At present, energy-saving turbine technologies are practically not used in oil fields. This situation is associated with an uncontrolled change in the density of the gas-liquid mixture in the flow channels of the turbine. This density varies in a wide range of values from 1 to 1,000 kilograms per cubic meter. There is a need to create new compressor technology for complicated conditions of use in oil and gas fields.

The purpose of the ongoing research work is to find and study new technical opportunities to develop promising pumping and compressor equipment adapted to the complicated operating conditions of oil and gas production in the presence of solid abrasive particles in the flow of the pumped medium (of liquid, gas or gas-liquid mixture).

The following main tasks were set to create a new turbine technology: 1) development of a reliable jet control system based on advanced scientific developments, including in the field of gas dynamics and hydrodynamics (Abugov and Bobylev, 1987); 2) development of a new turbine design capable of operating in conditions with an uncontrolled change in the density of the gas-liquid mixture in the flow channels, when this density changes in a wide range of values from 1 to 1,000 kilograms per cubic meter; 3) creation of the simplest and cheapest turbine design and control system, to reduce costs and to reduce the payback period of investments.

The specialists of the Gubkin Russian State University of Oil and Gas have developed and patented a new technology for compressing gas through a jet compressor, which implies that the ejector works in a pulse mode (Sazonov *et al.*, 2019). When creating new equipment, reliable technical solutions and methods were used that have successfully passed a long test (Trabold, Esen, and Obot, 1988; Shamanov, Dyadik, and Labinsky, 1989; Croft, Williams, and Tay, 1978; Coleman, Kim, and Spalart, 2003; Gao and Zhuang, 2004), including methods for creating nozzle devices, multiphase jet devices using computer calculation programs. According to preliminary estimates, this technology will make it possible to realize single-stage isothermal gas compression to pressures at the level of 10...40 MPa. Pulse operation of the ejector compared to continuous operation reduces energy consumption for gas compression multiply. The energy recovery technology, which requires a special mesh turbine of the flow part, has been proposed and subsequently patented to increase the energy efficiency of the jet compressor unit. This scientific field of research is at the initial stage today. In this connection, the study and improvement of energy recovery technology and technology for a jet compressor unit are relevant scientific and practical objectives.

2. MATERIALS AND METHODS:

For computer modeling and computational research, the FloEFD computational fluid dynamics software package developed by the Mentor Graphics company was used. The 3D model was created using the SolidWorks CAD system. In the process of modeling, the complete system of averaged Navier – Stokes equations was solved, described by mathematical expressions of the laws of conservation of mass, energy, and momentum. In the entire computational domain, the system automatically performed the transition between laminar and turbulent states. By default, the turbulence parameters were set automatically. To calculate the turbulent parameters for the closure of the Navier – Stokes system of equations, the authors used the model of turbulent viscosity modified by Lamb – Bremhorst. For the calculation, a structured Cartesian grid was generated. FloEFD uses sliding mesh technology to simulate rotation.

Two well-known additive technologies were used to manufacture a prototype of a mesh turbine and a jet control system: "Material Extrusion", "Sheet Lamination". Material Extrusion technology provides for the "extrusion of material" or layering of molten material through an extruder, which is the main unit of a 3D printer. “Sheet Lamination” technology provides for “joining sheet materials” or layer-by-layer formation of a product from sheet materials. In the presented work, sheet plastic and sheet steel were used to manufacture parts that make up the turbine prototype and the jet control system. For laboratory tests, samples of a mesh turbine with rotor diameters of 30 mm, 60 mm, 100 mm, 120 mm were made. Were also prepared samples of nozzles with a channel diameter from 1 mm to 10 mm.

In the course of laboratory hydraulic tests, the properties of the new turbine were investigated. During the measurements, the values of physical quantities were found using special technical means, including the use of an infrared frequency meter “Testo 465” with a measurement range from 1 to 99999 rpm with a measurement error of 0.02% (Testo, Germany), weight scale “CAS SWN” with a measurement error of 1 gram at a measurement range of 0.04 kg to 5 kg (manufactured by CAS Corporation, Republic of Korea), frequency converter “Altivar 312-ATV312HU75N4” (Schneider Electric, France), radial pressure gauge ROSMA TM-510P.00 1/2" 10 bar (CJSC ROSMA, Russia), Casio HS-3V-1R stopwatch (Casio, Japan).

The scheme of the laboratory bench installation is shown in Figure 1.

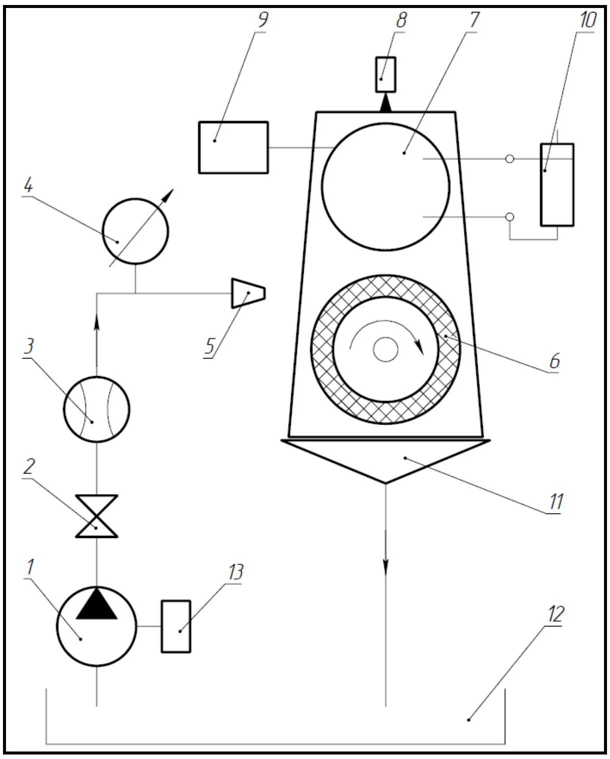

Figure 1. *The scheme of laboratory bench installation: 1 - pump; 2 – gate valve; 3 - flowmeter; 4 – pressure gauge; 5 - nozzle; 6 - turbine; 7 - electric generator; 8 - tachometer; 9 - weight scale; 10 - electrical resistance; 11 - casing; 12 - vessel; 13 - frequency converter*

Turbine 6 and electric generator 7 were mounted on a common shaft. In the process of testing the turbine, a direct method of measuring the power on the turbine was used. The direct method of measuring the power on the shaft of a hydraulic machine is to measure the torque and speed and is used, as a rule, when testing low-power installations. In this case, an electric braking device was used to determine the torque. The torque control was carried out by changing the electrical resistance 10 in the electrical circuit of the electric generator 7. To determine the torque by means of the braking device, the following values were measured: length of the brake lever; the weight of the brake lever; force on the brake lever.

When carrying out hydraulic tests of the turbine, it was used pump 1 with a nominal head of 100 meters and a flow rate of 5 to 50 liters per minute, the pump brand Pedrollo PQ-3000 (manufactured by the Italian firm Pedrollo).

3. RESULTS AND DISCUSSION:

Up to the present moment, the scientific and technological capabilities of hydrodynamic and gas-dynamic systems, which have wide opportunities to control the processes associated with changing the direction of the flow of liquid or gas, have not been completely realized. As the direction of liquid or gas flow changes, the operating mode of a pump or compressor unit radically changes. Within the framework of ongoing scientific research, the typical and the most straightforward scheme of a compressor unit is considered, represented in Figure 2.

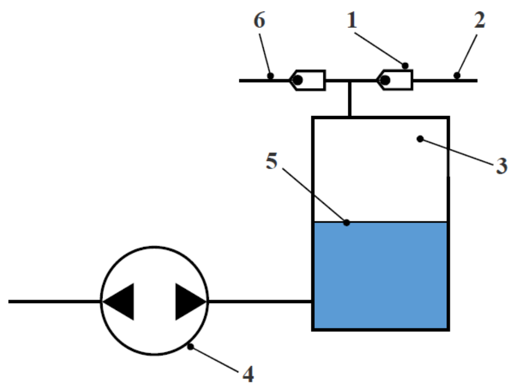

Figure 2. *Schematic diagram of a compressor unit equipped with a reversible pump*

The valve actuating gear 1 contains the suction valve and the discharge valve, making it possible to periodically connect the working chamber 3 to either the low-pressure gas pipeline 6 or the high-pressure gas pipeline 2. In the working chamber 3, a force impact is applied to the pumped gas, making it possible to compress the gas and direct it to the high-pressure gas pipeline 2. Such a force impact on the gas is provided by the liquid pumped by the reversible pump 4 into the working chamber 3. The interface between liquid and gas is marked on the diagram by position 5. When the liquid is pumped, the boundary surface 5 is displaced upwards, and the gas pressure increases in the working chamber 3 while the compressed gas is pushed out through the discharge valve into the high-pressure gas pipeline 2. The direction of flow is then changed through the reversible pump 4, and the liquid is pumped out from the working chamber 3. In this case, the boundary surface 5 is displaced downwards, and the pressure in the working chamber 3 is reduced, and the gas from the low-pressure gas pipeline 6 is fed through the suction valve into the working chamber 3. The described operation cycle is repeated.

In the reversible pump, as a rule, the direction of flow is changed due to the change of the rotation direction of the rotor. The area of the practical application of such systems is very limited due to inertial processes. Practical and scientific interest represents the issue of technical possibilities for developing a special switch-gear, which will make it possible to generate reverse flows when using any type of pump, and without changing the rotation direction of the rotor.

For illustration purposes, Figures 3 and 4 represent the connection diagram of the switch-gear 1 to the centrifugal pump 4. The pump 4 has an input channel 3 and an output channel 5. The flow of pumped media is directed from channel 2 to channel 6.

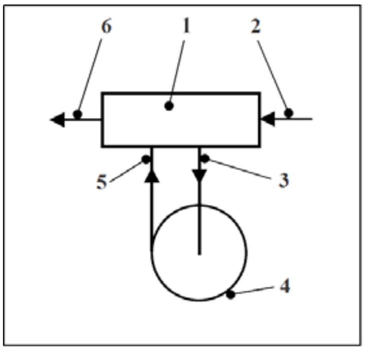

Figure 3. *Connection diagram of the switch-gear*

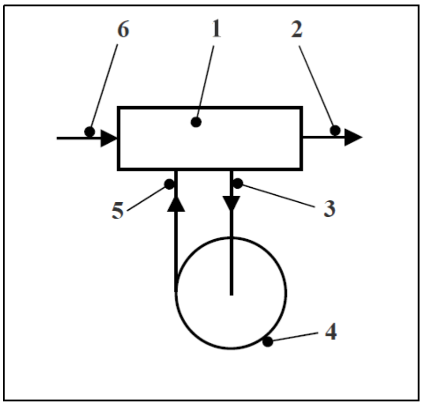

Figure 4. *Connection diagram of the switch-gear after switching the flow direction to the opposite one*

Figure 4 represents a diagram that corresponds to the operating mode after switching the switch-gear 1.

According to the diagram in Figure 4, the pumped media flow is already directed opposite from channel 6 to channel 2. After this switching, the pump 4 does not change its operating mode while the fluid flow in the pump keeps the same flow direction from inlet channel 3 to outlet channel 5, as shown by the arrows in Figures 3 and 4.

Within the framework of solving practical problems for the oil and gas industry, the complicated working conditions for switch-gears, pumping, and compressor equipment are considered. Complications are related to solid abrasive particles in the flow of liquid, gas, or gas-liquid mixture. At this stage of research work, switch-gear options are considered, which provide a relatively short time interval for switching – at the level of 0.1 seconds. It is known from the state of the art that such a time interval for switching is quite achievable using electromagnetic devices. To solve practical problems, particular interest variants of systems with the pump (or compressor) unit from several dozens to several hundreds of kW.

To improve energy efficiency in hydrocarbon production, turbine technologies are also being considered, which, among other things, ensure more rational use of reservoir energy. As the most interesting scientific perspective, multi-mode turbine units with wide opportunities for practical application in oil and gas fields have been considered.

Figure 5 represents the switch-gear variant of connection with possibilities to change (control) the flow direction. In this example, the liquid flow is fed to the pump 4 through the inlet channel 3. The liquid is fed into the switch-gear 1 at high pressure through the output channel 5. At the outlet of the switch-gear 1, one (or two) liquid jets 2 and 6 are formed, flowing into the surrounding space. In this case, the surrounding space can be filled with liquid or gas. The diagram shows the centerline 7 and angles "α" and "β" to quantify the jet direction.

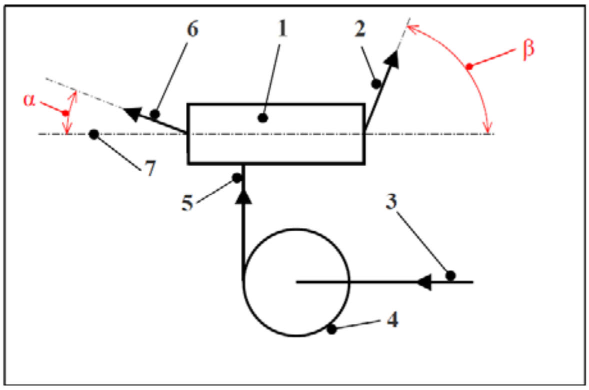

Figure 5. *Switch-gear connection diagram with possibilities for changing (regulating) the flow direction*

According to Figure 5, gas or a gas-liquid mixture can be used in the technical system instead of the liquid, and the compressor, gas generator, or another source of compressed gas can be used instead of the pump.

For illustration purposes, Figure 6 shows the option of connecting the switch-gear to the conical turbine with possibilities for changing the flow direction. In this example, the conical turbine 1 is connected to the electrical generator 2. The liquid (or gas) is fed into the switch-gear 4 through the inlet channel 3. The switch-gear 4 makes it possible to change the direction of the downstream flow. This may be an option with the direction marked in the diagram as position 5. Other variants, according to positions 6 or 7 are also possible. In this case, the liquid (or gas) jet impacts the conical turbine 1 and brings this turbine into the rotary movement.

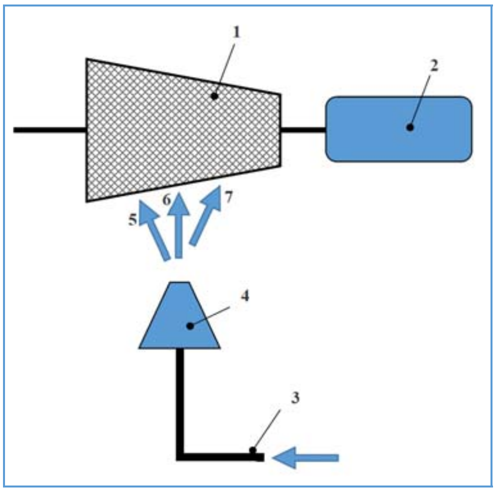

Figure 6. *Diagram of connecting the switch-gear to the conical turbine with possibilities for changing the flow direction*

For illustration purposes, Figure 7 shows the option of connecting the switch-gear to the disk turbine, with possibilities to change the flow direction. In this example, disk turbine 1 is connected to the electric generator 2. Inlet channel 3 supplies liquid (or gas) to the switch-gear 4. The switch-gear 4 allows the direction of the outgoing flow to be changed; this may be the option with the direction marked in the diagram as position 5. Other options, according to position 6 or 7, are also possible. In this case, the liquid (or gas) jet impacts the disc turbine 1 and brings this turbine into the rotary movement.

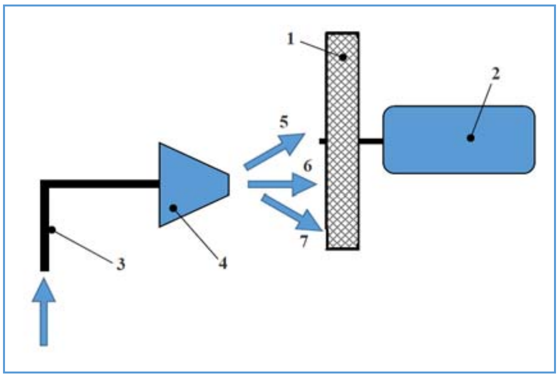

Figure 7. *Diagram of connecting the switch-gear to the disc turbine with possibilities for changing the flow direction*

In the examples, according to Figures 6 and 7, as the flow direction changes, the point at which the force is applied to the turbine rotor will also change. In this case, the working radius – the distance from the rotor axis of rotation of the turbine to the point of force application, will change. In this case, the rotational moment on the turbine shaft will also change. The specific feature of this control system is that when the flow rate of the working fluid (or gas) increases, it is possible to slow down the rotor speed of the turbine or even to force the turbine to rotate backward. For well-known power plants, such modes of turbine operation are not considered at all. However, for energy-saving technologies in oil and gas production, such modes can be useful because the turbine can perform several technological functions simultaneously.

At the present stage of research works, certain basic principles have been considered for the development of the multi-mode mesh turbine with possibilities to control the flow of the working medium and with possibilities to change the distance from the revolution axis of the turbine rotor to the point of force application, where the force interaction of the liquid flow with the hard wall of the vane on the turbine rotor is carried out.

Within the ongoing research framework, special designs of turbines, pumps, and compressors have been considered. The specific feature consists of using the mesh structure when profiling the rotor and stator flow. Figure 8 illustrates the mesh vane prototype manufactured on a 3D printer to investigate impeller machines with the mesh structure of channels.

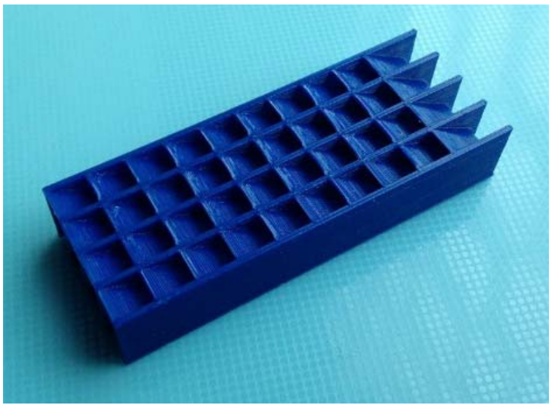

Figure 8. *Experimental prototype of the mesh vane manufactured on a 3D printer for investigation of impeller machines with the mesh structure of channels*

In design and engineering works, the term “prototype” is usually understood as the working model developed to demonstrate the working capacity and substantiation of the product being developed. The technology of fast prototyping provides the fast implementation of the basic functionality of the future product. At present, the fast development of the “prototype” became possible for a wide range of researchers and experts due to various additive technologies, including 3D-printers' application.

Figure 9 illustrates the variant of the computer model for carrying out numerical experiments when investigating impeller machines with the mesh structure of channels. Various variants with the application of liquids and gases have been considered. In this example, the ejector, as an element of the switch-gear, is used. For the oil and gas industry, ejector switch-gears are of special scientific and practical interest because of their universality. The ejector can operate both in jet pump mode and in jet compressor mode, and multiphase pump mode.

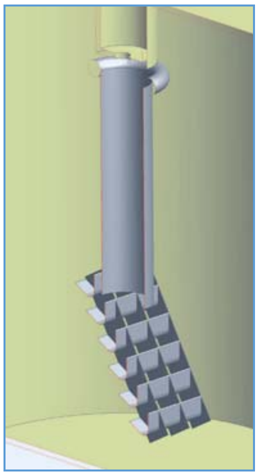

Figure 9. *Variant of a computer model for carrying out numerical experiments when investigating impeller machines with the mesh structure of channels*

In the example, the flow conditions of one vane in the gas medium have been considered. Figure 10 graphically illustrates the velocity diagrams based on the results of numerical experiments carried out following the model represented in Figure 9.

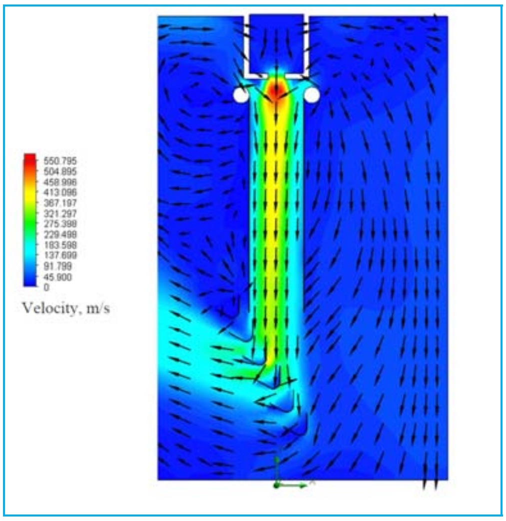

Figure 10. *Example with the results of numerical experiments when investigating impeller machines with the mesh structure of channels*

Computer modeling results have been used for design engineering within the framework of developing experimental models of new equipment.

For conducting laboratory tests, prototypes of turbines (experimental prototypes and turbines) have been developed. For example, Figures 11 and 12 demonstrate photographs of some experimental prototypes manufactured using additive technologies. As illustrated in Figure 11, the model (prototype) of the turbine was placed directly on the shaft of an electric generator for a faster transition to laboratory testing.

Figure 11. *Experimental prototype (pre-production model) of the disk turbine manufactured on a 3D printer for investigating impeller machines with the mesh structure of channels*

Figure 12. *Experimental prototype (pre-production model) of the conical turbine manufactured on a 3D printer for investigating impeller machines with the mesh structure of channels*

Laboratory tests of the created mesh turbine prototypes have been carried out. When testing the turbine prototype, the rotor speed was brought to the level of 20,000 to 30,000 rpm. To simulate the change in the density of the working medium, compressed air and water were used during the turbine tests. In the course of laboratory tests, the efficiency of the created turbine equipment was confirmed. During hydraulic tests of the turbine prototype, the efficiency values were fixed at the level of 50%, the ways were outlined for solving the optimization problem and for increasing the efficiency of the new technology being created, taking into account the capabilities of the jet control system.

Several special experiments have been carried out with a mesh turbine prototype. The jet control system was used to brake the turbine rotor and spin the turbine rotor in the opposite direction. The rotor in such reversible turbines can rotate both forward and backward. Such reversible turbines open up new opportunities for developing technologies for the extraction and treatment of oil and gas.

Figure 13 demonstrates the photograph of the switch-gear prototype. This switch-gear prototype is based on the diagram shown in Figure 5. For pneumatic testing, the blowing machine (and compressor) was used instead of the pump.

Figure 13. *Experimental prototype (pre-production model) of the switch-gear manufactured with the application of additive technologies*

During switch-gear testing, photography and video recording were made in order to capture the specific performance features of the developed prototype. To observe the change in angle "α" (as illustrated in Figure 5), the indicator thread (or interweaving of several threads) illustrated in Figure 14 was used. One end of the indicator thread was attached at the output channel to the wall of the switch-gear. Another end of the indicator thread was left free. Under these conditions, the indicator thread has always been drawn into the moving air current coming out of the switch-gear. This allows the researcher to observe the change in the flow direction without using complex laboratory equipment. This monitoring system was given the working name "ponytail". This system can also be used in the training process.

Figure 14. *Experimental prototype of the switch-gear with the indicator thread ("ponytail") when the air current is cut off*

Figure 15 illustrates the experimental prototype of the switch-gear equipped with an indicator thread ("ponytail") when air flows through the outlet channel for the conditions when the angle "α" is equal to zero degrees according to the diagram in Figure 5.

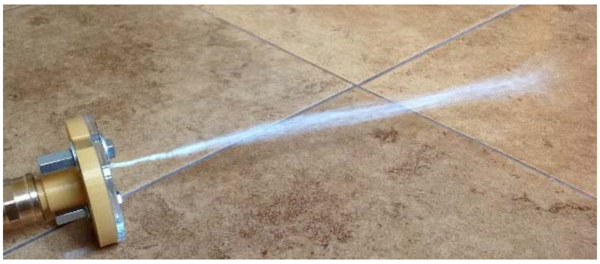

Figure 15. *Experimental prototype of the switch-gear equipped with the indicator thread ("ponytail") when the air flows through the outlet channel for the conditions when the angle "α" is equal to zero degrees*

Figure 16 illustrates the experimental prototype of the switch-gear equipped with an indicator thread ("ponytail") when the air flows through the outlet channel for the conditions when the angle "α" is more than zero degrees but less than ninety degrees according to the diagram in Figure 5.

Figure 16. *Experimental prototype of the switch-gear equipped with the indicator thread ("ponytail") when air flows through the outlet channel for the conditions when the angle "α" is more than zero degrees but less than ninety degrees*

Figure 17 illustrates the experimental prototype of the switch-gear equipped with an indicator thread ("ponytail") when the air flows through the outlet channel for the conditions when the angle "α" is equal to ninety degrees according to the diagram in Figure 5.

Figure 17. *Experimental prototype of the switch-gear equipped with the indicator thread ("ponytail") when air flows through the outlet channel for the conditions when the angle "α" is equal to ninety degrees*

During the laboratory tests, the working capacity of the impeller machine prototype with the mesh structure of the channels has been confirmed (Figures 11 and 12). During the tests, the process of electricity generation using the mesh turbine was simulated. A set of diode lamps was used as a load for the electric generator. Besides hydraulic tests, pneumatic testing with compressed air at pressure up to 0.5 MPa has been performed. Pilot testing with water vapor for the mesh turbine rotation has also been carried out. Tests of the turbine prototype have been carried out using the switch-gear prototype (Figure 13) that enables changing (adjusting) the direction of the working fluid (gas) flow.

There is an urgent problem restraining the introduction of many technologies to improve the efficiency of oil and gas production. This problem is related to the high price of high-pressure compressors with pressure from 10 to 40 MPa. Due to the high cost of these compressors, the practical application of such technologies as the compressor-assisted gas lift technology, the technology of gas injection into the productive formation for enhanced oil recovery, the technology of air injection into the productive formation for the implementation of oxidizing processes as part of work to improve the oil recovery factor, and technology of pumping gas-liquid mixtures is limited. The reservoir energy in oil and gas production due to the lack of reliable turbine equipment capable of operating in complicated conditions is weakly used. To solve this urgent problem, it is necessary to develop a new compressor and turbine equipment, which will ensure the profitability of hydrocarbon field development.

Jet control systems performed using ejectors are of scientific and practical interest. Control systems for ejectors are known to be used when a conical needle is placed in the nozzle cavity. The conical needle can be moved along the longitudinal axis of the nozzle, and the cross-sectional area of the passage channel at the nozzle is controlled, which in turn makes it possible to regulate the flow of the working fluid passing through the nozzle into the ejector mixing chamber. The well-known ejector regulation circuit can be improved if the conical needle can move not only along the longitudinal axis of the nozzle but also in a radial direction relative to this longitudinal axis of the nozzle, as demonstrated in our previous publication (Sazonov *et al.*, 2019). In this case, the more mobile conical needle significantly increases the possibilities for ejector regulation. In these conditions, it is possible to regulate the hydraulic fluid flow rate and control the direction of the hydraulic fluid flowing through the nozzle. For the time being, there are still some new issues regarding the ejector's adjustment taking into account the changes in the direction of the working fluid jet. With the use of modern computer technologies, additional opportunities have been added to study the working process of the ejector, taking into account changes in the direction of the jet of the working fluid (gas or gas-liquid mixture). In the case of radial displacement of the conical needle, the jet of the working fluid, flowing through the nozzle, changes. In this case, there are additional possibilities for independent regulation of the ejector operation mode and the power pump operation mode. There are opportunities to adjust the ejector's operating mode while maintaining the same operating mode of the power pump.

The results of research activities demonstrate that expensive positive displacement compressors can be replaced with jet compressor units, which differ by high reliability and low price (Sazonov *et al.*, 2019). The developed turbines can help to solve the problem of improving the energy efficiency of equipment under complicated conditions of oil and gas production.

With the development of computer technology, new opportunities open up for the automation of turbine technology and the progress towards developing intelligent turbines and intelligent compressor units. Jet control systems can be easily adapted to computerized control systems.

With modern computer technologies, many expensive physical experiments can be abandoned while replacing physical experiments with numerical ones. Jet elements from the field of science called “pneumonics” are relatively poorly studied. Modern computer programs make it possible to expand this research field due to more large-scale application of numerical experiments. Known developments in aviation and automation systems seem to represent only a fraction of the enormous potential that jet technology and the science of “pneumonics” have. Our research work deals with jet elements in combination with multi-threaded ejectors of various designs and combinations with electromagnetic control systems when solving control tasks for liquid and gas flows, according to our previous paper (Sazonov *et al.*, 2019).

The results of ongoing research can develop technologies for compressing and pumping various gases, such as methane, associated petroleum gas, nitrogen, carbon dioxide, air, hydrogen, or another gas, depending on the technology applied. The prospect of applying new turbines and compressors to develop particular internal combustion engines, where the combustion of the fuel-air mixture is carried out at a constant volume or constant pressure, is outlined. The development of cheaper and more economical turbines and compressors will make it possible to solve urgent problems of supplying electric and thermal energy to enterprises, including those in remote Arctic oil and gas fields.

Specific findings of the work performed can be used to develop jet control systems for air-based and sea-based unmanned aerial vehicles, which are used in research, rescue operations, or prospecting works, including the development of offshore oil and gas fields. Certain gas (liquid) flow control principles at the nozzle outlet have been considered in the presented work. For example, the same principles can be used to control the thrust vector on unmanned aerial vehicles. Part of the presented research work has been conducted at the junction of two scientific directions: 1 – turbine technologies and jet control systems, and 2 – rocket and aviation control systems. Typical thrust vector control systems are known from available digital information sources ("Missile Control Systems", n.d.) and printed publications like the monograph (Chanut, 1961; Bailey, 1982). This published information has been evaluated for applying certain known technical solutions in developing the jet control system for our mesh turbine under development. To save time and reduce financial costs, the verification of the selected published data was performed only using computer simulation and rapid prototyping technologies. Working capacity of the developed microlevel models and the basic known principles of thrust vector control has been tested in laboratory conditions during hydraulic and pneumatic tests using fast prototyping technologies for manufacturing new models and already known models. When using rapid prototyping technology and following accepted terminology (Karasev, 2000), the following methods of thrust vector control were tested in laboratory conditions: “Liquid Injection”, “Jet Vane”, “Axial Plate”, “Jet Tab”, “Movable Nozzle”.

The published data follows that for the known control systems, the largest deviation angle of the thrust vector can vary in the range from plus 20 degrees to minus 20 degrees. According to the published data, the angle “α” could vary from plus 20 degrees to minus 20 degrees based on the diagram demonstrated in Figure 5 in this paper. Somewhat different numerical values have been obtained in laboratory tests, according to which the angle “α” can vary from plus 90 degrees to minus 90 degrees in any direction within the hemisphere. Therefore, it is possible to draw a preliminary conclusion that the adjustment range by the angle of deviation of the thrust vector can be significantly extended compared to the published data. Besides, it should be noted that with a more complex approach to design, the adjustment range could be extended even further. When designing multi-mode and universal turbine technologies, the authors have set a goal to achieve an extensive adjustment range. the authors are interested in the following adjustment range for changing the angle “α” – from plus 180 degrees to minus 180 degrees in all directions. Preliminary design studies and laboratory tests of microlevel models have shown that this goal is achievable since the angle “α” can indeed vary in the range from plus 180 degrees to minus 180 degrees in any direction, within a full three-dimensional sphere. the authors plan to publish more detailed information on this subject after further additional patent research.

The system approach to analyzing the accumulated and incoming scientific information developed by the authors have been used according to our previous publications (Sazonov *et al.,* 2019). The following interrelated issues and processes are always considered in close integration: vane and vortex working processes; the pumping and turbine working process; coalescence and dispersion; cavitation in liquid and gas-liquid mixture; separation in multiphase media; presence of solid particles in the flow; point or distributed energy supply; sequential and parallel connection of machines; single or multistage machines; hydraulic losses due to friction and shock losses with the process of partial pressure recovery; constant and variable resistance coefficients; the development or attenuation of certain processes in different points of the working chamber of the machine at changes in the flow rate of the working fluid; changes in the physical properties of liquid or gas-liquid mixture in different points of the flow part of the machine; the presence of axial symmetry for solid walls and for the flow; used methods of the machine adjustment; and steady-state and impulse flow modes in certain areas. Considering the variety, interrelationships, and complexity of the listed issues, it is possible to speak about great opportunities to apply computer technologies in designing new machines and equipment. This list of questions and processes expands depending on the design or scientific task being solved. Given the possible prospects for the development of the intelligent computerized turbine, the following additional issues should be included in the presented list of interrelated issues: the switch-gear can be equipped with an additional electromagnetic, hydraulic, pneumatic, or hybrid control system; the flow regime through the mesh turbine channels can be at subsonic or supersonic velocities; in the capacity of the working body gas, steam, steam-gas mixture, liquid or gas-liquid mixture with the inclusion of abrasive solid particles can be used; continuous or periodic operation can be assigned to the mesh turbine. Besides, the energy from the mesh turbine can be used to drive one machine or several different machines (including an electric generator, pump, compressor, ventilator, separator, propeller, and air screw). In energy recovery mode, the mesh turbine can be connected to the shaft of an electric engine or the shaft of an internal combustion engine, including for the primary engine afterburning operation mode implementation.

The literature data analysis made it possible to outline a promising research direction concerning urgent problems in the oil and gas industry. This direction is associated with impulse turbines with a mesh structure of flow channels. Moreover, to control these turbines, it is advisable to use jet control systems. Within the framework of the well-known classification (Glaznev, Zapryagaev, and Uskov, 2000), either the interaction of a jet with an obstacle or the interaction of several jets with each other is considered. In both cases, the jet of gas or liquid is called an "impact jet". The impact jet structure is significantly complicated if a flow chamber of the ejector is placed between the nozzle and the mesh turbine rotor. Such a complicated scheme will be considered within the framework of a separate research work to study in more detail the features of the ejection flow and flow along curved surfaces, taking into account the heat transfer between flows and solid surfaces.

To solve urgent oil and gas production problems, it is advisable to create special stationary gas turbine engines with a constant volume heat supply. An integral part of such an engine is a pulse turbine (Tarasov, 2009), which makes it possible to improve the specific performance of the engine in comparison with a traditional gas turbine engine, where heat is supplied at constant pressure.

It is known that the heat transfer process can be activated in the flow of an impact jet (Pakhomov and Terekhov, 2011; Sadin, Lyubarskiy, and Gravchenko, 2017). The impact jet in the ejector also makes it possible to solve the problem of a controlled decrease in temperature before the hot gas enters the channels of the mesh pulse turbine.

A hybrid scheme is of practical and scientific interest, which combines the properties of the developed grid turbine and the Wales turbine described in the work by Dovgyallo and Shimanov (2015). In this case, the direction of rotation of the turbine rotor does not change when the direction of flow in the turbine rotor changes to the opposite direction.

When discussing gas-dynamic and hydrodynamic processes occurring in a mesh turbine, it is necessary to take into account the process of ventilation of the blades in a pulsed mode of gas or liquid supply (Konchakov, 2001). Usually, this ventilation process is associated with vortex processes, which somewhat reduce the efficiency of the turbine. However, in the preparation of oil and gas, this ventilation process can play a positive role, for example, in a turbine separator. This area of science and technology, associated with supersonic flows in rotating systems, has not lost its relevance for many years (Volov, 2011).

The question of the interaction of a gas (or liquid) jet with a solid wall can also be considered from new positions. An impenetrable solid wall is usually considered (Mordasov, Savenkov, and Chechetov, 2015). However, in problems with mesh turbines, the model of a semi-permeable solid wall can be additionally considered. In this case, it is necessary to consider in more detail the issues of designing individual jet elements intended for the jet control system as a whole. Modern computer technologies make it possible to consider tasks to calculate and design jet elements at a new and higher technical level (Ilyina and Prodan, 2015). Simultaneously, due to such computer technologies, for well-known technical solutions (Rekhten, 1980; Znamensky, Sokolov, and Chekmasov, 1996; Coanda, 1936), a new field of application can be opened, including in the production of hydrocarbons in oil and gas fields. The combination of the Coanda effect (Rekhten, 1980; Coanda, 1936) with deflectors for deflecting the jet may well be considered a new direction in creating jet control systems for pulsed turbines, including mesh turbines. For computer modeling and computational studies, the FloEFD computational fluid dynamics software package can be used. To create 3D models, for example, SolidWorks CAD systems are used. In the process of modeling, the complete system of averaged Navier – Stokes equations is solved, described by mathematical expressions of the laws of conservation of mass, energy, and momentum. All this allows using the results of classical works in the field of gas dynamics and hydrodynamics at a new technical level (Drozdov, 2011; Demyanova, 1998; Borovykh, 2003; Karambirov and Chebaevsky, 2005; Spiridonov, 2005; Temnov, 2003), axisymmetric and plane-parallel jets, free jets, and jets in a concurrent flow are considered.

In some cases, especially in the presence of abrasive solid particles in the flow, it is advisable to reduce the flow rate at the turbine inlet. In such cases, a stream of gas or liquid is passed through an ejector. The efficiency or efficiency of energy transfer through the ejector ranges from 50% to 90%, depending on the ratio of the nozzle and mixing chamber diameters (Brudny-Chelyadinov, 1971). The solution of optimization problems, when determining the geometric dimensions of the ejector, is performed, taking into account the composition of the multiphase working medium (Kabdesheva, Verbitsky, Dengaev, and Lambin, 2003; Verbitsky, Goridko, Fedorov, and Drozdov, 2016). It should be noted that the calculation of an ejector for multiphase media is still a complex theoretical problem, even with modern computer programs. In this regard, published experimental data on ejection processes remain in demand regardless of the publication date, since only a physical experiment is the most accurate source of scientific information in the field of gas dynamics and hydrodynamics. The results of physical experiments (Pavlechko, 2020) have established a scientific foundation for inkjet technology that is applied across a variety of industries. The creation of a new mesh turbine and jet control system is planned to take into account the peculiarities of ejection processes described in classical works (Drozdov, 2008).

In contrast to the known turbines, the developed turbine prototype was developed for complicated application conditions, with a possible uncontrolled change in the density of the gas-liquid mixture in the flow channels. This density varies in a wide range of values from 1 to 1,000 kilograms per cubic meter. In contrast to the known turbines, the developed mesh turbine allows changing and adjusting the torque by changing the distance from the axis of rotation to the point of application of forces (to the point at which the jet interacts with the solid wall of the turbine blade).

Considering the issues mentioned above, it is possible to draw an intermediate conclusion that some of the results of scientific research performed can be used in various industries, including energy, transport, and robotics.

4. CONCLUSIONS:

As a result of the current scientific research, the following main conclusions can be drawn:

1) a prototype of a mesh turbine with a jet control system was developed, capable of

effectively solving the problem of energy conversion when a multiphase flow moves through the flow channels of an impeller machine;

2) the operability of the created turbine equipment was confirmed both when performing numerical experiments and during laboratory tests;

3) during laboratory tests of the prototype of the jet system, it was shown that the angle of deflection of the working jet can be increased to 90 degrees for any direction within the geometric hemisphere;

4) the results of pneumatic and hydraulic tests confirmed the suitability of the mesh turbine for its operation under conditions of changing the density of the working medium, in a wide range - 1 to 1000 kilograms per cubic meter;

5) during the prototyping process, it was shown that a disk (or conical) mesh turbine can be manufactured on the basis of additive technologies using commercially available 3D printers.

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