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The study on the influence of the injected flow swirling on the characteristics of the jet pump

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ABSTRACT

Purpose: of this paper is to analyze the possibility of increasing the efficiency of wellbore jet pumps by twisting the injected flow. The absence of moving parts, easy transfer of energy, the ability to operate a wide range of performance and low cost have resulted in the use of ejection systems in many oil and gas deposits. The main disadvantage of borehole ejection systems is the insufficient value of the jet pump efficiency. The energy efficiency of downhole jet pumps can be improved by swirling the mixed flows.

Design/methodology/approach: To characterize the effect of circulating flows was used an additional factor in the form of the values of the inclination angle of guiding elements that swirl the flow or the rotation frequency of jet pump elements. In the process of determining the values characterizing the operating process of ejection systems, the flow rates of the working and injected flow and the pressure values in front of the nozzle, the receiving chamber and the chamber at the outlet from the diffuser of the jet pump are subject to direct measurement. Swirling of the injected flow was carried out by placing a sleeve with guiding elements, manufactured using 3D printing technology, in the receiving chamber of the jet pump.

Findings: The analysis revealed that in the design of downhole jet units, there are used guiding elements, mainly the screw, blade and tangential type, to swirl the flow. A highlighted list of factors that have a direct effect on the flows mixing process. During experimental studies of swirling injected flow type jet pump characteristics, there is obtained an increase in pressure and energy parameters.

Research limitations/implications: The task of further research is to determine the characteristics of a downhole swirling injected flow type jet pump for conditions of combined swirling of the working and injected flows.

Practical implications: The obtained results make it possible to take into account the presence of guiding elements in the flow path of the jet pump for swirling the flow.

Originality/value: It is established that the relationship between the design and technological parameters of the local swirling of the mixed medium is determined by the ratio of rotating and axial components of the flow velocity in the flow path of the jet pump.

Keywords: Jet pump, Ejection, Ejection system, Twisting flow, Efficiency

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MANUFACTURING AND PROCESSING

1. Introduction

The first oil downhole jet pump was used in 1875. The jet pump was steam driven and required a significant borehole diameter, with result that it did not find wide commercial use in the oil industry. In 1933, the University of California published the theoretical foundations for the use of jet pumps. In the 50s of the last century, computational algorithms were developed to select the design and operating parameters of borehole jet pumps, and in 2005 the ejection system was first placed under water to operate a well, the mouth of which was on the seabed [1,2]. In order to reduce the cost of oil production, jet units began to be used in hybrid layouts in conjunction with fountain equipment [3-5], gas-lift [6,7], electrocentrifugal [8], sucker-rod [9,10] and screw submerged units. The above-bit ejection system began to be used simultaneously with oil jet pumps. The use of above-bit ejection systems made it possible to intensify bottom hole flushing [11] and reduce the pressure in the well [12] during the initial opening of the productive horizon. Downhole jet pumps allow for increasing the cleaning efficiency of pipe systems in comparison with the use of mechanical devices [13] and special fluids [14,15]. The development of oil and gas ejection technologies caused the emergence of new unconventional areas for the use of jet pumps designed to eliminate hydrate formation [16,17].

The main disadvantage of borehole ejection systems is the low efficiency of the jet pump. The energy efficiency of downhole ejection systems can be improved by swirling the mixed flows [18-20].

The purpose of the research, the results of which are presented in this article, is to classify downhole jet ejection systems, analyze the structures of elements for swirling mixed flows and experimentally study of a swirling injected flow type jet pump characteristics.

2. Construction of oil jet pump

A downhole jet pump for oil production consists of a tubing string (tubing) 1 and a jet pump in the form of a mixing chamber two connected to a diffuser and the nozzle 3. The flowing part of the jet pump may include guiding elements for swirling the operating and injected flow that can be installed on the outer surface of the nozzle (shown in Fig. 1) or the inner surface of the receiving chamber.

Through radial hole 4, nozzle 3 of the jet pump is connected to the annular space, which is formed by the outer surface of the apparatus and the wall of well 5. To separate the areas of high and low pressure, the scheme of the ejection system includes a packer six installed below the jet pump.

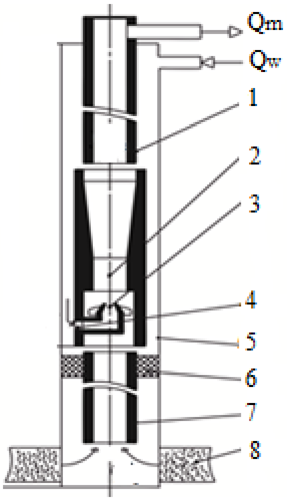

Fig. 1. Scheme of an oil jet pump installation in a well: 1 – a hydraulic channel of the tubing string; 2 – a mixing chamber and a diffuser; 3 – a nozzle; 4 – a radial channel; 5 – walls of the well; 6 – a packer; 7 – the lower section of the tubing string; 8 – a productive horizon

The lower section of the tubing string seven is designed to create a hydraulic connection between the suction line of the jet pump and the productive horizon. Power fluid with a flow rate Q_w (Fig. 1) is created by a surface pumping unit and is directed into the annulus of the well; it enters the mixing chamber 2 of the jet pump through the radial hole 4 and the working nozzle 3. The high flow rate of fluid from the nozzle forms an area of low pressure, which is the cause of an upward flow of formation fluid in the hydraulic channel of the lower section of the tubing string 7.

The mixed flow with the flow rate Q_m (Fig. 1) comes to the surface after exiting the diffuser of the jet pump through the tubing string 1.

The presence of a guiding element for swirling the injected flow causes an increase in hydraulic resistance to its movement, and a decrease in the head and flow rate of the jet pump is likely. However, at the same time, the hydraulic losses associated with the mixing of flows are reduced. The presence of counter processes allows for optimizing the hydraulic processes in the flow path of the jet pump and improving the pressure, flow and energy characteristics of the downhole ejection system.

The probability of cavitation when the flow interacts with inclined guiding elements can be reduced by increasing the pressure in the suction line of the jet pump and decreasing the speed of fluid movement in the hydraulic channels of the vortex nozzle with an increase in the area of its flow sections. The probability of bursting flows formation in the flow path of the jet pump decreases with the use of downhole ejection systems operated under conditions of significant (up to 40 MPa and more) hydrostatic pressures. Reducing the risk of cavitation in downhole ejection systems is also regulated by changing the required flow rate of the working flow and the ability to adjust the depth of the jet pump in the well.

3. Classification of downhole swirling injected flow type jet pumps

The scheme for the classification of downhole swirling injected flow type jet pumps developed by the author provides for the use of four classification features:

method of flow swirling;
a type of flow swirling;
orientation in the well;
design of guiding elements.

According to the method of twisting the flow, swirling injected flow type jet ejection systems can be divided into two groups. For the first group, flow swirling is carried out by rotating the jet pump itself or its individual parts. In systems of the second group, the vortex field or swirl of the flow is formed using guiding elements placed in the flow.

The next classification feature defines the type of flow (operating, injected or mixed), which is provided with rotation. The type of flow, which is swirled, determines the features of the next simulation of the jet pump workflow.

According to the orientation in the well, jet pumps can be divided into two groups: with symmetric and asymmetric placement in the well. The need to introduce this classification feature is associated with the significant influence of the jet pump orientation in the well on the radial distribution of velocities in its flow path and on the characteristics of the ejection system. In particular, the eccentric placement of the jet pump in the well corresponds to an asymmetric velocity diagram in the characteristic sections of the jet pump, which must be taken into account when simulating its working process.

The fourth classification feature determines the design of guiding elements that implement the flow swirling. A common feature that unites various designs of guiding elements and should be taken into account when modeling the working process of a swirling injected flow type jet pump is the inclination angle of the spiral trajectories of fluid particle motion. The zero inclination angle of vortex lines to the horizon, obviously, takes place with a tangential flow connection.

Let us determine the characteristic features of individual guiding elements, which despite their design differences, form a screw flow in the flow part.

Screw guiding elements are the most common (Fig. 2a) and are used for swirling both central and annular flow.

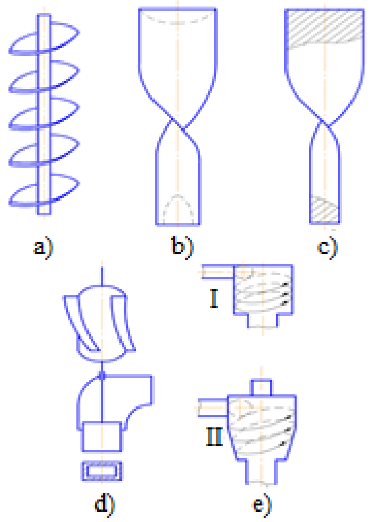

Fig. 2. Design of elements for swirling the flow: a) screw element; b) nozzles with mutually perpendicular cross sections; c) a twisted plate; d) hydraulic turbine; e) tangential feed with cylindrical (I) and conical (II) chambers

To swirl the working flow, there can be used nozzles of the jet pump in the form of two adjacent mutually perpendicular oval sections (Fig. 2b). Placing the inlet and outlet oval sections at an angle of 90° causes the appearance of a rotating component of the flow velocity, and the rectilinear flow lines take the form of helical spirals.

The guiding element for swirling the fluid can be made (Fig. 2c) in the form of a swirling plate, the initial and final sections of which are rotated by 90°, and it is placed in the hydraulic channel.

Power fluid swirling can be carried out in two stages. The incoming flow provides rotary motion to the oblique blade turbine, which in its turn rotates guiding elements to swirl the flow. A typical design of a turbine-driven jet apparatus is shown in Figure 2d. The section of the nozzle has a rectangular shape and rotates with the help of a hydraulic turbine, as a result of which the power fluid is swirled.

Tangential flow feed (Fig. 2e) is one of the most common ways of swirling. The tangential feed can be considered as a limiting case of using screw elements, the inclination angle of which approaches 90°.

The inlet chamber of the hydrocyclone jet pump has a conical shape (Fig. 2 (e) II). Considering that the suction line of a jet pump is connected to the slurry branch pipe of the hydrocyclone in hydrocyclone pumping units, only the injected flow is swirled.

The analysis revealed that:

in the design of downhole swirling injected flow type jet units, there are used guiding elements, mainly of the screw, blade and tangential type, to swirl the flow;

operating, injected and mixed flows are swirled;

in some devices, the flow is swirling simultaneously by guiding elements and rotation in the well.

4. Methodology of experimental studies

The hydraulic diagram of the laboratory setup for the experimental verification of the obtained equations and the visual appearance of the jet pump models are shown in Figure 3.

The laboratory unit is designed to study the effect of swirling of an operating, injected or mixed flow on the characteristics of a downhole jet pump. The laboratory unit consists of four full-size parallel-connected jet pumps located in a horizontal plane, each of which is formed by nozzle one and mixing chamber with a diffuser 2. The jet pumps are connected to common pressure 3, operating four and suction five collectors. Pressure collector three is connected with pressure six and suction seven lines. In order to approach conditions similar to operating a jet pump in a well with the help of a receiving-pressure vessel 8, a constant hydrostatic pressure is formed in the hydromechanical system of a laboratory installation, the value of which is determined by the excess of the vessel installation height 8 of the level of jet pumps placement.

To simulate the hydraulic load, which is created by jet nozzles of the bit, a local narrowing nine is installed in the pressure line in the mixed flow path. Suction line 7 connects pressure line 6 with suction collector 5. The pumping of the flow is carried out using a centrifugal pump 10, the suction line 11 of which is connected to reservoir 8, and the initial line is connected to the operating collector 4.

The flow rate of the working and injected flows is determined by flow meters 12 13. Pressure values of the working injected and mixed flows are determined by manometers (manovacuum meters) 14, 15 and 16. The gate valve 17 allows us to change the flow rate of the injected flow, and the gate valve 18 – the working flow. The use of valves 19 enables us to turn off individual jet pumps for the purpose of their individual examination.

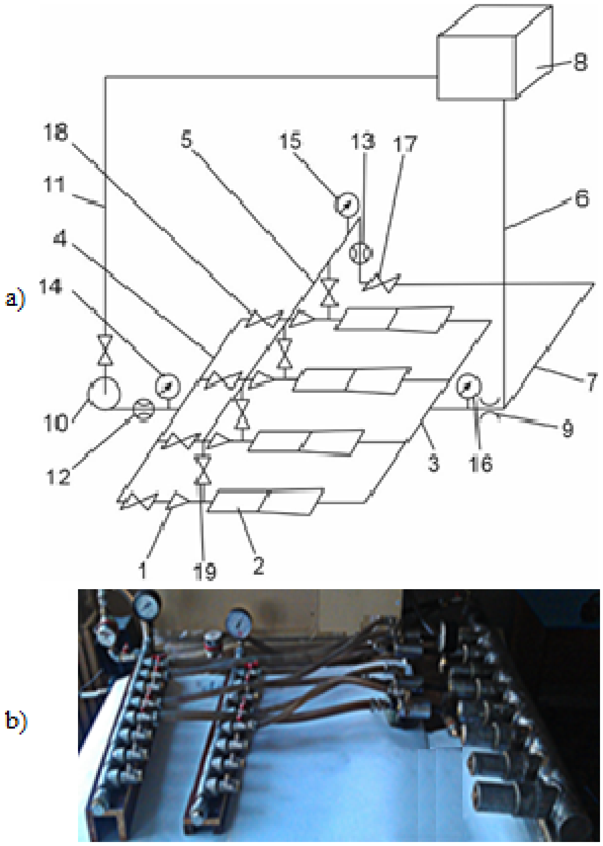

Fig. 3. Laboratory setup for investigating the operating process of a jet pump in conditions of swirling flow by guiding elements: hydraulic diagram (a), the visual appearance of the jet pump models (b)

When conducting experimental studies, we used a NOVATOR class B water meter with a relative measurement error of ± 5%, an MP-100 class 1.5 pressure gauge with a relative measurement error of ± 1% and OBM class 1.0 manometers with relative measurements ± 1%. Process water was used as a working medium.

Taking into account the world experience in the experimental study of ejection systems, the physical essence of the phenomenon of mixing media in the flow path of the jet pump and logical ideas about the influence of existing circulation flows on the nature of the connection of flows when planning an experiment, it is necessary to highlight a list of factors that have a direct effect on the process. We consider a complete list of factors in the form of variable quantities, which take on certain values at some point in time and can be measured using the equipment that is part of the experimental stand.

In the process of determining the values characterizing the operating process of ejection systems, the flow rates of the working and injected flow and the pressure values in front of the nozzle, the receiving chamber and the chamber at the outlet from the diffuser of the jet pump are subject to direct measurement. To characterize the effect of circulating flows, we use an additional factor in the form of the values of the inclination angle of guiding elements that swirl the flow or the rotation frequency of jet pump elements.

The study of the operational process of the jet pump is carried out in two stages.

1. Determination of the pressure characteristic $h = f(i)$ (where h = the relative pressure of the jet pump, i = injection coefficient of the jet pump) of the direct-flow jet pump.
2. Determination of the pressure characteristic $h = f(i)$ of the jet pump under the conditions of the swirling injected flow.

In the process of determining the pressure characteristic, each of the experimental models is sequentially tested. When conducting research, valves 18, 19, which are directly connected to the elements of the tested jet pump, are open, and the similar valves of the other three pumps are closed. After starting the power drive of the laboratory setup (centrifugal pump 10), using flow meter 12, the working flow is determined by the volumetric method. The value of the working flow Q_w during the study of the pressure characteristic is kept constant. The flow rate of the injected flow is determined by flow meter 13. The change in the flow rate of the injected flow Q_s is achieved by adjusting the degree of opening of valve 17, which changes the hydraulic resistance of the suction line 7 and the operating mode of the jet pump. The change of the hydraulic pressure in the suction line affects the pressure of the mixed P_m and injected flow P_s. At the same time, the pressure P_w of the working flow remains unchanged since its flow rate remains constant. The pressure of the working P_w, mixed P_m and injected P_s flows is determined by manometers 14, 16 and manovacuum meter 15. After determining the research parameters Q_w, Q_s, P_m, P_s, P_w, there are determined relative indicators

$$h = \frac{P_m - P_s}{P_w - P_s}; \; i = \frac{Q_s}{Q_w} \tag{1}$$

and the pressure characteristics $h = f(i)$ are made for each jet pump model, which can be transformed into energy characteristics $\eta = f(i)$ using relation

$$\eta = \frac{hi}{(1-h)} \tag{2}$$

where η = efficiency of the ejection system.

Swirling of the injected flow was carried out by placing a sleeve with guiding elements, manufactured using 3D printing technology, in the receiving chamber of the jet pump (Fig. 4)

Fig. 4. A sleeve with guiding elements for swirling the injected flow

The tilt angle of guiding elements was 45°, and the coil thickness was 2.5 mm. The presence of a central sleeve (to ensure the rigidity of the auger) reduced the normal cross-sectional area of the intake chamber of the jet pump by 8.7%. In addition, the presence of screw turns, rotation of fluid particles and a continuous change in the direction of the injected flow motion also affect the hydraulic resistance of the jet pump flow path. The swirling efficiency of the injected flow obtained during the research exceeds the negative effect on the characteristics of the jet pump by the growth of hydraulic resistance and its receiving chamber caused by a decrease in its cross-sectional area.

The next research stage concerns the determination of the influence of the working flow rate on the value of the injection coefficient of the jet pump. At this stage of research, using valves 18, and 19, the jet pump being tested at this point is isolated. Valve 17 remains fully open, and the operating mode of the ejection system is regulated by the degree of opening valve 18, which relates to the tested jet pump. We begin experimental studies for a fully open valve 18. After starting centrifugal pump 10, like in the previous research stage, we determine the operating flow rate Q_w (using flow meter 12), injected flow rate Q_s (using flow meter 13) and pressure values P_m, P_s, P_w using manometers 14, 16 and manovacuum meter 15. The fully open valve 18 corresponds to the first experimental point. For subsequent experimental points, the parameters of the laboratory setup are determined for smaller degrees of valve 18 opening.

Experimental tests are completed after reaching the values of the operating flow rate close to zero. After completing the experimental tests, we determine the relative flow rate of the jet pump (injection coefficient) and form the dependence.

In order to generalize the results of experimental studies, it is advisable to represent the value of the operating flow rate in the form of the Reynolds number of the operating flow.

$$R_{ew} = \frac{V_w d_w}{\nu} = \frac{4Q_w}{\pi d_w \nu} \tag{3}$$

where V_w = the flow rate in the channel of the nozzle with a diameterd_w, ν = coefficient of the kinematic viscosity of the fluid.

During the experimental study of the ejection system characteristics, there were used jet pump models with different values of the main geometric parameter K_p, the relative distance between the nozzle and a mixing chamber $\bar{l}_w$, and a relative length of the mixing chamber $\bar{l}_c$ (Tab. 1).

Table 1.
Geometric dimensions of jet pump models

No	K_p	$\bar{l}_w$	$\bar{l}_c$
1	6.464	1.53	20.3
2	5.012	1.04	17.9

The relative distance between the nozzle and the mixing chamber was determined as the ratio of a nozzle diameter d_w and an absolute distance l_w to a mixing chamber $\bar{l}_w = \frac{d_w}{l_w}$. The relative length of the mixing chamber was calculated as the ratio of its absolute length l_c and the diameter d_w of the nozzle $\bar{l}_c = \frac{l_c}{d_w}$. The diameter and the absolute length of the mixing chamber for both models is respectively 15 mm and 120 mm.

According to the accepted classification the studied jet pumps are low-pressure ($K_p < 4.0$).

5. Results and discussion

The dependences of the injection coefficient value on the Reynolds number for flow are approximated in the form of asymptotic functions (Fig. 5)

$$i = \frac{R_{ew}}{b + aR_{ew}} \tag{4}$$

the values of which approach at infinity horizontally.

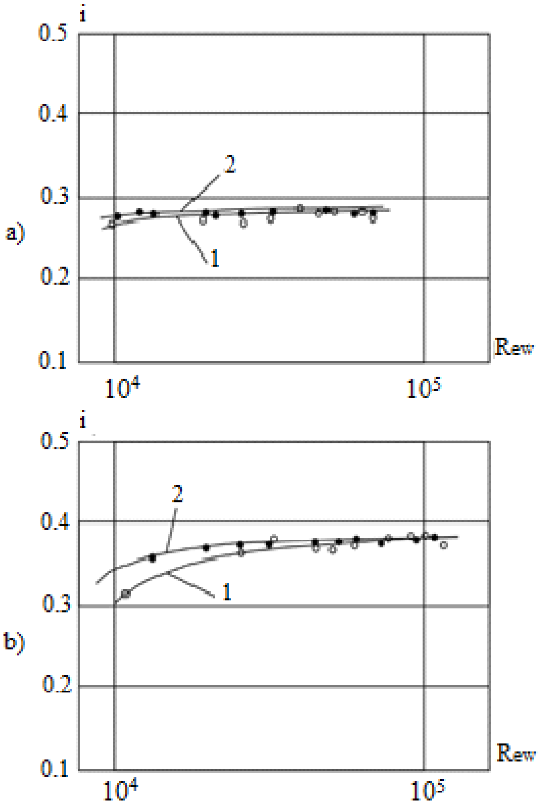

Fig. 5. Dependence of the injection coefficient on the Reynolds number of the flow for a jet pump with geometric relationships K_p=5.012 (a) and K_p= 6.464 (b): 1 – no flow swirling; 2 – swirling of the injected flow

The values of empirical coefficients *a, b* and the correlation coefficient *r* for tested jet pump models with the tilt angles of the guiding elements α_s=0, α_s=45° are shown in Table 2.

Table 2.
Values of empirical functions coefficients and correlation coefficients for various angles of the injected flow swirling

K_p	α_s, °	*a*	*b*	*r*
6.464	0	2.545	8299	0.9526
6.464	45	2.603	2968	0.9764
5.012	0	3.581	1617	0.4873
5.012	45	3.55	1491	0.8545

Low values of the correlation coefficients for individual regression equations are explained by using empirical functions of the same type for all tested models. In the author's opinion, they correspond as much as possible to the physical meaning of mixing processes in the flow path of the jet pump.

The value of the swirling parameter of the injected flow S was determined by taking into account the ratio of the circular V_θ and axial V_a projections of the swirling flow velocity $G = \frac{V_\theta}{V_a}$ by the formula.

$$S = \frac{\frac{G}{2}}{1-\left(\frac{G}{2}\right)^2} \qquad (5)$$

For experimental studies, the value of the flow swirling parameter was $S = 0.667$.

The qualitative nature of dependences obtained (Fig. 5) is repeated for both models of jet pumps: the efficiency of injected flow swirling is maximum for small values of the Reynolds number and gradually decreases with an increase in their value. The maximum efficiency of injected flow swirling occurs for the jet pump, which corresponds to the main geometric parameter K_p=6.464: the value of the injection coefficient increases by 11.1%. The efficiency of injected flow swirling was determined by comparing the values of the injection coefficient obtained for the swirling injected flow type and direct-flow jet pump. The analysis of the results obtained indicates a tendency for the efficiency of swirling injected flow to increase with a decrease in the Reynolds number and, in particular, during the production of high-viscosity oil.

Empirical functions for pressure characteristics when testing jet pump models with inclination angles of guiding elements α_s= 0, α_s= 45 (Fig. 6) are given in Table 3, and the value of the research coefficients – is in Table 4.

Table 3.
Regression equation for pressure characteristics of jet pumps

K_p	$\alpha_s = 0°$	$\alpha_s = 45°$
6.464	$h = a + bi^2$	$h = a + bi^2 + ci^4$
5.012	$h = (a + bi^2)^{0.5}$	$h = a + bi^2$

Table 4.
The values of empirical coefficients of the regression equations for the pressure characteristics of jet pumps

K_p	α_s, °	a	b	c
6.464	0	0.1816	-0.3606	-
6.464	45	0.1884	-0.4642	1.2492
5.012	0	0.0348	-0.2309	-
5.012	45	0.2365	-0.9642	-

The correlation coefficient ranges from r = 0.9784 to r = 0.9953. The analysis of the obtained experimental pressure characteristics (Fig. 6) indicates that the maximum increase in the pressure caused by the swirling of the injected flow is $\Delta\bar{h}$ = 20.94% and corresponds to the jet pump with the value of the geometric parameter K_p = 5.012.

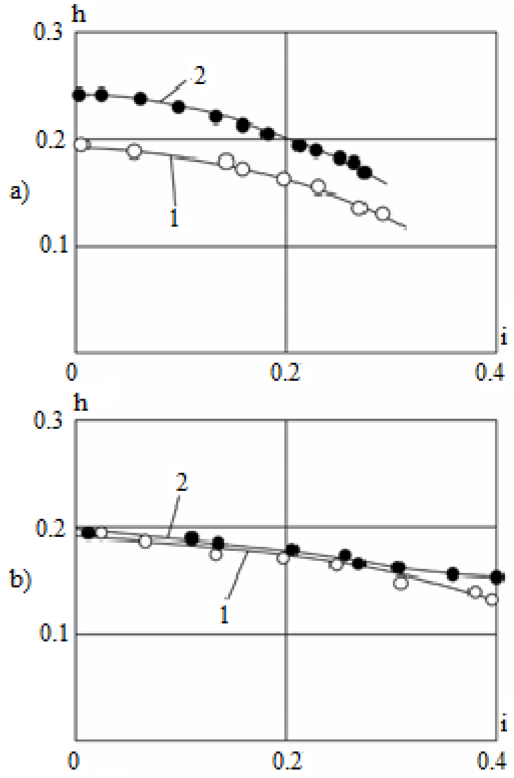

Fig. 6. Pressure characteristic for different ratios of the geometric parameter of the jet pump K_p=5.012 (a) and K_p=6.464 (b): 1 – no flow swirling; 2 – swirling of the injected flow

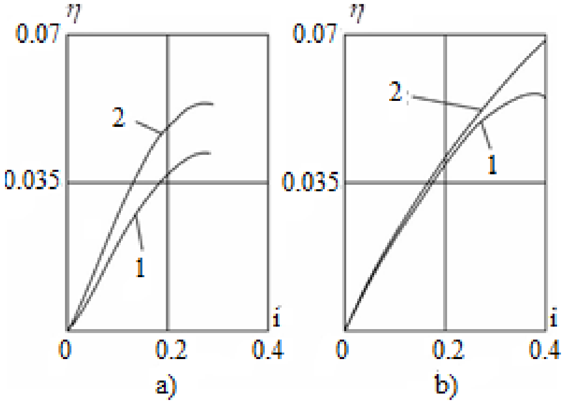

Fig. 7. Dependence of the jet pump efficiency on the injection coefficient for various ratios of the geometric parameter of the jet pump K_p=5.012 (a) and K_p=6.464 (b): 1 – no flow swirling; 2 – swirling of the injected flow

The dependences of the efficiency on the injection coefficient of the jet pump (Fig. 7) were obtained using the empirical pressure characteristics given in Table 3. Therefore, they do not contain experimental points. In the process of determining the efficiency value, equation (2) was used.

The maximum increase in efficiency caused by the swirling of the injected flow corresponds to the jet pump model with the geometric parameter K_p=5.012 and is $\Delta\bar{\eta}$ = 26.1%.

6. Conclusions

The energy efficiency of downhole jet pumps can be improved by swirling the mixed flows. Downhole vortex jet pumps can be classified according to the method of the flow swirling (rotation of pump parts and guiding elements), the swirling of the medium (working, injected or mixed), orientation in the well (symmetric and asymmetric) and design of guiding elements (screw, with displaced sections, swirling plates, hydraulic turbines, tangential flow feed). In some units, there is a simultaneous swirling of the flow by guiding elements and rotation in the well.

The main design and technological factors that determine the hydrodynamic parameters of the local swirling of the mixed medium are the angles of inclination of guiding elements, the diameter of the helical trajectory, which is described by the fluid particles, and the flow rate of a swirling flow. These values determine the angular velocity of the mixed flow rotation, which is a determining factor in the influence on the energy efficiency of a downhole swirling injected flow type jet pump.

In the process of experimental studies of swirling injected flow type jet pump characteristics, it has been determined that the efficiency of injected flow swirling is maximum for small values of the Reynolds number, and it gradually decreases with an increase in their value. an increase in the value of the injection coefficient by 11.1%, the value of the relative pressure by 20.94% and efficiency by 26.1% were obtained.

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