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# Determination of Experimental Characteristics of a Jet-vortex Pump

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**Abstract**

A methodology has been developed and the results of experimental studies of high-pressure jet-vortex pump models with a mixing chamber and working nozzle area ratio of 3.429 and 3.795 have been obtained. In the flow part of the pump, inclined guide elements for swirling the mixed flows are installed. An increase in the velocity of swirling screw jets increases the level of turbulence, intensifies the energy exchange of the mixed media, and improves the conditions for transferring kinetic energy from the working flow to the injected one. Improvement of the flow mixing mechanism allows increasing the energy efficiency of jet pumps. The velocity of swirling screw jets is determined by the angle of inclination of the guide elements and the flow rate of the mixed flows. The efficiency of simultaneous swirling of the mixed media may be less than the efficiency of swirling a separate flow if there is a difference in the directions of the velocity vectors of the swirling jets. There has been obtained the dependence of the injection coefficient on the Reynolds number of the working flow, pressure and energy characteristics for a straight-through jet pump for the case of swirling of the exclusively injected flow and simultaneous swirling of the working and injected flows. According to the results of the conducted studies, an increase in the injection coefficient, relative pressure and efficiency caused by swirling of the mixed flows was established by 26.34%, 19.43% and 23.75%, respectively.

**Keywords**

jet pump, flow mixing, flow swirling, screw jets, injection coefficient

## 1 Introduction

The design of a jet pump was proposed by Thompson, J. back in 1852, and its first use is attributed to Venturi, G. B., who in 1859 used a water meter pipe he developed to drain marsh lands in Northern Italy (near Modena). The foundations of the theory of jet devices were laid in the works of Zeiner, G. (1863) and Rankine, M. (1870). A simple design, no moving parts, mechanical durability and reliability, ease of maintenance, resistance to high temperatures, the ability to transport aggressive liquids with a high content of mechanical impurities and gases and the ability to install in hard-to-reach places have expanded the use of jet devices in agriculture [1], mining [2] and the oil production industries [3]. One of the traditional areas of ejector technologies development is the use of jet devices in the cooling systems of heat engines [4]. The main disadvantage of a jet pump is its low energy characteristics.

A new stage in the development of ejector systems is associated with the use of inclined guide elements in the design of a jet pump, placed in the working and injected flow. The presence of guide elements in the working nozzle or the receiving chamber allows optimizing the process of mixing flows in the flow part of the jet pump. Swirling the working and injected medium reduces hydraulic losses during mixing of flows and promotes an increase in the value of the efficiency of the ejector system. In view of the long-term nature of the implementation of technological processes associated with the use of jet pumps, optimization of their energy characteristics allows increasing the economic advantage of using ejector systems and is an urgent research task.

A special feature of the working process of the ejector system is the presence of the coaxial working and injected flows in the mixing chamber of the jet pump with a shear

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flow of variable width with an uneven distribution of hydrodynamic parameters located between them [5]. The effect of the swirling process of the working and injected medium on the characteristics of the jet pump is determined by the dependence of the hydrodynamic parameters of the shear flow on the kinematics of the mixed flows. Flow swirling creates additional turbulence and expands the area of the shear layer localized between the concentric working and injected flows [6]. The circular component of the swirling flow velocity is almost constant along the length of the ejector, and the axial component of the velocity increases along the flow [7]. Based on the results of studies of the gas-liquid ejector, there was established an increase in pressure along the flow part of the jet apparatus, caused by swirling of the flow [8]. Studies conducted at the French Institute of Petroleum established an increase in the injection coefficient of the jet pump under conditions of active flow rotation [9]. At the same time, due to the increase in hydraulic losses caused by the presence of guide elements and additional turbulence during flow mixing, a decrease in the efficiency of the jet pump is noted. A significant number of researchers note the existence of optimal swirl angles of mixed flows. High intensity of mixed flows swirl reduces the suction capacity of the jet pump [10]. Moderately swirled flow is characterized by greater suction capacity and, thus, contributes to an increase in the efficiency of the jet pump working process. In work [11], an extreme nature of the dependence of the pressure and efficiency of the jet pump on the angle of inclination of the working nozzles was obtained, which is associated with the effect of swirl of the mixed media on the amount of energy losses in the near-wall regions and high viscosity of dispersion of swirling flows. The maximum suction capacity and efficiency of the jet pump correspond to inclination angles of the working nozzles of 15°. By comparing the obtained results with the characteristics of a straight-through jet pump, an increase in the injection coefficient of the jet pump by 4.5% and an increase in its energy efficiency by 5% were obtained. Asahi Organic has developed a circular jet pump in which the working flow is swirled in a peripheral channel, after which the vortex region spreads to the central section [12]. Flow swirling made it possible to reduce the flow mixing time fourfold compared to a straight-through jet device. Three models of a water-air ejector with flow swirling angles of 0°, 30° and 50° were tested in experimental studies at the Indian Institute of Technology Madras (Chennai) [13]. According to the results of the studies, the maximum increase in the injected flow rate occurs when using an ejector with guide element inclination angles of 50° and it is 21.3%. The effect of the swirling intensity of the mixed flows on the suction capacity of the ejection system is confirmed by studies of a gas ejector conducted at the University of Windsor (Canada) [14]. The results of a study of the design features of a flow swirling device on the characteristics of a jet device are presented in [15]. Using numerical modeling, there were studied two types of vortex generators used to swirl the working flow of a gas ejector with a central nozzle. The working flow was swirled by inclined blades and by profiled channels. A comparative analysis of the obtained results showed that the use of inclined blades increases the injection coefficient by 5%, while the use of profiled channels increases it by 15%. Petrogulf Misr Co. (Cairo, Egypt) conducted numerical studies of the working process of a jet pump using the Ansys Fluent commercial CFD code [16]. According to the obtained results, it was established that the optimal swirl angle of the injected medium was 45°, which increased the energy efficiency of the jet pump by 12.76% compared to the same configuration of the ejector system with zero swirl of the flow in the suction line. The results of experimental studies of a jet pump with a ratio of the areas of the mixing chamber and the working nozzle of 5.012 are presented in [17]. Swirling of the injected flow by guide elements with a blade inclination angle of 45° increased the injection coefficient and efficiency of the jet pump by 11.1% and 26.4%, respectively. At the Norwegian University of Science and Technology (Trondheim, Norway), CFD modeling was used to study the working process of a two-phase vortex ejector, in which part of the flow from the mixing chamber returns to the receiving chamber of the jet device via a bypass line through a tangentially installed nozzle and produces swirling [18]. There was established a significant effect of the localization of the place of selection of the return flow along the mixing chamber and the magnitude of its velocity at the entrance to the receiving chamber on the performance of the jet device. There are also designs of ejector systems that consist exclusively of a vortex chamber [19] with tangential flow input. As a result of the creation of a vortex in the central part of the device, a low-pressure region is generated and conditions for the suction of the injected flow are formed. In the design of the above-bit ejection system, due to the placement of the jet pump axis at an angle to the well axis, a vortex field is generated at the outlet of the diffuser, creating ascending electrified screw flows in the above-bit region [20]. In the process of creating a combined vortex field for swirling the working medium, several nozzles with tangential flow supply were used, and the rotational-translational motion of the injected flow was provided with the help of inclined blades [21]. Compared with a straight-through jet pump, the efficiency increased by 10–15%. In the case of asymmetric swirling of the injected medium, the angular velocity of rotation of the liquid particles decreases compared to symmetric swirling and the value of the additional dynamic pressure caused by the influence of the circulation motion of the mixed flows decreases [22]. The value of the additional dynamic pressure decreases with an increase in the asymmetry of swirling of the injected flow.

The systematization of the designs of jet-vortex ejection systems made it possible to identify three main methods for creating circulation flows in the flow section of a jet apparatus: individual swirling of the working and injected medium and combined simultaneous swirling of both mixed flows. The working process of a jet pump under conditions of simultaneous swirling of mixed flows has been less studied. In the process of analyzing studies devoted to determining the characteristics of jet-vortex ejection systems, it was found that the most common means of modeling the working process of a jet pump are simulation programs. Swirling of mixed flows is associated with the need to model the hydrodynamic processes occurring in the vortex shear layer located between the working and injected medium. Under these conditions, there is an increase in requirements for constructing a grid model and optimizing the choice of semi-empirical turbulent theories, which are an integral part of simulation programs and largely determine the reliability of modeling the working process of a jet-vortex pump. Evaluation of the reliability of the modeling results leads to the need for a comparative analysis of the theoretical and experimental characteristics of the jet pump.

The aim of the work is an experimental study of the working process of a jet pump under conditions of simultaneous swirling of the working and injected flows.

## 2 Design of a jet-vortex pump and analysis of its working process features

Unlike a direct-flow ejector system, a jet-vortex pump contains inclined guide elements placed in the working and injected flow supply channels (Fig. 1). The presence of inclined guide elements makes local swirling of mixed flows. These elements for swirling the flow can be made in the form of a screw profile, twisted plates, spirals, inclined straight and curved ribs, screw grooves, nozzles shifted at an angle, which are uniformly placed in the annular channel and form discrete jets, belt and screw elements, cyclone-type swirlers, a curved channel adjacent to a straight section of the pipe.

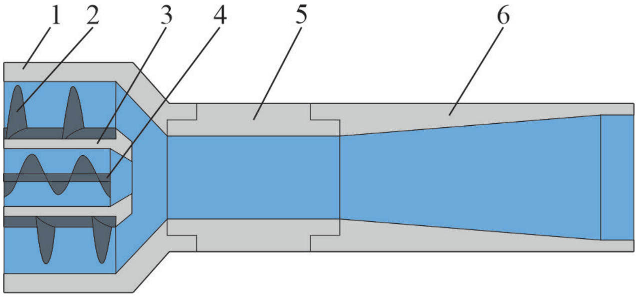

**Fig. 1** Design of a jet-vortex pump: 1 – receiving chamber; 2 – screw elements for swirling the injected flow; 3 – working nozzle; 4 – screw elements for swirling the working flow; 5 – mixing chamber; 6 – diffuser

Screw guide elements are the most common. The limiting case of using guide elements provides tangential flow supply. Flow swirling can be carried out by a nozzle made in the form of two adjacent mutually perpendicular sections of oval cross-section, the axes of which are shifted at an angle of 90° or by placing a twisted plate with an expanded initial and end section in the hydraulic channel. Twisted plates can be considered as a simplified version of screw elements. For swirling of the mixed jets, thus, screw, vane and tangential type guide elements can be used.

The additional pressure created by swirling of the working $h_{aw}$ and injected $h_{ae}$ flows is determined respectively by Eqs. (1) and (2) [22]

$$h_{aw} = \frac{\varphi_1^2}{K_p} tg^2 \alpha_w \tag{1}$$

$$h_{ae} = \frac{2\varphi_1^2 i^2 tg^2 \alpha_s \left(1+K_p^{-1}\right)}{(1+K_p^{0.5})^2 \left(K_p - 1\right)}, \tag{2}$$

where $\varphi_1$ – the velocity coefficient of the working nozzle of the jet pump;

$K_p$ – the main geometric parameter of the jet pump;

$a_w$, $a_s$ – the angle of inclination of the guide elements located in the working and injected flows;

$i$ – the injection coefficient of the jet pump.

According to Eqs. (1) and (2), the value of the additional pressure of the jet pump is directly proportional to the swirling angles of the mixed flows. Unlike the additional pressure caused by swirling of the injected flow $h_{ae}$, the value of the additional pressure caused by swirling of the working flow $h_{aw}$ does not depend on the ratio of the flow rates of the injected and working jets.

The effect of flow swirling on the operating characteristics of a jet apparatus is determined by the properties of the swirling jet. The helical movement of the flow occurs due to the superposition of transverse circulation on the translational motion. In addition to the axial velocity, the swirling flow has a radial and rotating component. The degree of flow swirling depends on the ratio of consumption creating the circulation and translational motion. The gradual rotational motion of the flow causes the appearance of inertial centrifugal forces. In this case, the liquid particle is affected by pressure forces (caused by external mechanical action), viscosity forces (as a result of the relative motion of adjacent liquid layers) and mass (inertial) forces. Swirling flows are characterized by significant turbulent pulsations, which cause additional generation of kinetic energy of the pulsating flow. The increase in turbulence of the injected flow contributes to the intensification of the mixing process and a more rapid decrease in its axial velocity. The rotation velocity of the liquid particles in the cylindrical mixing chamber of the jet apparatus changes according to a linear law and takes zero values on the axis. The screw swirled flow has a 3-4 times higher transport capacity than the straight-through flow, and the throughput capacity of a nozzle with flow swirling elements is 25% higher than that of a cylindrical nozzle. The increase in the length of the flow particle trajectory caused by its swirling increases the efficiency of energy exchange in the mixing chamber of the jet pump. When using rectilinear nozzles, the maximum velocity and kinetic energy of the working jet occur in its central part. In the shear flow region, where energy exchange between the active and injected flows occurs, the velocity of the central working flow takes on minimum values, as a result of which the jet pump is determined by insignificant efficiency. The increase in the resulting velocity of the swirled working flow intensifies its energy exchange with the injected medium. The use of guide elements located at the outlet of the active nozzle allows for the action of the swirled working jet to be extended in the radial direction from the axis of the jet apparatus. The radial spread of the active medium in the volume of the mixing chamber increases the surface area of interaction between the working and injected flows. At the same time, the conditions for the transfer of kinetic energy from the active passive medium are improved and the efficiency of the jet apparatus increases.

Simultaneous swirling of the working and injected flows has the following features:

1. The ratio of the rotation velocities of the external and internal flows is not constant, since the rotation velocity of the injected flow depends on the value of the injection coefficient, which is inversely related to the relative pressure of the jet pump.
2. Due to the possibility of forming unfavorable ratios of movement directions of the injected and working flows, the efficiency of simultaneous swirling may be less than the efficiency of swirling one of the flows.

## 3 Methodology of experimental studies of a jet-vortex pump

An experimental study of the working process of a borehole jet pump was carried out on a laboratory setup (Fig. 2), which consists of four models of a jet pump in the form of a working nozzle 1 and a mixing chamber with a diffuser 2, a pressure 3, working 4 and suction 5 collector, pressure 6 and suction 7 lines, a receiving and pressure tank 8, a local flow narrowing 9 (to simulate the hydraulic load created by the drilling bit flushing system), a centrifugal pump 10 with a suction channel 11, flow meters 12, 13, pressure gauges 14–16, and latches 17–19.

Latch 17 allows changing the flow rate of the injected flow, and latches 18 – of the working flow. The use of latches 19 allows us to turn off individual jet pumps for the purpose of personifying them. Latches 17 and 18 allow us to adjust the flow rate of the working and injected flows.

Jet pumps are connected to common pressure, working and suction manifolds. The pressure manifold is connected to the pressure and suction lines. In order to approximate conditions similar to the use of a jet pump in a well,

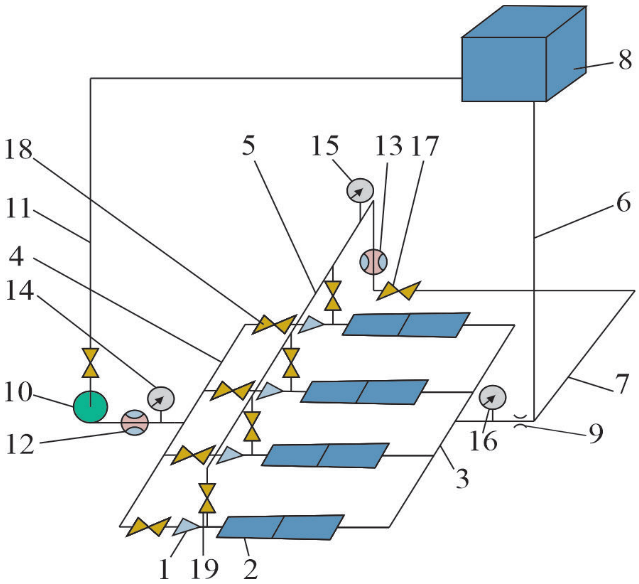

**Fig. 2** Schematic diagram of the laboratory setup: 1 – working nozzle; 2 – mixing chamber with diffuser; 3 – pressure collector; 4 – working collector; 5 – suction collector; 6 – pressure line; 7 – suction line; 8 – tank; 9 – local flow narrowing; 10 – centrifugal pump; 11 – suction channel of the centrifugal pump; 12, 13 – flow meters of working and injected flow; 14, 15, 16 – pressure gauges for measuring the pressure of the working, injected and mixed flows; 17, 18, 19 – adjusting latches

a constant hydrostatic pressure is created in the hydromechanical system of the laboratory setup using a receiving and pressure tank 8, the value of which is determined by the excess of the installation height of the tank 8 over the placement level of the jet pumps. The suction line 7 connects the pressure line 6 with the suction manifold 5. The injection of the working flow is carried out using a centrifugal pump, the suction line of which is connected to the tank 8, and the outlet line is connected to the working manifold 4.

The value of the working flow rate during the study of the pressure characteristic is maintained constant. The change in the flow rate of the injected flow is achieved by adjusting the degree of opening of the latch 17, which changes the hydraulic resistance of the suction line 7 and the operating mode of the jet pump. During the studies, there are determined the experimental values of the flow rate of the working and injected flows and the pressures of the working, injected and mixed flows. The experimental values of the costs are presented in the form of a dimensionless ratio – the flow rate coefficient (Eq. (3)), and the pressure value is used to calculate the relative pressure (Eq. (4)).

$$i = \frac{G_s}{G_w}; \quad (1+i) = \frac{G_w + G_s}{G_w} = \frac{G_m}{G_w} \tag{3}$$

$$\Delta P_m = P_m - P_s; \quad \Delta P_w = P_w - P_s; \quad h = \frac{\Delta P_m}{\Delta P_w} \tag{4}$$

$$K_p = \frac{f_3}{f_w}; \quad K_p - 1 = \frac{f_3 - f_w}{f_w} = \frac{f_s}{f_w}, \tag{5}$$

where $h$ – the relative pressure of the jet pump;

$G_w$, $G_s$, $G_m$ – mass flow rates of the working, injected and mixed flows;

$\Delta P_m$, $\Delta P_w$ – pressure drop created by the jet pump and pressure drop of the working flow;

$P_w$, $P_s$, $P_m$ – pressure values of the working, injected and mixed flows;

$f_w$, $f_s$, $f_3$ – cross-sectional area of the working, injected and mixed flows.

The obtained ratios of the flow rate and pressure make it possible to determine the empirical dependences of the injection coefficient on the Reynolds number of the working flow and the pressure characteristic of the jet pump.

The Reynolds number of the working flow was calculated in accordance with the relationship

$$R_{ew} = \frac{V_w d_w}{\nu}, \tag{6}$$

where $V_w$ – the velocity in the outlet section of the working nozzle;

$d_w$ – the diameter of the working nozzle;

$\nu$ – the kinematic viscosity coefficient of the working medium.

During the study of the working process of ejection systems under conditions of simultaneous swirling of the working and injected flows, high-pressure jet pumps were tested, the ratio of the cross-sectional areas of the mixing chamber and nozzle for which equals $K_p = 3.429$; $K_p = 3.795$. Swirling of the injected flow was performed by a screw auger with an inclination angle of the guide elements $\alpha_s = 45°$ (Fig. 3(a)).

The working flow was swirled by a plate, the initial and final sections of which were rotated by 180° with an average value of the guide surface inclination angle $\alpha_w = 15°$ (Fig. 3(b)).

The study of the features of simultaneous swirling of the working and injected flows was carried out in three stages:

1. Determining the dependence of the injection coefficient on the Reynolds number of the working flow $i = f(R_{ew})$.
2. Studying the pressure characteristic of the jet pump $h = f(i)$.
3. Studying the energy characteristic of the jet pump $\eta = f(i)$.

During the studies, the absolute and relative values of the injection coefficient $i$, pressure $h$ and efficiency $\eta$ of the jet pump were determined. To conduct a comparative analysis, three types of absolute indicators were determined for the following conditions:

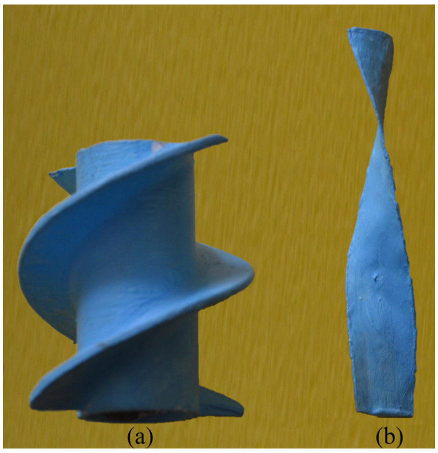

**Fig. 3** Screw elements for swirling the injected (a) and working (b) flows

- no flow swirling;
- swirling of the injected flow;
- simultaneous swirling of the working and injected flows.

When analyzing the relative indicators, two types of curves were determined:

- a change in the injection coefficient $i$, pressure $h$, and efficiency $\eta$ caused by swirling the injected flow compared to the straight-through movement of the liquid in the flow section of the jet pump;
- a change in the above-mentioned values caused by the simultaneous swirling of the injected and working flows compared to its straight-through movement.

## 4 Results of the study of a jet-vortex jet pump

Considering that the pressure of a vortex jet pump is formed as a result of the action of viscous and centrifugal forces, it can be assumed that with an increase in the Reynolds number, the effect of swirling the working flow decreases and the value of the injection coefficient approaches a constant value. The hydraulic resistance of the working nozzle also has a significant effect on the value of the injection coefficient of the jet pump. A typical dependence of the hydraulic resistance coefficient of the nozzles is determined by a descending curve approaching the horizontal with an increase in the Reynolds number. Reducing the hydraulic resistance coefficient reduces energy losses in the working nozzle of the jet pump, as a result of which the efficiency of the mixing process and the value of the injection coefficient increase. After reaching the limiting value, the hydraulic resistance coefficient takes constant values, the value of hydraulic losses becomes unchanged, as a result of which the process of mixing the working and injected flows is stabilized $i = const$. The mutual influence of the values of the injection coefficient and the hydraulic resistance coefficient explains the asymptotic nature of the dependence of the injection coefficient on the Reynolds number of the working flow. Taking into account the physical content of the process of creating pressure by a jet pump for approximating the results of experimental studies, it is advisable to choose an empirical function in the form of a horizontal asymptote, for example, a hyperbolic dependence of the following form

$$y = \frac{x}{b_0 + b_1 x} \quad \text{or} \quad i = \frac{R_e}{b_0 + b_1 R_e}, \tag{7}$$

the empirical coefficients $b_0$, $b_1$ are given in Table 1.

**Table 1** Coefficients of the regression equation for the dependence of the injection coefficient on the Reynolds number of the working flow

| $K_p$ | Value of the coefficients | | | | | |
|---|---|---|---|---|---|---|
| | $b_0$ | | | $b_1$ | | |
| | Angle of twist of mixed flows | | | | | |
| | $\alpha_w = 0$<br>$\alpha_s = 0$ | $\alpha_w = 0$<br>$\alpha_s = 45°$ | $\alpha_w = 15°$<br>$\alpha_s = 45°$ | $\alpha_w = 0$<br>$\alpha_s = 0$ | $\alpha_w = 0$<br>$\alpha_s = 45°$ | $\alpha_w = 15°$<br>$\alpha_s = 45°$ |
| 3.429 | 25934 | 12353 | 4887 | 4.327 | 4.08 | 4.1314 |
| 3.795 | 3878 | 2097 | 2679 | 3.568 | 3.394 | 3.3667 |

Zero swirl angles of the working $\alpha_w = 0$ and injected $\alpha_s = 0$ flows correspond to a straight-through jet pump, the ratio of swirl angles $\alpha_w = 0$; $a_s = 45°$ determines the dependence of the injection coefficient on the Reynolds number of the working flow for the case of swirl of the injected flow only, and the ratio of angles $\alpha_w = 15°$ and $a_s = 45°$ characterizes the simultaneous swirl of both mixed flows.

The experimental characteristics of the straight-through jet pump were determined for a comparative analysis of the study of the mixed flows swirl on the working process of the ejection system.

Empirical formulas obtained from the results of experimental determination of pressure characteristics of the studied models of the jet pump are presented in the form of logarithmic, irrational, rational and algebraic functions and are given in Table 2.

The maximum efficiency of flow swirl in the flow part of the jet pump is determined by comparing the corresponding experimental characteristics and is given in Table 3.

**Table 2** Empirical formulas for determining the pressure characteristics of the jet-vortex pump

| Swirl angle | Empirical formula |
|---|---|
| Geometric parameter $K_p = 3.429$ | |
| $\alpha_w = 0$; $\alpha_s = 0$ | $h = 0.2252 + 0.6297 i^2 \ln i$ |
| $\alpha_w = 0$; $\alpha_s = 45°$ | $\ln h = -14.514 + 10.1045 i + 13.2394 e^i$ |
| $\alpha_w = 15°$; $\alpha_s = 45°$ | $h = \sqrt{0.2005 - 0.131 e^i}$ |
| Geometric parameter $K_p = 3.795$ | |
| $\alpha_w = 0$; $\alpha_s = 0$ | $h = 0.3108 - 0.00304 i^3 - 0.1086 e^i$ |
| $\alpha_w = 0$; $\alpha_s = 45°$ | $h = 0.2388 - 0.8502 i^2$ |
| $\alpha_w = 15°$; $\alpha_s = 45°$ | $h = 4.0786 + 20.9091 i^2$ |

**Table 3** Maximum efficiency of flow swirl in the flow part of a jet pump, %

| Flow swirl characteristic | Injection coefficient | | Relative pressure | | Efficiency | |
|---|---|---|---|---|---|---|
| | Geometric parameter $K_p$ | | | | | |
| | 3.429 | 3.795 | 3.429 | 3.795 | 3.429 | 3.795 |
| $\alpha_w = 0$; $\alpha_s = 45°$ | 19.12 | 8.9 | 19.43 | 17.152 | 11.88 | 21.29 |
| $\alpha_w =15°$; $\alpha_s = 45°$ | 26.34 | 8.073 | 14.7 | 18.76 | 16.07 | 23.75 |

The values of the efficiency coefficient of the jet-vortex pump given in Table 2 are determined by the formula

$$\eta = \frac{hi}{1-h} . \tag{8}$$

The obtained experimental dependencies are shown in Figs. 4 and 5.

The efficiency of swirling of mixed flows is determined by obvious formulas: $\bar{i} = i_n/i_b$; $\bar{h} = h_n/h_b$; $\bar{\eta} = \eta_n/\eta_b$. The indices *b* and *n* refer to the basic and improved values of the parameters under study, respectively.

The increase in the injection coefficient caused by swirling of mixed flows is inversely proportional to the Reynolds number of the working flow, and the dependences of the relative pressure and efficiency on the injection coefficient are of a descending or extreme nature. It is also necessary to note the existence of sections of the experimental characteristics, for which the efficiency of swirling of the exclusively injected flow exceeds the efficiency of simultaneous swirling of both mixed flows.

The features of the change in the obtained dependencies are consistent with the results of studies of the pressure and energy characteristics of low-pressure direct-flow [17] and jet-vortex [22] pumps, the geometric parameter of which is $K_p$ = 5.012 and $K_p$ = 6.464. The analysis of the obtained results indicates the existence of a tendency for the jet pump characteristics to increase due to the simultaneous swirling of the working and injected flows compared to the swirling of the injected flow only.

## 5 Conclusions

The results of experimental studies of the working process of a jet-vortex pump with different values of the main geometric parameter allowed us to formulate the following conclusions:

- the values of the injection coefficient with an increase in the Reynolds number of the working flow approach the horizontal asymptote and can be approximated as an empirical hyperbolic dependence;
- the pressure characteristic of a jet-vortex pump is determined by a descending monotonic nonlinear dependence;
- the energy characteristic of a jet-vortex pump is determined by an increasing nonlinear dependence;
- the maximum increase in the injection coefficient, relative pressure and efficiency of a jet pump caused

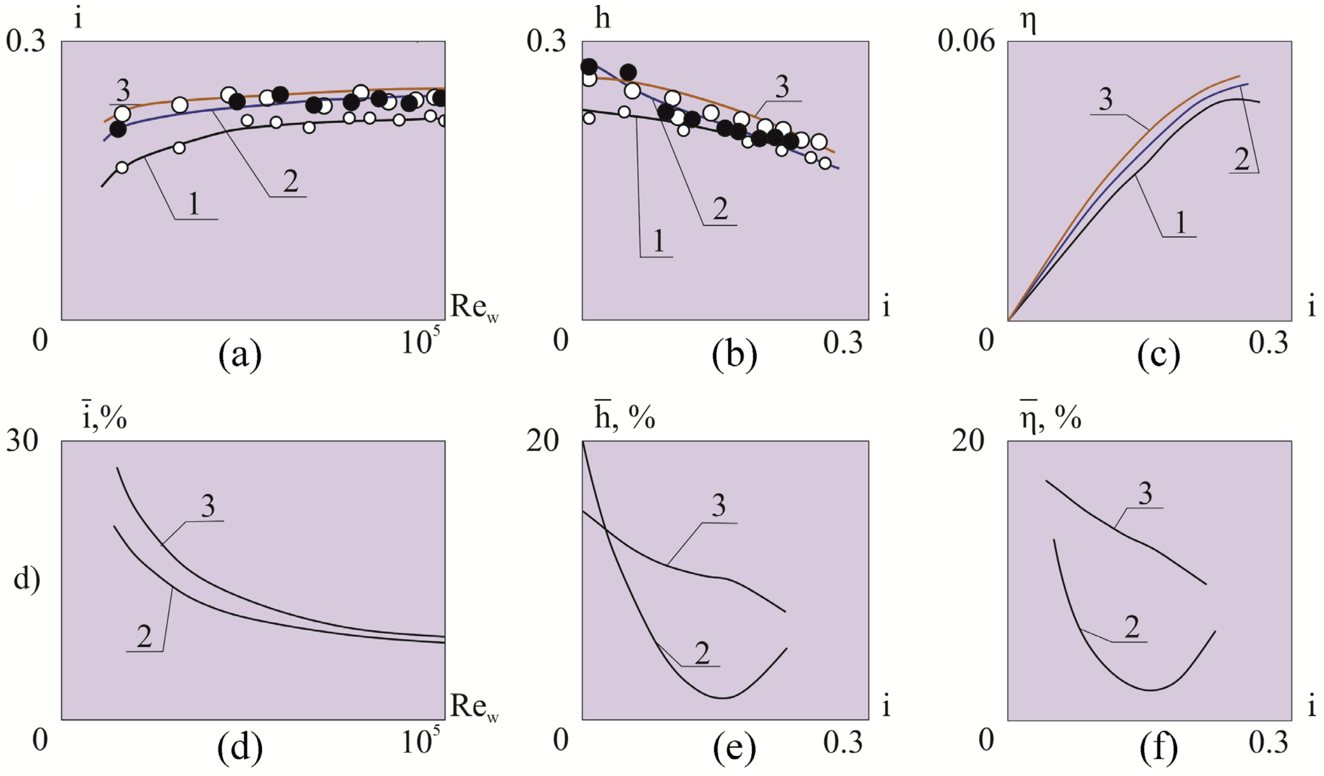

**Fig. 4** (a) Absolute values of the injection coefficient, (b) Absolute values of the relative pressure, (c) Absolute values of the efficiency, (d) Relative values of the injection coefficient, (e) Relative values of the relative pressure and (f) Relative values of the efficiency of a jet pump for the main geometric parameter: $K_p$ = 3.429; where the numbered curves mean: 1 – no flow swirl; 2 – swirl of the injected flow; 3 – simultaneous swirl of the working and injected flows

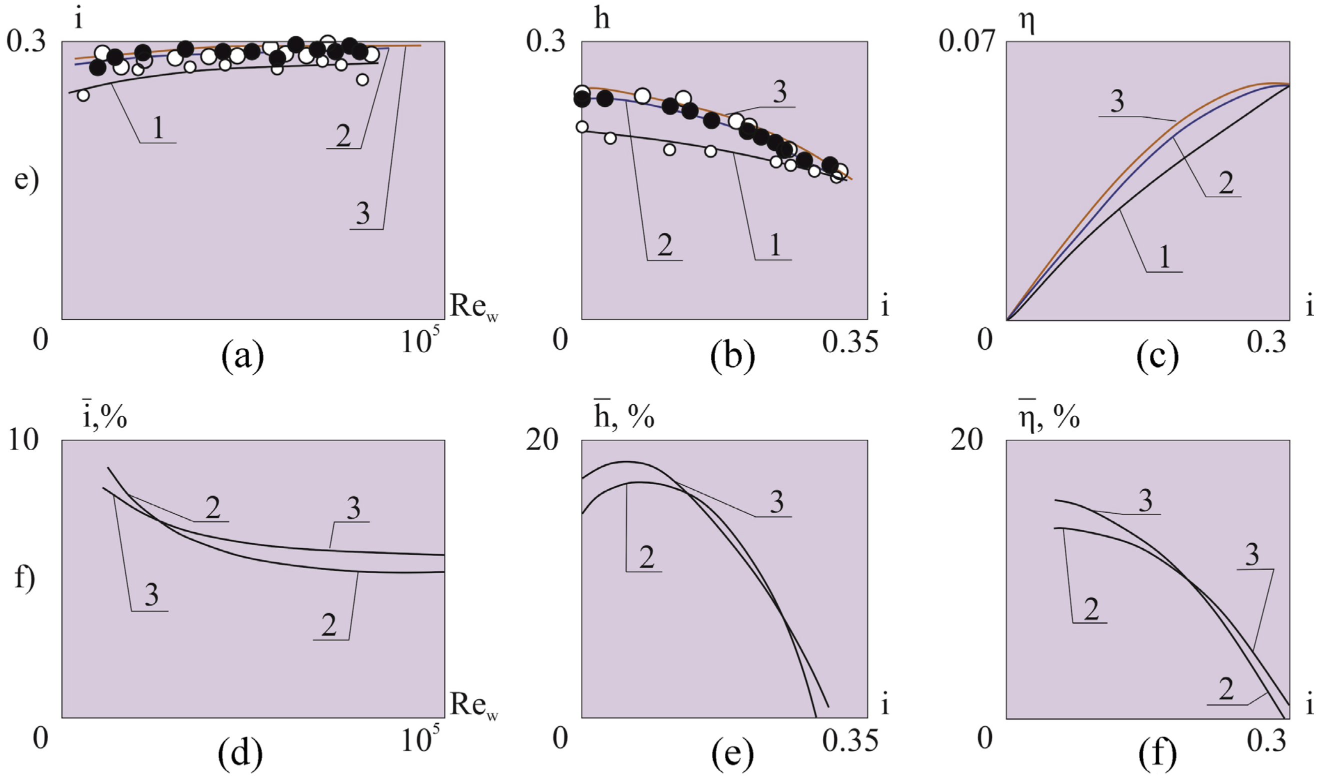

**Fig. 5** (a) Absolute values of the injection coefficient, (b) Absolute values of the relative pressure, (c) Absolute values of the efficiency, (d) Relative values of the injection coefficient, (e) Relative values of the relative pressure and (f) Relative values of the efficiency of a jet pump for the main geometric parameter: $K_p = 3.795$; where the numbered curves mean: 1 – no flow swirl; 2 – swirl of the injected flow; 3 – simultaneous swirl of the working and injected flows

by swirling of the mixed media corresponds to the region of small Reynolds numbers;

- the efficiency of simultaneous swirling of the working and injected flows, taking into account the possibility of formation of unfavorable ratios of the directions of their movement, may be less than the efficiency of swirling of one of the flows;
- the maximum efficiency of simultaneous swirling of the working and injected flows obtained during experimental studies is: for the injection coefficient –26.34%; for the relative pressure –19.43%; for the efficiency –23.75%.

The task of further research is to develop a computer model of the working process of the jet-vortex pump.

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