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Mathematical model of the ejection system working process during the rotation of the jet pump in the well

Model matematyczny procesu pracy układu wyrzutowego podczas obrotu pompy strumieniowej w otworze

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ABSTRACT: A mathematical model of an above-bit jet pump has been developed for the conditions of its rotation in a well, based on the use of hydrodynamic functions of a complex variable. These functions take the form of a sum of partial solutions of differential equations describing the potential motion of radial, circulation and homogeneous flows. The working flow is considered as a leak for a stationary jet pump or as a vortex in the case of rotation. The injected flow corresponds to a homogeneous one. The mixed flow is assessed in accordance with the principle of superposition by summing the complex potentials of elementary flows. The complex potential of the total flow determines the velocity field in the mixing chamber of the jet pump and allows us to set the configuration of the zero flow line, which separates the working and injected flows. In the process of integrating the velocity profile, the coefficient of uneven distribution of kinematic parameters is assessed, the value of which is included in the structure of the equation for the pressure characteristic of the jet pump and determines the effect of circulation flows on the working process of the ejection system. It has been established that the maximum velocity of the symmetrical rotation of the jet pump in the well increases the generated pressure and efficiency by 7.79% and 9.57%, respectively. Using the experimental head characteristic of the jet pump, obtained for the case of simultaneous swirling of the working and injected flows by the guide elements, the value of the relative head corresponding to the same rotation velocity of the mixed media has been assessed. The investigated values of the relative head pressure are used to verify the adequacy of the developed mathematical model of the ejection system for the rotation of the jet pump in the well. The maximum discrepancy between the theoretical and experimental values of the relative head pressure of the jet pump is 3.64%.

Key words: above-bit jet pump, potential flows, hydrodynamic functions, complex potential, velocity profile.

STRESZCZENIE: Opracowano model matematyczny pompy strumieniowej umieszczonej nad świdrem dla warunków jego obrotu w odwiercie, oparty na wykorzystaniu funkcji hydrodynamicznych zmiennej zespolonej. Funkcje te mają postać sumy cząstkowych rozwiązań równań różniczkowych opisujących potencjalny ruch przepływów promieniowych, cyrkulacyjnych i jednorodnych. Przepływ roboczy jest traktowany jako wyciek w przypadku stacjonarnej pompy strumieniowej lub jako wir w przypadku rotacji. Przepływ wynikający z tłoczenia odpowiada przepływowi jednorodnemu. Przepływ mieszany jest szacowany zgodnie z zasadą superpozycji poprzez sumowanie potencjałów złożonych przepływów elementarnych. Złożony potencjał całkowitego przepływu określa pole prędkości w komorze mieszania pompy strumieniowej i pozwala ustawić konfigurację zerowej linii przepływu, która oddziela przepływ roboczy od wynikającego z tłoczenia. W procesie całkowania profilu prędkości oceniany jest współczynnik nierównomiernego rozkładu parametrów kinematycznych, którego wartość jest uwzględniana w strukturze równania charakterystyki ciśnieniowej pompy strumieniowej i określa wpływ przepływów cyrkulacyjnych na proces roboczy układu wypływowego. Ustalono, że maksymalna prędkość symetrycznego obrotu pompy strumieniowej w odwiercie zwiększa generowane ciśnienie i wydajność odpowiednio o 7,79% i 9,57%. Wykorzystując eksperymentalną charakterystykę podnoszenia pompy strumieniowej, uzyskaną dla przypadku jednoczesnego zawirowania przepływu roboczego i tłoczonego przez elementy prowadzące, oszacowano wartość względnej głowicy odpowiadającej tej samej prędkości obrotowej mieszanego materiału. Analizowane wartości względnego ciśnienia zostały wykorzystane do sprawdzenia adekwatności opracowanego modelu matematycznego układu wypływowego w odniesieniu do obrotów pompy strumieniowej w odwiercie. Maksymalna rozbieżność między teoretycznymi i eksperymentalnymi wartościami względnego ciśnienia pompy strumieniowej wynosi 3,64%.

Słowa kluczowe: pompa strumieniowa umieszczona powyżej świdra, przepływy potencjalne, funkcje hydrodynamiczne, potencjał złożony, profil prędkości.

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Introduction

The complexity of conditions for the construction of production wells has led to the development of non-traditional drilling technologies. One such technology aimed at improving the efficiency of drilling oil and gas wells is the use of downhole jet pumps. The industrial use of jet pumps in drilling began in the 1950s. In 1955, the Standard Oil Co. (Eckel et al., 1955) funded the development of a new fractional jet pump drilling method that optimized the cost of well construction using this technique. Over the next almost 20 years, the technology of using jet pumps in drilling was improved. In the early 1970s, jet pump technology for drilling was brought to commercial use (Hughes, 2014). The creation of backwashing of the bottomhole when using jet pumps for core drilling made it possible to increase the efficiency of the core recovery. The use of suction and injection-suction ejection systems can reduce the pressure in the bottomhole zone of the well by 0.45 MPa and 0.2 MPa, respectively (Zhu and Liu, 2015). Reducing the differential pressure in the well improves the operating conditions of the bit at the bottomhole (Zhu et al., 2012), increases the ROP by up to 40% (Zhu et al., 2014), and the passage of the bit by 30% (Cholet, 1978), reduces the intensity of flushing solution in the process of opening productive horizons with abnormally low reservoir pressure. The use of jet pumps in horizontal wells intensifies the process of bottomhole cleaning from cuttings (Chen et al., 2016). Optimization of the geometric dimensions of the ejection system makes it possible to obtain a simultaneous increase in the quality of bottomhole cleaning and a decrease in differential pressure in horizontal and deviated wells (Chen et al., 2020).

The next stage in the development of technology for the use of downhole jet pumps resulted from the need to increase the efficiency of the initial opening of the productive horizon. The pressure drop when using a jet pump prevents the penetration of drilling filtrate into the productive horizon, preventing its contamination. This results in an increase in well flow rate and volumes of withdrawn oil and a decrease in field development costs. An alternative option to reduce bottomhole hydrostatic pressure during "balanced" drilling is to reduce the density of the drilling fluid by aerating it or using foams (Khalid et al., 2020). The decrease in pressure in the well can also be achieved by blowing it in the process of opening the productive horizon (Djuraev et al., 2020). The advantage of using the jet pump is pressure reduction directly in the bottomhole zone while maintaining its value along the entire length of the well. After the cessation of flushing the well, the hydrostatic pressure action is instantly resumed, as a result of which the risk of uncontrolled oil and gas manifestations is reduced.

The efficiency of using downhole ejection systems is determined by the choice of the optimal mode of the jet pump operation. The operating mode of a jet pump is determined (Suryanarayana et al., 2004) by its design, installation scheme in the well, type of associated equipment, hydrodynamic parameters, and physical properties of the flushing fluid. Predicting the operating mode of a jet pump involves the development of a mathematical model of the working process. The most common mathematical model of the workflow is based on the application of the laws for conservation in fluid dynamics and energy in the jet pump mixing chamber (Kumar et al., 2019). The mentioned laws implement the one-dimensional theory of flow mixing, which does not allow for taking into account the rotational motion of the jet pump in the well. Modelling the workflow of dual-loop ejection systems requires a lot of application of the calculation features of ring hydraulic networks (Wyrostkiewicz and Panevnyk, 2022). The two-dimensional fluid motion is described by the Navier-Stokes differential equations and makes it possible to take into account the presence of shear flows with a significant difference in the velocities of the mixed flows (Yong et al., 2016). The addition of the basic laws of hydrodynamics with certain provisions of the theory of helical flows made it possible to take into account the rotation of the working (Guillaume and Judge, 2003) and injected (Panevnyk, 2021) mediums by guide elements installed in the flow part of the jet pump. It should be noted that swirling the flow with guide elements increases the injection capacity of the jet pump, but reduces the efficiency (Wittrisch and Trapy, 2003). The tangential supply of the injected flow in the design of the jet-vortex pumps (Shrestha and Choi, 2022) provides the maximum impact on the performance of the ejection system. The efficiency of a jet-vortex pump is almost twice that of a direct-flow ejection system (Rogovyi and Lukianets, 2022). The effect of the tangential supply of the injected flow on the characteristics of the ejection system is preserved when using multi-nozzle jet pumps (Morrall et al., 2018).

In relation to downhole jet pumps, it is possible to distinguish between local and general flow swirling. Local swirling of the flow is achieved using guide elements. Under the action of viscous forces, the flow structure changes along the length of the hydraulic channel, and its rotational motion is retarded. The transformation of the hydrodynamic structure of the flow is completed at a certain distance from the place of its swirl when the helical flow lines turn into straight ones. Total swirl of the flow is produced by the rotation of the jet pump in the well with a drill or tubing string. In this case, dissipative forces do not reduce the degree of flow swirl. Unlike local swirling of the flow, the mechanism for mixing working media under the conditions of rotation of downhole jet pumps elements has not been studied enough. As a result of the drill string rotation, the near-bit ejection system additionally acquires features that characterize dynamic pumps. The occurrence of circulation flows in the flow part of the jet pump, the trajectory of which is located in perpendicular planes of the well axis, changes the type of pressure, energy, and cavitation characteristics of the ejection system. Modern mathematical models of the working process of the above-bit jet pump do not take into account the possibility of its rotation in the well, as a result of which the accuracy of predicting the regime parameters of the ejection system decreases, the energy characteristics decrease and the probability of its operation in the cavitation mode increases.

The aim of the study is the development and experimental verification of a mathematical model of the working process of a jet pump, taking into account the peculiarities of its rotation in the well.

Table 1. Characteristic features of the use of above-bit jet pumps

Tabela 1. Charakterystyczne cechy zastosowania pomp strumieniowych z wypływem powyżej świdra

Feature of use	Type of ejection system		
	Suction	Discharge	Discharge – suction
Nature of the pump connection	consistent	consistent	parallel
Type of bottomhole hydraulic system	single circuit	single circuit	double circuit
Downhole stream name	suction	mixed	working
Nature of the bottomhole washing	reverse	direct	combined
Downhole consumption	$Q_b = Q_w i$	$Q_b = Q_w(i + 1)$	$Q_b = aQ_w$

Table shows: Q_b – the flow rate of the flushing solution at the bottom; i – coefficient of injection of the jet pump (the ratio of the flows of the injected Q_e and working Q_w streams, $i = Q_e / Q_w$), a – the share of the performance of the mud pump ($a < 1$)).

Downhole ejection system design

Today, three main types of designs of near-bit ejection systems are commonly used (Figure 1): suction, discharge, and discharge-suction. The main elements of these systems are the working nozzle and the mixing chamber of the jet pump. Additionally, ejection systems that consist of a combination of injection and injection-suction jet pumps in one near-bit configuration exist (Kryzhanivskyi and Panevnyk, 2020).

Suction ejection systems are mainly intended for drilling with core selection. The creation of local backwashing of the hole allows the use of suction ejection systems as part of the devices for cleaning the hole. Injection ejection systems make it possible to significantly intensify the washing of the wellbore with the constant performance of the drilling pump. Pump-suction ejection systems create direct flushing of the bottomhole and reverse flushing of the near-bit area. The designs of above-bit ejection systems determine the characteristics of their use (Table 1).

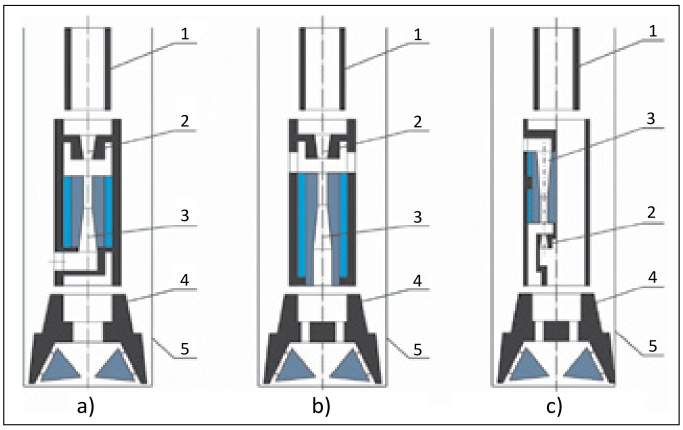

Figure 1. Schematic diagrams of the suction (a), discharge (b) and discharge-suction (c) near-bit ejection system: 1 – drill string; 2 – the working nozzle of the jet pump; 3 – mixing chamber with jet pump diffuser; 4 – drill bit; 5 – well wall (casing column)

Rysunek 1. Schematy układu ssącego (a), tłoczącego (b) i tłocząco-ssącego (c) w pobliżu świdra: 1 – przewód wiertniczy; 2 – dysza robocza pompy strumieniowej; 3 – komora mieszania z dyfuzorem pompy strumieniowej; 4 – świder wiertniczy; 5 – ściana odwiertu (kolumna rur okładzinowych)

The conducted studies have established that the maximum flow rate at the bottom of the well is ensured by the use of above-bit injection ejection systems, and the maximum pressure reduction at the bottom of the well is provided by injection--suction systems.

As a result of the rotation of the near-bit jet pump during drilling, the mixed flows receive additional energy of external origin. The rotation of the ejection system thus causes the jet pump to generate additional pressure.

Determining the characteristics of the jet pump for the conditions of its rotation in the well

In the process of analysing the experience of using near-bit ejection systems, it has been found that the minimum error in the theoretical determination of the pressure of a jet pump occurs when the law for the conservation of momentum in fluid dynamics is used to derive the equation for its pressure characteristic. The mentioned mathematical model is taken as a basis for modelling the working process of a jet pump rotating in a well. The relative rotation of the ejection system changes the velocity profile of the flows in the mixing chamber of the jet pump. As a result of the action of centrifugal forces during rotation, the boundary between the external injected and internal working flows is shifted in the direction of the axis of symmetry of the jet pump, while the velocity of the liquid increases in the peripheral sections located near the walls of the mixing chamber. The velocity profile becomes more uniform, resulting in an increase in the flow rate and pressure of the mixed flow. The most common hydraulic model of the jet pump working process takes into account the uneven distribution of velocities in the mixing chamber using the velocity factor φ. This coefficient can be defined as the ratio of the average and maximum flow rates (Kryzhanivskyi and Panevnyk, 2019). The study of the influence of the rotational velocity of the ejection system on its characteristics, therefore, is reduced to determining the influence of this parameter on the change in the value of the flow velocity coefficient in the mixing chamber of the jet pump.

According to the mechanism proposed by the author regarding the influence of rotation of the ejection system on the characteristics of the jet pump, we believe that the alignment of the velocity profile is equivalent to the transfer of kinetic energy by the circulation flow to the external injected flow. A comparative analysis of the velocity profiles in the mixing chamber for the case of rotation and for a stationary ejection system makes it possible to determine the effect of the circulation flow on the characteristics of the jet pump. The mathematical model of the flow mixing proposed by the author is based on the use of hydrodynamic functions of a complex variable in the form of a sum of partial solutions of differential equations of the potential motion of radial, circulating, and homogeneous flows. According to the proposed model (Figure 2), the working flow of a jet pump symmetrically placed in the well is considered as a leak and is determined by the radial function of a complex variable $W(Z)_r$.

In the case of a stationary ejection system, the working flow has the form of a radial flow (position 1 in Figure 2a). The rotation of the flow is modelled as a circulation flow, which is created by a vortex and is determined by the complex potential in the form of a vortex function $W(Z)_c$. For jet pump rotation conditions, the working flow is formed by a radial circulation (position 2 in Figure 2a II) flow. The injected (external) flow corresponds to a homogeneous flow 3 and is determined by the complex potential of the rectilinear flow $W(Z)_o$. The mixed flow, given the superposition principle is determined by summing the complex potentials of individual flows $W(Z)_{r-c-o} = W(Z)_r + W(Z)_c + W(Z)_o$. The separation boundary of the injected and working flows 4 (Figure 2b), separating the homogeneous flow from the radial (Figure 2b-I) or radial circulation (Figure 2b-II) flow, due to the action of inertia forces during the rotation of the working flow, is shifted in the direction of mixing chamber walls. At the same time, the area of the velocity diagram, the average velocity of the mixed flow, and the value of the non-uniformity coefficient increase.

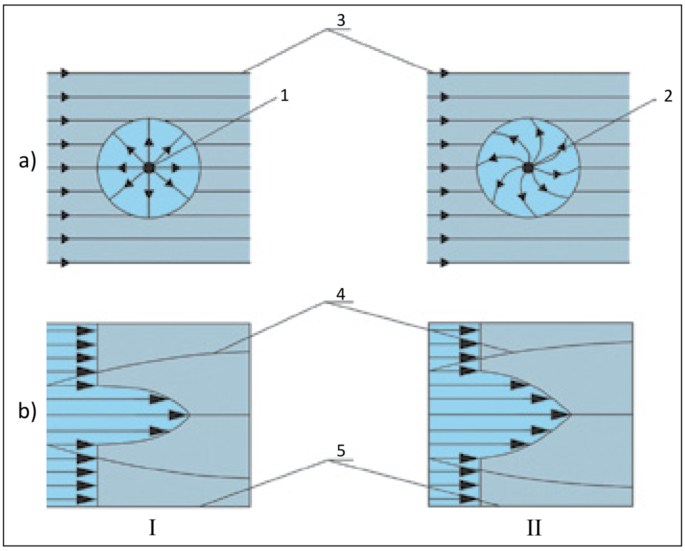

Figure 2. Statement of the research problem: a) flow around a leak (I) and a vortex source (II) with a uniform flow; b) velocity profiles of radially homogeneous (I) and radially circulating homogeneous (II) mixed flow: 1 – leakage; 2 – vortex; 3 – uniform flow; 4 – borders of flow delimitation; 5 – mixing chamber wall

Rysunek 2. Określenie problemu badawczego: a) przepływ wokół wycieku (I) i źródła wirów (II) przy przepływie jednorodnym; b) profile prędkości przepływu radialno jednorodnego (I) i radialno cyrkulacyjnego jednorodnego (II) przepływu mieszanego: 1 – wyciek; 2 – wir; 3 – przepływ jednorodny; 4 – wyznaczone granice przepływu; 5 – ściana komory mieszania

The research task can thus be reduced to the search for the boundaries of the delimitation of the injected and working flows and the integration of the velocity profile.

The value of the complex potential $W(Z)_{r-c-o}$ makes it possible to determine the velocity field in the flow path of the jet pump and calculate the velocity coefficient φ, which is part of the initial equation of the basic technique for determining the characteristics of the ejection system. In contrast to the basic technique, the coefficient φ allows, by using the vortex function, to take into account the rotation of the flow. The combination of partial solutions of the differential equations of elementary flows' motion makes it possible to establish the structure of the mixed flow function, to investigate its kinematics, and to reveal the patterns of change in the pressure and energy characteristics of the jet pump under conditions of its symmetrical rotation in the well.

Let us consider the nature of the mutual orientation of the flow lines, which arises when a homogeneous flow is superimposed on a radially circulating flow. In a uniform flow that moves with a velocity V_e in the direction from left to right (Figure 3), in the centre of the cylindrical coordinate system (point 0) there is a vortex with a flow rate Q.

The vortex generates the flow, the velocity of which is V_w. Let us determine the position of the flow line separating the internal working flow from the external injected flow. A stream

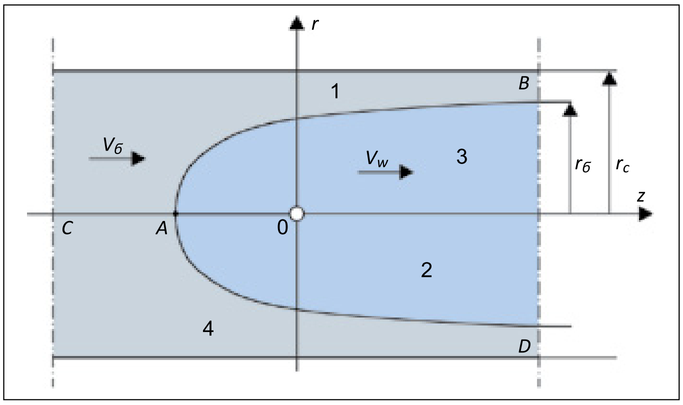

Figure 3. Superposition of a uniform flow on a radial circulation flow: 1 – external (injected) flow; 2 – internal (working) flow; 3 – delimitation line of flows; 4 – mixing chamber

Rysunek 3. Superpozycja jednorodnego przepływu na radialny przepływ cyrkulacyjny: 1 – przepływ zewnętrzny (tłoczony); 2 – przepływ wewnętrzny (roboczy); 3 – linia rozgraniczająca przepływy; 4 – komora mieszania

of internal working flow leaving point 0 and moving in a horizontal direction from the left encounters an oppositely directed stream of a uniform flow. Given that the fluid velocity in a uniform flow is constant at all points, and the velocity in the internal field decreases with distance from the vortex current, then there should be a point to the left of the coordinate centre (point A in Figure 3), for which these velocities will be the same in magnitude. The flow line *CA* emanates from infinity and at point *A* branches into the flow lines *AB* and *AD*. Since the flow velocity should not have discontinuities in direction at the branching point (point *A*), this point is critical and the velocity at it equals zero. The configuration of the flow line passing through the critical point of the combined flow is determined by the type of the characteristic function of the potential flow.

In the process of determining the structure of the characteristic function equation, we take into account that the sum of partial solutions of the Laplace equation, as a result of linearity, is also its solution. The complex potential of the combined flow is defined (Prandtl, 2020) as follows:

$$W(z) = \varphi(z,r) + \psi(z,r) \qquad (1)$$

where:

$\varphi(z,r)$ – the potential of velocities at a point of liquid with coordinates z, r,

$\psi(z,r)$ – the flow function at a fluid point with coordinates z, r.

Then, using the relation for the velocity potential and flow functions of radial, circulating and homogeneous flows (Prandtl, 2020), we obtain the characteristic function equation with a symmetrical placement of leakage and vortex:

$$W(z) = \left(-\frac{Q}{4\pi}\frac{1}{\sqrt{z^2+r^2}} + \frac{\Gamma}{4\pi}\operatorname{arctg}\frac{r}{z} + V_5 z \right) - \\ -i\left(\frac{Q}{4\pi}\frac{z}{\sqrt{z^2+r^2}} + \frac{\Gamma}{4\pi}\sqrt{z^2+r^2} - \frac{1}{2}V_5 r^2 \right) \qquad (2)$$

where: Γ is the circulation of the vector of the translational velocity of the fluid in a closed loop.

The expressions in parentheses of equation (2) are obtained by algebraic summation of the velocity potentials and flow functions of radial, circulating, and homogeneous flows and, accordingly, determine the velocity potential and flow function of the mixed flow.

The function $W(z) = \varphi + i\psi$ is determined up to a constant component, which can be chosen so that $W(z)$ is equal to zero at point *A*. Then at this point, the velocity potential is equal to zero $\varphi = 0$, and the flow function is equal to zero $\psi = 0$ not only at this point, but also along the entire *BAD* branched flow line. For a symmetrical placement of the vortex, taking into account the characteristic function (2), we write the equation of the *BAD* flow line:

$$\psi = -\frac{Q}{4\pi}\frac{z}{\sqrt{z^2+r^2}} - \frac{\Gamma}{4\pi}\sqrt{z^2+r^2} + \frac{1}{2}V_\infty r^2 = 0 \qquad (3)$$

After making substitutions:

$$Q = Q_w,\; z = l_w,\; \Gamma = 2\omega S = \pi^2 n d_c^2;$$

$$V_e = V_\infty = \frac{Q_e}{\pi(r_c^2 - r_i^2)},\; r = r_i$$

where:

l_w – the distance between the working nozzle and the mixing chamber of the jet pump,

ω – the angular velocity of the relative rotation of liquid particles,

S – the area of the liquid circulation circuit,

n – the frequency of rotation of the drill string,

d_c – the shear chamber diameter.

We obtain the equation that determines the position of the flow line:

$$\frac{Q_w}{4\pi}\frac{l_w}{\sqrt{l_w^2+r_i^2}} + \pi n r_c^2\sqrt{l_w^2+r_i^2} - \frac{Q_e r_i^2}{2\pi(r_c^2 - r_i^2)} = 0 \qquad (4)$$

The solution of equation (4) with respect to the parameter makes it possible to determine the configuration of the zero flow line and construct the velocity profile of the mixed flow (Figure 4).

Let us analyse the velocity field for a two-layer mixed flow structure rates (Kryzhanivskyi and Panevnyk, 2019):

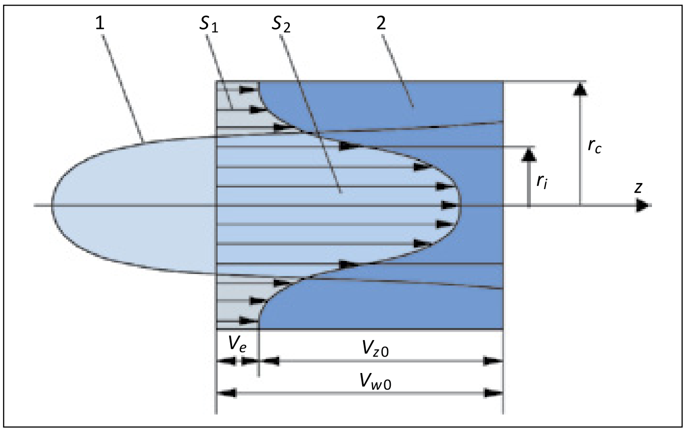

Figure 4. Mixed flow velocity profile: 1 – working jet limit; 2 – mixing chamber

Rysunek 4. Profil prędkości przepływu mieszanego: 1 – granica strumienia roboczego; 2 – komora mieszania

$$S_1 : r_c \le r \le r_i, \quad V = V_e$$
$$S_2 : 0 \le r \le r_i, \quad V = V_e + V(r)\Delta V \tag{5}$$

$$V(r) = 1 - \eta^3, \quad \eta = \frac{r}{r_i}, \quad \Delta V = V_{w0} - V_e \tag{6}$$

where:

$V(r)$ – the velocity profile accepted in the region S_2,

ΔV – the difference between the velocities of the working and injected flows,

η – a dimensionless parameter determined by the ratio of the current radius and the jet radius,

V_{w0} – the maximum velocity of the working flow.

The coefficient of uneven distribution of velocities is determined by the formula rates (Kryzhanivskyi and Panevnyk, 2019):

$$\varphi = \frac{V_a}{V_{w0}} = \frac{V_a}{V_e + V_{z0}} \tag{7}$$

where: V_a – the average velocity of the mixed flow.

The average mixed flow velocity V_a is determined by integrating the velocity profile (Figure 4) using formulas (5), and (6).

Let us define other components of equation (7). The maximum value of the horizontal component of the radial flow velocity (Prandtl, 2020) takes place on the axis of the mixing chamber:

$$V_z = V_{z0} = \frac{Q_w}{4\pi l_w^2} \tag{8}$$

The rate of a homogeneous (injected) flow V_e is determined by the obvious relation (Prandtl, 2020)

$$V_e = \frac{Q_e}{\pi (r_c{}^2 - r_i{}^2)} \tag{9}$$

Then, using the relation to determine the jet pump injection coefficient $i = Q_e/Q_w$, the equation for determining the coefficient of uneven distribution of velocities takes the following form:

$$\varphi = 0.6 \left(\frac{r_i}{r_c} \right)^2 \left[1 + \frac{0.667}{1 + \dfrac{r_c^2 - r_i^2}{4 l_w^2 i}} \left(1 + 2.5 \frac{r_c^2 - r_i^2}{r_i^2} \right) \right] \tag{10}$$

Let us determine the influence of the presence of circulation currents on the working process of the jet pump by comparing the characteristics of the mobile and stationary ejection systems.

The head characteristic of a jet pump is determined (Sokolov and Zinger, 1989) by the formula:

$$h = \frac{\varphi_1^2}{K_p} \left[2\varphi_2 + \left(2\varphi_2 - \frac{1}{\varphi_4^2} \right) \frac{i^2}{K_p - 1} - (2 - \varphi_3^2) \frac{(1+i)^2}{K_p} \right] \tag{11}$$

where:

h – the average velocity of the mixed flow,

φ_1, φ_2, φ_3, φ_4 – the velocity coefficients in the characteristic sections of the jet pump,

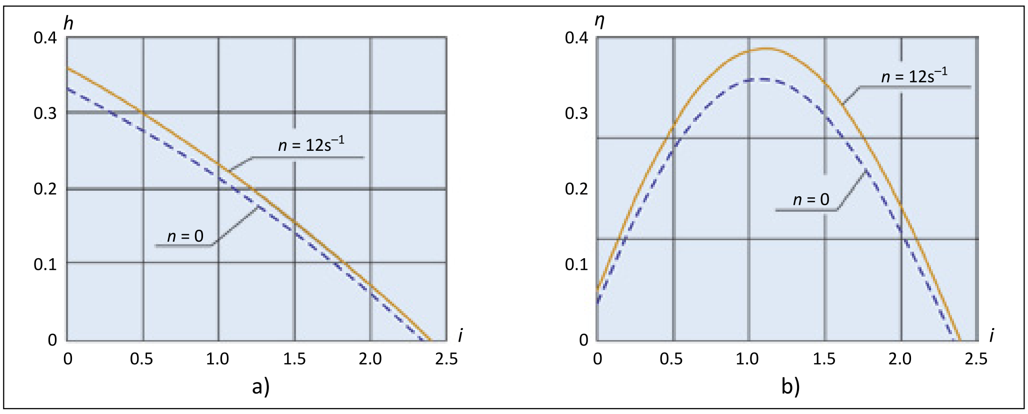

Figure 5. Dependence of pressure (a) and efficiency (b) on the injection coefficient of the jet pump

Rysunek 5. Zależność ciśnienia (a) i wydajności (b) od współczynnika tłoczenia pompy strumieniowej

K_p – the ratio of the cross-sectional areas of the mixing chamber and the working nozzle.

The impact of the drill string rotation is determined by the value of the coefficient, which is included in the equation (11) of the jet pump characteristic and is calculated by the formula (10) (where $\varphi = \varphi_2$).

The pressure characteristic of the jet pump is transformed into its energy characteristic through the ratio (Sokolov and Zinger, 1989):

$$\eta = \frac{hi}{1-h} \quad (12)$$

where: η – a jet pump`s efficiency.

The pressure characteristics of a jet pump with geometric parameter $K_p = 4$ are shown in Figure 5.

The solid line shows the dependence for the rotation frequency of the jet pump $n = 12\ s^{-1}$, and the dashed line shows the dependence for the stationary pump. The comparative analysis of the pressure characteristics shows an increase in the pressure of the jet pump caused by the rotation of the drill string, which is explained by the additional effect on the injected flow of centrifugal forces. According to the calculations, the maximum increase in the relative pressure and efficiency of the jet pump are 7.79% and 9.57%, respectively.

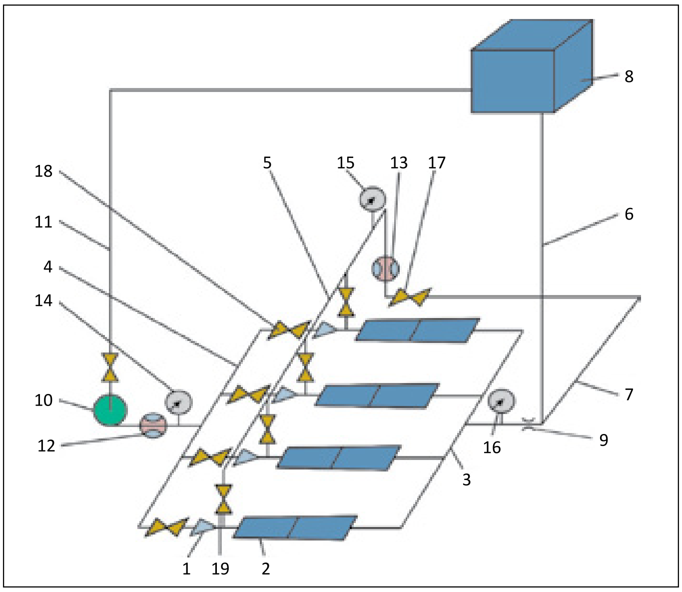

Figure 6. Scheme of a laboratory setup for the study of a jet pump

Rysunek 6. Schemat stanowiska laboratoryjnego do badania pompy strumieniowej

Experimental verification of the jet pump characteristics for the conditions of its rotation in the well

The complexity of modelling the conditions corresponding to the rotation of the jet pump in the well lies in the need to use movable joints in the design of the laboratory installation. This allows the rotation of individual structural elements and, at the same time, ensures the tightness of the supply of the working and injected flows and the removal of a mixed one. In addition, it becomes difficult to measure pressures and flows in characteristic sections of the ejection system. The rotation of individual parts of the laboratory bench requires the creation of stationary sections of pipelines, which include flow meters or elements that ensure the connection of pressure gauges. The presence of such areas greatly complicates the construction of a laboratory stand. The difficulty of reproducing the circumstances of the rotation of a jet pump in laboratory conditions requires the use of indirect methods of studying the influence of circulation flows on the characteristics of the ejection system.

Let us determine the main difference between the nature of the interaction of circulation flows for the case of jet pump rotation and the simultaneous swirling of the working and injected flows. In the process of simultaneous swirling, the rotational velocity of the working flow remains unchanged, and the value of the rotational velocity of the injected flow is directly proportional to the value of the injection coefficient and the flow rate of the injected flow. By comparing the dependence of the rotational velocity of the injected flow on the injection coefficient $\omega_e = f(i)$ with a constant rotational velocity of the working flow ω_w, it is obviously possible to determine the value of the injection coefficient, which would ensure the equality of the angular velocities of the external and internal flows $\omega_e = \omega_w$. This circumstance determines the possibility of the existence of an indirect method for studying the characteristics of a jet pump for its rotation in a well. The layout of a laboratory setup consisting of four jet pump models is described in detail in (Wyrostkiewicz and Panevnyk, 2022).

The composition of the laboratory installation includes a working nozzle 1, a mixing chamber with a diffuser 2 of a jet pump, pressure 3, working 4, and suction 5 collectors, pressure 6 and suction lines 7, tank 8, local flow constriction 9 (for simulation hydraulic load), centrifugal pump 10, suction channel 11, flow meters 12, 13, pressure gauges 14–16 and valves 17–19.

In the course of an experimental study of a jet pump at the outlet of the diffuser, the pressure of the mixed flow P_m is determined, the pressure of the working flow P_w is measured in front of the working nozzle, and the pressure of the injected flow P_e is measured in the suction manifold. The flow rate of the working Q_w and injected flow Q_e is determined according to the readings of the flow meters 12, 13. Mode of operation of the jet pump is changed by adjusting the degree of opening of the latch 17 while maintaining a constant flow rate of the working flow. The value of pressures and flow rates in the characteristic sections of the jet pump is presented in relative form (Sokolov and Zinger, 1989):

$$h = \frac{P_m - P_e}{P_w - P_e},\ i = \frac{Q_e}{Q_w}$$

and we build a pressure $h = (i)$ and energy $\eta = (i)$ characteristic.

In the process of conducting experimental studies, four models of jet pumps are used, the geometric dimensions of which are shown in Table 2. Taking into account the developed indirect research method, guiding elements with different flow swirling angles were installed on the path of the working and injected medium (Table 3).

Table 2. Geometric dimensions of jet pump models

Tabela 2. Wymiary geometryczne modeli pomp strumieniowych

No.	Nozzle diameter, d_w [mm]	Geometric parameter, K_p	Distance to the mixing chamber		Relative mixing chamber length, $\overline{l_c}$
			absolute, l_w [mm]	relative, $\overline{l_w}$	
1	5.9	6.464	9.0	1.53	20.3
2	8.1	3.429	10.0	1.23	14.8
3	6.7	5.012	7.0	1.04	17.9
4	7.7	3.795	7.0	0.91	15.6

Note:

1. The diameter and length of the mixing chamber for all models are 15 mm and 120 mm, respectively.
2. The relative length of the mixing chamber is calculated as the ratio of its absolute length and the diameter of the working nozzle $\overline{l_c} = l_c / d_w$.

Table 3. Values of the swirl angles of the working and injected flows

Tabela 3. Wartości kątów zawirowania przepływu roboczego i tłoczonego

No.	Geometric parameter, K_p	Flow swirl angle [deg.]	
		working, α_w	injected, α_e
1.	6.464	6	70
2.	3.429	8	70
3.	5.012	6	70
4.	3.795	8	70

Let us determine the value of the injection coefficient, which ensures the equality of the rotation velocities of the working and injected flow $\omega_e = \omega_w$. For the workflow, we write the obvious relations (Panevnyk, 2021):

$$V = \frac{V_0}{\cos\alpha_w},\ V = \frac{V_\theta}{\sin\alpha_w},\ V_0 = \frac{4Q_w}{\pi d_w^2},\ V_\theta = \omega_w \frac{d_w}{2} \quad (13)$$

where:

V – the swirling flow velocity,

V_θ, V_0 – the rotating and axial velocity components.

When defining the component V_θ, the maximum value of the rotating velocity is taken into account. Taking into account formulas (13), we write an equation for determining the angular velocity of the working flow:

$$\omega_w = \frac{8}{\pi} \frac{Q_w}{d_w^3} \mathrm{tg}\alpha_w \quad (14)$$

A similar expression for the injected flow for a symmetric velocity diagram (in the case of zero distance between the axes of the well and the jet pump) has the following form (Panevnyk, 2021):

$$\omega_e = \frac{4Q_e \mathrm{tg}\alpha_e}{f_i (1 + \sqrt{K_p}) d_w} \quad (15)$$

where: f_i – the cross-sectional area of the injected flow at the inlet to the mixing chamber.

We equate equations (14), (15), and taking into account that $i = Q_e/Q_w$, $K_p = f_c/f_w$ (where f_c is the cross-sectional area of the mixing chamber) and $f_i = f_c - f_w$, we obtain the formula for determining the injection coefficient, which ensures the equality of the rotation velocities of the working and injected flow in the case of their swirling by guiding elements:

$$i = \frac{\mathrm{tg}\alpha_w}{2\mathrm{tg}\alpha_e}(1 + \sqrt{K_p})(K_p - 1) \quad (16)$$

Table 4 shows the empirical functions and values of the coefficients of the regression equations obtained from the results of experimental studies of four models of jet pumps with elements for swirling the liquid placed in the external and internal flows.

After determining the values of the injection coefficients that ensure the equality of rotation velocities of the working and injected flow (according to formula 16) and after substituting them into the regression equations given in Table 4, we

Table 4. Empirical head characteristics for simultaneous swirling of the working and injected flow
Tabela 4. Empiryczna charakterystyka wysokości podnoszenia dla jednoczesnego zawirowania przepływu roboczego i tłoczonego

No.	Geometric parameter, K_p	Regression equation	Empirical coefficients		Correlation coefficient, r
			a	b	
1	6.464	$h^{0.5} = a + bi^2$	0.4362	–0.4071	0.9863
2	3.429	$h^2 = a + be^{-i}$	–0.1002	0.1728	0.9775
3	5.012	$h^{0.5} = a + bi^{1.5}$	0.4955	–0.6124	0.9930
4	3.795	$h = a + bi/\ln i$	0.2461	0.3587	0.9789

Table 5. Comparison of theoretical and experimental values of jet pump head for its rotation
Tabela 5. Porównanie teoretycznych i eksperymentalnych wartości podnoszenia pompy strumieniowej dla jej obrotów

No.	Geometric parameter, K_p	Zero line radius, r_i [m]	Irregularity coefficient, φ_2	Relative head		Calculation error, δh [%]
				theoretical, h_c	experimental, h_{ex}	
1	6.464	0.007075	0.9773	0.1449	0.1448	0.070
2	3.429	0.007170	0.9714	0.2190	0.2110	3.640
3	5.012	0.007045	0.9440	0.1713	0.1759	2.615
4	3.795	0.007080	0.9402	0.1918	0.1975	2.886

calculate the values of the relative head pressure corresponding to the rotation conditions of the four models of the jet pump. For the same values of the injection coefficient, we calculate the value of the theoretical (calculated) relative pressure, for which there are used equations (10), (11). The results of the values of the relative pressure calculations and their comparison with the experimental values are shown in Table 5.

The error of the theoretical determination of the relative pressure for four jet pump models, taking into account the results of the studies, does not exceed 3.64%, which indicates the adequacy of the developed mathematical model of the ejection system working process for its rotation in the well.

Conclusions

1. For the first time, the necessity and expediency of modelling the interaction of flows in the mixing chamber of a jet pump are demonstrated and justified, presenting it as a sum of partial solutions of the Laplace equation for the radial, plane-parallel, and circulation three-dimensional hydrodynamic function of a complex variable:
   - the value of the complex potential enables the formation of the velocity field and evaluation of the nature of the distribution of kinematic parameters in the flow part of the jet pump;
   - the configuration of the separation line of the working and injected flows can be determined by imposing a potential uniform flow on the radial circulation flow.
2. The new formulation of the problem made it possible to establish regularities and formulate the basic principles for evaluating the working process of a jet pump during its symmetrical rotation in the well:
3. the relative rotation of the ejection system changes the flow velocity profile in the mixing chamber of the jet pump: due to the action of centrifugal forces, the distribution of kinematic parameters becomes more uniform, and the flow rate and pressure of the mixed flow increase. The degree of non-uniformity in the distribution of kinematic parameters can be considered as a criterion for evaluating the influence of jet pump rotation on its performance;
   - a two-layer structure of a mixed flow with a variable limit of separation of the working and injected flows is proposed and investigated, with a uniform distribution of velocities in the outer layer and a profile approximated by a polynomial of the third degree in the inner layer. The task of studying the mechanism of flows interaction in the mixing chamber of a jet pump in the case of its rotation in a well can thus be reduced to finding the boundaries of delimitation of the injected and working flows and integrating the velocity profile;
   - an increase in the relative head and efficiency of the jet pump, caused by the symmetrical rotation of the jet pump in the well, is established, by 7.79% and 9.57%, respectively.
4. A technique for experimental studies of the symmetrical rotation of a downhole ejection system has been developed based on a comparison of the empirical characteristics of a jet pump with guiding elements for simultaneous swirling

of the working and injected flows and modelling conditions that ensure the same angular velocity of rotation of the mixed media. In the process of checking the adequacy of the proposed mathematical model for the interaction of potential elementary flows, it has been found that the error in the theoretical determination of the relative pressure of a jet well pump does not exceed 3.64%.

The task of further research is to develop a system for automated prediction of the operating parameters of the jet pump for the conditions of its rotation in the well.

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