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Investigation of the characteristics of an oil jet pump when using a group ground drive

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ABSTRACT

A computer model of the working process of the pump-circulation system has been developed, which includes a series of downhole oil jet pumps and a group ground power drive. The design space of the pump-circulation system is presented as a combination of 3D models of the inlet and outlet collectors with a parallel connection of jet pumps located between them. Boundary conditions in the form of flow rates and pressures of the total working and mixed flows were set in sections before the inlet and after the outlet collectors. The productivity of the ground pumping unit varied in the range from 0.0037 m^3/s to 0.01 m^3/s, and the pressure in the characteristic sections of the jet pump is from 2.26 to 2.53 MPa. In addition to hydrodynamic parameters, the computational model takes into account the design of wells, the configuration of the flow path of jet pumps and the state of their working surfaces, the physical properties and flow regimes of interacting flows. The generated working space is used to construct a set of discrete volumetric elements, the placement density of which increases in high- gradient flow regions. Calculation procedures for three standard sizes of jet pumps are implemented based on the use of the finite element method with the help of SolidWorks software products. The distribution diagrams of velocities and pressures obtained by modeling are presented in the form of dimensionless regime parameters of jet pumps: ejection coefficient and relative pressure. The conducted studies have established the increasing nature of the dependence of the ejection coefficient of the jet pump on the performance of the ground pumping unit. With an increase in the productivity of the ground pumping unit in a given range, the value of the ejection coefficient increases from 0.12 to 0.52. The results of computer simulation were compared with the classical method for determining the parameters of mixed coaxial flows, based on the use of the laws of conservation of energy and flow continuity. The deviation of the flow characteristics of the jet pump, obtained using the proposed computer model and the classical laws of hydrodynamics, does not exceed 6.47%. The proposed model makes it possible to automate the process of designing optimal operating modes for a group hydro -jet oil-producing pump-circulation unit.

Introduction

Despite the intensive development of renewables, the share of oil and gas in the global energy mix will be 17% and 11% respectively in 2050 [1]. The significant amount of hydrocarbons used requires improved extraction methods. The selection of oil and gas extraction methods takes into account their yield, depth, construction, reservoir pressure value, water cut, gas factor, temperature, viscosity and corrosivity of the reservoir fluid, presence of sand during extraction and other factors [2]. A priority in selecting a method of mechanized oil and gas production is the value of the capital and operating costs associated with lifting and transporting the products from the wells [3].

The desire to maintain the profitability of producing aging hydrocarbon fields has led to the use of hydro-fracturing as a method of oil and gas extraction. The implementation of the hydro-fracturing method of well operation implies the use of nozzle pumps. Jet pumps are distinguished by the absence of moving parts, the possibility of use in deviated and curved wells, the possibility of use in offshore fields and in remote areas. They can be removed from the borehole for replacement without the need to lift the tubing. The advantages of the hydroejector method of oil and gas production are most evident in the late stages of marginal well operations [4]. Given the significant impact of pump efficiency on hydrocarbon recovery at well depth, improving oil and gas production technology using hydrojetting is an urgent task.

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Analysis of recent research

Since the introduction of jet pumps in the US in the 1970 s, Kobe, National and Guiberson have gained the most experience in operating oil well displacement systems. Kobe has developed the Solo Unit package of stand-alone surface equipment for hydraulic pumping units with piston or jet pumps. The equipment consists of separators, hydrocyclones and three-cylinder pumps driven by electric or gas engines [7]. A characteristic feature of the Solo Unit surface facility layout is the ability to maintain the standard layout of the discharge pipelines and storage tanks near the wellhead. The output of the Kobe three-piston pumps is determined by the diameter of the replaceable cylindrical casings and is adjustable from 0.279 m^3/h to 29.375 m^3/h. National's Unidraulic onshore system has five sizes of three- or four-cylinder power pumps that can optionally be equipped with a four-speed gearbox. In addition, the Unidraulic system can be connected to a centralised working fluid distribution system from a pumping station or multiple adjacent wells. Piston, piston, screw, diaphragm, diaphragm, and centrifugal multistage pumps are used today in the design of groundwater well operation equipment. Ground pumps can be driven by the combustion of stripped petroleum gas [5]. The versatility of ejection technology has led to the emergence of non-traditional applications. An example of the expanded application area of jet pumps is the removal of hydrate deposits in underground wells [8]. The specifics of mixing of the streams in the jet pump flowing section determine the energy efficiency of using the arrangement as part of a surface drive system and a downhole displacement system. The need to increase the efficiency value of the ejection system has led to several studies aimed at optimizing the kinematic and hydrodynamic parameters of the flooded flows and improving their mixing mechanism. The nature of the working current supply has a significant influence on the characteristics of a deep ejection system consisting of multiple jet pumps placed in series [6].

A group hydrojet pumping unit is used to operate several closely spaced wells. The development of the group drive ground pump was an attempt to optimize the operating costs in the hydro-jetting method of oil production. The use of a surface pump drive for multiple wells has reduced the initial capital investment associated with the installation of a surface hydroblasting facility.

Highlighting part of the unsolved problem

A characteristic feature of the use of group driven nozzle pumps is the increased probability of deviation of the operating flow from the recommended value for the given operating conditions. Deviation of the operating flow rate below the minimum allowable flow rate makes it impossible to bring the product from the well to the surface due to insufficient displacement produced by the jet pump. If the operating flow rate exceeds the maximum permissible value (for cavitation conditions), this will cause a sharp drop in the performance of the jet pump and wear on the elements of its flow path. Deviation of the operating flow rate from the optimum value reduces the energy indicators of the ejector system use, increases the cost of oil and gas production and may become the reason for unprofitable operation of the jet pump. The likelihood of deviation of the operating flow rate when using a group ground drive is increased due to the need to periodically adjust the operating mode of the jet pump as a result of changes in wellbore conditions. In particular, adjusting the jet pump output by changing its flow components changes the hydraulic resistance in the flow of the oil-gas mixture and causes a redistribution of the operating flow rates in the cells of the hydraulic system of the group land drive. The use of flow measurement devices in the links of a surface drive hydraulic system is limited by the direct operation process of the wells and cannot be used in the prediction phase of their operating modes. At present, there are a considerable number of methods to determine the operating mode of a deep well injection system, but the issue of flow distribution in the group ground drive linkages of multiple jet pumps is not sufficiently investigated and requires further research.

Thus, an unreasonable bias of the required value of s expense working flow outside the operating range causes emergency wear of the elements of the ejection system, a critical decrease in performance jet pump and well productivity and leads to a catastrophic decrease in the energy performance of the hydraulic pump-circulation unit. Due to the presence of a hydraulic connection between the elements of a branched pump-circulation installation, errors in the operation of one jet pump inevitably cause negative deviations in the working process of neighboring parallel-connected ejection systems. In this case, the performance of the entire pump-circulation system deteriorates and the volume of oil production decreases. The development of a hydraulic model for parallel connection of a series of jet pumps with a common inlet and outlet line makes it possible to increase the efficiency of predicting the performance characteristics of a group of oil wells equipped with a single hydraulic drive.

Formulation of the research objective

The aim of the work is to simulate the operation of an ejector system consisting of several jet pumps and a group ground drive.

Summary of background material

According to the schematic diagram (Fig. 1) of the group ground drive, the ready-to-use working fluid is received from the reservoir 2 into the surface pumping unit 3 and pressurized to the device 5 at the wellhead.

After entering the borehole, the working fluid passes through the annular channel and the working nozzle to the flow section of the jet pump. Due to the high flow rate of the working fluid, a low pressure region is formed in the outlet section of the working nozzle, which creates conditions for suction of the formation fluid from the payzone. The working stream mixes with the forming fluid and moves upwardly through the flow portion of the jet pump 6 via the lifting pipe. After exiting the well, the mixed flow is routed through the discharge pipe to the accumulation tank 4 and after dewatering, cleaning and degassing, it enters the reservoir 2. A portion of the formation fluid is conveyed to the production well collection system and another portion forms a closed circulation loop and is repeatedly conveyed to the wells to drive the jet pumps. The nature of the flow distribution in the ejection system of the deep well pumping and circulation complex is determined by the hydraulic resistance of its individual elements. The modeling of the flow distribution process is based on the application of computational methods of branched pipes (Fig. 2a) and the peculiarities of

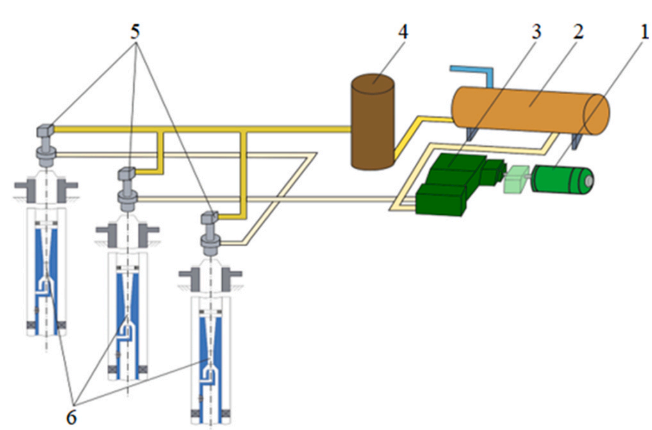

Fig. 1. Schematic diagram of the operation of a hydroturbine in an oil well with a group ground drive - 1 - surface pumping unit drive; 2 - tank; 3 - surface pumping unit; 4 - storage tank; 5 - wellhead equipment; 6 - jet pumps.

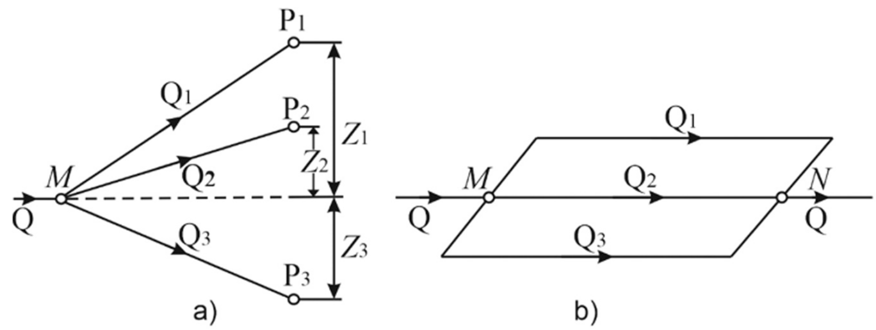

Fig. 2. Hydraulic schematic of a borehole pumping and circulation system: a) branched pipelines; b) parallel connection of single pipelines.

determining hydrodynamic parameters in the joints of parallel interconnection of several simple pipes (Fig. 2b).

Q -total flow rate; Q_1, Q_2, Q_3 - operating flow rate of individual wells; P_1 , P_2 , P_3 - working flow pressure at the inlet to the wells; Z_1, Z_2, Z_3 - geometric positions of the well heads.

If the surface part of the pumping and circulation system is considered as a branched pipe, the hydraulic scheme of the surface pumping unit consists of a number of simple linear elements connecting the flow distributor with the production wells and having a common cross-section - the branching point (point M in Fig. 2a). Influencing the nature of the flow distribution in the underground part of the pumping-circulation system is achieved through the use of predefined values of the working pressure P_1 , P_2 , P_3, directed into the annular space of the individual oil wells.

In the case of a pump-circulation system analysis, the parallel connection of several single pipes (Fig. 2b), the distribution of the total operating flow is made at point M (at the well inlet) and the connection of the total mixed flow is made at point N (at the well outlet).

For the branched connection, we write a system of n + 1 equations (where n is the number of single pipes).

$$Q = Q_1 + Q_2 + Q_3 \quad P_M = P_1 + Z_1 + K_1 Q_1^m \tag{1}$$

$$P_M = P_2 + Z_2 + K_2 Q_2^m \quad P_M = P_3 + Z_3 + K_3 Q_3^m \tag{2}$$

P_M - pressure at the branching point of the working flow;.

K_1 , K_2 , K_3 - general hydraulic resistance of the pipe; m - fluid flow regime index.

Eq. (1) determines the cost balance at the nodal point, and Eq. (2) - the total flow rates in the surface pipelines and in the pump-circulating well system. The parameter $Z_n + K_n Q_n^m$characterizes the hydraulic losses in a separate surface pipeline, which are much lower than the working pressure at the wellhead $Z_n + K_n Q_n^m < < P_n$.

Failure to take into account the value of hydraulic losses in the surface pipe $Z_n + K_n Q_n^m \approx 0$.

The flow distribution in a parallel piping system is determined by the flow balance equations for nodal point M (or point N in Fig. 2b)

$$\Sigma Q_i = Q_1 + Q_2 + Q_3 = 0 \tag{3}$$

and the loss of flows Δh_1, Δh_2, Δh_3 in parallel cells of the system, where:

$$\Delta h_i = \Delta h_1 = \Delta h_2 = \Delta h_3 \tag{4}$$

SolidWorks Corporation's Solidworks software product was used to simulate the workflow of an ejector system consisting of several descending jet pumps and a group ground drive in order to predict the performance of products with increased complexity.

Modeling of the working process of the pumping and circulating system provides for the construction of 3D models of the inlet manifold, downhole jet pumps and the outlet manifold. The totality of the obtained three-dimensional geometric models forms a single design space of the pumping and circulating system. Boundary conditions in the form of flow rates and pressures were set in sections before the inlet and after the outlet collectors. In accordance with the finite element method, the generated computational space is represented as a set of discrete volumetric elements. Calculation operations were implemented on the basis of iterative procedures within discrete elements using standard SolidWorks software products.

The initial data for modeling the nature of the hydraulic connections of the elements of the ejection system are the design of the well, the geometric dimensions of the inlet and outlet manifolds, dimensionless ratios, the mutual orientation and condition of the working surfaces of the structural components of the jet pump, the performance and pressure of the surface pumping unit, physical parameters, kinematic characteristics and flow regimes mixed streams. The initial configuration used to close the averaged values of the hydrodynamic parameters of the Reynolds and Navier-Stokes equations is the k-omega (k-ω) turbulence model. The accepted initial data ensured the implementation of a finite-difference model of an extensive pump-circulation system consisting of a parallel connection of a series of downhole jet pumps and a group surface power drive.

The working stream generated by the surface drive enters the inlet manifold 1 and is routed through three surface pipes into the annular space between the jet pumps 2 and the borehole walls (Fig. 3).

Outlet (drain) head 3 is where the mixed flow from the jet pumps is connected. The number of finite-difference elements is largely determined by the depth of the borehole, resulting in higher hardware requirements and longer computational time. When using a group ground drive, adjacent wells are usually located at close depths, so

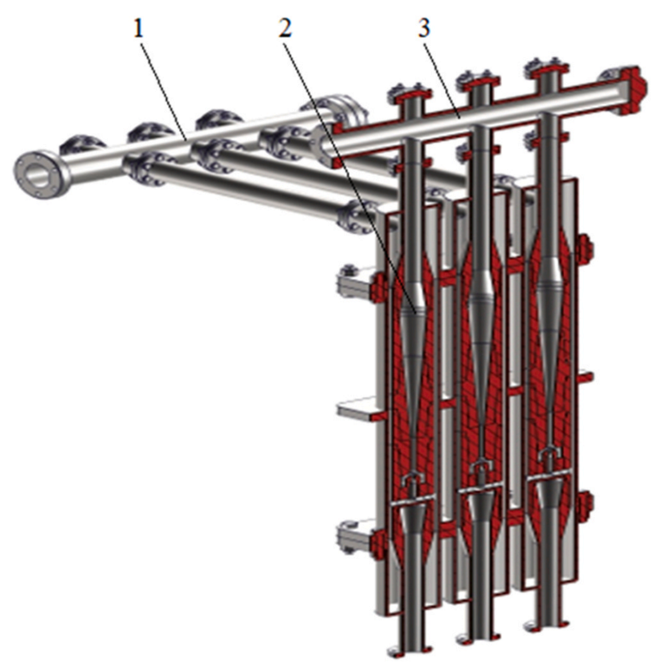

Fig. 3. Geometric model of the circulator-pump system.

Table 1
Geometric dimensions of the jet pump models.

The pump number	d_w, m^3/s	d_m, m^3/s	K_p	l_w, m	$\bar{l}_w$
1	0,0084	0,01331	2511	0,01345	0625
2	0,00741	0,01171	2497	0,01345	0551
3	0,00953	0,01512	2518	0,01345	0709

excluding geometrically similar channel sections with the same shape and length from the model cannot significantly affect the ratio of the hydraulic resistances of the individual pumping and circulating system elements. In addition, it should be noted that for all cells of the parallel connection of the jet pumps in the hydraulic channels connecting them to the wellhead, the smooth-wall friction regime is maintained, i.e. there is a partial dynamic similarity of the fluid motion regimes.

This circumstance allows the presence of circular and annular hydraulic channels of considerable length (up to 5000 m or more) connecting the jet pumps to the inlet and outlet manifolds to be disregarded in the modeling.

Considering the assumption adopted in the problem statement, the modeling of the operation process of the ejector system is carried out in three stages. In the first stage, we determine the distribution of the working flows in the inlet pipe of the pump circulating system. The output parameters, which are set on the surfaces bounding the inlet pipe, are the value of the working flow produced by the surface pump unit and the value of the inlet pressures to the individual wells. The second modeling stage allows the operational parameters of the ejector system to be determined using the previously determined operating flow rates and jet pump outlet pressures. The jet pump outlet pressures set in this phase of the study take into account the hydrostatic pressure at the actual depth of the ejector system in the well. This approach allows for the presence of hydraulic channel sections that are not part of the geometric model of the pump-circulation system. In the third stage of the simulation, the output parameters are the mixture flow rate and the pressure value at the outlet pipe. This phase allows to assess the validity of the computational operations performed in the previous simulation phases by means of an obvious relation

$$Q_{m\Sigma} = Q_p + Q_{e\Sigma} \quad (5)$$

Where $Q_{m\Sigma}$, Q_p, $Q_{e\Sigma}$, - the total mixed flow at the outlet pipe, the surface pump output and the total induced flow. The capacity value of the surface pump Q_p unit is given in the first modeling step, while the total induced flow $Q_{e\Sigma}$ and total mixed flow $Q_{m\Sigma}$are determined in the second and third calculation steps. The configuration of the flow area of the jet pump is defined by the following geometrical parameters: - working nozzle diameter d_w; - mixing chamber diameter d_m; - the ratio of the areas of the mixing chamber and the working nozzle K_p; - the absolute distance between the working nozzle and the mixing chamber l_w; - the relative distance between the working nozzle and the mixing chamber (determined by the ratio of the diameter of the working nozzle to the absolute distance from the mixing chamber) $\bar{l}_w$ - the length of the mixing chamber l_m.

For the investigation of the pump-circulation system working process, jet pump models are used, the basic geometrical dimensions of which are given in Table 1.

The global and local network methods were used to develop a network model of the jet part of the plant. This made it possible to set the global parameters of the network model with a basic cutting accuracy and to make it denser at locations that require a higher accuracy of the flow calculation. Network cells are split in high gradient flow regions that were resolved prior to computation or during the preliminary network crushing during solution adaptation, and merged in low gradient regions.

The velocity and pressure distribution diagrams of the inlet and outlet manifold (Fig. 4) and the jet pumps (Fig. 5) obtained in the modeling allow to analyse the characteristics of the working process of the pump-circulation system.

Network models of the components of the pumping and circulation system are constructed (Fig. 4) for the following values of the surface pumping unit performance: 0.003676 m^3/s; 0.005257 m^3/s; 0.006838 m^3/s; 0.008419 m^3/s; 0.010 m^3/s.

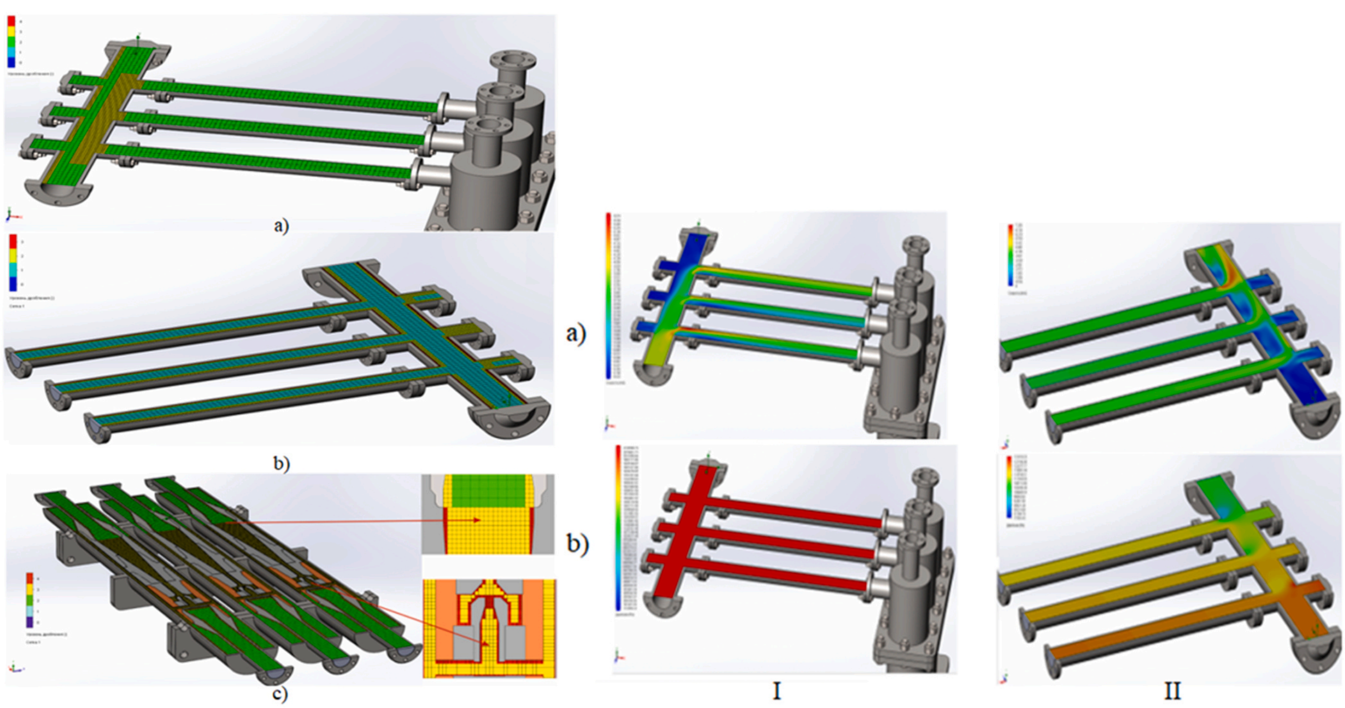

Fig. 4. Network models of pump-circulation system components: a) inlet manifold; b) outlet manifold; c) jet pumps and Ddiagrams of velocity (a) and pressure (b) distribution in inlet (I) and outlet (II) pipes.

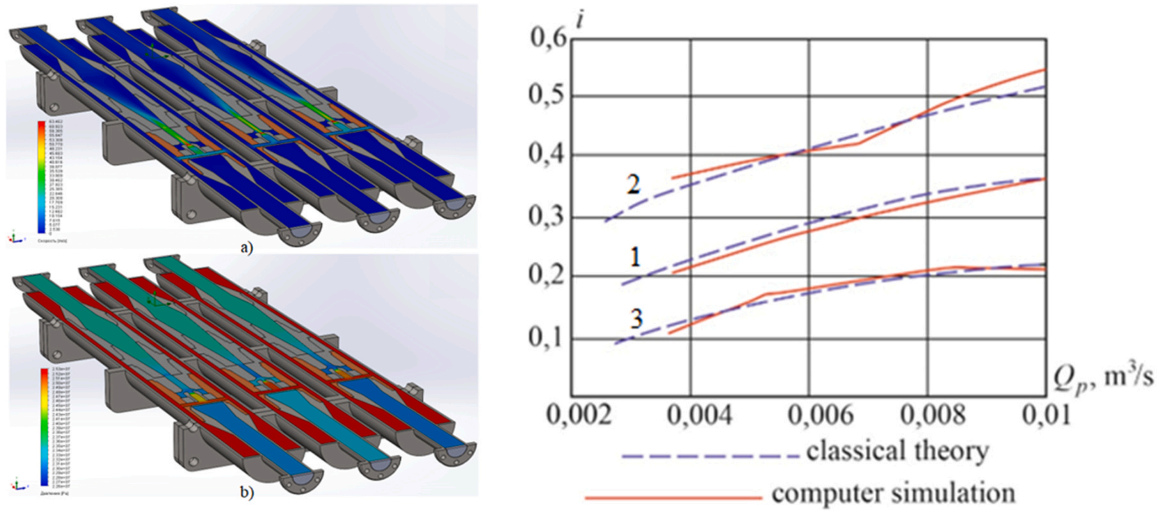

Fig. 5. Diagrams of velocity (a) and pressure (b) distribution in the flow section of the jet pumps and dependence of the induction coefficient value on the unit surface pumping power for a jet pump with working nozzle diameters: 1 - d_w 0,0084 m; 2 - d_w = 0,00741 m; 1 - d_w = 0,00953 m.

The pressure value in the flowing part of the jet pump (at its location at a depth of 2400 m) ranges from 2.26 to 2.53 MPa and the velocity ranges from 0 to 63.462 m/s. According to the general principles of jet pump operation, the maximum flow velocity and the minimum pressure value are reached at the outlet of the working nozzle. The jet pump diffuser is characterised by a maximally non-uniform velocity distribution in its cross-section.

The obtained velocity values allow to calculate the flow characteristics of the circulating-circulating system by means of the dependence of the value of the induction coefficient of the jet pump on the performance of the surface pump unit $i = f(Q_p)$, where the value of the induction coefficient is defined by the ratio of the displacement induced Q_e and the working Q_w flow rate $i = Q_e/Q_w$.

The prototype of the proposed model of the working process of a group ejection system is the traditional methods for calculating branched and ring hydraulic systems using the classical laws of conservation of energy and flow continuity, as well as the features of the mixing mechanism of coaxial flows under conditions of a significant difference in speeds and pressures. In contrast to classical methods, the proposed model makes it possible to automate the process of designing optimal operating modes for oil jet pumps when using a group power drive. The procedure for using the developed model provides for the automatic construction of diagrams of the distribution of hydrodynamic parameters in the elements of the ejection system for a given productivity of the ground power drive, the design of the oil well, and the configuration of the flow path of the jet pump. If it is necessary to regulate the operating mode of jet pumps, the proposed model allows determining the predicted productivity of oil wells.

The dashed lines (Fig. 5) show the dependencies obtained using classical theory, which involves the sequential determination of the flow rate, Reynolds number, linear hydraulic resistance coefficient, hydraulic losses in linear and local resistances, the discharge characteristic of the jet pump, the characteristics of its hydraulic system, the working point of the pump unit, and the operating parameters. The marginal deviation of the obtained flow characteristics determined by the classical method and the computer simulation is $\delta = 6{,}47\%$.

Conclusions

A computer operating model of an ejection system consisting of several nozzle pumps and a group ground drive has been developed to determine the distribution of operating flows and the characteristics of the pump-circulation system.

1. The problem of determining the nature of the distribution of the operating flow in the elements of a branched pump-circulation system, the individual elements of which consist of consistently located linear and local hydraulic resistances, is formulated. The calculation of the pump-circulation system is based on the use of the flow balance equations for nodal points and the balance of head losses in parallel cells of closed circulation loops.
2. The geometric model of the pump-circulation system is developed in the form of inlet and outlet manifolds with parallel-positioned pumps with nozzles in the wells. The proposed model allows for different designs of wells and jet pumps in the pumping and circulation system.
3. The network model of the pumping and circulation system is executed with different degrees of finite difference element fragmentation due to the non-uniform distribution of the required accuracy of the computational operations in its individual parts. In volumes constrained by complicated geometry, a denser network of computed elements is used.
4. The distribution of kinematic parameters in the cross-section of the elements of the flowing part of the jet pump is characterized by considerable irregularity. The most asymmetric distribution of the kinematic parameters of the mixed flow is observed in the diffuser with the jet pump.
5. The induction coefficient of the jet pump and the capacitance of the surface unit are coupled by a nonlinear increasing relationship. The deviation of the flow characteristics determined by the classical method and the computer simulation does not exceed 6,47%.

The task of further research is the experimental verification of the developed computer model of the working process of the ejector system consisting of several jet pumps and a group surface drive.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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