Vol. 24, No. 1
2024

PROSPECTING AND DEVELOPMENT
OF OIL AND GAS FIELDS

https://pdogf.com.ua/en

Received: 28.12.2023. Revised: 26.04.2024. Accepted: 31.05.2024

UDC 622.276:004.896

DOI: 10.69628/pdogf/1.2024.23

Study of the kinematic field of mixed flows

Oleksandr Panevnyk*
Doctor of Technical Sciences, Professor
Ivano-Frankivsk National Technical University of Oil and Gas
76019, 15 Karpatska Str., Ivano-Frankivsk, Ukraine
https://orcid.org/0000-0003-2765-3776

Abstract. The relevance of the study is determined by the ability of borehole jet pumps to increase the efficiency of technological processes in difficult mountainous and geological conditions. The aim was to establish the laws of transformation of the velocity profile in the production inlet chamber of a borehole jet pump based on the construction and subsequent analysis of the distribution of kinematic parameters of the total working and injected flows. Simulation of the operating process of the ejection system was performed in the ANSYS software and calculation module for four three-dimensional models of a borehole jet pump. The geometric models are constructed with an uneven density of calculation elements in places of complex geometry and a high gradient of hydrodynamic parameters. For each of the studied models, a series of velocity profiles placed at regular intervals at different distances from the pump throat section of the production inlet chamber was constructed. The constructed velocity profiles include sections with uniform and nonlinear distribution of kinematic parameters of mixed flows. It is established that the maximum values of the velocity of mixed flows are present on the axis of the jet pump and are the same for all the studied models. The axial velocity of the mixed flows decreases as the distance to the pump throat section of the production inlet chamber increases. The minimum axial velocity was obtained for a jet pump model with a maximum production inlet chamber length. For two models of a jet pump with a production inlet chamber length of 287 mm and 328 mm, stabilisation of the axial velocity values of the total working and injected flows was obtained. The immutability of kinematic parameters for these jet pump models indicates the completion of the process of equalising the velocities of mixed flows. Taking into account that if the required dimensions of the kinematic stabilisation section are exceeded, hydraulic losses in the flow part of the ejection system increase, its optimal design corresponds to a model with a jet pump production inlet chamber length of 287 mm. The practical value of the study lies in the fact that this design provides the maximum efficiency of a borehole jet pump

Keywords: borehole jet pump; ejection system; production inlet chamber; velocity profile; kinematic parameter distribution; flow stabilisation

Introduction

The rapid pace of global energy consumption has contributed to the search for alternative methods for the exploration of hydrocarbon deposits, a special group of which includes technologies for using jet pumps. The main benefits of using ejection technologies include preserving the natural permeability of productive horizons during their initial discovery, increasing the life of aging oil and gas fields, increasing well productivity during bottom-hole cleaning, implementing oil production stimulation methods, and preventing environmental pollution in hydrocarbon extraction and processing systems. The use of eddy current pumps contributes to increasing the energy efficiency of pipeline transportation of oil and petroleum products. The inclusion of jet pumps in the technological pipeline branching system helps to reduce the cost of transporting high-viscosity oils with a significant formation fluid content. The prevalence of oil and gas ejection technologies indicates their global importance and the relevance of research aimed at improving the efficiency of operation of borehole jet pumps.

V. Kotak *et al.* (2023) found that despite the simple design, the jet pump's operating process is based on the

Suggested Citation: Panevnyk, O. (2022). Study of the kinematic field of mixed flows. *Prospecting and Development of Oil and Gas Fields*, 24(1), 23-31. doi: 10.69628/pdogf/1.2024.23.

*Corresponding author

implementation of a complex mixing mechanism for coaxial potential flows separated by a boundary turbulent layer of variable structure with an uneven profile of hydrodynamic parameters. Significant complications in predicting the operating process of jet pumps are also associated with an increased tendency for cavitation phenomena to occur in their flow parts. According to J. Gan *et al*. (2022), the probability of loss of flow continuity increases with operating ejection systems with a centrally located working nozzle. Scientists Y.-D. Cho & U. Shrestha (2020) concluded in their paper that cavitation phenomena can also occur when using annular jet pumps. The solution of the system of equations that characterise the interaction of mixed flows is usually carried out by an approximate method by neglecting the value of individual components, which reduces the efficiency of modelling the operating process of a jet pump. Based on the research results of A. Kurniawan *et al*. (2023), the use of numerical simulation modelling and modern software packages makes it possible to increase the reliability of the choice of design and operating parameters of borehole gas ejection systems. In particular, in the process of modelling the interaction of gas flows, the optimal ratio of the cross-sectional areas of the production inlet chamber and the nozzle of the gas ejector is established.

Increasing the reliability of predicting the characteristics of a jet pump is provided by using neural network models, as indicated by K. Xu *et al.* (2021). In the process of optimising the flow part of the jet pump, an increase in the pressure created by it by 30.46% was obtained. By combining computational fluid dynamics (CFD) with the Kriging correlation model, K. Xu *et al.* (2020) established an optimal relationship between the flow configuration of an annular jet pump and the ratio of injection and operating flow rates. Based on the results of modelling a single-phase flow vortex in a shear layer between the operating and injected flow using a Reynolds-averaged system of Navier-Stokes equations and experimental measurements, A. Morrall *et al.* (2020) determined the influence of the nozzle diameter and flow swirl on the performance of the jet pump. The swirling of the flow due to centrifugal forces allows for an increase in the injection coefficient of the jet device. Scientists A. Rogovyi & S. Lukianets (2022) established the effect of swirling mixed flows on the energy efficiency of using jet devices. Based on the solution of the Reynolds, continuity and Rayleigh-Plesset equations in the Ansys CFX software package, it is shown that the swirling of mixed flows can double the efficiency of the jet device. The use of SNAP-type software to analyse the characteristics of a borehole jet pump makes it possible to increase the efficiency of using special application programmes, as described by E. Zafarullah *et al*. (2021). The analysis of the relationship between the productive horizon and surface equipment obtained using this software helped to increase the well flow rate by 42.9%.

A significant amount of research is devoted to optimising the design of borehole jet pumps. In the CFD process of modelling the operating process of the gas ejector, V. Kumar *et al*. (2019) found that the maximum ejection coefficient corresponds to zero distance between the working nozzle and the production inlet chamber of the jet machine. In the process of numerical modelling, Z. Wang *et al.* (2023) determined that the optimal value of the main geometric parameter of an oil jet pump provides a 10% increase in the efficiency of the borehole ejection system. The obtained result was confirmed in the course of experimental tests of an oil jet pump using orthogonal lattices developed by the Taguchi method during the planning of the experiment. By solving the Navier-Stokes equations of motion of a three-dimensional stationary flow for five models of the ejection system, Y. Yang *et al.* (2023) established the significant influence of the geometric dimensions of the diffuser on the formation of inhomogeneous eddy reverse currents in the flow part of the jet pump, which reduces its performance. The conducted studies have determined the optimal value of the production inlet chamber diameter from the point of view of ensuring maximum performance of the jet pump, which is 16-17 mm.

In the course of the analysis, it was found that when modelling the operating process of a jet pump, the influence on its characteristics of the hydrodynamic parameters of the environment, the physical properties of the mixed flows, the configuration of the elements of the ejection system, the ratio of the cross-sectional areas of the production inlet chamber and the working nozzle, their relative orientation, and the parameters of the diffuser part are usually studied. At the same time, the influence of the nature of the velocity distribution in the production inlet chamber of a jet pump on the features of its operating process is insufficiently studied. The analysis of the kinematics of mixed flows for an incompressible working medium makes it possible to optimise the borehole jet pump's operating process and increase the efficiency of oil and gas ejection technologies. The study aimed to establish regularities of transformation of the velocity profile in the production inlet chamber of a borehole jet pump. This goal involved performing the following research tasks: constructing velocity profiles of the operating and injected flows along the production inlet chamber of the jet pump; establishing the nature of changes in the maximum velocities of the mixed flows; determining the length of the velocity stabilisation section in the production inlet chamber of the jet pump.

Materials and Methods

Determining the nature of the velocity distribution of the operating and injected flows along the production inlet chamber of the jet pump involved the following stages of research: construction of a geometric model of a borehole jet pump; selection of boundary surfaces of the design volume and boundary parameters of the operation of the borehole jet pump; construction of a grid (design) model of the borehole jet pump; solving the system of equations obtained using the finite element method. The construction of mixed flow velocity profiles was carried out for four models of a jet pump with the following geometric characteristics: diameter of the working nozzle $d_w = 14$ mm;

production inlet chamber diameter $d_i = 28$ mm; basic geometric parameter of the jet pump $K_{jp} = 4.0$; absolute length production inlet chambers $L_{i1} = 164$ mm; $L_{i2} = 246$ mm; $L_{i3} = 287$ mm; $L_{i4} = 328$ mm; relative length of the production inlet chamber $\bar{L}_{i1} = \frac{L_{i1}}{d_i} = 5.86$; $\bar{L}_{i2} = \frac{L_{i2}}{d_i} = 8.79$; $\bar{L}_{i3} = \frac{L_{i3}}{d_i} = 10.25$; $\bar{L}_{i4} = \frac{L_{i4}}{d_i} = 11.71$; diffuser diameter $d_d = 71$ mm; diffuser length $L_d = 280$ mm.

Due to the design features of the jet pump, the typical cross-sections of the ejection system were used in the process of allocating the calculated volume (Chen *et al.*, 2020). The calculated volume was limited to the surfaces drawn at the inlet of the operating flow to the working nozzle, at the inlet of the injected flow to the receiving chamber, and at the outlet of the mixed flow from the jet pump diffuser. When choosing the restrictions imposed on the allocated design volume, the generally accepted ratio of hydrodynamic parameters is used in the form of a combination of flow rates and pressures of operating, injected and mixed flows (Deng & Dong, 2021). The boundary conditions in the process of modelling the operation of the four jet pump models were set by the corresponding flow rates of the mixed flows and pressures in the characteristic cross-sections of the borehole ejection system. Considering that for a given jet pump design, the maximum efficiency (efficiency factor) of the ejection system corresponds to the value of the injection coefficient $i = 1.0$, when justifying the choice of boundary conditions, the same values of the flow rates of the operating and injected flow are assumed $Q_p = Q_i$. In the studied models of the jet pump, the liquid velocity of the injected flow at the inlet to the production inlet chamber was 40 m/s, and the working flow was 100 m/s.

In the process of constructing a calculated model of a borehole jet pump, the geometric model is divided into finite elements according to the specified grid parameters. The process of building a calculation model is implemented using the built-in grid creation module in the ANSYS software product – ANSYS Meshing (Fig. 1). The constructed geometric model corresponds to zero distance between the working nozzle and the production inlet chamber of the jet pump.

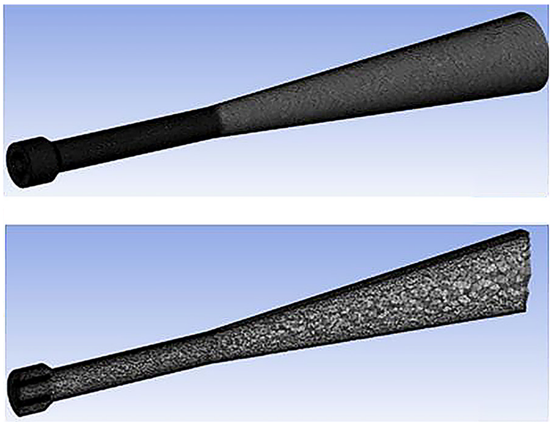

Figure 1. Calculation grid of a three-dimensional jet pump model

Note: a – internal volume of the jet pump model; b – its section
Source: created by the author

In order to reduce the duration of calculation operations while maintaining the required accuracy, an uneven density of the calculation grid was used when constructing the geometric model. The higher density of the calculated elements corresponds to the working nozzle and the receiving chamber of the internal volume of the jet pump, and the lowest density corresponds to the output section of the diffuser. For each of the studied models, a series of velocity profiles for different distances X from the inlet cross-section of the production inlet chamber in increments $\Delta X = 20.5$ mm is constructed. Due to the different geometric dimensions of the studied models, the number of constructed profiles increases with increasing length of the production inlet chamber of the jet pump.

Modelling of the jet pump operation process was carried out in the ANSYS software and calculation module Fluent, which provides high accuracy in solving problems related to the complex interaction of mixed flows. In the process of creating the computational model, the following parameters were chosen: the type of calculator is "pressure based", which is developed and traditionally used for incompressible media; the turbulence model is k-epsilon (standard) with standard wall functions. The adopted turbulence model focuses on mechanisms that affect the turbulent kinetic energy, and allows us to take into account processes in the boundary shear layer of variable width between the operating and injected flow with a high degree of reliability.

Results

According to the classical scheme of interaction of submerged jets, the operating flow flowing out of the working nozzle gradually expands due to the addition of the injected liquid and connects to its walls at a certain distance from the inlet section of the production inlet chamber (Fig. 2). The jet boundaries are delineated by straight lines i-i, and they have an unequal slope to the pump axis in the initial and final sections.

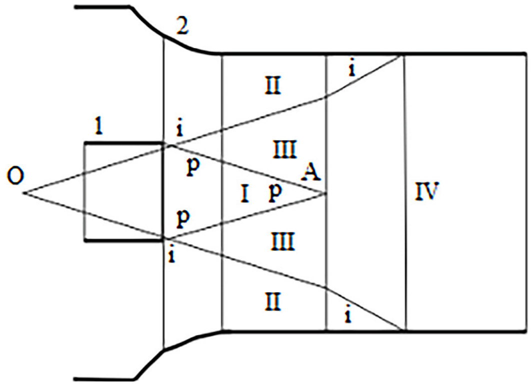

Figure 2. Flow structure in the production inlet chamber of a jet pump

Note: 1 – working nozzle; 2 – production inlet chamber
Source: created by the author

The i-i lines separating the working jet pass through its pole (point O). In the central part of the operating jet there is a potential core I, bounded by the lines p-p, whose width decreases with a constant rate along the flow and takes on zero values at point A. The injected flow moving in the production inlet chamber (area II) has the form of an annular confuser. Areas I and II are zones of unbroken potential flow with constant values of the axial velocity along the length of the production inlet chamber. Between areas I and II, a slow-motion zone is formed (area III) – a boundary turbulent layer in which two flows mix). The most difficult area to analyse is area III, which is characterised by an incoherently variable velocity profile. Area III ends with the establishment of a fully developed current. Areas I, II, and III thus form a three-layer flow structure, the outer and central layers of which are marked by a close to uniform velocity profile, and the internal shear flow is characterised by intense eddy formation and an uneven distribution of kinematic parameters.

In area IV, the alignment of the speed profiles continues, and the mixing process of the operating and injected flows is completed. Depending on the geometric dimensions of the elements of the flow part of the jet pump and the hydrodynamic parameters of the mixed flows, point A may be located to the right of the contact section of the line i-i with the wall of the production inlet chamber. The flows of the operating and injected medium enter the production inlet chamber, where the velocity equalisation occurs, usually accompanied by an increase in pressure (Fig. 3).

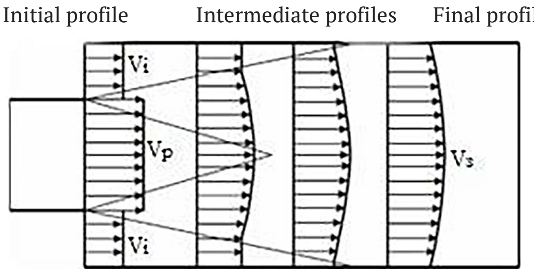

Figure 3. Dynamics of changing velocity profiles in the production inlet chamber of a jet pump
Source: created by the author

The central (operating) jet enters the production inlet chamber at a uniform speed V_p. The peripheral (injected) flow also has a uniform V_i but lower speed $V_i < V_p$. A significant difference in velocities is the reason for the formation of a boundary turbulent layer in which energy dissipation occurs. Significant losses associated with mixing flows are the reason for the low efficiency of the jet pump. The initial velocity profile is marked by a uniform distribution of kinematic parameters of the operating and injected flow, which characterises the potential flow movement. When moving away from the inlet section of the production inlet chamber, the profile section decreases with a uniform distribution of the operating and injected flow rates. Intermediate velocity distributions are characterised by constant values of the speed of the operating and injected flows, respectively, in the central and peripheral parts of the production inlet chamber. The final velocity distribution is parabolic in nature and does not contain sections of a uniform profile. The constant velocity profile is maintained until the initial cross-section of the production inlet chamber (Fig. 4).

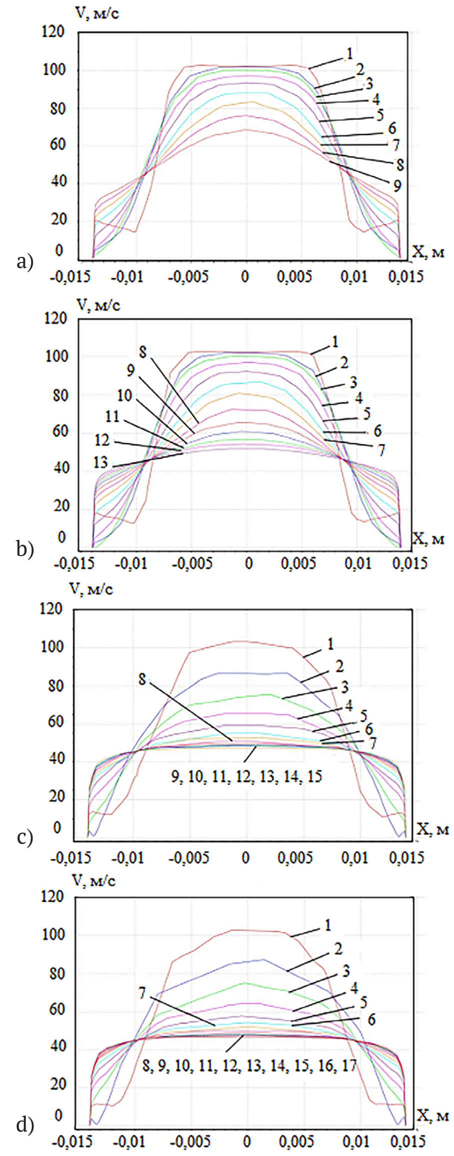

Figure 4. Velocity profiles for different distances *X* from the inlet section

Note: a) production inlet chamber length 164 mm: 1 – 0, 2 – 20.5 mm, 3 – 41 mm, 4 – 61.5 mm, 5 – 82 mm, 6 – 102.5 mm, 7 – 123 mm, 8 – 143.5 mm, 9 – 164 mm; b) production inlet chamber length 246 mm: 1 – 0, 2 – 20.5 mm, 3 – 41 mm, 4 – 61.5 mm, 5 – 82 mm, 6 – 102.5 mm, 7 – 123 mm, 8 – 143.5 mm, 9 – 164 mm, 10 – 184.5 mm, 11 – 205 mm, 12 – 225.5 mm, 13 – 246 mm; c) production inlet chamber length 287 mm: 1 – 0, 2 – 20.5 mm, 3 – 41 mm, 4 – 61.5 mm, 5 – 82 mm, 6 – 102.5 mm, 7 – 123 mm, 8 – 143.5 mm, 9 – 164 mm, 10 – 184.5 mm, 11 – 205 mm, 12 – 225.5 mm, 13 – 246 mm, 14 – 266.5, 15 – 287 mm; d) production inlet chamber length 328 mm: 1 – 0, 2 – 20.5 mm, 3 – 41 mm, 4 – 61.5 mm, 5 – 82 mm, 6 – 102.5 mm, 7 – 123 mm, 8 – 143.5 mm, 9 – 164 mm, 10 – 184.5 mm, 11 – 205 mm, 12 – 225.5 mm, 13 – 246 mm, 14 – 266.5, 15 – 287 mm, 16 – 307.5 mm, 17 – 328 mm
Source: created by the author

Alignment of the mixed flow velocity field is provided with the appropriate length of the production inlet chamber of the jet device. If the length of the production inlet chamber is insufficient, the deterioration of the pump characteristics is associated with the incomplete flow mixing process. If the required length of the mixing chamber is exceeded, hydraulic losses in the flow part of the jet pump increase and the pressure created by it decreases. Calculating the length of the mixed flow velocity field alignment section allows to determine the optimal length of the production inlet chamber of the jet pump from the point of view of ensuring minimal energy consumption. Despite the different distances to the inlet cross-section of the production inlet chamber, the calculated velocity profiles include several characteristic sections (Fig. 4). The central part of the profile is marked by a uniform or eccentric distribution of kinematic parameters, and its peripheral part has a uniform or nonlinear profile. Between the central and peripheral parts is a section of a nonlinear profile with a configuration that varies depending on the distance to the entrance to the production inlet chamber.

The width of the central section of uniform velocities decreases when the section under study is removed from the entrance to the production inlet chamber. For all the studied profiles, the maximum values of the movement velocity of mixed flows occur on the axis of the jet pump. As the distance to the inlet section of the production inlet chamber increases, the axial velocity of the mixed flows decreases. Thus, the qualitative change in the configuration of the velocity profiles of the total operating and injected flows along the production inlet chamber of the jet pump shown in Figures 2-3 is confirmed. For the studied jet pump models, the axial velocity of the mixed flows varies in the range: for a production inlet chamber with a length of 164 mm: from V_{max} = 102 m/s to V_{min} = 68 m/s; for a 246 mm production inlet chamber: from V_{max} = 102 m/s to V_{min} = 52 m/s; for a production inlet chamber with a length of 287 mm: from V_{max} = 102 m/s to V_{min} = 48 m/s; for a 328 mm production inlet chamber: from V_{max} = 102 m/s to V_{min} = 47 m/s. The maximum values of the movement velocity of mixed flows are the same for all the studied models, and the minimum value of kinematic parameters decreases with increasing length of the production inlet chamber. The change in axial velocities along the production inlet chamber for all the models under consideration is determined by an asymptotic relationship (Fig. 5).

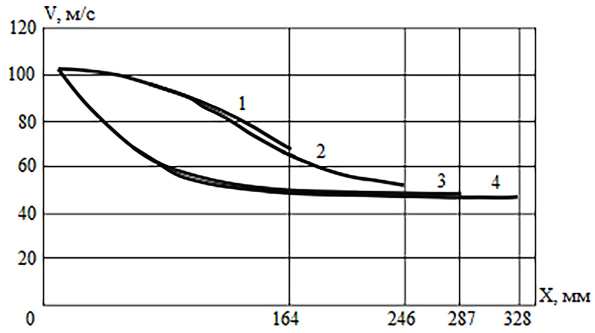

Figure 5. Change of the axial velocity along the production inlet chamber of different lengths

Note: 1 – L_{i1} = 164 mm; 2 – L_{i2} = 246 mm; 3 – L_{i3} = 287 mm; 4 – L_{i4} = 328 mm

Source: created by the author

According to the results obtained for models with a production inlet chamber length L_{i1} = 164 mm and L_{i2} = 246 mm, the axial velocity of the mixed flow decreases from the inlet to the output section. For these jet pump sizes, the speed equalisation process is not completed, which reduces the efficiency of the ejection system. For models with a production inlet chamber length of L_{i3} = 287 mm and L_{i4} = 328 mm when approaching the initial cross-section, the axial velocity takes constant values, which indicates the alignment of the velocity profile and the completion of the mixing process. Thus, in order to reduce hydraulic losses in the flow part of the jet pump, it is necessary to use a production inlet chamber with a length of L_{i3} = 287 mm (L_{i3} = 0.25).

Discussion

Based on the study of the operating process of the ejection system using the ANSYS Meshing and ANSYS Fluent software modules as part of the pressure-based calculator and the k-epsilon turbulence model, velocity profiles of the total operating and injected flows were constructed for different distances to the inlet cross-section of the jet pump production inlet chamber. The consistency of the results obtained should be analysed in comparison with the research materials of other authors. According to Y. Qian *et al*. (2021), the maximum efficiency of the jet device corresponds to the relative length of the production inlet chamber , which varies in the range from 2.5 to 4.0. This range of optimal ratios of the production inlet chamber length of the jet device was obtained in the process of numerical and experimental study of the features of transportation of various operating media with a significant content of solid inclusions. In the course of simulation modelling, a model of a jet pump was used with the diameters of the output cross-section of the working nozzle and the production inlet chamber of 8 mm and 32 mm, respectively. The nature of the interaction of mixed flows obtained in the CFD modelling process confirms the existence of an extreme dependence of the efficiency of the jet device on the length of the production inlet chamber. The ratio of cross-sectional areas of mixed and operating flows in a jet device for hydraulic transport is twice as high as the similar parameter of the models studied by the author, as a result of which the path required for levelling the velocity profiles of mixed flows and the optimal length of the production inlet chamber are reduced.

Ye.I. Kryzhanivskyi & D.O. Panevnyk (2019) developed a three-layer mathematical model of mixing flows in the form of coaxial potential flows with a uniform velocity distribution and a variable structure with an algebraic velocity profile placed between them. Using the theory of a submerged jet moving in a concurrent flow, the flow structure at the inlet to the production inlet chamber of a jet pump is analysed, and the possibility of modelling the process of mixing coaxial flows in the form of automodel velocity profiles of potential and shear flows of variable cross-section with a three-layer structure is shown. For the regions of potential flows, a uniform velocity profile is assumed, and for the shear flow placed between them, a nonlinear profile is assumed, which retains approximate automodelicity throughout the entire initial section of the submerged jet. By integrating the accepted velocity profile taking into account the transition conditions between potential and shear flows, the theoretical velocity distribution for mixed flows in the flow part of the jet pump is determined. The mathematical model of flow mixing is supplemented with computer modelling data using the SolidWorks program. The presented research results made it possible to obtain an analytical expression for determining the velocity profile exclusively for the inlet section of the production inlet chamber and cannot be used to analyse the dynamics of changes in the kinematic field when the mixed flow propagates in the direction of the jet pump diffuser.

Researcher S. Karabaev (2021) notes that the optimal length of the production inlet chamber of a jet device should be in the range from 20 to 22. The optimal design of the jet device was obtained during bench tests of a gas-liquid oil ejector. The diameters of the working nozzle and production inlet chamber of the studied models were 3.3 mm and 5.4 mm, respectively. In the course of research, three models of jet pumps with a relative length of the production inlet chamber were used: L_{i3} = 11.1; 20.37; and 29.63. Industrial water was used for the operating flow, and atmospheric air was used for the injected flow. Bench tests were performed for different pressure ratios of the injected flow. The criteria for optimising the design of a gas-liquid ejector were the efficiency value and the injection coefficient value. According to the author, a significant excess of the optimal length of the production inlet chamber obtained during bench tests in comparison with the results obtained by the author is associated with the gaseous state of the injected flow. Due to the different aggregate state, the formation of a homogeneous gas-liquid emulsion requires a longer path length than the alignment of velocity profiles in a single-phase flow. The low density and viscosity of the injected flow have a significant effect on the production inlet length of the flow.

The nature of the distribution of axial velocities along the flow part of the jet pump obtained by the author is consistent with the results of studies conducted at Xi'an University of Technology (China) by T. Cao *et al*. (2023). In this paper, when analysing the operating process of an ultra-long ejection system, the inverse nature of the dependence of the operating flow rate on the distance to the inlet section of the production inlet chamber of a jet pump is confirmed. The increase in the operating flow rate at the entrance to the production inlet chamber of a jet pump is associated with the conical shape of its initial section, in contrast to the cylindrical production inlet chamber of constant diameter in the models studied by the author. The decrease in the speed of the operating flow along the production inlet chamber of the jet pump is explained by a decrease in its kinetic energy, part of which is spent on increasing the speed of the injected flow. Given that the nature of changes in the kinematic parameters of the injected flow is not presented in this paper, the conducted studies do not allow us to determine the distance to the inlet section of the production inlet chamber, which corresponds to the alignment of the velocity profile of the mixed flows.

The formation of a parabolic velocity distribution in the end sections of the production inlet chamber is confirmed by modelling the operating process of the NSFB 39/45 oil jet pump using the ANSYS software environment. A. Rogovyi *et al.* (2022). The speed of the injected and mixed flow during the construction of the computer model was assumed to be 16 m/s and 19.5 m/s, respectively. In the course of research, a cavitation mass transfer model based on the Rayleigh-Plesset equation was implemented, which made it possible to take into account the possibility of reducing the pressure in the flow part of the jet pump to the pressure of saturated vapours of well products. The article shows the velocity profiles of the mixed flows for different distances from the inlet section of the production inlet chamber, but the reverse flow of the liquid caused by cavitation led to a shift in the transit flow and a distortion of the kinematic field in the flow part of the jet pump. The significant asymmetry of the obtained velocity profiles made it impossible to determine the area of stabilisation of kinematic flow parameters and establish the optimal length of the production inlet chamber of the jet pump obtained from the results of this study.

The nature of the relationship between the ratio of the mixing path length of the flows, the axial dimensions of the production inlet chamber, and the efficiency of the ejection system is confirmed by the results of studies conducted by J. Zheng *et al*. (2022) at the China Clean Energy Research Institute. In the course of comparative studies, the hydraulic characteristics of two models of jet devices with different lengths of the production inlet chamber were determined. In one of the studied models, the length of the production inlet chamber was equal to the length of the flow mixing path, and in another model, the alignment of velocity profiles was completed at the initial section of the diffuser. According to the results of the conducted studies, if the flow mixing process is completed in the diffuser part of the jet device, the flow rate of the mixed flow is reduced by 15.6%. The disadvantage of the results of the conducted research is the lack of an analytical expression that would combine the optimal length of the production inlet chamber of the jet pump and the pressure, cavitation and energy characteristics of the ejection system. Insufficient geometric, kinematic and hydrodynamic similarity of the working processes of ejection systems does not allow us to generalise the results obtained and effectively use them in the case of differences in the absolute and relative geometric dimensions of the elements of the flow part of the jet pump, the ratios of velocities, costs and pressures of mixed flows.

Conclusions

Hydraulic losses during the mixing of flows are associated with vortex formation in the shear boundary layer due to a significant difference in the velocity of the operating and injected flows and linear pressure losses in the production inlet chamber of the jet pump. Linear pressure losses in the production inlet chamber persist after the process of levelling the profile of kinematic parameters is completed and are characterised by high velocity values and a turbulent mode of mixed flow. Determining the length of the production inlet chamber section that corresponds to the completion of the speed equalisation process increases the energy efficiency of the jet pump operating process. The obtained velocity profiles of mixed flows at the entrance to the production inlet chamber have a three-layer structure with a predominantly uniform distribution of kinematic parameters in the central region at the inlet sections of the operating and injected flow and close to uniform distribution in the peripheral region. A section with a nonlinear distribution of kinematic parameters is located between the central and peripheral regions. The width of the central and peripheral regions decreases as the distance to the production inlet chamber of the jet pump increases. In the direction of the jet pump diffuser, the velocity profile of the mixed flows becomes parabolic.

The maximum values of the movement velocity of mixed flows occur on the axis of the jet pump. The maximum value of the operating flow rate corresponds to the inlet cross-section of the production inlet chamber of the jet pump and does not depend on its length. The limit value of the injected flow rate decreases as the length of the production inlet chamber of the jet pump increases. As the distance to the inlet section of the production inlet chamber increases, the axial velocity of the mixed flows decreases according to asymptotic dependence. The length of the production inlet chamber of the jet pump was determined, which ensures the stabilisation of the values of kinematic parameters and minimal energy loss when levelling the velocity profiles of the operating and injected flows. The determination of the axial velocity stabilisation region can be used to select the optimum length of the production inlet chamber of the jet pump, which ensures maximum efficiency of the ejection system. The task of further research is to develop a system for automated selection of the optimal length of the production inlet chamber of a jet pump in accordance with the existing operational factors.

Acknowledgements

None.

Conflict of Interest

None.

References

[1] Cao, T., Chen, X.-Y., Yu, K.-A., & Tang, L. (2023). Hydraulic modeling and optimization of jet mill bit considering the characteristics of depressurization and cuttings cleaning. *Petroleum Science*, 20(5), 3085-3099. doi: 10.1016/j.petsci.2023.04.007.

[2] Chen, X., Cao, T., Yu, K., Gao, D., Yang, J., & Wei, H. (2020). Numerical and experimental investigation on the depressurization capacity of a new type of depressure-dominated jet mill bit. *Petroleum Science*, 17, 1602-1615. doi: 10.1007/s12182-020-00472-8.

[3] Cho, Y.-D., & Shrestha, U. (2020). Cavitation performance improvement of an annular jet pump by j-groove. *The KSFM Journal of Fluid Machinery*, 23(4), 25-35. doi: 10.5293/kfma.2020.23.4.025.

[4] Deng, X., & Dong, J. (2021). Experimental and numerical investigation of two-phase flow and mass transfer in a self-excited oscillation pulse jet pump. *Experimental and Computational Multiphase Flow*, 3(2), 131-136. doi: 10.1007/s42757-020-0062-6.

[5] Gan, J., Wang, Y., Wang, D., & Zhang, K. (2022). Research on the law of head loss of jet pumps in the cavitation state. *ACS Omega*, 7, 12661-12679. doi: 10.1021/acsomega.1c06895.

[6] Karabaev, S. (2021). Investigations of the liquid-jet gas pump's mixing throat lengths for well operations and associated petroleum gas utilization. *IOP Conference Series: Earth and Environmental Science*, 666, article number 062003. doi: 10.1088/1755-1315/666/6/062003.

[7] Kotak, V., Pathrose, A., Sengupta, S., Gopalkrishnan, S., & Bhattacharya, S. (2023). Experimental investigation of jet pump performance used for high flow amplification in nuclear applications. *Nuclear Engineering and Technology*, 55(10), 3549-3559. doi: 10.1016/j.net.2023.06.017.

[8] Kryzhanivskyi, Ye.I., & Panevnyk, D.O. (2019). The study on the flows kinematics in the jet pump's mixing chamber. *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu*, 1, 62-68. doi: 10.29202/nvngu/2019-1/7.

[9] Kumar, V., Subbarao, P.M.V., & Singhal, G. (2019). Effect of nozzle exit position (NXP) on variable area mixing ejector. *SN Applied Sciences*, 1, article number 1473. doi: 10.1007/s42452-019-1496-y.

[10] Kurniawan, A., Nuzuladzmi, R.N., & Afni, A.L.N. (2023). CFD simulation and efficiency analysis of natural gas ejector-booster system. In *National seminar on chemical engineering "Kejuangan". Development of chemical technology for processing of natural resources of Indonesia* (pp. 1-10). Yogyakarta: UPN "Veteran" Yogyakarta.
[11] Morrall, A., Quayle, S., & Campobasso, M.S. (2020). Turbulence modelling for RANS CFD analyses of multi-nozzle annular jet pump swirling flows. *International Journal of Heat and Fluid Flow*, 85, article number 108652. doi: 10.1016/j.ijheatfluidflow.2020.108652.
[12] Qian, Y., Wang, Y., Fang, Z., Chen, X., & Miedema, S.A. (2021). Numerical investigation of the flow field and mass transfer characteristics in a jet slurry pump. *Processes*, 9(11), article number 2053. doi: 10.3390/pr9112053.
[13] Rogovyi, A., & Lukianets, S. (2022). Kinematic parameters of the oil flow in a vortex chamber pump. *Bulletin of the National Technical University "KhPI". Series: Hydraulic Machines and Hydraulic Units*, 1, 59-65. doi: 10.20998/2411-3441.2022.1.09.
[14] Rogovyi, A., Kostiuk, M., & Azarov, A. (2022). Improving energy parameters of oil jet pumps. *Bulletin of the National Technical University "KhPI". Series: Hydraulic Machines and Hydraulic Units*, 1, 25-32. doi: 10.20998/2411-3441.2022.1.04.
[15] Wang, Z., Lei, Y., Wu, Z., Wu, J., Zhang, M., & Liao, R. (2023). Structure size optimization and internal flow field analysis of a new jet pump based on the taguchi method and numerical simulation. *Processes*, 11(2), article number 341. doi: 10.3390/pr11020341.
[16] Xu, K., Wang, G., Wang, L., Yun, F., Sun, W., Wang, X., & Chen, X. (2020). Parameter analysis and optimization of annular jet pump based on Kriging model. *Applied Sciences*, 10(21), article number 7860. doi: 10.3390/app10217860.
[17] Xu, K., Wang, G., Zhang, L., Wang, L., Yun, F., Sun, W., Wang, X., & Chen, X. (2021). Multi-objective optimization of jet pump based on RBF neural network model. *Journal of Marine Science and Engineering*, 9(2), article number 236. doi: 10.3390/jmse9020236.
[18] Yang, Y., Wu, S., Wang, C., Jiao, W., Ji, L., An, C., & Ge, J. (2023). Effect of effuser throat diameter on the internal flow structure and energy characteristics of the jet pump. *Energy Reports*, 9, 2075-2086. doi: 10.1016/j.egyr.2023.01.025.
[19] Zafarullah, E., Ansari, U., Habibullah, H., Ahmed, I., & Ahmed, M. (2021). Developing well performance analysis for improving the pump capacity of jet pumps using snap software. *International Journal of Current Engineering and Technology*, 11(2), 168-172. doi: 10.14741/ijcet/v.11.2.4.
[20] Zheng, J., Hou, Y., Tian, Z., Hongkui, J., & Chen, W. (2022). Simulation analysis of ejector optimization for high mass entrainment under the influence of multiple structural parameters. *Energies*, 15(19), article number 7058. doi: 10.3390/en15197058.

Дослідження кінематичного поля змішуваних потоків

Олександр Паневник

Доктор технічних наук, професор
Івано-Франківський національний технічний університет нафти і газу
76019, вул. Карпатська, 15, м. Івано-Франківськ, Україна
https://orcid.org/0000-0003-2765-3776

Анотація. Актуальність дослідження визначається здатністю свердловинних струминних насосів підвищити ефективність реалізації технологічних процесів у складних гірськогеологічних умовах. Мета полягала у встановленні закономірностей трансформації профілю швидкостей у камері змішування свердловинного струминного насоса на основі побудови та наступного аналізу розподілу кінематичних параметрів сумарного робочого та інжектованого потоків. Моделювання робочого процесу ежекційної системи здійснено в програмно-розрахунковому модулі ANSYS для чотирьох тривимірних моделей свердловинного струминного насоса. Геометричні моделі побудовані з нерівномірною у місцях складної геометрії та високого градієнта зміни гідродинамічних параметрів щільністю розміщення розрахункових елементів. Для кожної з досліджуваних моделей побудовано серію профілів швидкостей розміщених через рівні проміжки на різних відстанях від вхідного перерізу камери змішування. Побудовані профілі швидкостей включають ділянки з рівномірним та нелінійним розподілом кінематичних параметрів змішуваних потоків. Встановлено, що максимальні значення швидкості руху змішуваних потоків мають місце на осі струминного насоса та є однаковими для всіх досліджених моделей. Осьова швидкість руху змішуваних потоків зменшується при збільшенні відстані до вхідного перерізу камери змішування. Мінімальне значення осьової швидкості отримано для моделі струминного насоса з максимальною довжиною камери змішування. Для двох моделей струминного насоса з довжиною камери змішування 287 мм та 328 мм отримано стабілізацію значень осьової швидкості сумарного робочого та інжектованого потоків. Незмінність кінематичних параметрів для даних моделей струминного насоса свідчить про завершення процесу вирівнювання швидкостей змішуваних потоків. Враховуючи, що у випадку перевищення необхідних розмірів ділянки стабілізації кінематичних параметрів зростають гідравлічні втрати в проточній частині ежекційної системи, її оптимальна конструкція відповідає моделі з довжиною камери змішування струминного насоса 287 мм. Практична цінність дослідження полягає в тому, що така конструкція забезпечує максимальний коефіцієнт корисної дії свердловинного струминного насоса

Ключові слова: свердловинний струминний насос; ежекційна система; камера змішування; профіль швидкостей; розподіл кінематичних параметрів; стабілізація потоку