

The study of hydromechanical characteristics of a well jet pump

Badanie charakterystyk hydromechanicznych otworowej pompy strumieniowej

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ABSTRACT: A principle is proposed for the joint analysis of the hydrodynamic and strength characteristics of the elements of a downhole oil jet pump. Using ANSYS software, a 3D model of the ejection system was constructed, with is the geometric space limited by the boundary surfaces drawn through the annular section of the ejection system's annular space, the suction line connecting the receiving chamber of the jet pump with the sub-packer diagonal and the outlet section diffuser. Fluid and solid mesh models were generated using virtual topology tools and a condensed layout of calculated finite elements in places of complex geometry and high pressure gradients. Stress in the body elements of the jet pump is caused by the difference in pressure acting on the outer and inner surfaces, accompanied by changes in the configuration of the flow path. The distribution of forces within the elements of the downhole ejection system was systematized: the working nozzle is subjected to tensile stress, while the receiving chamber, mixing chamber and diffuser of the oil jet pump are subjected to compressive stress. An increase in the magnitude of compressive stresses in the body elements of the jet pump toward the outlet section of the diffuser was calculated. Numerical modelling results indicate that the body elements of the receiving chamber and the outlet section of the jet pump diffuser are subjected to the heaviest loads. In experimental studies, the operating parameters of the ejection system corresponding to the occurrence of maximum stress compression in the jet pump components were determined. The maximum stresses in the body elements of the jet pump correspond to the minimum values of the injection coefficient of the jet pump, which are observed at the initial stage of formation fluid during the oil wells development. The results obtained support the recommendation to increase the internal diameter of the jet pump, which, under compressed well conditions, ensures an increase in its productivity without altering external overall dimensions.

Key words: oil jet pump, ejection system, stress-strain state, tensile and compressive stress, finite element analysis, equivalent stresses, cavitation, injection coefficient, operating parameters.

STRESZCZENIE: W artykule zaproponowano zasadę wspólnej analizy charakterystyk hydrodynamicznych i wytrzymałościowych elementów otworowej pompy strumieniowej służącej do wydobywania ropy naftowej. Z wykorzystaniem oprogramowania ANSYS zbudowano trójwymiarowy model układu wyrzutowego, którego przestrzeń geometryczna została ograniczona powierzchniami granicznymi poprowadzonymi przez pierścieniowy przekrój przestrzeni pierścieniowej układu eiekcyjnego, przewód ssawny łączący komorę odbiorczą pompy strumieniowej z przekątną strefy pod pakierem oraz przekrój wylotowy dyfuzora. Modele siatkowe cieczy i bryły stałej wygenerowano z użyciem narzędzi topologii wirtualnej oraz zagęszczonego rozmieszczenia obliczeniowych elementów skończonych w miejscach o złożonej geometrii i dużych gradientach ciśnienia. Naprężenia w elementach korpusu pompy strumieniowej są wywołane różnicą ciśnień działających na powierzchnię zewnętrzną i wewnętrzną, przy jednoczesnych zmianach konfiguracji kanału przepływowego. Usystematyzowano rozkład sił w obrębie elementów głębokiego układu eiekcyjnego: na dyszę roboczą działają naprężenia rozciągające, natomiast na komorę odbiorczą, komorę mieszania i dyfuzor pompy strumieniowej działają naprężenia ściskające. Obliczono wzrost wartości naprężeń ściskających w elementach korpusu pompy strumieniowej w kierunku przekroju wylotowego dyfuzora. Wyniki modelowania numerycznego wskazują, że elementy korpusu komory odbiorczej oraz przekroju wylotowego dyfuzora pompy strumieniowej są poddane największym obciążeniom. W badaniach eksperymentalnych określono parametry pracy układu wyrzutowego odpowiadające występowaniu maksymalnych naprężeń ściskających w komponentach pompy strumieniowej. Maksymalne naprężenia w elementach korpusu pompy strumieniowej odpowiadają minimalnym wartościom współczynnika iniekcji, które występują na początkowym etapie napływu płynu złożowego podczas rozruchu odwiertów ropy naftowej. Uzyskane wyniki uzasadniają zalecenie zwiększenia średnicy wewnętrznej pompy strumieniowej, co w warunkach ograniczonej przestrzeni odwiertu umożliwia zwiększenie jej wydajności bez zmiany zewnętrznych wymiarów całkowitych.

Słowa kluczowe: pompa strumieniowa do wydobywania ropy naftowej, układ wyrzutowy, stan naprężeń i odkształceń, naprężenia rozciągające i ściskające, analiza metodą elementów skończonych, naprężenia zredukowane, kawitacja, współczynnik wttrysku, parametry eksploatacyjne.

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Introduction

The industrial application of hydraulic jet pumps began in the 1950s. While in the previous century the use of hydraulic jet pumps was considered a supplementary technology, today oil and gas injection technologies have gained independent significance and are capable of addressing a wide range of tasks involved in the performance of most technological operations of the development of hydrocarbon deposits. Hydraulic jet pumps are currently employed in the direct deepening of wells in order to increase the efficiency of the core output and improve the technical and economic indicators of drilling (Wyrostkiewicz and Panevnyk, 2022). They are also used for removing foreign objects left on the wells and for eliminating drill string catches. The combined use in of jet pumps, milling cutters and magnetic systems (Coll et al., 2013) makes it possible to increase the efficiency of foreign objects removal from wells compared to conventional well-cleaning equipment (Romanyshyn et al., 2020). The design of above-bit jet pumps allows their use in combinations with serial bits and other downhole equipment (Panevnyk et al., 2018). A significant advantage of ejection technologies lies in the ability of jet pumps to maintain performance under difficult mining and geological conditions and particularly when drilling in environments with abnormally low pressures (Melnikov and Buglov, 2023) and during the construction of deep wells.

The development of wells using jet pumps reduces the duration of operations required to induce an influx of formation fluid and contributes to an increased oil recovery rate throughout the subsequent operational period of the well. The technology for inducing the influx of formation fluid involves integrating a jet apparatus in the downhole assembly (Shaidakov et al., 2018) or surface equipment (Lyakh et al., 2017). Advances in the design of surface-based jet devices reflect a broader trend in the development of vortex ejection systems (Kaliuzhnyi et al., 2022). Well development operations can be combined with geophysical studies of the productive horizon (Wibisono and Sitaresmi, 2020). The use of a jet pump as part of a universal well assembly enhances the efficiency of both production processes. The hydrojet method of oil extraction enables an increased rate of product selection at the initial stages of operation of shale wells (Panevnyk, 2021). The simple design of the jet pump and its ability to maintain performance in aggressive environments and in the presence of mechanical impurities allow for prolonged, economically viable operation of depleted hydrocarbon deposits. A significant reduction in the cost of implementing the hydrojet method of oil recovery is achieved through the development of a hydraulic method for replacing ejection system components in a well, thereby eliminating the need for traditional, costly tripping

operations. The effectiveness of the hydro jetting method of operating oil wells has further improved with the advent of gas engines for surface pumping units. These engines are driven by flared petroleum gas from the same well, thereby reducing the overall cost of hydrocarbon production. Heating the working flow that drives a downhole jet pump enhances the production efficiency of high-viscosity oils (Singh et al., 2013). The addition of targeted inhibitors to the working fluid (Yoshimoto et al., 2020) prevents wax deposition and mitigates corrosion of downhole equipment. The energy characteristics of a jet pump can be improved by swirling the mixed flows, however, the generation of vortex flows increases the risk of cavitation phenomena occurring in the working environment (Yakimechko, 2014).

Originally developed in the late 1950s, the technology for washing sand plugs using a jet pump (Jia et al., 2023) has been enhanced by integrating the ejection system with a flexible pipe string. The rapid advancement of this technology is due to the widespread adoption of multi-stage hydraulic fracturing.

Utilization of low-pressure oil gas accumulated in the free space of oil reservoirs and in the separators of the well production collection and treatment system is one of the traditional applications of ejection technologies (Leagas et al., 2016). Jet devices offer technical and economic advantages compared to traditional compressors for oil gas recovery systems and require less installation space. The latter characteristic has contributed to the use of jet devices on offshore platforms.

One of the promising directions for the development of ejection technologies is the advancement of hybrid methods of oil production (Wang et al., 2023). Currently, jet-fountain, jet-gas-lift, jet-electric centre, jet-plunger and jet-vortex (Rogovyi et al., 2023) well assemblies have become widespread. Experimental efforts are underway to introduce jet-screw deep-well pumping units. The combination of traditional oil and gas production methods with hydrojet enables the benefits of both types of well assemblies to be obtained.

The development of ejection technologies has led to the emergence of new applications of hydraulic jet pumps. The ability of ejection systems to create a low-pressure zone has enabled the development of riser tubing hydrate elimination technology, in which a jet pump is lowered into the wellbore on a coiled tubing string (Duque et al., 2012). As the jet pump moves, a mobile low pressure zone is created in the riser pipe string. Low pressure facilitates the transition of hydrate formations from the solid to the liquid phase, allowing the resulting liquid to be transported to the surface along with the well production. Another example of the advancement of ejection technologies is the development of a method for using surface jet pumps to improve the efficiency of pipeline transport of water-cut, high-viscosity oil (Toteff et al., 2022).

Despite the wide range of applications and the widespread use of oil and gas hydrojet technologies, studies on the operating process of downhole ejection systems remain limited, with existing research primarily focusing of identifying patterns related to pressure-flow (Qian et al., 2021), cavitation (Xu et al., 2022), energy (Xu et al., 2021) and vortex (Rogovyi et al., 2021) characteristics of jet pumps as well as the interaction of jets with non-uniform distribution of hydrodynamic (Ivaniv et al., 2021) and operating parameters (Cherniuk et al., 2021). Some studies are devoted to the analysis of the processes of water-abrasive wear of the elements of the flow part of a jet pump (Mohammed, 2016) and the determination of the minimum acceptable thickness of the wall of its receiving chamber from a strength perspective (Velychkovych and Panevnyk, 2017). The limited number of studies focused on the strength characteristics of jet pump components contributes to premature failure of the elements of the downhole ejection system.

The purpose of the study is to establish the relationship between the hydrodynamic and strength characteristics of the downhole ejection system based on simulation modelling of its operating process and experimental determination of operating parameters corresponding to the maximum effective stresses in jet pump components.

Establishing the relationship between the hydrodynamic and strength characteristics of the well ejection system involves two stages of research:

- analysis of the distribution of equivalent stresses in characteristic sections of the ejection system under conditions of variable pressure based on simulation modeling;
- establishment of the experimental dependence of the pressure at the inlet to the receiving chamber of the jet pump on the main design and operating parameters of the ejection system.

Oil jet pump design

The oil jet pump consists of a diffuser (3), a mixing chamber (4) located inside the receiving chamber (5) of the working nozzle (6) and a distribution sleeve (7) (Figure 1). The working nozzle is connected to the annular channel via the radial channel of the distribution sleeve and two radial holes. The diagram of the ejection system presented in Figure 1 assumes a parallel orientation of the injected and mixed flows. Separation of the working flow line from the injected flow line is achieved using a packer (8), which is installed between the lifting and production string. The working flow enters the receiving chamber at a right angle. A characteristic feature of the working process of the ejection system is the formation of a low-pressure zone at the outlet of the working nozzle, which creates the conditions

for suction of formation fluid from the sub-packer zone into the receiving chamber of the jet pump.

The design of an oil jet pump is determined by the following geometric dimensions:

- working nozzle diameter, $d_w = 8.4$ mm;
- mixing chamber diameter, $d_m = 13.3$ mm;
- ratio of the areas of the mixing chamber and the working nozzle, $K_p = 2.507$;
- absolute distance between the working nozzle and the mixing chamber, $l_w = 14.039$ mm;
- relative distance between the working nozzle and the mixing chamber, $\bar{l}_w = l_w/d_w = 1.671$;
- absolute length of the mixing chamber, $l_m = 80$ mm;
- relative length of the mixing chamber $\bar{l}_m = l_m/d_m = 6.015$;
- outlet diameter of the diffuser, $d_d = 60$ mm;
- diffuser length, $l_d = 303$ mm;
- diameter of the radial inlet holes in the housing for the input of the working flow, $d_h = 14$ mm;
- diffuser opening angle, $\alpha_d = 8^\circ$;

The pressure in the annular space formed by the riser pipe string (1) and the production string (2), depending on the depth

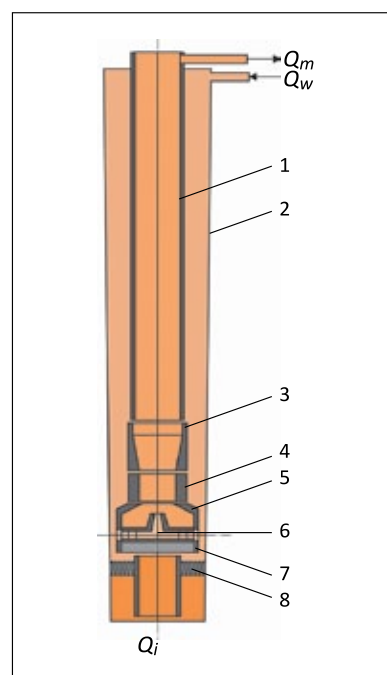


Figure 1. Schematic diagram of an oil jet pump: 1 – tubing string; 2 – production string; 3 – diffuser; 4 – mixing chamber; 5 – receiving chamber; 6 – working nozzle; 7 – distribution sleeve; 8 – packer; Q_w – flow rate of the working flow; Q_m – mixed flow rate; Q_i – flow rate of the injected flow

Rysunek 1. Schemat ideowy pompy strumieniowej do wydobywania ropy naftowej: 1 – kolumna rurowa tłocząca; 2 – kolumna produkcyjna; 3 – dyfuzor; 4 – komora mieszania; 5 – komora ssąca; 6 – dysza robocza; 7 – tuleja rozdzielająca; 8 – pakier; Q_w – natężenie przepływu medium roboczego; Q_m – natężenie przepływu medium zmieszanego; Q_i – natężenie przepływu medium wtryskiwanego

of the well and the density of the working medium, can reach 40–50 MPa or higher. At the same time, a vapor–gas cavity may form in the flow section of the jet pump, where the absolute pressure approaches zero.

The nature of the loads acting on the elements of the ejection system, caused by the action of the pressure difference in the annulus of the well, in the sub-packer zone and the flow part of the jet pump, was analysed. The pressure in the sub-packer zone exceeds that in the receiving chamber of the pump, as a result of which the distribution sleeve (7) is subjected to bending stress (i.e., stress induced in the material during bending due to action of distorting forces). The stress-strain state of the distribution sleeve (7) is further complicated by the presence of stress concentrators in the form of radial channels for supplying the working flow and axial channels for suction of formation fluid. Tensile stresses (i.e., normal stresses caused by internal forces) occur in the material of the working nozzle (6), and compressive stress (i.e., normal stresses caused by external forces) occurs in the receiving chamber (5), mixing chamber (4) and diffuser (3). Considering the formation of a low pressure zone in the outlet section of the working nozzle, the cylindrical section of the receiving chamber (5) is the heavily loaded element of the jet pump.

Features of building a model of the stress-strain state of jet pump elements

Modeling the relationship between the hydrodynamic and strength characteristics of individual elements of a downhole jet pump involves the development of a 3D model of an oil jet pump, the creation of mesh models of liquid and a solid body, the generation of distribution diagrams of hydrodynamic parameters of mixed flows, and the calculation of the strength characteristics of individual jet components.

A 3D model (Figure 2a) of an oil jet pump with a diameter of 89 mm was constructed using the Autodesk Inventor software.

The selection of the design volume configuration is determined by the nature of the hydraulic connection between the working and injected flows. Based on this criterion, two groups of downhole ejection systems can be distinguished: jet pumps with hydraulically connected and separate supply lines for the working and injected flow and mixed flow outlet. The first group includes above-bit ejection systems of traditional design and jet pumps for bottom-hole cleaning. The second group comprises packer and two-pipe oil jet pumps and above-bit suction ejection systems with a movable seal located in the annular channel between the outlet section of the diffuser and the inlets of the slurry channels. The oil jet pump under study

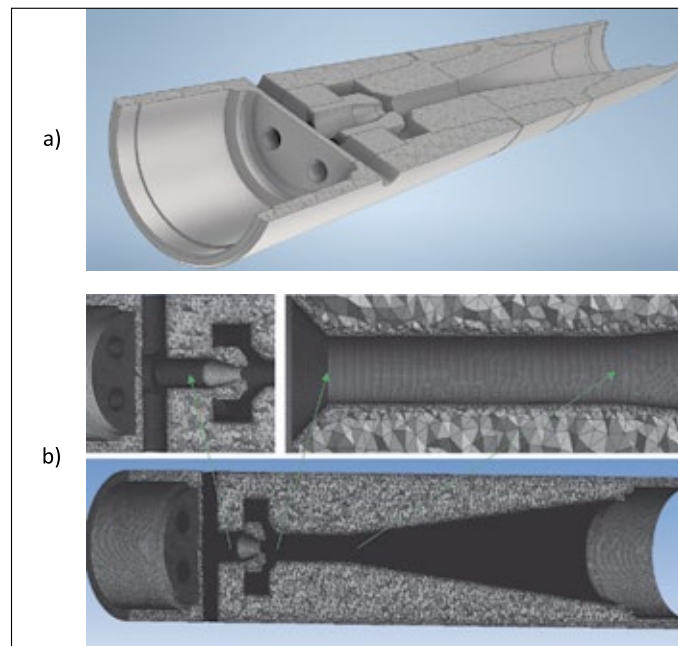


Figure 2. A 3D model (a) and a mesh model (b) of the solid body of an oil jet pump

Rysunek 2. Model 3D (a) oraz model siatkowy (b) bryły pompy strumieniowej do wydobywania ropy naftowej

is characterised by separate lines for supplying the working and injected flow and discharging the mixed flow. For this design of the ejection system, the design volume is limited to three boundary surfaces drawn through the characteristic sections of the ejection system: the inlet of the working and injected flows and the outlet of the mixed flow. The analysis of the stress-strain state of the jet pump elements imposes additional requirements on the definition of the design volume of the ejection system: a boundary surface that determines the influence of the working flow, drawn through the annular channel of the annulus at the level of the upper section of the bottom-hole assembly. This configuration of the design volume makes it possible to account for the pressure acting on the outer surface of the jet pump.

Using the built-in Ansys Fluent module, the following design limit conditions were selected:

- working flow rate $Q_w = 1.215 \times 10^{-3} \text{ m}^3/\text{s}$ is designed for the inlet channel of the internal annulus between the riser pipes and the production casing, which is connected through radial channels to the working nozzle (6) (Figure 1);
- injected flow rate $Q_i = 0.28 \times 10^{-3} \text{ m}^3/\text{s}$ is specified in the axial channels of the distribution sleeve (7) (Figure 1);
- mixed flow pressure $P_m = 24.31 \text{ MPa}$, selected at the outlet of the diffuser, adjusted for the formation of reverse flows.

Typical boundary conditions, no-slip conditions, and standard wall functions for wall modelling were applied to solid surfaces limiting the flow path of a jet pump.

The construction of mesh models and subsequent computational operations were carried out using Ansys Workbench modules. The optimal configuration, dimensions and number of mesh elements were determined based on the design characteristics and operating conditions of downhole ejection systems. During the mesh model construction, maximum density of finite elements was applied in regions exhibiting high gradients of changes in the hydrodynamic parameters of mixed flows. Based on practical experience in modelling the operating process of ejection systems, it was established that regions with a higher density of finite elements should be localized at the final conical section of the receiving chamber and at the initial section of the mixing chamber of the jet pump. To increase the reliability of modelling results, the automatically generated finite element mesh was adapted to the conditions of velocity profiles transformation in the area of potential working and injected flows and in the shear layer placed between them.

To ensure high-quality of numerical modelling results, Ansys Mosaic meshing technology was used, enabling increased accuracy of the mesh model in volumes limited by complex geometry. Enlarged mesh models of such regions are shown in the upper portion of Figure 2b. Computational fluid dynamics (CFD) modelling was performed in steady-state in an absolute coordinate system. Particular attention was paid to mesh element sizes in areas that are directly in contact with mixed flows. To improve the quality of which additional modules of surface and volume geometric topology were used. The model constants were taken as typical: $C_\mu = 0.09$, $C_{1\epsilon} = 1.44$, $C_{2\epsilon} = 1.92$. Wall roughness conditions corresponded to realistic technological parameters of the treated steel surfaces: a roughness height of 0.00015 m with a standard roughness constant of 0.5 were applied. For the fluid model, the surface mesh was generated with a minimum element size of 0.0006 m, a maximum of 0.004 m, and a growth factor of 1.2. The volume mesh was created using the Poly-Hexcore (Fluent Mesh Solver) method, which combines polyhedral and hexagonal elements with prismatic boundary layers for an accurate description of turbulent effects. The use of two buffer layers resulted in increased resolution near the walls. The volume of mesh element size ranged from 0.0006 to 0.001 m, enabling an effective balance between accuracy and resource consumption of numerical calculations. For numerical modelling of the stress-strain state, the average element quality index was 0.72, with a maximum of 1.0, and a minimum fixed at 0.91. Medium smoothing was employed during the meshing process to ensure a balance between quality and numerical stability of the model. The minimum element size was set at 2×10^{-3} m and the diagonal length of the computational domain was 0.5 m, ensuring sufficient resolution for a detailed stress analysis in

critical structural regions. The average element density for the fluid model was 6.02×10^8 elements per m^3 , and for the solid model – 4.28×10^8 elements per m^3 . Convergence in CFD calculations was achieved by reducing the residuals of the basic equations (momentum, kinetic energy of turbulence and its dissipation rate) to 10^{-6} , confirming the stability and accuracy of the calculations. Second Order Upwind discretization was applied to the basic equations and the Least Squares Cell-Based method for the gradients. To calculate the stress-strain state, the Sparse Direct Solver method was used with a convergence criterion for residual reactions at the anchor points set to not exceed 0.5% of the maximum reaction forces. The use of the Boundary Layer module enabled an increase in the mesh element number in regions of the geometry adjacent to the surface by influencing the local size of the computational mesh element. The MultiZone module allowed for automatic decomposition of the geometry into mapped structured areas and free (unstructured) regions with the subsequent construction of a „clean” hexagonal mesh and filling of complex areas with an unstructured mesh.

The final elements in the flow domain were tetrahedrons, while layers of prismatic cells were generated in the vicinity of solid surfaces. The use of a non-uniform mesh model made it possible to improve the duration of computational procedures. The fluid and solid mesh models contained 2895684 and 3876278 calculated finite elements, respectively.

The movement of the working and injected flows in the mixing chamber of a jet pump is characterized by the presence of shear flow and a pressure gradient, determined by a system of Navier-Stokes differential equations. The introduction of the average Reynolds number into the Navier-Stokes equation renders the system of equations unclosed due to the appearance of additional unknowns in the form of Reynolds stresses. To resolve this, the equations of motion of mixed flows using the Fluent software module are supplemented with the realizable $k-\epsilon$ turbulence model, which enables prediction of the propagation of coaxial jets taking into account their rotation, shear flows in the fluid boundary layer, recirculation and the presence of pressure gradients. In modelling turbulence, a turbulence intensity of 5% and a viscosity ratio (Turbulent Viscosity Ratio) of 10 were adopted. According to the adopted turbulence model, the Navier-Stokes equations are supplemented with relations incorporating convection and diffusion of turbulent energy.

Modelling of the flow mixing process is using a pressure-based solver that employs an iterative method for solving nonlinear equations. The adopted type of solver implements a sequential (separate) solution of analytical dependencies. The iterative solution method was adopted due to the nonlinearity of the basic equations describing the mixing flows. To imple-

ment the computational algorithm, the time condition was set as „steady state-flow process” and the velocity equation was defined as „velocity formulation (absolute)”.

Results of modelling the stress-strain state of jet pump elements

The authenticity of the constructed model was assessed through the analysis of the kinematic field and the nature of the pressure distribution in the flow path of the jet pump. The pressure value in the flow part of the jet pump ranged from $P_{\min} = 24.13$ MPa to $P_{\max} = 24.5$ MPa, with the maximum flow velocity recorded at $V_{\max} = 24.3$ m/s (Figure 3).

According to the results of modelling the hydrodynamic parameters of mixed flows, the minimum pressure value and maximum flow rate occur in the area located at the outlet of the working nozzle of the jet pump. The maximum pressure was noted in the annular channel between the jet pump housing and the well wall. The width of this area decreases towards the diffuser and reaches zero values in the central section of the mixing chamber. The inlet peripheral section of the mixing chamber displayed a uniform velocity and pressure profile, the width of which decreases along the flow direction. The non-uniform distribution of velocity and pressures decreased in the direction of the outlet section of the mixing chamber. In the direction of the diffuser, a gradual restoration of pressure and a decrease in the movement velocity of the mixed flows were noted. A characteristic feature was the asymmetrical distribution of hydrodynamic parameters, associated with the formation of vortex regions in certain sections of the flow part of the jet pump.

The pressure in the outlet section of the diffuser ranged between the pressure of the flow upstream of the working nozzle and the pressure of the injected flow at the entrance to the receiving chamber. This relationship of the jet pump parameters ensures the existence of a working section of the pressure characteristic, which is defined by positive values of the relative pressure and the injection coefficient. The distribution diagrams of hydrodynamic parameters obtained during the modelling process allow for control of the ratio of the mentioned pressures. The pressure in the central region of the working flow and the peripheral zone of the injected flow at the outlet of the receiving chamber significantly exceeds the saturated vapor pressure of the pumped liquid, which clearly indicates the implementation of a non-cavitation operating mode of the jet pump. The hydrostatic pressure generated by the column of working fluid compensates for the decrease in pressure in the flow path of the jet pump caused by hydraulic losses in the working nozzle.

The stress in the jet pump body is caused by the difference in pressures acting on the outer surface and in the flow path. The pressure on the outer surface of the jet pump, according to the modelling results, is 24.5 MPa, and the change in pressure in the flow path is presented in Figure 3a. The distribution of equivalent stresses reflects the change in pressure difference along the flow path of the jet pump (Figure 4), taking into account the diameter of its elements. The magnitude of equivalent stresses in the jet pump parts ranged from $\sigma_{\min} = 4.49$ MPa to $\sigma_{\max} = 44.63$ MPa.

The values of equivalent stresses are determined at characteristic points (Figure 4) of the jet pump elements (Table 1). The maximum stresses in the housing elements were observed in the receiving chamber of the jet pump (characteristic points 3, 5 and 6). This is due to the minimum pressure value and the maximum pressure difference acting on the wall of the receiving

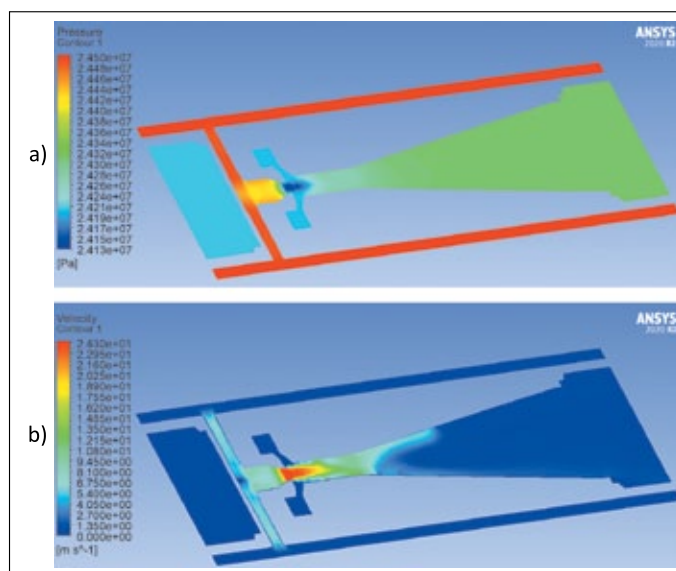


Figure 3. Distribution of pressures (a) and velocities (b) of mixed flows in the flow path of a jet pump

Rysunek 3. Rozkład ciśnień (a) i prędkości (b) przepływów mieszanych w kanałach przepływowych pompy strumieniowej

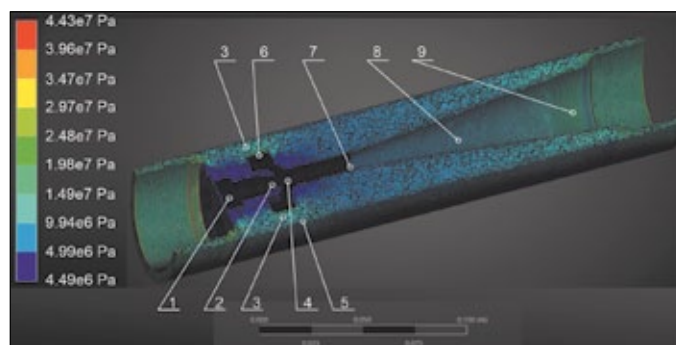


Figure 4. Distribution of equivalent stresses at characteristic points of a jet pump

Rysunek 4. Rozkład naprężeń zredukowanych w charakterystycznych punktach pompy strumieniowej

Table 1. Equivalent stresses at characteristic points of the jet pump
Tabela 1. Naprężenia zredukowane w charakterystycznych punktach pompy strumieniowej

Characteristic point [number]	Location of the characteristic point	Equivalent stress value [MPa]
1	Inlet section of the working nozzle	4.7340
2	Outlet section of the working nozzle	4.5000
3	Average diameter of the receiving chamber wall	11.7720
4	At the inlet to the mixing chamber	5.9823
5	On the outer wall of the receiving chamber	9.6919
6	On the inner wall of the receiving chamber	14.7880
7	At the outlet from the mixing chamber	5.8487
8	In the middle of the diffuser	8.7433
9	At the outlet of the diffuser	13.9780

chamber. At the entrance to the mixing chamber, the equivalent stress values decrease (characteristic point 4), which is due to an increase in the wall thickness of this structural element of the jet pump. In the outlet section of the mixing chamber, the equivalent stresses further decrease (characteristic point 7) compared to the inlet section, since the pressure increases and the pressure difference decreases. Moving downstream from the outlet section of the mixing chamber, the internal pressure in the diffuser part of the jet pump increases and the pressure difference across the diffuser decreases. However, due to the reduced thickness of the diffuser section of the jet pump, the equivalent stress values gradually increase (characteristic points 8 and 9).

The maximum permissible stress values significantly exceeded the obtained values. This finding makes it possible to recommend the use of a larger standard size of the flow section of a jet pump (characterized by increased productivity) while maintaining unchanged external dimensions, which is essential in production wells under compressed conditions.

Experimental determination of the limiting ratios of hydrodynamic and strength characteristics of a jet pump

In the course of experimental research, it is necessary to identify the operating mode of the jet pump, for which the minimum pressure values and the maximum pressure difference acting on the body elements are established in its

flow path. This operating mode is characterized by maximum equivalent stresses in the body components of the jet pump. The experimental determination of operating parameters corresponding to the maximum effective stresses in the parts of the ejection system was carried out using a laboratory test bench for studying jet pumps. Given that the pressure in the flow upstream the working nozzle during experimental studies remains unchanged, during laboratory measurements, the pressure of the injected flow at the inlet to the receiving chamber of the jet pump was determined. The influence of the design features of the jet pump on the pressure in its flow path (which characterizes the action of equivalent stresses in the elements of the ejection system) was determined by changing the main geometric parameter in the form of the ratio of the cross-sectional areas of the mixing chamber and the working nozzle. The value of this parameter for downhole jet pumps ranged from $K_p = 2$ to $K_p = 6$. The influence of the jet pump operating mode on the pressure in its flow path (and the effective equivalent stresses in the elements of the ejection system) was determined by changing the ratio of the flow rates of the injected and working flows.

The magnitude of the injected flow pressure P_i had a direct impact on the nature of the stress-strain state of the body elements of the jet pump in the regions of the injected flow supply, the receiving chamber, the mixing chamber and the diffuser. Experimental studies involves establishing the functional dependence of the pressure of the injected flow P_i on the relative flow rate of the jet pump:

$$P_i = f(i) \quad (1)$$

where:

i – the injection coefficient (ratio of injected and working flow rates) of the jet pump, $i = Q_i/Q_w$.

The injected flow pressure was calculated by the readings of pressure-vacuum gauge (16) (Figure 5), and the flow rate of the working and injected flow is calculated by the readings of flow meters (12) and (14). Adjustment of the relative flow rate and operating mode of the jet pump was achieved by regulating the degree of opening of the latch (11) located on the suction line of the jet pump.

The injected flow pressure P_i was determined during the study of three models of a jet pump for varying absolute and relative values of its geometric dimensions (Table 2):

- diameter of the working nozzle, d_1 ;
- mixing chamber diameter, d_2 ;
- absolute distance between the working nozzle and the mixing chamber, l_w ;
- relative distance between the working nozzle and the mixing chamber, $\bar{l}_w = l_w/d_1$;
- the main geometric parameter of the jet pump, $K_p = (d_2/d_1)^2$.

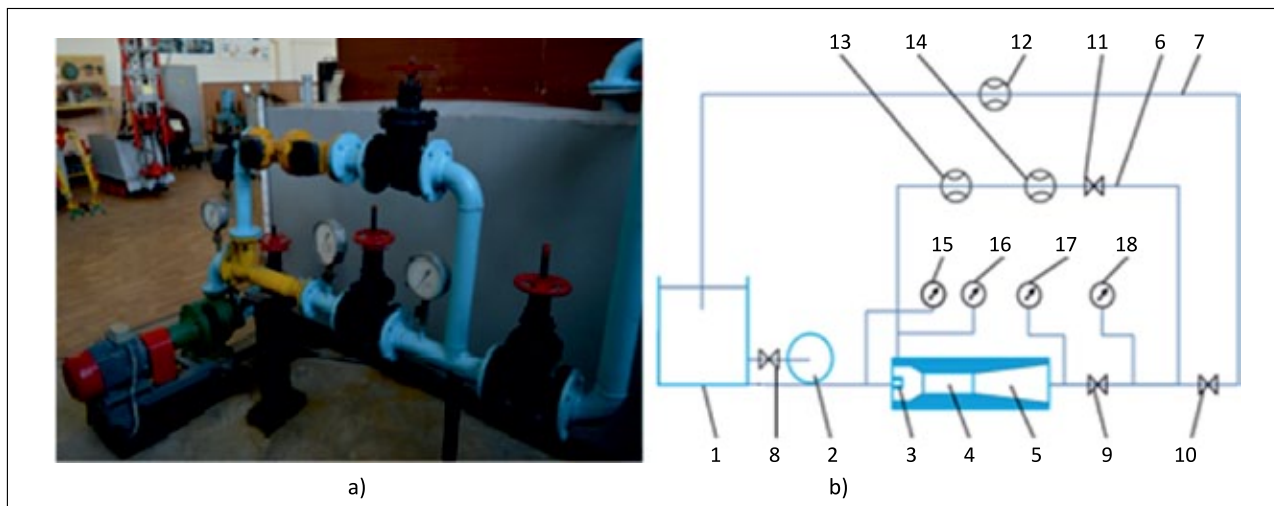


Figure 5. Appearance (a) and hydraulic diagram (b) of the stand for studying jet pumps: 1 – receiving tank; 2 – power drive; 3 – working nozzle; 4 – mixing chamber; 5 – diffuser; 6 – suction line; 7 – pressure line; 8–11 – valves; 12–14 – flow meters; 15–18 – pressure gauges and pressure-vacuum gauge

Rysunek 5. Wygląd (a) i schemat hydrauliczny (b) stanowiska do badania pomp strumieniowych: 1 – zbiornik odbiorczy; 2 – napęd; 3 – dysza robocza; 4 – komora mieszania; 5 – dyfuzor; 6 – przewód ssawny; 7 – przewód tłoczny; 8–11 – zawory; 12–14 – przepływomierze; 15–18 – manometry i manowakuometr

Table 2. Geometric dimensions of jet pump models

Tabela 2. Wymiary geometryczne modeli pomp strumieniowych

Model number	d_1 [mm]	d_2 [mm]	l_w [mm]	$\bar{l}_w$	K_p
1	16.0	40	26.5	1.656	6.250
2	18.0	40	16.5	0.917	4.938
3	22.5	40	36.5	1.622	3.160

d_1 – diameter of the working nozzle; d_2 – mixing chamber diameter; l_w – absolute distance between the working nozzle and the mixing chamber; $\bar{l}_w$ – relative distance between the working nozzle and the mixing chamber; K_p – the main geometric parameter of the jet pump

The experimental dependence of the injected flow pressure (P_i) on the injection coefficient (i) of the jet pump (Figure 6) is linear:

$$P_i = ai + b \quad (2)$$

where:

a, b – empirical coefficients.

It was experimentally established that an increase in the injection coefficient from $i = 0$ to $i = 1.0$ increases the pressure in the jet pump from $P_i = -0.1$ MPa to $P_i = -0.03$ MPa (Figure 6).

The empirical coefficients a, b and correlation coefficients r^2 for the studied jet pump models are given in Table 3.

The minimum pressure in the ejection system corresponds to the maximum stress in the jet pump components.

For all values of the main geometric parameter K_p , the maximum equivalent stresses in the jet pump components occur in the region of low injected flow rates. An increase in the injected flow rate and the value of the injection coefficient increases the pressure in the flow part of the jet pump and,

Table 3. Coefficients of empirical relationships and correlation coefficients for the studied jet pump models

Tabela 3. Współczynniki zależności empirycznych oraz współczynniki korelacji dla badanych modeli pomp strumieniowych

Model number	a	b	r^2
1	0.5906	−0.8946	0.9943
2	0.6094	−1.0407	0.9528
3	1.3725	−1.1367	0.9396

a, b – empirical coefficients of equation (2); r^2 – correlation coefficient for the experimental dependence determined by equation (2)

according to the results of numerical modelling, reduces the equivalent stresses in the elements of the ejection system. In the region of low injected flow rates, the minimum pressure values correspond to the jet pump design, the main geometric parameter of which is $K_p = 3.16$. For such a jet pump design, the equivalent stresses in its components are at their maximum. In the region of injection coefficient values $i > 0.33$, the dependence of pressure on the value of the main geometric

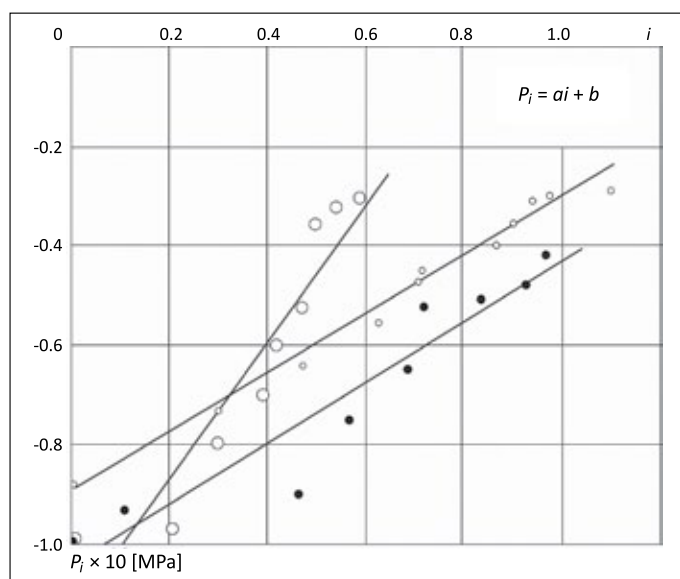


Figure 6. Dependence of the injected flow pressure on the injection coefficient for the main geometric parameter of the jet pump $K_p = 6.25$ (dependence 1 (small and transparent points)), $K_p = 4.938$ (dependence 2 (black points)), $K_p = 3.16$ (dependence 3 (big and transparent points))

Rysunek 6. Zależność ciśnienia strumienia zasysanego od współczynnika iniekcji i głównego parametru geometrycznego pompy strumieniowej: $K_p = 6,25$ (zależność 1 (małe, transparentne punkty)); $K_p = 4,938$ (zależność 2 (czarne punkty)); $K_p = 3,16$ (zależność 3 (duże, transparentne punkty))

parameter $P_i = f(K_p)$ are extreme. Initially, an increase in the parameter K_p causes a decrease in pressure and an increase in the value of equivalent stresses. With a further increase in the parameter K_p , an increase in pressure and a decrease in equivalent stresses occurs.

Thus, the most unfavourable operating mode in terms of ensuring the required structural strength, corresponds to a zero injection coefficient. This operating condition for a downhole jet pump is implemented when inducing inflow from a productive horizon after completion of well construction or the application of oil recovery enhancement methods.

Discussion

The need to study the stress-strain state of jet pump elements is associated with the existence of a persistent trend of increasing the depth of oil and gas fields involved in the development. As the depth of production wells increases, the magnitude of hydrostatic and hydrodynamic pressure acting on the outer surface of the jet pump housing also increases, and the magnitude of internal pressure in the limiting case can decrease to the value of the pressure of saturated vapors of the pumped liquid. Under these conditions, the housing elements of jet pumps are subjected to significant loads, which can cause

their depressurization and failure. Therefore, the combination of hydraulic and strength calculations makes it possible to increase the reliability of using jet pumps during drilling and operation of deep wells.

The consistency of the obtained results with the materials of other authors' research was analysed. Studies conducted at the Metropolitan Autonomous University-Iztapalapa (Mexico) confirm the possibility of failure of the joints of the ejection system parts under the influence of stresses arising in the jet pump body components (Espinosa-Paredes et al., 2023). In this study, the probability of failure of a jet pump with a mixing chamber diameter of 0.196 m was determined based on a three-dimensional analysis using the methodology of computational hydrodynamics and structural analysis. The COMSOL Multiphysics® simulation environment was used to model the operational process of the jet pump.

Sheha et al. (2018), using a CFD solver, developed a jet pump model with the main geometric parameter value of $K_p = 3.69$, a relative length of the mixing chamber of $\bar{L}_c = 5.48$ and the diffuser opening angle of $\alpha_d = 5^\circ$. To assess the influence of operational and geometric parameters on the performance of the ejection system, experimental studies of the jet pump model were conducted with subsequent comparative analysis with the results of simulation modelling. During the studies, the relative pressure of the jet pump ranged from 0 to $h = 0.4$, and the injection coefficient — from 0 to $i = 3$. The gradual increase in pressure and decrease in the velocity of mixed flows towards the outlet section of the diffuser, obtained during modelling the stress-strain state of the ejection system components, was found to be consistent with the results of a study of the nature of the distribution of hydrodynamic parameters in the working nozzle, receiving chamber, mixing chamber, and diffuser of the jet pump.

According to research conducted at Aksaray University in Turkey (Aldaş and Yapıcı, 2014), the maximum flow velocity was localized in the region located at the jet outlet from the working nozzle of the jet pump. The radius of the region of maximum velocities in the initial section remained constant and gradually decreased in the direction of mixed flow. The final cross-section of the region of maximum velocities for small values of the injection coefficient ends at the initial section of the jet pump mixing chamber. For larger values of the injection coefficient, the boundary of the region of maximum velocities was at the initial section of the diffuser. The study used a jet pump model with the following geometric dimensions: the main geometric parameter $K_p = 5.92$, the distance between the working nozzle and the mixing chamber $l_w = 0.0281$ m, and the length of the mixing chamber $L_c = 0.27$ m. The injection coefficient i values were: 0.29, 1.62 and 2.44. The Ansys Fluent software package was employed to develop the com-

puter model. The localization and configuration of the region of maximum velocities of the working stream obtained during the modelling process corresponds to the results of the studies presented by the authors of this article. However, the absence of information on the nature of the pressure distribution does not allow assessing the strength characteristics of the elements of the ejection system.

The limitation of the results of the conducted research extends to the operation of the jet pump in conditions of low injection coefficient values. In the region of low injected flow rates, due to a significant difference in the velocities of the mixed media, the probability of the formation of vortex zones and reverse fluid flows increases. The complication of the flow mixing mechanism reduces the effectiveness of the application of classical laws of hydrodynamics in modelling the working process of the jet pump.

Low pressure values contribute to the occurrence of hydrodynamic cavitation at the outlet of the working nozzle and at the inlet of the injected flow into the mixing chamber. The formation of a vapor-gas phase within the flow prevents the application of the conventional form of the flow continuity equation. These factors significantly reduce the reliability of the results of simulation modelling of the flow mixing process in the region of low injected flow rates.

The advantage of the method of studying the strength characteristics proposed by the authors lies in its ability to model the hydromechanical connections of the elements of oil and gas equipment without the need to involve a previously created mathematical description of its working process. When examining the influence of design and operational factors – whose number may reach thousands and tens of thousands – on the characteristics of oil and gas equipment, each individual change in the configuration of its elements or operating parameters requires the refinement of the geometric and mesh model as well as the corresponding boundary conditions. If it is necessary to use volumetric arrays of source data, which create a significant number of possible combinations, each of which requires the performance of separate calculation operations, it is advisable to use dedicated application software instead of the model proposed by the authors.

The experimental dependences obtained in the study do not account for the effect of hydrostatic pressure, which occurs in actual well conditions. The error in determining the experimental characteristics of the working process of the jet pump may increase when modelling the cavitation mode of operation of the ejection system if the effect of significant hydrostatic pressure is not taken into account.

The current stage of development of oil and gas ejection technologies is characterized by the creation of a new generation of jet pumps incorporating elements for inducing swirl in

the mixed flows in the flow path. At the same time, jet pumps acquire additional characteristics similar to those of centrifugal pumps. The helical motion of the working media reduces hydraulic losses during mixing of flows and increases the efficiency of the ejection system. Given the need to increase the energy efficiency of oil and gas ejection technologies, further research should focus on modelling the stress-strain state of jet pump elements under the conditions of swirling mixed flows.

Conclusions

1. The following features of simulation modelling of the stress-strain state of oil jet pump components were formulated:
 - the difference in modelling the stress-strain state of the elements in a downhole ejection system with separate supply lines for the working and injected flows lies in the need to include the annular channels – located between the outer surface of the jet pump housing and the production string – within the design volume;
 - during the selection of boundary conditions, the pressure values acting on the outer surface of the jet pump must account for the current hydrostatic pressure and hydraulic losses in the elements of the ejection system;
 - a comprehensive analysis of the hydrodynamic and strength characteristics of an oil jet pump necessitates the construction of a liquid and solid mesh models.
2. A relationship was established between the hydrodynamic parameters of the mixed flows and the magnitude of equivalent stresses in the housing elements of the ejection system:
 - the most heavily loaded components are the receiving chamber and the outlet section of the jet pump diffuser. The minimum equivalent stresses are observed in the mixing chamber;
 - the working nozzle and the radial channel for supplying the working flow are subjected to tensile forces, whereas compressive stresses act on the receiving chamber, mixing chamber and diffuser;
 - analysis of the ratios of actual and maximum permissible stresses in the jet pump components enables a reduction of the wall thickness and increases the internal diameter of the housing elements of its flow path. This ensures an increase in the productivity of the jet pump and reduces the risk of cavitation under operating conditions, while maintaining the same standard production string size and a constant maximum permissible outer diameter of the jet pump.
3. The operating mode of the downhole ejection system corresponding to the occurrence of maximum stresses in its elements was identified:

- the minimum pressure and maximum forces in the components of the jet pump during operation at zero injected flow rate and zero injection coefficient;
- it has been established that an increase in the injection coefficient from zero to one more than triples the pressure value in the flow part of the jet pump.

To meet strength conditions, the implementation of short-term technological operations involving ejection systems in the zero injection coefficient mode should be accompanied by the use of a jet pump of a smaller standard size with a subsequent increase in its outer diameter after causing inflow from the productive horizon.

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OFERTA BADAWCZA ZAKŁADU INŻYNIERII NAFTOWEJ

- analiza przyczyn oraz badania stopnia uszkodzenia skał zbiornikowych w strefie przyotworowej,
- ocena głębokości infiltracji fazy ciekłej do skał zbiornikowych,
- ocena wpływu roztworów soli i cieczy wiertniczych na skały ilaste strefy przyotworowej,
- pomiary parametrów reologicznych cieczy i niektórych ciał stałych w zakresie temperatur od –40 do 200°C oraz ciśnieniu do 150 bar,
- ocena stateczności ścian otworów wiertniczych,
- symulacja eksploatacji kawernowych podziemnych magazynów gazu ziemnego wykonanych w utworach solnych, z uwzględnieniem konwergencji komór,
- zastosowanie technologii mikrobiologicznych do stymulacji odwiertów oraz usuwania osadów parafinowych w odwiertach i instalacjach napowierzchniowych,
- projektowanie zabiegów mikrobiologicznej intensyfikacji wydobywania ropy (MEOR),
- projektowanie zabiegów odcinania dopływu wód złożowych do odwiertów,
- określanie nieredukowalnego nasycenia próbek skały wodą złożową,
- testy zawadniania z użyciem wody, solanki lub CO₂,
- fotograficzne dokumentowanie rdzeni wiertniczych wraz z dowiezaniem wyników badań laboratoryjnych i innych informacji,
- określanie właściwości mechanicznych oraz sejsmoakustycznych skał w próbach okruchowych,
- oznaczenie kątów kontaktu, napięć powierzchniowych i międzyfazowych,
- badania ściśliwości przestrzeni porowej skał,
- analiza zjawisk migracji i ekshalacji gazu ziemnego oraz występowania ciśnień w przestrzeniach międzyrurkowych,
- interpretacja wyników opróbowań i testów hydrodynamicznych metodami oprogramowaniem autorstwa INiG–PIB,
- określanie zdolności produkcyjnej odwiertów,
- opracowywanie specjalistycznego oprogramowania z zakresu inżynierii naftowej.



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