Investigation of gas-liquid mixture flow in the stage submersible pump

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Abstract: - The analysis of the features of the working process of a submersible electric centrifugal pump is carried out when pumping gas-liquid mixtures. Approaches to the modeling of gas-liquid flows are shown. The advantages of numerical experiments in front of field experiments are substantiated. Recommendations are given on the choice of the type of the grid and the choice of turbulence parameters, as well as the solver for calculating multiphase currents in the OpenFOAM program. Dependences of head losses, distribution of static pressure along the blade of the stage are obtained in the presence of gas in the pumped liquid. The flow of the gas-liquid mixture in the impeller is visualized. The theoretical and experimental statements on the structure of the flow of a multiphase fluid are visually confirmed. The coefficients for converting the pressure characteristic from water to a two-phase mixture are derived.

Key-Words: - centrifugal pump, stage, gas-liquid mixture flow, mathematical model, turbulence model, pressure, structured mesh.

1 Introduction

Typically, centrifugal pumps designed for clean liquids. However, operation of electric submersible pumps (ESP) in the extraction of oil from the wells showed that part of the pump has to pump multiphase - gas-liquid mixture (GLM). The presence of gas in the pump inlet plays a negative role deteriorating the pressure characteristics of the pump and energy. On the other hand, the gas caught in the tubing (tubing), creates a "gas lift effect", which contributes to raise liquid to the surface, reducing the required pump head. Usually at high GOR oil production wells in front of the ESP set gas separator. The maximum allowable value of gas content at the pump inlet is recommended to take no more than 25%.

Pumping GLM subject of numerous studies. Note the most basic research - work Muraveva IM, Mischenk I., Lyapkov P., Sharipov A., Minigazimov M., Drozdov A. H Igrevskiy V. [1-6]. It should be noted experimental studies of foreign authors: Turpin J.L., Lea J.F., Bearden J.L., Dunbar C.E., Cirilo R. [7-9]. Analysis of these studies showed that entering the free gas pump with the pumped fluid leads to a significant deformation pressure and energy characteristics of the pump - reduction of the liquid supply pressure, And efficiency and increase capacity. The negative influence of free gas is especially true on the pitch, the smaller supply the optimum mode. In the presence of free gas in the liquid in the cavities of impellers and guide vanes gas cavity formed not involved in the flow. The consequence of this reduced bandwidth is broken pump energy exchange with the fluid flow process deteriorates blades. Ultimately, all these factors lead to the disruption of supply pump.

Analysis of the experimental studies [10] showed that the major parameters that affect the operation of submersible centrifugal pump, is the level of gas content and pressure at the pump intake, and the water content of the oil product.

Carrying out experiments to investigate the physical hydrodynamic one- and two-phase flow patterns in the interblade channels of a rotating impeller ESP it has always been associated with the complexity of the imaging and measurement parameters studied. If the flow pattern imaging issues interblade channels of the impeller recently technically solved by making the walls of the pump stage of transparent material and fixing the flow pattern with the help of high-speed recording [11], the problem of measuring pressures and velocities in the flow passages of the impeller to date hampered. Therefore, affordable method for studying the flow parameters in the ESP impeller is conducting numerical (calculated) experiment.

Modern development of hydrodynamic modeling fluid flow and gas flow channels of hydraulic units allows for more qualitative research on the effect of GLM ESP performance

GLM flow in the flow part of the ESP stage has a complicated structure, so its current numerical modeling is difficult to perform. We distinguish two main approaches of mathematical modeling of GLM in ESP

The first approach - the mechanistic modeling, based on the solution of one-dimensional, stationary differential equations of conservation, closed by empirical correlations. The most famous works - Sachdeva R. [12], Minemura K. [13], Sun D. [14] (2001), and Mikhailov V., Petrov P. [15]. One major limitation of this mathematical model (MM) is the assumption that the trajectory of motion of the gas lines coincide with the liquid flow - basic equation MM recorded along streamlines. It is proposed that the current line coincides with the line of blades. The pressure gradient from the wall friction phases are determined by the laws of hydraulics - hydraulic friction coefficients. The friction forces between the phases are considered for bubble flow regime. Taking into account loss of pressure shock for GLM. semi-empirical dependence used in the work, obtained in experimental studies at the University of Tulsa (United States, Oklahoma). In recent years, improved model for transient regimes calculations.

The second approach - numerical simulation of three-dimensional turbulent flow of the multiphase medium in the computational domain. Depending on the approach to the simulation model of multiphase flows are divided into two main classes: the model and the Euler Lagrange. The Lagrange approach is based on the consideration of the movement of individual particles (or groups of particles) of the secondary dispersed phase. The Euler approach is based on the consideration of changes in flow parameters (velocity, pressure) at the points of the space. For multiphase flows thus introduces the notion of volume fraction of the phases - one additional parameter of the flow. Euler approach presented models VOF (Volume of Fluid - fluid volume method), Mixture (model of the multiphase mixture) and Eulerian (Euler full model).

In [16,17] of numerical simulation results of the hydrodynamic equations 2-phase flow in the approach Euler using modern software.

In conclusion, it should be noted that due to the growth of computing power and the development of computational fluid dynamics software (CFD), as a license (e.g. ANSYS CFX And c integrable open platform for numerical simulation of the mechanics of continuous media (e.g., OpenFOAM) Holding a numerical experiment of two-phase flow in the channels ESP structure analysis for different modes of operation of the pump is the actual direction of work.

2 Problem Formulation

A numerical simulation of turbulent flow of the viscous liquid flow into the pump stage ESP5-80 (Fig. 1). The studies of structure 2-phase flow at off-design and Q_{opt} estimated modes (0.75 Q_{opt}, 1.25 Q_{opt}) for two values of the volume fraction of gas (gas content) at the pump inlet βg: 3% and 10%. Define the dependence of the change in the pressure of the impeller alone and the whole stage of the gas content.

Physical properties of the liquid and gas in the calculation process are not changed. the effect of temperature is not considered.

To perform a numerical experiment with the help of modern software, it is necessary to justify the choice of a mathematical model, computational grid, turbulence parameters, boundary conditions and solver for calculation of multiphase flows in OpenFOAM program.

2.1 Mathematical model

To perform numerical studies was chosen MM turbulent flow of two-phase flow of water gas Euler formulation. The phases are treated as interpenetrating environment: continuous liquid phase and a dispersed gas phase. Movement of each of the phases of matter modeled own system of equations of motion and continuity, averaged over time (Reynolds). According to this model, equations are written for each phase and are solved together. Pressure is considered the same for each phase. Phase linked interfacial momentum transfer.

Below is a system of conservation of mass and momentum equations for steady flow two-phase medium ($f = l,g$) in a Cartesian coordinate system rotating with the angular velocity around the axis passing via its beginning.

The continuity equation for each phase:

$$\nabla\left(\beta_f \rho_f \vec{u}_f\right) = 0 \quad (1)$$

Where ∇- Nabla operator; β_f - volume fraction; ρ_f - density; u_f - vector phase velocity. In addition, the volume fractions of the phases must satisfy the relation:

$$\sum_f \beta_f = 1 \,. \quad (2)$$

momentum equation for a continuous liquid phase:

$$\nabla(\beta_l \rho_l \vec{u}_l \vec{u}_l) = -\beta_{lg} \nabla p + \nabla(\beta_l (\tau_l + \tau_l^T)) + \vec{F}_{D\ l,g}, \quad (3)$$

to disperse the gas phase:

$$\nabla(\beta_g \rho_g \vec{u}_g \vec{u}_g) = -\beta_g \nabla p + \nabla(\beta_g (\tau_g + \tau_g^T)) + \vec{F}_{\omega g} - \vec{F}_{D\ l,g}, \quad (4)$$

Where τ_f, τ_f^T - molecular and turbulence (pulsation) components of the stress tensor for each phase; p - pressure (considered common to both phases); $\vec{F}_{\omega g}$ - mass specific force, taking into account the rotation of the impeller; $\vec{F}_{D\ l,g}$ - transfer of interfacial phase pulse per unit volume.

During the rotating impeller centrifugal pump is seen in the relative frame of reference, the term $\vec{F}_\omega$ on the right side of the momentum equation expresses the action of centrifugal and Coriolis forces:

$$\vec{F}_\omega = -\rho_i (2\vec{\omega} \times \vec{u} + \vec{\omega} \times (\vec{\omega} \times \vec{r})), \quad (5)$$

Where $\vec{\omega}$ - angular speed of rotation, $\vec{r}$ - radius vector (modulus which is equal to the distance from this point to the axis of rotation).

Turbulence of flow for a continuous liquid phase modeled based SST model [18, 19]. To account for the interaction between the two phases of additional terms used in turbulent flow. The turbulence of the second phase is calculated using the semi-empirical model. Calculation formulas and their rationale are presented in [20, 21].

Resistance force between the gas and the liquid phase (interfacial momentum transfer) is represented by the equations:

$$\vec{F}_{D\ l,g} = C_{D\ l,g} \frac{3}{4} \rho_l \frac{\beta_g}{d_b} \left| \vec{u}_g - \vec{u}_l \right| (\vec{u}_g - \vec{u}_l), \quad (6)$$

Where *CD* - drag coefficient exerted by the gas phase to the liquid phase [17, 21].

In [22, 23] are presented and analyzed basic principles and ability to work with open OpenFOAM package for modeling the turbulent flow of a viscous fluid in the hydraulic ducts. Compares the test solutions of the problem of the turbulent flow of a viscous fluid in the channel stops ESP experimental data.

We briefly describe the main stages of the modeling of the problem in OpenFOAM package.

1. Construction of 3D model design scheme interblade channel impeller and guide vanes of a centrifugal pump. In the future, it is exported to the «parasolid» format for the construction of grid generator ICEM CFD.
2. Filling in the computational domain graphic three-dimensional circuit cells of the computational grid in
package ICEM CFD Student Version.
3. Import grid with the help of «fluent3DMeshToFoam» team.
4. Setting the boundary conditions (preprocessor).
5. Running the solver. In modeling the gas-liquid mixture flow in the impeller of the pump is used solver MRFMultiphaseInterFoam.
6. Determination of the unknown quantities, a graphic visualization of the design parameters of fields (postprocessor).

Fig. 1 is a sketch of a submersible pump stage ESP5-80.

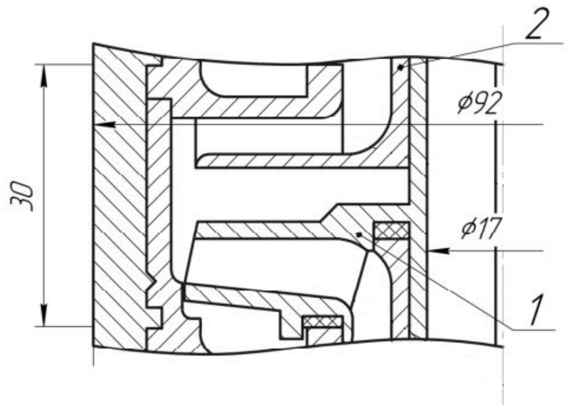


Fig. 1: - ESP stage:
1 - impeller; 2 - a guiding device

In [24, 25] indicate that for the study of three-dimensional flow in a flow of hydraulic parts for the convenience and time-saving built unstructured computational grid with tetrahedral cells. In this paper, a comparative calculation of the two grid types: unstructured and structured. Calculation results showed that a structured grid (Fig. 2) with a hexagonal cell shape provides a more reliable picture of the flow. It has a number of advantages such as a smaller number of cells, the orientation of the current lines, the best quality. This grid is used in subsequent calculations.

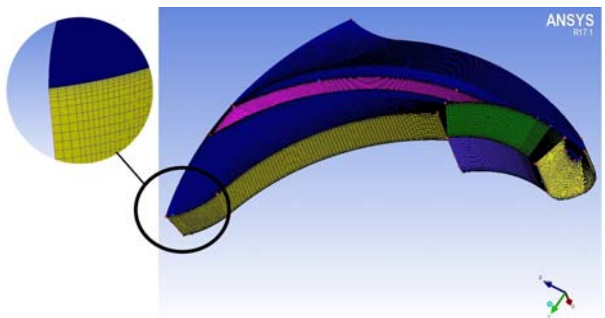
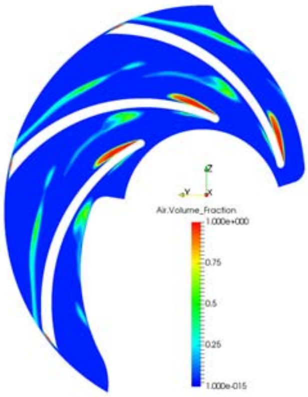


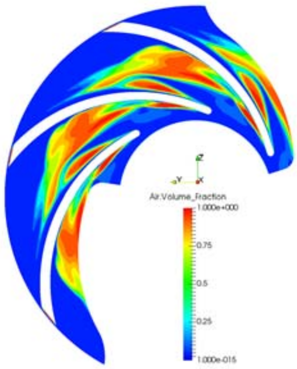
Fig. 2: Computational grid study area

Border conditions: The boundary conditions at the inlet was set total mixture velocity, which is defined as $V = \left(Q_g + Q_l\right)/F$. And volumetric fraction of each phase (seen in 3% and 10% gas by volume of the whole mixture). At the outlet pressure is equal to zero.

Analysis of the simulation results. Fig. 3 a, b show a significant change in the distribution of air phase volume fraction of the channel of the impeller while increasing gas content from 3% to 10% at a constant rate.



a



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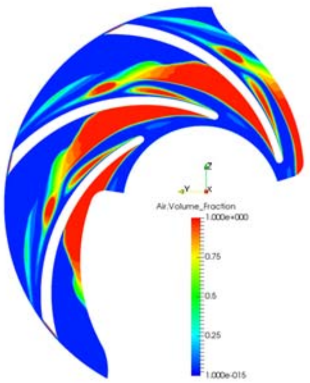

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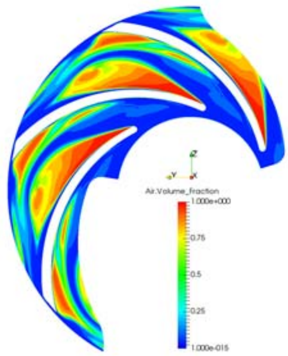
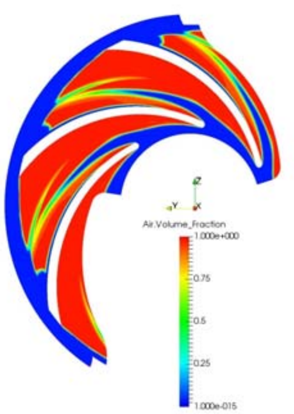


d

Fig. 3: Distribution of the volume ratio of air in the rotating impeller:
a - Q_{opt}, β_g = 3%; b - Q_{opt}, β_g = 10%; c - Q_{min}, β_g = 10%; d - Q_{max}, β_g = 10%



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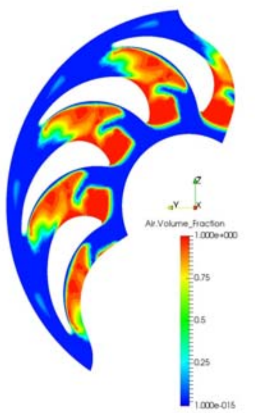

b

Fig. 4: Distribution of air volumetric fraction in ESP5-80 stage at Q_{max}, β_g = 10%:
a - impeller; b - a guiding device

Fig. 3, c and d shown that when the flow increases from Q_{min} = 60 m^3/day to Qmax = 100 m^3/day (Inlet gas content accepted 10%) air "bag" in the channel is displaced from the inlet zone to the trailing edge of the impeller. The probability of stalling longer at low flow rates. Comparison visualization flows in the channel of the impeller obtained by calculation and experimentally [1, 4, 11] shows qualitative convergence. It should be noted that in the published literature [11, 16] GLM numerical simulation was performed with the guide apparatus.

3 The results of the calculation of the flow in the ESP stage

Further numerical investigations conducted for all channel stage impeller - a guiding device. It is known that the main function of HA in step - outlet stream from impeller and supply it to the next stage impeller. A guiding device generates the flow pattern in the impeller stages. Impact on the flow pattern in impeller can be seen by comparing the ratio of air volume distribution in impeller shown in Fig. 3, and in Fig. 4a. Due to the pressure reduction in the flow section a guiding device in interblade channels of small gas bubbles formed in gas cavities, which prevents the passage of pumped liquid. For large values of gas content at the inlet to the pump it may lead to disruption of supply (Fig. 4b) or significantly reduce the pressure and the pump efficiency, increase in power consumption.

Fig. 5 shows graph static pressure distribution along the blade for the three values of gas content at the inlet to the impeller: $\beta_g = 0$; 3 % and 10 %. With increasing gas content at the inlet of the impeller, the pressure difference between the inlet and outlet edges of the impeller is reduced due to the presence of gas voids channels of impeller and guiding device

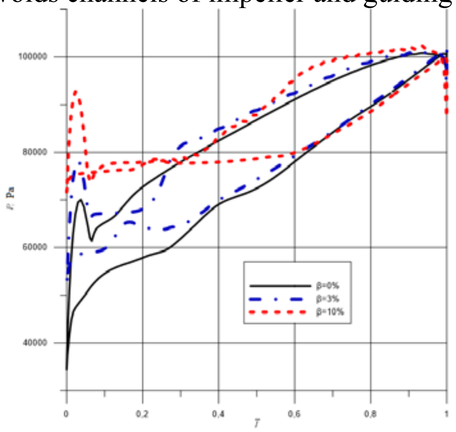

Fig. 5: Static pressure distribution along the impeller vane

Fig. 6 shows the dependence of the pressure decrease the magnitude of the gas content at the inlet of a pump for three values of the flow.

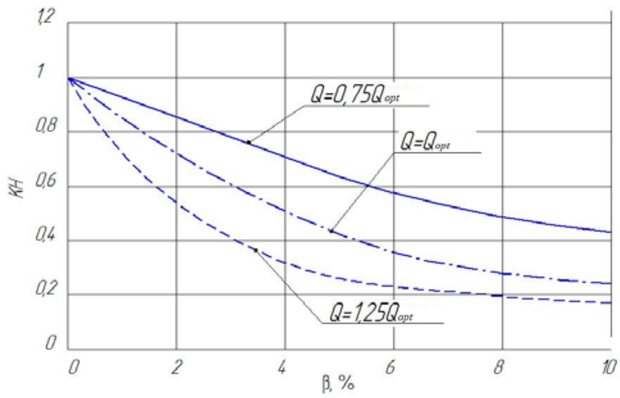

Fig. 6: Graph of coefficient of pressure reduction of the gas content at the inlet to stage

4 Conclusion

Analysis of the results obtained by the numerical calculation of viscous flow in the liquid mixture of stage ESP CFD program illustrates the generation of gas cavities in rotating impeller channels. It should be noted that when conducting an experiment at a current numerical multiphase mixture ESP need only consider the full stage consisting of an impeller and guide vanes, as the latter has a significant influence on the flow pattern in RK. In further work is planned to take into account the influence of variable operating conditions (viscosity of the fluid, its water content, gas content, the flow structure) on the energy level indicators.

Analysis of the experimental studies of the influence of gas content on the ESP performance showed that the overall nature of the change pump parameters relative rapidity close same. Decrease of relative pumps parameters is practically independent of their mode of operation [1].

It is known that electric submersible pump is a unique design of the multistage centrifugal pump. Due to the limitations of overall diametrical dimensions of the well, the pressure of one pump stage is -. 6.4 m therefore to provide a desired pressure (pressure), the number of steps reaches the ESP average 100-500 units. It is also known that with increasing pressure along the pump (from stage to stage) decreases the content of free gas in the product due to its dissolution in the oil and water. Therefore, depending shown in Fig. 6, can be used for calculating the total multistage pump characteristics when pumping GLM.

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