Comparison of various simulation methods of a two-phase flow in a multiphase pump

A Boyarshinova1,2, V Lomakin1 and A Petrov1

1Bauman Moscow State Technical University, 5 Second Baumanskaya Street, Moscow, 105005, Russian Federation

2E-mail: a.boyarsh@yandex.ru

Annotation The article presents a mathematical model of a two-phase flow in a multiphase helico-axial pump. In this paper, the model of a multiphase incompressible fluid flow \( (\rho = \text{const}) \) were used. Numerical simulation is based on solving discrete analogues of the basic hydrodynamic equations. The hydrodynamic simulation of the described mathematical model was performed in two ways: in a simplified form, using a multiphase volume of fluid model (VOF), and the segregated flow method. The results of the calculation of two-phase flows for various values of the gas content are given. The influence of gas content on the pump performance and its pressure is considered. A comparison of calculation results of two methods of hydrodynamic simulation of two-phase flow is shown.

Introduction

Multiphase flow is a flow of a mixture of substances in various aggregative states - phases. A continuous or discrete phase can be a solid, liquid or gaseous state of matter. In terms of simulation, a phase can be defined as the amount of a substance in a system that has its own physical properties in order to distinguish it from other phases in the system [1]-[2]. Two-phase flow is a special case of multiphase flow, containing only two different components. These are liquids with solid or gas inclusions, gases with liquid drops or solid particles. The structure of two-phase flows can be very diverse. It is determined by the size, distribution of the elements of the dispersed phase in a continuous medium and their direct interaction. Multiphase media in nature are smoke, smog, fog, rain, in turn, in the technique typical examples of such media are emulsion, sludge, boiling liquid, etc. [3]-[4].

The problem of numerical simulation of the hydrodynamics of two-phase flows is relevant, since for many years one of the main methods for studying such media has been experiment. However, the development of numerical methods and computing hardware made it possible to calculate the fields of velocities, pressures and other parameters of two-phase flows in different engineering tasks[5]-[7].

The aim of the work is to describe a mathematical model of a two-phase flow and develop methods for hydrodynamic simulation of water flow with different gas content in a multiphase pump, as well as to determine the best way for calculating two-phase flow.

One of the possible solutions to the task is to use a helico-axial multiphase pump for the calculation [8]-[9]. It was designed for pumping a media with gas content up to 99%, during continuous operation[10]. Such pumps were designed primarily for oil production with associated gas without the use of additional units [11]-[12]. This two-phase pumping technology reduces pollutants and CO\(_2\) emissions, minimizes environmental impact, avoids gas or crude oil leaks, and is also more cost-
effective than oil extraction using separation plants [13]. The design of one stage of the pump is shown in Fig. one.

![Fig. 1. The design of the stage of the helico-axial multiphase pump](image)

The stage of the helico-axial multiphase pump is an axial impeller followed by a guide vanes [14]. The idea is that the impeller disperses the multiphase flow, and due to expansion of cross section of guide vane, the volume of gas bubbles decreases [15]-[16]. Thus, the gas is not shut off the flow.

In this paper hydrodynamic simulation was carried out using several methods of two-phase flow. The simulation was performed in the STAR CCM + software package.

**Methodology**

Hydrodynamic simulation of a two-phase flow can be calculated by following methods:

1) homogeneous multiphase volume of fluid model (VOF), is a simplified model that simulates a multiphase flow in the form of a suspension. It is used when two phases of the same substance (for example, water and steam) are involved, which are in thermodynamic equilibrium and have common fields of speed, pressure and temperature[17]-[18].

Basic assumptions of the two-phase mixture model:

- The mixture of phases behaves like a single fluid. A set of following equations: transport equations for mass, momentum, and energy, is solved for the mixture as a whole.
- Phases are in thermal equilibrium. The two phases have the same temperature, and the phase distribution is calculated on the basis of the heat balance.
- There is no relative (sliding) speed between phases.

2) segregated multiphase flow model uses the same set of equations as the two-phase thermodynamic equilibrium model (mass and momentum transfer equations), but solves them separately for each phase (except for the general pressure field).

The mathematical model of segregated multiphase flow consists of a set of differential and algebraic equations [19]-[20]:

1. The volume of the i-th phase in each cell is calculated as:

\[ V_i = \int_{\Omega} \alpha_i dV \]

where \( \alpha_i \) – is the concentration of the i-th phase in the cell.

The sum of the concentrations of all phases in the cell is equal the one.
2. The equation of mass conservation (continuity equation):

\[ \sum_{i=0}^{n} \alpha_i = 1 \]

\[ \frac{\partial}{\partial t} \left( \int_{\gamma} \alpha_i \rho_i dV + \int_{A} \alpha_i \rho_i \overrightarrow{V}_i d\alpha \right) = 0 \]

where \( \rho_i \) - i-th phase density;

\( \overrightarrow{V}_i \) - i-th phase velocity (in the case of turbulent flow simulation by a RANS-type model, velocity averaged over time [21]-[23]).

3. The quantity of motion changing:

\[ \frac{\partial}{\partial t} \left( \int_{\gamma} \alpha_i \rho_i \overrightarrow{V}_i dV + \int_{A} \alpha_i \rho_i \overrightarrow{V}_i d\alpha \right) = -\int_{\gamma} \alpha_i \nabla p dV \]

\[ + \left( \int_{\gamma} \alpha_i \rho_i \overrightarrow{g} dV + \int_{A} \left[ \alpha_i \left( T_i + T_i'' \right) \right] d\alpha \right) + \int_{\gamma} \overrightarrow{M}_i dV \]

where \((\overrightarrow{V}_i \overrightarrow{V}_i)\) - tensor multiplication of the velocity vector of the i-th phase;

\( p \) - pressure;

\( \overrightarrow{g} \) - mass intensity vector (in this case, the gravity force is 9.81 m/s² and the inertial force due to the rotation of the computational domain);

\( T_i \) - molecular viscosity stress tensor;

\( T_i'' \) - turbulent stress tensor;

\( \overrightarrow{M} \) - the vector of the total intensity of phase interaction forces per unit volume, for the vector \( \overrightarrow{M}_i \) the equality is true:

\[ \sum_{i} \overrightarrow{M}_i = 0 \]

The vector \( \overrightarrow{M}_i \) characterizes all the forces that separate phases interact with each other.

\[ \overrightarrow{M}_i = \sum_{i \neq j} \left( \overrightarrow{F}_{ij}^D + \overrightarrow{F}_{ij}^{VM} + \overrightarrow{F}_{ij}^L + \overrightarrow{F}_{ij}^{TD} + \overrightarrow{F}_{ij}^{WL} \right) \]

where \( \overrightarrow{F}_{ij}^D \) - resistance force;

\( \overrightarrow{F}_{ij}^{VM} \) - virtual mass force;

\( \overrightarrow{F}_{ij}^L \) - lifting force;

\( \overrightarrow{F}_{ij}^{TD} \) - force caused by turbulent dispersion;

\( \overrightarrow{F}_{ij}^{WL} \) - force caused by wall effect.

4. Resistance force

In flow simulation of continuous and dispersed media, the resistance force acting on the dispersed medium I from the side of the continuous medium j is equal to:

\[ \overrightarrow{F}_{ij}^D = A_d \overrightarrow{V}_r \]
Where $A_D$ – linearized resistant coefficient;

$$
\bar{V}_r = \bar{V}_j - \bar{V}_i - \text{relative velocity of mediums;}
$$

$$
A_D = C_D \frac{1}{2} \rho_C \left| \bar{V}_r \right| \left( \frac{a_{cd}}{4} \right)
$$

Where $C_D$ – resistant coefficient;

$\rho_C$ – continuous phase density;

$a_{cd}$ – interaction area of the phases (in this case, the term $\frac{a_{cd}}{4}$ is the area of the projection of the spherical particle on the plane).

Resistant coefficient is based on the relation:

$$
C_D = f_D C_{D\infty}
$$

Where $C_{D\infty}$ - coefficient of resistance of a single spherical particle moving in an infinite flow;

$f_D$ – coefficient taking into account the concentration of particles.

$C_{D\infty}$ can be found from relation:

$$
C_{D\infty} = \frac{24}{Re_d} \left( 1 + 0.15 Re_d^{0.687} \right) \text{ when } Re_d < 1000
$$

or

$$
C_{D\infty} = 0.44 \text{ when } Re_d > 1000
$$

$l$ – characteristic interaction length or bubble size;

$\mu_C$ – dynamic viscosity coefficient of continuous medium;

Coefficient $f_D$ can be found from relation:

$$
f_D = \alpha_C \frac{a_d}{n_D}
$$

$\alpha_C$ – continuous phase concentration;

$n_D = -8.3$ for spherical particle.

5. Virtual mass

The inertia of the surrounding fluid affects the acceleration of the particle immersed in the fluid. This effect is simulated by adding mass to the dispersed particle.

The force from the virtual mass acting on phase i moving accelerated relative to phase j is found as:

$$
\bar{F}_{ij}^{VM} = C_{VM} \rho_C \alpha_C \left( \bar{a}_j - \bar{a}_i \right)
$$

$a_{j,i}$ – acceleration of $j$-th and $i$-th phase;

$C_{VM} = 0.5$ – virtual mass coefficient for a spherical particle.

6. Lifting force

In the case when the flow surrounding the dispersed particle is inhomogeneous or the particle is swirling, the force is perpendicular to the relative velocity.

$$
\bar{F}_{ij}^{L} = C_{L\text{eff}} \rho_d \alpha_d \left( \bar{V}_r \times \left( \nabla \times \bar{V}_r \right) \right)
$$
\( \bar{V}_r \) – relative phase velocity;  
\( \bar{V}_c \) – continuous phase speed;  
\( \alpha_d \) – dispersed phase concentration;  
\( C_L = 0,25 \) – lifting force coefficient.

7. Turbulent dispersion force

Additional change in phase concentrations caused by flow turbulence is modeled as the force of turbulent dispersion

\[
F_{\text{TD}} = A_D \bar{V}_{\text{TD}}
\]

– resistant force coefficient;  
\( \bar{V}_{\text{TD}} \) – relative slip speed;

\[
\bar{V}_{\text{TD}} = D_{\text{TD}} \left( \frac{\nabla \alpha_d}{\alpha_d} - \frac{\nabla \alpha_c}{\alpha_c} \right)
\]

\( D_{\text{TD}} = C_0 \frac{\nu' c}{\sigma_\alpha} I \) – turbulent diffusion tensor; \( C_0 = 1; \)

\( \nu' c \) – kinematic coefficient of turbulent viscosity;

\( \sigma_\alpha \) – turbulent Prandtl number;

\( I \) – unit tensor;

\[
\sigma_\alpha = \sigma_0 \sqrt{1 + C_\beta \xi^2} \frac{1 + \eta}{b + \eta}
\]

\( \sigma_0 = 1 \) – unmodified turbulent Prandtl number;

\( C_\beta = 1,8 \) – correction factor;

\( \xi \) – article sliding velocity related to the speed of turbulent fluctuations;

\( \eta \) – particle interaction time related to relaxation time;

\( b \) – the ratio of the accelerations of the continuous / dispersed phase;

\[
b = \frac{1 + C_{VM}}{\frac{\rho_d}{\rho_c} + C_{VM}}
\]

\[
\eta = \frac{\tau_I}{\tau_R}
\]

\( \tau_I \) – characteristic time of interaction of a particle and a turbulent vortex;

\( \tau_R \) – particle relaxation time;

\[
\eta_c = \frac{1}{\sigma_0 \sqrt{1 + C_\beta \xi^2}}
\]

\( \eta_c \) – continuous phase turbulence energy dissipation rate;

\[
\tau_R = \tau_D \left( 1 + \frac{\rho_c}{\rho_d} C_{VM} \right)
\]
\[ \tau_D = \frac{\rho_d d^2}{18 \mu_c} \] - characteristic time scale for a dispersed particle;

\[ \xi = \frac{|V_r|}{\sqrt{\frac{2}{3} k_c}} \]

\( k_c \) – kinetic turbulence energy of the continuous phase.

8. Wall influence

When gas bubble located near the solid wall, it undergoes an asymmetrical action from the liquid. The force per unit volume that a gas bubble experiences is equal to:

\[ F_{ij}^{WL} = -C_{WL} y_w \alpha_p \rho_c \frac{|V_{r,\tau}|^2}{d_p} \hat{n} \]

where \( y_w \) – distance from the wall;
\( \alpha_p \) – dispersed phase concentration;
\( \rho_c \) – dispersed phase density;
\( d_p \) – bubble diameter;
\( C_{WL} \) – coefficient, which is the function of the distance from the wall and decreasing with increasing distance;
\( \hat{n} \) – normally oriented to the wall unit vector at the point closest to the bubble;
\( V_{r,\tau} \) – tangent to the wall component of the relative velocity;

Coefficient \( C_{WL} \) is as:

\[ C_{WL} = \max \left( C_{W1} + \left( \frac{C_{W2}}{y_w} \right) d_p, 0 \right) \]

Coefficients equal to: \( C_{W1} = -0.01, C_{W2} = 0.05 \). Thus the force caused by the influence of the wall disappears at a distance from the wall equal to the five diameters of the bubble.

The 3D model of the helico-axial multiphase pump for the calculation is shown in Fig. 2.

Fig. 2. 3D model of the flow part of the pump
For the calculation two pump stages were chosen for a more visual representation of the two-phase flow.

Boundary conditions: inlet velocity and outlet pressure, and for a split flow model, it is necessary to indicate the velocity of both the liquid and the gas. The calculation was carried out by gradually increasing the gas content value at the inlet boundary of the pump.

The grid in longitudinal and cross-section, presented in Fig. 3, consists of 508,000 cells. Near the solid walls, the cells elongated in the direction perpendicular to the wall (boundary layer), in the core of the flow the grid is not structured, consists of polyhedra of various shapes and sizes.

Although the simulation was performed in different ways, the grid was constructed identically.

Results

The flow of the two-phase medium in the flow part of the pump, obtained as a result of the simulation, is shown in the illustrations below.

For a visual representation of the two-phase flow, the scalar distribution of the volume fraction of water is showed on Fig.4 (the liquid phase is red, the gas phase is blue).

Fig. 3. The grid in the cross section of the pump

Fig. 4. The volume fraction of water in the pump at 50% of the gas at the inlet (simplified model)
At Fig. 4 it can be seen that the pump push through the liquid-gas mixture in a 50/50 ratio, and after the first stage the amount of gas has decreased.

At Fig. 5 showed the current flow lines in first stage of a multiphase pump.

The following are the scalar scenes of the distribution of the volume fraction of water in the cross section of the pump so as to get a visual representation of what is happening in impeller and guide vanes. In order to compare the two calculation methods, all the results are presented for the simplified model, then for the segregate flow model. In Fig. 6-11 are presented from left to right: impeller of the first stage, guide vanes of first stage, then impeller of second stage and the guide vanes of second stage (the liquid phase is red, the gas phase is blue).
Fig. 6. The volume fraction of water in the cross sections of the pump with 20% of the gas at the inlet (simplified model)

Fig. 7. The volume fraction of water in the cross sections of the pump at 20% of the gas at the inlet (segregated flow model)
Fig. 8. The volume fraction of water in the cross sections of the pump with 50% of the gas at the inlet (simplified model)

Fig. 9. The volume fraction of water in the cross sections of the pump with 50% of the gas at the inlet (segregated flow model)
Comparing Fig. 6, 8, 10 with fig. 7, 9, 11, it can be seen that the flow distribution significantly differs in the simplified model and in the segregated flow model. This can be explained by the fact that in full model appear diffusion of gas and liquid, which corresponds to reality. However, in the simplified model, the physics of the process is clearly visible: the liquid in impeller is thrown away to the periphery by centrifugal force and gas spreads throughout the flow, but accumulates closer to the center. Also in the guide vanes gas accumulates on the back side of the blades. But in reality, most likely, such an obvious phase separation in the pump does not occur. In both models, the amount of gas in the second stage is less than in the first.

The simulation results are summarized in table 1.

| Gas content α, % | Homogeneous multiphase model | Segregated multiphase flow model |
|------------------|-------------------------------|----------------------------------|
|                  | VOF                           |                                  |
|                  | H, м  | Q, м³/ч | ηl, %  | H, м  | Q, м³/ч | ηl, %  |
| 0                | 6,9   | 80,2    | 58,6   | 6,53  | 81,05   | 56,2   |
| 10               | 6,93  | 72      | 79,6   | 6,5   | 72,3    | 53,1   |
| 20               | 7     | 64,6    | 84,2   | 6,43  | 64,24   | 48     |
| 30               | 6,9   | 55,9    | 73,5   | 6,2   | 56,7    | 43,1   |
| 40               | 6,7   | 48,52   | 38,7   | 5,7   | 48,2    | 36,2   |
| 50               | 6     | 40      | 32,4   | 4,9   | 39,9    | 30,9   |
| 60               | 4,78  | 32,3    | 25,8   | 3,7   | 33      | 25,7   |
| 70               | 2,8   | 24,3    | 18,8   | 2,6   | 24,3    | 18,5   |
| 80               | 1,6   | 15,8    | 11,5   | 1,58  | 16,4    | 12,5   |
The dependences of pump head, efficiency and productivity on gas content are presented in Fig. 12-14 (dependencies obtained using a homogeneous multiphase VOF model are shown in blue, red shows a multiphase segregated flow model).

![Fig.12. Dependencies of head and pump efficiency on gas content](image1)

![Fig.13. Dependence of pump flow on gas content](image2)

From Fig.12-13, it can be concluded that pump head calculated by the VOF method is overestimated relative to the other model, and the efficiency with gas content from 10% to 40% is unreasonably high.

**Conclusion**

The paper describes a mathematical model of a multi-phase flow, which was implemented by two methods of calculation in the STAR CCM + software package.

The performed simulation showed physically results in both cases. As a first approximation the homogeneous multi-phase VOF model can be used. Its advantage is that the calculation requires significantly less computing power. But still, this is a simplified model and errors in it are no exception, for example, too high efficiency in the calculated flow section of the pump. Using a multi-
phase segregated flow model, it was possible to calculate fluid flow with gas content up to 95%; in turn, the simplified model showed the result only up to 80% of the gas phase.

In fact, a more complex two-phase flow structure in a multiphase pump is possible. The multiphase flow models contain many empirical coefficients, so an experiment is required to validate this model.

Bibliography

[1] Gläser, D., Flemisch, B., Helmig, R., Class, H. A hybrid-dimensional discrete fracture model for non-isothermal two-phase flow in fractured porous media (2019) GEM - International Journal on Geomathematics, 10 (1), № 5.

[2] Mikelić, A., Wheeler, M.F., Wick, T. Phase-field modeling through iterative splitting of hydraulic fractures in a poroelastic medium (2019) GEM - International Journal on Geomathematics, 10 (1), № 2.

[3] Pinilla, J.A., Guerrero, E., Pineda, H., Posada, R., Pereyra, E., Ratkovich, N. CFD modeling and validation for two-phase medium viscosity oil-air flow in horizontal pipes (2019) Chemical Engineering Communications, 206 (5), pp. 654-671.

[4] Feng, T., Wang, M., Song, P., Liu, L., Tian, W., Su, G.H., Qiu, S. Numerical research on thermal mixing characteristics in a 45-degree T-junction for two-phase stratified flow during the emergency core cooling safety injection (2019) Progress in Nuclear Energy, 114, pp. 91-104.

[5] Lomakin, V.O. Investigation of two-phase flow in axial-centrifugal impeller by hydrodynamic modeling methods (2015) Proceedings of 2015 International Conference on Fluid Power and Mechatronics, FPM 2015, № 7337302, pp. 1204-1206.

[6] Putra, R.A., Schäfer, T., Neumann, M., Lucas, D. CFD studies on the gas-liquid flow in the swirl generating device (2018) Nuclear Engineering and Design, 332, pp. 213-225.

[7] Cao, S., Peng, G., Yu, Z. Hydrodynamic design of rotodynamic pump impeller for multiphase pumping by combined approach of inverse design and CFD analysis (2005) Journal of Fluids Engineering, Transactions of the ASME, 127 (2), pp. 330-338.

[8] Shi, G., Wang, Z., Wang, Z., Li, Z., Liu, X. Research on the pressurization performance of an impeller in a multi-phase pump under different working conditions (2019) Advances in Mechanical Engineering, 11 (3), .

[9] El Hajem, M., Morel, R., Champagne, J.Y., Vilagines, R., Pagnier, P. The study of the flow in an anhelico-axial pump using laser Doppler velocimetry [Article@Exploration par anémométrie laser Doppler de l’écoulement dans une pompe hélico-axiale] (2001) Houille Blanche, (3-4), pp. 34-39.

[10] Shi, G.-T., Wang, Z.-W., Luo, K. Analysis of the Turbulent Flow Intensity and Dissipation Characteristics of an Oil-gas Multiphase Pump in Its Compression Stages [Article@油气混输泵压缩级内湍流强度及湍流耗散特性分析] (2018) RenengDongliGongcheng/Journal of Engineering for Thermal Energy and Power, 33 (6), pp. 115-121.

[11] Falcimaigne, J., Brac, J., Charron, Y., Pagnier, P., Vilagines, R. Multiphase pumping: Achievements and perspectives [Article@Pompagepolyphasique: Réalisationsetperspectives] (2002) Oil and Gas Science and Technology, 57 (1), pp. 99-107.

[12] ANIN Framo Engineering Multiphase pumping - a technology and field testing status report (1994) World Pumps, 339, pp. 29-30.

[13] Jiang, J., Rui, Z., Hazlett, R., Lu, J. An integrated technical-economic model for evaluating CO 2 enhanced oil recovery development (2019) Applied Energy, 247, pp. 190-211.

[14] Shi, Y., Zhu, H., Zhang, J., Yin, B., Xu, R., Zhao, J. Investigation of condition parameters in each stage of a three-stage helico-axial multiphase pump via numerical simulation (2017) Proceedings of the International Offshore and Polar Engineering Conference, pp. 156-162.
[15] Zhang, J.Y., Li, Y.J., Cai, S.J., Zhu, H.W., Zhang, Y.X. Investigation on the gas pockets in a rotodynamic multiphase pump (2016) IOP Conference Series: Materials Science and Engineering, 129 (1), № 012007.

[16] Zhang, Y., Di, Y., Liu, P., Li, W. Simulation of tight fluid flow with the consideration of capillarity and stress-change effect (2019) Scientific Reports, 9 (1), № 5324.

[17] Lomakin, V.O., Kuleshovav, M.S., Bozh’eva, S.M. Numerical Modeling of Liquid Flow in a Pump Station (2016) Power Technology and Engineering, 49 (5), pp. 324-327.

[18] Lomakin, V.O., Kuleshova, M.S., Kraeva, E.A. Fluid Flow in the Throttle Channel in the Presence of Cavitation (2015) Procedia Engineering, 106, pp. 27-35.

[19] Brennen, C.E. Hydrodynamics of pumps (2011) Hydrodynamics of Pumps, 9781107002371, pp. 1-270.

[20] Brennen, C.E. Fundamentals of Multiphase Flows (2005) Cambridge:Cambridge University Press, pp. 1-410.

[21] Gouskov, A.M., Lomakin, V.O., Banin, E.P., Kuleshova, M.S. Minimization of Hemolysis and Improvement of the Hydrodynamic Efficiency of a Circulatory Support Pump by Optimizing the Pump Flowpath (2017) Biomedical Engineering, 51 (4), pp. 229-233.

[22] Lomakin, V., Cheremushkin, V., Petrov, A. The development of the theory of calculation of the hydrodynamic coupling (2019) IOP Conference Series: Materials Science and Engineering, 492 (1), № 012012.

[23] Lomakin, V.O., Chaburko, P.S., Kuleshova, M.S. Multi-criteria Optimization of the Flow of a Centrifugal Pump on Energy and Vibroacoustic Characteristics (2017) Procedia Engineering, 176, pp. 476-482.