

# Conceptual features for improving the flow part of the multiphase stages of ESP submersible plants for small and medium feeds for extracting stratal liquid with a high free gas content

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**Annotation.** This article analyzes the operation numerical simulation for serial and multiphase stages of various manufacturers on water and gas-liquid mixtures (GLM). Are identified the local gas separation areas in serial stages, which can lead to the formation of gas plugs and disruption of the pump supply.

These factors include: the creation of a finely dispersed flow structure at the entrance of the stage, the preservation along the flow with small free gas bubbles diameters, the sustenance of the value for the allowed free gas content by circulation means of fluid part in the impeller, a defined relationship between the pressure gradient and the GLM flow rate. A mathematical model is selected, hydrodynamic calculations of structural options, optimization are carried out, a conceptual option is selected. Bench tests were carried out, confirming the high parameters of the product when working on GLM.

## Introduction

There is a steady tendency in the world to increase the number of low-yield wells, which make up about 30-40% of the total well stock in the Russian Federation. In order to increase the oil recovery coefficient (ORC), the down hole pressure is reduced, respectively, the free gas content and solids at the pump inlet increases.

Serial submersible pumping equipment for operating wells is often unable to operate in such difficult conditions.

It is valid to question about effective technology for operating low-production wells with high average production time [1], [2].

In oil wells with a high free gas content, an increase in the efficiency of electric centrifugal pumps (ECPs) is achieved by installing multiphase stages at the inlet. The task of the stages is to effectively disperse, grind the gas-liquid mixture, reduce the diameter of the free gas bubbles and compress, in order to partially transfer the gas from the free state to the dissolved one, to reduce the free gas content at the pump inlet. After passing through the pump, free gas is released in the tubing and due to the effect of the gas lift helps to deliver the stratal liquid to the surface.



The efficiency of multiphase stages depends significantly on the dispersion of the gas-liquid structure of the pumped fluid, on the diameters of gas bubbles, water cut of the formation fluid, the presence of surface-active substances, pressure at the inlet and outlet of the pump [3, 4]. The average diameter of the gas phase bubbles in the stratal liquid at the pump inlet can be quite large: 300 — 1 mm or more. As a result of dispersion, it is in the range from 30–40  $\mu\text{m}$  for non-watered oil, about 130  $\mu\text{m}$  for watered oil [5], [6]–[29].

To increase the efficiency of the oil production process from low-production wells, Rimera Group has developed and offers complete equipment, mainly transferred to serial production. That is the conceptual design of low flow stages, gas separator, multiphase module, hydroprotection.

Multiphase stages can be installed directly at the section inlet or in a separate multiphase phase converter module at the pump inlet.

The topic is also of interest for the creation of small-sized gas-liquid compressors, for general industrial use, for small-sized aircraft engines of unmanned vehicles (drones). If the engine compressor runs on a mixture of gas and liquid fuel, the mass fraction of which reaches 10%, the density and, accordingly, the pressure of the gas-liquid fuel increases by two orders of magnitude, respectively, the diameters can be reduced by about ten times, and the quality of mixing fuel with gas can noticeably increase. Compression occurs according to a quasi-isothermal process, which can increase the efficiency of the installation.

### Analysis of structural schemes.

The fig. 1 shows the multiphase stages main structural schemes of pumps for small and medium flows.

1. Series multiphase stages with axial stages, see Fig. 1a.
2. An analog of multiphase stages of one of foreign manufacturers, impellers of a half-open type without a cover disk, with holes in the drive disk made at the entrance to the impeller, see Fig. 1b.
3. New multiphase stages with fluid circulation in the impeller, see Fig. 1c.
4. New multiphase centrifugal-disk stages with fluid circulation in the impeller, differing from stages on the point 3 by the presence of a longitudinal cut in the middle part of the blade, this design is at the patenting stage.

Multiphase stages can be installed directly or in a separate module at the entrance to the section, while their operation on the GHS is essentially the same.

### Mathematical model

In this article, we use the model of a multiphase incompressible fluid flow ( $\rho = \text{const}$ ). Numerical simulation is based on solving discrete analogs of the basic hydrodynamic equations.

The calculation is carried out on the basis of a mathematical model of a divided multiphase flow. That is, for each phase, the equations of mass and momentum transfer are solved separately, but the pressure field is the same for all phases.

The mathematical model consists of a set of differential and algebraic equations:

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

$$V_i = \int \alpha_i V dV$$

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 one

$$\sum_{i=1}^n \alpha_i = 1$$

2. The equation of conservation of mass (continuity equation):

$$\frac{\partial}{\partial t} \int_V \alpha_i \rho_i dV + \int_A \alpha_i \rho_i \vec{V}_i d\vec{a} = 0$$

where  $\rho_i$ —i-th phase density

$\vec{V}_i$ —i-th phase velocity (in the case of turbulent flow modeling by a RANS-type model averaged over time)

3. The equation for the change in the amount of motion:

$$\frac{\partial}{\partial t} \int_V \alpha_i \rho_i dV + \int_A \alpha_i \rho_i (\vec{V}_i \vec{V}_i) d\vec{a} = - \int_V \alpha_i \nabla p dV + \int_V \alpha_i \rho_i \vec{g} dV + \int_A [\alpha_i (T_i + T_i^t)] d\vec{a} + \int_V \vec{M}_i dV$$

where  $(\vec{V}_i \vec{V}_i)$  — tensor product of the velocity vectors of the i-th phase.

$p$ — pressure

$\vec{g}$ — mass intensity vector (in this case, the gravity force is 9.81 m / s<sup>2</sup> and the inertial force due to the rotation of the computational domain)

$T_i$ — molecular viscosity stress tensor

$T_i^t$ — turbulent stress tensor

$\vec{M}$ — vector of total intensity of interfacial interaction forces per unit volume, for a vector  $\vec{M}_i$  fair

equality:  $\sum \vec{M}_i = 0$

Vector  $\vec{M}_i$  characterizes all the forces that separate phases interact with each other.

$$M_i = \sum_{i \neq j} (\vec{F}_{ij}^D + \vec{F}_{ij}^{VM} + \vec{F}_{ij}^L + \vec{F}_{ij}^{TD} + \vec{F}_{ij}^{WL})$$

Where

$\vec{F}_{ij}^D$ — resistance force,  $\vec{F}_{ij}^{VM}$  power of the virtual mass

$\vec{F}_{ij}^L$ — lifting force

$\vec{F}_{ij}^{TD}$ — turbulent dispersion force

$\vec{F}_{ij}^{WL}$ — turbulent dispersion force

### Power of resistance

In the case of modeling the flow 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:

$$\vec{F}_{ij}^D = A_D \vec{V}_r,$$

Where

$A_D$ — linearized drag coefficient

$\vec{V}_r = \vec{V}_j - \vec{V}_i$ — relative velocity of one medium relative to another

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

Where

$C_D$ — drag coefficient

$\rho_C$ — continuous phase density

$a_{cd}$ — interaction area of the phases (in this case, the member  $a_{cd}/4$  is the projected area of the spherical particle on the plane).

The drag 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

$fD$ — coefficient taking into account the concentration of particles

$$C_{D\infty} = \frac{24}{R_d} (1 + 0.15 R_d^{0.687}) n p u R_d < 1000,$$

and

$$C_{D\infty} = 0.44 n p u R_d > 1000$$

$$R_d = \frac{\rho_c |V_r| l}{\mu_c}$$

$l$ — characteristic interaction length or bubble size

$\mu_c$ — dynamic viscosity coefficient of continuous medium

Coefficient  $fD$  is the ratio:

$$f_D = \alpha_c^{nD}$$

$\alpha_c$ — continuous phase concentration

$nD=8.3$  for spherical particle

Virtual mass

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

The force from the virtual mass acting on phase I, moving rapidly with respect to phase j is found as:

$$\overline{F_{ij}^{VM}} = C_{VM} \rho_c \alpha_c (\overline{a_j} + \overline{a_i})$$

$a_j, \overline{a_i}$ — acceleration of jth and ith phase

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

Lift force

In the case where the flow surrounding the dispersed particle is non-uniform or the particle is swirling, it experiences a force perpendicular to the relative velocity.

$$\overline{F_{ij}^L} = C_{Leff} \rho_c \alpha_d (\overline{V_r} \times (\nabla \times \overline{V_c}))$$

$\overline{V_r}$ — relative phase velocity

$\overline{V_c}$ — continuous phase speed

$\alpha_d$ — dispersed phase concentration

$C_L=0.25$  — lift force coefficient

Turbulent dispersion force

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

$$\overline{F_{ij}^{TD}} = A_D \overline{V_{TD}}$$

$$F_{ij}^{TD} = A_D V_{TD}$$

$A_D$ —drag force coefficient

$V_{TD}$ —relative lip speed

$$V_{TD} = D_{TD} (\nabla \alpha_d \alpha_d - \nabla \alpha_c \alpha_c)$$

$D_{TD} = C_0 \nu_{ct} \sigma \alpha I$ —turbulent diffusion tensor

$C_0=1$

$\nu_{ct}$ — turbulent viscosity coefficient kinematic  $\sigma \alpha$ — turbulent Prandtl number

$I$ — unit tensor

$$\sigma_{\alpha} = \sigma_0 \sqrt{1 + C_{\beta} \xi^2} \frac{1 + \eta}{B + \eta}$$

$$\sigma_{\alpha} = \sigma_0 \sqrt{1 + C_{\beta} \xi^2} \frac{1 + \eta}{B + \eta}$$

$\sigma_0=1$  — unmodified turbulent Prandtl number

$C_{\beta}=1,8$  — correction factor

$\xi$ — particle 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

$$\tau_I = \frac{\tau_T}{\sigma_0} \frac{1}{\sqrt{1 + C_{\beta} \xi^2}}$$

$$\tau_T = \frac{2}{3} C_{\mu} \frac{k_c}{\epsilon_c}$$

$\epsilon_c$ —continuous phase turbulence energy dissipation rate

$$\tau_R = \tau_D \left( 1 + \frac{\rho_c}{\rho_d} C_{VM} \right)$$

$$\tau_D = \frac{\rho_d d^2}{18 \mu_c} \text{—characteristic time scale for a dispersed particle}$$

$$\xi = \frac{|\vec{V}_r|}{\sqrt{\frac{2}{3} k_c}}$$

$k_c$ — kinetic turbulence energy of the continuous phase

Wall strength

Being located near the solid wall, the gas bubble undergoes an asymmetrical action from the liquid.

The force per unit volume that a gas bubble experiences is equal to:

$$\vec{F}_{ij}^{VL} = -C_{WL} \gamma_w \alpha_D \rho_c \frac{|\vec{V}_r|^2}{d_p} \vec{n}$$

Where

$y_w$ — distance from the wall

$\alpha_D$ — dispersed phase concentration

$\rho_c$ — dispersed phase density

$d_p$ — bubble diameter

$CWL$ — coefficient is a function of the distance from the wall and decreasing with increasing distance

$\vec{n}$ — unit normal to the wall at the point closest to the bubble

$Vr, \vec{\tau}$ — tangent to the wall component of the relative velocity

Coefficient  $CWL$  is like:

$$C_{WL} = \max \left( C_{w1} + \left( \frac{C_{w2}}{\gamma_w} \right) d_p, 0 \right)$$

Coefficients are  $CW1=-0,01$ ,  $CW2=0,05$ .

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 mathematical modeling results.

To carry out hydrodynamic calculations, models of the flow part of the serial stage and multiphase stages, which were presented above in the analysis of structural schemes, were built.

In fig. Figure 2 shows the results of numerical simulation of the operation of a serial stage on water. 2a and on the GLM, see Fig. 2b.

An analysis of the serial stage operation shows that there are two areas between the impeller disks and the upper (region 1) and lower (region 2) disks of adjacent guide vanes installed above and below the impeller in which there is no main stream flow. In these “stagnant” areas, conditions have been created for the separation of gas bubbles, enlargement, and the possibility of periodic exit of large gas bubbles beyond the outer diameter of the driving and driven disks into the flow part of the impeller. Since the pressure gradient, even with partial liquid separation during operation on the GLM, is quite high, see Fig. 2b for the separation of large bubbles from the exit to the input of the impeller with the possibility of the formation of a gas plug and a stall

For reliable operation of multiphase stages, areas in which separation and enlargement of free gas bubbles should be excluded.

A numerical simulation analysis of the stages using water and GLM helps to analyze the factors affecting the stages effective operation on the GLM without interruption of supply, on the possibility of increasing the permissible free gas content at the inlet to the centrifugal pump, with multiphase stages installed at it. Such factors include: creating a finely dispersed flow structure with small diameters of free gas bubbles at the entrance to the stage and maintaining the entire length of the flow, maintaining the value of the permissible content of free gas, for example, due to the circulation of a part of the liquid in the impeller, a certain ratio between the pressure gradient and GLM flow rate. The conceptual option is selected, see Fig. 3.

A new concept of the operation of compressor dispersing stages (CDS) is the circulation of a part of the liquid in the impeller. When working in each step (see Fig. 3) can distinguish the next points:

1. The GLM enters to the impeller, ejection by a jet of partially separated liquid,
2. Dispersion due to special grooves and a special blade design,
3. Compression in the flowing part of the impeller,
4. Partial gas separation at the impeller outlet
5. Gas with the main stream goes to the center and up to the next stage.
6. Part of the fluid, through the radial clearance, is directed to the entrance of the same impeller.

The design principle of operation allows to ensure the free gas content value in the impeller at the level that is necessary for reliable operation, without interruption of supply.

The CDS are crushed, the bubbles of the gas-liquid mixture are dispersed, and a homogeneous, finely dispersed flow structure is prepared, pre-compressed and fed to the main stages of the pump.

When the pump is working together with the GDS, the maximum volumetric free gas content at the inlet is allowed 15% higher compared to using a pump without GDS.

The Fig. Figure 4 shows the numerical simulation results of the multiphase stages assembly on water. The stages are sequentially installed:

1. A multiphase stages analogue of one of the foreign manufacturers, the impeller is half-open type without a cover disk, with holes in the drive disk made at the inlet, see Fig. 1b.
2. A new multiphase centrifugal-disk stage with a longitudinal cut in the middle of the blade.
3. Multiphase stage with a new operating concept, with fluid circulation in the impeller, see Fig. 1c

The stages differed only in the design of the impellers, the guiding devices were the same.

In Fig. 4a shows the velocity plots, in Fig. 4b pressure plots.

In Fig. Figure 5 shows the calculated values of efficiency (a), head (b) and mass flow (c). The numbers indicate the values for each of the successively set stages, the number 4 shows the integral values for the stages assembly.

An analysis of the data shows that the highest pressure and efficiency values have a stage with the circulation of part of the liquid inside the impeller. The flow rate through the impeller in stages with circulation is higher than the flow rate of traditional stages by the amount of flow from the output back to the input of this wheel. The step 3 has a higher mass flow through the wheel, since the pressure of this step is higher than the pressure of the centrifugal - disk stage, and accordingly, higher than the fluid flow through the gap between the guide sleeve and the driven wheel disk.

However, due to better dispersion, the centrifugal - disk stage will be able to work better in off-design modes.

Theoretically, the stages with the circulation of a part of the separated liquid can, in contrast to the known analogues, also work at a 100% free gas content and can be used as gas-liquid compressors. In known multiphase stages, at a certain content of free gas, coalescence processes begin, combining gas bubbles, which lead to a failure of the supply. The new design guarantees a certain amount of fluid circulates in the stages, ensuring reliable operation.

For calculation, the StarCCM software package was used. The previously constructed flow geometry was imported as a surface mesh.

The following parameters are accepted as a physical model:

- Multiphase interaction, the scale of the interaction length is 0.1 mm.
- The phases are water H<sub>2</sub>O and gas Air (air)
- Initial liquid / gas distribution 1/0
- The input pressure is set to a total pressure of 0 Pa and a liquid / gas ratio of 4/1
- A negative velocity value of 4.5 m / s is set at the fluid outlet boundary
- Atmospheric pressure is set at the gas outlet boundary

The following parameters were taken as the studied parameters: head, separation coefficient (fraction of water at the separator outlet) and power depending on the flow rate.

### Results of bench tests.

The Fig. Figure 6 shows the results of bench testing of a section on industrial water with air, without surface active substances (SAS), with multiphase dispersing stages of various designs installed at the inlet:

1. Axial Stages, see Fig. 1a.
2. Stages with impellers of a half-open type, with holes in the drive disk, see Fig. 1b.
3. Stages with fluid circulation in the impeller, see Fig. 1c.

Analysis of the results shows the advantages of multiphase stages of a conceptual design.

### Design features of a multiphase module.

In the universal module for pumps for small and medium flows, the module is filled only with multiphase centrifugal compressor dispersing stages. For low feed pumps, it is advisable to install an additional stage in the form of a labyrinth-screw pair for preliminary dispersion of large gas bubbles.

In Fig. 7 shows the design of a new multiphase module, which has been put into mass production for low-flow pumps.

### Conclusions

The results of numerical modeling and bench tests showed that:

1. A new conceptual design of the multiphase stage has been developed.
2. The conceptual novelty of the design is the circulation of part of the liquid in the centrifugal impeller, due to this, the required ratio between the amount of free gas and liquid in the flowing part of the impeller is maintained, which ensures reliable operation of the stage. An issue has been resolved that limits the allowable free gas content in known similar steps.
3. The results of bench tests on GLM the characteristics of new stages exceed the level of the best serial products.
4. The conceptual ideas inherent in the design can serve as the basis for the development of multiphase stages for other sizes.

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