Simulation of regenerative pump performing on multiphase mixture

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Annotation: The features of gas-liquid mixtures hydrodynamic modeling during the separation process are described. The paper considers the model of a centrifugal pump, which is a part of mobile objects, such as wheeled and tracked vehicles etc. The simulation is carried out in the STAR-CCM + software. A comparison of the effect of gas separators various designs on the flow during the operation of the pump on a two-phase mixture is carried out and the most suitable configuration is identified.

Introduction

Currently, regenerative pumps are widely used in rural water supply, small automatic pumping stations, in municipal services and in the chemical industry for supplying aggressive reagents [1]. This happens since regenerative pumps have simple design and the ability to work on a mixture of liquid and gas, they are easy to operate and can run in self-suction mode.

The disadvantage of the regenerative pump is its relatively low efficiency (the efficiency of existing pumps does not exceed 45% at the operating mode), this circumstance does not allow to use them at high power [2,3].

Regenerative pumps are preferred for short-term pumping of volatile liquids, working on a mixture of liquid and gas (in aircraft tankers, in automobile gas stations), on vessels for the supply of drinking water and as a nutrient for auxiliary boiler installations.

As it was mentioned earlier, one of the most important qualities of a regenerative pump is the ability to work on a mixture of liquid and gas, as well as in self-suction mode. Regenerative pumps of the closed type with an open channel, without additional devices, do not operate on gas and do not possess self-suction capacity. To ensure self-suction ability, a separating cap and a separator are installed at the outlet of the discharge pipe. From a theoretical point of view, this process of pump operation is practically not studied. Therefore, the problem of numerical simulation of a regenerative pump operation on a gas-liquid mixture is relevant. Existing design recommendations were obtained after processing only experimental data and require mathematical justification.

In this article, it has been attempted to compute the flow of a gas-liquid mixture in a flow part of a closed-type regenerative pump using computational hydrodynamics methods. Moreover, the self-suction process was described and optimal design parameters from the point of view of pump operation on a two-phase mixture were obtained.

The object under consideration is the regenerative stage with a pressure pipe and a separator.

Figure 1 represents the 3D-model of the pump flow part with the pressure cap and the separator.
Figure 1. The flow part of the pump with the pressure cap and the separator

To compare the results of numerical calculation with the experimental data, a comparative simulation of the fluid flow in the flow part with various separator designs, which were manufactured for existing regenerative pumps, was carried out. Figure 2 shows 3D-models of separator designs under consideration.

Figure 2. 3D-models for several separator configurations

Methods
The method of numerical simulation is based on solving discrete analogs of the basic equations of hydrodynamics [4–8]. For incompressible fluid ($\rho = const$) they look like:

Mass conservation equation (continuity equation)

$$\frac{\partial u_j}{\partial x_j} = 0,$$
where $\overline{u}_j$ — the projection of fluid velocity averaged value on the j-axis (j=1,2,3);

The equation of conservation of momentum (Reynolds averaging):

$$
\rho \left[ \frac{\partial U_i}{\partial t} + U_j \frac{\partial U_i}{\partial x_j} \right] = -\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_i} \left[ T_{ij}^{(v)} - \rho \overline{u}_i \overline{u}_j \right],
$$

where \(U, P\) — averaged velocity and pressure;

$$
T_{ij}^{(v)} = 2\mu \overline{S}_{ij} — \text{viscous stress tensor for incompressible fluid};
$$

$$
\overline{S}_{ij} = \frac{1}{2} \left[ \frac{\partial \overline{u}_i}{\partial x_j} + \frac{\partial \overline{u}_j}{\partial x_i} \right] — \text{instantaneous strain rate tensor};
$$

\(\rho \overline{u}_i \overline{u}_j\) — Reynolds stresses.

The introduction of the Reynolds averaged Navier – Stokes equation leaves the system of equations unclosed, since additional unknown Reynolds stresses appear. To solve this system, a semi-empirical k-ω SST turbulence model was used. It introduces the necessary additional equations: the equations for the transfer of the turbulence kinetic energy and the relative rate of dissipation of this energy:

$$
\frac{\partial k}{\partial t} + U_j \frac{\partial k}{\partial x_j} = P_k - \beta k \omega + \frac{\partial}{\partial x_j} \left[ (v + \sigma_k \omega) \cdot \frac{\partial k}{\partial x_j} \right]
$$

$$
\frac{\partial \omega}{\partial t} + U_j \frac{\partial \omega}{\partial x_j} = \alpha \cdot S^2 - \beta \cdot \omega^2 + \frac{\partial}{\partial x_j} \left[ (v + \sigma_\omega \omega) \cdot \frac{\partial \omega}{\partial x_k} \right] + 2 \cdot (1 - F_i) \cdot \sigma_{\omega 2} \cdot \frac{1}{\omega} \cdot \frac{\partial k}{\partial x_j} \cdot \frac{\partial \omega}{\partial x_j}
$$

To simulate the process of gas separation, a two-phase model with approach known as VOF (Volume of Fluid) [9] was used. The VOF method considers multiphase medium as a single fluid, the properties of which vary according to the volume ratio of present phases:

$$
\alpha_i = \frac{V_i}{V}, \text{where}
$$

where $V_i$ — i-phase volume in the cell,

$V$ — cell volume.

Volume ratio of each phase in the cell should satisfy the condition:

$$
\sum_{i=1}^{N} \alpha_i = 1,
$$

where $N$ — the number of phases.

Depending on the volume fraction, the presence of different phases or liquids in the cell can be distinguished:

- $\alpha_i = 0$ — there is no i-phase in the cell
- $\alpha_i = 1$ — the cell is filled with i-phase
- $0 < \alpha_i < 1$ — there are several phases in the cell

The equation for the mass concentration of each phase is:

$$
\frac{\partial (\alpha_i \rho_i)}{\partial t} + \nabla \cdot (\alpha_i \rho_i V) = 0
$$

The minimum bubble size and the minimum gas concentration in any cell are strictly limited to very small, but non-zero values. The time step was chosen based on the characteristic flow rates and
The selected time step is $1e^{-5}$ s. The number of inner iterations at each time step is 15. To obtain discrete analogs of the original continuous equations STAR-CCM + software package uses the control volume method described in [10].

The computational grid built for the regenerative pump with the separator consists of 400 000 polyhedral cells, base size is 5 mm, the grid is shown in Figure 3.

![Figure 3. The computational grid of the regenerative pump with the pressure cap](image)

When the regenerative pump operates on a mixture of liquid and gas, the flow part is pre-filled with liquid. In order to recreate the actual working conditions, a function that allows filling of the pump flow part with water to the desired level was created. Figure 4 presents the distribution of the liquid and gas phase in the flow part at the initial moment of time $t = 0$. In the process of simulation, a mixture of gas and water enters through the inlet boundary of the pump. The flow rate of the mixture at the inlet and the pressure at the outlet were set as boundary conditions.

The criteria for assessing the quality of separator designs are the average gas flow rate at the outlet from the cap and the manufacturability of the separator.
Results
Figures of water volume fraction distribution for different separator configurations were created during the two-phase simulation of the pump.

Figure 4. Initial state of the pump

Figure 5. The distribution of water volume fraction in separator#1
According to the figures the pump works on approximately 50/50 mixture of gas and water. The results for several separator configurations are shown in table 1.

| Separator configuration | Head, m |
|-------------------------|---------|
| 1                       | 18      |
| 2                       | 25      |
| 3                       | 31      |
Obtained distributions and results indicate the need for further research and simulation in this field.

References
[1] V Cheremushkin and APolyakov 2019 IOP Conf. Ser.: Mater. Sci. Eng. 589 012001
[2] V Tkachyk et al 2019 IOP Conf. Ser.: Mater. Sci. Eng. 589 012010
[3] V Tkachyk et al 2019 IOP Conf. Ser.: Mater. Sci. Eng. 589 012011
[4] E Morozova et al 2019 IOP Conf. Ser.: Mater. Sci. Eng. 589 012012
[5] K Abramov 2019 IOP Conf. Ser.: Mater. Sci. Eng. 589 012013
[6] A Boyarshinova et al 2019 IOP Conf. Ser.: Mater. Sci. Eng. 589 012014
[7] N Sosnovsky and D Ganieva 2019 IOP Conf. Ser.: Mater. Sci. Eng. 589 012016
[8] M Saprykina and V Lomakin 2019 IOP Conf. Ser.: Mater. Sci. Eng. 589 012017
[9] A Boyarshinova et al 2019 IOP Conf. Ser.: Mater. Sci. Eng. 589 012028
[10] A Martynyuk et al 2019 IOP Conf. Ser.: Mater. Sci. Eng. 589 012029