Interphase forces analysis in the whole flow passage of a multiphase rotodynamic pump

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Abstract. To understand the internal flow and interphase forces characteristics in the multiphase rotodynamic pump, simulations were performed using ANSYS_CFX for the whole flow passage with medium combination of air-water. The reliability of simulation was verified by comparing with the experimental data of external characteristics. The results showed that the drag is dominant for the interphase forces in the impeller and guide vane passages, followed by the lift and added mass forces, then the turbulent dispersion force, and it can be neglected relative to drag. With the increased IGVF (inlet gas void fraction), all interphase forces in the impeller and guide vane passages will increase, also, the variation range of interphase forces in the impeller was greater than that in the guide vane.

1. Introduction
The multiphase pump handling gas-liquid two-phase flow is generally grouped into two types, one is the positive displacement pump and the other is rotodynamic pump. Compared to the former type, the latter has many advantages, such as smaller volume, larger flow rates, lower requirement for manufacture precision, lower sensitivity to solid particles in the flow field, and easier to use and repair, and so on [1]. In recent years, many studies on the multiphase pump handling gas-liquid two-phase flow were focused on the optimization design [2-5] and the transport properties [6-8].

Although the interphase behavior is difficult to understand in two-phase flow field, various studies on interaction between gas-liquid phases have been performed for same and different flow patterns at certain condition. Ishii and Zuber analyzed the formula of interphase behavior for dispersed two-phase flow and obtained the empirical formula of drag coefficient at different conditions of IGVF, flow pattern and particle [9]. The traditional linear empirical formula of added mass coefficient for bubble flow was analyzed by Laurien, and they found it will significantly underestimate the magnitude of actual added mass force if IGVF exceeds 20% [10]. These studies were conducted using horizontal or inclined pipes only, in the non-rotating machinery. While for the phase interaction characteristics in multiphase pumps, although Yu et al. [11] analyzed the magnitude of interphase forces and obtained the drag is dominant, the understanding of gas-liquid interphase behavior in multiphase rotodynamic pumps is still insufficient. Actually, the gas-liquid two-phase flow is more disordered in multiphase rotodynamic pumps because of the rotation of impeller and the rotor-stator interaction.

On the whole, less research was performed on the interaction characteristics between the gas-liquid phases. Therefore, this study reports the results of three-dimensional (3D) simulation for a whole passage of a multiphase rotodynamic pump handling gas-liquid two-phase flow. The internal flow
phase interaction characteristics in the impeller and guide vane passages were conducted at various IGVFs. The objective of the present study was to develop an understanding of movement law of gas phase and interaction characteristics between the gas-liquid phases, which will help in the optimization design of the multiphase rotodynamic pumps.

2. Research object

2.1. Test system

The schematic diagram of the test system of the multiphase pump is shown in Figure 1. Here, air-water was used as the working medium so as to ensure the safety of experiment and the reusability of equipment. In the experiment, the water that flowed out from the water tank 1 was mixed evenly with the air that provided by a compressor in a mixer 4, and they entered the multiphase pump 5, then the gas and water flowed back to the water tank 1 together. Meanwhile, In order to observe the gas-liquid two phase flow characteristics in this pump by a high-speed camera, the shells of impeller and guide vane were made of the organic glass. Figure 2 shows the test pump model with its inlet and outlet pipes, impeller and guide vane.

Figure 1. Schematic diagram of the test system of the multiphase pump.

Figure 2. The test pump model.

2.2. Computational model and structured mesh

The main design parameters of the multiphase pump are as follows: the numbers of impeller and guide vane blades (Z₁ and Z₂) are 4 and 11, respectively, the designed rotational speed \( n \) is 2950r/min, the designed head \( H \) is 15m, and the designed discharge \( Q_d \) is 50m³/h. Figure 3 shows the computational
model of the multiphase pump with its inlet and outlet pipes, impeller and guide vane. Meanwhile, the mesh of the first two parts was generated using ICEM_CFD, and the mesh of the latter two parts were generated using TurboGrid, as shown in Figure 4. The final mesh number for the whole computational domain was determined as 3.68 million after mesh independence analysis at pure water design condition. The detailed mesh information for each part of the computational domain is listed in Table 1.

![Figure 3. Computational model.](image)

![Figure 4. Structured mesh for impeller and guide vane passages.](image)

### Table 1. Detailed mesh information for each part of the computational domain.

| Mesh information | Inlet pipe | Impeller | Guide vane | Outlet pipe | Total (million) |
|------------------|------------|----------|------------|-------------|-----------------|
| Elements         | 54516      | 590416×4 | 105840×11  | 99540       | 3.68            |
| Nodes            | 63360      | 629696×4 | 116964×11  | 112000      | 3.98            |

3. Numerical methods

3.1. Governing equations

The two-fluid model was used to solve the gas-liquid two-phase flow to predict the internal flow of the multiphase pumps [12-14]. The steady Reynolds-averaged Navier-Stokes (RANS) equations were solved using ANSYS CFX 16.0. The continuity and momentum equations for incompressible flow were written in Cartesian coordinate system as follows [15-18]:

**Continuity equation:**

\[
\nabla \cdot (\alpha_k \rho_k U_k) = 0
\]

**Momentum equation:**

\[
\nabla \cdot (\alpha_k \rho_k U_k U_k - \alpha_k \tau) = -\alpha_k \nabla p + M_k + \alpha_k \rho_k f_k
\]
where subscript \( k = l \) or \( g \) represent liquid or gas phase, respectively, \( \rho_k \) denotes the density, \( \alpha_k \) is the volume fraction, where \( \alpha_l + \alpha_g = 1 \), \( p \) is the pressure, \( U_k \) is the velocity, \( M_k \) is the interphase force per unit volume; \( f_k \) stands for the mass force, and \( \tau \) denotes the viscous stress tensor related to the molecular viscosity and turbulence viscosity. The components of viscous stress tensor can be expressed as follows:

\[
\tau_{ij} = 2\mu_k s_{ij} + \frac{2}{3}\rho_k k \delta_{ij} \quad (3)
\]

where \( i, j = 1, 2, 3 \) stand for the three directions of the relative coordinate system related to the impeller rotation, \( S_{ij} \) denotes the strain tensor, and \( \mu_k \) and \( \mu_t \) represent the dynamic viscosity and the turbulence viscosity, respectively. Here, the turbulence viscosity \( \mu_t \) is solved using the shear stress transport (SST) \( k-\omega \) model which combines the advantages of \( k-\varepsilon \) and \( k-\omega \) turbulence models, namely the \( k-\varepsilon \) and \( k-\omega \) models are employed for the near-wall and main flow regions, respectively, and it can be expressed as follows [19-20].

\[
\mu_t = \frac{\rho_{mix} a_t k}{\max(a_t, SF)} \quad (4)
\]

where \( a_t \) is the model constants (\( a_t = 5/9 \)), \( \rho_{mix} \) represents the mixture density, \( S \) is the invariant measure of the strain rate, \( F \) is the blending function, and \( k \) and \( \omega \) stand for kinetic energy and turbulence frequency, respectively.

### 3.2. Interphase forces

According to the previous studies, the interphase forces between the gas-liquid two phases in the multiphase pump usually include drag, added mass, lift, and turbulent dispersion [21]. Therefore, the total interphase force \( F_k \) can be written as follows:

\[
F_k = F_{D,k} + F_{A,k} + F_{L,k} + F_{T,k} \quad (5)
\]

here, \( F_{D}, F_{A}, F_{L} \) and \( F_{T} \) represent the interphase forces of drag, added mass, lift and turbulent dispersion, respectively. Their expressions are listed as follows:

\[
F_{D,l} = F_{D,g} = \frac{3}{4} C_D \frac{\rho_l}{D_b} \alpha_g \left( U_g - U_l \right) \left| U_k - U_l \right| \quad (6)
\]

\[
F_{A,l} = F_{A,g} = -\rho C_A \alpha_g \left( \frac{DU_g}{Dt} - \frac{DU_l}{Dt} \right) \quad (7)
\]

\[
F_{L,l} = F_{L,g} = C_L \alpha_g \rho_l \left( U_g - U_l \right) \times (\nabla \times U_l) \quad (8)
\]

\[
F_{T,l} = F_{T,g} = -C_T \rho_l k \nabla \alpha_l \quad (9)
\]

where \( U_g \) and \( U_l \) stand for the velocity of gas and liquid, respectively, \( \alpha_g \) stands for the gas void fraction, \( \rho_l \) is the liquid density, and \( D_b \) denotes the diameter of gas bubble. The coefficients of added mass, lift, and turbulent dispersion (\( C_A, C_L \) and \( C_T \)) are 0.5, 0.5 and 0.1, respectively [22-23,9], whereas the coefficient of drag \( C_D \) is the key factor to the magnitude of the drag and it can be expressed as follows according to the reference [24].

\[
C_D = \max(C_{D1}, C_{D2}) \quad (10)
\]

\[
C_{D1} = \frac{24}{Re_b} (1 + 0.1 \text{Re}_{b}^{0.75}) \quad (11)
\]

\[
C_{D2} = \frac{2}{3} D_b \sqrt{\frac{(\rho_l - \rho_g) g}{\sigma}} (1 - \alpha_g)^{0.5} \quad (12)
\]
3.3. Boundary condition and numerical solution
The bulk mass discharge and the corresponding gas void fraction of each medium were specified at the inlet of computational domain and the average static pressure was applied at the outlet. At all the wall boundaries, the no-slip condition was adopted and in the rotor-stator interaction region, the frozen-stator was imposed. Additionally, high resolution scheme was adopted for the advection and transient terms, and the RMS residual of $1 \times 10^{-4}$ was used as the convergence criteria.

4. Results and discussions

4.1. Performance prediction and validation
The simulation and experimental results with different discharges at conditions of $n=2950$ rpm and $\phi=0.274$ are shown in Figure 5. The $Q$-$\eta$ and $Q$-$H$ curves from the simulation show close agreement with the experimental results. The errors of efficiency and head at design discharge are 0.94% and 2.97%, respectively. The definition of $IGVF$ (inlet gas void fraction) is described by the following expression. Here, $Q_g$ and $Q_l$ represent the volume discharge of gas and liquid, respectively. Table 2 listed the values of head with different $IGVF$s at $Q=50$ m$^3$/h. All relative errors of head between simulation and experiment are relative small at $IGVF$s of 9%, 15% and 21%, and they are 1.89%, 3.27% and 1.45%, respectively. According to the above analysis, the conclusion can be drawn that the numerical method used in our study is reasonable.

$$IGVF = Q_g/(Q_g + Q_l)$$ (13)

![Figure 5](image-url) Performance curves from simulation and experiment ($IGVF=0\%$).

Table 2. Values of Head with different $IGVF$s between simulation and experiment ($Q=50$ m$^3$/h).

| $n$ (rpm) | $IGVF=9\%$ | $IGVF=15\%$ | $IGVF=21\%$ |
|-----------|-------------|-------------|-------------|
|           | $H_{CFD}$ (m) | $H_{EXP}$ (m) | Error (%) | $H_{CFD}$ (m) | $H_{EXP}$ (m) | Error (%) | $H_{CFD}$ (m) | $H_{EXP}$ (m) | Error (%) |
| 2950      | 16.19       | 15.89       | 1.89       | 15.45       | 14.96       | 3.27       | 14.71       | 14.50       | 1.45      |

4.2. Interaction characteristics between gas-liquid phases at $IGVF=15\%$
To analyze the interaction characteristics between gas-liquid phases in the multiphase rotodynamic pump, the area average of interphase forces including drag, added mass, lift and turbulent dispersion are extracted along the flow direction. The interphase forces in impeller and guide vane passage at $IGVF=15\%$ are shown in Figure 6, where the range of “Streamwise” in the horizontal axis is from 0 to...
2, that is, from the impeller inlet to the guide vane outlet. Overall, the drag is largest for these four interphase forces, followed by the lift and added mass forces, then the turbulent dispersion force.

Figure 6 also shows that the interphase forces of drag, lift and added mass increased dramatically near the impeller inlet and rotor-stator region (impeller outlet-guide vane inlet). On the one hand, this is due to the rotation of the impeller and rotor-stator interaction between rotating impeller and static guide vane, the flow near the impeller inlet and rotor-stator region is more disordered, thus resulting in the increased gas-liquid velocity difference therein, as shown in Figure 7. On the other hand, the liquid phase with a larger density, experienced larger centrifugal force than gas phases, and as a result, moved toward the impeller shroud, whereas the gas will move to and gather at the impeller hub (gas distribution as shown in Figure 8). Then combined with equations (6-8), it can be known that the magnitude of interphase forces has a positive correlation with the gas void fraction and the gas-liquid velocity difference, which leads to the obvious increase of interphase forces of drag, lift and added mass near the impeller inlet and rotor-stator region.

In order to analyse the magnitude of these four interphase forces, the magnitude ratio of non-drag forces to drag in impeller and guide vane passages at IGVF=15% is shown in Figure 9. Overall, the magnitude ratio of non-drag forces to drag is general less than 1, and the magnitude ratio of turbulent dispersion force to drag is always less than 0.2, which illustrates that the drag is dominant and the turbulent dispersion force can be neglected relative to the drag.
4.3. Influence of IGVF on interaction characteristics between gas-liquid phases

According to the above analysis, the turbulent dispersion can be neglected relative to the other three interphase forces, thus Figure 10 only compares the magnitude of drag, lift and added mass in the impeller and guide vane passages at IGVFs of 3%, 9%, 15% and 21%. Generally, the distribution rules of interphase forces are similar at different IGVFs: (1) the drag is dominant and the interphase forces in the impeller is greater than that in the guide vane; (2) all interphase forces will increase dramatically near the impeller inlet and the rotor-stator interaction region.

Figure 10. Distribution of interphase forces along the flow direction at different IGVFs.
With the increased $IGVF$, the interphase forces in the impeller and guide vane passages increased gradually, this is because the degree of aggregation of the gas in impeller and guide vane will increase if the $IGVF$ increased, as shown in Figure 11, then the cross-sectional area is reduced, and hence, the flow become more disordered. It can be also seen that the variation range of the interphase forces in impeller is greater than that in guide vane. This is ascribe to the rotation of the impeller, the gas superficial velocity in the impeller increased obviously with $IGVF$ increased, as shown in Figure 12. From Figure 12, at $IGVF$s of 15% and 21%, a larger gas velocity region appears near the suction surface of impeller blades (Figure 12c, 12d), which illustrates that the gas-liquid flow in the impeller is more disordered at these two conditions.

![Figure 11. Distribution of gas void fraction along the flow direction at different $IGVF$s.](image)

![Figure 12.](image)
5. Conclusions

Through the numerical calculation, the internal flow and interaction characteristics between the gas-liquid phases in the impeller and guide vane passages of a multiphase rotodynamic pump were conducted at various IGVF's. The results can be summarized as follows:

1. For the interphase forces in the impeller and guide vane passages of the multiphase rotodynamic pump, the drag is dominant, followed by the lift and added mass forces, then the turbulent dispersion force. Along the flow direction, the magnitude ratio of turbulent dispersion force to drag is always less than 0.2, which illustrates that it can be neglected relative to the drag.

2. Due to the rotation of impeller and the rotor-stator interaction between the impeller and guide vane, the interphase forces of drag, lift and added mass increased dramatically near the impeller inlet and rotor-stator region.

3. With the increased IGVFs, the interphase forces in the impeller and guide vane passages increased, also, the variation range of interphase forces in the impeller was greater than that in the guide vane.

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