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The effect of solid particle size and concentrations on internal flow and external characteristics of the dense fine particles solid-liquid two-phase centrifugal pump under low flow condition

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ABSTRACT

In the energy conversion device and fluid transport equipment, the solid–liquid two-phase centrifugal pump occupies a large proportion, but the transport mechanism of dense fine particles has not been studied in detail. In this work, the solid–liquid two-phase flow in a centrifugal pump was numerically simulated by the mixture model. Two-phase performance tests with different particle concentrations and particle sizes at a low flow rate (0.6Qd) were conducted, and dimensionless analysis on the effect of particle concentrations and particle sizes on head and efficiency was conducted. The results show that the increase in particle size and particle concentration can increase the influence coefficient of head and efficiency and the influence of the two parameters on efficiency is greater than that on the head on the whole. The increase in particle size and concentration will lead to more uneven distribution of the solid volume fraction in the pump. The transport of dense fine particles absorbs a large amount of energy, which leads to the relative decrease in the kinetic energy of the liquid phase and inhibits the generation of the vortex in the impeller passage.

I. INTRODUCTION

In the dredging industry, a large number of solid–liquid two-phase centrifugal pumps have been used to meet the requirements of transporting solid–liquid two-phase fluid. In practical engineering, the condition that the solid medium contains small particles with a high concentration is very common, which was called dense fine particle solid–liquid two-phase flow. Because the internal flow of dense particles is much more complex than that of thin particles, which makes the flow mechanism inside the centrifugal pump more complex. The collision and wear of dense particles on the flow parts greatly reduce the service life of the pump, and the energy loss is particularly serious. Many scholars have researched the solid–liquid two-phase flow in centrifugal pumps from different perspectives through numerical simulation and experimental verification. Li et al. studied the wear of large particles on a centrifugal pump by using the computational fluid dynamics (CFD)-discrete element method (DEM) method; their results showed that the instantaneous wear rate of the pump presented periodic changes and the wear rate increased with the increase in particle concentration. Pagalthivarthi and Visintainer simulated the pump and calculated the wear rate according to the wear coefficient determined empirically; the results showed that the wear rate was closely distributed near the cut water area and the wear was not uniform. Zhao, Zhang, and Wang et al. found that with the increase in particle size and volume concentration, the internal pressure in the centrifugal pump flow field decreased, the volume fraction of the solid phase in the impeller flow passage decreased as a whole, and particles gradually migrated from suction to the pressure surface. Wu et al. studied the influence of unstable flow characteristics on solid–liquid two-phase flow and pump performance of a mud pump and found that high-speed particles would wear more on the blade tail. Cheng et al. used the Eulerian multiphase flow model to calculate the salt particles transported by the molten salt pump and found
that except for the larger salt particles, the performance of the molten salt pump with a larger blade was higher than that of the other two experimental pumps. Shen et al.22 calculated the solid–liquid two-phase flow in a spiral centrifugal pump, and the results showed that the wear of the impeller was mainly concentrated on the working face, the wear of small particles on the wall was more uniform, the movement trajectory was longer, and the wear of larger particles on the wall was more concentrated. Noon and Kim7 numerically simulated the erosion and wear of lime slurry on the pump and found that the volute tongue and abdomen were the most severely worn areas and the rate of erosion and wear increased with the increase in the particle impact rate, particle concentration, and particle size. Zhao et al.23 carried out numerical simulation of solid–liquid two-phase flow of a centrifugal pump under non-design conditions and found that the sand distribution in the pump flow passage was extremely uneven under the non-design conditions. Wang et al.11,12 analyzed the solid–liquid flow in the slurry pump; the results showed that with the increase in particle diameter and particle concentration, the intensity and size of the vortex in the guide vane increase obviously, the velocity changes more dramatically, the working capacity of the impeller decreased, and the shaft power increased. Li et al.13 found that at a low flow rate, the solid phase characteristics basically had no effect on the performance of the centrifugal pump, but when the particle size and volume fraction increased, the maximum efficiency of the centrifugal pump decreased, and the optimal efficiency point tended to the direction of the low flow rate. Tarodiya and Gandhi14 used the predicted results of the Eulerian–Eulerian model to find that the sand distribution in the pump flow passage was extremely uneven under the non-design conditions. Wang et al.15 established a Lagrange numerical model based on the particle motion equilibrium equation and found that if the blade profile is similar to the particle motion trajectory, the influence of particles on blade wear will be minimized. Huang et al.16 found that the wear of the volute accounted for about 70% of the total wear of the pump; under low flow conditions, the wear of the impeller crown was relatively large, and with the increase in flow, the wear of the pressure side of the blade and the hub increased significantly. Peng et al.17 and Li et al.18 analyzed the flow of a centrifugal pump at a small flow rate; the result showed that the flow is very unstable, the distribution of solid particles on the surface was very uneven, and the local wear is strong. Tang and Kim19 found that in the solid–liquid flow in a single-channel pump, small particle size had a larger velocity distribution range and velocity peak while large particle size had a larger contact force, and the blade and volute wall were subjected to a larger contact force. Gao et al.20 analyzed the solid–liquid two-phase flow in a vortex pump and found that there are three different transport modes for particles. In the diffusion section to the volute outlet area, particles flow out with the liquid in a spiral manner. Shi et al.21 used the wear equation proposed to predict the volute wall wear, and both the predicted and tested areas of high erosion intensity were located near the volute 180° angle and the tongue. Liu et al.22 through the simulation of solid–liquid two-phase flow found that the particle concentration near the back of the blade was higher, and with the increase in particle diameter, the particle tended to move toward the back of the blade. Ning and Wang23 analyzed the influence of different particle parameters on pump performance and found that the erosion velocity ratio of the flow channel wall increases with the increase in the volume fraction. Abdolahnajed et al.24 and Mrinal et al.25 studied the transport of non-Newtonian fluids by centrifugal pumps, and the results showed that with the increase in fluid viscosity, the head and efficiency of the pump decreased.

The result of the collision of dense solid particles in a centrifugal pump is complex and difficult to measure, and the current research on the centrifugal pump is mainly focused on the solid–liquid two-phase flow with low concentration and large particles. For the solid–liquid two-phase flow with dense fine particles transported by the centrifugal pump, a large number of experiments and numerical simulation studies are needed. In this work, the influence of dense fine particles on the performance of the centrifugal pump under the condition of low flow rate was studied. The mixture model was used to simulate the flow field distribution in the centrifugal pump. Combined with the experimental results, the influence of particle size and particle concentration of dense fine particles on the external characteristics of a centrifugal pump was analyzed. The flow mechanism of dense fine particles transported by the centrifugal pump under a low-flow rate condition is revealed, which provides a theoretical basis for loss reduction and optimal design of centrifugal pumps.

II. CALCULATION MODEL

A. Governing equations

Due to the interaction between the liquid phase and the dense particle phase, there are a high momentum and energy transfer between the two phases in the mixture flow transported by the centrifugal pump. The following assumptions are adopted to simplify the calculation:

(1) The continuous phase (water) is an incompressible fluid, and the physical properties are constant.
(2) The particle size is uniform and spherical; the solid phase is assumed to be a continuous medium. Collisions between particles are ignored.
(3) The effect of temperature on the two-phase flow field is ignored.
(4) The collision between the particle and the wall is elastic collision.
(5) The liquid and the particle are coupled bidirectionally.

The Eulerian–Eulerian method is used to study the solid–liquid two-phase coupling; the particle is regarded as a fluid, and the dispersion of the particle in the fluid is regarded as the “particle fluid” penetration in the fluid. In order to improve the operation quality and save the operation cost, the mixture model, which is more mature than the Eulerian–Eulerian model, is selected. The governing equation of continuity of the mixed phase is as follows:

$$\frac{\partial}{\partial t} (\rho_m) + \nabla \cdot (\rho_m \mathbf{u}_m) = 0,$$

where $\rho_m$ is the density of the mixed phase and $\mathbf{u}_m$ is the average velocity of the mixed phase.

The momentum governing equation of the mixed phase is as follows:

$$\rho_m \frac{D}{Dt} \mathbf{u}_m + \nabla \cdot (\tau) = \rho_m \mathbf{g}.$$
where $\mu_m$ is the average viscosity coefficient of the mixed phase, $F$ is the volume force, $n$ is the number of phases in the mixed phase (including fluid clear water and particle fluid, so $n = 2$), $a_k$ is the volume fraction of phase $k$, $\rho_k$ is the density of phase $k$, and $u_{dr,k}$ is the drifting velocity of phase $k$.

For two phases (both liquid), the sliding velocities of different phases should be determined before the drift velocities can be further determined. The sliding velocity $u_{ji}$ is defined as the velocity of the secondary phase ($i$) relative to the main phase ($j$), which can be written as

$$u_{ji} = u_i - u_j.$$  

Therefore, the governing equations of the drifting velocity and sliding velocity of two phases can be expressed as

$$u_{dr,i} = u_i - \sum_{k=1}^{n} a_k \rho_k u_{dr,k}. $$

According to the continuous phase governing equation of the secondary phase ($i$) and the relationship between volumes, the volume fraction governing equation of the corresponding secondary phase ($i$) can be derived, which can be expressed as follows:

$$\frac{\partial}{\partial t} (\alpha_i \rho_i) + \nabla \cdot (\alpha_i \rho_i u_i) = -\nabla \cdot (\alpha_i \rho_i u_{dr,i}). $$

### B. Centrifugal pump model and grid independence verification

The centrifugal pump model and grid are shown in Fig. 1; the prototype is a single-stage centrifugal pump. The main design parameters of the centrifugal pump are listed in Table 1. A 0.2 m pipeline is added to the upstream of the inlet, and a 0.1 m pipeline is added to the outlet. Tetrahedral meshes are used, and the quality of meshes proved that the mass and minimum angle meet the calculation requirements. Five sets of grids were divided, and the grid independence verification is shown in Fig. 2. After the total number of grids is 4 120 245, the head tends to be stable, so the first set of grids is adopted.

### C. Boundary conditions

The mixture model and the turbulence model RNG k-ε were used to calculate the effects of high concentration particles on the centrifugal pump characteristics at a low flow rate. The inlet of the centrifugal pump is set as the speed inlet ($\omega = 1.35$ m/s), and the outlet is set as the outflow. Assumed that the liquid and solid phases have uniform velocities at the inlet, that is, the initial velocities of the solid and liquid phases are equal. The medium containing water and particles of “quasi-fluid” was analyzed. The density of water is 998.2 kg/m$^3$, and the dynamic viscosity was 0.001 006 Pa s. In the calculation domain, the impeller speed remains constant, and the inlet and outlet pipes and the volute remain static. In the calculation domain, the rotating speed of the impeller remains constant at 1450 rpm, and the inlet and outlet pipes and the volute remain stationary. The SIMPLC algorithm is used to complete the coupling calculation between speed and pressure. The entire flow field of the centrifugal pump is calculated by the transient method. The time taken by the impeller to rotate 3° is taken as a calculation time step, which is 0.000 345 s. The accuracy of convergence residual is set to $10 \times 10^{-6}$. 

![Fig. 1. Centrifugal pump model and grid.](image1)

![Fig. 2. Mesh independence.](image2)
III. CENTRIFUGAL PUMP EXPERIMENTAL STUDY

The influence of different particle sizes and particle concentrations on the performance of the centrifugal pump was studied experimentally. The diagram of the experimental device was shown in Fig. 3. The pressure gauge was set at $8d_1$ from the centrifugal pump inlet ($d_1$ is the inlet tube diameter, $d_1 = 50$ mm) and $10d_2$ from the pump outlet ($d_2$ is the outlet tube diameter, $d_2 = 25$ mm) to measure the pressure and monitor the change in the centrifugal pump head. A torque meter is set between the driving motor and the centrifugal pump to measure the torque and speed of the pump shaft to calculate the power and efficiency of the centrifugal pump. The inlet and outlet of the centrifugal pump are equipped with ball valves to regulate the flow rate in the system, and the flow rate is measured by a flowmeter.

The numerical calculation results were compared with the experimental results when the particle concentration was 20% and the particle size was 0.106 mm, and the results are shown in Fig. 4. The weighted average error of the curves of numerical calculation results and experimental results in Fig. 4 remains below 10%, and the overall trend of the two results is basically the same; the simulation results are slightly larger than the experimental results. Considering that there are various error factors in the centrifugal pump conveying system in the actual process (such as the processing factors of valves and various components) and some flow losses are ignored in the simulation process, it can be considered that it is feasible to use the mixture model to simulate the transport of dense fine particles in the centrifugal pump.

IV. RESULT AND DISCUSSION

The effects of different particle parameters on the centrifugal pump external characteristics (head and efficiency), the total pressure in the centrifugal pump, and the relative velocity streamline of the liquid phase were compared and analyzed under the condition of low flow rate, which is $0.6Q_d$ ($Q_d$ is the design flow rate). In order to study the internal characteristics of the centrifugal pump more intuitively, the volute center interface was selected as the research object. In order to compare the influence of different working conditions on the external characteristics of the centrifugal pump with its changing trend, the influence coefficient of head $k_1$ and the influence coefficient of efficiency $k_2$ were defined as follows:

$$k_1 = \frac{H - H_l}{H},$$
$$k_2 = \frac{\eta - \eta_l}{\eta},$$  (6)

where $H$ is the head of the centrifugal pump conveying clear water, $H_l$ is the head of the centrifugal pump conveying particles with different properties, $\eta$ is the efficiency of the centrifugal pump to transport clear water, and $\eta_l$ is the efficiency of the centrifugal pump conveying particles with different properties.
A. Influence of particle size on performance of the centrifugal pump

To study the influence of particle size on performance of the centrifugal pump, the variations in the influence coefficient of the head and efficiency with particle size were analyzed, and the total pressure distribution, the vorticity-streamline distribution of the liquid phase, and the volume fraction distribution of the solid phase at different particle diameters including 0.048, 0.106, 0.15, 0.27, and 0.38 mm were simulated at 20% particle volume concentrations.

Figure 5 shows the variation in the influence coefficient of the head and efficiency with particle size. The increase in particle size causes the influence coefficient of the head and efficiency to increase, that is, the increase in particle size leads to the decrease in the head and efficiency and the effect of particle size on efficiency is higher than that on the head.

Figure 6 shows the total pressure distribution of the centrifugal pump related to different particle sizes at 0.6\(Q_d\) and reveals that the total pressure distribution of the centrifugal pump conveying clear water and conveying different particle sizes is basically similar. The pressure value of the centrifugal pump decreases with the increase in particle size and changes more gently [Figs. 6(b)–6(e)]. This is because the smaller the particle size is at the same particle concentration, the larger the particle number will be, that is, the collision between particles is more intense, and at the same time, the change in particle size also affects the total pressure at the volute tongue; there is a high-pressure area at the volute tongue [refer to area 1 in Fig. 6(a)], and it tends to decrease with the increase in particle size. For the low-pressure area at the volute outlet [refer
to area 2 in Fig. 6(a), it first decreases slightly and then increases with the increase in particle size. Compared with the clear water condition, the existence of particles reduces the low-pressure area of the impeller passage [refer to areas 3 and 4 in Fig. 6(a)]. The volute pressure decreases counterclockwise, and the increase in particle size makes its overall pressure decrease gradually, but its overall pressure distribution basically remains unchanged. The volute pressure decreases counterclockwise, and its overall pressure decreases with the increase in particle size, but its pressure distribution basically remains unchanged. There is a high-pressure area in the lower left flow passage of the volute [refer to area 5 in Fig. 6(a)], and the pressure value and range of the high-pressure area decrease with the increase in particle size. This is attributed to the decrease in the number of particles aggregated in this region with the increase in particle size.

Figure 7 shows the vorticity-streamline distribution of the liquid phase related to different particle sizes at 0.6Qd. According to Fig. 7(a), vortexes appear in the first two, the fourth, and the last flow channels along the impeller in the counterclockwise direction [refer to areas 1, 3, 5, and 6 in Fig. 7(a)], the starting point of some streamlines is on the impeller wall [refer to area 2 in Fig. 7(a)], and the third flow channel has a tendency to generate vortexes [refer to area 4 in Fig. 7(a)]. However, as shown in Figs. 7(b)–7(f), the vortexes in the flow channels completely disappear except the third flow channel, and streamlines also start slightly differently. The vorticity magnitude under clear water condition is also obviously larger. The change in particle size has little effect on the overall vorticity-streamline distribution in the volute.

Figure 8 shows the volume fraction distribution of the solid phase related to different particle sizes at 20% particle concentrations. The particles are mainly concentrated at the inlet, the outer wall of the volute, and the front end of the impeller, and the movement trend of particles is more inclined to the pressure surface of the impeller. This is because the particles are inhaled from the inlet and diffused in the volute under the action of the impeller, and because the solid density is higher than that of the liquid phase, the particles are affected by greater centrifugal force, thus being transported out along the outer wall of the volute. With the increase in particle size, the volume fraction at the aggregation place of particles increases. This is put down to the larger particle size; the worse the followability of particles is, the easier it is to aggregate.

**FIG. 7.** Vorticity-streamline distribution of the liquid phase at different particle sizes.
B. Influence of particle concentration on the centrifugal pump

To study the influence of particle volume concentration on performance of the centrifugal pump, the variations in the influence coefficient of the head and efficiency at different particle concentrations were analyzed, and the total pressure distribution, the vorticity-streamline distribution of the liquid phase, and the volume fraction distribution of the solid phase at different particle volume concentrations, namely, 0%, 10%, 15%, 20%, 25%, and 30%, were simulated at the 0.106 mm particle size.

Figure 9 shows the variation in the influence coefficient of the head and efficiency with particle concentration. The increase in particle concentration will increase the influence coefficient of the head and efficiency, that is, the increase in particle concentration will increase the decrease value of the head and efficiency. When the volume concentration of particles is less than 15%, the change in particle concentration has less effect on efficiency than that of head, while when the volume concentration is greater than 15%, the opposite is true.

Figure 10 shows the total pressure distribution of the centrifugal pump at different particle concentrations at 0.6Q_d. The distribution of the total pressure in the centrifugal pump conveying clear water is basically similar to that in conveying the flow with different particle concentrations, but the pressure value and changing trend increase with the increase in particle concentration. This is because the higher the particle concentration, the more the energy absorbed by the particles will be, and the greater the pressure in the area where the particles are concentrated. There is a high-pressure area at the...
FIG. 10. Total pressure distribution at different particle concentrations at $0.6Q_d$.

(a) clear water  (b) $C_v=10\%$  (c) $C_v=15\%$

(d) $C_v=20\%$  (e) $C_v=25\%$  (f) $C_v=30\%$

FIG. 11. Vorticity-streamline distribution of the liquid phase at different particle concentrations.
tongue and the lower left of the volute [refer to areas 1 and 5 in Fig. 10(a)], which increases with the increase in particle concentration. For the low-pressure area at the volute outlet [refer to area 2 in Fig. 10(a)], it basically decreases with the increase in concentration. Compared with the clear water condition, the existence of particles reduces the low-pressure area of the impeller passage [refer to areas 3 and 4 in Fig. 10(a)], but the change in particle concentration basically does not affect the low-pressure area of the impeller root.

Figure 11 shows the vorticity-streamline distribution of the liquid phase at different particle concentrations at 0.6\(Q_d\). The same as Fig. 7, particles inhibit the generation of the vortex in the passage of the impeller [refer to areas 1, 3, 4, 5, and 6 in Fig. 11(a)], and the starting point of some streamlines is also changed in the second passage of the impeller [refer to area 2 in Fig. 11(a)]. The change in particle concentration has little effect on the overall vorticity-streamline distribution in the volute.

Figure 12 shows the volume fraction distribution of the solid phase at different particle concentrations. The particles are mainly concentrated at the inlet, the wall of the volute, and the front end of the impeller. With the increase in concentration, the distribution of the solid volume fraction in the pump is basically the same, but the value and span of the volume fraction increase accordingly. This is because the number of particles increases suddenly after the solid phase concentration increases, which leads to the accumulation of particles at the inlet, the wall of the volute, and the front end of the impeller.

V. CONCLUSION

In this work, to study the influence of particle size and volume concentration properties on the internal and external characteristics of a centrifugal pump that transports dense fine particle solid–liquid two phase flow under the condition of low flow rate, the mixture model was used to carry out numerical simulation, and the following conclusions were derived:

1. The increase in particle size will increase the influence coefficient of the head and efficiency, and the change in particle size has more influence on the efficiency than that on the head.
2. The increase in particle concentration will increase the influence coefficient of the head and efficiency. When the volume concentration of particles is less than 15%, the change in particle concentration has less effect on the efficiency than that on the head; when the volume concentration is greater than 15%, the opposite is true.
3. Under the same particle concentration, the smaller the particle size is, the larger the particle number is, and the more intense the collision between particles will be. The total pressure value in the centrifugal pump decreases with the increase
in particle size, but it increases with the increase in particle concentration.

4. The dense fine particles absorb a large amount of energy, which leads to the relative decrease in the kinetic energy of the liquid phase and inhibits the generation of the vortex in the impeller passage.

5. Both the particle size and concentration affect the distribution of the solid volume fraction. The larger the particle size is, the more uneven the distribution of the solid volume fraction will be. The particle concentration mainly affects the value and distribution area of the solid volume fraction.

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NOMENCLATURE

- $C_v$: particle volume concentration (%)
- $d_p$: particle diameter (mm)
- $d_1$: inlet tube diameter (mm)
- $d_2$: outlet tube diameter (mm)
- $F$: volumetric force (N)
- $H$: head of conveying clear water (m)
- $H_1$: head of conveying particles (m)
- $k_1$: influence coefficient of the head
- $k_2$: influence coefficient of efficiency
- $n$: number of phases
- $Q_{df}$: design flow rate ($m^3/s$)
- $u_{dr,k}$: drifting velocity of phase $k$ (m/s)
- $u_i$: velocity of the secondary phase ($i$) (m/s)
- $u_j$: velocity of the main phase ($j$) (m/s)
- $u_{sl}$: sliding velocity (m/s)
- $u_{av}$: average velocity of the mixed phase (m/s)
- $α_k$: volume fraction of phase $k$ (%)
- $η$: efficiency of conveying clear water (%)
- $η_t$: efficiency of conveying particles (%)
- $H_m$: average viscosity coefficient of the mixed phase (Pa s)
- $ρ_m$: density of the mixed phase (kg/m$^3$)

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

REFERENCES