Study on solid-liquid two-phase unsteady flow characteristics with different flow rates in screw centrifugal pump

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Abstract. The screw centrifugal pump is used as an object, and the unsteady numerical simulation of solid-liquid two-phase flow is carried out under different flow rate conditions in one circle by choosing the two-phase flow of sand and water as medium, using the software FLUENT based on the URANS equations, combining with sliding mesh method, and choosing the Mixture multiphase flow model and the SIMPLE algorithm. The results show that, with the flow rate increasing, the change trends for the pressure on volute outlet are almost constant, the fluctuation trends of the impeller axial force have a little change, the pressure and the axial force turn to decrease on the whole, the radial force gradually increases when the impeller maximum radius passes by half a cycle near the volute outlet, and the radial force gradually decreases when the maximum radius passes by the other half a cycle in a rotation cycle. The distributions of the solid particles are very uneven under a small flow rate condition on the face. The solid particles under a big flow rate condition are distributed more evenly than the ones under a small flow rate condition on the back. The theoretical basis and reference are provided for improving its working performance.

1. Introduction

The screw centrifugal pump is a new type structural impurity pump designed according to screw and centrifugal principles. The pump has good performance with non-clogging and no injury, and also possesses the advantages of forced feed, no overload, constantly high efficiency, lower power consumption, good abrasion resistance and long service life. It is an ideal piece of equipment for aquatic products, chemical engineering, light industry, environmental protection, minerals and other industries [1].

Screw centrifugal pump model is shown in figure 1 [2]. The screw centrifugal pump impeller consists of a three dimensional helical blade and a conical hub. Based on the asymmetric structure, large fluctuations come into being for the axial force and radial force of the impeller, and the surface pressure of the volute, which has a very big effect for the operation stability and service life of the pump in the process of pump operation.

At present, the numerical study of screw centrifugal pump is mostly steady characteristic research. Although steady research can reflect the character of flow field in screw centrifugal pump impeller to some extent, it can't satisfy the requirement of accurately describing the internal flow characteristics. With the development of computer technology and computational fluid dynamics [3-4], numerical analysis of the inner flow characteristics of the screw centrifugal pump has gradually developed from steady research to unsteady research.
In this paper, the screw centrifugal pump of type 150×100LN-32 is calculated under the conditions of 0.6\(Q\), 0.8\(Q\), 1.2\(Q\) and 1.4\(Q\) [5], which are based on the design flow rate \(Q=165\text{m}^3/\text{h}\), when it transports a sand-water two-phase fluid. For every calculation working condition, the median particle diameter \(d=0.076\text{mm}\), the volumetric fraction of solid phase \(\varphi=10\%\), and the particle density \(\rho=2650\text{kg/m}^3\). And the characteristics and rules of pressure distribution on volute outlet, axial force, radial force and the distributions of volumetric fractions of solid phase in the channel with the flow rate change at different moments in one cycle can be obtained by the solid-liquid two-phase numerical simulations of unsteady flow.

2. Calculation model and numerical simulation method

2.1 Calculation model

The model of the screw centrifugal pump impeller of type 150×100LN-32 chosen is shown in figure 2. The design parameters of the model pump are shown as follows: the design flow rate \(Q=165\text{m}^3/\text{h}\); the design head \(H=32\text{m}\); the rated speed \(n=1480\text{r/min}\). The semi-open impeller is used in the simulation, and the length of the axial plane projection of the blade is 0.328m. The blade wrap angle is 781.1°. The wrap angle of the spiral segment is 686.6°, and the wrap angle of the centrifugal segment is 94.5°.

2.2 Numerical simulation method

The unstructured tetrahedron hybrid meshes for the model are created by ICEM software in the preprocessing, and the verification for grid independence is carried out. The total number of the divisory grids is 562508, and the number of the grids for import extension, impeller and volute is respectively 12076, 392489 and 157943. Then the meshes are transferred into Fluent 6.3.26 pressure-based solver, and the standard \(k-\varepsilon\) equation turbulence model is used in numerical simulations. All variables are simultaneously solved. Meanwhile, the time-averaged continuity equation and the unsteady Reynolds averaged Navier-Stokes equations in relative coordinate systems are solved.

The calculation area includes import extension, impeller and volute three parts. The four coupling surfaces are respectively established in import extension, impeller and volute. The sliding mesh technique is used because of the unsteady flow in the flow channel. The mixture multiphase flow model and separation, implicitly and unsteady calculation method are both used in numerical simulations. The SIMPLE algorithm is used in pressure-velocity coupling, and the first-order upwind is used in the discretizations of turbulent kinetic energy, turbulent dissipation and the momentum equation. Velocity inlet is used as the boundary condition of the impeller inlet, and the natural flow is used as the boundary.
condition of the impeller outlet. No slip is selected as the boundary condition for the solid surface, and
the action of gravity is taken into consideration. 5° that the impeller passes is taken as a time step, so
there’re a total of 72 time steps in one circle. And the time of each step is 0.00056306s. The impeller
operates two cycles in the calculation process, therefore, the total computation time is 0.08108s. The
more stable results in the second cycle are selected for analysis.

3. Calculation results and comparative analysis

3.1 The comparative analysis of pressure distribution on volute outlet

The continuous pulsation curves for the pressure distribution on volute outlet as the function of the
rotation angle of the impeller in one cycle under the working conditions of five kinds of flow rates
including 0.6Q, 0.8Q, Q, 1.2Q and 1.4Q are shown in figure 3.

![Figure 3](image3)

**Figure 3.** The pulsation curves for the volute outlet pressure with the impeller rotation angle at different
flow rates in one cycle.

From figure 3, it can be seen that the wavelengths of the pulsation curves for the pressure on volute
outlet are almost constant with the increase of the flow rate, and the pressure turns to decrease on the
whole. When the pump respectively operates at the flow rates of 0.6Q, 0.8Q, 1.2Q and 1.4Q, the
maximum pressure increases by 34.6%, increases by 16.4%, decreases by 15.0% and decreases by
27.7% compared to the flow rate of Q. Since the flow section area of the impeller outlet changes
slightly compared to the impeller inlet, the change trend of the pressure on volute outlet reflects the
change trend of the pump head to some extent. The model pump can get a biggish variation range of the
head when the flow rate changes a little, which indirectly proves that the screw centrifugal pump has a
good adjustment performance and can ensure the stable operation of the pump. And the feature is very
suitable for wastewater treatment. The fluctuation intensity of the pressure of the volute outlet is greater
under a small flow rate condition, which has greater destructiveness for the pump equipment. Therefore,
we should try to avoid the screw centrifugal pump operation at a small flow rate on the aspects of
operation and maintenance for the screw centrifugal pump.

3.2 The comparative analysis of the axial force of the impeller

The continuous pulsation curves for the axial force of the impeller as the function of the rotation angle
of the impeller in one cycle under the working conditions of five kinds of flow rates including 0.6Q,
0.8Q, Q, 1.2Q and 1.4Q are shown in figure 4.

![Figure 4](image4)

**Figure 4.** The pulsation curves for the impeller axial force with the impeller rotation angle at different
flow rates in one cycle.

From figure 4, it can be seen that, with the increase of the flow rate, the fluctuation trends of the
axial force of the impeller have a little change, but the size of the axial force turns to decrease, and the fluctuation range of the axial of the impeller turns to increase. It can be seen that the fluid gets into the impeller along the axial direction, and flows out along the radial direction from the flow state of the sand-water two-phase fluid in the screw centrifugal pump impeller. The impeller makes the fluid complete the transition from the axial direction to the radial direction. The axial velocity size of the fluid changes from large to small, however, the change trend of the radial velocity size is just the opposite [6]. The direction of the fluid changes because of the effect of the impeller when the flow rate increases. The reaction force that the fluid gives the impeller increases, and the opposing axial force increases. As a result, the axial force size decreases with the increase of the flow rate.

3.3 The comparative analysis of the radial force of the impeller
The continuous pulsation curves for the radius vector distribution of the radial force of the impeller as the function of the rotation angle of the impeller in one cycle under the working conditions of five kinds of flow rates including $0.6Q$, $0.8Q$, $1.0Q$, $1.2Q$ and $1.4Q$ are shown in figure 5. In the figure, the radius vector from the coordinate origin to each point represents the size and direction of the radial force, and the projection on X-axis, Y-axis of each point respectively represents the size of the X, Y axial radial force of the impeller at the moment.

![Figure 5](image.png)

**Figure 5.** The pulsation curves for the impeller radial force with the impeller rotation angle at different flow rates in one cycle.

Four corresponding positions of impeller at different flow rates in one action cycle are shown in figure 6. Each position has marked the direction of the radial force and the location of the maximum radius of the impeller. The direction of the radial force of the impeller at position A, B, C, D is respectively parallel to the positive direction of Y-axis, the negative direction of X-axis, the negative direction of Y-axis and the positive direction of X-axis.

![Figure 6](image.png)

**Figure 6.** The four positions of impeller at different flow rates in one cycle.

Based on figure 5 and figure 6, it can be seen that the radius vector distribution of the radial force of the screw centrifugal impeller is approximately elliptical in one cycle, and the center of the approximate ellipse moves in the direction of the positive direction of Y-axis with the increase of the flow rate. And the approximate elliptical radius vector distribution of the impeller radial force appears some distortion when the impeller operates from the position of D to the position of A under the condition with the flow rate of $1.4Q$. The absolute value of the radial force in Y-axis direction gradually increases, the absolute value of the radial force in X-axis direction changes a little, and the radial force gradually increases with the increase of the flow rate when the impeller operates from the position of D to the position of B. The absolute value of the radial force in Y-axis direction gradually decreases, the absolute value of the radial force in X-axis direction changes a little, and the radial force gradually decreases with the increase of the flow rate when the impeller operates from the position of B to the position of D. The
radius vectors of the radial force of the positions with a leading rotation angle 7°, a lagging rotation angle 7° relative to the positions of B, D are Y-axial symmetric under various flow rate conditions. Compared to the maximum radius, the radial force always has a lagging rotation angle 90° in the process of one operation cycle of the impeller. In other words, the radial force gradually increases with the increase of the flow rate when the maximum radius of the impeller passes by half a cycle near the volute outlet, and the radial force of the impeller gradually decreases with the increase of the flow rate when the maximum radius of the impeller passes by half a cycle far away the volute outlet.

3.4 The comparative analysis of the volumetric fractions of solid phase
In order to analyze the influence that the flow rate has on the distributions of volumetric fractions of solid phase in the flow channel in the screw centrifugal pump, a comparative analysis is made about the volumetric fractions of solid phase of the blade face and back at the initial time and the half time in one cycle under the working conditions of two kinds of flow rates including 0.6Q and 1.4Q based on the design flow rate Q=165m$^3$/h.

Figure 7 shows that the distributions of volumetric fractions of solid phase on the face of the blade at the initial time and the half time in one cycle under the working conditions of two kinds of flow rates including 0.6Q and 1.4Q.

![Figure 7. The distributions of solid volume fractions on blade face at the initial time and the half time at the flow rates of 0.6Q and 1.4Q in one cycle.](image)

From figure 7, it can be seen that the volumetric fractions of solid phase along the flange are bigger than the ones along the hub on the face on the whole. The distributions of the solid particles are very uneven, and the range of the volumetric fractions of solid phase is greater under a small flow rate condition. The regions of the solid particles with the highest volumetric fractions of solid phase are along the flange whose wrap angle is in the range of 0°~150°, and the solid particles are mostly distributed on the flange side on the face. With the radius increasing from the wrap angle of 150° to the blade outlet on the face, the influence that the centrifugal force has on the solid particles increases, which results in the decrease of the volumetric fractions of solid phase on the hub side of the blade face and the increase of the volumetric fractions of solid phase on the flange side of the blade face. The change of the volumetric fractions of solid phase is slight, and the change gradients of the volumetric fractions of solid phase are slight on the flange side and on the hub side of the blade face when the pump operates on the condition with a big flow rate compared with a small flow rate. The volumetric fractions of solid phase are higher in the region with the wrap angle of 0°~150°, which is easy to cause the wear of the blade face.

The distributions of volumetric fractions of solid phase on the back of the blade at the initial time and the half time in one cycle under the working conditions of two kinds of flow rates including 0.6Q and 1.4Q are shown in figure 8.

![Figure 8. The distributions of solid volume fractions on blade back at the initial time and the half time at the flow rates of 0.6Q and 1.4Q in one cycle.](image)

From figure 8, it can be seen that the volumetric fractions of solid phase on the blade back are bigger.
than the ones on the blade face on the whole, and the solid particles on the back are distributed more evenly than the ones on the face. Under a big flow rate condition, a local high volumetric fraction region appears at the joint position of the blade inlet edge and the hub, and the solid particles are distributed fairly evenly on other locations where the volumetric fractions of solid phase are generally around 10%. A local region with high volumetric fractions appears in the inlet section of the blade back under a small flow rate condition. The distributions of the solid particles are relatively uniform from the wrap angle of 90°~500°, and the fractions are generally 10.2%. The obvious change gradients of the volumetric fractions of solid phase appear on the flange side and the hub side of the blade back from the wrap angle of 500° to the blade outlet, and solid particles are mostly distributed on the flange side.

On the whole, the solid particles are mostly distributed in the inlet segment, and there are some local concentrated regions. The volumetric fractions of solid phase on the back are higher than the ones on the face. The solid particles on the back are distributed more evenly than the ones on the face, and the solid particles under a big flow rate condition are distributed more evenly than the ones under a small flow rate condition. The volumetric fractions of solid phase under a big flow rate condition are smaller than the ones under a small flow rate condition on the back on the whole.

4. Conclusion
(1) With the increase of the flow rate, the wavelength of the pulsation curve and the change trend for the pressure on volute outlet are almost constant, the pressure turns to decrease on the whole, and the fluctuation trends of the axial force of the impeller have a little change in a rotation cycle. Under a smaller flow rate condition, the fluctuation intensity of the pressure of the volute outlet is greater, the fluctuation range of the axial of the impeller is smaller, but the axial force is greater. Therefore, it has great destructiveness for the pump equipment when the pump operates at a small flow rate, and we should try to avoid the screw centrifugal pump operation at a small flow rate on the aspects of operation and maintenance for the screw centrifugal pump.

(2) The radial force gradually increases with the increase of the flow rate when the maximum radius of the impeller passes by half a cycle near the volute outlet, and the radial force of the impeller gradually decreases with the increase of the flow rate when the maximum radius of the impeller passes by half a cycle far away the volute outlet. The radius vectors of the radial force of the positions with a leading rotation angle 7°, a lagging rotation angle 7° relative to the positions of B, D are Y-axial symmetric under various flow conditions. Compared to the maximum radius, the radial force always has a lagging rotation angle 90° in the process of one operation cycle of the impeller.

(3) The volumetric fractions of solid phase on the blade back are bigger than the ones on the blade face on the whole, and the solid particles on the back are distributed more evenly than the ones on the face. The distributions of the solid particles are very uneven, and the range of the volumetric fractions of solid phase is greater under a small flow rate condition on the face. The solid particles under a big flow rate condition are distributed more evenly than the ones under a small flow rate condition, and the volumetric fractions of solid phase under a big flow rate condition are smaller than the ones under a small flow rate condition on the back on the whole.

Acknowledgments
This project is supported by National Natural Science Foundation of China (Grant No. 51079066 and 51209113).

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