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SIMULATION AND ANALYSIS OF FLOW FIELD AND COARSE PARTICLE MOVEMENT IN LIFTING PUMP OF DEEP-SEA MINING SYSTEM

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Abstract: For coarse particle clogging in a pump happens frequently, it is important to study the characteristics of coarse particles' movement in lifting pump for deep-sea mining system safety. Considering the size of deep-sea minerals, we used mathematical model to simulate two cases, i.e. pure water and water-solid mixture. The flow field and particle motion in lifting pump were analysed deeply. The results showed that (1) there is a heavy pound at the inlet of impeller, suggesting the designed setting inlet angle of impeller is too large; (2) the water velocity in guide vane increases first and then decreases from inlet to outlet, indicating the smallest velocity occurs in the middle of vane; There is backflow in the back of the vane; (3) The large diameter particles lead to the long particle retention period, which is at high risk of particle clogging in pump. The results provide a reference for the design of lifting pump.

KEY WORDS: deep-sea mining; lifting pump; flow field; particle trajectory

1. INTRODUCTION

There are abundant mineral deposits in deep sea, which is of great significance to relieve the resource shortage in China (Xiao Tibin et al., 2004; Xiao Yexiang, et al., 2014; Ding Liuhuai, et al., 2003). Hydraulic lifting system is the most feasible method in ocean mining (Xu Shaojun, et al., 2007; Yang Kang, 2012). As the key part of the lifting system, lifting pump not only supplies power to transport minerals but also ensures coarse particles of diameter of 10-30mm passing through (Yang Ning, et al., 2014). For decades, many countries have developed some lifting pumps, such as 6-stage submersible motor pumps developed by KSB Cop. of Germany (Kuntz, 1979). Among them, semi-axial pump is the feasible one because of high delivery lift and wide flow passage, which can provide enough power and ensure nodules passing through. In 1990's, China started researches on deep-sea mining technologies and had developed a 2-class lifting pump during the 11th five-year plan (Zou Weisheng, 2006; Zou Weisheng, 2007). Whereas particle clogging happened frequently within pump in experiment, the pump couldn't work consistently (Zou Weisheng, 2000; Wang Yingjie, et al., 2012). In order to design or develop lifting pump, it is necessary to study the solid-fluid two-phase flow mechanism and determine the relation between the pump shape and particle diameter.

In this paper, we used mathematical model simulate water movement and particle movement in a lifting pump. The velocity field in the pump and the movement of particles were analyzed, which provides reference for lifting pump design in deep sea mining system.

2. MATHEMATICAL MODEL

2.1 3-D STRUCTURE OF THE LIFTING PUMP

The parameters of the studied lifting pump is as follows: the diameter of impeller at the inlet D_0=73 mm, at outlet D_2=98 mm, the width at the outlet b_2=21 mm, blades number $z_1 = 3$, blade inlet angle is 25°, blade outlet angle is 20°; the diameter of the guide vane at the inlet D_4=106 mm, at outlet D_6=73 mm, blades number z_2=8, the minimum width of the passage is 14 mm, blade inlet angle is 30°.

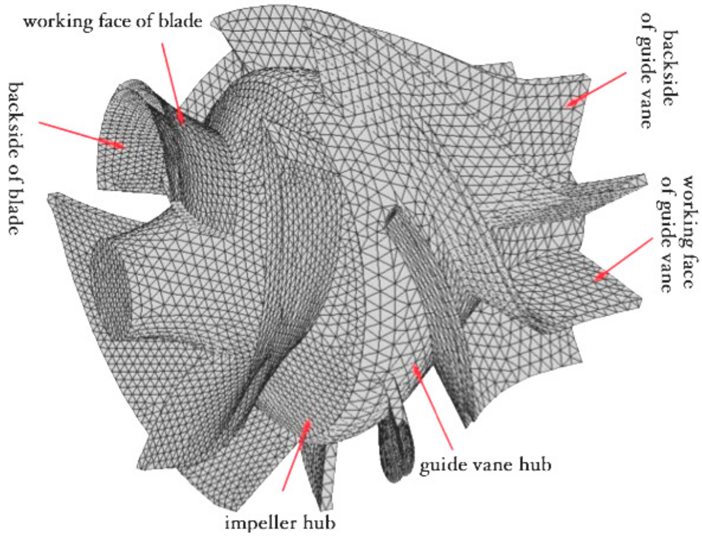


Fig. 1 spatial structure and gird of lifting pump

The designed flow is Q=28 m^3/h, designed head H=5 m, rated speed n=2875 r/min, total efficiency η=65%, and specific speed n_s=277. In order to make impeller bring the fluid into guide vane easily, transition region of 5mm width is added between the impeller and vane. In addition, the front part of the impeller and the rear part of the vane are both prolonged, which will make water flow develop sufficiently. In total, the axial length between the impeller and vane is 108mm.

The grid was generated separately in 4 parts: prolonged inlet, impeller, guide vane, and prolonged outlet. Unstructured meshes were adopted in impeller and guide vane because the complexity of their shapes, while structured meshes in prolonged inlet and prolonged outlet. The total grid number is 367,976.

2.2 GOVERNING EQUATIONS

For incompressible fluid, Reynolds time-averaged Navier-Stokes equations are adopted. The property of turbulence is computed by standard $k-\varepsilon$ turbulence model. Simplec algorithm is applied to solve the equations. Reynolds time-averaged

Navier-Stokes equations are as follows (Wu Bo, et al., 2009),

$$\frac{\partial \overline{u_i}}{\partial x_i} = 0 \tag{1}$$

$$\frac{\partial\left(\rho \overline{u_i}\right)}{\partial t} + \frac{\partial\left(\rho \overline{u_i}\,\overline{u_j}\right)}{\partial x_j} = -\frac{\partial \overline{p}}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\eta \frac{\partial \overline{u_i}}{\partial x_j} - \rho \overline{u'_i u'_j}\right) \tag{2}$$

where, ρ is density of the fluid; $\overline{u_i}$ is the Reynolds time-averaged velocity component in the i th direction; $\overline{p}$ is the Reynolds time-averaged pressure; η is the kinetic viscosity.

Turbulent energy k at the inlet and outlet interfaces are obtained by

$$k = \frac{3}{2}\left(\overline{u} I\right)^2 \tag{3}$$

$$I = 0.16\left(Re_{DH}\right)^{-1/8} \tag{4}$$

where, $\overline{u}$ is the time-averaged velocity, I is the turbulent intensity, Re_{DH} is the Reynolds number computed by hydraulic diameter. For circular section, hydraulic diameter is the diameter of the section. For noncircular section, hydraulic diameter is the equivalent diameter of a circular section.

Turbulent energy dissipation rate ε at the inlet and outlet interfaces are obtained by,

$$\varepsilon = C_\mu^{3/4} \frac{K^{3/2}}{0.07L} \tag{5}$$

where, C_μ=0.084, l=0.07L, L is the characteristic length of the inlet part.

The particle trajectory is computed by differential equations under Largrangian coordinate system. The particle momentum equation under Cartesian coordinate system is:

$$\frac{du_p}{dt} = F_D + \frac{g_x\left(\rho_p - \rho\right)}{\rho_p} + F_x \tag{6}$$

$$F_D = C_D \times \frac{3\rho_m}{4\rho_P d_p}\left|u - u_p\right|\left(u - u_p\right) \tag{7}$$

where, F_D is the drag force acted on per unit mass particle, u is the fluid velocity, u_p is the solid particle velocity, ρ is the fluid density, ρ_p is the particle density, F_x is mass forces, including Coriolis force, and other virtual mass force(such as the centrifugal force), d_p is the particle diameter, C_D is the drag coefficient, which is a function of Reynolds number. It should be noted that the collisions between particles are neglected to highlight the influence of pump shape on particle clogging, which lowers the result accuracy.

The mathematic model was validated by Cai Chao (2015). The computed data agrees with the experimental data very well, which shows the model is reliable and efficient.

2.3 COMPUTED CONDITONS

Case 1 is to simulate pure water movement. The inlet velocity is set according to the designed flow mentioned above; the outlet adopts free outlet boundary condition; the solid wall is assumed impenetrable and no-slip. Multi-coordinate system is adopted in the simulation, rotating coordinate system in guide vane (impeller speed n =2875 r/min) and static coordinate system in other region. Interface is used to link these two different coordinate systems to ensure the identical flux between them.

Case 2 is to simulate water and particle mixture flow to observe particle movement in the pump. Four incident lines were distributed equally in the inlet. Each incident line was set 5 identical diameter particles along radial direction. The initial particle velocity is set to be the same as the ambient water. The particle is spherical. Collisions between particle and the wall are assumed as perfect elastic collision. The objective of this paper is to study the influence of the pump shape on the movement of particles, influences of collision between particles and influences of particles on water flow are neglected. In fact, when the particle concentration is high, particle movement is more complicated. The particle density is 2300 kg/m^3. Four different diameters, including 1 mm, 3 mm, 5 mm, and 7 mm, were studied.

3. RESULTS AND DISCUSSIONS

3.1 FLOW FIELDS OF PURE WATER

Figure 2 shows the relative velocity field in the impeller. The flow in each passage is similar and no back flow occurs. The velocity near the blade working surface is larger than that near the backside if the blade. At the inlet, velocity direction changes dramatically indicating water lashes the blade strongly, which leads to large energy loss and reflects the inlet angle of designed blade is too large.

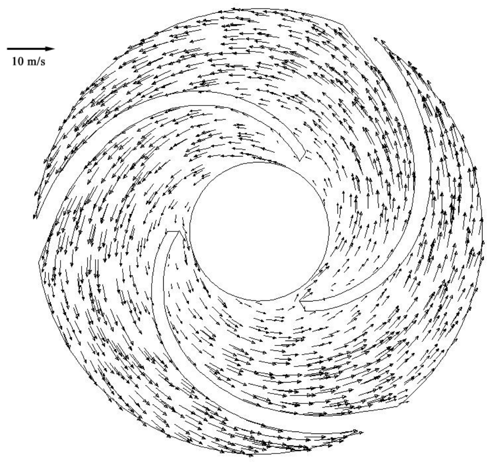
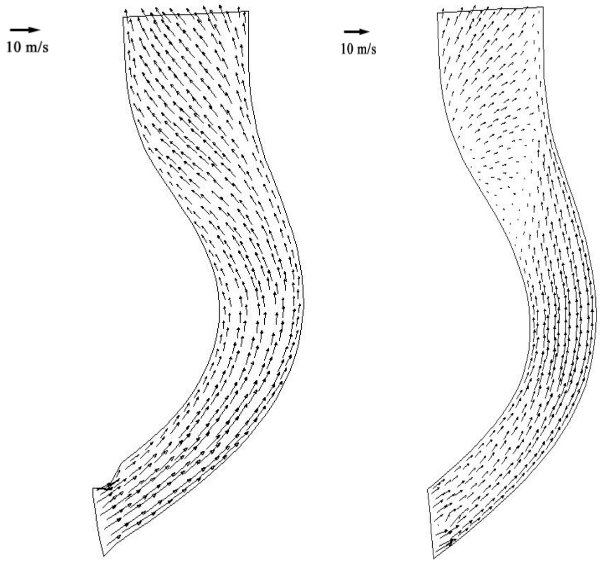


Fig. 2 the relative velocity field in the impeller central-symmetrical faces

Figure 3 shows the velocity field in the guide vane region. Water moves along the vane surface. The velocity decreases and then increases from the inlet to the outlet. The minimal velocity occurs at the middle of the vane, because the flow section is the largest there. The velocity near the edge is larger than that near the hub because water near the edge is impacted by larger centrifugal force. Back flow happens at the backside of the vane (as shown in figure 3(b)) for the water accumulates at the low pressure area. After it flows out of the impeller, the water hits the vane obliquely, which makes the vane surface pressure higher than the backside. When the water progresses to the middle, the pressure difference between the surface and backside leads to boundary-layer separation near the backside. Thus back flow happens near the backside.



（a） the working face （b） backside face

Fig. 3 velocity filed in the guide vane

3.2 PARTICLE TRAJECTORIES OF DIFFERENT DIAMETERS

Particle trajectories of different diameters under rated flow were simulated by the mathematical mode.

The particle velocity direction is axial before it enters the impeller. After entering into the pump, particles obtain circumferential velocity component from blade forces and radial velocity component from centrifugal force. Generally, particles spiral upward. At the second half, the velocity direction is tangential to the blade face with the increasing of the circumferential velocity component.

The particle incident location also impacts trajectories strongly. The nearer particle incident location to the pump wall, the acceleration stronger is because higher fluid velocity brings stronger drag force acted on the particle. For the radius is larger near the pump wall, trajectories is longer and retention period in pump is longer.

Different incident locations lead to different collision possibilities. Three incident locations were studied：impeller blade working face, the impeller blade backside face, the location between two blades. a) particles, entering the pump from blade working face, move along the working face with frequent collisions with the face. b) particles, entering the pump from blade backside face, move toward the working face, which takes longer time to arrive working face than ones entering the pump near the working face. c) the very few particles, entering the pump from the location between two blades, also move toward the working face, but without collision possibilities with the working face.

Diameter also has important impacts on particle trajectories. The smaller the diameter is, the smaller centrifugal force is, the closer the solid velocity is to the fluid velocity, the more similar the relative velocity direction is to the blade surface and the smaller probabilities of collision or in the smaller angle the particles collide the blade. The larger the diameter is, the stronger centrifugal force and inertial force's influences are , the harder the solid particle velocity changes, the larger probabilities of collision and the closer collision location is to the blade inlet, the more frequent the second collision happens in the middle or the .second half of the blade, which makes the trajectories is more turbulent.

When lifting pump is in operation, particles seldom clog in the impeller region due to high speed of the blade. While the water velocity is slowed down in guide vane because of energy losses and energy transferring from kinetic energy to pressure energy, the guide vane region is at high risk of particle clogging if the design is not proper. It is significant to observe the particle trajectories in the guide vane region.

The results also show that particle collides inevitably in guide vane region. The particles with diameter of 1mm have the smallest collision frequency with the average value of 2, while the particles with diameter of 7mm have the largest collision frequency with the average value of 4. The location collision happens mainly at the inlet of the backside face, the middle of the working face, and the outlet of the backside face.

For small particles, i.e. diameter of 1 mm, particles enter the vane tangential to the vane working face. After the first collision, particles move along the backside face of the vane and the second collision happens near the outlet of vane. When particles move out of the vane, their velocity directions are identical and axial mostly.

With the increase of particle diameter, such as diameter of 3mm, diameter of 5mm, the angle changed by collision at the backside face of vane is larger and velocity direction is altered strongly, which makes particles move toward working face and lead to the second collision. Then particles move along the working face to the outlet of vane and collides happens the third time at the postmedian part of the working face. At last, particle velocity direction tends to axial and moves out of the vane.

For large particles, i.e. diameter of 7 mm, particles move in the vane region chaotically and irregularly. The collision frequency is between 2 and 4. It's partly because the incident angles are different from each other and partly because large particles have large inertia and velocity direction changes severely after collisions. During lifting pump operation, the more chaotic trajectories are, the larger the collision frequency is, which will lead to kinetic energy loss, particle accumulation, and pump clogging.

3.3 PARTICLE RETENTION PERIOD IN PUMP

For particle trajectories are stochastic in a large degree, we use statistical approach to evaluate particle retention period in pump. 1500 particles were set evenly at the inlet. Particle density is 2300 kg/m^3, with diameters of 1 mm, 3 mm, 5 mm and 7 mm.

From Tab.1, it can be seen the particle retention period in pump is advanced with the increase of diameter. According to particle trajectory results, when particle diameter is large collision frequency is large, which will alter velocity direction and make the trajectories longer. As a result, large particle leads to large retention period in pump.

The computed standard deviation shows the dispersion degree of retention period increases with diameter also. This is also because particle collision leads to uncertainty of trajectories because of large diameter.

Tab. 1 Statistics of collision frequency and retention time of different diameter particles

Diameter of particles（mm）	1	3	5	7
Particle sample number	20	20	20	20
Averaged collision frequency	2	3	3	3
Averaged retention period in pump(s)	0.063	0.068	0.069	0.070

3. CONCLUSIONS

To satisfy the demand of transporting solid-fluid two-phase flow, wide flow passageway lifting pump was designed. Two cases, including pure water and water-particle mixture, were simulated. The analysis of flow field and particle movement in pump shows:

(1) The flow in impeller region is relative ideal but the designed inlet angle is a bit too large. The large inlet angle leads to water pounding at the blade and blade abrasion. The water pounding also costs a lot of kinetic energy and the velocity will decrease, correspondingly. Velocity decrease makes particle movement more difficult.

(2) In the guide vane region, water velocity decreases first and then increases from the inlet to the outlet. The minimal velocity occurs at the middle of the vane. There is backflow in the backside of the guide vane. The appearance of backflow leads to large energy loss and particle accumulation, which makes the area at the high risk of particle clogging.

(3) The larger the diameter is, the longer the particle retention period in pump is and the larger the standard deviation of particle retention period is. The longer particle retention period will lead to particle clogging easily. The larger standard deviation of particle retention period reflects the pump works unsteadily and cannot work continuously.

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