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CHINA'S RESEARCH AND DEVELOPMENT OF SLURRY PUMP FOR LIFT MARINE MINERAL RESOURCES

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ABSTRACT: The R&D of mining and lift technologies for marine mineral resources has been carried out in China since the establishment of the China Ocean Mineral Resources R&D Association (COMRA). A lift pump is the key piece of equipment in the deep-sea mining system for the transportation of seabed ore from seabed mining vehicles to surface mining vessels. The research in this paper focuses on the key equipment of a slurry pump in a hydraulic lifting system, a flow model, and the theory of pumps to lift coarse-particle slurry. It is proposed that the slurry pump used in deep-sea mining is a kind of axial and mixed flow pump with a high specific speed, high head, and backflow for coarser particles to pass through. The theories for increasing flow rate as well as equal power in the design are also introduced. Pumps with such optimized designs were all tested with slurry in the laboratory and also verified in the sea for pumping undersea mineral slurry. These theories and technologies have been applied in the design and development of a six-stage pump, and the testing results of its characteristics are also presented in this paper

KEY WORDS: marine mineral resources; coarse-particle slurry; slurry pump; tests of pump characteristics

1. INTRODUCTION

Exploitation of marine mineral resources is a promising new industry in the 21st century, and it is considered that the hydraulic pipeline lifting system driven by a lift pump has the greatest prospect in commercial deep-sea mining. A lift pump, usually connected to a vertical pipeline, is not only required to have a high head but can also have coarse-grained seabed ore slurry pass through and backflow after stopping. Furthermore, it should also be designed with axial flow. Therefore, a lift pump, as the key piece of equipment, will play an important role in deep-sea mineral resource mining in the future.

A great deal of research has been carried out at home and abroad on such pumps for lifting coarse seabed ores. The KSB company has developed a six-stage lift pump. Its flow passage has an inner diameter equivalent to 75mm, through which particles with a maximum size of 25mm can pass. OMI Company has verified the effectiveness of this pump in a trial mining operation at a depth of 5200m below sea level (Shaw,1993). The Manufacturing Institute of Japanese Ehara has developed an eight-stage centrifugal pump for lifting purposes (Kazuhiko, 1996), which is composed of a four-stage pump in the upper part and another four-stage pump in the lower part. A submersible motor is arranged between two pumps, and the outlet of the lower pump and the inlet of the upper pump are connected with a valve through a short pipe. And Nautilus Mining Company had its lift pump developed by GE Hydil Company (Leach and Smith, 2012), which was a diaphragm pump or positive displacement pump, similar to the diaphragm pump used for pipeline transportation of slurry in terrestrial mines. In 2002, Professor Zou Weisheng from Hunan University in China started to carry out research on a four-stage lift pump and then successfully manufactured a two-stage lift pump for testing, which has ever attracted great attention (Zou, 2007; Li, 2013). This is a kind of mixed-flow pump with a high specific speed, which represents the development direction of high-head pumps used for the transportation of coarse particles. Also, technologies and theories have been developed for the mixed-flow pump with a high specific speed and high lift head used for lifting coarse particles. With the development and application of CFD numerical simulation technologies, simulation analysis and performance prediction of flow in a pump can be adopted in lift pump design for design optimization. Based on the research of a four-stage lift pump, Zou Weisheng has finally developed lift pumps for several key R&D projects for deep-sea mining. This paper also introduces the R&D of lift pumps for transporting undersea mineral slurry.

2. CHARACTERISTICS OF UNDERSEA MINERAL SLURRY AND STRUCTURAL DESIGN OF A LIFT PUMP

2.1. CHARACTERISTICS OF UNDERSEA MINERAL SLURRY

Undersea mineral slurry in a lifting system during deep-sea mining is a solid-liquid two-phase flow consisting of seabed ore particles and seawater, in which the solid phase includes seabed sediments and fine particles generated by crushers with particle sizes of 20mm, and the slurry is characterized by particles with a coarser size and wider size fraction. In view of such characteristics, Zou Weisheng has developed a calculation model for coarse particle-homogeneous slurry. In this model, particles with larger sizes are regarded as coarse particles in the solid phase, and the homogeneous slurry formed due to the mixture of water with smaller particles is regarded as a liquid-phase carrier. This carrier fluid is treated as a pseudo-homogeneous fluid in the Bingham body model to ensure accuracy in simulating the moving characteristics of such two-phase flow (Zou et al. 2019) and also save the required time and resources for calculation. Based on the numerical simulation of the lift pump using the slurry model and CFD, a design optimization process for lift pumps is proposed, which consists of optimizing structural parameters in the design, fluid analysis, characteristics prediction, and reversal design. A design optimization process for the lift pump is shown in Figure 1. Based on a study on the flow characteristics of solid-liquid two-phase flow of subsea minerals, the performance of the lift pump is predicted, and the obtained results are used for modification to improve the flow characteristics and working characteristics of pumps for optimizing the design.

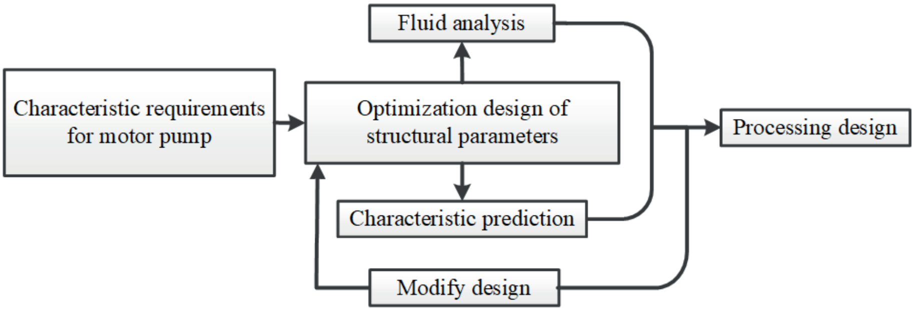

Fig. 1. Technologies for design optimization of lift pumps

2.2 STRUCTURAL DESIGN OF LIFT PUMP

According to the technical requirements for lift pump operation, the pump is designed to have a whole casing. The six-stage pump with mixed-flow impellers and the submersible motor, which is connected with the pump, were installed into the casing. The impellers take all the pump pressure and the motor weight, while the casing withstands the externally implied static and dynamic loads. There is one section on both ends of the pump, with one side connecting the pump with flanges and the other side connecting to a pipe with a similar joint, serving as the connection between the pump and pipes. In the pump design, both the designed flow rate and specific speed of the pump are appropriately increased, and the design point of the pump is properly separated from its duty point. As a result, the wide flow passage can ensure the smooth passage of coarser seabed minerals and the backflow of particles through the working impeller after the pump is stopped. In the design of the working performance of the pump, equal power is adopted to make the power vary gently with the increase of flow rate, thus preventing motor power changing excessively due to the variation of pump flow rate caused by different resistances of lifting pipeline in deep-sea mining environment. So, the motor won't be overloaded.

2.2.1 RESEARCH OF LIFT MOTOR PUMP DURING 2002-2005

For the first time in China, Zou Weisheng from Hunan University carried out research on lift pumps for deep-sea mining during the period from 2002 to 2005 (Zou, 2007). He designed a four-stage lift pump and manufactured and tested a two-stage pump. The overall structural design of the pump is shown in Figure 2. The lift pump, with its impeller and guide vane made of some kind of material with high strength and good abrasion resistance, is suitable for transporting slurry containing coarser particles with high concentration and strong abrasion. Furthermore, it can also be arranged maximally in six stages based on working conditions. The principal parameters of a four-stage lift pump are as follows: the operation depth of 400m below the sea, 3 impellers and 4 pieces of guide vane, flow rate (l/s) of Q=420m3/h and rotation speed of n=1450r/min; the designed head for a single stage of the pump is H=40m, and the efficiency of the pump with clear water is η=50~60%; the outlet diameter is Dd=200mm, and particles passing through the pump are required to have a maximum size of Dmax = 40mm; the maximum volume concentration of slurry in the pump is Cv =10%.

Fig. 2. An overall view of a four-stage pump and a manufactured two-stage pump (2000-2005) (right, author)

2.2.2 RESEARCH OF LIFT MOTOR PUMP DURING 2015-2020

According to the requirements of national deep-sea mining research projects, Zou Weisheng carried out the R&D of a six-stage lift pump from 2015 to 2020. At a flow rate of 420 m3/h, the designed lift head for the single stage of the pump was a 45m water column, and the pump was tested with both clear water and slurry (Zou et.al., 2019).

2.2.3 RESEARCH OF LIFT MOTOR PUMP DURING 2020-2023

According to the requirements of a provincial deep-sea mining research project, a six-stage lift pump was developed from 2020 to 2023. At a flow rate of 420 m3/h, the designed lift head for the single stage of the pump was a 48m water column. Also, the pump has been tested with clear water and will be tested with slurry soon. In Fig. 3, the structure of the motor pump is changed, a six-stage pump is on the lower part of the motor pump, and the submersible motor is on the upper part.

Fig. 3. Overall view and manufacturing of a six-stage pump (2015-2020) (right, author)

3. GEOMETRY MODEL AND MESH GENERATION

3.1 GOVERNING EQUATIONS

The pump converts mechanical energy into hydraulic energy through its impeller. The impeller rotating with fluid can transmit the torque to the fluid, which changes the movement of the fluid, leading to energy transmission. The basic pump formula is the relationship between the variation in the movement of fluid before and after passing through the impeller and the energy per unit weight converted by the impeller to the fluid (i.e., the theoretical pump head), which is also the calculation formula of the theoretical head H_t of a pump (Guan,1987) being expressed as the following:

$$Ht=g2-12\pi$$

where: 2 and 2 are velocity circulation at the outlet and inlet of an impeller; is the rotating speed of an impeller.

Fig. 4. Overall design of the six-stage pump (2020-2023)

The flow of fluid in the lift pump is numerically simulated by computer, and the head and efficiency of the pump are predicted by using CFD to check the correctness and rationality of the hydraulic design, which provides a basis for the hydraulic design and improvement of the pump (Tang et. al. 2006). In the non-inertial coordinate system with the rotation of the impeller, the flow in the impeller is considered to be steady and can be expressed by two equations: The continuity equation (i.e., expression of conservation of mass) and the Navier-Stokes equation (reflection of the law of conservation of momentum). The continuity and momentum equations of incompressible flow in a pump are as follows:

uixi=0 uiuj=-1δpxi+μ+tuixj+ujxixi+fi

where p is the pressure, fi is the Coriolis force, u is the relative velocity, is the dynamic viscosity, t is the turbulent viscosity.

3.2 GEOMETRIC MODELING

The design of a six-stage lift pump is shown in Fig. 4, and the section of a single-stage impeller with guide vanes is shown in Fig. 5. The three-dimensional modeling is done with CFturbo for the pump, including the inlet section, impeller, guide vane, and casing. CFturbo is an interactive design software for turbomachinery components, including impellers and volutes, among others. It can enable users to create and analyze several geometry variations based on combination of fundamental conceptual design equations, empirical correlations. and extraordinary geometrical capabilities. The sectional view of axial flow passage in an impeller with guide vane of a single-stage pump generated with this software is shown in Figure 5, and the structure of the impeller is shown in Figure 6.

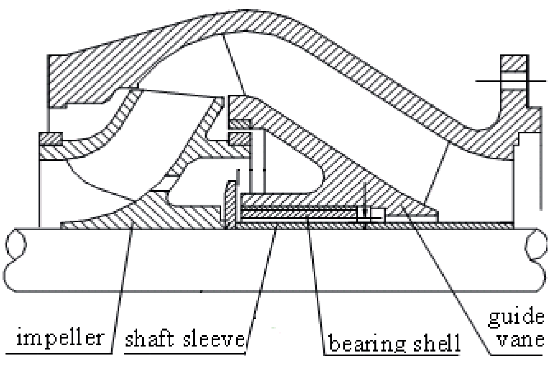

Fig. 5. Sectional view of a single-stage impeller with guide vane

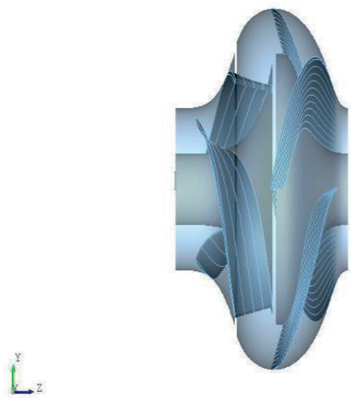

Fig. 6. Sectional view of axial flow passage in an impeller

4. MESH GENERATION AND NUMERICAL ANALYSIS

4.1. MESH GENERATION AND SETTING OF MODEL BOUNDARY CONDITION

Pumplinx is a 3D Computational Fluid Dynamics (CFD) tool that provides accurate virtual testing for the analysis of pumps, with all operations performed on one interface, including geometry modeling, mesh generation, solution, and post-processing. With Pumplinx, mesh generation and calculation become very simple and efficient, and it also takes shorter time to simulate a multi-stage pump. It is characterized by simple operation, fast calculation, and an accurate result.

Figure 7 is the geometry of a single-stage pump obtained from Cfturbo, and Figure 8 is the grids of the impeller of a single-stage pump generated in Pumplinx, and the total grid number of the six-stage pump is 5,938,899.

Pumplinx is adopted to simulate the pump with a different flow rate (i.e., the flow rate at the outlet). The boundary conditions are as follows: the inlet pressure is 1.013 × 105Pa (1atm), and the flow rate at the outlet is determined according to the flow rate of the pump; seawater is taken as the liquid phase with the density of 1,028kg/m3, and seabed ore is taken as the solid phase with the density of 2,000kg/m3; seawater is used as medium in the test with clear water, while the seabed mineral slurry is taken as the medium in the test with solid-liquid two-phase flow; and it rotates clockwise at a speed of 1,450 r/min. In the CFD simulation, the standard k-ε model based on the N-S equation is usually adopted for turbulence, which is also adopted in this paper. Steady flow analysis is run for pumps with clear water medium, and unsteady flow analysis is run for pumps with solid-liquid two-phase flow.

Fig. 7 Grids of single-stage pump

Fig.8 Grids of an impeller

4.2 FLOW ANALYSIS

Figure 9 is the pressure nephogram from CFX simulation of a flow model with single-phase medium at a flow rate of 420m,³/h. It can be seen that as the fluid flows in the passage, the pressure rises continuously and smoothly, presenting an obvious pressure gradient. With the inlet pressure at 1atm, the pressure at the outlet of the four-stage pump reaches around 34atm and also rises rapidly. Figure 10 shows the particle trajectory in the single stage of a six-stage pump, presenting the complex movement of particles in the flow passage. The figure also shows a rough law of particle trajectory, i.e., particles move relatively close to the outside, because particles, with densities greater than those of the fluid phase are usually accumulated in the region relatively close to the casing of the pump due to the obvious action of centrifugal force and Coriolis force, which leads to wear usually occurring on the outer cover plate of the pump. Particles within the impeller present rotation with the impeller, move near the pump wall, and collide with the wall to some extent due to the action of centrifugal force and gravity, which also leads to wear in the nearby region.

Those regions of a lift pump that are prone to wear can be optimized in the design or strengthened with special material according to the above law of particle flow, to prolong its service life and optimize its performance.

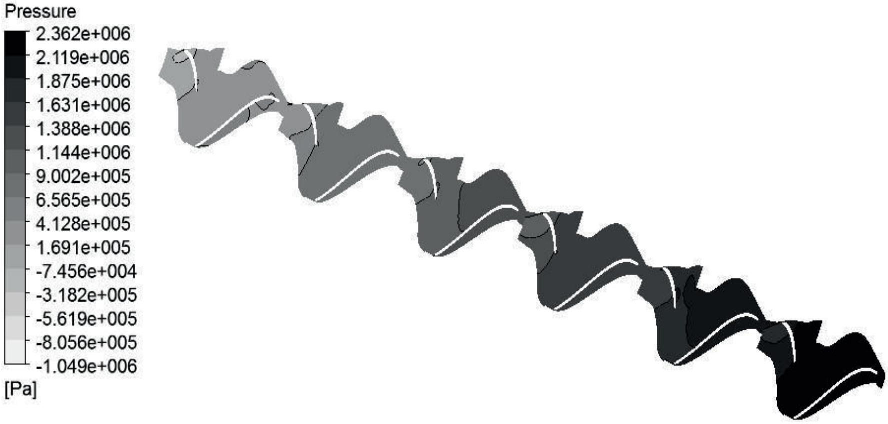

Fig. 9. Pressure nephogram of pump (with clear water)

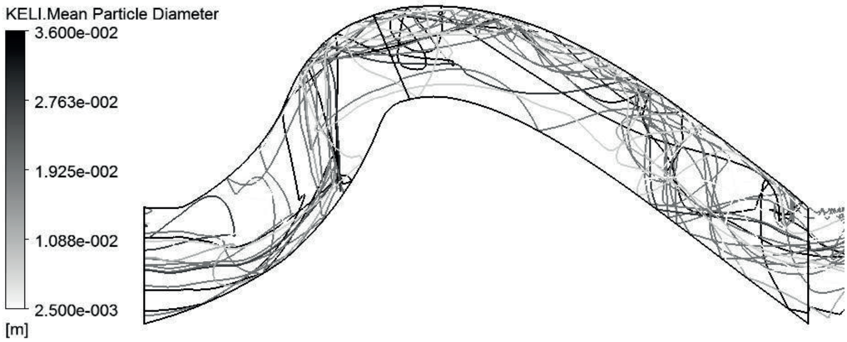

Fig. 10. Trajectory of particles in a single stage of a six-stage pump

5. PREDICTION OF PUMP CHARACTERISTICS

The flow field of a six-stage pump with different flow rates is simulated to analyze the performance and parameters and predict the characteristics of the pump under all working conditions. The obtained results are compared with the testing results of the first two-stage lift pump developed in China. Figure 11 shows the simulation results of the single-stage head and efficiency of a six-stage motor pump and the testing results of the single-stage head and efficiency of a two-stage motor pump.

It can be seen from Figure 11 that this six-stage lift pump presents better performance and a better head-flow curve. With a flow rate of 420m^3/h, the single-stage head of this lifting system can reach 48.8 m, and the pump efficiency is 56.8%. The value maybe a little bit lower, but it is already a very good result for a mixed-flow pump with a wide flow passage for coarse particles. As the flow rate increases, the head decreases, and the efficiency of the pump increases. However, with the flow rate approaching 420m3, the head of the lift pump begins to decrease slowly, thus the whole lifting pipeline system runs stably and presents good lifting characteristics. Based on the comparison between the test results in the test pool of Shipong Group of the first two-stage lift pump developed by Zou Weisheng in China and the testing results of the lifting system of Changsha Institute of Mining and Metallurgy Co, Ltd., it is found that the six-stage pump has its single-stage head higher by 4.5 m water column and the efficiency increased by 5% in the simulation with the designed flow rate of 420m3/h (Zou, 2007). It is shown that the hydraulic design of this six-stage pump is much more reasonable compared to the previous two-stage pump. Due to the maximum particle size of seabed ore falling from 50mm to 20mm, the section of the pump for fluid passing through decreases, which also leads to the pump efficiency improving to some extent. Generally, the head and efficiency of these two pumps are similar, with little difference in the data. It is proven that the simulation result of the six-stage pump is correct and credible. After being approved by the relevant authorities, this pump will be manufactured and put into testing. Therefore, part of the experiment can be replaced by the CFD simulation for exploring the performance of a lift pump as the reference in its design, which can not only reduce costs but also provide prediction for the performance and parameters of a pump.

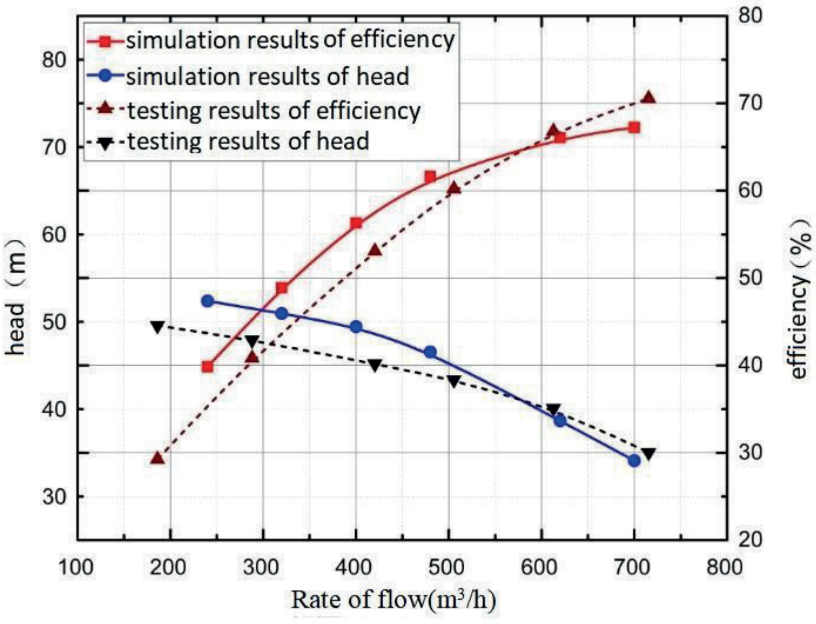

Fig. 11. Simulation results of single-stage head and efficiency of a six-stage pump

6. CONCLUSION

(1) A design optimization process is put forward for the lift pump with high head and high specific speed, which is used for coarse particles in deep-sea mining, including structural parameter optimization, flow analysis, characteristics prediction, and reversal design for modification.

(2) This optimization process has been adopted to perform design optimization, flow analysis, and characteristics prediction for an eight-stage lift pump used by China in the sea testing system for mining deep-sea poly-metallic nodules. It is proven that the pump presents good characteristics and that its head meets the requirements of the sea testing system in the mining of poly-metallic nodules.

(3) Based on numerical simulation, it can be seen that for such an axial and mixed flow pump, hydraulic losses in the lift pump are substantially attributed to vortex formation in the flow field of guide vanes, and the wear in a lift pump caused by particles mainly occurs in the outer cover plate and the surface of the pump body near the impeller.

(4) Compared with the experimental results of the first two-stage lift pump developed in China, the simulation results of the six-stage lift pump show that its single-stage head and efficiency have been greatly improved, indicating that this design optimization process for the lift pump is reasonable and feasible.

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REFERENCES

1. Guan X.,, 1987. Modern Pump Theory and Design. Beijing. China Aerospace Publishing House. 1987. 13-15
2. Kuntz G, 1979. The technical Advantages of Submersible Motor Pumps in Deep Sea Technology and Delivery of Manganese Nodules: Proceedings of the 11th Annual OTC Conf. Houston: Tex Press. 1979. 85-91.
3. Leach S., Smith G., 2012. SME Special Session: Subsea Slurry Lift Pump Technology - SMS Development. The Offshore Technology Conference, pp.1-12.
4. Shaw J. L, 1993. Nodule Mining - Three Miles Deep ! Marine Georesources and Geotechnology 11(2). 1993. 181-197.
5. Sugiyama K., 1996, Study on Pumps for Lifting Manganese Nodules: Proceedings of deep-sea mining technology. Beijing. 1996. 282-293.
6. Tang X., Xin Y., Songchang R., 2006. Solid-Liquid Two-Phase Fluid Dynamics and Its Application in Hydraulic Machinery. Zhengzhou: Yellow River Water Conservancy Press. 2016. 68-76.
7. Zhehuan Li Z., 2013. Numerical Simulation and Performance Prediction of Flow Field in Electric lift Pump. Hunan University, 2013.
8. Zou Weisheng, 2007. COMRA's Research on Lifting Motor Pump. Proceedings of The Seventh ISOPE Ocean Mining Symposium. 2007.177-180.
9. Zou W., Liu R. and Liu S., 2019. Motor Pump Study for Lifting Coarse Particle Slurry in Sea bed Mining. China Mechanical Engineering 30(24). 2019. 2899−2904.