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Theoretical analysis of effect of solid phase on cavitation performance of deep-sea mining pump ∗

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Abstract: In view of the present situation of low cavitation performance of deep-sea mining slurry pump, the effect of solid phase on the cavitation performance of deep-sea mining pump is analyzed theoretically. The relationship between gas and liquid phases are established by cavitation nucleon theory and mass energy equation as well as solid phase and liquid phase, and then we explored the relationship between gas phase and solid phase. The results show that the critical bubble radius and solid-phase concentration flow rate during the cavitation can be related to the liquid pressure. Eq. (19) show that the larger the solid particle concentration and the solid phase flow, the earlier the cavitation will occur, and pump anti-cavitation performance will decline.

Keywords: deep-sea mining pump; solid-liquid two-phase flow; cavitation; theoretical analysis

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1 Introduction

With the decline of land resources, people's demand for deep-sea mining technology becomes more and more important. So far, Germany, the United States, Japan, South Korea and other countries have realized the deep sea mining experiments. All developed countries are actively realizing the commercial exploitation of marine resources [1]. Deep-sea mining system is widely studied in the world, and it is generally believed that the deep-sea mining system which composed of ore-collecting system, conveyor system, surface support system and control system has the most commercial exploitation prospect. The role of transportation system is to transport ore from the seabed to the surface, and the performance of pulp pump directly affect the delivery system efficiency. Countries mainly use space guide vane multistage slurry pump as the pump type. For example, Germany KSB company researched on the transport of coarse particles lifting pump from hydraulic model flow. Finally used the mixed flow pump which with a mixed characteristics of centrifugal pump and axial flow pump as a lifting pump in the 1970s [2]; In the early 21 century, the Korea Institute of Geological Resources carried out numerical simulation and performance test on the centrifugal solid-liquid pump [3]. The results show that the solid-liquid slurry pump is hard to meet

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the requirements of the hydraulic pipeline lifting system. Based on the theory of vertical pipeline hydraulic transportation, Yang et al. [4] put forward the theoretical formula of slurry pump design parameters, and analyzed the influence of geometric parameters on pump performance by numerical simulation method. Chen [5] built a three-dimensional model of slurry pump, and got on the solid-liquid two-phase flow numerical simulation and performance prediction. A non-clogging multi-stage centrifugal pump had conducted successfully in the sea trials in June 2016, which was developed by the Changsha Institute of Mining and Metallurgy. And it can ensure the smooth flow of coarse particles and the stability of the pipeline force, realizing the stable transportation of coarse particles and high concentration simulated multi-metal nodules under long-distance large flow [6].

Domestic and foreign scholars have done a lot of research on the deep-sea mining slurry pump, mainly about the pulp pump structure design and solid-liquid two-phase flow analysis. Less research has been done about the cavitation.

Cavitation is a common phenomenon in hydraulic machinery and has an important influence on the normal operation for pumps. The occurrence of cavitation tend to affect the normal flow of the fluid in the pump, cavitation damage, vibration, noise as well as the pump external parameters (such as flow, head, and shaft power), even make the whole system stopped [7]. So the study of the pump cavitation performance is necessary and valuable. At present, various types of pumps are mostly studied about the cavitation characteristics. For example, Li [8] used the full cavitation model to calculate the head-NPSH curve of the centrifugal pump. Although the trend is consistent with the experimental results, the deviation is larger. The FBM turbulence model and the Zwart cavitation model were used by Zhao et al. [9] to analyze the cavitation characteristics of a single-stage axial-flow pump and a serial-type pump, and calculated the cavitation characteristic curve of single-stage axial flow pump, which had a good agreement with the experimental results.

Deep-sea mining slurry pump delivery the solid-liquid flow. The occurrence of cavitation will form a complex three-phase flow problem. The theoretical analysis of the interaction among the three phases will lay a foundation for the establishment of the three-phase flow control equation, and will be of great significance for the judgment of numerical simulation results and the prediction of experimental results.

2 Model analysis

According to the “Handbook of Modern Pump Design”of Guan [10] and the design method of the slag pump’s impeller blade of He [11], the deep-sea mining slurry pump is designed as shown in Fig. 1. And the main design parameters are $D_0 = 240$ mm, $D_1 = 244$ mm, $D_2 = 401.7$ mm, $b_2 = 54$ mm, $Z_1 = 3$, $Z_2 = 4$, $Q = 800$ m^3/h, $H = 70$ m, $n = 1\ 450$ r/min, $NPSH_r$ =6 m, where D_0 is the inlet diameter of the pump, D_1 is the inlet diameter of the impeller inlet, D_2 is the impeller diameter, b_2 is the impeller outlet width, Z_1 is the impeller blade number, Z_2 is the guide vane leaf number, H is the head, Q is the design flow, n is the speed, and $NPSH_r$ is the NPSH required.

As shown in Fig. 2, there are two cross-section selected in the first stage. 1 is for the initial entrance and 2 is for the critical cavitation department. The correlation between the solid and liquid gases from 1 to 2 is analyzed.

2.1 Gas phase and liquid phase correlation

According to the theory of cavitation nucleon, when the local pressure of the fluid is lower than the saturated vapor pressure, it will make the gas nucleus explosive growth in the liquid [12]. When the bubble bursts, the high pressure will assault the pump structure, and the continuous action makes the pump performance gets lower and lower.

According to Hervey proposed the edge of the wall surface gap gas model in 1947 [13-15], suppose the equilibrium spherical vacuoles contain water vapor and other small gas, ignoring the gas diffusion, the vacuous static equilibrium condition is

$$p = p_{\mathrm{v}} + p_{\mathrm{g}} - \frac{2\delta}{r_{\mathrm{b}}}, \tag{1}$$

where p is the liquid pressure, p_{v} is the vapor pressure of steam in cavitation, p_{g} is the gas component pressure in cavitation, δ is the liquid surface tension coefficient, and r_{b} is the cavity radius.

The change of p_{g} in the vacuole can be changed according to the equation of state of the ideal gas and the isothermal process.

Variation of the equation of ideal gas state equation is

$$p_{\mathrm{g}} = \frac{NT}{r_{\mathrm{b}}^{3}}, \tag{2}$$

where N is the gas constant and T is the absolute temperature.

Ideal gas isothermal process variation is

$$p_{\mathrm{g}} = p_{\mathrm{g0}}\left(\frac{r_{\mathrm{b0}}}{r_{\mathrm{b}}}\right)^{3}, \tag{3}$$

where p_{g0} is initial state of the bubble in the gas pressure and r_{b0} is the initial radius of vacuole.

Corresponding to the above two processes, we can get two expressions of Eq. (1) as follows.

Variation of the equation of ideal gas state equation is

$$p = p_{\mathrm{v}} + \frac{NT}{r_{\mathrm{b}}^{3}} - \frac{2\delta}{r_{\mathrm{b}}}. \tag{4}$$

Ideal gas isothermal process variation is

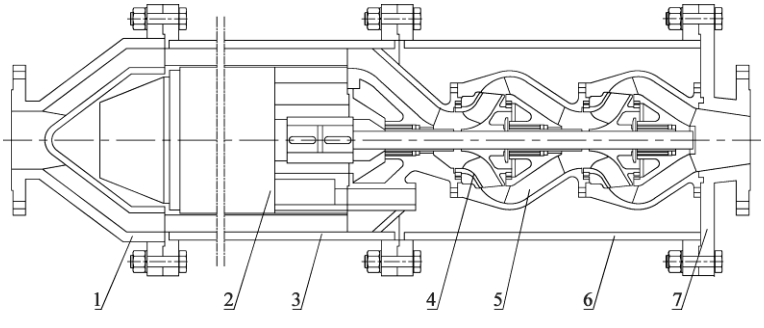
$$p = p_{\mathrm{v}} + p_{\mathrm{g0}}\left(\frac{r_{\mathrm{b0}}}{r_{\mathrm{b}}}\right)^{3} - \frac{2\delta}{r_{\mathrm{b}}}. \tag{5}$$

The process from the initial entrance 1 to the critical cavitation department 2 was analyzed by the ideal gas state equation:

$$p_1 = p_{\mathrm{v}} + \frac{NT_1}{r_1^{3}} - \frac{2\delta}{r_1}, \tag{6}$$

$$p_2 = p_{\mathrm{v}} + \frac{NT_2}{r_2^{3}} - \frac{2\delta}{r_2}, \tag{7}$$

where p_1 is the liquid pressure in section 1, p_2 is the liquid pressure in section 2, r_1 is the bubble radius in section 1, and r_2 is the bubble radius in section 2.



1. import flange; 2. submersible motor; 3. motor cylinder; 4. impeller; 5. space guide vane; 6. pump cylinder; 7. export flange

Fig. 1 Mineral pump structure diagram

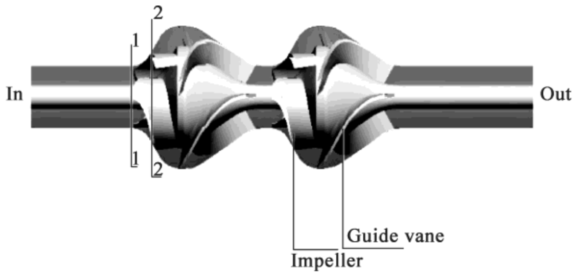


Fig. 2 Model diagram

$$N=\left(p_1-p_v+\frac{2\delta}{r_1}\right)\frac{r_1^3}{T_1}\,, \tag{8}$$

$$p_2=p_v+\left(p_1-p_v+\frac{2\delta}{r_1}\right)\frac{T_2}{T_1}\left(\frac{r_1}{r_2}\right)^3-\frac{2\delta}{r_2}\,. \tag{9}$$

From section 1 to section 2 as a process of isothermal changes, $T_1=T_2$, and the type can be written as

$$p_2=p_v+\left(p_1-p_v+\frac{2\delta}{r_1}\right)\left(\frac{r_1}{r_2}\right)^3-\frac{2\delta}{r_2}\,. \tag{10}$$

The pulp pump cross-section 2 is the bubble burst critical state. The pressure p_2 is the critical pressure. As for Eq. (10), the critical state value can be obtained when $\frac{\mathrm{d}p_2}{\mathrm{d}r_2}=0$. The differentiation is

$$\frac{\mathrm{d}p_2}{\mathrm{d}r_2}=\left(p_0-p_v+\frac{2\delta}{r_1}\right)\frac{-3r_1^3}{r_2^4}+\frac{2\delta}{r_2^2}=0\,. \tag{11}$$

The solution is

$$r_2=\sqrt{3\left(p_1-p_v+\frac{2\delta}{r_1}\right)\frac{r_1^3}{2\delta}}\,. \tag{12}$$

Combine Eqs. (10) and (12), and the critical radius is

$$r_2=-\frac{4\delta}{3\left(p_1-p_v\right)}\,. \tag{13}$$

The critical pressure is

$$p_2=p_v-\frac{4\delta}{3r_2}\,. \tag{14}$$

The relationship between the gas phase and the liquid phase is established by the liquid pressure and bubble radius.

2.2 Solid-liquid phase correlation

There are the following relationship exists in solid-liquid phase fluid.

$$Q_m\rho_m=Q_s\rho_s+Q_w\rho_w\,, \tag{15}$$

where Q_m is the slurry flow, Q_s is the solid flow, Q_w is the water flow, ρ_m is the slurry density, ρ_s is the solid density, and ρ_w is the water density.

The fluid from section 1 to section 2 critical cavitation occurred, according to the mass energy equation, the process can be listed as

$$\left(p_1-p_2\right)Q_m=\rho_s Q_s\frac{v_{2s}^2-v_1^2}{2}+\rho_w Q_w\frac{v_2^2-v_1^2}{2}\,, \tag{16}$$

where v_1, v_2, and v_{2s} are the liquid velocity at 1 point, the liquid velocity at 2 points, and the solid velocity at 2 points, respectively.

To illustrate the effect of solid-phase properties on the bubble, the formula should contain only the solid-phase correlation parameters. Substitute Eq. (15) into Eq. (16), and divided by $Q_m\rho_m g$ for both sides, we can get

$$\frac{p_1-p_2}{\rho_m g}=\frac{v_2^2-v_1^2}{2g}\left[1+\frac{Q_s\rho_s}{Q_m\rho_m}\left(\frac{v_{2s}^2-v_1^2}{v_2^2-v_1^2}-1\right)\right]. \tag{17}$$

The relationship between the solid phase and the liquid phase is established by the relevant parameters in Eq. (17). It can be seen that the solid particle concentration and the solid flow volume have an effect on the pressure variation in process 1 to process 2.

2.3 Solid phase and gas phase correlation

The relationship between the gas bubble radius and the liquid pressure as well as the relationship between the solid concentration flow rate and the liquid pressure were established in Section 2.1 and 2.2. The relationship between gas phase and solid phase was established by pressure. Substituting Eq. (14) to Eq. (17) leads to

$$\frac{p_1 - p_\mathrm{v} + \dfrac{4\delta}{3r_2}}{\rho_\mathrm{m} g} = \frac{v_2^2 - v_1^2}{2g}\left[1 + \frac{Q_\mathrm{s}\rho_\mathrm{s}}{Q_\mathrm{m}\rho_\mathrm{m}}\left(\frac{v_{2\mathrm{s}}^2 - v_1^2}{v_2^2 - v_1^2} - 1\right)\right]. \quad (18)$$

The equal of external pressure and saturated vapor pressure make the bubble burst. $p_1 = p_\mathrm{v}$ and the type is

$$\frac{4\delta}{3r_2\rho_\mathrm{m} g} = \frac{v_2^2 - v_1^2}{2g}\left[1 + \frac{Q_\mathrm{s}\rho_\mathrm{s}}{Q_\mathrm{m}\rho_\mathrm{m}}\left(\frac{v_{2\mathrm{s}}^2 - v_1^2}{v_2^2 - v_1^2} - 1\right)\right]. \quad (19)$$

According to Eq. (19), it can be seen that the bubble burst critical radius is related to the solid phase particle density and the solid phase flow. When other parameters are invariable, as ρ_s and Q_s increasing, the temporary radius of bubble burst will decrease, which means that the cavitation will be earlier and the anti-cavitation performance of the pump will be worse. This conclusion has been verified in the simulation and experiment of other pumps.

3 Conclusions

1) The effect of solid-phase particle density and solid-phase flow on the cavitation performance of deep-sea mining pulp pump is explained theoretically. With the increase of solid concentration, the cavitation will occur earlier and the anti-cavitation performance will be worse.

2) The relationship of the bubble radius, the solid-phase particle density and the solid-phase flow rate is established by the liquid pressure, which provides the research idea for exploring the interaction equation of the three-phase flow.

3) The cavitation characteristics of this particular deep-sea mining slurry pump are further studied by simulation and experiment, which provides more evidence for the theoretical analysis conclusion.

4) The concentration of slurry pump not only affects the output of the deep sea mining system, but also affects the performance of the transport system. From the perspective of cavitation, finding the best parameters of the solid properties has a great significance for the stability and efficiency of the deep-sea mining systems.

References

[1] 董冰洁.我国海洋多金属矿产资源研究现状及战略性开发前景[J].世界有色金属,2016(12):168-169.
DONG B J. Research status and strategic development prospect of marine polymetallic mineral resources in China [J]. World Nonferrous Metals, 2016(12): 168-169. (In Chinese).

[2] 刘少军,刘畅,戴瑜.深海采矿装备研发的现状与进展[J].机械工程学报,2014,50(2):8-18.
LIU S J, LIU C, DAI Y. Status and progress on researches and developments of deep ocean mining equipments [J]. Chinese Journal of Mechanical Engineering, 2014, 50(2): 8-18. (In Chinese).

[3] YOON C H, PARK Y C, LEE D K, et al. Hydraulic pumping test system of KIGAM for deep-sea manganese nodules [C]//Proceedings of 33rd Underwater Mining Institute, Hawaii: International Marine Minerals Society, 2002: 131-135.

[4] 杨放琼,陈奇,曾义聪,等.深海采矿矿浆泵的设计方法研究[J].合肥工业大学学报:自然科学版,2014(12):1413-1418.
YANG F Q, CHEN Q, ZENG Y C, et al. Research on design method of slurry pump for deep-sea mining [J]. Journal of Hefei University of Technology: Natural Science Edition, 2014(12): 1413-1418. (In Chinese).

[5] 陈奇.深海采矿矿浆泵内固液两相流数值模拟及性能预测研究[D].长沙:中南大学,2014.
CHEN Q. Numerical simulation on solid-liquid two phase flow and performance prediction of slurry pump for deep-sea mining [D]. Changsha: Central South University, 2014. (In Chinese).

[6] 广东造船编辑部.我国首次深海扬矿泵管系统海试取得成功[J].广东造船,2016,35(4):84.
EDITORIAL OFFICE OF GUANGDONG SHIPBUILDING. China’s first deep-sea Yang pumping tubing system sea trial to be successful [J]. Guangdong Shipbuilding, 2016, 35(4): 84. (In Chinese).

[7] 姬凯.轴流泵叶轮内空化流动实验研究与数值计算[D].镇江:江苏大学,2010.
JI K. Experimental study and numerical calculation of cavitating flow in impeller of axial flow pump [D]. Zhenjiang: Jiangsu University, 2010. (In Chinese).

[8] 李文广.全空化模型预测离心泵汽蚀性能的准确度[J].水泵技术,2013(5):1-7.
LI W G. Prediction of cavitation performance of centrifugal pump by full cavitation model [J]. Water Pump Technology, 2013(5): 1-7. (In Chinese).

[9] 赵宇,王国玉,吴钦,等.基于计算流体力学的串列轴流泵空化性能分析[J].机械工程学报,2014,50(6):171-176.
ZHAO Y, WANG G Y, WU X, et al. Analysis of cavitation performances of an axial flow tandem pump based on computational fluid dynamics [J]. Chinese Journal of Mechanical Engineering, 2014, 50(6): 171-176. (In Chinese).

[10] 关醒凡.现代泵理论与设计[M].北京:中国宇航出版社,2011.
GUAN X F. Theory and design of the pump [M]. Beijing: China Aerospace Press, 2011.

[11] 何希杰.渣浆泵工作原理和设计方法[J].流体机械,1994,22(9):17-22.
HE X J. Working principle and design method of slurry pump [J]. Fluid Machinery, 1994, 22(9): 17-22.

[12] 章昱.水力空化及CFD数值模拟[D].杭州:浙江工业大学,2011.
ZHANG Y. Numerical simulation of hydrodynamic cavitation [D]. Hangzhou: Zhejiang University of Technology, 2011. (In Chinese).

[13] R.T.柯乃普,J.W.戴利,F.G.哈密脱.空化与空蚀[M].北京:水利出版社,1981.
KNAPP R T, DAILY J W, HAMMITT F G. Cavitation [M]. Beijing: Water Conservancy Press, 1981. (In Chinese).

[14] 黄继汤.空化与空蚀的原理及应用[M].北京:清华大学出版社,1991.
HUANG J T. The principle and application of cavitation [M]. Beijing: Tsinghua University Press, 1991. (In Chinese).

[15] 吴玉林,唐学林,刘树红等.水力机械空化和固液两相流体动力学[M].北京:中国水利水电出版社,2007.
WU Y L, TANG X L, LIU S H, et al. Hydraulic machinery and cavitation solid-liquid two-phase fluid dynamics [M]. Beijing: China Water Conservancy and Hydropower Press, 2007. (In Chinese).