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Studies on the effects of vessel nozzle parameters on the ore transportation efficiency in deep-sea mining

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A B S T R A C T

As it is difficult to control the ore volume concentration of pump-vessel combined ore transporting equipment for deep-sea mining during the ore pulp conveying process and it can't remain continuous, stable and reliable in the process, the SIMPLE algorithm is adopted to calculate and analyze the rules of the vessel nozzle parameters effects on the ore transportation concentration and conveying efficiency based on the Euler-Euler model and standard $\kappa-\varepsilon$ turbulence model, and the conclusion is experimentally verified that ore transportation volume concentrations can be controlled and adjusted by controlling vessel nozzle parameters. Simulation results are drawn as follows: with the vessel nozzle diameter bigger, the ore transportation volume concentration becomes bigger and the water jet impacting force on ores becomes weaker so that the transporting process gets more stable. With the nozzle outlet height from the vessel bottom greater, the ore transportation volume concentration also becomes bigger, but the transporting process gets less stable. When the nozzle outlet height from the vessel bottom equals to 800 millimeters or 900 millimeters, it can ensure that the ore transportation volume concentration get bigger and the transporting process gets stable simultaneously.

Keywords: Deep-sea mining, Ore transportation, Vessel nozzle, Volume concentration, Solid-liquid two-phase flow.

Introduction

Manganese nodules lie widely on seabed deep about from 3000 meters to 6000 meters (Yang et al., 2020). One of key links in deep-sea mining research recently is how to transport ores from 6000 meters sea floor to the mining ship at sea level continuously, stably and efficiently and simultaneously ensure its transmission process reliable, economic and advance (Li et al., 2016). At the beginning of 20th century main developed countries in the world have all carried out much theoretical and experimental research (Cao et al., 2020). And it is widely recognized that the hydraulic transporting system has great potential for industrial appliance (Pang, 2020).

In the pump-vessel combined ore lifting equipment, as shown in Figure 1, the new ore lifting system is invented according to the hydraulic transportation principle, which has many advantages such as high transmission efficiency, long service life, safe and reliable transmission (Takano et al., 2020; Slade et al., 2020). It consists of a water pump, two vessels, transportation pipes and seven control valves. Each vessel is equipped with a nozzle. Before the mining system begins to work, the Valve 3 and 7 is turned on, whilst the other valves are turned off. When the water pump is turned on, sea water will be transported to sea level through the transportation pipe by the pump. After the mining crawler starts working, ores will flow into vessel 1 through valve 3, and some sea water in vessel 1 will be drained away through valve 3. When vessel 1 is filled with ores, turn off valve 3 and turn on valve 1, 2 and 6. Then ores in vessel 1 will flow into the flexible hose, and be transported to the mining ship. Since valve 3 is turned off, ores will flow into vessel 2 through valve 6. When ores in vessel 1 are carried over and vessel 2 is filled with ores, turning off valve 1, 2 and 6, meanwhile turning on valve 3, 4 and 5, ores in vessel 2 will flow into the transportation pipe and be transported to the mining ship, while ores flow into vessel 1 through valve 3. Repeating the above working steps, through turning on or off valves, ores in two vessels will be transported to the transportation pipes alternately, and then ores in the pipes will be lifted to the sea level continuously by the water pump (Xu et al., 2020; Leal Filho et al., 2021).

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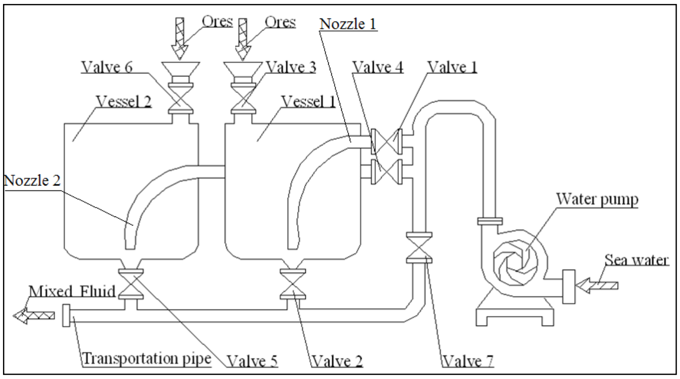


Figure 1. *Schematic diagram of pump-vessel combined ore lifting equipment*

In transporting ores, if the ore transportation concentration is too low, it may reduce conveying efficiency and economic benefits. If the concentration is too high, it may also affect the transmission reliability. So the ore transportation concentration should be controlled in a reasonable degree to make the whole transporting process efficient and reliable (Kotoky et al., 2018a; Hu et al., 2020). When the lifting equipment is working, ores in the vessel will flow from the vessel bottom into the transportation pipe under its own gravity and the pressure of the water jet out of a nozzle, and then it will be lifted to the mining ship at sea level. The vessel nozzle and the water jet out of the nozzle will affect the flow of ores in the vessel to the transportation pipe directly, and then the ore transportation volume concentration. So the key to raise ore conveying efficiency is to study the vessel nozzle parameters effects on the ore transportation concentration for deep-sea mining (McLoone and Quinlan, 2020).

For above problems, with a pump-vessel combined ore lifting equipment for a study object, with seawater for conveying medias, with manganese nodules for conveying materials, the SIMPLE algorithm will be used in this paper to calculate and analyze the vessel nozzle parameters effects on the ore transportation concentration when manganese nodules are lifted by the pump-vessel combined ore lifting equipment based on the Euler-Euler model of the Fluent software and the standard turbulence model. The mathematical model, calculation results and analysis, experimental study and conclusions are explained in the next section.

1. Mathematical model

1.1. Fundamental assumptions

In order to ensure calculations feasible and results reliable, some assumptions are made for the model as follows (Kotoky et al., 2018b):

The temperature of the flow field is equally distributed.

The solid-liquid two-phase flow is continuous and incompressible, whose physical property values are constant. The main phase flow is sea water. The second phase flow is ore particles of manganese nodules.

The particles of the particle phase are spherical and homogeneous. Take no account of the phase change of the flow. The maximum filling volume fraction of ore accumulation is 0.67.

There is dual-phase coupling between the particles and sea water. But the particle collision problem is ignored.

The mass of particles in the transportation pipe is conservational. The deposition effects of particles on the pipe wall are ignored.

1.2. Control equation

Because the volume percentage of the particle phase is greater than 10% and there is a strong interactive solid-liquid flow between the solid and liquid, the Dual-Euler model is used to perform simulation combined with particles dynamics theory. And also because the speeds of solid-liquid two phases are different and the initial ore particles in the vessel are stacked, the Euler-Euler model of the Fluent software is selected to perform calculations. Assuming the solid phase flow and liquid one are continuous filled with the whole flow field, their continuity equation and momentum equation can be obtained separately as follows (Eshghinejadfard et al., 2019; Jebakumar et al., 2018).

In the solid phase flow condition, a continuity equation and a momentum equation will be obtained as follows;

$$\frac{\partial C_V}{\partial t}+\frac{\partial C_V u_s}{\partial x}=0 \tag{1}$$

$$\frac{\partial}{\partial t}(C_V u_s)+\nabla\,(C_V u_s u_s)=-\frac{1}{\rho_s}\nabla\,(C_V P)+\frac{1}{\rho_s}\nabla\,(C_V \tau_s)+C_V F_s+\frac{M_s}{\rho_s} \tag{2}$$

In the liquid phase flow condition, a continuity equation and a momentum equation will be obtained as follows;

$$\frac{\partial(1-C_V)}{\partial t}+\frac{\partial\left[(1-C_V)u_l\right]}{\partial x}=0 \tag{3}$$

$$\frac{\partial}{\partial t}[(1-C_V)u_l]+\nabla\,[(1-C_V)u_l u_l]=-\frac{1}{\rho_l}\nabla\,[(1-C_V)P]+\frac{1}{\rho_l}\nabla\,[(1-C_V)\tau_l]+(1-C_V)F_l+\frac{M_l}{\rho_l} \tag{4}$$

Here C_v is the solid-phase volume concentration, u_l is the velocity of the liquid phase, u_s is the velocity of the solid phase, r_l is the density of the liquid phase, r_s is the density of the solid phase, P is the average pressure, t_l is the stress tensor sustained by the liquid phase, t_s is the stress tensor sustained by the solid phase, F_l is the external force per unit mass sustained by the liquid phase, F_s is the external force per unit mass sustained by the solid phase, M_l and M_s are the interaction forces between the two phases. In the two-phase flow of solid-liquid, the interaction forces belong to the internal forces, so

$$M_l+M_s=0 \tag{5}$$

The two phases of the Dual-Euler model are coupled by Equation 5, and then they can be solved.

1.3. Control equation Vessel computational model and grid of vessel model

Ore conveying equipments that work on seabed about 5000 meters deep are under very high pressure, so the vessel is designed into a container made up of a cylinder barrel, an upper hemisphere shell and a lower hemisphere shell, to improve its loading conditions. The vessel volume V and inside diameter D_i can be obtained by the formula as follow:

$$V=\frac{\pi}{6}D_i^3+\frac{\pi}{4}D_i^2 h \tag{6}$$

Here V is the vessel volume, D_i is the vessel inside diameter and h is the vessel barrel height.

Among ore conveying equipments, an ore relay warehouse connected between hard pipe and hose is joined at the bottom of the lift hard pipe, whose weight and volume have much effect on the lift pipe's loading conditions. The vessel is fixed in the relay warehouse, which occupies the largest proportion of weight and volume, so the suitable vessel volume should be selected. According to Chinese sea general design requirements v5.0, the discharging capacity of the ore relay warehouse is the collection capacity of the collector for 10 minutes so the ore warehouse's volume is designed to 6m^{-3}. The vessel inside diameter is designed to 1800mm. According to Equation 6, the vessel height can be calculated. So basic parameters of the vessel shown in Table 1 can be obtained.

***Table 1.** Basic parameters of vessel*

Name	Volume(m^3)	Inside diamete (mm)	Height(mm)
Parameter	V	D_i	h
Value	6	1800	1158

In order to improve transmission efficiency, the ore conveying equipments adopt two vessels to transport ores alternately, so the two vessels have absolutely same structure and transmission way. So as to save computer resources, this paper only considers the effects of single vessel nozzle diameter and the height of the nozzle outlet from the vessel bottom on the ore transportation concentration. The ore particles outlet at the vessel bottom is designed into a venturi tube to strengthen roll suction and impact forces when the fluid flows in high speed so that ores in the vessel flow towards the transport pipe more smoothly. Simplifying the loading hopper and inlet valve, the computational model is obtained as shown in Figure 2. The computational model mainly consists of a vessel, a nozzle and transportation pipe. According to the computational model characteristic, the model is meshed into five parts using the Gambit software, which the grid unit size is size 8 or size 10. The vessel model grid is shown in Figure 3. The five parts are the vessel cavity, the vessel outlet part, the nozzle, the inlet and outlet part of transportation pipe.

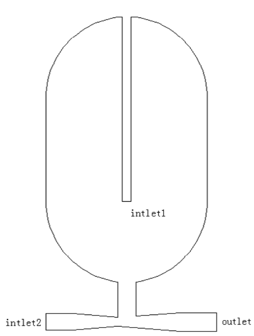


***Figure 2.** Vessel computational model*

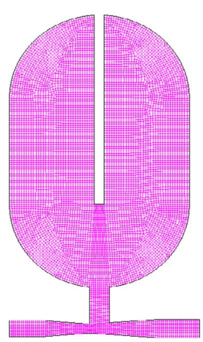


***Figure 3.** Vessel model grid*

As different transmission condition parameters have much effect on the volume concentration of ore transportation, other main parameters of conveying equipments take fixed values so that it can prevent them from affecting calculation and analysis results of the vessel nozzle parameters (Dai et al., 2021). According to calculation and analysis results of the solid-liquid two-phase flow in the vessel, transmission condition parameters of ore conveying equipments are taken as shown in Table 2.

***Table 2.** Vessel transmission condition parameters*

Parameters(Units)	Values
Stack height of ores(mm)	900
Grain size of ores(mm)	8
Diameter of transportation pipe's *outlet*(mm)	200
Diameter of transportation pipe's *inlet2*(mm)	160
Inlet velocity of nozzle's *inlet1*(m/s)	2.0
Inlet velocity of transportation pipe's *inlet2* (m/s)	5.0

1.4. Operating environment and boundary conditions setting Define the velocity entrance as an inlet boundary.

By using an inlet boundary that is homogeneous, stationary and has a given velocity along the axial direction, the entrance velocity is set according to different transmission working conditions such as valve openings, flow rates and etc.

Give the estimates of the turbulent kinetic energy and the dissipation rate.

Define the slurry outlet as a free flow boundary.

2. Calculation results and analysis

2.1. Analysis on vessel nozzle diameter effects on ore transportation concentration

When vessel basic parameters and transmission condition parameters are constant, with a nozzle diameter increment of 25mm, six sets of parameters are selected from 25mm to 150mm for simulation calculations. Then the simulation results are obtained as shown in Figure 4.

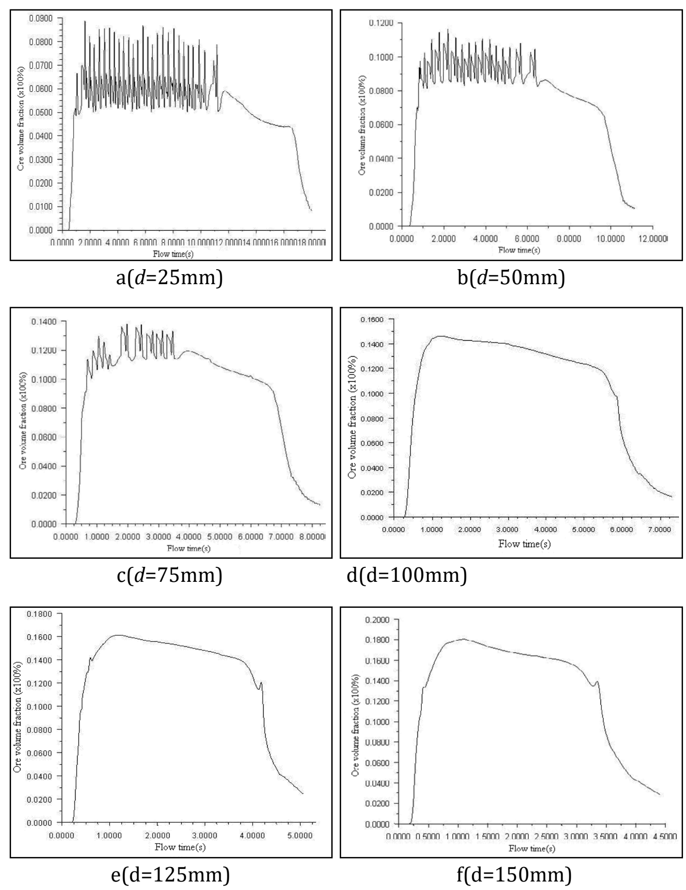
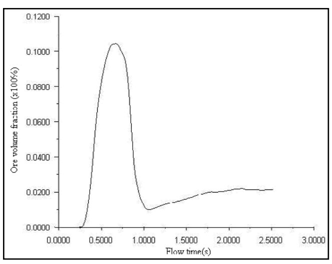


***Figure 4.** Ore volume fraction curves in different nozzle diameters*

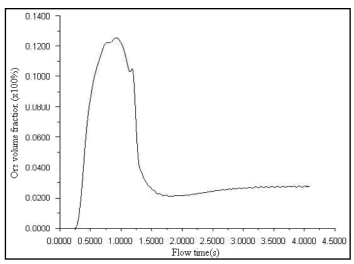
As shown in Figure 4-a, Figure 4-b and Figure 4-c, the ore transportation volume concentration will present a zigzag wave along with the conveying time when the nozzle diameter is less than 75mm. And the smaller the nozzle diameter, the bigger the fluctuation amplitude is and the longer the fluctuation time is. It follows that when the nozzle diameter is smaller, the flow rates and impact forces become weaker and the ore outflow is not easy to control so that the ore volume concentration has an extraordinary change. As shown in Figure 4-d, Figure 4-e and Figure 4-f, when the nozzle diameter is bigger, the flow rates and impact forces become larger, the stress area of the ore layer also increases, and the force condition of ore is relatively more balanced so that ores flow into the transportation pipe smoothly under the gravity and suction. So the ore transportation volume concentration has very small fluctuation or even no fluctuation.

2.2. Analysis on effects of height of nozzle outlet from vessel bottom on ore transportation concentration

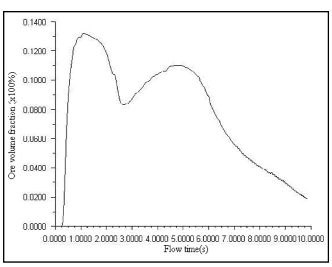
According to the vessel nozzle diameter effects on the ore transportation concentration, as known, the bigger the nozzle diameter, the higher the ore conveying efficiency is, and the more stable the transportation process is. When the nozzle diameter takes 100mm, effects of the nozzle outlet height from the vessel bottom on the ore transportation concentration has been analyzed, which the height changes from 200mm to 1200mm with an increment of 200mm. By monitoring results of ore volume fraction in the outlet, ore volume fraction curves are obtained as shown in Figure 5.



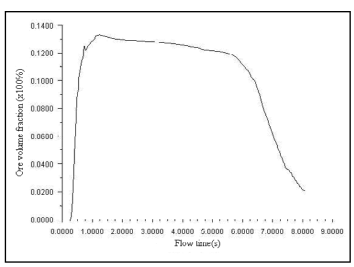
a(h=200mm)



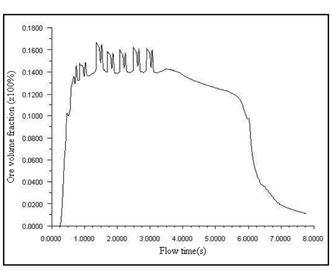
b(h=400mm)



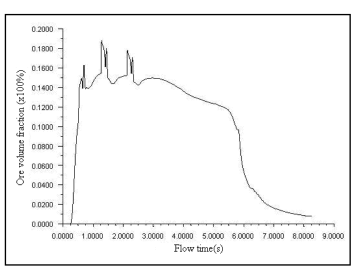
c(h=600mm)



d(h=800mm)



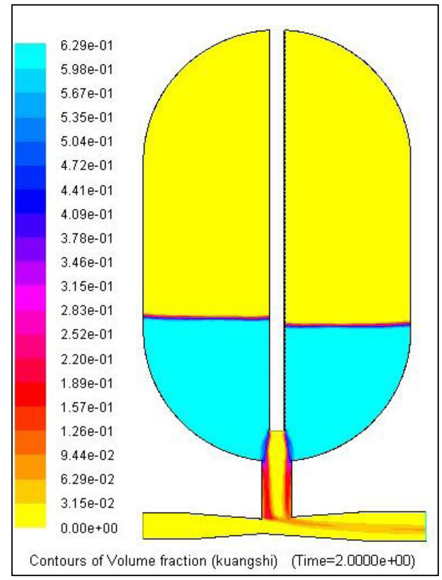
e(h=1000mm)



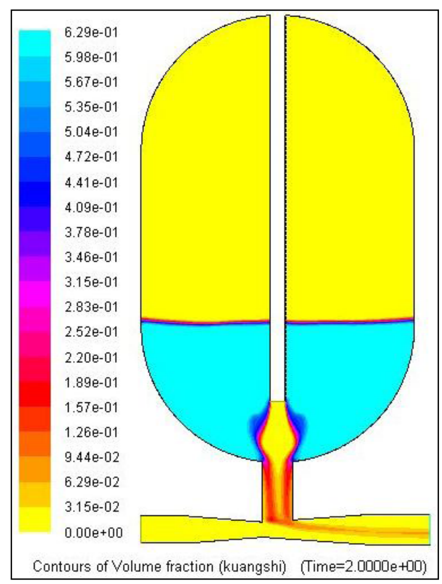
f(h=1200mm)

Figure 5. *Ore volume fraction curves in different heights from nozzle to vessel bottom*

Based on analysis on Figure 5-a and Figure 5-b, when the nozzle outlet height from the vessel bottom is less than 600mm, the ore volume fraction in the outlet of transportation pipes will be in a higher state within a short time after the beginning of transportation, then decline dramatically, and finally in a stable stage of slow rise. By analysis on the ore volume fraction contour when h is equal to 200mm and 400mm shown in Figure 6, it is obtained that ores in the vessel almost doesn't change after conveying 2.0s. But from the impact situation of the nozzle jet on the ores, the greater the nozzle outlet height from the vessel bottom, the larger the impact area of the nozzle jet on the ores is, and the longer the time of ores in a highly efficient transporting state is.



a(h=200mm, t=2.0s)



b(h=400mm, t=2.0s)

Figure 6. *Ore volume fraction contour of two different device parameters in the same flow time*

When the height of the nozzle outlet from the vessel bottom is equal to 600mm, as shown in Figure 5-c, the ore volume concentration in conveying will change in a hump shape with time, which it will increase firstly, decline dramatically again, and then also suddenly increase. This will affect the stability of the ore conveying seriously.

As shown in Figure 5-d, the ore conveying process is stable and highly efficient when the height of the nozzle outlet from the vessel bottom is equal to 800mm, which can be basically completed from 0.25s to 6.5s. The ore volume fraction curve looks smooth without fluctuations. The ore volume fraction basically keeps in a certain range and has a slightly declining trend.

When the height of the nozzle outlet from the vessel bottom is equal to1000mm or 1200mm, as shown in Figure 5-e and Figure 5-f, the whole ore conveying process looks fluent. The two ore volume fraction curves in the outlet keep good similarity, but the ore transportation volume concentration in conveying will have a violent fluctuation that presents a zigzag wave, which shows that feeding is not uniform and the conveying process is not stable. The ore volume concentration fluctuation is of randomness and its rule is very difficult to control, so it is difficult to adopt an automatic way to control the transportation concentration consistency. This transmission scheme does not meet requirements that the ore conveying process keeps stable in the deep-sea mining.

All above analysis shows that the ore conveying process will be stable and highly efficient when the nozzle outlet height from the vessel bottom is 800mm or from 800mm to 900mm.

3. Experimental study

A single vessel lifting system as shown in Fig.ure 7a is designed according to the lifting principle of the equipment. A test equipment of ore lifting system as shown in Figure 7b is built in accordance with the experimental schematic (Figure 7a).

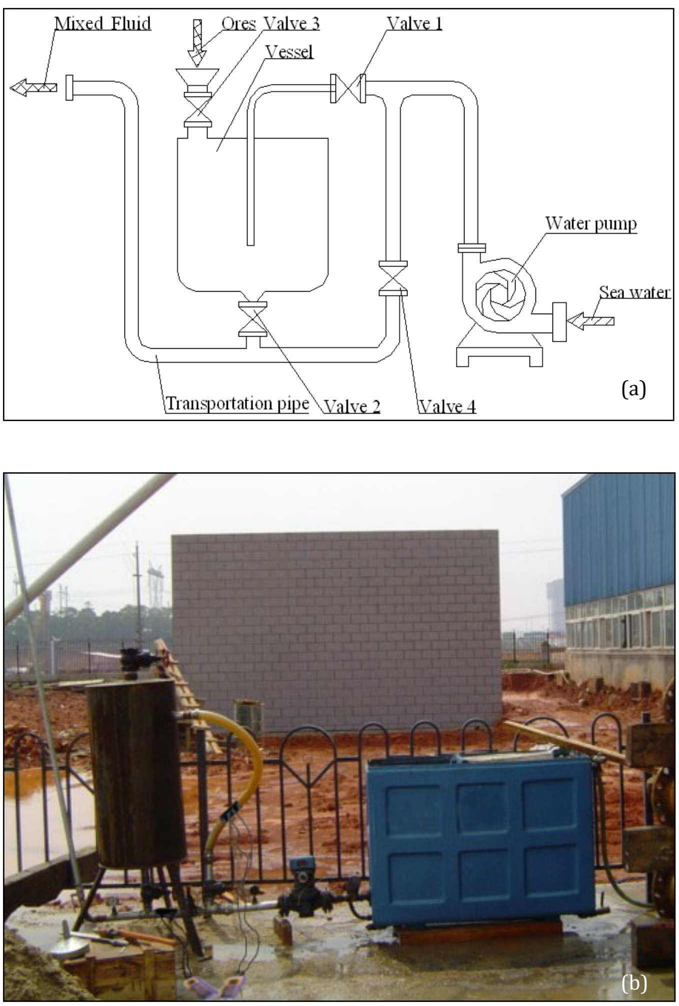


Figure 7. Notation of experimental study

When other parameters of the test equipment are kept constant, the equipment is installed with different diameter nozzles. When the required time of ore stable conveying process is taken as ore transmission time, the average volume fraction in stable ore transportation is taken as the ore transportation volume concentration, results can be obtained as shown in Table 3.

***Table 3.** Ore volume concentration and transmission time in different nozzle diameters*

Nozzle diameter (mm)	25	50	75	100	125	150
Transmission time (s)	18	11	8	7	5	4.2
Ore volume concentration (%)	5.5	9.2	11.2	13.1	14.8	16.9

As shown in Table 3, when the nozzle diameter takes the minimum value of 25mm, the ore transportation volume concentration is smallest and only 5.5%, and the transmission time is longest and equal to 18s. When the nozzle diameter takes the maximum value of 150mm, the ore transportation volume concentration is equal to the maximum value of 16.9%, and the transmission time is relatively shortest and the whole process takes only 4.2s. So it can be seen that the nozzle diameter can affect the ore conveying efficiency when other conditions are same. The bigger the nozzle diameter, the higher the ore conveying efficiency is, the weaker the water jet impact force on ores becomes, and the more stable the transportation process is.

When other parameters of the test equipment are kept constant, the equipment is installed nozzles with different heights from the vessel bottom. When the required time of ore stable conveying process is taken as ore transmission time, the average volume fraction in stable ore transportation is taken as the ore transportation volume concentration, results can be obtained as shown in table 4. As shown in Table 4, the test results show that the ore volume concentration of the equipment increases with the height of the nozzle outlet increases.

***Table 4.** Ore volume concentration and transmission time in different nozzle heights*

Nozzle height (mm)	200	400	600	800	1000	1200
Transmission time (s)	3	4	9	8	7	8
Ore volume concentration (%)	4.8	5.3	7.2	12.5	13.2	13.5

The lifting test shows that the bigger the nozzle diameter, the higher the ore conveying efficiency is. Similarly the ore lifting system is tested by adjusting the nozzle outlet height from the vessel bottom when other parameters of the equipment are kept constant. Test results show that the transport capacity of the equipment increases with the nozzle outlet height increases. The results are consistent with the above analysis, which also verifies the correctness of the simulation results. It further proves that it is feasible to control the ore transportation concentration by changing the nozzle diameter and the nozzle outlet height from the vessel bottom.

Conclusions

After numerical simulation analysis on the vessel nozzle diameter and the nozzle outlet height from the vessel bottom in this paper, which shows how they affect the ore conveying efficiency, some conclusions are obtained as follows:

The bigger the nozzle diameter when other vessel parameters are kept constant, the higher the ore conveying efficiency is, the weaker the water jet impact on ores becomes, and the more stable the transportation process is.

When the nozzle diameter takes 100mm and the nozzle outlet height from the vessel bottom is less than 600mm, the ore volume fraction in the transportation pipes outlet will be in a higher state within a short time after the beginning of transportation, and then drop dramatically. When the height is more than or equal to 800mm, the ore conveying process is stable and highly efficient, at which ore volume fraction basically keeps in high range and has a slightly declining trend. But when the height is more than 1000mm, the ore volume fraction in conveying will has a violent fluctuation that presents a zigzag wave, which shows that feeding is not uniform and the conveying process is not stable. So the ore conveying process is stable and highly efficient when the height takes 800mm.

A single vessel lifting test equipment has been designed in accordance with the experimental schematic. The experiment verifies effects of the nozzle diameter and the nozzle outlet height from the vessel bottom on the ore conveying efficiency for deep-sea mining.

There are many factors affecting the ore conveying efficiency for deep-sea mining. The next step is to explore the optimal working parameters of conveying equipment such as conveying concentration, conveying speed, head, flow, etc. The influence on sensitivity of these parameters will be also studied in the future.

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