Experimental and numerical study on the efficiency of hydraulic collection utilizing two different suction inlets

Hui Cheng¹, ²*, Yuxiang Chen¹ and Hong Xiong¹

¹Institute of Deep-sea Science and Engineering, Chinese Academy of Sciences, Sanya, Hainan, 572000, China
²College of Materials Science and Opto-Electronic Technology, University of Chinese Academy of Sciences, Beijing, 100049, China
*Corresponding author’s e-mail: chengh@idsse.ac.cn

Abstract. Hydraulic collection has been shown to be a promising technology in deep sea mining. However, the efficiency of hydraulic collection is affected by many factors. For understanding the effect of inlets distinct from shapes on collecting efficiency, a series of upward pumping experiments was conducted on spheres. Flow fields at different inlets were described by numerical simulation and compared to uncover the influence of inlet shape on collecting the sphere. The experimental results indicate that straight cylindrical pipe with flanged inlet has a higher efficiency in collecting than the straight cylindrical pipe without flanged inlet. The numerical results show that the restriction of the flanged inlet lead to a larger area of negative pressure on the top of the sphere, which means a bigger upward force.

1. Introduction

The contradiction between rising demand for mineral resources and irreversible exhaustion of land resources has led to a desire for marine mineral resources. Among various mineral resources, polymetallic nodules come into focus in deep sea mining for their huge reserves and high economic value. Dispersing on the deep seabed, polymetallic nodules are potato-shaped lumps containing mainly manganese and cobalt. Efficient collection of nodules is a key technology for commercial deep sea mining. Since the 1980s, studies on nodules collection have proposed mechanical, hydraulic and hybrid methods.

A 4-year project in France indicated the feasibility of hydraulic collection in deep sea mining[1]. Manganese nodules were lifted hydraulically through a rigid pipe at nominal speed of 0.65 m/s and maximum capacity of 600 t/h by a self-propelled miner. Oebius et al.[2-3] carried out a series of experiments on detaching the nodules from the seafloor sediment on board and in the laboratory. The experimental results showed that the sediment was subject to the least possible disturbance by hydraulic collection. Grupe et al.[4] measured the traction force of nodules removed from undisturbed sediment samples under laboratory conditions. Hong et al.[5] tested a hydraulic nodule lifter in a 2-D flume tank and noted that bottom pressure distribution was in correlation with the efficiency of nodules collection. Yang et al.[6] analyzed the capturing parameters for design of a hybrid pick-up device and denoted that catching part was determinative. Through the results of both experiments and numerical simulation, Zhao et al.[7-8] revealed that the vibration of the lift force was greatly caused by the variation of the wake vortex. Xiong et al.[9] numerically investigated the process of lifting a sphere particle into a vertical pipe.
by a CFD-DEM (Computational Fluid Dynamics, Discrete Element Method) model performed with CFD-DEM coupling software.

Many previous studies have been conducted on hydraulic collection in deep sea mining, but rarely about the influence of the shape of the inlet on the efficiency of collection. In this article, the process of nodules collection was analyzed and the relationship among dimensionless parameters concerned with the nodules collection efficiency was given. Two suction heads in disparate shapes were used in the experiment of hydraulic lifting a spherical particle. Numerical simulation of the flow field coupled with the particle further revealed the effect of inlet shape on hydraulic collection. By discussing the results of the study, a potential approach to improve the efficiency was given.

2. Analysis of hydraulic collection

2.1 Simplified physical model of a kind of hydraulic collection

A joint collaborative program in the field of deep sea mining was initiated by National Institute of Ocean Technology (NIOT), India and Institut für Konstruktion (IKS) of University of Siegen, Germany[10]. An underwater crawler has been developed and validated for mining operations at 410 m water depth. The crawler is shown in figure 1. The hydraulic principle of nodules collection by the crawler is to lift the nodules mainly by hydraulic gradient force induced by suction.

Figure 1. An underwater crawler developed jointly by NIOT and IKS[10].

In reference 5, it is proven that vertical suction force of the sphere has a relationship with the ratio of bottom clearance to diameter of the sphere and the diameter ratio of the suction pipe to the sphere. However, for different shapes of the inlets, diverse complicated flow field are formed when the pump runs, which will result in disparate hydraulic gradient force. Therefore, it is necessary to experimentally study the influence of inlet shape on the picking efficiency. According to the hydraulic principle of nodules collection, simplified physical models are set up to simulate the process of hydraulic collection in deep sea mining, as shown in figure 2.
Figure 2. Simplified physical model of hydraulic collection, (a) straight cylindrical pipe without flanged inlet and (b) straight cylindrical pipe with flanged inlet.

The spherical particles of glass are used to simulate the nodules and collected by the suction pipes with inlets of unlike shapes. The main parameters which have an effect upon the flow field around the inlet of suction pipe are listed in table 1.

Table 1. Main parameters for simplified physical model of hydraulic collection.

| Parameter | Definition                        |
|-----------|-----------------------------------|
| $D$       | Diameter of suction pipe          |
| $d$       | Diameter of the sphere            |
| $h$       | Bottom clearance                  |
| $\rho_s$  | Density of the sphere             |
| $\rho_f$  | Density of the fluid              |
| $U$       | Flow velocity in suction pipe     |
| $\mu$     | Dynamic viscosity of the fluid    |
| $g$       | Gravitational acceleration        |

2.2 Dimensionless analysis

The flow velocity of lifting single sphere in hydraulic collection depends on the density of the sphere $\rho_s$, the fluid density $\rho_f$, the gravitational acceleration $g$, the diameters of the sphere $d$ and the suction pipe $D$, bottom clearance $h$ and the dynamic viscosity of the fluid $\mu$. Therefore, the following function can be obtained by dimensionless theoretical analysis:

$$Fr = f\left(\frac{\rho_s}{\rho_f}, Re, \frac{D}{d}, \frac{h}{d}\right)$$  \hspace{1cm} (1)

Froude number $Fr$ and Reynolds number $Re$ are given by:

$$Fr = \frac{U}{\sqrt{gd}}$$  \hspace{1cm} (2)

$$Re = \frac{\rho_f Ud}{\mu}$$  \hspace{1cm} (3)

And the relationship between the flow rate $Q$ and the flow velocity $U$ is given by:

$$Q = \frac{U\pi D^2}{4}$$  \hspace{1cm} (4)
3. Experimental description

3.1 Experimental setup

To obtain details of hydraulic collection with suction heads in dissimilar shapes, a series of experiments are carried out. The experimental system consists of two main subsystems, as shown in figure 3, monitoring and control subsystem and hydraulic execution subsystem.

![Schematic view of the experimental system.](image)

In hydraulic execution subsystem, the fluid flow is driven by a pump and circulated between pipeline with same diameter and a glass tank. The tank is placed horizontally with dimensions of 2 m×1.5 m×1 m. The entrance section of pipeline is a vertical collecting tube, and the tube can be switched to one with a flanged inlet. The vertical collecting tube made of polyethylene is used to pick up a sphere of glass by suction flow. In order to reduce the impact of circulated water on hydraulic collection, a honeycomb baffle is installed near the outlet of pipeline in the tank. The bottom clearance $h$ and the flow rate $Q$ are precisely controlled by two lift platforms and the variable-frequency drive Emerson EV2100-4T0110A respectively. The magnetic flow meter Meacon LDG-MIK-DN80 is installed for measuring the flow velocity $U$ and its data is transmitted to and recorded on the computer automatically.

3.2 Test cases

According to the analysis, a series of values are set in test cases for two parameters, the diameter of the sphere $d$ and the ratio of bottom clearance to diameter of the sphere $h/d$. The diameters of the sphere $d$ are 20 mm, 30 mm and 40 mm, and the ratio of bottom clearance to diameter of the sphere $h/d$ are ranged from 1 to 2 with the increment of 0.2. Two kinds of collecting tubes with a diameter of 100 mm are used in the experiment, straight cylindrical tube with and without a flanged inlet. The flanged inlet has a diameter of 290 mm and a thickness of 2 mm. The chosen values for the experimental parameters are listed in table 2.

| Parameter | Unit | Value |
|-----------|------|-------|
| $D$       | mm   | 100   |
| $d$       | mm   | 20, 30, 40 |
3.3 Numerical simulation
For obtaining accurate flow field and further analyzing, the SST-DES (Shear-Stress Transport, Detached Eddy Simulation) model is adopted to simulate the hydraulic lifting process at both inlets. DES is a hybrid RANS/LES (Reynolds-Averaged Navies-Stokes, Large-Eddy Simulation) model in which the closure is a modification to the Spalart-Allmaras model, employing RANS in the attached regions and LES in the separated regions\cite{8}. By applying the DES model, the flow field around the sphere can be obtained with a balance between low mesh number and high accuracy. According to the experimental setup, the computational domain and boundary conditions are set, shown in figure 4.

![Figure 4. Computational domain and boundary conditions, (a) straight cylindrical pipe without flanged inlet and (b) straight cylindrical pipe with flanged inlet.](image)

To simplify the simulation, the sphere is fixed on the bottom surface. The diameter of the sphere is chosen as 40 mm and the bottom clearance is chosen as 80 mm. The computational mesh is generated as shown in figure 5. The neighboring mesh is refined as closer to the sphere. The mesh number of figure 5(a) and 5(b) are 852674 and 658688, respectively, and time step is 0.001 s.

![Figure 5. Front view of the mesh model, (a) straight cylindrical pipe with flanged inlet and (b) straight cylindrical pipe without flanged inlet.](image)

4. Result and Discussion
Froude number converted from the flow rate for different ratio \( h/d \) are shown in figure 6, and lines in figure 6 are linearly fitted by experimental data. From the trend, Froude number increases linearly with the ratio \( h/d \). For the same ratio \( D/d \), especially a large ratio \( D/d \), the required flow rate in hydraulic collection is significantly smaller in condition of the straight cylindrical pipe with flanged inlet than without flanged inlet, which means a higher efficiency.
Figure 6. Froude number for different ratio of bottom clearance to diameter of the sphere.

Under both kinds of suction pipes, the sphere is observed to whirl and revolve around the central axis of the pipe then be lifted after a sudden acceleration. The rotating motion of the sphere under the edge of suction pipe is supposed to benefit the process of hydraulic collection, because the Magnus force generated by the rotating sphere contributes to the lift of the sphere from the bottom. However, the diameter of moving path of the sphere is smaller under the flanged inlet, the reason for this is that when pumping with a flanged inlet, the water flow is more likely to form a swirl around the sphere. The cavitation that occurred after the lift of the sphere indicates the presence of the swirl flow under the flanged inlet.

The velocity distribution and pressure distribution at the time of the sphere is about to be lifted are respectively shown in figure 7 and 8. It can be seen from figure 7 that the flanged inlet restrains the suction area from expanding above the bottom clearance, while the suction zone formed by the straight cylindrical tube extends above the height of the inlet. The different suction zones further result in the difference of the velocity of fluid shedding from the top of the sphere. The stagnation zone born on the top of the sphere in figure 7(a) is smaller than that of figure 7(b). Disparate velocity distributions around the inlet of two suction pipes lead to different fields of pressure. The area of the negative pressure distribution on the top of the sphere in figure 8(a) is larger than that in figure 8(b), therefore the pressure distribution in figure 8(a) is more conducive to the lifting of the sphere.
Figure 7. The velocity distribution around the suction pipe inlet, (a) straight cylindrical pipe with flanged inlet and (b) straight cylindrical pipe without flanged inlet.

Figure 8. The pressure distribution around the suction pipe inlet, (a) straight cylindrical pipe with flanged inlet and (b) straight cylindrical pipe without flanged inlet.

The time-history curves of numerical results of lifting forces and their mean values are shown in figure 9. The lifting force on the sphere is damped to a roughly steady value after 1 s. Obviously, the lifting force acting on the sphere is larger when the flanged inlet is utilized.
5. Conclusions
Many previous papers on hydraulic collection in deep sea mining have rarely mentioned the effect of the inlet shape on pick-up efficiency. Therefore, experimental study and numerical simulation are conducted on hydraulically collecting the glass sphere in condition of different inlets. By changing experimental parameters, the process of collecting the sphere has been analyzed and served to get the following conclusions:

1. Compared to the straight cylindrical pipe without flanged inlet, a lower flow rate is needed when the flanged inlet is used to collect the spheres of the same diameter. This phenomenon is more pronounced for the large diameter spheres.

2. Rapidly rotating motion of the sphere is observed to be beneficial to hydraulic collection due to the Magnus force produced by rotation.

3. Because of the restriction of the flanged inlet, the stagnation zone on the top of the sphere is smaller, accordingly the negative pressure area is larger than in the condition of straight cylindrical pipe without flanged inlet. Consequently, lower flow rate is required when utilizing the straight cylindrical pipe with flanged inlet in hydraulic collection.

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