PAPER • OPEN ACCESS

Study on Characteristics of Particle Dynamics with Coarse Particles in Vertical and Inclined Pipeline

To cite this article: Wanlong Ren *et al* 2023 *J. Phys.: Conf. Ser.* **2458** 012037

Study on Characteristics of Particle Dynamics with Coarse Particles in Vertical and Inclined Pipeline

Wanlong Ren[1, 2], Xuhui Zhang[1, 2], Yan Zhang[1, *] and Xiaobing Lu[1,2]

[1] Key Laboratory for Mechanics in Liquid Solid Coupling Systems, Institute of Mechanics, Chinese Academy of Sciences, Beijing 100190, China

[2] School of Engineering Science, University of Chinese Academy of Sciences, Beijing 100049, China

[*]zhangyan162@imech.ac.cn

Abstract: The pipeline hydraulic transport is an important component of the deep-sea mineral resources. The characteristics of particle dynamics with coarse particles is investigated by using the CFD-DEM method in the vertical and inclined pipeline. The normal pipeline and abnormal pipeline mentioned in this paper refer to vertical pipeline and inclined pipeline, respectively. The particles of the normal pipeline mainly move in the middle of the pipeline, while the particles mainly concentrate on the pipeline wall in the abnormal pipeline. The velocity difference of the abnormal pipeline between liquid and particle is much greater, which can be prone to cause particle aggregation. Finally, the pipeline to be blocked can be easy to be caused by the particle aggregation in the wall of abnormal pipeline. An appropriate increase in liquid velocity can improve the phenomenon.

1. Introduction

With the decreasing reserves of terrestrial mineral resources, marine-rich resources such as manganese nodules and hydrates are expected to become essential support for the future energy strategy of countries around the world. Therefore, it is crucial to master deep-sea mineral resources' mining and transportation technology. Efficient and environmentally friendly deep-sea mining projects have become an important part of the development of marine resources [1]. The normal pipeline and abnormal pipeline mentioned in this paper refer to vertical pipeline and inclined pipeline, respectively.

How to transport the rich mineral resources in the deep sea from the seabed of several kilometers to the land is one of the urgent problems faced by the current deep-sea mineral projects. It is recognized that the safest and most promising is the hydraulic conveying system. The core of the deep sea hydraulic conveying is to study the particle dynamics formed by the two phases flow in the pipeline [2]. Many researchers have conducted extensive experiments on the hydraulic conveying of normal pipelines. A device to simulate deep-sea mining systems was established, and obtained the sedimentation velocity of manganese nodules through experiments, and the relationship between the nodules concentration and the velocity difference between liquid and particle was found [3]. The velocity and particle volume fraction transitioning regimes were measured to study the stability of vertical tubes and provide recommendations for transport parameters [4]. Dai et al. [5] analyzed the particle dynamics with different liquid velocities and particle diameter es in the ascending process through a vertical hydraulic lifting pipeline. In addition, some researchers have studied the movement of particles in abnormal pipelines, but most studied fine particles [6].

Over the past decade, numerical simulation has become a meaningful way to obtain motion information of particles and fluids in normal pipelines [7]. Researchers began studying particle transport characteristics in normal pipelines using the CFD-DEM method. Motion characteristics of particles and flow field information in a normal pipeline are studied [8]. They found that particles tend to flow in the middle of the pipeline, which was not found in the experiment. The particle clustering on the suspension settlement of high-concentration particles was studied by Yao et al. [9]. The characteristics of the hydraulic conveying in normal pipelines was studied [10]. However, few researchers have studied the particle transport characteristics of abnormal pipelines. It is challenging to keep the pipeline vertical due to the influence of external forces in hydraulic conveying. Therefore, study the hydraulic transportation characteristics of is important to in abnormal pipelines.

The particles transported by deep-sea mining pipelines are coarse. Coarse particles transported by pipeline means $D/d < 10$ [11],where D and d mean the pipeline and particle diameter, respectively. Since the general CFD-DEM method requires a particle size smaller than the mesh size, it is difficult to solve the problem of coarse particle transport. Therefore, we proposed a new numerical method for solving coarse particles and successfully implement it on CFDEM platform [12].

This paper mainly studies particle dynamics and flow field information with coarse particles in normal and abnormal pipelines using the optimized CFD-DEM method in the context of deep-sea mining. In Sect. 2, the CFD-DEM method is introduced. The computational model is set up in Sect. 3. Sect. 4 is the analysis of results. Finally, the Sect.5 summarizes the particle dynamics and flow field information of normal and abnormal pipelines.

2. Numerical methods

2.1. Liquid phase description

Flow field is solved by the mass and momentum conservation equations [13]:

$$\nabla \cdot \mathbf{u}_l = 0 \tag{1}$$

$$\frac{\partial(\varepsilon_l \mathbf{u}_l)}{\partial t} + \nabla \cdot (\varepsilon_l \rho_l \mathbf{u}_l \mathbf{u}_l) = -\varepsilon_l \nabla P + \nabla \cdot (\varepsilon_l \boldsymbol{\tau}_l) + \varepsilon_l \rho_l \mathbf{g} + \mathbf{F}_{pl} , \tag{2}$$

where ε_l is the liquid volume fraction, $\mathbf{u}_l$ and ρ_l are the velocity and density of liquid, respectively, P means the liquid pressure, $\mathbf{F}_{pl}$ is the solid-liquid interaction force, and $\boldsymbol{\tau}_l$ is the liquid shear stress tensor.

2.2. Solid phase equations

Position and velocity information of a single particle is obtained by solving momentum and angular momentum equations [14]:

$$m_p \frac{d\mathbf{u}_p}{dt} = \mathbf{F}_{lp} + \mathbf{F}_{con} + m_p \mathbf{g} , \tag{3}$$

$$I_p \frac{d\omega_p}{dt} = \mathbf{M} , \tag{4}$$

where m_p and $\mathbf{u}_p$ mean the mass and the velocity of particles, respectively. $\mathbf{F}_{lp}$ and $\mathbf{F}_{con}$ mean the solid-liquid force and the particle-particle/wall collision force, respectively. I_p and ω_p mean the moment of inertia and the angular velocity, respectively. $\mathbf{M}$ is the particle-particle/wall torque. These physical quantities are commonly used in particle dynamics.

2.3. Liquid-solid interaction

There are many empirical force models between solid and liquid. In this paper, the main empirical force models are drag force model and pressure gradient force model [7]:

$$\mathbf{F}_{pl} = \mathbf{F}_d + \mathbf{F}_p , \tag{5}$$

where $\mathbf{F}_d$ and $\mathbf{F}_p$ mean the drag and the pressure gradient forces, respectively. More details can be found in [10]. An new numerical method can be found in Refs [12].

3. Numerical setup

A pipeline with a diameter of 100 mm inner diameter and 1.5 m long is formed in Figure.1. The essence of an abnormal pipeline is the angle between the pipeline and the direction of gravity. In this paper, the abnormal pipeline is formed by changing the direction of gravity by 45° based on the normal pipeline. The Table 1 is the parameters of the numerical simulation. The particles initially rest on the bottom, then rises with the liquid force.

Table 1. The numerical Parameters of hydraulic collection

Parameters	Values
Water properties	
Density ρ_l	1000 kg/m^3
Viscosity ν_l	1.0×10^{-6} m^2/s
Velocity u_0	2 - 3 m/s
Particle properties	
Density ρ_p	2450 kg/m^3
Diameter d_p	10 mm
Young's modulus E	1.0×10^9 Pa
Poisson's ratio ν	0.45

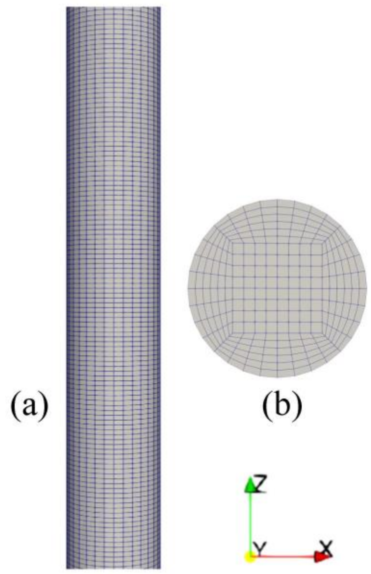


Figure 1. Geometry: (a) front meshes, and (b) inlet meshes.

4. Analysis of results

4.1. Method validation

The CFD-DEM method is verified based on the CFDEM platform in this part. The minimum fluidization velocity (MFV) is compared between the numerical and theoretical results with different viscosities [15]. Particle density is ρ_p = 2200 kg/m^3, and particle size is 10 mm. Liquid defaults to the normal temperature water and the viscosity of μ_l = 0.03, 0.04, 0.05, 0.06, 0.07, 0.08, 0.09 kg/(m. s). Under the action of fixed fluid velocity at the inlet, particles at the bottom begin to fluidize. When the pressure change value in the pipeline is a constant, the fluid velocity is the MFV. The MFV between numerical and theoretical results is in Figure 2. The results of numerical simulation are close to the experimental results, so the new numerical method can be used to obtain particle dynamics with coarse particles.

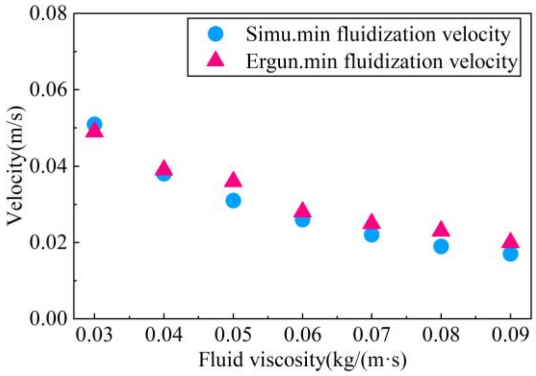


Figure 2. MFV between numerically and theoretically calculated.

4.2. Qualitative results

To measure the particle and liquid data at a steady state, we set up a monitoring area with a height of 0.1 m at 0.75 m long in pipeline. Parameter variations such as liquid, particle velocity, and local volume fraction in the region are obtained.

This part qualitatively analyzes the variation of particle local volume fraction at 0.75 m of normal and abnormal pipelines lengths. The contours of the local volume fraction distribution of particles at 0.75 m of the cross-section of the normal and abnormal pipelines in Figure 3 at an inlet liquid velocity of 2 m/s, respectively. Overall, the local concentration distribution of particles in the normal pipeline is uniform, and this transport state is what we hope in engineering in Figure 3a. The particles of the normal pipeline mainly move in the middle of the pipeline, so the local concentration distribution of particle in the wall is small in the normal pipeline. However, in the abnormal pipeline, the particles of the abnormal pipeline mainly concentrate on the pipeline wall in Figure 3b. The state in which particles concentrate on the pipeline wall is particularly easy to lead to pipeline damage, which is not an ideal conveying mode. Because of the complex marine environment, abnormal pipeline transportation is common. Therefore, how to ensure the uniform transport of particles in abnormal pipeline is a research topic to be solved at present.

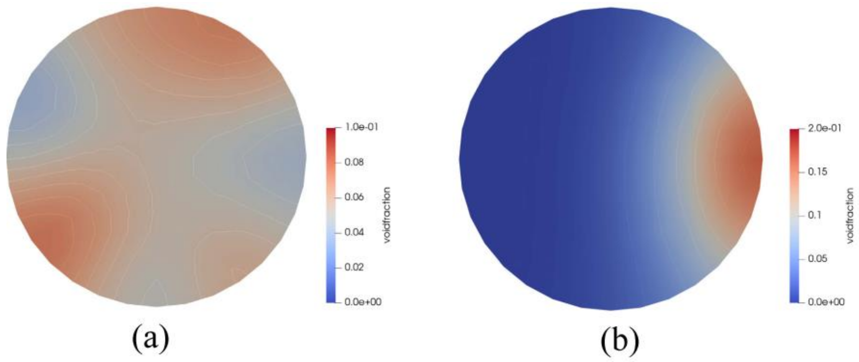


Figure 3. Particle volume fraction cloud map: (a) normal pipeline, and (b) abnormal pipeline.

4.3. Quantitative analysis of the particle

This section mainly analyzes the variation of particle local volume fraction and slip velocity at 0.75 m of normal and abnormal pipelines lengths. In this part, we investigate the variation in the velocity difference between liquid and particle by changing liquid velocities. We study the variation of the velocity difference at different liquid velocities in normal and abnormal pipelines, respectively. The velocity difference of the abnormal pipeline between liquid and particle is much greater, which can be easy to cause particle aggregation in Figure 4. Large slip velocity will lead to poor followability of particles, which can easily cause particle aggregation and cause pipeline blockage in the abnormal pipeline.

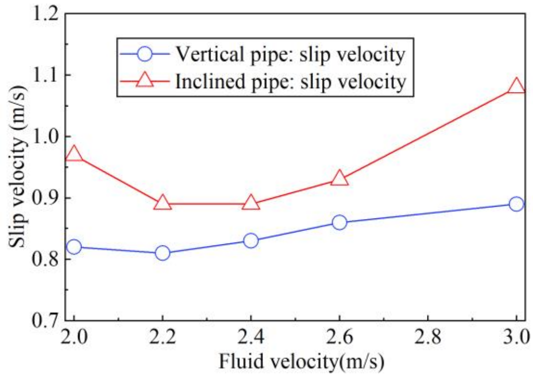
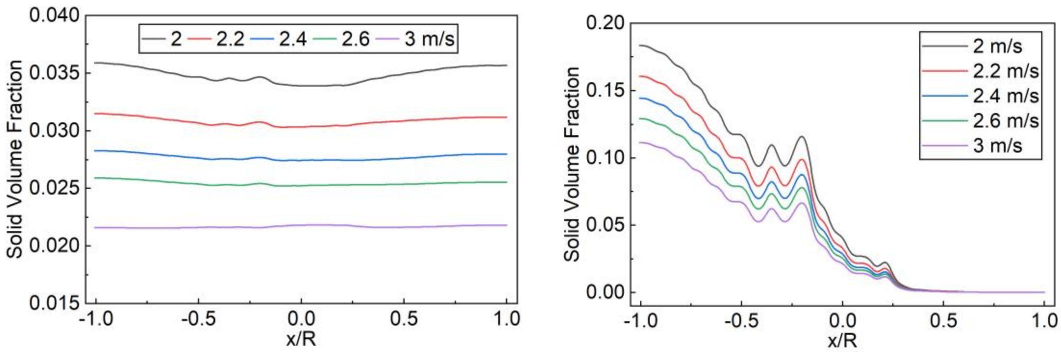


Figure 4. The variation of velocity at liquid velocity in the normal and abnormal pipelines.

The local concentration distribution of particles decreases with the increase of fluid velocity in Figure 5a. The local concentration distribution of particles is also more uniform in horizontal direction, and it is not easy to pipeline blockage. The particles gather at the wall is very high in Figure 5b. This is consistent with the phenomenon in Figure 3b. In addition, we find that the minimum inlet velocity required for abnormal pipelines is significantly greater than that of normal pipelines, and particle aggregation occurs easily in abnormal pipelines. Therefore, Once the pipeline is inclined, an appropriate increase in liquid velocity is required in practice.



(a) (b)

Figure 5. The changes of average local volume fraction of particles.

5. Conclusions

The characteristics of particle dynamics with coarse particles is investigated by using the CFD-DEM method in vertical and inclined pipelines. The normal pipeline and abnormal pipeline mentioned in this paper refer to normal pipeline and inclined pipeline, respectively.

- Firstly, the particles of the normal pipeline mainly move in the middle of the pipeline, while the particles of the abnormal pipeline mainly concentrate on the wall. Uniform distribution of particles in the pipeline is an ideal conveying condition.
- Secondly, the slip velocity of particles in abnormal pipelines is significantly greater than that in normal pipelines, which is easier to cause particle aggregation.
- Finally, the radial variation of the concentration distribution of particles in normal and abnormal pipelines is analyzed, respectively. Compared with normal pipelines, abnormal pipelines are prone to particle aggregation and cause pipeline blockage, which is a problem that we need to solve in engineering.

Acknowledgments
In the process of writing this article, I especially thank the National Natural Science Foundation of China (Grant No.12132018), the Strategic Priority Research Program of the Chinese Academy of Sciences (Grant No. XDA22000000), and the Youth Innovation Promotion Association of Chinese Academy of Sciences (No.2017027) for providing support.

References
[1] Glasby G. Lessons learned from deep-sea mining [J]. *Science*, 2000, **289**(5479): 551-3.
[2] Chung J S, Tsurusaki K.1994 Advance in deep-ocean mining systems research [C]. In: The Fourth International Offshore and Polar Engineering Conference. OnePetro.
[3] Xia J, Ni J R, Mendoza C. Hydraulic lifting of manganese nodules through a riser [J]. *J Offshore Mech Arct Eng*, 2004, **126**(1): 72-7.
[4] Van Wijk J, Talmon A, van Rhee C. Stability of vertical hydraulic transport processes for deep ocean mining: An experimental study [J]. *Ocean Engineering*, 2016, **125**: 203-13.
[5] Dai Y, Zhang Y, Li X. Numerical and experimental investigations on pipelineline internal solid-liquid mixed liquid for deep ocean mining [J]. *Ocean Engineering*, 2021, **220**: 108411.
[6] Archibong-Eso A, Aliyu A, Yan W, et al. Experimental study on sand transport characteristics in horizontal and inclined two-phase solid-liquid pipeline flow [J]. *Journal of Pipelineline Systems Engineering and Practice*, 2020, **11**(1): 04019050.
[7] Xie Z, Wang S, Shen Y. CFD-DEM study of segregation and mixing characteristics under a bi-disperse solid-liquid fluidised bed [J]. *Advanced Powder Technology*, 2021, **32**(11): 4078-4095..
[8] Zhou M, Wang S, Kuang S, et al. CFD-DEM modeling of hydraulic conveying of solid particles in a vertical pipeline [J]. *Powder Technology*, 2019, **354**: 893-905.
[9] Yao Y, Criddle C S, Fringer O B. The effects of particle clustering on hindered settling in high-concentration particle suspensions [J]. *Journal of Liquid Mechanics*, 2021, **920**.
[10] Sun D, Liu H, Guo R. A probability model for predicting the transport efficiency in vertical pipes considering the particle size distribution[J]. *Powder Technology*, 2023, **415**: 118104..
[11] Cúñez F D, Franklin E M. Mimicking layer inversion in solid-liquid liquidized beds in narrow tubes [J]. *Powder Technology*, 2020, **364**: 994-1008.
[12] Zhang Y, Lu X-B, Zhang X-H. An optimized Eulerian-Lagrangian method for two-phase flow with coarse particles: Implementation in open-source field operation and manipulation, verification, and validation [J]. *Physics of Liquids*, 2021, **33**(11): 113307.
[13] Zhao G, Xiao L, Yue Z, et al. Performance characteristics of nodule pick-up device based on spiral flow principle for deep-sea hydraulic collection [J]. *Ocean Engineering*, 2021, **226**: 108818.
[14] Guo Y, Curtis J S. Discrete element method simulations for complex granular flows [J]. *Annual Review of Liquid Mechanics*, 2015, **47**: 21-46.
[15] Ergun S, Orning A A. Liquid flow through randomly packed columns and liquidized beds [J]. *Industrial & Engineering Chemistry*, 1949, **41**(6): 1179-84.