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THE MOTION AND RESISTANCE LOSS OF COARSE-GRAINED SLURRY IN HORIZONTAL PIPELINE

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Abstract: This paper investigates the motion state and resistance loss of coarse-grained slurry in pipeline under different conditions of concentration, diameter, and transportation velocity by experiments. With the increasing of transport velocity, there are four kinds of motion states : starting status, discontinuous load movement status (contact movement status), continuous load movement status, suspension movement status. Among these types, the resistance loss is the lowest in load movement status. Basing on the experimental data, a relation of additional loss ($(i_m - i_0)/(Cv \times i_0)$) and the influencing factors is obtained, including grain diameter, velocity, and volume concentration, which can be used to judge the motion status and to calculate the additional loss in slurry transportation.

KEY WORDS: coarse-grained slurry; motion state; resistance loss

1. INTRODUCTION

At present, pipeline hydraulic transport system was a prospective method for deep-sea mining. For this coarse ore transportation, it is critical to reveal the movement mechanism of solid-liquid flow in pipeline. This solid-liquid two-phase flow consumes more energy due to large friction and frequent collision. Therefore, it is important to study the resistance loss of course-grains in pipeline under different conditions of concentration, diameter, and transportation velocity (*Matousek*,2009;*Vlasak* and *Chara*,2004).

Based on a lot of experimental results, Durand and Gibert established a relationship of $(i_s - i_o)/C_v \cdot i_o$ and Froude numbers *Fr* (*Durand R.*,1953; *Gibert R.*,1960) as follows,

$$\frac{i_s - i_o}{C_v \cdot i_o} = \beta \cdot Fr^{-\alpha} \tag{1}$$

where β and α are parameters related of slurry material, which can be determined from experimental data. The relationship of the $(i_s - i_o)/C_v \cdot i_o$ and Fr could be represented by a linear dependence in a log-log plot (*Vlasak*, 2011).

The above Durand formula can be used for a wide range of slurry condition by introducing friction coefficient C_D and the factor of specific gravity (*Govier*,1961). Smith(1955) and Graf (1971) deemed that Durand formula can be applied to the range of a higher concentration, i.e. $C_v \leq 33\%$. whereas, Durand formula isn't accurate within the lower and higher velocity range, especially for strong-stratified and fully suspended flow pattern (*Vlasak* et al.,2012). Zandi and Govatos (1967) pointed out that the Durand formula is invalid if the saltation mode of solids transport occurs.

In addition, the flow behaviors of coarse-grained and complex slurries were investigated for the safe, reliable and economical design and operation of pipeline technology (Vlasak et al.,2012). According to the motion characteristics of particles in horizontal pipes, Newitt (1955) proposed that there are four kinds of motion forms, i.e. homogeneous, heterogeneous, load movement and sedimentation. Subsequently, particle motion were divided into load movement and suspended flow pattern by Fei Xiang-jun （1994) , according to the mechanical mechanism. In recent years, the motion law of the coarse-grained slurry was analyzed and discussed in heterogeneous flow (Wang Zhaoyin et al.,1997; Wilson et al.,2002; Liu Bo et al.,2009;Cao Bin et al.,2012). During the experiments, the main three motions pattern of coarse solids can be observed, these are suspension, sliding and rolling on the pipe invert. The motion of coarse solid is closely related to grain size, volume concentration, and grain density(Cao Bin et al., 2012). Matousek(2005) suggested one model based on the physical description of slurry flow behavior in a pipeline.

For the relation of resistance loss and the flow behaviors is very important for the parameter design of hydraulic transport system. Durand(1952) and Vlasak (2012) have studied the relation of additional loss and *Fr*, which built a foundation for the judgement standard of different motion status in horizontal pipeline. There are many experimental results about resistance loss of slurry in pipeline, however, the experimental system parameter, materials size distribution and density, and the transportation concentration are different in these experiments, therefore, it is difficult to summarize all experimental results. In addition, studies on coarse-grained flow are rarely conducted (Sommerfeld, 1998; Shook et al.,1969; Mehmet et al., 2001; Souza Pinto et al.,2014).

This paper studies the motion state and resistance loss of coarse-grained slurry in pipeline under different conditions of concentration, diameter, and transportation velocity by self-built pipeline hydraulic transport simulation system. We propose an additional loss formula of coarse-grained slurry in horizontal pipeline, providing reference for deep-sea mining system design.

2. EXPERIMENTAL SYSTEM AND METHODS

An hydraulic transportation experimental installation was built with pipeline subsystem, power control subsystem, and measurement subsystem. The pipe is 50mm in diameter and 20m in length. The system adopts the star-shaped impeller type feeder feeding. After the solid-liquid two phase flows are separated by the solid-liquid separation mesh filter, the solid particles will get into the feeder box directly which avoids the crush and efflorescence of the material effectively and ensures the large solids basically remaining unchanged in the test process. The transmission power is provided by clean water pump. The feeder and vortex pump adopt frequency conversion ensuring stepless speed regulation. There is a 2m long transparent organic glass tube in central horizontal tube to record the particles' motion and speed with high-speed camera. High precision digital pressure gauge was installed in the horizontal pipe section to measure resistance loss.

The liquid phase is clear water in the test, and the solid phase is natural quartz sand.

Experiment materials are divided into four groups according to their size, which are 1.5mm and 2.5mm, 3.5mm, and 4.5mm. The transportation volume concentration is 10%, 15%, 20%, and 25%, respectively. Start the pump first and then add the particle of identical size and concentration into chute feeder during the test. The rotation rate of pump is controlled by frequency conversion. The camera is used to observe the thickness of particles with different motion state. The conveying speed and concentration of materials were obtained through the sampling calibration.

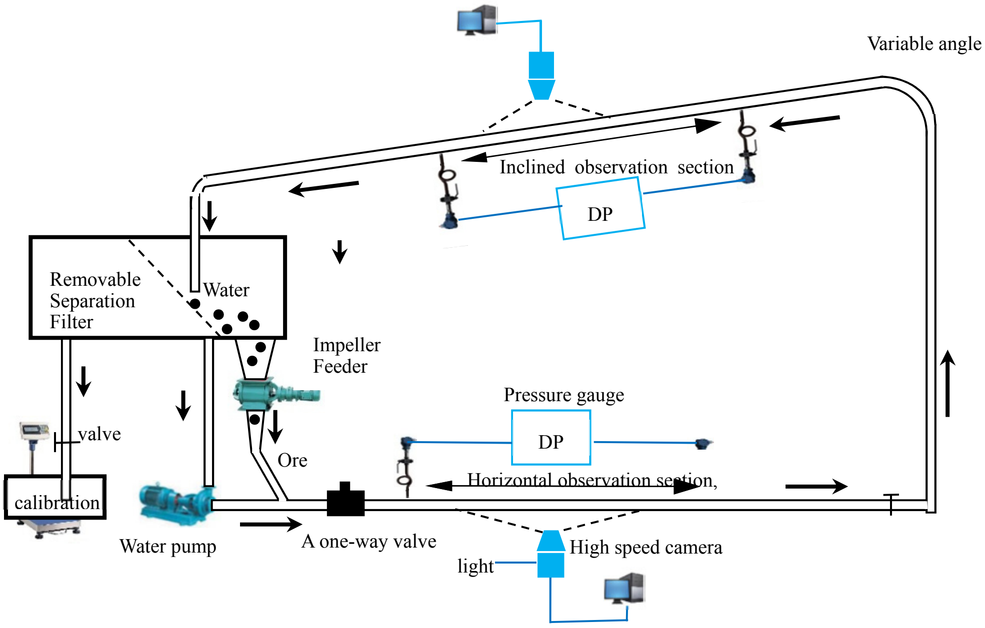


Fig.1 Schematic diagram of experiment system for the hydraulic transportation

3. RESISTENCE LOSS UNDER DIFFERENT MOTION STATUS

The resistance loss in the transportation of solid materials can be represented by the drop of pressure. This paper uses hydraulic gradient to express the resistance loss between two points. The relation between hydraulic gradient and velocity under different diameters is shown in Fig.2.

Fig.2 shows that hydraulic gradient has a close relation with velocity. With the increasing of velocity, hydraulic gradient falls firstly and then rises.

In horizontal pipeline, the motion status of coarse particles can be divided into four types, with the increasing of velocity, there are starting status, discontinuous load movement(contact movement), continue load movement and suspension movement.

(1) Starting status

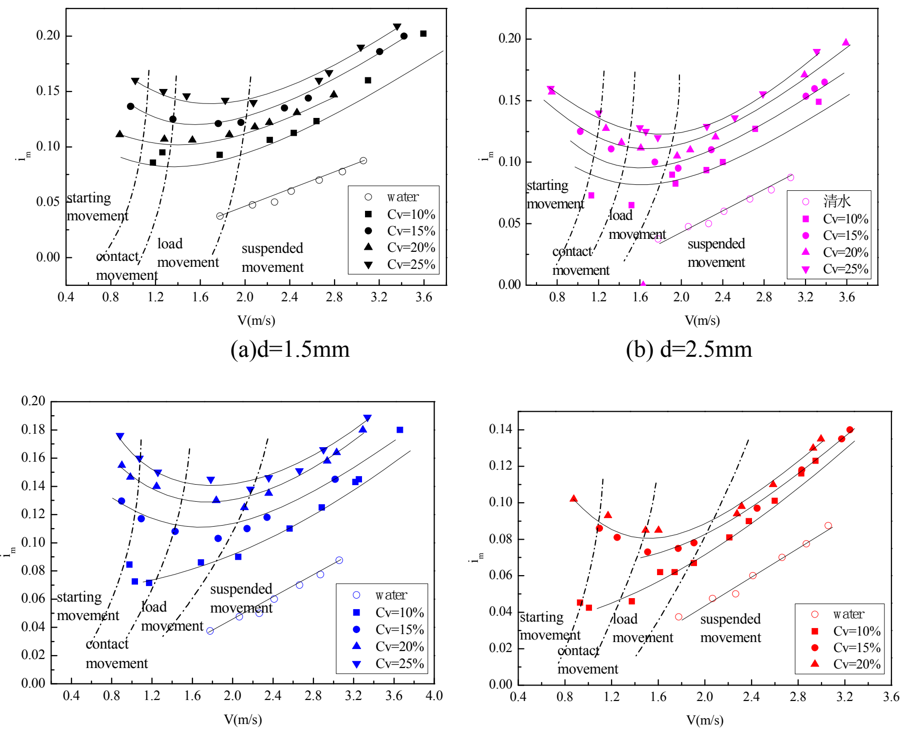
The characteristics of this movement are mainly as follows: the grains out of bed are likely to move and bear large towing force. The resistance loss is mainly caused by frictions between different grains or between grains and water. The hydraulic gradient will decrease as the velocity increases. Hydraulic gradient will approach a minimum value, indicating this type of movement causes great resistance loss.

(2) Load movement status

Load movement status types include discontinuous load movement, and continue load movement. It is the main type of movement state in horizontal pipeline. As the velocity increases, the water's drag force will increase. Shear movement occurs between different layers and grains will bear vertical discrete force at the same time. The lowest hydraulic gradient appears in this movement.

(3) Suspension movement status

The suspension status results from large scale water turbulence, from which grains get energy and support force. In this movement state, the hydraulic gradient is large. As the velocity increases, the hydraulic gradient will increase also.



(a)d=1.5mm (b) d=2.5mm

(c)d=3.5mm (b) d=4.5mm

Fig.2 The relationship between hydraulic gradient and velocity

In summary, the contact movement state of motion is not the optimal state for transportation, for its low transportation velocity and small conveying capacity. The suspended movement state only happens under smaller coarse-grained and higher velocity condition, which causes more energy consumption. The load movement state is the ideal state for coarse-grained slurry transportation.

4. THE CALCULATION OF ADDITIONAL LOSS

To analyze the quantitative relationship between the movement state of motion and resistance loss, additional loss parameter $(i_m - i_0)/(Cv \times i_0)$ is employed to represent resistance loss (i_m , i_0 are the hydraulic gradient of the slurry and of the water, respectively). According to the existing research results, the main factors of additional loss of pipeline include flow velocity and the diameter of grains, so two parameters are used: one is $\mathrm{Fr} = v^2/gD$(v represents the velocity of the slurry, g represents gravity acceleration, D represents the diameter of the pipeline), the other is: d/D (d represents the diameter of grains).

4.1 THE RELATION OF ADDITIONAL LOSS AND VELOCITY

To analyze the relationship between additional loss and solid-liquid velocity, Fig.3 has been obtained, which showed the relationship of additional loss and Fr .

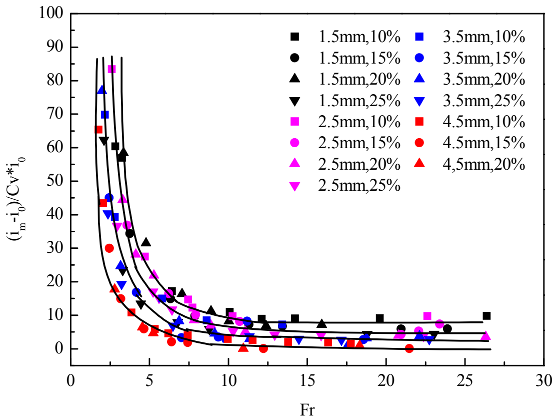


Fig.3 The relationship between additional pipeline loss and Fr

According to Fig. 3, the relationship between additional loss and Fr as follows can be analyzed as follows,

$$\frac{i_m - i_0}{C_v i_0} \propto k_1\left(\frac{v^2}{gD}\right)^{-1.3} \tag{2}$$

When $(i_m - i_0)/(Cv \times i_0)$>45, the type of movement is mainly the contact movement state and $(i_m - i_0)/(Cv \times i_0)$ will decrease sharply with the increase of v^2/gD. When grains move as the contact movement state, the velocity is low and coarse grains are in dense contact state. At this state, the inter particle friction and seepage contribute a lot to resistance loss, and the friction between liquid phase and pipe wall can be neglected. In summary, the lower the solid-liquid velocity is, the more frequent the collision and friction between particles is, and the higher the additional loss will be.

When 10≤$(i_m - i_0)/(Cv \times i_0)$≤45, the type of movement is mainly the load movement state. The term $(i_m - i_0)/(Cv \times i_0)$ will decrease mildly with the increase of v^2/gD. The load movement state happens when the velocity is relatively high and the resistance loss mainly results from the friction between the water and the pipe wall, the friction between grains and the pipe wall, and the friction between different grains. When they move as the load movement state, grains can get energy from water turbulence kinetic energy and the coarse grains movement changes from the dense contact state to the loose state of surface. The higher the solid-liquid velocity is and the looser grains contact with the bed, the lower the additional loss will be. Therefore, as the velocity increases, the additional loss will decrease.

When $(i_m - i_0)/(Cv \times i_0)$<10, the type of movement is mainly the suspended movement state of motion. At this state, the term $(i_m - i_0)/(Cv \times i_0)$ doesn't change apparently with the increase of v^2/gD. Under the suspended movement state, the velocity is high and the resistance loss mainly results from the friction between water and pipe wall or the discrete force between grains. Grains get energy from the water turbulence kinetic energy, which helps grains suspend in water. The higher the velocity is, the more the turbulence kinetic energy grains will get, the likelier they will suspend. The space between particles is much larger than the particle size when grains are suspended in the water, so the additional loss of the pipeline approaches to a constant value.

4.2 THE RELATION OF ADDITIONAL LOSS AND GRAIN SIZE

Many researchers found that the additional loss in the pipeline is also related to particle size of the transported grains. In order to analyze the quantitative relationship between additional loss and the grain diameter, the parameter d/D is introduced to represent grain diameter influences.

According to Fig. 4, the relationship of additional and *d/D* is built as follows,

$$\frac{i_m - i_0}{C_v i_0} = k_2 \left(\frac{d}{D}\right)^{-0.6} \quad (3)$$

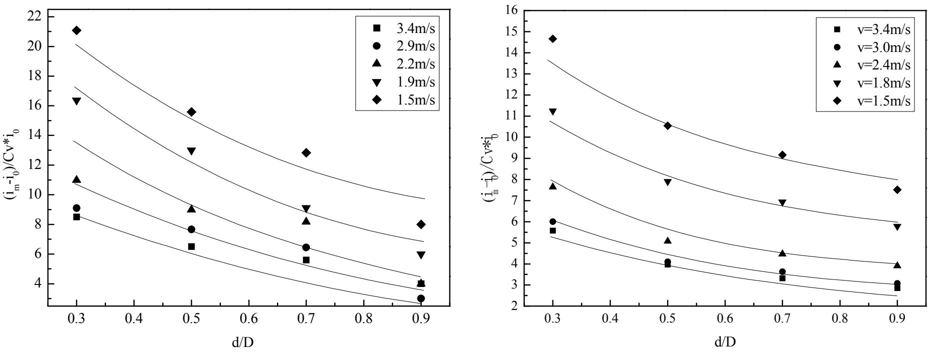
From the above formula, we can draw some conclusions: in horizontal pipeline, the additional loss decreases with the increasing of diameter within a certain concentration range. The reason behind it is that under the same concentration, the smaller the diameter is, the larger the grain number will be and the greater the probability of particle collision is, the greater the energy loss of solid phase is. In a certain concentration and diameter range, the lower the velocity is, the larger the energy loss caused by grain collision and fractionating will be, because under low velocity grains mainly move as the contact movement state and colliding and fractionating between grains will increase energy loss, but as the velocity increases, grains get more energy from water turbulent kinetic energy and convert to suspension movement. In suspension movement, the distance between grains increases, the probability of grain collision and the collision between particles and pipe wall are reduced, so the energy dissipation is reduced.

Summarizing the formula (2) and (3), we develop the formula of additional loss:

$$\frac{i_m - i_0}{C_v i_0} = k_2 \left(\frac{d}{D}\right)^{-0.6} \left(\frac{v^2}{gD}\right)^{-1.3} \quad (4)$$

Basing on existing results, we can conclude $(i_m - i_0)/(Cv \times i_0) \propto C_D^{0.75}(s-1)^{1.5}$. ($C_D$ represents the drag coefficient, s = ρ_s/ρ_w, ρ_s, ρ_w represent the particle density and liquid density, respectively). According to the dimensionless principle, the formula of the pipeline additional loss is obtained as follows:

$$\frac{i_m - i_0}{C_v i_0} = K C_D^{0.75} (s-1)^{1.5} \left(\frac{d}{D}\right)^{-0.6} \left(\frac{v^2}{gD}\right)^{-1.3} \quad (5)$$



(a) $C_v = 10\%$ (b) $C_v = 20\%$

Fig.4 The relationship between additional pipeline loss and *d/D*

5. CONCLUSIONS

(1) The motion states of coarse-grain can be divided into four types with the increasing of transport velocity, i.e. starting movement state, contact movement state, load movement state, suspended movement state. According to the variation of resistance loss versus mean flow velocity, the load movement state has the highest transportation capacity and the lowest resistance loss, which is the ideal state for coarse-grain movement in horizontal pipeline.

(2) In order to build the quantitative relationship between additional loss and the motion state, we introduce additional loss and Fr, and propose a criterion to distinguish motion states in horizontal pipeline. When $(i_m - i_0)/(Cv \times i_0)$>45, the type of movement is mainly the contact movement state and $(i_m - i_0)/(Cv \times i_0)$ decreases sharply with the increase of v^2/gD; When 10⩽$(i_m - i_0)/(Cv \times i_0)$⩽45, the type of movement is mainly the load movement state and $(i_m - i_0)/(Cv \times i_0)$ decreases mildly with the increase of v^2/gD; When $(i_m - i_0)/(Cv \times i_0)$<10, the type of movement is mainly the suspended movement state of motion. At this state, the changes of $(i_m - i_0)/(Cv \times i_0)$ are very small with the increase of v^2/gD.

(3) Considering the factors of additional loss, we establish a quantitative expression of the pipeline addition loss and the velocity and also the particle size. Finally, we establish the formula of additional loss of pipeline.

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