PRESSURE LOSS OF FLEXIBLE HOSE IN DEEP-SEA MINING SYSTEM

Yao Nijun, Cao Bin, Xia Jianxin

College of Life and Environmental Science, Minzu University of China, Beijing 100081, China, jxxia@vip.sina.com.

The flexible hose of deep-sea mining system is an essential part connected to a relay warehouse and mineral collector. Transportation safety and flow characteristics are required strictly because of the complex spatial form. The flow characteristics in flexible pipe were investigated based on the experimental system. The hydraulic gradient of coarse particle slurry in flexible hose increases with the increase of particle volume concentration and mixture velocity, and it decreases with the increase of particle size. This change rule is similar with hydraulic transportation research results in inclined pipeline. In addition, with hose curvature increasing, the particle easily moves in turbulence, and the hydraulic gradient increases. Compared of hydraulic gradient in inclined pipe and flexible hose, the hydraulic gradient computational equations of coarse particles in flexible hose were proposed.

KEY WORDS: Deep-sea Mining; Pressure loss; Flexible hose; Transport parameters.

1. INTRODUCTION

There are abundant mineral deposits in deep seabed, such as manganese nodules, cobalt shell and sulphide massive. From 1970s, more than ten kinds of methods were proposed for deep-sea mining, but the most prospective mining system is the hydraulic lift pipeline and the mining collector, the collector is employed to harvest manganese nodules on the seabed and a series of lifting pumps were installed in the vertical pipeline to lift the nodules to mining ship (Tang et al. 2015, Cai et al. 2016), as shown in Fig.1. This system is mainly composed of rigid pipe, buffer, flexible hose, mining vessel and mining collector. The flexible hose that connects the mining collector and buffer systematically plays an important role in deep-sea mining system, which is used so that the collector can move freely in a certain range and lifting system length can be adjusted in the condition of great topographic relief. The spatial configuration of the hose is complex (Yang and Xia 2000), horizontal, vertical and inclined section could be occurred at the same time, in which the coarse particle is easy to sediment and the hose is easy to be clogged during the transportation.
Fig.1 Deep-sea mining system schematic illustration
(Left: two-phase solid-liquid fluid pipeline lifting system right: possible three-dimensional spatial configuration of flexible hose)

As a critical parameter of pipeline transportation engineering design, pressure loss has received extensive attention from both domestic and foreign scholars. Amount of theoretical and experimental researches have been done around pressure loss. However, scholars mainly carried out researches into single form pipes, for example horizontal pipe, inclined pipe and vertical pipe instead of flexible hose (Fei 1994, Ye 2011, Vlasák et al. 2014, Bagci et al. 2003). Few achievements in transportation parameters of flexible hose various configurations have been reported. Only Yoon et al. (2001, 2002, 2009) designed flexible hose apparatuses to investigate the flow characteristics such as particle size, mixture velocity and two-phase mixture velocity of solid-liquid two-phase mixture in flexible hose. But only spatial configuration of flexible hose was performed, which could not simulate the dynamic changes of flexible hose on deep-sea working conditions.

This research aims to study on pressure drop of flexible hose according to the particle size, particle volume concentration and different miner position based on many experiments.

2. EXPERIMENTAL SYSTEM AND METHODS

2.1. EXPERIMENTAL SYSTEM

The experimental system (Fig.2) is consisted of the following parts: calibration system, solid feeder, pump, pipeline, simulation nodule collector and tanks. The pipeline is 25m in length and 50mm in diameter consisting of a flexible 10m long hose. The flexible hose is placed in a tank whose dimensions are 8×1.5×2 m. Calibration system is employed to determine flow rate and solid concentration. Particles are putted to the system uniformly by mean of a solid feeder. The pump rotation speed can be adjusted by frequency conversion.
Pressure meters were set up at both ends of flexible hose to measure hydraulic gradient. The flexible hose was designed to be able to observe the flow phenomenon of the solids in the hose. Two buoyancy balls were installed at (0.5 – 0.75) L of the flexible hose (L is total length of the flexible hose). Flexible hose is connected to simulation nodule collector, which moves at a special speed on the bottom of the tank to simulate the spatial shape of flexible caused by mining collector in practical working conditions.

The liquid phase used in the experiment is clear water, and the solid phase is quartz sand. The experiments are conducted with particle size in 1mm, 3mm and 5mm, respectively. The transportation volume concentration is 5%, 10% and 15%, respectively. Solid particle sizes are sorted by sieves in international standard. As for flexible hose shape, the moving distance of miners S=0m and S=0.5m were taken into experiment.

2.2. EXPERIMENTAL METHODS

The experimental procedures can be summarized in the following steps: firstly, the water tanks are filled with water, and using motor controller to control mining collector moving on the bottom of the tank, at the same time, the spatial shape of flexible hose is recorded. Then, start the pump to make system running. Next, run the solid feeder and the particles were fed to the pipe system. Two high precision waterproofs pressure meters were set at both sides of the flexible hose to measure the pressure change of hose and study on the change of pressure loss.

3. EXPERIMENTAL RESULTS

As the most important parameter of pipeline transportation, pressure loss is a key reference for pump design. The internal mechanism of solid-liquid two-phase flow pressure loss in pipeline transportation is energy loss. This energy loss mainly appears in on-way resistance pressure drop (hydraulic gradient) (Cheng 2008). The pressure loss in pipeline mainly includes: 1. Friction loss of carrier (liquid phase) and pipe wall. 2. Energy loss caused by particle collision. 3. Energy loss or addition due to lifting or dropping solid materials. This paper studied hydraulic gradient in different particle diameters, volume concentration, velocities of mixture and different shape of flexible hose. The hydraulic gradient in this experiment was defined as total pressure drop divided by total length of flexible hose.
Fig. 3 Relationship between hydraulic gradient and mean mixture velocity in different particles volume concentrations

As shown in Fig. 3, with the volume concentration of particle increases, the hydraulic gradient of flexible hose increases, respectively. The thought here is that increase of volume concentration means increase of particle quantity for single diameter particles, which means more energy consumed to transfer particles from the static into a state of motion or maintain particles’ constant motion state. This phenomenon is consistent with various results on horizontal and incline pipelines hydraulic transportation researches.

Fig. 4 Relationship between hydraulic gradient and mean mixture velocity in different diameter particles
Fig. 4 shows that hydraulic gradient of flexible hose has a close relation with particles diameter. With the decreasing of particle diameter, hydraulic gradient increases, respectively. This is because under condition of one volume concentration, the smaller diameter is, the greater quantity of solid particle has. It means more probability of particle collision and friction. So the energy loss would be increase. On the contrary, this probability would be decrease along with increase of particles size, and the energy loss would be decrease compared with small diameter particles.

In Fig. 5, it is shows that as the collector moving distance increase, the hydraulic gradient will increase also, that is to say, hydraulic gradient increase with hose curvature and rise height increases. Flexible hose is divided to 3 sections: inclined upward section, curve section and inclined downward section due to flexibility of hose. As for inclined upward section, the component force of effective gravity in the coarse particles movement direction increases with the dip increase, and particle is easy to get into suspension state, that is, friction effect of coarse particle with tube wall and particles mutual collision and friction would be weakened, meanwhile the influence of gravity to pressure loss would be strengthen. As for inclined downward section, because coarse particle move from high to low, potential energy would be transformed into kinetic energy. So, solid-liquid two-phase
flow pressure loss decreases with hose dip increases. As for curve section, line of force, force direction and motion mechanism of particle materials change drastically, which cause turbulence and addition to pressure loss. In general, the hydraulic gradient increase with the distance of mining collector movement increase, hose curvature increase and both sides of hose droop.

4. RESULTS DISCUSSION

Flexible hose transporting part has 2 important functions. On the one hands, using hose to lift the nodules to buffer, on the other hand, guaranteeing the free motion of the mining collector by its variable spatial configuration. Therefore, shape of flexible hose is complex dropped or rose, but generally there is an upward distance from inlet to outlet. Due to inclination angle changes in different section of flexible hose and it can’t be precisely measured in practical mining process. Determined \( L_r \) is hose length from the start to vault, \( L_z \) is hose straight distance from the start to vault, is the horizontal inclination of the \( L_z \). When investigating pressure loss of flexible hose, compared it to the inclined pipe whose length is \( L_z \), rake is.

2.1. HYDRAULIC GRADIENT OF INCLINE STRAIGHT PIPE

Currently, there have been many studies on the hydraulic gradient of slurry transportation in incline pipe. Pavel et al., 2014 presented physical model with the flow characteristics of coarse particles in horizontal pipe and inclined pipe with different volume, different volume concentration and different velocity, and the results are similar to Kao et al., 1967’s result, which is hydraulic gradient increase with pipe inclination angle increases when the pipe inclination angle is less than 30°, but hydraulic gradient decrease with pipe inclination angle increases when it is more than 30°. Based on these research results in inclined pipe, Peng et al., 2015 proposed a formula to calculate hydraulic gradient of inclined straight pipe.

\[
\begin{align*}
    i_m &= i_0 + C_v (s - 1) \sin \theta + 82C_D i_0 \left[ \frac{v^2 C_v}{g D (s - 1)} \right]^{1.5} \cos \theta
\end{align*}
\]

In which \( i_m \) is two-phase flow hydraulic gradient, \( i_0 \) is water friction loss, \( C_v \) is volume concentration, \( s \) is the proportion of solid-liquid two-phase density, \( \theta \) is the inclination angle (take tilted up positive, take tilted down negative), \( v \) is two-phase flow average velocity, \( C_D \) is resistance coefficient, on the condition of this experiment \( C_D = 0.51 \), \( g \) is gravitational acceleration, \( D \) is the pipe diameter.

The second term on the right side is the hydraulic gradient due to the solid potential energy, and the third term on the right side is hydraulic gradient due to the particle collision. While particle size larger(\( d \geq 1\text{mm} \)) and carrier is water, the addition of solid has few effect on the viscosity of the water, in this situation the hydraulic gradient of carrier is calculated by Darcy-Weisbach formula:

\[
    i_0 = \frac{\xi L_f v^2}{2gD}
\]
In which, $\xi$ is additional friction coefficient (when traction load exists, $\xi = 1.08$; when the water is filled, $\xi = 1$); $\lambda_f$ is coefficient of friction resistance, on the condition of this experiment $\lambda_f = 0.0525$.

2.2. HYDRAULIC GRADIENT OF FLEXIBLE HOSE

Based on formula (1) and (2), compared of hydraulic gradient in inclined pipe and flexible hose, the hydraulic gradient equation in flexible hose was proposed:

\[
\frac{i_r - i_m}{i_m} = 0.097C_v^{0.02} \left( \frac{L_c - L_z}{L_z} \right)^{-0.057} \left( \frac{d}{D} \right)^{-0.008} \left( \frac{v^2}{gD} \right)^{-0.142}
\]

(3)

In which, $i_r$ is hydraulic gradient of flexible hose, $i_m$ is hydraulic gradient of inclined pipe, $L_c$ is length of inclined pipe, $L_z$ is length of flexible pipe. $L_c - L_z$ on the right side showed the effect of hose shape on hydraulic gradient, $\frac{d}{D}$ showed the effect of particle diameter and pipe diameter on hydraulic gradient, $\frac{v^2}{gD}$ showed the pressure loss of particle collision.

Figure 6 is the comparison of the experimental and numerical results. As considering various factors in flexible hose, the average value of relative error ± 1.6%.

![Fig.6 Comparison between the experimental and numerical results](image)

5. CONCLUSIONS

Hydraulic gradient change regulation was analyzed with different particle sizes, different particle volume concentrations, different mixture velocities and different flexible spatial shape based on experimental results conducted. There is relativity between hydraulic gradient in flexible hose, horizontal and vertical pipes. It is confirmed that the hydraulic gradient increases as the particle volume concentration increases or particle size increases, respectively. The hydraulic gradient increases with mixture velocity increases. Besides, the hydraulic gradient increases as the more curved the flexible is.

Derived a formula for an empirical relationship between hydraulic gradient with flexible hose and hydraulic gradient with inclined pipe, and proposed optimization method of deep sea hose transportation. During the deep-sea mining, in order to avoid clogging and reduce energy consumption, transportation parameters of flexible hose should be controlled according to different mining areas.
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