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Study on Air-Aided Transport Means of Cutter-Suction Dredger

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Abstract: This study proves the effectiveness of air-aided transport in reducing pipeline resistance and lengthening transport distance. The adopted experimental apparatus is unique in its chosen pipes (120 mm), transmission mediums (including clean water and slurries concentrated at 10, 20 and 30%, respectively) and experiment comparisons between air-aided transport and traditional relay pump transport. Factors such as resistance, transport distance and energy consumption are compared through the data from laboratory experiments, thus proving the evident advantages from air-aided transport. The total energy consumption in air-aided transport is less than that of relay pump, especially within its resistance reducing scope, where slurry flow ranges from $65m^3/h$ to $90\ m^3/h$. It also exists within resistance reducing scope where slurry flow of air-aided transport is less than that of relay pump transport and may reach its limited effective distance. Thus, the findings of this study can provide valuable insight for the optimization design of air-aided transport of cutter-suction dredger.

Keywords: Air-aided transport, dredger pipeline, energy consumption, relay pump transport

INTRODUCTION

In dredging projects, cutter-suction dredger transport sand-slurry mixture, a mixture of solid and liquid through long pipeline. This technique has many advantages such as longer transport distance, few auxiliary equipments, low expenditure and simple operation (Bray *et al*., 2007; Shen, 2010). However, as the dense slurry flows slow in large quantities and easily gets separated into solid and liquid, such transport is prone to strong resistance, high energy consumption and easy blockage, resulting in projects delay and increased costs for corresponding breakdown, maintenance and cleansing. As for the advantages and disadvantages above, researchers are working on to find effective techniques and new transportation equipments (Tao *et al*., 2006).

In recent years, gas injection on the pipeline transport of slurries has made fast progress, which started originally in chemical industry rather than in dredging projects and was mainly applied to transport high-concentration slurries. Lockhart and Martinelli (1949) first put forward injecting gas to the pipe. But they found gas injection had increased the pressure gradient in pipeline, in other words, gas injection had increased pipeline resistance. Afterwards, a sequence of related experiments was conducted by scholars and demonstrated that gas injection would result in resistance climbing. In late 1970s some scholars pointed out that gas injection would reduce the resistance if shear-thinning or pseudo-homogeneous slurries took the form of slug flow. Such phenomenon was first found out by Ward and Dallavalle and then by Oliver and Young-Hoon (1968). Similar finding also appeared when Mahalingam and Valle transported different types of Kaolin clay and trass. Farooqi and Richardson (1982) also made researches on pressure drop analysis of two-phase gas-liquid flow in smooth horizontal pipes. They divided the two-phase gas-liquid flow into four types and built corresponding mathematical models to evaluate the effect of gas on pressure gradient in the pipes. Heywood and Charles (1980) explored the effect of the two-phase flow between gas and non-Newtonian liquid on flow resistance in pipes, compared its pressure gradient with that of the one-phase liquid flow and offered resistance-reducing indicator in gas injection.

Subsequently, Heywood and Richardson made further researches on it (Farooqi *et al*., 1980; Heywood and Charles, 1980; Heywood and Richardson, 1981; Heywood, 1999; Heywood and Alderman, 2003). Their gas injection researches were made on both horizontal and vertical pipes, including layer flow, turbulent flow, slug flow and laminated flow.

In 2005, another systemic research was conducted by Aluf (2005). He made improvement based on the models of Farooqi *et al*. (1980), turning the two-phase flow into the three-phase one and taking into consideration solids' settling and their fluidized beds' sliding at the bottom of pipes. He successfully

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established the first mathematical model applicable to gas-injected transport of both settling and non-settling Newtonian slurries, with larger scope of application compared to models in literature. His research comes to the conclusion that gas injection, whether for Newtonian or non-Newtonian slurries, reduces resistance in laminar conditions and turbulent conditions. What is more, there exists a critical value for slurry velocity (transport speed). The closer it is to the value, the better effect the resistance reduction has and the further the worse effect.

To sum up, previous researches mainly focus on small pipe diameter (smaller than 50 mm) and reach no consensus despite some empirical equations for resistance calculation. Because dredger projects usually choose large pipe diameter and slurries are prone to settle in pipes, previous researches cannot be applied to real dredger projects.

To overcome the problem mentioned above, this study aims to investigate the resistance calculation and reduction effect using the gas injection in large diameter pipes. Experimental apparatuses for large pipe diameter are established to demonstrate the advantages of adopting gas injection in slurry transport. And this study chooses the experimental data of 120 mm pipe diameter for introduction. In the experiments, two transport methods in dredging projects are tested, one being the proposed gas injection transport and the other being commonly applied relay pump transport. The experimental results show the resistance change in gas injection transport. After offering the comparative analysis between the two methods in the terms of energy consumption, this study proposes their corresponding applicable scopes and makes the conclusion that air-aided transport can effectively reduce the gross energy consumption especially within its resistance reducing scope, where slurry flow ranges from 65 m^3/h to 90 m^3/h.

MECHANISM ANALYSIS OF AIR-AIDED TRANSPORT

In traditional dredging projects, slurry takes a two-phase flow of both solid and liquid with an approximate concentration at 25 percent, similar to chemical liquids in pipelines. After the gas is injected, great changes take place in inner slurry organization. The mechanism is reflected in the following two aspects:

- After the injection of a certain amount of gas to the two-phase flow of solid and liquid, on the one hand, it intensifies turbulent fluctuation in water flow and destructs inner close-knitted flocculation in slurry. Tiny gas bubbles permeate through grains, layers and pipe surfaces, reducing friction in inner slurry and shearing stress on the pipe wall, on the other hand, vaporous bubbles involve in turbulent fluctuation, break up and float upwards. They deter solid particles from sinking and push upward thicker particles lying at the pipe bottom, to the effect of evenly distribution of density and participles along the vertical pipe. As a result, fewer particles meet the pipe surface and transport resistance is greatly decreased (Yang and Qian, 1986).
- After gas injection, a closed water membrane circle is formed above the pipe wall and lubricates it. As the mass concentration, viscosity and flow speed have a gradient decrease, shearing stress on the surface of boundary layer decreases and results in a lower resistance.

Regarding certain slurry and its speed, there are optimum values for gas injection amount and corresponding gas pressure. It is generally acknowledged that under the circumstance of high concentration and slow flow, appropriate air injection can reach a good resistance-reducing effect. But with concentration lowering and flow speeding, the effect above becomes less evident. This phenomenon can be explained as gas membrane formed in inner boundary layer improves the slurry flow and thereby destructs slurry flocculation (Wang, 1994).

EXPERIMENTAL APPARATUS DESIGN

According to resistance-reducing mechanism of air-aided transport, this study puts forward a design for air-aided transport apparatus with consideration to practical needs in dredging projects. The design sets the slurry pump as the main motor. It first formulates the two-phase flow and then injects air to pipeline by air compressor. The design transports mainly liquid with air as an auxiliary force.

Air aided transport system: The experimental apparatus is shown diagrammatically in Fig. 1. There are two sets of experimental pipelines, with diameters of 219 mm and 120 mm. The total length of the experimental pipes is 150 m. Two experimental pipelines share a slurry pool (T) with a volume of 12 m^3. In order to make the slurry fully suspend, an agitator pump (B3) is used to mix the slurry. Liquid can be withdrawn from pool to pipelines made of 90 mm and 219 mm internal diameter steel tubes by a centrifugal pump (B1). The liquid flow is measured by an electromagnetic flow meter (C1). Air is supplied from a compressor (E), controlled by valve and measured by an airflow meter (C2) and two electronic pressure transducers (P13, P14). The air temperature is measured by a thermistor (T1, T2). The air is injected into the liquid in the pipeline through a swirling jet device (J). The injector connects with two air pipes and a jet pipe connecting a jet pump (B2), as shown in

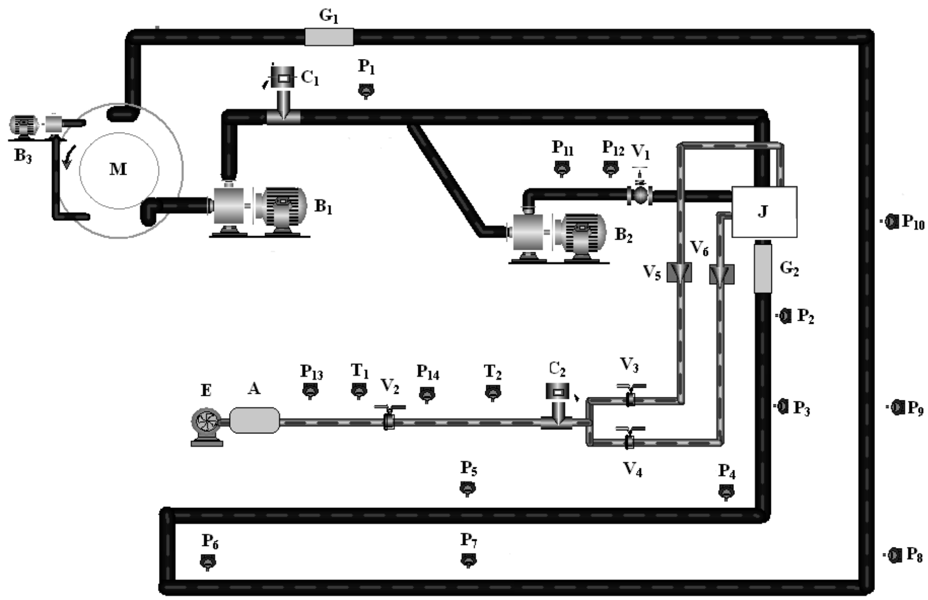

Fig. 1: Hydraulic circuit of the pipeline apparatus; A-air tank; B1-primary pump; B2-jet pump; B3-agitator pump; C1-electromagnetic flow meter; C2-air flow meter; E-compressor; G1,G2-transparent glass pipes; J-air injector; M-slurry pool; P1 to P14-pressure transducers; T1,T2-temperature sensors; V1-ball valve; V2-pressure relief valve; V3,V4-valves; V5,V6-Single-phase Valves

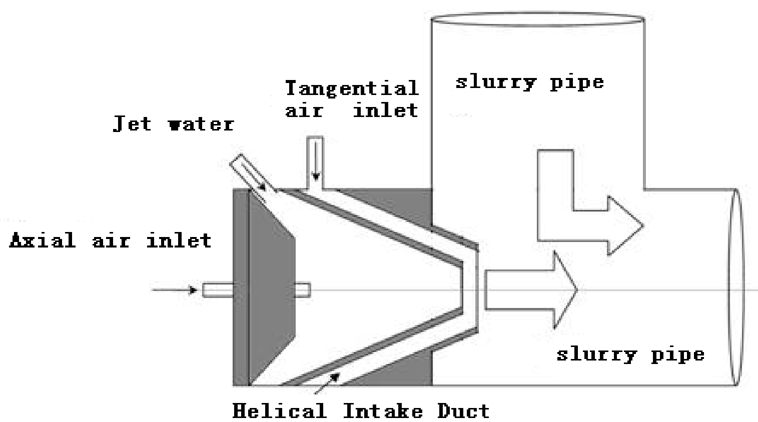

Fig. 2: Structure diagram of air injector

Fig. 2. The jet device can promote homogeneous mixing of air and mud. The pressures in pipeline are measured by twelve pressure transducers in locations P1to P12. The flow patterns can be observed through two transparent glass pipes (G1, G2).

Relay pumps transport system: In order to make a comprehensive comparison between air-aided transports and relay pump transport, a relay pump transport system is also designed. The experimental apparatus of relay pump, shown in Fig. 3, is as same as hydraulic circuit of the pipeline apparatus in Fig. 1, except for B4, i.e., the air-aided system replaced by relay pump.

EXPERIMENTAL METHODS

All of the key factors below, such as slurry concentration, flow rate, air injection methods and air pressure, are differently chosen to experiment the pressure of pipeline. And the relevant analysis is made from the aspect of impact of above various parameters on pipeline pressure gradient (Aluf, 2007). The chosen data in the experiment for the slurry volume concentration and flow-rate come from the real dredging projects. This study makes research on reducing slurry resistance in pipelines due to air injection. Transmission mediums are clean water and slurries concentrated at 10, 20 and 30%, respectively.

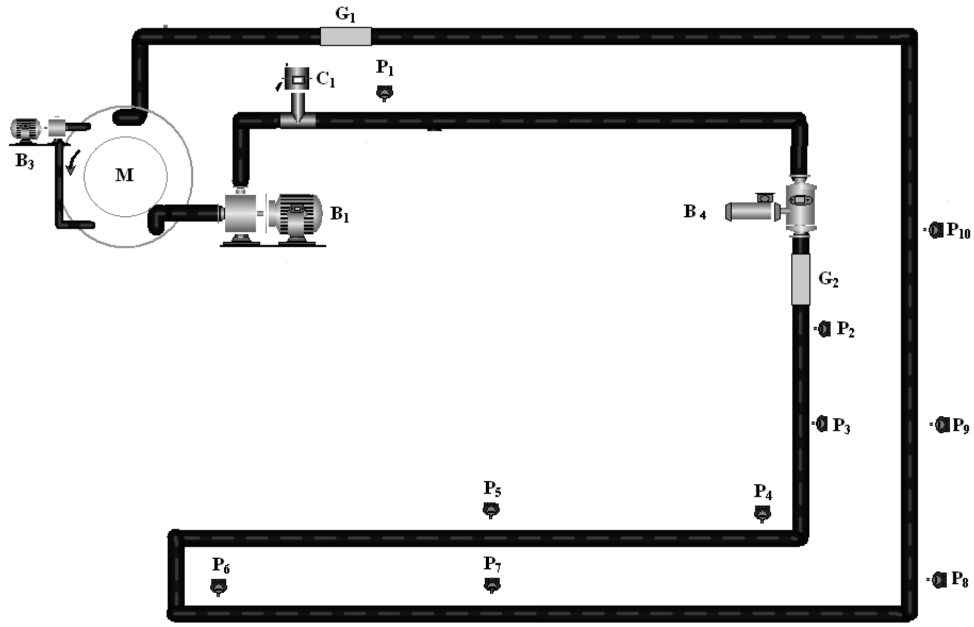

Fig. 3: Relay pump transport system

Experiments with air aided transport: Pressure gradients are measured in pipelines at various flow rates of slurry and the flow rate is adjusted by frequency conversion motor of main pump from 150 m^3/h to 400 m^3/h. Initial measurements are obtained when there is only slurry without air injection. Then air is injected into the slurry at flow rate ranging from 2 m^3/h to 13 m^3/h and is measured at the injection point. The additional pressure data is collected by using pressure sensor P1 to P14.

In each experiment, after the liquid flow and air flow have been adjusted to the set values, the combined flows are allowed to stabilize for a period which equals to the mean transit time of the fluid mixture through the apparatus, plus an additional 1 minute. Thereafter, pressure and flow data is collected by pressure sensor every 1 second among 180 sec before the air and/or liquid flow is adjusted. The liquid temperature remains the range from 10°C to 25°C.

Comparative experiments between air-aided transport and relay pump transport: The comparative experiments choose same concentration of the same slurry, set equal transport distance for both the air-aided transport and relay pump transport and make corresponding indoor simulation for means above. The experiments measure energy consumption and calculate related efficiency to compare their energy saving. Given different slurry properties and concentration, the experiments have been conducted accordingly. Thus the experiments results show how the energy is saved based on energy consumption and related efficiency changes by slurry properties and concentration.

RESISTANCE CHARACTERISTIC ANALYSIS

The experiments based on above stated design have collected data for flows of clean water and slurries concentrated at 10, 20 and 30%, respectively, for gas flow and for pipeline pressure. These data can be used to analyze the resistance characteristics. In industrial application, pipeline pressure gradient is usually used to evaluate the pipeline resistance coefficient. When pressure gradient increases, the internal pressure of pipes will have an evident drop and pipeline resistance coefficient will be on the increase and vice versa. How pressure gradient relates with gas flow, slurry concentration and transport distance can help to identify the influence of air-aided transport on pipeline resistance characteristics. Their relationships are respectively shown as follows.

Relation between pressure gradient and gas flow: Speed of gas flow in pipe is a crucial factor for pressure gradient. Experiments show that resistance reduction has a better effect in air-aided transport when slurry is concentrated at 30%. With 30% as the slurry concentration, relation between pressure gradient and superficial gas velocity is shown as Fig. 4.

As shown in Fig. 4, pressure gradient first climbs up and then down as gas is injected. There is in gas amount a critical point, where exerts the best influence on resistance. After the point, the pipeline resistance intensifies as pressure gradient rises. As the motor frequency of main pump gradually increases, that is, as the pressure gradient gradually increases, resistance intensifies too. Therefore, it can be concluded that there will be a better effect on reducing resistance if the

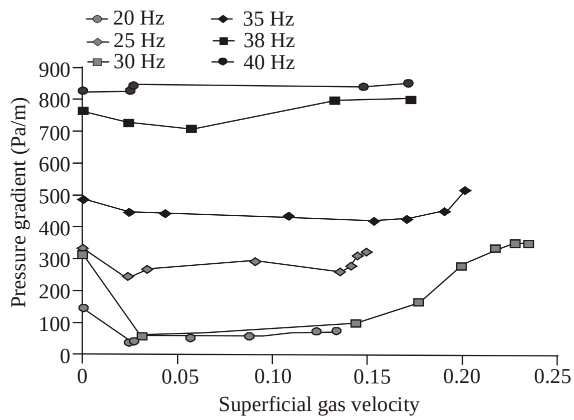

Fig. 4: Relation between pressure gradient and superficial gas velocity under different frequencies of main pump

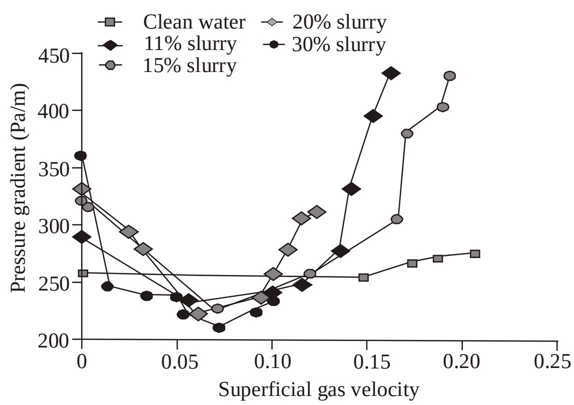

Fig. 5: Relation between pressure gradient and superficial gas velocity under different slurry concentrations

slurry flow is at a low speed in pipe. Such conclusion is consistent with that of theoretical research by Aluf (2007).

Relation between pressure gradient and slurry concentration: Research also shows that slurry concentration is another crucial factor. Thus this study analyzes the cases under different concentrations of slurry with same flows. Take the example of 35 Hz setting for the frequency of main pump, relation between pressure gradient and superficial gas velocity is shown in Fig. 5. As shown in Fig. 5, at the same speed of slurry flow and with increasingly dense slurry, pressure gradient gradually increases without air injection, but gradually decreases with air injection. It is noted that pressure gradient curve of slurry is greatly different from that of clean water. In the case of clean water, no apparent effect is seen on resistance reducing after air injection, since pressure gradient climbs in step with gas speed. However, a turning point appears in the curve when slurry concentration increases and the resistance reduction increase in air-aided transport as

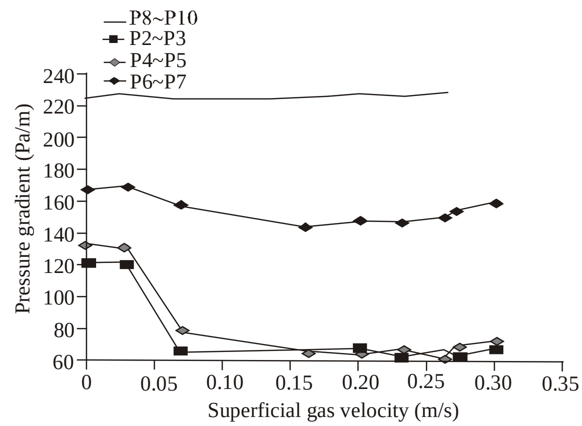

Fig. 6: Relation between pressure gradient and superficial gas velocity in different spots of pipe

concentration climbs. Such phenomenon accords with the reported in Bjerkholt *et al*. (2005), where high slurry concentration offers a high possibility of resistance reducing. Comparison of different slurry concentrations in the pressure gradient curve shows that resistance force reaches the least when the slurry concentration is 30%. There is an optimal gas speed at which slurry transport has the least resistance. It turns out to the critical speeds can reach among the scope between 0.05 m/s and 0.1 m/s under different slurry concentrations.

Relation between pressure gradient and transport distance: Dredging projects usually require long distance transportation, sometimes up to dozens of kilometers. Due to its much lower density than slurry, gas is inclined to change its state in pipe during the period of long distance transportation. Therefore, it is necessary to make analysis of pressure data in different parts of pipes, which is neglected by existed research but is given into consideration in this experiment. From the experimental apparatuses, ten spots have been chosen for pressure experiment and the pipes have been divided into four vertical ones. The corresponding distances of these four vertical pipes are respectively 15.38 m between pressure sensor P2 and P3, 15 m between P4 and P5, 12 m between P6 and P7 and 27.55 m between P8 and P10. The relation between pressure gradient and superficial gas velocity is shown in Fig. 6.

As shown in Fig. 6, the first two pipes P2~ P3 and P4 ~ P5 go through evident pressure drops, but as the distance extends, pressure drop diminishes. The last pipe P8 ~ P10 almost has no evident pressure drop, which manifests that distance weakens the effect on resistance reducing in air-aided transport. The extension of distance results in separation of gas and liquid. Tiny bubbles accumulate into big gas bubbles and then float in the pipeline. The smooth flow of gas-liquid mixture turns into slug flow and finally gas separates from liquid. The increasing friction in pipe weakens the effect on resistance reducing.

It can be concluded from results of the different experiments that low flow speed and high slurry concentration ensures a marked effect on resistance reducing, which is meanwhile limited by transport distance.

ANALYSIS OF TRANSPORT DISTANCE AND ENERGY CONSUMPTION

In view of the ultimate purpose in this experiment to reduce energy consumption of cutter-suction dredger, energy consumption analysis is necessary to be made in air-aided transport and so is comparative analysis on energy consumption between air-aided transport and relay pump transport. Experiments on air-aided transport and relay pump transport have been respectively conducted so as to compare their advantages and disadvantages. Corresponding figures have been calculated for the comparative analysis of transport distance and energy consumption.

Comparative analysis of transport distance: In dredging projects, transport distance often receives special consideration and accordingly the ultimate goal of this study also is to lengthen the transport distance of cutter suction dredger. Transport distance can be calculated in the following formula after related calculation of pressure loss and pressure gradient:

$$H_Z = H_r + H_c + H_h \tag{1}$$

where,
H_z = The total head of dredger
H_r = The suction head
H_h = The height head
H_c = The distance head

The distance head equals pipeline pressure drop and can be expressed by Eq. (2):

$$H_c = \gamma \cdot \lambda \cdot \frac{L}{D} \cdot \frac{v^2}{2g} \tag{2}$$

where,
γ = The specific gravity of slurry
λ = The drag coefficient
v = The slurry velocity
L = The pipe length
D = The pipe diameter

Transport distance L_1 in common transportation can be calculated by Eq. (1) and (2):

$$L_1 = \frac{H_Z - H_r - H_h}{\lambda \cdot \gamma} \cdot \frac{D \cdot 2g}{v^2} \tag{3}$$

In air-aided transport, air compressor injects air into the pipe and brings about energy. For the sake of convenient calculation, this study chooses the conversion head, represented by $H_z^{/}$, to calculate the energy brought about by the air compressor. Here, transport distance is expressed in Eq. (4):

$$L_2 = \frac{H_z^{/} - H_r - H_h}{\lambda \cdot \gamma} \cdot \frac{D \cdot 2g}{v^2} \tag{4}$$

where,
$H_z^{/}$ = The conversion head in the air-aided transport and can be calculated in Eq. (5):

$$N \cdot \eta + K \cdot \eta^{/} = \frac{\rho^{/} Q^{/} H_Z^{/}}{102} \tag{5}$$

where,
$\rho^{/}$ = The mixed density of air and slurry
$Q^{/}$ = The mixed flow of air and slurry
N =The efficiency of the main slurry pump
η = The efficiency of the main slurry pump
K = The efficiency of the air compressors
$\eta^{/}$ = The efficiency of the air compressors

Transport distance L_3 in relay pump transport can be calculated by Eq. (6):

$$L_3 = \frac{H_j + H_Z - H_r - H_h}{\lambda \cdot \gamma} \cdot \frac{D \cdot 2g}{v^2} \tag{6}$$

where,
H_j = The head of relay pump.

Based on Eq. (3), (4) and (6), as well as a comprehensive comparison with ordinary transportation, the transport distances are graphed in Fig. 7 from angles of air-aided transport and relay pump transport.

As shown in Fig. 7, both air-aided and relay pump transport have longer transport distance. Besides, under same amount of flow, air-aided transport longer than relay pump transport in its resistance reducing scope while the situation goes to opposite direction beyond the scope.

Comparative analysis of energy consumption: Energy consumption in air-aided transport in theory comprises energy consumption of main pump and air compressor. Given intermittent process of air compressor, the experiment connects a three-phase watt-hour meter with air compressor in series to evaluate the total consumption in a certain working period of air compressor. Since air-aided transport experiment is carried out independently from relay pump transport experiment, it is not convenient to

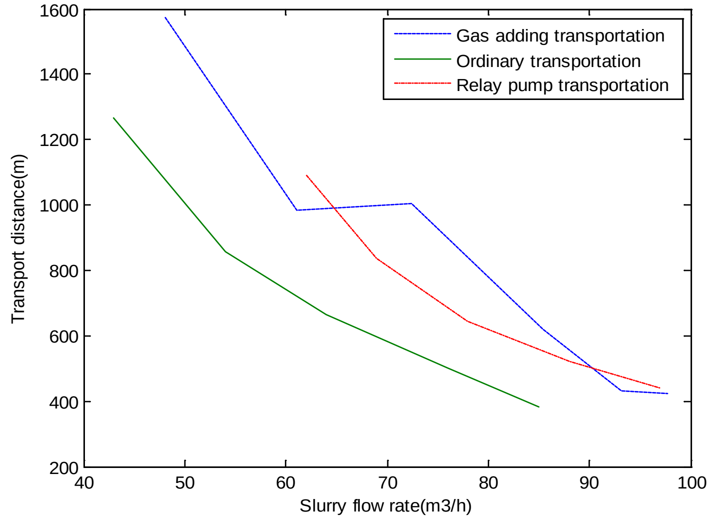

Fig. 7: Transport distance in different transport means

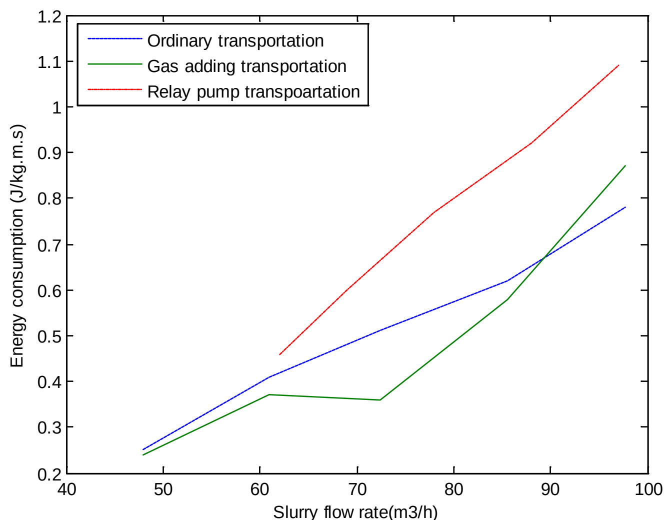

Fig. 8: Unit energy consumption in different transport means

compare their total energy consumption. Hence, unit energy consumption is applied to make comparison. It means the energy consumed in transporting unit mass slurry to unit distance within unit time. Unit energy consumption has the formulas like Eq. (7) and (8) and its base unit is J/ kg/m/s.

$$EC_1 = \frac{N \times t + E_k}{Q \times q \times t \times L_2} \tag{7}$$

$$EC_2 = \frac{N + N_j}{Q \times q \times L_3} \tag{8}$$

where,

EC_1 = The unit energy consumption of air-aided transport

EC_2 = The unit energy consumption of relay pump transport

E_k = The energy consumption of the air compressors

q = The density of slurry

A comprehensive analysis of unit energy consumption among ordinary transportation, relay pump transport and air-aided transport is shown in Fig. 8.

As shown in Fig. 8, under the same amount of slurry flow, air-aided transport exhibits less unit energy consumption than that of both ordinary and relay pump. Especially in its resistance reducing scope, air-aided transport shows unit energy consumption less than 50% that of relay pump. Obviously, it is economical to adopt air-aided means under such circumstances.

CONCLUSION

Regarding the existing problems of slurry transport for cutter-suction dredger, this study puts forward the solution of air-aided transport. It conducts researches on effect of air injection on pipeline resistance, makes an all-round experiment design and finally makes the following conclusions after comparison between indicators for air-aided transport and relay pump transport commonly applied in projects.

Air-aided transport exerts better effect on resistance reducing and increases the slurry concentration in the case of high slurry concentration and low slurry flow, but worse effect on resistance reducing in the case of low slurry concentration and high slurry flow. There are various optimal slurry flow and optimal gas flow regarding different experiment conditions.

Air-aided means works effectively for transportation of high concentration slurry. In this case, air-aided transport consumes less total energy than relay pump transport, especially far less within its resistance reducing scope. But it transports less amount of slurry than relay pump transport and is also limited in terms of effective distance.

The above conclusions are based on pipeline experiments. The instantaneous concentration of slurry has not been monitored and it is also not clear how different slurry concentrations scatter along the pipeline. Therefore, the analyzed data in this study are based on the average slurry concentration and there may be some deviations. The future research plans to improve the experimental accuracy by adopting Electrical Capacitance Tomography (ECT) system to monitor the instantaneous concentration of slurry. To sum up and based on experiments, air-aided transport is suitable for projects in cities demanding pollution-free and low energy consumption, while relay pump transport is suitable for projects featuring urgent time limit and long transport distance.

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