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Hydraulic transport of sand-water mixtures in pipelines Part I. Experiment †

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Abstract

The hydraulic transport characteristics of sand-water mixtures in circular and square pipelines are experimentally investigated by changing the Reynolds number and volumetric delivered concentration. The hydraulic gradients are increased along with the Reynolds number. When the mean velocity is larger than the critical velocity, the hydraulic gradient of sand-water mixture in the square duct is larger than that in the circular pipe. The deposition-limit velocity in the square duct is smaller than that in the circular pipe. Thus, it can be concluded that the square duct transports sands more effectively than the circular pipe in a low operating range of velocity. The empirical correlation between the hydraulic gradient and the Reynolds number is obtained. It is believed that the present data and empirical equation can be used to validate the numerical methods developed for the analysis of the transport characteristics of slurry in the circular and square pipelines.

Keywords: Slurry flow; Sand-water mixture; Hydraulic transport; Experiments; Deposit-limit velocity

1. Introduction

The hydraulic transport of solids in pipelines has been used in chemical and waste-disposal industries such as, in mining and dredging, to move large amounts of solids in long distances. Both time and pumping power required for hydraulically transporting huge amounts of soils in a state of slurry (sand-water mixture) are crucial factors for successful dredging and reclaiming projects [1]. Thus, the main concern of this research is to focus on the reduction of the enormous energy required for the hydraulic transportation of solids. There are several methods for reducing the required power such as the addition of polymer solution or the use of helical ribs inside the pipes. The helical flow supports the suspended solid particles floating inside the pipe flow and helps the sands on the bed to be lifted and floated again. It has an effect of reducing the deposition-limit velocity and the frictional loss. However, high initial costs and frequent maintenance problems put the limitations on using the helical ribs [1]. Thus, the design of an efficient hydraulic transport system is required to reduce fundamentally the cost of the power consumed in pumping the slurry. The effective design and operation of the hydraulic transport system requires the reliable estimation of pressure drop in the pipeline.

In the general fluid flow, the working flow is mainly dependent on the fluid density and viscosity. However, the sand-water mixture flow is not only dominated by the physical properties of the working fluid itself, but it is also dependent on the kinds, sizes, and concentration distributions of solid particles, and the mixture ratios between the solid particles and the fluid. The various governing parameters do not allow an easy prediction. The first predictive tools were developed in the 1950s as a form of empirical correla-

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tions to predict the basic slurry pipeline characteristics such as frictional head loss and deposition-limit velocity. Durand and Condolios [2] constructed a popular model that is still in use in industrial fields. It focuses on the prediction of frictional head loss due to the solid particles in the internal flow by introducing the concept of the critical deposit velocity required for setting the maximum efficient operation condition. Turian and Yuan [3] developed a set of empirical correlations for various slurry flow patterns by summarizing their measured data (a total of 936) and the data in the published literature (a total of 1,912). Wilson [4] introduced a semi-empirical model for a heterogeneous flow in pipelines. Since the mid 1980s, a general model for solid-liquid flow in pipelines has been constructed using a microscopic approach. An infinitesimal control volume of slurry is assumed, and the governing equations for the control volume are derived as a set of differential equations for conservation of mass, momentum, and energy. Roco and Shook [5], Hsu *et al*. [6], and Shook and Roco [7] developed models considering the interaction between the phases within a slurry stream.

Macroscopic modeling techniques were also developed by applying the conservation equations to a larger control volume of slurry with approximated uniform concentration of solids. Newitt *et al*. [8] obtained friction-loss equations for several slurry flow regimes. Wilson [9, 10] introduced the concept of a mechanic force-balance model to find the limit velocity of stationary deposition in a fully-stratified flow. Matousek [11-13] measured the velocity profiles and concentration distributions and verified the validity of the two-layer model suggested by Wilson [10]. Gilles *et al*. [14] calculated the required energy to transport the solid particles in the laminar flow. Gilles and Shook [15] extended the two-layer model to the 35% concentration by considering the increase in the friction head loss due to the solid-particle concentration. Sundqvist [16] analyzed the effect of solid-particle concentration on the friction head loss by using various sizes of sands. It was found that the friction head loss due to the velocity change in the thick solid-particle concentration distribution is larger than that in the thin concentration distribution. Sahaan *et al*. [17] found that the shapes of solid particles do not affect the friction head loss. Most literatures have been focused on the hydraulic transport phenomenon in the circular pipes.

Chiu and Seman [18] reported that square ducts may be more efficient than the circular pipes due to the secondary flow formation. Prasad *et al*. [19] compared the head loss between a circular pipe and a rectangular duct. They performed the test by changing the aspect ratios of the duct while maintaining its cross-sectional area. They found that the duct has better performance in the operating range of a slow velocity. Karabelas [20] derived a closed-form expression for predicting the solid concentration profiles in the turbulent core of the rectangular ducts for dilute suspensions. Recently, Kaushal *et al*. [21, 22] found that Karabelas' model [20] for the rectangular ducts shows a good agreement with the experimental data.

The hydraulic transport characteristics of solid-water mixtures in the pipelines have not been well understood despite the large number of published literatures due to the intrinsic theoretical and experimental limitations. Experimental study is limited by the required huge size and cost of testing facilities with long pipelines of large diameters. Most experiments have been performed under laboratory conditions characterized by short pipeline length, small pipeline diameter, and steady flow conditions. Thus, the empirical models work well only in the specific flow conditions where the experiments are performed [1]. The lack and uncertainty of theory describing the microscopic processes in the solid-liquid flow is also a drawback to the development of powerful prediction tools. Moreover, the required complex computational scheme and computing costs make the model unattractive in practical use.

In the present study, the performances of circular and square pipelines are investigated to provide necessary data for the validation of the numerical study in the next publication. The present study is mainly focused on the heterogeneous and homogeneous flow regimes. Both friction head loss and deposition limit velocity of the sand-water mixture flows are measured by changing the mean velocity and the volumetric delivered concentration. The effect of the secondary flow in the square duct is discussed with regard to the reduction in the hydraulic gradient and the deposition-limit velocity.

2. Experiments and parameters

2.1 Performance parameters

The definitions and notations in the present section are adopted from Ref. 1 and Ref. 23. The mean velocity (V_m) is a bulk velocity of the mixture defined as the volumetric flow rate of a matter passing through a pipeline, Q_m, divided by the cross-sectional area, A.

$$V_m = \frac{Q_m}{A} = \frac{4Q_m}{D^2} \tag{1}$$

where Q_m equals the sum of Q_s and Q_f that represent the flow rates of the solid particles and the fluid, respectively. Solid particles are non-uniformly distributed in a pipeline flow. If the flow velocity is slower than a certain value or if the size of the particles is extremely large, the lift force that makes the particles adrift in the pipeline will decrease. With the reduction in the lift force, solid particles start to deposit at the bottom part of the pipeline. The deposition causes the ineffectiveness of the piping system or even the potential danger of blocking the pipeline. The mean slurry velocity at the limit of stationary deposition is called the deposition-limit velocity (V_{dl}) or critical velocity (V_c). The deposition-limit velocity is crucial for the safe and economic operation of the hydraulic transport system.

The amount of solids delivered inside the pipeline is represented by the volumetric delivered concentration (C_{vd}) that is calculated as the ratio between solid and slurry flow rates (Q_s/Q_m). The volumetric spatial concentration (C_{vi}) represents the fraction of solids residing in a pipeline when the slurry flow is suddenly blocked. The volumetric spatial concentration is calculated as the ratio between the solid and slurry volumes in a pipeline section. In the two-phase flow, the difference in density (or viscosity) results in the slip of one phase relative to the other. It has been known that the velocity and concentration profiles are the main factors influencing the slip [24], which can be quantified by using the slip ratio (V_s/V_m). The slip ratio is also represented as C_{vd}/C_{vi} since

$$C_{vd} = \frac{Q_s}{Q_m} = \frac{V_s A_s}{V_m A} = \frac{V_s C_{vi} A}{V_m A} \tag{2}$$

In practice, the density-measuring device using a radioactive isotope measures the volumetric spatial concentration (C_{vi}). Thus, the flow rate of solids (Qs) calculated as $C_{vi}V_mA$ overestimate the real solid flow rates unless the slip is negligible.

The energy loss due to friction can be assessed by using the hydraulic gradient (I_m), which is the pressure gradient for a mixture expressed as the height of water per length of line.

$$I_m = \frac{\Delta p}{\rho_f g L} \tag{3}$$

In evaluating the additional friction loss due to the solid particles, the solid effect represented by (I_m-I_w) is used. I_w is the friction gradient for water alone at the flow rate equal to the mixture flow rate (Q_m).

A general empirical correlation for slurry flow was established by Durand and Condolios [2]. It was found that the model fails for slurry flow with coarse particles [1]. Later, a semi-empirical model for the fully-stratified flow was suggested by Wilson *et al.* [4] as the relationship between the relative solid effect and the mean slurry velocity. Thus, the relative solid effect is a function of the mean velocity with a power-law approximation.

$$\frac{I_m - I_w}{S_m - 1} \approx f\left(\frac{V_m}{V_{50}}\right) \tag{4}$$

where S_m is the specific gravity of the slurry.

$$S_m = S_w + (S_s - S_w) C_v = 1 + (S_s - 1) C_v \tag{5}$$

In Eq. (5), S_w=1 because the working fluid is water. Wilson *et al.* [4] found that Eq. (6) can be represented as follows:

$$\frac{I_m - I_w}{S_m - 1} \approx 0.22\left(\frac{V_m}{V_{50}}\right)^{-M} \tag{6}$$

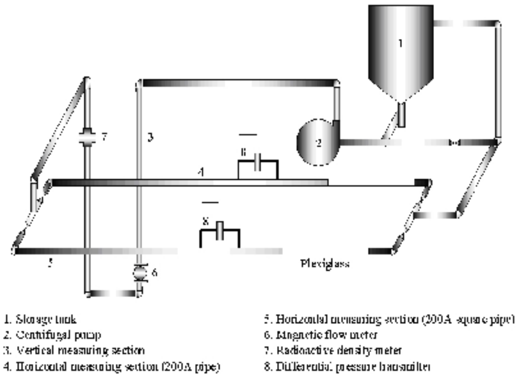
where 0.22 represents the value of the relative solid effects when V_m=V_{50}. The magnitude of M is a function of normal stress of solids (granular pressure).

The Reynolds number is defined as $V_m D_h \rho_w/\mu_w$, where D_h and μ_w represent the hydraulic diameter of the pipes and the viscosity of the water, respectively. In this paper, the definition of the Reynolds number is also used for water and slurry flows together.

2.2 Experimental setup

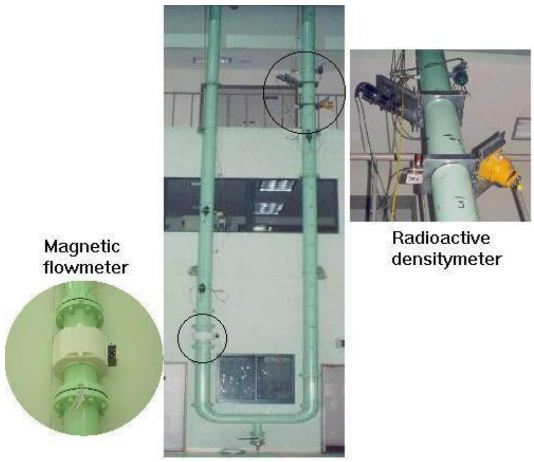
Fig. 1 shows the experimental facility of the present study. The circuits in Fig. 1(a) consist of a 234-meter long test loop with one wide vertical U-tube and two horizontal pipes. The pipes are made of commercial steel. Sand particles are first introduced into connecting pipes, and then stored in a sump tank (D=2 m, H=3 m) at the end of each experimental run. With its top open, the circular sump tank is placed near the inlet of a centrifugal pump. A 255 KW diesel engine with variable revolutions ranging from 540 rpm to 2,200 rpm is connected to the pump via a V-belt. The design flow rate and maximum head of the pump are 15 m^3/min and 50 m, respectively.The sump tank is equipped with a funnel-shaped overflow pipe that can be lifted within the tank. The elevation of the pipe regulates the path of slurry flow through the tank. The part underneath the tank is connected to a transparent plexi-glass tube that shows the supply conditions of sand particles. A valve is used to control the amount of supplied sand particles. The tank can also be bypassed during the tests. Both hydraulic gradient (I_m) and deposition-limit velocity (V_{dl}) are measured in the horizontal pipelines in Fig. 1(b). The length of the test section for each pipeline is 73D. Static tabs are placed at two points of 40D and 50D away from the U-tube to avoid the effect of curvature in the bend part of the vertical U-tube on the flow characteristics. To observe the deposition condition of the solid particles inside the pipelines, an 800 mm-long transparent plexi-glass pipe is installed. The mean velocity (V_m) is measured using an ABB magnetic flow meter in the descending limb of the vertical U-tube. A density-measuring device using a radioactive isotope is attached to the ascending limb of the vertical U-tube [Fig. 1(c)]. With a two-meter interval, static tabs are placed at both ascending and descending limbs. The differential pressure at each static tab is measured using a Sensotec differential pressure sensor with a resolution of 68965.5172 Pa (1 psi). The values of the measured pressure are transmitted to the diaphragm of the transmitter via a medium in a hose. Transparent PVC hoses connect the differential pressure transmitters to the sedimentation pots. The presence of air bubbles or sediment deposits can be observed through the PVC hoses. Sensors are calibrated using a Wykeham-Farranc pressure control panel.

The magnetic flow meter measures the mean slurry velocity in the laboratory circuit by employing the Faraday's law of electromagnetic induction. The induced voltage is proportional only to the flow velocity without being affected by density, viscosity, pressure, or temperature of the liquid. The range of flow meter is from 0 m^3/h to 1,800 m^3/h. The flow regime in the present experiment is homogeneous where the slurry velocity is larger than the transition velocity. To avoid the effect of gravity on the solid particles, the measured slurry velocity is assumed as the mean



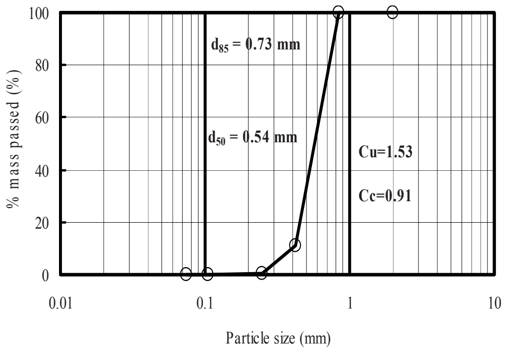
(a) Schematic diagram

(b) Horizontal measuring section

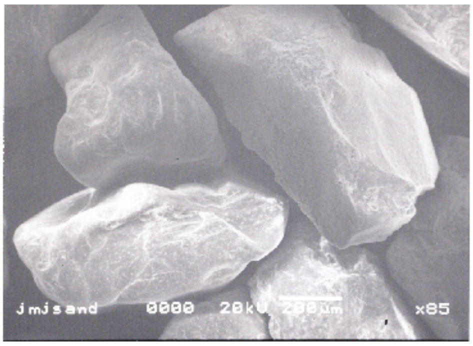


(c) Vertical measuring section (U-Pipe)

Fig. 1. Experimental facility.



(a) Particle sizes



(b) Photograph of Jumunjin sands

Fig. 2. Particle size distributions and Jumunjin sands.

velocity in the pipeline cross section. The local values of slurry density in the pipeline cross section are sensed by a radiation density meter Berthod LB 444 with Cs-137 sources. The attenuation of the radiation beam is a function of slurry density in the beam path [26]. The values of density, pressure, and flow velocity are accumulated using a Wykeham-Farrance AT 2000 data acquisition system.

Fig. 2 shows the particle size distributions and picture of the Jumunjin sand particles used in the test. The picture in Fig. 2(b) is scanned using a scanning electric microscope (SEM). The specific gravity (Ss) and diameter (d_{50}, or d in this paper) of the sand are 2.65 and 0.54 mm, respectively. The shape of the sand particles is not spherical; their uniformity coefficient (Cu) and curvature coefficient (Cc) are 1.53 and 0.91, respectively.

3. Results and discussion

The manometric pressure gradients and concentration distributions are measured for the circular and square pipelines. Both pipelines have the same hydraulic diameter (D_h = 200 mm). Both hydraulic gradient (I_m) and deposition-limit velocity (V_{dl}) are measured by changing the volumetric delivered concentrations of the sand (5%, 15%, and 22%). When the temperature of the water is high, the effect of the temperature should be considered. The effect of the temperature on the slurry flow characteristics is neglected in this paper.

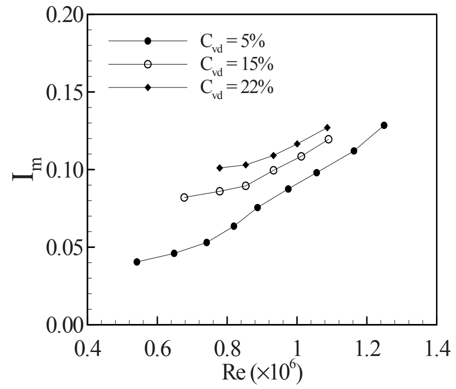
Fig. 3 shows the changes in the hydraulic gradient (I_m) and the solid effect (I_m-I_w) due to the variation of the Reynolds number in the circular pipe (200 A pipe). With the Reynolds number escalating, the hydraulic gradient increases while the solid effect decreases. The hydraulic gradient of the slurry flow with the high delivered volumetric concentration is larger than that of the slurry flow with the low delivered volumetric concentration. When the Reynolds number is low, the volumetric delivered concentration affects the hydraulic gradient significantly. The typical relationship of the hydraulic gradient with the mean velocity is as follows [23].

$$\frac{\mathrm{I_m} - \mathrm{I_w}}{S_m - 1} \approx 0.22\left(\frac{V_m}{V_{50}}\right)^{-M} \tag{7}$$

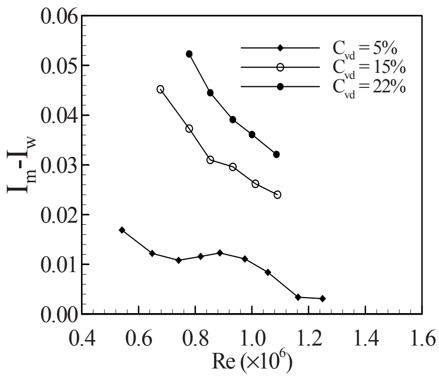
When the magnitude of the mean velocity is reduced, the effect of the second term in Eq. (2) increases. Thus, the hydraulic gradient is proportional to the volumetric delivered concentration for a fixed velocity. Thus, it can be said that the present results approximately agree with the general characteristics of the hydraulic gradient for the slurry. The solid effect plotted in Fig. 3(b) represents the friction loss due to the presence of the solid particles. A large number of solid particles with the high volumetric delivered concentration induce the augmented interaction (such as collision or friction) between the particles and form the stationary deposition of the particles that cause the friction between the particles and the bed in the pipeline. Thus, the solid effect proportionally increases with the volumetric delivered concentration ratio.

Along with the data in Fig. 3, an empirical correlation of the relative solid effect as a function of the Reynolds number is obtained for the power-law approximation. The data for the three volumetric delivered concentrations are shown to be merged into a single curve as follows:

$$\frac{\mathrm{I_m} - \mathrm{I_w}}{S_m - 1} \approx 0.22\left(\frac{V_m}{V_{50}}\right)^{-M} \tag{8}$$



(a) Hydraulic gradient (I_m)



(b) Solid effect (I_m-I_w)

Fig. 3. Reynolds number effect on the hydraulic gradient (I_m) and the solid effect (I_m-I_w).

where the values of coefficient A and exponent M are obtained as 0.0941 and 1.6519, respectively. Clift *et al*. [25] estimated the value of M as 1.7 for slurries with a narrow particle grading. Thus, it can be said that the present results agree with the published data.

Fig. 5 shows the comparison of the hydraulic gradient ($I_w = 2f_wV_m^2/gD$) of water between the circular (200A pipe) and square (200A square pipe) pipelines. As shown in the figure, the hydraulic gradient increases with the Reynolds number. Thus, the frictional loss increases with the velocity. The hydraulic gradient of the water in the circular pipe is larger than that in the square duct. This can be simply explained by considering the friction coefficient of pipelines with various shapes of cross sections. When both circular and square pipelines have the same hydraulic diameter and mean velocity, the friction coefficients of water (f_w) for laminar flow can be represented as C/Re. The values of C for circular and square cross

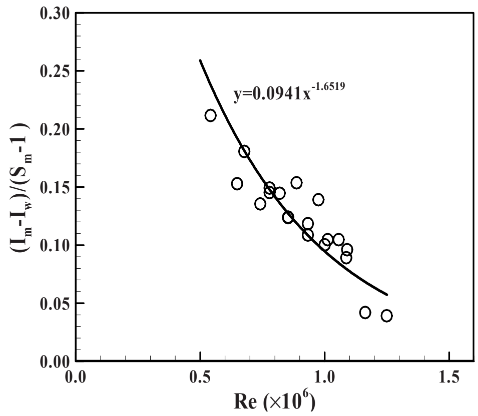


Fig. 4. Empirical correlation of data for the relative solid effect (I_m-I_w)/(S_m-S_w) as a function of the Reynolds number.

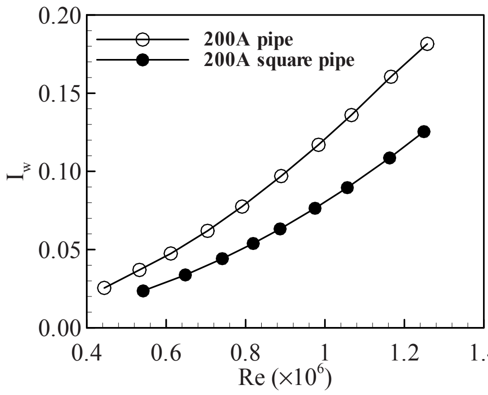
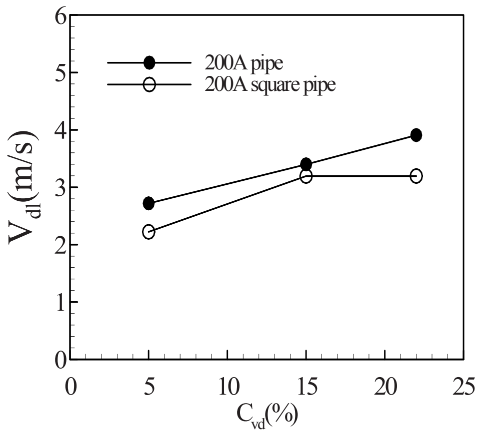


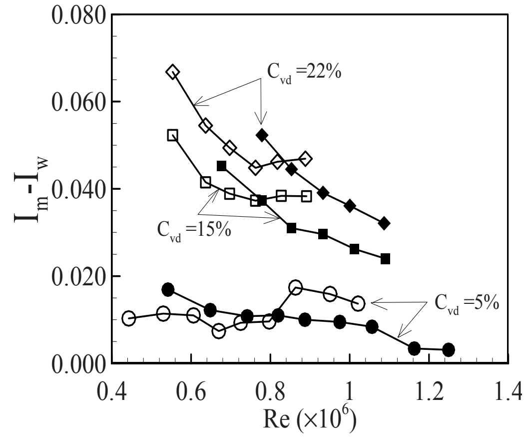
Fig. 5. Comparison of the hydraulic gradient (I_w) of water between circular and square pipelines.

sections are 64 and 56, respectively. Thus, at least for the laminar flow and at the same Reynolds number, the frictional loss of the square duct is less than that of the circular pipe.

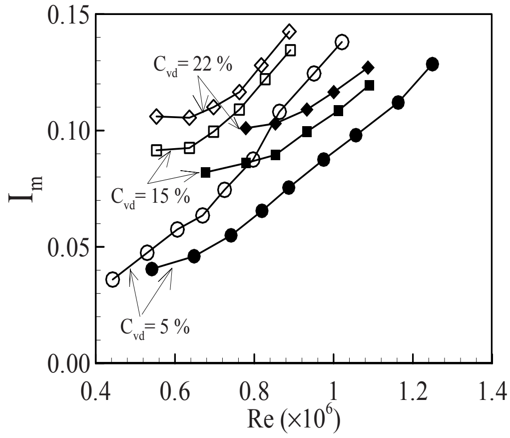
Fig. 6 shows the comparison of the hydraulic characteristics between circular and square pipelines. Fig. 6(a) shows that the deposition-limit velocity in the square duct is lower than that in the circular pipe. According to Wilson and Judge [27], a change in the relative density does not influence the form of the relation that represents the change of the deposition-limit velocity as a function of other influential parameters such as particle size, pipe diameter, and friction coefficient of fluid. The secondary flow inside the square pipe affects the friction coefficients of both water and mixture together, resulting in the reduction of the deposition-limit velocity. It can be concluded that the square duct can be used to transport sand at a



(a) Deposition-limit velocity (V_{dl})



(b) Solid effect (I_m-I_w)



(c) Hydraulic gradient (I_m)

Fig. 6. Comparison of the hydraulic characteristics between circular and square pipelines (hollow symbol: 200 A square pipe, filled symbol: 200 A pipe).

slower velocity than the circular pipe. In Fig. 6(b), the solid effect of the square duct is compared with that of the circular by changing the Reynolds number. The figure shows that there might be a critical Reynolds number of 0.8×10^6. When the Reynolds number is smaller than the critical Reynolds number, the solid effect of the circular pipe is larger than that of the square duct and vice versa. The solid effect represents the extra friction loss caused by the conveyed solids.

When the Reynolds number is smaller than the critical value, the friction loss due to the solid particles in the circular pipe is smaller than that in the square duct. It can be deduced from the results above that the square duct is more effective than the circular pipe when the flow velocity is small. Recently, Kaushal and Tomita [22] found that the reduction of head loss in rectangular ducts is due to the secondary flow that helps the particles stay suspended, and it reduces the friction between the solid particles and the pipelines. Fig. 6(c) shows the change of the hydraulic gradient due to the variation of the Reynolds number. At the same Reynolds number, the hydraulic gradient of the square duct is larger than that of the circular pipe. Current data are obtained when the slurry flow velocity is larger than the deposition limit velocity. Thus, it is not clear with the current data whether the hydraulic gradient of the square duct is still larger than that of the circular pipe below the deposition velocity. However, it can be deduced that the secondary flow effect in the square duct is not effective when the Reynolds number is large (homogeneous flow).

Fig. 7 shows the relative solid effect $(I_m-I_w)/(S_m-1)$ of the 200A square pipe. It is shown that the relative

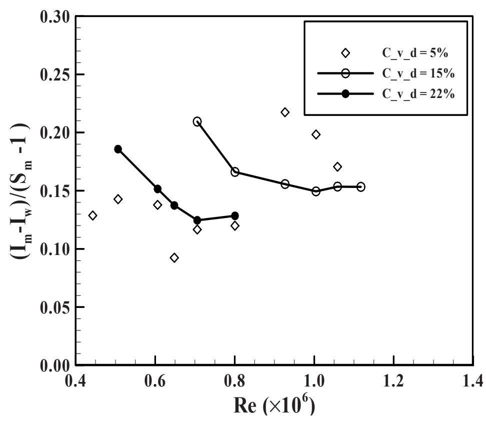


Fig. 7. The relative solid effect $(I_m-I_w)/(S_m-1)$ as a function of the Reynolds number.

solid effect decreases with the increase in the volumetric delivered concentration. Note that the relative solid effect in the square duct is strongly dependent on the change of the volumetric delivered concentration. The secondary flow that affects the performance characteristics of the square duct may also be a function of the concentration distribution.

4. Conclusions

An experimental study on the transport of sand-water mixtures in circular and square pipelines is conducted, focusing on the economic transport of solid particles. The measured data of the hydraulic gradient, solid effect, and deposition-limit velocity for both circular pipe and square duct are compared with each other.

The hydraulic gradient of water in the circular pipe is larger than that in the square duct because of the secondary flow in the square duct. The hydraulic gradient of sand-water mixture in the square duct is larger than that in the circular pipe. It is found that the hydraulic gradient of the slurry flow in the circular and square pipelines increases with the volumetric delivered concentration and Reynolds number. The solid effect decreases with the Reynolds number. An empirical correlation for the relative solid effect in the circular pipe is obtained as a function of the Reynolds number. When the Reynolds number is smaller than approximately 0.8×10^6, the solid effect in the circular pipe is larger than that in the square pipe. The deposition-limit velocity in the square duct is smaller than that in the circular pipe. Thus, it can be said that the square pipe transports sand more effectively than the circular pipe in a low operating range of velocity.

It is believed that the present data can be used to validate the numerical methods developed for the analysis of the transport characteristics of slurry in the circular and square pipelines.

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