EFFECT OF PARTICLE SIZE DISTRIBUTION ON THE HYDRAULIC TRANSPORT OF SETTLING SLURRIES

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ABSTRACT

The effective design, control and safe operation of a slurry hydraulic transport system require the successful prediction of slurry flow behavior in the pipeline. Slurry flow behavior is not only dependent on the properties of both solids and carrier, but also it is strongly affected by mutual particle-particle and particle liquid interaction.

To decrease specific power consumption and increase overall the transport system efficiency, the carrying capacity should be increased. Particle size distribution plays an important rule to obtain higher concentrated slurries and higher carrying capacity. Therefore, economic advantage can be gained by adjusting particle size distribution.

The aim of study is experimentally investigate the effect of solids size distribution on the flow behavior and pressure frictional losses of settling slurries flowing in pipes. Measurements of three different sorts of sand solids (ρ_s = 2650, d_{50} = 0.2, 0.7 and 1.4 mm) at different concentration ($C_v \approx$ 4 to 33%) were obtained by laboratory pipeline test loop (D = 26.8mm). Investigation of the effect of solids particle size distribution widening has been obtained by measurements of two created sand mixture slurries by the three sand sorts with different ratios.

Keywords: Settling slurry, size distribution, flow behavior

INTRODUCTION

Slurries could be classified rigidly between two limiting cases of settling and non-settling as a result of behavior of a static sample of the slurry. This classification could provide a rational basis for describing the physical appearance and flow behavior of the slurries. The particles tendency to settle in horizontal flow depends upon gravitational settling velocity, the turbulence within the liquid, carrier properties and particle- particle interaction, [1].

Non-settling slurries, whose particles settle very slowly, consist of fine particles, which are likely to be uniformly distributed over the pipe cross-section. Their flows appear to be homogeneous, and when increasing solids content, the mixture can no longer be regarded as two individual components. The resulting fluid could have non-Newtonian characteristics implying a more complicated relation between the shear stress and shear rate. For many cases of slurry flow this uniformity does not occur. Particles concentration is larger near the bottom of the pipe and smaller near the top, indicative of settling behavior. Such concentration gradients are often associated with frictional losses larger than those of homogeneous slurries, [2].

The effective design, control and safe operation of a hydraulic transport system require the successful prediction of slurry flow behaviour in the pipeline. Settling slurries are showing distinct two-phase behaviour which is strongly affected by mutual particle-particle and particle liquid interaction, [3].

Settling Slurry Flow Features

The flow features exhibited by settling slurry result from the complex processes of momentum interchange between the two phases. Flow features provide considerable guidance for the rational selection of techniques to predict hydraulic behaviour and for suitable operating conditions for pipelines, [4].

The settling slurries can exhibit a complex range of flow patterns, depending upon the physical properties of carrier fluid and transported solids, the superficial velocity and concentration of slurry. At one extreme, the solids are present as a gravity bed. Such a flow regime is referred to as fully segregated or two layer (sliding bed/stationary bed). The other extreme, at very high velocities with favourable solid and liquid properties, the solids may approach a pseudo-homogeneous flow. Between the two extreme cases lie the saltation and heterogeneous flow regimes, [5].

Pressure Loss Reduction

Pumping power is primarily determined by frictional pressure losses in the pipelines. To minimize the size of pumps, motors, gearboxes and other such capital items, there is, therefore, an incentive to minimize the frictional pressure losses.

One of the limiting factors of conventional hydraulic transport of solids in the turbulent flow regime is the upper particle size that can be carried without excessive power consumption or wear in pipes. El-Nahhas et al. [6] demonstrated the effect of particle size on the flow behavior and power consumption for sand slurries. Frequently, stabilized or dense-phase pumping has been proposed, [7]. In stabilized flow the rheological properties of the carrier fluid are such that the coarse material is maintained in suspension. The effect of the carrier rheological characteristics on the settling slurries flow behavior has been investigated by El-Nahhas et al. [8]. Dense-phase transport is the limiting case of a sliding bed where the slurry fills the complete pipe cross-section. For both methods the potentially low operating velocity should reduce power consumption and wear rate, [9]. Mixed regime flow results in a decreased energy gradient and a higher total solids concentration than an equivalent mixture of unisized particles. The increased concentration depends on particle size distribution. The increased carrying capacity results in a decrease in specific power consumption and overall increase in the transport system efficiency. Abrasive wear and particle attrition are also reduced. Sive & Lazarus [10] have reviewed and reported the mechanisms causing the decrease of the energy gradient for equivalent concentrations of mixed regime slurries compared with unisized slurries.

So, economic advantage can be gained by adjusting particle size distribution. When the main concern is to maximize the dry solids rate through the pipe, this can be achieved by maximizing solids concentration while keeping viscosity levels constant by adjusting particle size distribution. This approach has obviously implicated not only a reduction in cost per (*ton km*) of dry material moved but also a reduction in water usage, important when water supplies are limited, [11].

Slurry Flow Parameters

Important parameters for the design and operation of a slurry pipeline are those which provide information about the safety and economy of slurry pipeline operation.

Mean velocity in a pipeline is a basic parameter characterizing pipeline flow. It is defined as the bulk velocity, v, of a matter (solids, liquids or mixtures) obtained from the volumetric flow rate, Q, of a matter passing a pipeline divided by cross section of the area, A, (Q/A). The determination of an appropriate mean velocity of slurry is crucial to safe and economic pipeline operation.

An area in which slurries require a more careful treatment than single-phase fluids is that of the friction gradient or energy gradient. In the form of the pressure gradient dp/dx, the friction loss associated with the flow of slurry in a pipe will be clear. However, the expression of pressure loss as a “hydraulic gradient”, i, (in m water per m length of pipe) is so common in slurry pipelining, [2]. For settling slurries, the so-called solids effect, ($i-i_w$), and relative solid effect $(i-i_w)/i_w$ were introduced to express the extra pressure losses caused by the solids presence.

The specific energy consumption, *SEC*, determines the energy required to move a given quantity of solids over a given distance in a pipeline. It is given as

$$\mathrm{SEC} = 0.2778 \frac{i\,g}{S_s C_v} \tag{1}$$

The aim of study is experimentally investigate the effect of solids size distribution on the flow behavior and specific energy consumption of settling slurries flowing in pipes. Measurements of three different sorts of sand solids (ρ_s = 2650, d_{50} = 0.2, 0.7 and 1.4 mm) at different concentration ($C_v \approx 4$ to 33%) were obtained by laboratory pipeline test loop (D = 26.8mm). Investigation of the effect of solids particle size distribution widening has been obtained by measurements of two created sand mixture slurries by the three sand sorts with different ratios.

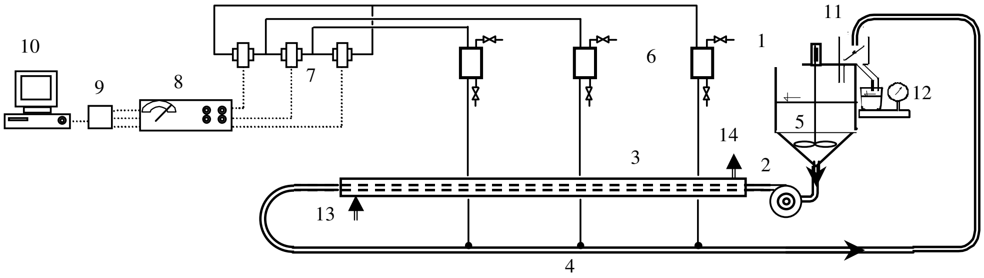
EXPERIMENTAL SETUP AND MEASURING FACILITIES

An open-loop recirculation pipeline system, shown schematically in Figure (1), was employed for testing the slurry flow behavior. A centrifugal pump (Warman ultra heavy-duty slurry pump – type 2/3) was used for forcing the slurries. The pump has a variable speed drive to allow slurry testing over a wide range of flow rates. A stainless steel holding tank (600 mm diameter and 1200 mm height) equipped with a funnel-shaped tube located inside its cone shaped bottom, to allow solids separation after finishing a set of measurements, was used. It was taken into considerations that the slurry level in the holding tank might be high enough to ensure that air was not entrained in the mixture entering the loop. The experiments with comparable results were made at same slurry level in the holding tank.

A stainless steel pipe loop of internal diameter 26.8 mm, with entire length of about 18 m, was used for slurry parameters measurement. The operating temperature was controlled by pumping cooling water, in counter flow direction, through the annulus of a double pipe heat exchanger. The heat exchanger which located in the front branch of the pipeline test loop keeps the temperatures during the experiments in a very narrow range. The test section is located in the back (downstream) branch of the piping loop system. The length-to-diameter ratios of the test sections exceed 400 (according to design criteria, [12]). A transparent section was mounted at the end of the test section. Differential pressure measurements were obtained over two sections of pipe. Therefore, the test section has three pressure tapping points, which are located on the upper part of the pipe perimeter at distances so that fully developed flow exists between them. The pressure is transmitted from the tapping points to three inductive differential transducers through transmission lines and plexi-glass sedimentation vessels filled with pure water. The sedimentation vessels prevent the penetration of solid particles from the slurry pipe into the pressure transducers and enable to vent the system.

Inductive differential pressure transducers were used to measure the pressure losses between the pressure tappings. The transducer output signals, which is proportional to the differential pressure at the transducer were amplified and displayed as an analogue value (in volts) by voltmeters. Also these analogue signals were converted to digital signal by analogue/digital modules. The digital data signal input to a computer, which is accessed with MATLAB software that enables for online supervisory, analysis and data acquisition.

At the downstream end of the test pipes a box divider was mounted and allows discharge to be diverted to a plastic container and measured by weight. Since the divider arm was connected to an electric stopwatch, the mass flow rate was precisely measured. If the plastic container was replaced by a glass calibrated cylinder, the slurry density and hence the volumetric concentration could be determined. This arrangement allowed a check on the concentration in the pipe during each experimental run. These data are input to the computer software for processing to present the supervisory plots online during the measurements. All pressure transducers had been calibrated periodically against the standard device, U-tube manometers.



1	holding tank	8	three channels carrier frequency amplifier
2	screw pump	9	analogue/ digital converter
3	double pipe heat exchanger	10	computer
4	test section	11	flow divider vessel
5	stirrer	12	measurement of discharge & density
6	sedimentation vessels	13	cooling water inlet
7	differential pressure transducers	14	cooling water exit

Figure 1. Schematic diagram of the experimental pipeline test loop

Three sorts of the mono-disperse quartz sands, ρ_s = 2650 kg/m^3, were used for preparing slurries of the experiments; fine (d_{50} = 0.2 mm), medium (d_{50} = 0.7 mm) and coarse (d_{50} = 1.4 mm). The solids volumetric concentrations ranged from C_v = 4% to 33%. To study the effect of the particle size distribution of the solids on the slurry flow characteristics, two sand mixtures at two different concentrations (of about C_v = 24% and 33%) were also prepared and tested. The mass mixture proportions were 1:1:1 and 1:2:1 of fine, medium and coarse sand respectively.

RESULTS AND DISCUSSIONS

The so-called solids effect, (i-i_w), and relative solids effect (i-i_w)/i_w were introduced for two-phase settling slurries to express the extra pressure losses caused by the presence solid particles. Figures (2) to (4) present the development of the relative solids effect with increasing the mean velocity, v, for fine, medium and coarse-sand slurries of different concentrations. The general remark is that increasing the solids concentration of certain slurry increases the flow friction loss. This is obviously shown for both fine and coarse sand slurries (Figures (2) and (4)) through whole velocity range. For medium sand slurry, the same behavior could be also noticed, but only at low velocity range. At higher velocities, (v >5 m/s), the excess in the relative solids effect due to increase in concentration is very limited and is not considered as a rule. In general, the curve shapes at higher velocities are observed to be different for flows of solids of different sizes.

It could be noted that at lower velocity ranges, as the mean velocity is reduced, the relative solids effect steeply increases. This could be closely associated with the formation of a bed of solids in the pipe.

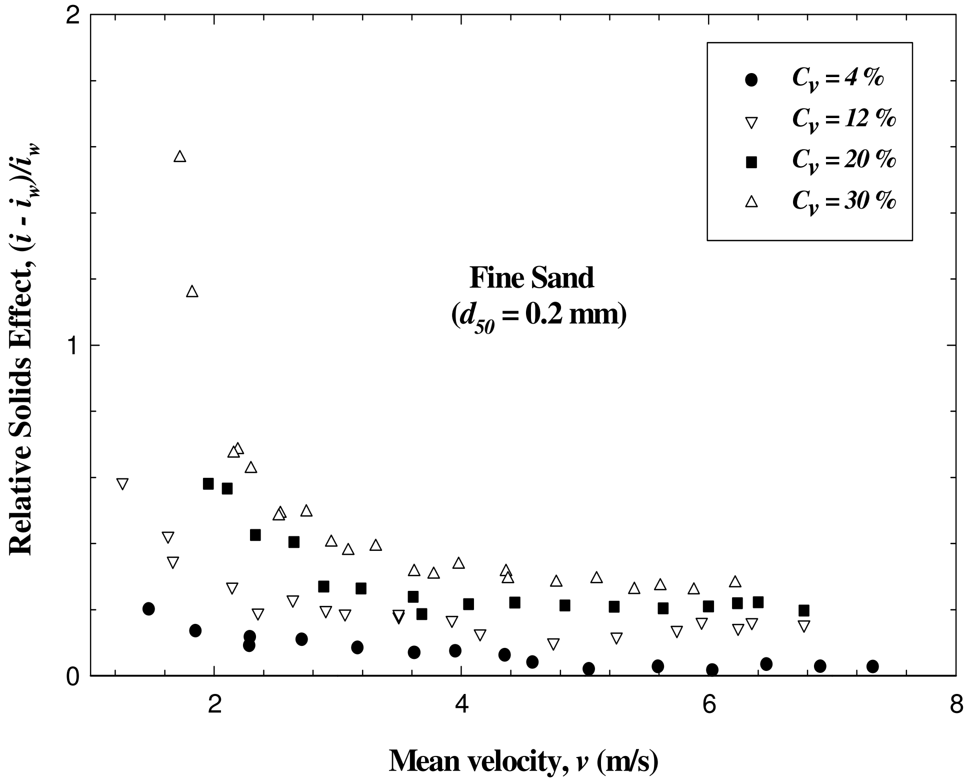


Figure 2. Effect of solids concentration on the flow behavior of fine sand slurries

The low-slope flat curve, at higher velocities, means that slight increase in pressure gradient could be resulted by much increase in mean velocity, and hence tend to be attractive economically taking into considerations the wear problems.

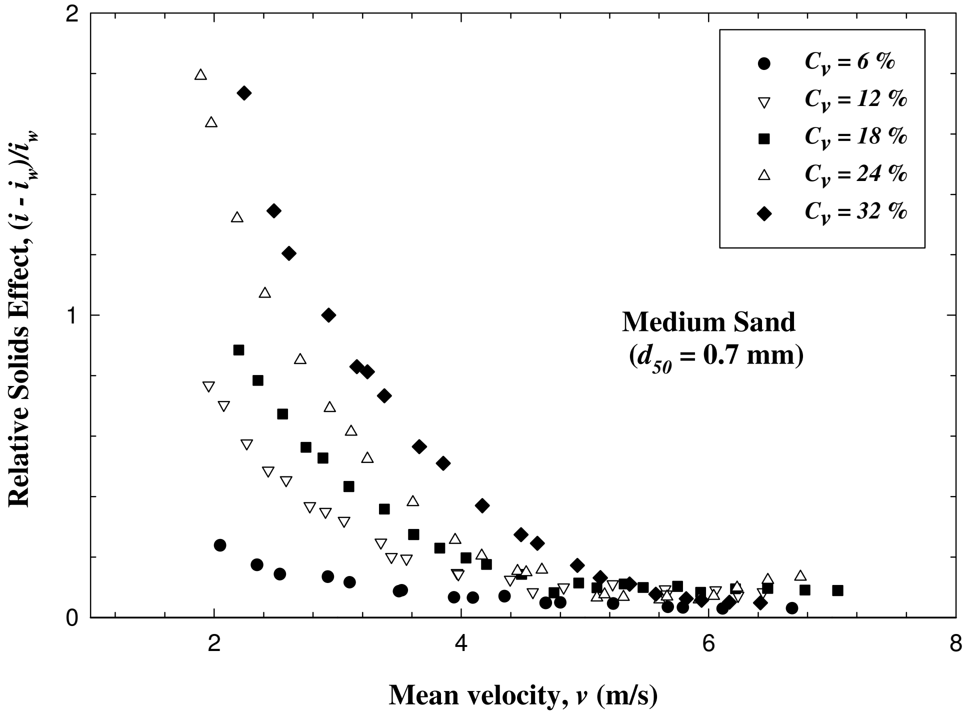


Figure 3. Effect of solids concentration on the flow behavior of medium sand slurries

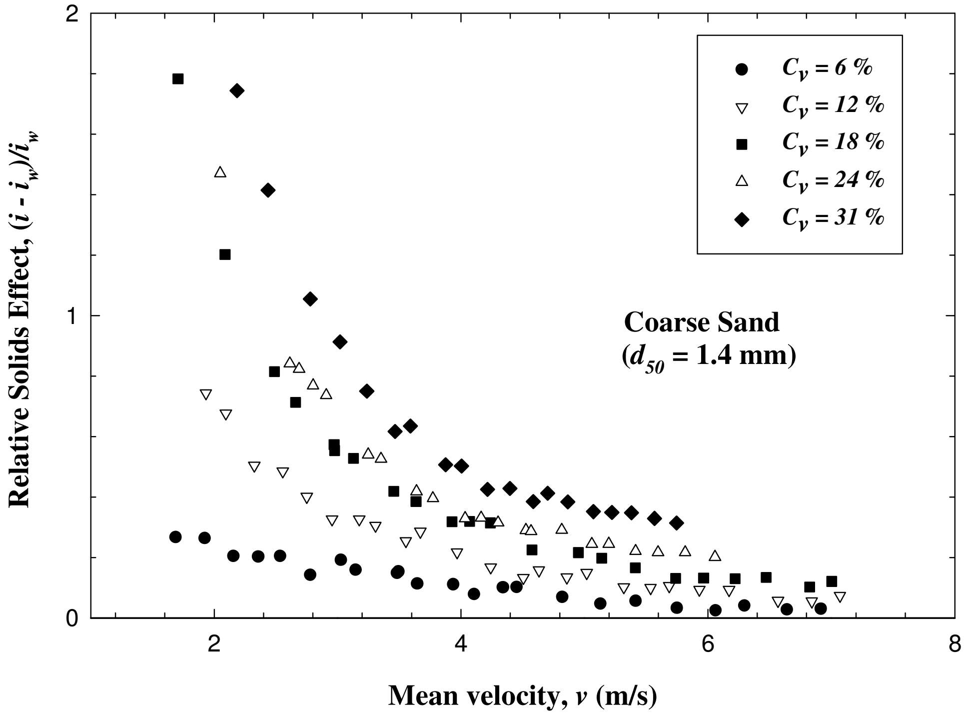


Figure 4. Effect of solids concentration on the flow behavior of coarse sand slurries

It was shown in the literature (e.g. [(13)], [14], and [15]) that the broader size distribution of the solids is better than the narrower one from the point of view that the power consumption could be reduced. To study the effect of the solids particles size distribution on the flow behavior of settling slurries, the two sand mixtures that were prepared by mixing fine, medium and coarse sand sorts were tested. It could be remembered that the sand mixture has the component ratios (1:1:1) and (1:2:1) of fine, medium and coarse sands respectively. The two sand mixtures with two volumetric concentrations (C_V = 24 and 33%) are compared with the nearest corresponding volumetric concentration of unisized coarse, medium and fine sand slurries as presented in Figures (5) and (6).

It could be noted that there is no significant difference between the relative solids effect curves of the two mixtures at the two considered concentrations. As shown in Figures (5) and (6), the coarse-sand slurries give more pressure losses than that are given by both sand mixtures at the two studied concentrations. For both medium and fine sand slurries, as it could be noted that its behavior compared with that of the two mixtures is dependent on the mean velocity range. The hydraulic losses for the medium sand slurry are higher than that of both mixtures at low mean velocity ranges. With higher mean velocities (at $V > 4$) the hydraulic gradients of both sand mixture slurries exceed that of medium sand slurries.

On contrary with the medium-sand slurries, the fine-sand slurries at low mean velocity range, have lower hydraulic gradients than that of both sand mixtures and with increasing the mean velocity, its hydraulic gradients gradually exceed that of the two sand mixture slurries.

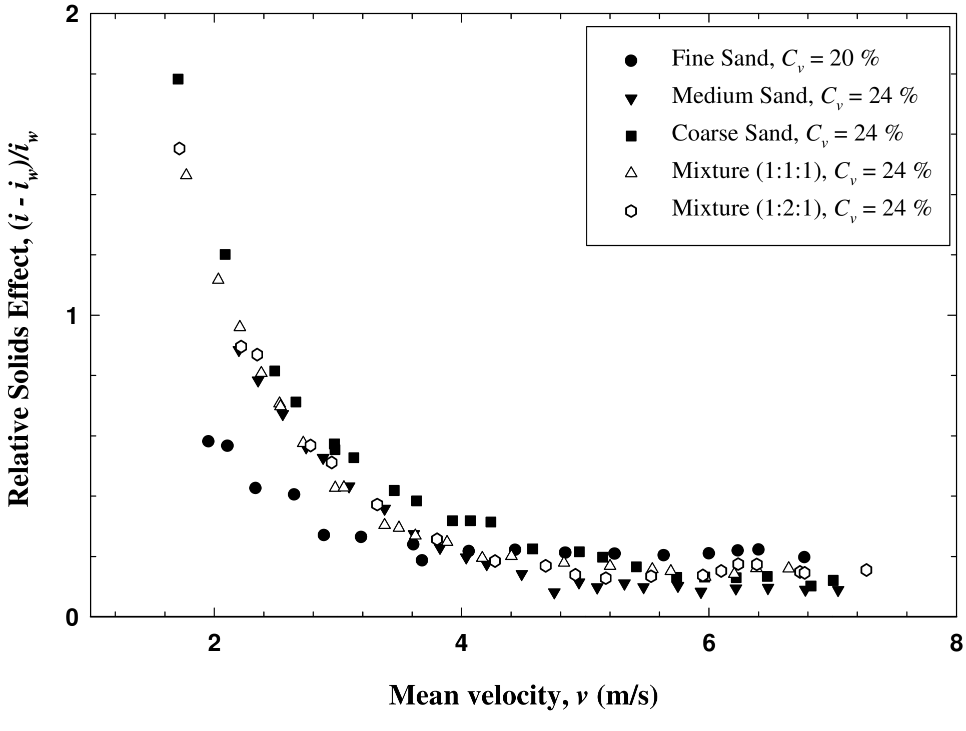


Figure 5. Effect of solids size distribution on the flow behavior of medium-concentrated sand slurries

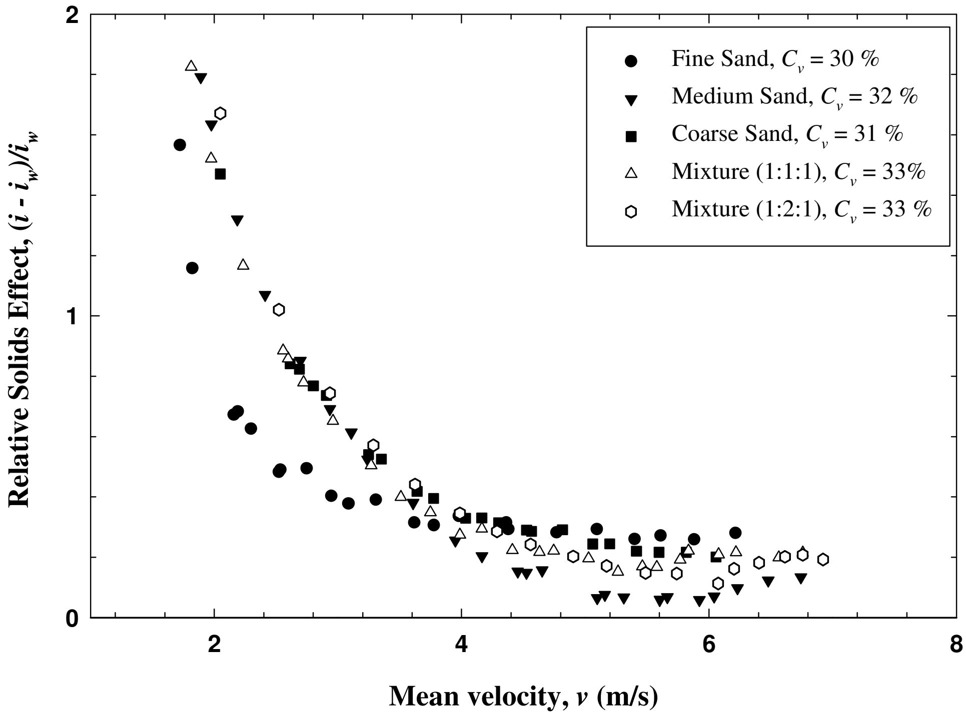


Figure 6. Effect of solids concentration on the flow behavior of high-concentrated sand slurries

The specific energy consumption, *SEC*, in units of [kW.hr/tonne.km] determines the energy required to move a given quantity of solids over a given distance in a pipeline. The *SEC* is plotted against solids throughput (the amount of dry solids delivered at the pipeline outlet over a time period). Figures (7) and (8) present the specific energy versus solids throughput relations of both sand mixture slurries, at the two considered concentrations (C_V = 24 and 33%), compared with that of mono-disperse sand slurries. A comparison between the two mixture slurries could show that *SEC* relations for the two mixtures are slightly different only for the higher concentration at low and high solids throughput ranges. For both sand mixture slurries, the higher mixture concentration the lower *SEC* values at certain solids throughput. Referring to Figure (7), it is shown, from the energy consumption point of view, that the mixture slurries are better than both separate fine sand slurry (at C_V = 20%) and coarse sand slurry (at C_V = 24%). It is also better than the medium sand slurry (at C_V = 24%) at lower mean velocity ranges (V < 3.6 m/s). Similar result could be observed from Figure (8) for higher concentration that the sand mixtures are better than both separate fine sand slurry (at C_V = 30%) and coarse sand slurry (at C_V = 31%). It is better than medium sand slurry (at C_V = 32%) for mean velocities lower than 4.9 m/s.

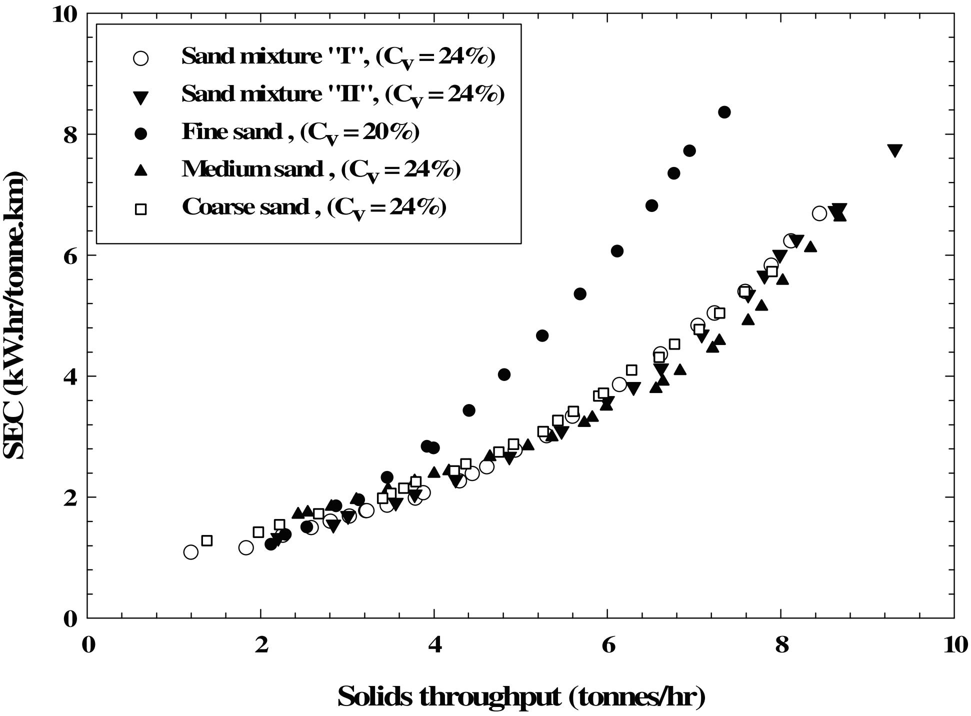


Figure 7. Effect of solids concentration on the specific energy consumption of medium-concentrated sand slurries

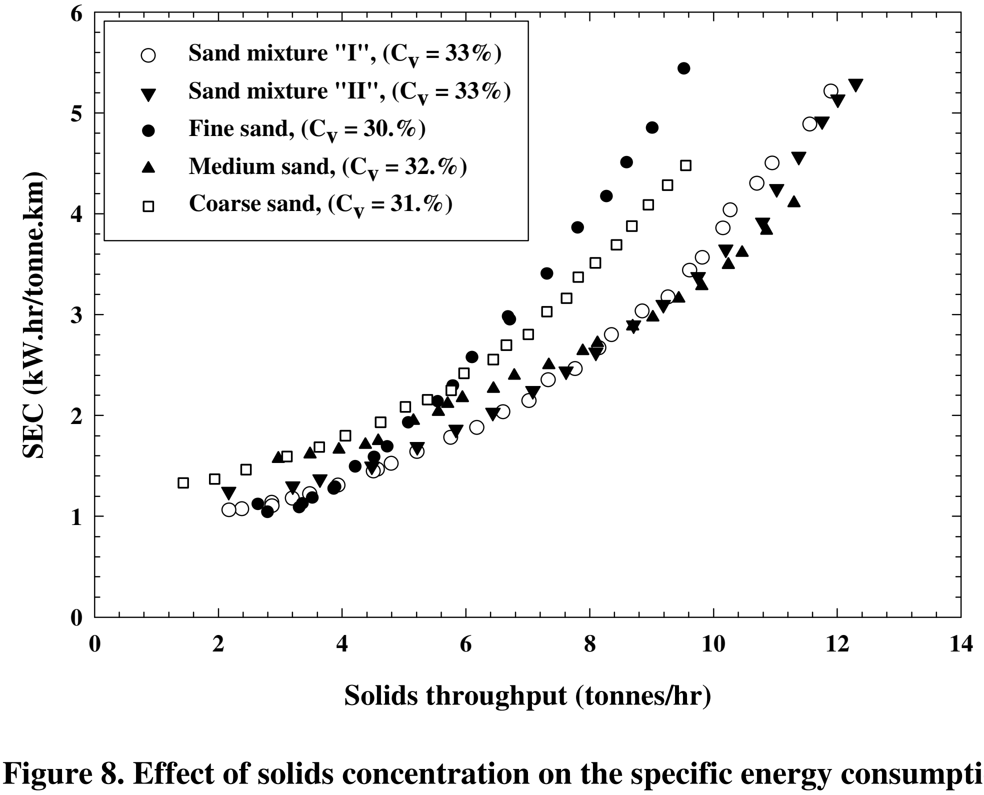


Figure 8. Effect of solids concentration on the specific energy consumption of high-concentrated sand slurries

CONCLUSIONS

According to the above discussions, the conclusions can be summarized and presented as the following points:

- For the tested sand slurries, the relative solids effect $(i-i_w)/i_w$ steeply increases when reducing the flow velocity, indicating to beginning of solids bed formation in the pipe.
- For the same solids throughputs, as the solids concentration increases the specific energy consumption decreases. Therefore, the hydrotransport of dense slurry could be more efficient and economic.
- Direct proportional relation between the relative solids effect (indicating the frictional losses) and the solids concentration was obviously shown for both for fine and coarse sand slurries. The medium sand slurry had different behavior at higher velocity ranges ($v > 5$ m/s); the solids concentration had a little effect and had not a certain rule.
- Widening the solids size distribution benefits depends on the solids concentrations and operating velocity range.

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NOMENCLATURE

A	area	[m^2]
C_v	volumetric concentration	[-]
D	pipe internal diameter	[m]
d_{50}	mass median particle diameter	[mm]
i	hydraulic gradient for slurry flow	[-]
i_w	hydraulic gradient for water flow	[-]
p	pressure	[Pa]
Q	volumetric flow rate	[m^3/h]
SEC	specific energy consumption	[kW.hr/tonne.km]
S_s	solids specific gravity	[-]
v	mean velocity	[m/s]
x	axial distance	[m]
ρ	density	[kg/m^3]
ρ_s	solid density	[kg/m^3]

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