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FLOW BEHAVIOUR OF SETTLING SLURRIES CONTAINING COLLOIDAL PARTICLES

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ABSTRACT

The particles tendency to settle in horizontal flow depends upon gravitational settling velocity, the turbulence within the liquid, carrier properties and particle- particle interaction.

When water is used, as a carrier, for the transportation of coarse particles, it is necessary to operate at velocities that remain the turbulent flow condition is in order to avoid the risk of blockage. The pressure drops may be too high and solids attrition and wear in pipes fittings and pumps can present serious problems. Flocculated suspensions of colloidal particles generally exhibit shear-thinning non-Newtonian characteristics and offer several advantages for the transport of coarse solids.

The aim of study is experimentally investigate the flow behaviour of settling slurries that contain colloidal particles studying the effect of carrier properties.

Two sorts of the sand (ρ_s = 2650 kg/m^3) were used for the experiments; medium (d_{50} = 0.7 mm) and coarse (d_{50} = 1.4 mm). Kaolin (d_{50} = 2.8 μm, ρ_k = 2546 kg/m^3) was added to the sand-water slurry to create non-Newtonian carrier liquid. Also, a chemical agent with peptizing effect was used to change physico-chemical properties of the slurry.

KEYWORDS:

Settling slurry, flow behavior, carrier properties.

INTRODUCTION

Hydrotransport of solid/liquid mixtures through pipelines is encountered in a numerous applications. These applications include chemical engineering, civil engineering, mineral processing, food industries, dredging works and water treatment activities. Also, the modern technologies prefer conveying large quantities of solid materials in the form of dense slurries through pipelines.

Dense-phase flow presents many advantages for water and power management. High solids concentrations with coarse particles are possible to be handled requiring no special preparation. This method is suitable for materials such as aggregate, gravel, etc., which can not normally be comminuted, [1]. Generally, dense slurries could be consisting of very fine particles uniformly distributed over the pipe cross-section. For many other cases of slurry flow, the solid particles are not distributed uniformly throughout the pipe. Particle concentrations are larger near the bottom of the pipe and smaller near the top indicative of settling behaviour. 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. For homogeneous slurry, the flow behaviour is related to the rheological properties that could be predicted with the aid of viscometric techniques. Viscometric techniques developed for single-phase fluids or homogeneous slurries are not applicable to settling slurries. Settling slurries are showing distinct two-phase behaviour which is strongly affected by mutual particle-particle and particle liquid interaction. The flow behaviour of settling slurries is affected not only by the solids properties (particle size, size distribution, particle density and particle shape) and solids concentration but also by the nature of the carrier fluid (Newtonian or non-Newtonian), [3].

When water is used for the transportation of coarse particles, it is necessary to operate at velocities at which the flow is turbulent in order to avoid the risk of blockage, and the pressure drops may be too high. Furthermore, solids attrition and wear in pipes fittings and pumps can present serious problems. Operation using highly viscous Newtonian fluids in order to achieve laminar flow is generally impracticable as such liquids give rise to high pressure gradients, are expensive and may well contaminate the solids. On the other hand, shear-thinning suspensions offer several advantages for the transport of coarse solids. Flocculated suspensions of colloidal particles generally exhibit shear-thinning non-Newtonian characteristics that offer several advantages for the transport of coarse solids. It can show extremely large variations in apparent viscosity over the cross-section when flowing in a pipe. The high apparent viscosity of the suspension in the low-shear regions in the core of the pipe is important in that it aids the suspension of the particles. At the same time, pressure gradients are at an acceptable level because the apparent viscosity of the suspension is low in the high shear-rate regions near the pipe walls, [4]. Since it is possible to operate at very high solids concentrations, the flow rate of transporting fluids is reduced, and thus the same solids throughputs may be achieved at very much lower velocities. Not only does this result in lower power requirements, but it also reduces wear attrition and alleviates problems of disposing of large volume of transporting fluid. The properties of such suspensions make them highly suitable for the transport of coarse particle under conditions of laminar pipe flow. On the other hand, the favorable rheological properties of flocculated suspensions exhibiting non-Newtonian shear-thinning characteristics represent an advantage. By virtue of their relatively high densities, suspensions of colloidal particles exert an increased buoyancy force, compared with water. Therefore, not only improved suspension could be obtained, but also a reduction in the normal reaction forces on the solids at the pipe walls. This is important because the principal component of the force giving rise to the pressure drop when coarse solids form a sliding bed is solids-wall friction. It could be concluded that the properties of flocculated suspensions of colloidal particles that generally exhibit shear-thinning non-Newtonian characteristics make them suitable for the transport of coarse particles under condition of laminar pipe flow as their enhanced density and high apparent viscosity in the core region give rise to an effective support mechanism, [4].

Vlasak et al. [5] studied the flow behaviour of slurries containing colloidal, clay, dust and coarse-grained particles. It has been shown that an intensive turbulent or addition of coarse-grained particles, i.e. bottom ash, can evoke the significant change of the flow behaviour of fluidic ash slurries. The hydraulic gradient of the fluidic ash slurry decreases markedly and the laminar/turbulent transition is reached at lower flow velocities, [5].

Sumner et al [6] studied the rheology of clay slurries containing large silica particles. The study showed that addition of large rigid solid particles to the clay slurries, characterized by Bingham rheological model, increased the yield stress and plastic viscosities of the mixtures.

Plewa et al [7] presented the results of measurements of fly-ash slurries with addition of coarse grains of waste rocks. They showed that the increase of pressure drops of mixtures containing coarse grains is proportional to the concentration of coarse particles and mixture density and inversely proportional to pipe diameter.

Duckworth et al [8] concluded that slurries formed from coarse coal (s.g. = 1.4) and mine waste (s.g. = 2.13) of top size 25 mm, suspended in Bingham type carrier fluids, appear to behave in very much the same way as the carrier fluid.

One possibility of the pressure loss reduction is based on change of physical-chemical behaviour of the slurry such as peptizing processes, as shown e.g. by Vlasak et al [9, 10 and 11], El-Nahhas [3] and El-Nahhas et al [12]. Due to the peptizing agent activity the attraction forces in the slurry decrease, the repulsion forces prevail and the aggregates of solid particles are destroyed, also the inner structure of the slurry is changed. Therefore, understanding of the inner structure and flow behaviour of slurry makes possible to optimize energy and water requirements.

The aim of study is experimentally investigate the effect of carrier properties on the flow behaviour of settling slurries by using both water and a non-Newtonian homogeneous slurry to carry the settling solid particles. Also, the effect of addition of peptizing agent to slurries consisting of settling solids in a non-Newtonian carrier fluid on the pressure losses has been studied.

BASIC DESIGN 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 cross section of the area, A. the equation $v = Q/A$ is for a circular pipe of an inner diameter D written as

$$\mathrm{v} = \frac{4\mathrm{Q}}{\pi \mathrm{D}^2} \tag{1}$$

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].

EXPERIMENTAL PROGRAM

An open-loop recirculation pipeline system was employed for testing the slurry flow behaviour. A centrifugal pump (Warman ultra heavy-duty slurry pump – type 2/3) were used for pumping 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, [13]). 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 enables to vent the system.

Inductive differential pressure transducers were used to measure the pressure losses between the pressure tappings, i.e. the losses through a certain length of the pipe. 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.

Two sorts of the sand (ρ_s = 2650 kg/m^3) were used for the experiments; medium (d_{50} = 0.7 mm) and coarse (d_{50} = 1.4 mm). Kaolin (d_{50} = 2.8 μm, ρ_k = 2546 kg/m^3) was added to the sand-water slurry to create non-Newtonian carrier liquid. To compare the effect of Newtonian and non-Newtonian carrier, a chemical agent with peptizing effect was used to change physico-chemical environment of the slurry and to suppress attractive inter-particle forces, which evoke non-Newtonian behavior of the slurry.

RESULTS AND DISCUSSIONS

The hydraulic gradients versus the mean velocity relations, which are called resistance curves, are useful mean when studying the slurry energy dissipation. Thus, the resistance curves have been produced for each experimental run maintaining the solids amount in the circuit.

Figures 1 presents the flow behaviour of both medium sand-water and medium sand-kaolin slurries. It could be noted that when using the kaolin slurry as a suspending agent for the medium sand the resulting mixture could form a homogeneous non-Newtonian slurry. It is obviously shown the non-Newtonian characteristic behaviour in the slope change of the $i - v$ relation after transition from laminar to turbulent flow regions. The presence of medium sand solids in the kaolin slurry causes increasing in the yield stress (indicated by the ordinate offset) and in the laminar/turbulent transition velocity.

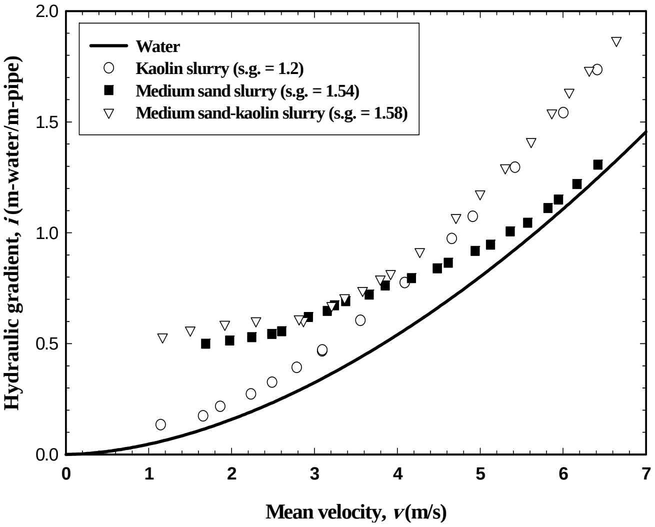

Figure 1 Flow behaviour of medium sand slurries

It is also shown that the solids effect of the medium sand on the mixture hydraulic gradient, which could be expressed by the parameter (i–i_f), decreases as the mean velocity increases, and its relatively higher value present in the laminar flow region is much reduced in the turbulent flow region at higher mean velocities. This behaviour is similar to that of medium sand-water slurry (compared with water plot) in which the solids effect (i–i_w) reaches a very limited value at higher mean velocity. However the medium sand-water slurry has lower resistance curve than that of the medium sand-kaolin in both laminar and turbulent flow regions. Only at the laminar/turbulent transition region the difference is very limited.

The mutual relation between the coarse sand-kaolin slurry and the kaolin carrier fluid is similar to that for medium sand-kaolin slurry in which the solids effect (i–i_f) decreases with increasing the mean velocity and reaches very limited values at high velocity ranges, as shown in Figure 2. However, the homogeneous characteristics are not as clear as shown by medium sand-kaolin slurry. This could be because the particles much larger than the flocs, it would reduce the distance between the flocs inhibiting the flocculation properties. Also, the medium sand solids could have some fine particles that could participate with the fine kaolin particles in flocculation process increasing the viscous forces. There is no significant difference between the hydraulic gradient of the coarse sand-kaolin slurry and coarse sand-water slurry at lower mean velocities. At higher mean velocities (v > 4 m/s) the coarse sand-water slurry has lower hydraulic gradient than that of the coarse sand-kaolin slurry.

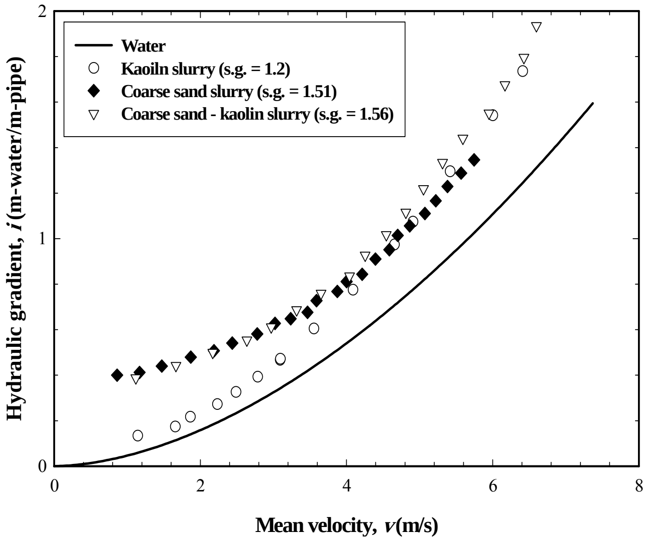

Figure 2 Flow behaviour of coarse sand slurries

Figures 3 and 4 show the effect of adding the sodium carbonate, as a peptizing agent, on the behaviour of sand-kaolin slurries. The peptizing agent to kaolin mass ratio was maintained as 0.15% as an optimum ratio detected by previous studies [3, 12]. For the medium sand-kaolin slurry, adding the peptizing agent obviously reduce the hydraulic gradient at the laminar flow region with no significant change in behaviour at turbulent flow region, Figure 3. Also, adding the peptizing agent to the coarse sand-kaolin slurry only reduces the hydraulic gradient at lower mean velocities with relatively small extent, Figure 4.

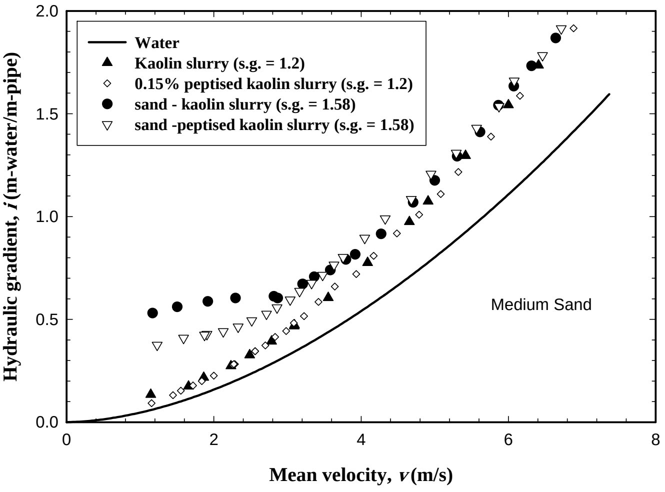

Figure 3 Flow behaviour of medium sand-peptised kaolin slurries

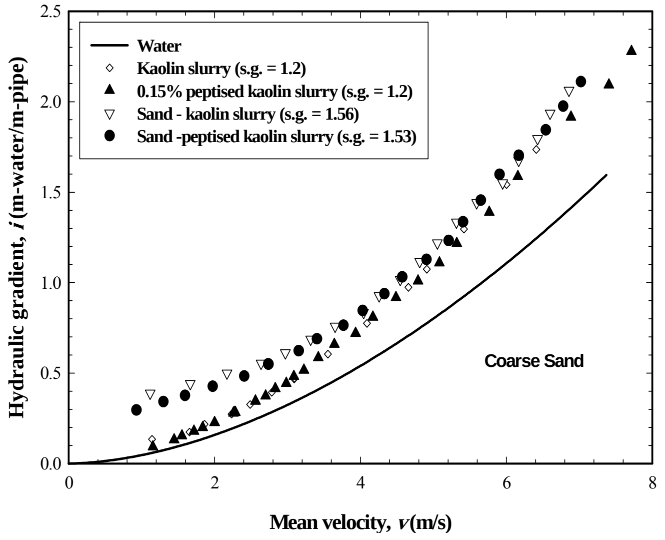

Figure 4 Flow behaviour of coarse sand-peptised kaolin slurries

Figures 5 and 6 present comparison between medium and coarse sand slurries with both kaolin and peptized kaolin carrier fluids respectively. The medium sand kaolin slurry has higher hydraulic gradient at the laminar flow velocity range than that of the coarse sand-kaolin slurry at the corresponding velocity range. At higher mean velocities the hydraulic gradients of both sands are more or less the same.

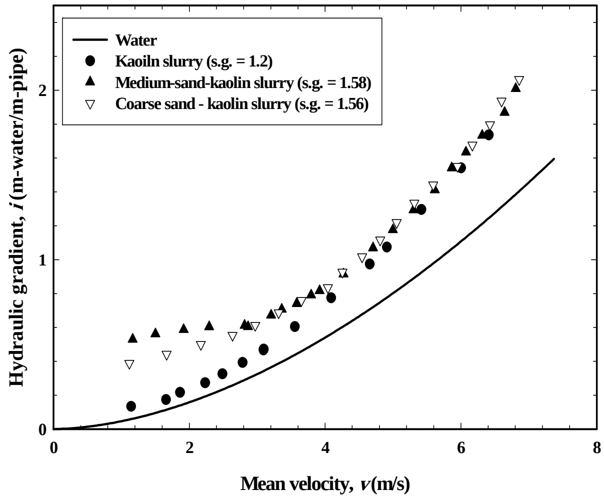

Figure 5 Comparison between flow behaviour of coarse and medium sand-kaolin slurry

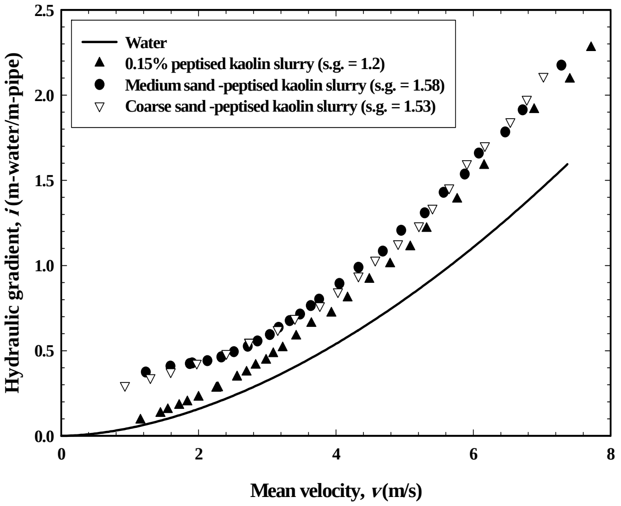

Figure 6 Comparison between flow behaviour of coarse and medium sand-peptised kaolin slurry

CONCLUSIONS

Settling slurries containing colloidal particles behave as non-Newtonian fluids. So, when using non-Newtonian kaolin slurry as a suspending agent for the medium sand the resulting mixture forms homogeneous non-Newtonian slurry.

The presence of sand solids in the kaolin slurry causes increasing in the yield stress and increasing in the laminar/turbulent transition velocity. However, this non-Newtonian characteristic behaviour is not so clear for coarse sand-kaolin slurry. The solids effect ($i–i_f$) for both medium and coarse-sand slurries decrease with increasing the mean velocity reaching very limited values at high velocity ranges.

Adding sodium carbonate as a peptizing agent to the medium sand-kaolin slurry obviously reduces the hydraulic gradient at the laminar flow region with no significant change in behaviour at turbulent flow region. Also, for coarse sand-kaolin slurry it only reduces the hydraulic gradient at lower mean velocities with relatively small effect. Therefore the study confirms the possibility of substantial reduction of the yield stress and viscosity of highly concentrated slurries containing colloidal particles by a modification of their physical-chemical behaviour.

NOMENCLATURE

A	cross sectional area	[m^3]
C_v	volumetric concentration	[-]
D	pipe internal diameter	[m]
d_{50}	mass median diameter	[μm]
i	hydraulic gradient of a slurry	[m water/m pipe]
i_f	hydraulic gradient of carrier fluid at the same velocity	[m water/m pipe]
i_w	hydraulic gradient of water at the same velocity	[m water/m pipe]
Q	volumetric flow rate	[m^3/s]
$s.g$	specific gravity	[-]
v	mean velocity	[m/s]
x	axial distance in a pipeline cross-section	[m]
ρ	density	[kg/m^3]

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