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EFFECT OF COARSE SOLIDS ON NON-NEWTONIAN SETTLING SLURRY FLOW REGIME TRANSITIONS: USING PRESSURE GRADIENTS AND ELECTRICAL RESISTANCE TOMOGRAPHY

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Methods and models for prediction of pipeline transport pressure gradients for coarse particle settling slurries are lacking due to incomplete information regarding flow patterns. Here, flow patterns for coarse particles transported in non-Newtonian carrier fluids obtained via electrical resistance tomography (ERT) were compared to those inferred from plots of pressure gradient vs. superficial velocity. The tests were done in a 56 mm uPVC pipe, at velocities ranging from 0.5 to 5 m/s, using kaolin at concentrations of 6, 10 and 15% by volume as the carrier fluid. Narrowly graded silica sand (d50 = 1.2 and 3.2 mm) were used as the coarse particles, at concentrations of 10, 20 and 30% by volume. Results showed that changes in solids concentration did not change the flow pattern, but only the pressure gradient. Transitional velocities between moving bed and heterogeneous flow identified from the ERT measurements compared well with those estimated from pressure gradient plots.

KEY WORDS: Flow patterns, stratification, electrical resistance tomography, settling slurries, non-Newtonian

1. INTRODUCTION

The design of industrial piping and pumping systems for the transport of coarse particle slurries (mixtures) requires knowledge of the friction (head, pressure or energy) losses and stratification behavior. When a settling slurry is transported in a pipe, significant gradients in the solids concentration across the pipe vertical cross-section develop under the influence of shear and gravity. Several studies in the field of slurry handling focused on flow of particles small enough to maintain ‘homogeneity’ (Buyevich, 1999). These ‘non-settling’ slurries are regarded as single-phase fluids that exhibit non-Newtonian behavior with a uniform concentration of particles across the pipe cross-section. This is not always the case though. As the size or density of solid particles increases, fluid and solids maintain their separate identities and the concentration profile becomes non-axisymmetric. Even the simplest suspension flows are subject to stratification. When the test region to be "visualized" is primarily resistive, as is the case for slurry flow in a pipe, then ERT is a good technique to choose (Dyakowski et al., 2000). By observing changes in tomograms with corresponding changes in flow velocity, it was shown that the method can be used to qualitatively characterize flow patterns (Randall et al., 2004; Dickin & Wang, 1996). Flow was identified as homogeneous, heterogeneous or stratified as defined in (Peker & Helvaci, 2008). As the mixture velocity increases suspension of the coarse particles increases and they become more homogeneously distributed across the pipe cross section.

Graham and Pullum (2004) investigated the hydraulic transport of low density solid particles at 7.7%, 13.4 % and 25% (v/v) and found that pressure gradients for low concentrations slurries were similar to that of water in turbulent flow. At higher concentrations, turbulent suppression occurred and the pressure gradients were lower than that of water. Pullum et al. (2015) modified the heterogeneous model for Newtonian suspensions and successfully predicted turbulent flow of 0.15mm sand particles in a non-Newtonian aqueous gel. In spite of the success of the model, the authors stated that minimum conveying velocities for coarser suspensions are still required.

Previous work done on the evaluation of tomographic techniques for flow regime characterization was mainly conducted on coarse particles in water and showed that the technique, although requiring refinement, can be used to extract useful information. Pachowko et al. (2003), Giguère et al. (2008), Matousek and Krupicka (2013), Krupicka and Matousek (2014), Faraj and Wang (2012) described the use of ERT for either glass beads or sand particles in water and found the technique enabled the identification of heterogeneous or "homogeneous" flow, although no estimates of transition velocities between the flow patterns were presented. More recently, Faraj et al (2015) applied signal analysis to ERT signals, relating mean concentration and mean square spectrum values to transport velocities, to determine flow regime boundaries. They reported a success rate of 90% based on tests in a 50 mm diameter pipe using coarse sand (.075 – 2.2 mm) at concentrations of 2 and 10% in water, at velocities between 1.5 and 5 m/s. Vlasak et al. (2014) investigated the effect of solids concentration and flow velocity on pressure gradient and solids concentration distribution (flow pattern) in a horizontal, inclined and vertical 100 mm smooth stainless steel pipe. Graded basalt pebbles (8 to 16.0 mm; d50 = 11 mm) were used and flow velocities varied from 1.5 to 5.5 m/s. Since the identification of flow patterns from tomograms is subjective, especially for the transition between homogeneous and heterogeneous flow, they developed a method to directly interpret ERT voltage measurements. Using this technique they were better able to identify homogeneous and heterogeneous flows without the need for image reconstruction. Results presented by Giguère et al. (2008) indicated that a moving bed appeared at a bulk velocity of between 0.9 and 1.1 m/s, increasing in depth as velocity decreased. They found ERT to be a useful tool, capable of detecting pipe slurry flow regimes from stratified to homogeneous flow. For their mixtures and test conditions, Pachowko et al. (2003) observed that once the bed depth exceeded approximately one eighth of the pipe diameter (as indicated by a tomogram) it could stop moving. Only Poloski et al. (2009) presented pressure gradient vs. superficial velocity plots and ERT tomograms for small, dense particles (nominal particle size 10 to 100 μm; density 2500 to 8000 kg/m^3) in water and in kaolin with Bingham plastic yield stresses of 3 and 6 Pa. Superficial velocities ranged from 0.3 to 2.4 m/s in a 76 mm pipe. They found the indicative ERT tomograms to be in agreement with the pressure gradient vs. superficial velocity plots in most cases, especially for critical deposition velocity.

From available literature it appears reliable identification of flow patterns for coarse particles transported in non-Newtonian carrier is still required. This study was conducted to address the identification of flow patterns for coarse particles in non-Newtonian carrier fluids of coarse particles of approximately 0.6 to 5.0 mm in opaque non-Newtonian carrier fluids, at concentrations up to 30% by volume and superficial velocities up to 6 m/s, as might be found in tailings co-disposal applications (Johnson & Vietti, 2003).

2. EXPERIMENTAL FACILITY, MATERIALS AND PROCEDURE

The flow and ERT data were collected in a test loop at the Flow Process and Rheology Centre (FPRC), Cape Peninsula University of Technology. This test loop was an open flow loop with 56 and 80 mm uPVC Class 12 test pipes that could be inclined to +15° (out) and -15° (return). The 56 mm out and return legs were 10.6 m long with a lead in distance to the first pressure tapping on each of 5.2 m. The 80 mm out and return legs were 11 m long, also each with a lead in distance to the first pressure tapping of 5.2 m. The 1500 l mixing tank was fitted with a 2 impellor Turbulator mixer, driven by an 18.5 kW electrical motor via a 3:1 belt reduction and a Variable Speed Frequency Drive (VSD). A Warman 3/2 AH was used for 6% and 10% kaolin carrier tests, with an 18.5 kW motor and VSD. The 15% kaolin carrier tests a Warman 4/3 pump with a 55 kW motor and VSD was used. A heat exchanger was used to maintain slurry temperature at approximately 25 ± 2 ºC. Pressure gradients were measured over 2 (overlapping) lengths in each test pipe, these being 2.54 and 3.64 m in the 56 mm pipes, and 2.50 and 3.64 m in the 80 mm pipes. A floating glass viewing piece within a PVC holder and the ERT rings were fitted within each test section.

The distribution of coarse particles over the pipe cross-section was visualized using the UCT ERT instrument, described in [Dyakowski et al., 2000; Randall et al., 2004;Dicken & Wang, 1996; Wilkinson et al., 2004). Data were recorded simultaneously from a maximum of 4 measurement planes, each with 16 electrodes spaced equidistantly around the pipe circumference, at a total frame rate of 566 frames/sec. The adjacent measurement strategy was used resulting in 104 independent voltage measurements from which to reconstruct an image. Regarding spatial resolution, the 104 independent voltage measurements imply the same number of "elements" to represent the image. This gives $\Delta L/D = 0.087$ (square, $\Delta L \times \Delta L$), or $d/D = 0.098$ (circular, diameter d), so the spatial resolution of the system is effectively about 10% of pipe diameter (Wilkinson et al., 2006). If the response of the instrument is linear, reconstructed images will be homogeneous for step changes in homogeneous conductivity of the test fluid. Voltages acquired for different conductivities and normalized in the range (0, 1) will then overlay exactly. The UCT instrument has an average error of 30% in this regard for the range of conductivities tested (Wilkenson et al., 2006). For stratified flow conditions the bed depth (at the pipe wall) given by ERT results could be qualitatively compared with that observed through a viewing window in the test pipe.

Kaolin slurries were selected as the non-Newtonian carrier fluids, at volumetric concentrations of 6, 10 and 15%. The densities of these kaolin mixtures varied from 1096 to 1236 kg/m^3 and their yield stresses (from curve fitting of wall shear stress τ_w versus nominal shear rate (8V/D) test data) from 7 to 64 Pa. The properties of the kaolin carrier fluids are given in Table 1. Narrowly graded silica sand was used as the coarse material. The d_{50} values of the sand were 1.2 and 3.2 mm (referred to here as 1 and 3 mm sand).

Table 1

Properties of kaolin carrier fluids

Material	**Density (kg/m^3)**	τ_y **(Pa)**	***K*** **(Pa.s^n)**	***n*** **(-)**	**RMSE (%)**
k06ss1	1096	7.34	0.0747	0.6435	1.90
k06ss3	1096	6.90	0.0416	0.7420	1.50
k10ss1	1160	19.35	0.3525	0.5192	1.86
k10ss3	1163	15.65	1.6746	0.3241	1.70
k15ss1	1229	55.46	1.2045	0.5000	1.91
k15ss3	1236	64.16	1.2241	0.5000	1.73

A basic test consisted of measuring a pressure drop for a set flow rate while collecting ERT data. Each test point represents the average of data sampled at 100Hz for 120 seconds. The set range of the flow meter was 0 to 50 l/s for all tests with accuracy of 0.5% of flow velocity V for $V \geq 0.5$ m/s and by (0.25/V)*100% for flow velocity $V < 0.5$ m/s. The ERT instrument calibration refers to a set of measurements made in the homogeneous carrier fluid to account for small amplifier gain and electrode differences. This calibration procedure was repeated for each carrier fluid. Each calibration was done at three different current injection levels, each for 500 and 1000 frame averages, to allow the current to be lowered if necessary as the solids concentration increased during a test, to avoid saturation. Error in pressure gradient for the ranges and measurement lengths varied between 0.2% and 0.7%. Water tests results were within ± 5% of those predicted by the Colebrook-White equation. Tube viscometry tests were performed to determine carrier fluid rheology, and the ERT "calibrations" were done. All the kaolin carriers were characterized as viscoplastic using Herschel-Bulkley rheological model. A fresh batch of kaolin was prepared for testing each sand size. After characterization, sand was added to achieve the volumetric solids concentration for the test mixture, and the pressure gradients were measured.

3. RESULTS AND DISCUSSION

Pressure gradients were measured from the lowest superficial velocity at which the bed was sliding ($V_{m,dep}$) up to a maximum of 4 to 6 m/s. Plots of pressure gradient versus superficial velocity were produced for each kaolin carrier and both sand sizes to evaluate the flow patterns and transition velocities. Figure 1 shows that the shape of the pressure gradients vs. velocity curves changes from the typically layered flow curve at kaolin concentration of 6 and 10% to one that resembles that of the carrier fluid alone at 15% kaolin.

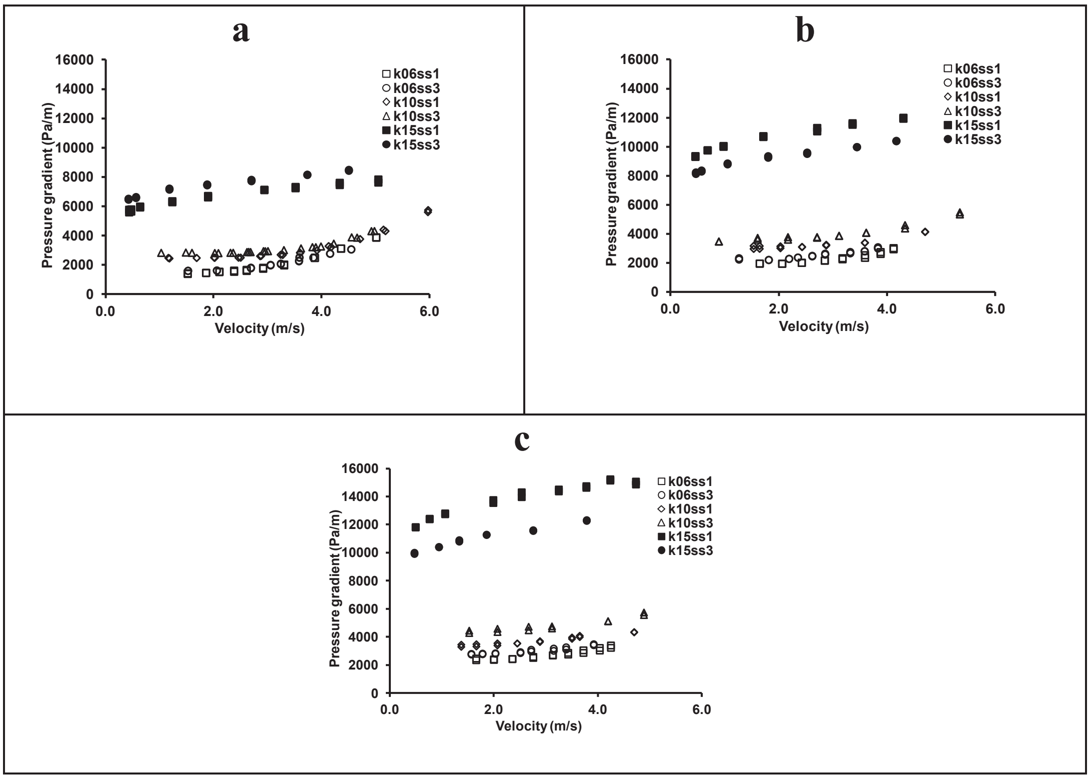
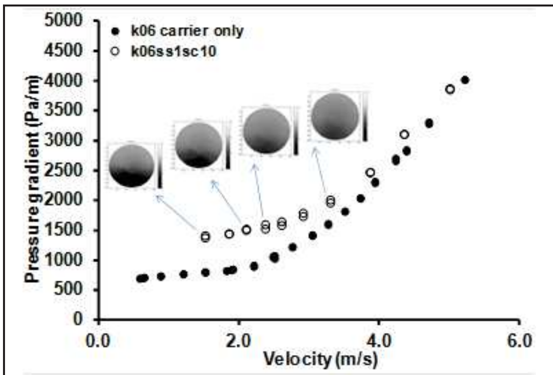
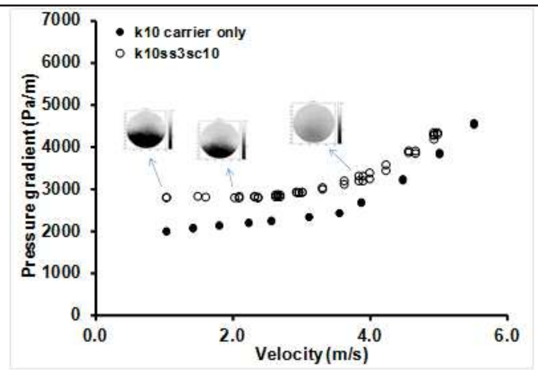


Fig. 1 Pressure gradients for 1 and 3 mm sand sizes at volume concentrations of (a) 10% (b) 20% and (c) 30% in 6, 10 and 15% kaolin carrier fluid

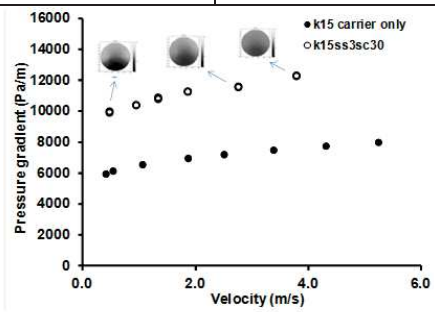
Plots of pressure gradient vs. velocity and selected corresponding pipe vertical centerline “concentrations” derived from the ERT measurements are given. It was observed from the ERT results (Fig. 2) that for 1 mm sand the concentration profiles tend to straighten, becoming almost vertical as the velocity or the carrier fluid concentration increases (where a vertical plot indicates a homogeneous distribution of coarse particles). Examination of the ERT relative conductivity profiles in conjunction with the tomograms enabled the compilation of Table 2, which summarizes flow patterns indicated by ERT measurements for all the mixtures at selected velocities of 1.5, 2.5 and 4 m/s. The flow patterns listed in Table 2 were determined from comparison of the solids distribution plot under consideration and the theoretical concentration profiles defined for each flow pattern in Peker and Helvaci (2008). At low velocity (~1.5 m/s), for the same sand size and concentration the flow patterns changed from moving bed to heterogeneous flow or from moving bed to homogeneous flow as the concentration of the kaolin carrier increased from 10 to 15% for the 1 mm sand. The increase from 6 to 10% kaolin carrier did not induce any change in flow patterns. For 3 mm sand the flow was moving bed regardless of the sand concentration and carrier concentration. For 1 mm sand in 15% kaolin carrier, no stratified bed was evident and the flow pattern tended towards homogeneous. The concentration of sand particles did not affect the flow patterns. At moderate velocities (~2.5 m/s) and moderate to high (20 to 30%) sand concentrations, the effect of carrier concentration on flow patterns was as in the case of low velocities where moving beds were observed, independent of sand size for the 6 and 10% kaolin. At low solids concentration (10%) the flow pattern changed even when the carrier concentration increased from 6 to 10%. Particle size affected the flow patterns in the high concentration (15%) carrier which could suspend the 1 mm sand but could not fully suspend the 3 mm sand. In this case the concentration of particles did not influence the flow patterns. At high velocities (~4 m/s) the 6 and 10% kaolin carrier mixtures were in heterogeneous flow for all sand concentrations and sizes, while the 15% kaolin carrier mixtures were in homogeneous flow with the exception of 30% of 3 mm sand, where the flow was heterogeneous.



6% kaolin carrier fluid with 10% by volume 1mm sand



10% kaolin carrier fluid with 10% by volume 3 mm sand



15% kaolin carrier fluid with 30% by volume 3 mm sand

Fig. 2 Pressure gradients and relative conductivity profiles from ERT

Table 2 compares estimates from both the pressure gradient vs. velocity plots (minimums of the plots) and the ERT tomograms and concentration profiles of the transition velocity at which the flow changed from laminar moving bed (two-layer) to laminar heterogeneous flow. Both techniques indicated similar transition velocities for moving bed to heterogeneous flow for the 6 and 10% kaolin carrier mixtures. No moving bed flow was detected for 1 mm sand in the high concentration (15%) carrier.

Table 2

Flow patterns identified from ERT results for all the tested mixtures

Mixture	**Velocity (m/s)**			**Transition velocity(m/s)**	
	1.5	**2.5**	**4**	**Pressure gradient**	**ERT results**
k6ss1sc10	Moving bed	Moving bed	Heterogeneous	2.8	2.8
k10ss1sc10	Moving bed	Heterogeneous	Homogeneous	2.8	2.8
k15ss1sc10	Heterogeneous	Homogeneous	Homogeneous	3.1	3.4^*

Mixture	Velocity (m/s)			Transition velocity(m/s)	
	1.5	2.5	4	Pressure gradient	ERT results
k6ss3sc10	Moving bed	Moving bed	Heterogeneous	2.7	2.7
k10ss3sc10	Moving bed	Moving bed	Heterogeneous	2.9	$2.9^{\#}$
k15ss3sc10	Moving bed	Heterogeneous	Homogeneous	3.1	3.4^{*}
k6ss1sc20	Moving bed	Moving bed	Heterogeneous	2	2
k10ss1sc20	Moving bed	Moving bed	Heterogeneous	2.4	$2.5^{\#}$
k15ss1sc20	Heterogeneous	Homogeneous	Homogeneous	2.6	$2.8^{\#}$
k6ss3sc20	Moving bed	Moving bed	Heterogeneous	2.6	2.6
k10ss3sc20	Moving bed	Moving bed	Heterogeneous	2.7	2.7
k15ss3sc20	Moving bed	Heterogeneous	Homogeneous	2.7	2.7
k6ss1sc30 k10ss1sc30 k15ss1sc30	Moving bed Moving bed Homogeneous	Moving bed Moving bed Homogeneous	Heterogeneous Heterogeneous Homogeneous	No layer or moving bed	No layer or moving bed
k6ss3sc30 k10ss3sc30 k15ss3sc30	Moving bed Moving bed Moving bed	Moving bed Moving bed Heterogeneous	Heterogeneous Heterogeneous Heterogeneous	No layer or moving bed	$0.4^{\#}$ $0.6^{\#}$ $0.6^{\#}$

* The transition velocity was difficult to see from tomograms - relative conductivity profiles were used. # The transition velocity was difficult to distinguish from relative conductivity profiles - tomograms were used.

4. CONCLUSIONS

ERT tomograms and pressure gradient vs. velocity plots were used to assess the effect of solids on the non-Newtonian settling slurry flow regime transitions. For the same sand concentration and superficial velocity, increasing the kaolin carrier concentration increases the total pressure gradients of the sand-kaolin mixtures and can change the flow pattern from moving bed to homogeneous. Sand concentrations of 10% to 30% by volume affect the magnitude of pressure gradients, but not the flow pattern. Comparison of ERT results with pressure gradient profiles, to identify the transition between moving bed and heterogeneous flow, showed that the two techniques gave similar transition velocities for low (6%) and moderate (10%) carrier concentrations. As the kaolin carrier or the sand concentration increased it became more difficult to distinguish this transition with ERT. Higher carrier concentrations promote more heterogeneous flow with constant excess pressure gradients over a range of superficial velocities, but at much higher total pressure gradients. For the high concentration (15%) carrier both the pressure gradient vs. velocity plots and the ERT results indicated that a heterogeneous model may be more appropriate than a layer model to predict required pumping pressure.

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