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ASSESSMENT OF A TWO-LAYER MODEL FOR LAMINAR PIPE FLOW OF SLURRIES COMPRISING A COARSE FRACTION IN NON-NEWTONIAN CARRIER FLUID

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It has been well demonstrated in the literature that slurries comprising a viscous carrier fluid plus coarse solids fraction segregate under laminar pipe flow conditions. Velocity and concentration distributions in the pipeline are non-symmetrical, with the coarse solids concentrated in a lower layer, with a particle-lean upper layer above. Laminar flow friction pressure gradient versus velocity plots for these flow conditions follow the general appearance of homogeneous laminar flow. However, the segregated, non-symmetrical flow has a significant effect on the friction pressure gradient. In this paper the authors evaluate the performance of a two-layer laminar flow model against measured laminar flow pressure gradient data for kaolin plus sand slurries published by Kabengele et al (2012). The model is based primarily on the work of Pullum et al (2004) as previously described by Fraser & Goosen (2019) and incorporating the concept of a “gelled bed” condition as described by Talmon et al (2004).

KEY WORDS: Laminar flow, non-Newtonian, slurry, rheology

1. INTRODUCTION

Environmental and economic pressures have made transporting high concentration viscous slurries (usually non-Newtonian) more commonplace in tailings disposal applications. Considering the wide particle size distribution typically present in these slurries, the finer particles can be considered to combine with the water to constitute a homogenous non-Newtonian carrier fluid, while the coarser particles are transported in this carrier fluid as a heterogeneous coarse solids load (Talmon & Mastbergen, 2004).

The yield stress of the carrier fluid may be several times greater than that required to balance the submerged weight of the coarse particles. Therefore, under stationary conditions, the coarser particles would be fully suspended in the fluid. However, when the carrier fluid is sheared, the viscosity of the carrier fluid, local to the coarse particle, drops allowing the coarse particle to settle (Cooke, 2002; Pullum & Graham, 2000): The supporting effect of the yield stress is lost. In the laminar flow regime there is no mechanism to re-suspend these particles and consequently these slurries are generally not homogeneous but are stratified, with coarse solids conveyed as a sliding bed and above this bed is a particle-lean upper layer (Pullum et al., 2004).

The stratified flow of a non-Newtonian slurry with coarse particle component under laminar steady-state flow in a horizontal pipe is analysed using a two-layer model as described by L. Pullum et al., (2004) and Talmon et al., (2004). This two-layer concept

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was originally developed by Wilson (1976) for turbulent two-layer flow of coarse solids in a Newtonian carrier fluid.

In this paper the authors evaluate the laminar flow two-layer model described by Pullum et al., (2004), against pipe loop pressure gradient data published by Kabengele et al. (2012) for a range of non-Newtonian kaolin clay carrier fluid mixes transporting silica sand. The analysis assumes a ‘gelled bed’ where the coarse particles in the un-sheared bed are supported by the yield stress of the non-Newtonian carrier fluid (Talmon et al., 2014).

2. STRATIFIED FLOW MODELLING - THE TWO LAYER MODEL

Various stratified or layered models exist in literature (e.g. Gillies & Shook, 2000; Matousek, 1997; Wilson, 1976). Shook & Roco (1991) provide a good description of the Wilson (1976) two-layer model. In this study, the two-layer model of Pullum et al., (2004) is used. The model assumes that all solids that are not part of the carrier fluid are confined in a lower sliding bed layer, with an upper, particle-lean layer flowing above as shown in Figure1.

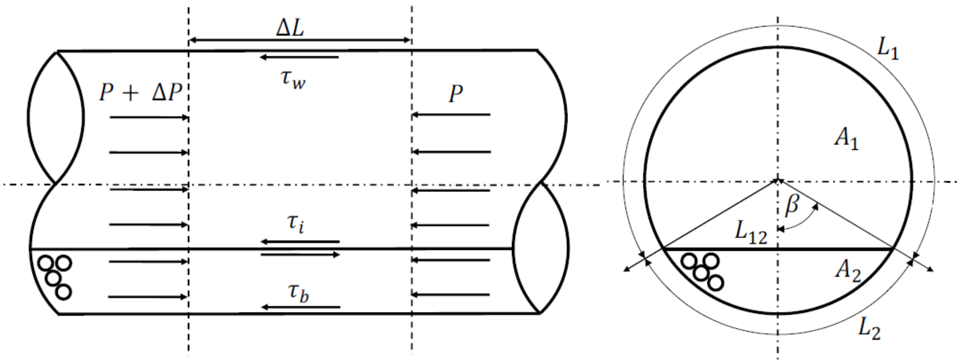

Figure 1. Generic definition sketch for two layer model (*Fraser & Goosen, 2018*)

In Figure 1, A_1 is the cross sectional area of the top layer, A_2 is the cross sectional area of the bottom layer and β is the half-bed angle defining the interface between the top and bottom layers. The forces acting on each of the two layers are evaluated as follows:

- Fluid shear stress at the pipe wall acting on the upper layer (τ_w)
- Fluid shear stress at interface between upper layer and sliding bed (τ_i)
- Fluid shear stress at the pipe wall acting on the sliding bed (τ_b)
- Mechanical friction between the sliding bed and pipe wall (F_r)
- The pressure differential (△P)

The process for solving for Newtonian carrier fluid two layer models (Wilson, 1976) and non-Newtonian carrier fluid two-layer models (Pullum et al., 2004) is to solve for the layer geometry that meets the solids and carrier fluid volume flow continuity, and force balance as shown in Equation 1 and Equation 2:

$$\Delta P\ A_1 = \tau_w D(\pi - \beta)\Delta L + \tau_i D sin(\beta)\Delta L \quad (1)$$

$$\Delta P\ A_2 + \tau_i\ D sin(\beta)\Delta L = \tau_b D\beta\Delta L \quad (2)$$

The main differences between the Newtonian, turbulent flow and the non-Newtonian, laminar flow two-layer model is the evaluation of the shear stresses, the concentration of the bed and the Coulombic friction term. The pressure differential over a unit length of pipe is determined by varying β to solve for the force balance. The analysis procedure used in this paper is explained further in Section 4.

3. EXPERIMENTAL DATA MEASUREMENTS

The experimental data measurements were obtained from Kabengele et al., (2012) experimental study which investigated flow patterns of coarse particles transported in non-Newtonian carrier fluids in a recirculating pipe loop. A typical experimental test involved measuring the pressure drop for a set flow rate and simultaneously logging electrical resistance tomography (ERT) solids concentration profile data.

Kabengele et al (2012) conducted tests in a ø56 mm uPVC pipe loop at the Flow Process and Rheology Centre, Cape Peninsula University of Technology in Cape Town. The pipe loop consisted of the following apparatuses: A mixing tank with a mixer, a heat exchanger, density meter and flow meter, various valves and slurry pumps controlled using variable speed drives (Kabengele et al., 2012).

The non-Newtonian carrier fluids were kaolin clay slurries, at volumetric concentrations of 6%, 10% and 15%. The coarse particles were two narrowly graded silica sands with d_{50} values of approximately 1 mm and 3 mm, with tests performed at sand volumetric concentrations of 10%, 20% and 30%.

Kabengele characterised the kaolin carrier fluid mixes as yield pseudo plastic materials with Herschel–Bulkley model parameters τ_y, K and n. These constants were evaluated from laminar flow data for the carrier fluid from the pipe loop tests. A summary of the rheological properties of the kaolin carrier fluids is given in Table 1. These kaolin carriers were used for transportation of the 1 mm and 3 mm sand size. The test samples presented in the first column of Table 1 were denoted as follows: k06 = kaolin at 6% volume concentration, k10 = kaolin at 10% volume concentration, k15 = kaolin at 15% volume concentration, ss1 = sand size of 1mm and ss3 = sand size of 3mm.

Table 1

Properties of the kaolin carrier fluids

Test Sample	Density (kg/m^3)	τ_y (Pa)	K ($Pa.s^n$)	n (-)
k06ss1	1096	7.34	0.0747	0.644
k06ss3	1096	6.90	0.0416	0.742
k10ss1	1160	19.4	0.353	0.519
k10ss3	1163	15.7	1.675	0.324
k15ss1	1229	55.5	1.205	0.500
k15ss3	1236	64.2	1.224	0.500

Plots of pressure gradient versus superficial velocity were produced for each kaolin carrier and both sand sizes (1 mm and 3 mm) to evaluate the flow patterns and transition velocities. The velocities ranged from 0.5 m/s at which the bed was sliding up to a maximum of 4 to 6 m/s. The pressure gradient loop test results are compared to the pressure gradient results evaluated from the non-Newtonian two-layer model.

4. TWO-LAYER MODEL ANALYSIS METHODOLOGY

The objective of the analysis is to evaluate the non-Newtonian two-layer model for the range of mixtures described in section 3 by comparing the results to the pipe loop test data obtained in Kabengele et al., (2012).

While the kaolin mixtures were characterised as yield pseudo plastic fluids in Kabengele's study, for the two-layer model, the kaolin mixtures were approximated as Bingham plastic fluids. The Bingham plastic properties are given in Table 2.

Table 2

Bingham plastic model rheological properties of the carrier fluid

Sample	Bingham Yield Stress (Pa)	Bingham Plastic Viscosity (Pa.s)
k06ss1	7.66	0.089
k10ss1	20.9	0.0152
k15ss1	65.5	0.0373

The pipe loop constants i.e. pipe diameter, pipe roughness were obtained directly from Kabengele et al (2012).

4.1 TOP LAYER ANALYSIS

The wall shear stress associated with the flow in the upper layer is evaluated by applying the Buckingham equation and applying an equivalent diameter to the upper layer flow area. The interfacial shear stress between the upper and lower layers is evaluated in a similar way, but with the velocity expressed as the difference between the upper layer and lower layer velocities.

4.2 LOWER LAYER ANALYSIS

The lower layer is assumed to be a 'gelled bed' and in this condition the weight of the coarse particles is not transferred through inter-granular contact to the pipe wall (Talmon et al., 2014). Consequently, the mechanical sliding friction component between the coarse solids and the pipe wall is eliminated because the solids in the bed do not interact with the pipe wall Fraser & Goosen, (2018).

The shear stress in the lower layer, between the bed and the pipe wall, results from viscous shear between the bed layer and the pipe wall. This shear stress is approximated by calculating the wall shear stress for the full pipe cross-section and considering the viscous properties of the bed layer.

The viscous properties of the bed layer are determined as described by (Thomas, 1999) considering the rheology augmentation effect of the close packed coarse solids on the carrier fluid yield stress and viscosity. Since the bed packing concentration is unknown, the experimental data set from each suspension type is fitted using the two-layer model to establish this parameter.

4.3 TWO-LAYER MODEL ANALYSIS SOLUTION

The pipeline friction pressure gradient ($\Delta P / \Delta L$ from Eq. 1 and Eq. 2) is determined by varying the half bed angle β (shown in Figure 1) until it satisfies the force balance and volume flow continuity of the carrier fluid and coarse solids. The friction pressure gradient obtained with the two-layer model is compared with the pipe loop experimental pressure gradient data from Kabengele et al., (2012).

5. RESULTS

Figure 2 shows some of the pressure gradient vs. velocity results obtained from the 56 mm pipe loop from Kabengele et al., (2012), together with the results of the two-layer model for the 6%, 10% and 15% kaolin by volume with 1 mm coarse sand at concentration 10% by volume.

The two-layer model was fitted to the pressure gradient data set for each of the slurries shown in Figure 2 by varying the bed packing concentration. It can be seen from Fig 2 that the model had good agreement only for the sand in 6% kaolin carrier fluid, and significantly over-predicts for the sand in 10% and 15% carrier fluid. It is suspected that the model over prediction is due to the flow tending towards homogeneous conditions in this small diameter pipe in the case of the more viscous carrier fluids. The 6% kaolin slurry had the lowest yield stress of 7.66 Pa compared to 20.9 Pa and 65.5 Pa for the 10% and 15% kaolin respectively, resulting in segregating flow – a core assumption of the two-layer model.

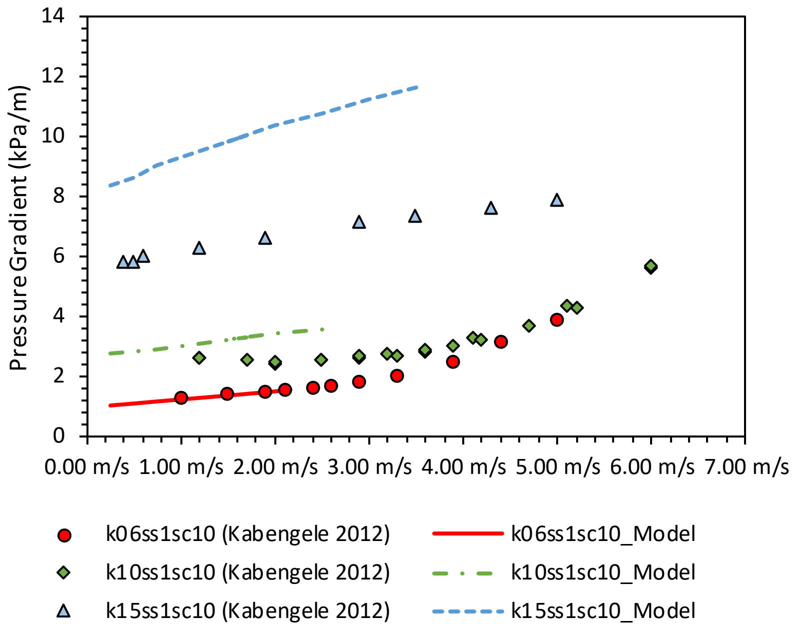

Figure 2. Typical two-layer predictions for the experimental results from Kabengele et al., (2012)

The bed packing concentrations was estimated for the 6% kaolin carrier fluid with varying coarse sand concentrations. The coarse sand concentration was varied at 10, 20 and 30% by volume denoted as sc 10, sc 20, sc 30 respectively. The results are summarised in Table 3. It was found that the bed packing concentration increased with the volume concentration of the coarse sand particles, as well as the size of the coarse sand particles.

Table 3

Estimated bed packing concentration of coarse sand particles for various slurries

Test Sample	k06ss1sc10	k06ss1sc20	k06ss1sc30	k06ss3sc10	k06ss3sc20	k06ss3sc30
Bed packing	38%	46%	50%	42%	50%	54%

Figure 3 shows a parity plot comparing Kabengele et al., (2012) measured data against the predicted pressure gradient data from the two layer model, for a variety of laminar flow data for 6% kaolin plus sand mixtures.

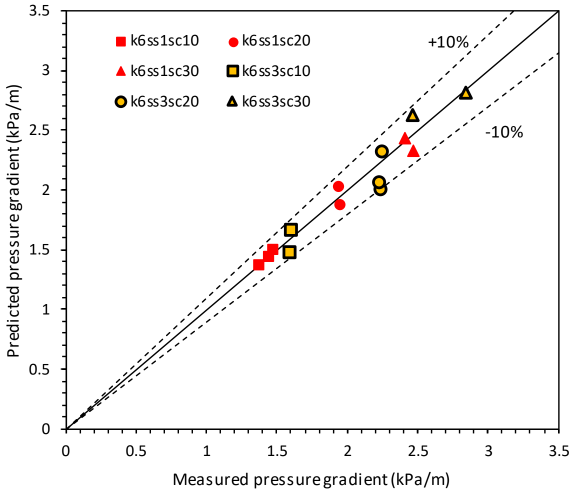

Figure 3. Parity plot comparing measured experimental data points and the two-layer model predicted data.

Figure 3 shows that the two-layer model predicted the measured laminar pressure gradients to within ±10% for the 6% kaolin plus sand mixtures (10%, 20% and 30% volume concentration for 1 mm and 3 mm sand).

Finally, using the ERT measurements from Kabengele et al., (2012), the bed depth to pipe diameter ratio was inferred for all the 6% kaolin plus sand mixtures, and compared to the ratio predicted by the two-layer model. Figure 5 shows a typical ERT output chart from Kabengele et al., (2012). Using the ERT output at a velocity of 1.5 m/s, the bed depth to pipe diameter ratio was measured against the scale. Figure 5 shows a bar graph that compares the bed depth to pipe diameter ratio results predicted using the two-layer model, against the results from Kabengele et al., (2012) ERT output results for all the 6% kaolin plus sand mixtures. It can be seen, from Figure 5, that the model agreement is very encouraging for all mixtures.

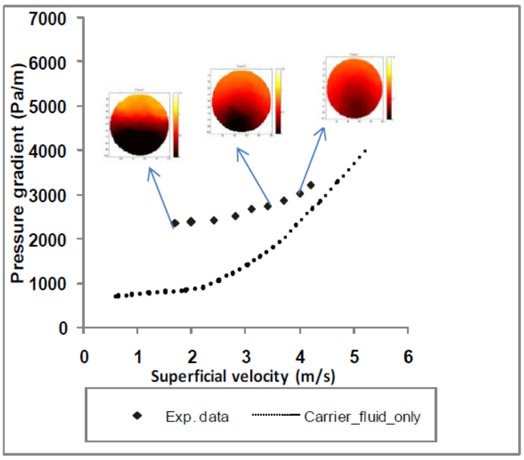

Figure 4. Pressure gradient with concentration profile from ERT (Kabengele et al., 2012)

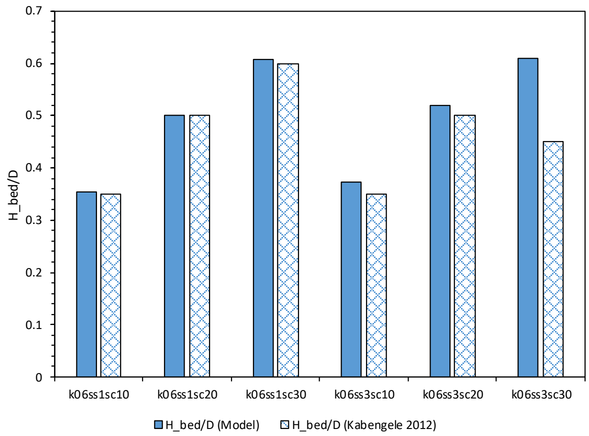

Figure 5. Comparison of the bed depth to pipe diameter ratio from ERT measurements to Two-layer predicted bed depth to pipe diameter ratio.

6. CONCLUSIONS

The Pullum et al. two-layer model was found to capture the slurry laminar flow behaviour well for the 6% kaolin plus sand mixtures. The model predicts the laminar pressure gradient for the low yield stress kaolin carrier fluid (6%) slurries to within ±10%. The predicted bed depth was also compared to ERT measured data and was found to be in excellent agreement.

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