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LABORATORY TESTING OF PIPE FLOWS OF BIMODAL COMPLEX SLURRIES

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This paper deals with pipe flow of coarse solids in non-Newtonian carrier. In industrial practise, such complex flows occur for instance in transportation of thickened tailings. We study transport characteristics of such flows using a laboratory analogue in the form of different fractions of glass beads in Carbopol carrier. We test a possibility to use a multi-component model developed originally for slurries with Newtonian carrier to predict frictional head loss in the non-Newtonian based turbulent flow of complex slurry in pipe.

KEY WORDS: non-Newtonian, rheological properties, suspension, component model, tailings.

NOTATION

C_v	volumetric concentration	[-]
D	pipe diameter	[m]
d_h	particle diameter	[m]
du/dy	strain rate	[s^{-1}]
K	coefficient of consistency	[-]
k	scaling coefficient	[-]
n	flow index	[-]
S	relative density	[-]
V_{50}	reference velocity	[$m \cdot s^{-1}$]
V_m	mean velocity	[$m \cdot s^{-1}$]
V_{sm}	deposition limit velocity	[$m \cdot s^{-1}$]
μ_{eq}	equivalent (secant) viscosity	[$Pa \cdot s$]
ν_r	kinematic viscosity ratio	[-]
ρ	density	[$kg \cdot m^{-3}$]
τ	shear stress	[Pa]
τ_y	yield stress	[Pa]

1. INTRODUCTION

Pipeline hydraulic transport has been considered a progressive technology for conveying large quantities of bulk materials for almost one century. Hydrotransport has been associated with long distance hauling of coal, minerals, ore and other solids commodities, as well as with dredging and mineral processing like backfilling, collection and disposal of solids wastes. Compared to mechanical transport, the hydraulic transport through a slurry pipeline ensures a dust free environment, demands substantially less space, makes full automation possible, while minimum number of operating staff is required. On the other hand, high quality of pumping equipment and control systems is demanded. Some high-concentrated fine-grain slurries of industrial interest exhibit a viscoplastic behavior and if a coarse solids fraction is present in the mixture as well, its contribution to the frictional head loss must be taken in account. An aim of the work presented in this paper is to examine suitability of the four-component model originally by Sellgren and Wilson (2007) to predict transport properties of complex slurries once the non-Newtonian carrier is incorporated as in the model modification by Pullum et al. (2015).

2. MODELLING APPROACH

For turbulent flow of complex slurries with broad spectrum of particle sizes, Pullum et al. (2015) suggested to modify the four-component model originally presented by Sellgren and Wilson (2007). The original four-component model is based on well-established semi-empirical formulas for Newtonian turbulent flows of each of the components. A total pressure gradient predicted by the component model is given as the sum of pressure gradients predicted for each component (fraction). Pullum et al. (2015) modified the model so that it considered three components in non-Newtonian carrier fluid (carrier-equivalent, heterogeneous, fully-stratified). The frictional head loss of the turbulent flow of the carrier was calculated by the Wilson-Thomas (1985) method. The method provided fairly accurate predictions for tested Carbopol solutions and thus laid a solid basis for the non-Newtonian three-component model.

To apply the component model, a special attention must be paid to a determination of two characteristic velocities employed in formulae for two components (heterogeneous component, stratified component). A formula for the heterogeneous component considers a reference velocity V_{50}. By its definition, the reference velocity V_{50} represents a value of the mean velocity, at which one half (by volume) of particles of the heterogeneous component is transported as suspended load and the other half as contact load. Therefore, it expresses the effect of particle suspension mechanisms as carrier turbulent diffusion and hydrodynamic lift and it is given by equation:

$$V_{50} = 44.1 d_h^{0.35} \left(\frac{S_s - S_e}{1.65} \right)^{0.45} \nu_r^{0.25} \quad (1)$$

where S_s and S_e are relative densities of solids and carrier fluid respectively and d_h (m) is the particle size. ν_r is the ratio of the kinematic viscosity of the carrier fluid to that of water at 20°C.

A formula for the stratified component employs the deposition limit velocity V_{sm}, which is the mean velocity of mixture flow at which solid particles start to form a stationary deposit at the bottom of a pipe. To authors' knowledge, there is no method available for a prediction of V_{sm} in slurry flows with non-Newtonian carrier (the non-Newtonian slurry deposition method by Poloski et al., 2009, predicts threshold velocities different from the deposition-limit velocity). In fully stratified flows, it is possible to calculate V_{sm} using a non-Newtonian two-layer model (e.g. Matoušek et al. 2015). For a determination of V_{sm} in the non-Newtonian three component model, it seems appropriate to look at the possibility to apply/modify the V_{sm} method (Wilson 1986) used in the original Newtonian four-component model. We test the option to implement non-Newtonian effects on V_{50} and V_{sm} through applying the equivalent viscosity μ_{eq} in calculations of the velocities. The equivalent viscosity parameter μ_{eq} is defined as:

$$\mu_{eq} = \frac{\tau}{\left(du / dy \right)} \tag{2}$$

For carrier fluid obeying the Herschel-Bulkley rheological model, the equivalent viscosity reads:

$$\mu_{eq} = \frac{\tau_y + K\left(V_m / D\right)^n}{V_m / D} \tag{3}$$

where τ_y is yield stress, V_m is mean velocity and D is pipe diameter.

3. EXPERIMENTAL WORK

3.1. EXPERIMENTAL RIG

Series of experiments were carried out in Water Engineering Laboratory of the Czech Technical University in Prague. A pipe loop (Fig. 1) was used to study the slurry flow behaviour. The loop was composed of pieces of a PE pipe (I.D. 51.4 mm, blank pipe in Fig. 1) and a piece of transparent acrylic pipe (I.D. 50.0 mm, grey pipe in Fig. 1). The total length of the loop was 22.96 m and its volume was 45.08 liter. The length of the horizontal section was 6.20 m. The pump EBARA 3M 40-200/7.5 kW was driven by an electric motor with a variable frequency converter TECO GD100-011G-4 11 kW. Pump parameters were: power 7,5 kW, impeller diameter 200 mm, maximum flow 11.67 l/s, total head from 58 m to 44 m (valid for water for maximum flow).

Differential pressures were measured over vertical Sections 1, 2 (1.3 m long) and the horizontal Section 3 (1 m long) using the differential pressure transducers Fischer Rosemount DP1151 (Sections 1 and 2) and the transducer Siemens Sitrans P DSIII

(Section 3). An electromagnetic flow meter Krohne Optiflux 5000 was used to measure the flow rate in the vertical pipe mounted to the discharge outlet of the centrifugal pump. The temperature of the flowing medium was measured in the vertical invert pipe. The rheology of fluids was determined in the rotational viscometer HAAKE VT550.

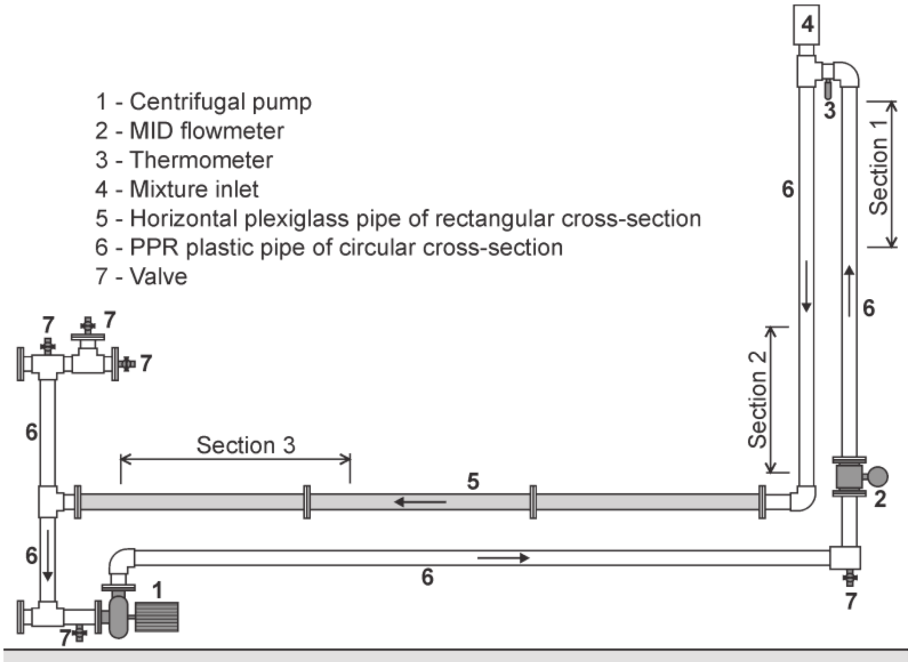

Fig. 1 Test pipe loop in Water Engineering Laboratory of CTU in Prague

3.2. CHARACTERIZATION OF MATERIALS

Tested mixtures were composed of Carbopol (Ultrez 10) carrier and fractions of glass bead. Carbopol is an acidic powder of particle size from 2 to 7 microns. After solution in water and neutralization, it forms a non-Newtonian (viscoplastic) fluid of Herschel-Bulkley type (rheology typical for thickened tailings). Values of the rheological parameters (τ_y, K, n) depend on a concentration of the powder in the solution. An advantage of Carbopol is its transparency and a quite simple preparation of solutions of various concentrations.

Table 1.

Solids parameters

Solids fraction	d_{18} [mm]	d_{50} [mm]	d_{84} [mm]	ρ_s [kg.m^{-3}]
B134	0.16	0.18	0.24	2460
B7	0.58	0.64	0.69	2452
TK1.5	1.52	1.55	1.59	2488

Three fractions of glass beads were used as conveyed solids (Table 1). The finest particle fraction B134 consisted of particles of sizes from 0.1 to 0.2 mm with the median size d_{50} = 0.18 mm and density ρ_s = 2460 kg/m^3. The B7 fraction was narrow graded (grain sizes from 400 to 750 microns) with d_{50} = 0.64 mm. The coarse fraction TK1.5 was virtually monodisperse with d_{50} = 1.55 mm, the sieving test showed that all grains were finer than 1.61 mm and coarser than 1.49 mm.

3.3. TYPICAL EXPERIMENTAL RESULTS

Pipe friction curves were measured for flows of slurries of different liquid and solids properties. Fig. 2 compares measured curves for the Carbopol carrier alone, for slurry of Carbopol and a coarse glass bead fraction (TK1.5), and for Carbopol-based slurry composed of three fractions of glass beads (B134+B7+TK1.5), each representing one component (carrier-equivalent-fluid, heterogeneous, stratified) of the 3-component slurry. Total volumetric concentration of solid fractions is 20 per cent for both slurries. The shape of the curves indicates that flow was laminar up to approximately 3 m/s. The deposition-limit velocity was 0.15 m/s for the TK1.5-slurry and 0.2 m/s for the 3-component slurry.

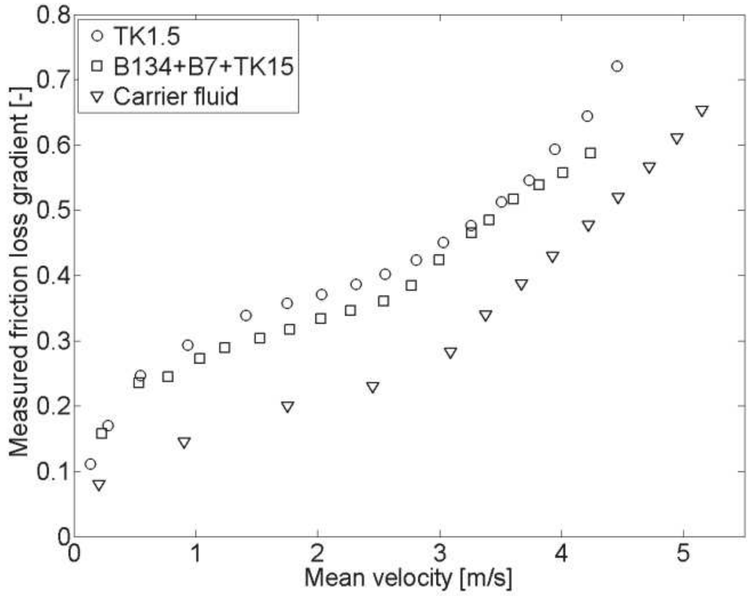

Fig. 2 Pipe friction curves measured in CTU test loop

4. DISCUSSION OF EXPERIMENTAL RESULTS

We use the three-component model by Pullum et al. (2015) to calculate frictional head losses for the sake of comparison with experimental results. Friction loss predictions are fitted to experimental data in turbulent flow regime and evaluated on the basis of the root-mean square error. The experimental database contains 15 test series with a volumetric solids concentration between 0.1 and 0.3. More detailed information about the test series, specified flow conditions and rheological properties is published elsewhere (Kesely 2016).

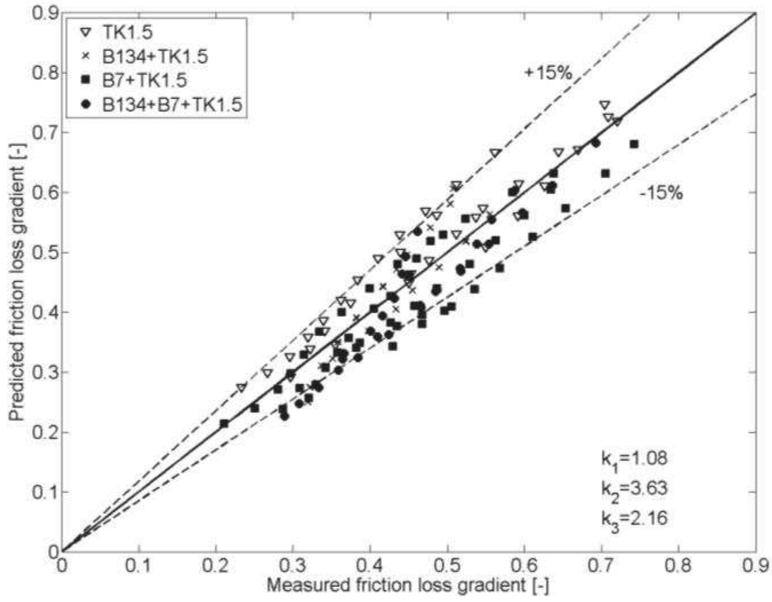

Fig. 3 Parity plot comparing observed and predicted friction loss gradients for variety of suspensions using the three component model and fixed values of scaling constants k_1 for carrier-equivalent component, k_2 for heterogeneous component, and for k_3 stratified component.

For all experimental data subjected to a comparison with the three-component model, values of Reynolds number are determined to check on the validity of turbulent flow regime. In the component model, the relative densities are calculated as in Sellgren et al. (2016). The measured parameters (τ_y, K, n, d_h, ρ_s, C_v) and calculated parameters (μ_{eq} by Eq. 3, V_{50} by Eq. 1, and V_{sm} by Wilson method as in the program VSCALC in Wilson et al. 1997) are used to calculate the frictional hydraulic gradient. The scaling constants for the three fractions contributing to the overall hydraulic gradient are set to: k_1 = 1.08 (B134-fraction), k_2 = 3.63 (B7-fraction), k_3 = 2.16 (TK1.5-fraction) (Fig. 3).

Although the model predictions of the frictional hydraulic gradient exhibit a very reasonable agreement with the experimental results for all types of tested slurries (for the different types of slurries see Legend of Fig. 3), a prediction of the deposit velocity V_{sm} used in calculating the hydraulic-gradient contribution by the stratified component is very unsatisfactory.

The values of V_{sm} calculated by VSCALC using the equivalent viscosity are considerably larger than the observed values (Fig. 4). The disagreement is not surprising if we realize that the observed deposition limit velocity actually occurred in laminar flow and way below the transition velocity. Hence, the use of VSCALC (originally for turbulent Newtonian flows) to calculate V_{sm} proved to be inappropriate for our conditions. In the component model, the pressure loss due to the stratified component is quite sensitive to V_{sm}. Just to get some sense for values, if visually observed values of the deposition limit velocity were increased with 1 m/s, the resulting values of predicted pressure gradient from stratified load fraction increased with approximately 50%. On the other hand, a contribution of the stratified component to the total hydraulic gradient tends to be relatively low while the viscous contribution of the carrier dominates (see Fig. 2).

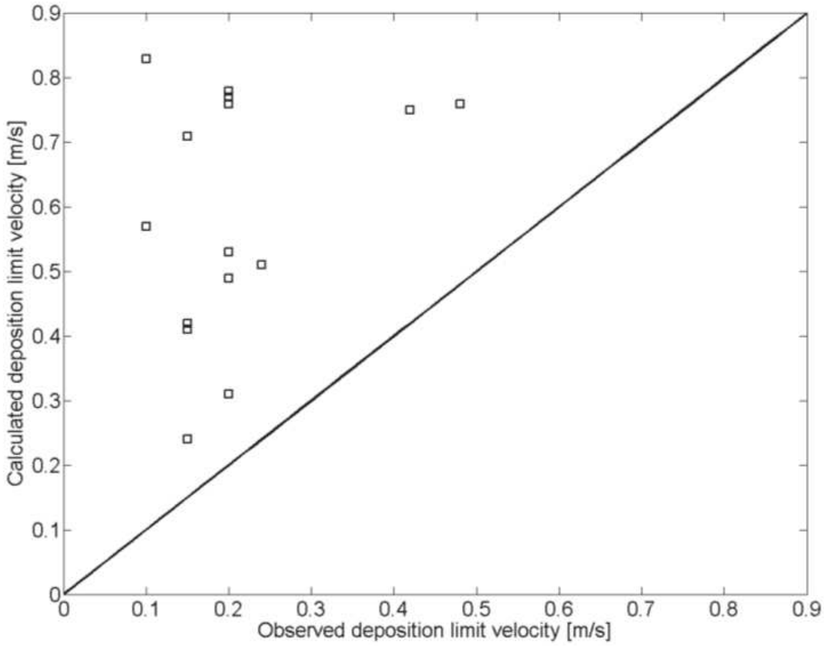

Fig. 4 Parity plot comparing observed and predicted deposition limit velocities

The use of μ_{eq} in a V_{50} calculation using Eq. 1 leads to both over prediction and under prediction of the hydraulic gradient by the heterogeneous component. The hydraulic gradient by the heterogeneous component is sensitive to V_{50}, hence an appropriate modification of Eq. 1 or a use of an alternative approach is suggested.

5. CONCLUSIONS

The results of experimental investigation of predicting frictional pressure drop in turbulent flows of slurries composed of mixtures of different solids fractions and viscoplastic carrier showed that the three-component model by Pullum et al. (2015) is suitable and reasonably accurate.

However, caution is required in predicting the reference velocities V_{50} and V_{sm} in the model. Modifications of formulae calculating both reference velocities are required and are subject to further research.

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