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COARSE-PARTICLES CONVEYING IN PIPES

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Abstract: *Flow behavior of coarse-grained slurry depends generally on particle size, shape, density and concentration. The present paper describes the results of experimental investigation of the model coarse-grained slurries on the pipe loop of inner diameter 36 mm with smooth pipes. Graded pebble gravel and glass balls conveyed in water were studied. Research was focused on evaluation of the effect of slurry velocity and concentration on hydraulic gradient versus slurry velocity relationship and the slurry flow behavior. Particle distribution in the pipe vertical cross section and motion of particles along the pipe bottom were studied in a transparent pipe section.*

Keywords: ***Coarse-grained slurry, gravel-water mixture, pressure drops, flow structure.***

1. Introduction

Many materials of commercial and industrial interest are handled and transported in the form of slurries in pipes that requires advance knowledge of their flow behavior in pipes, which is important for the safe and economical design of the transport technology.

The internal friction in the conveyed slurry and the friction between the pipe and the slurry produce pressure drops, which determine the power consumption and the technology of pumping. The pressure drops depend on the flow velocity, solids concentration, density, shape, and size distribution of the conveyed solid material, the size and roughness of the pipe, and also the mutual particle-liquid, particle-particle, and particle-pipe interactions. Power consumption represents a substantial portion of the pipeline transport operational costs. For that reason great attention was paid to the reduction of hydraulic losses. One possibility of the power requirement reduction, besides the use of macromolecular or micellar additives, is based on the use of optimal particle size distribution or on addition of a small percentage of fine particles (Vlasak & Chara, 2010; Vlasak et al., 2004).

The present paper describes experimental investigation of two different coarse-grained slurries on pipe loop with smooth pipes. The slurry flow behavior was experimentally investigated with respect to the effect of solid concentration and focused on the hydraulic gradient versus the slurry average velocity relationship. The studied slurries are model slurries for a pipeline transport and handling of poly-metallic nodules (PMK) mined from the sea bottom at a depth of several km (Sobota et al., 2009)

2. Experimental equipment and material

The slurry flow parameters were measured on an experimental re-circulation pipe loop with a test section of smooth stainless steel pipes with inner diameter D = 36 mm (Vlasak & Chara, 2010). The slurry was forced by a booster pump WARMAN 3/2 C – AH from an open storage tank, a variable speed drive was used to control slurry flow rates. The measurement section was equipped with three Hottinger-Baldvin PD-1 differential pressure transducers monitored by a computer. The slurry flow rate and concentration were measured by a KROHNE-CORIMASS-800 G+ mass flow-meter. The temperature of the slurry was maintained at about 12 °C by the heat exchanger. A two meter long transparent section was used for a visual observation of flow pattern of particle movement, which was recorded using the digital camera NanoSenze MKIII+ with a frequency up to 2 000 frames per second.

The effects of the two different solid materials, flow velocity V_s, and volumetric concentration c_v on pressure drops, slurry flow behavior and pattern were studied experimentally. Graded washed pebble

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gravel and glass balls were used as solids. The measured suspensions consisted of bulk materials of different particle shape, but of the same mean diameter, d_{50} = 6 mm. The glass balls were of uniform size (particle diameter d = 6 mm, density ρ_p = 2 540 kg/m^3), the graded pebble gravel has a narrow particle size distribution (d ranged from 4 to 8 mm, ρ_p = 2 650 kg/m3). Water was used as the carrier liquid. The volumetric concentration of the studied slurries reached relatively low values (c_v ranged from 2.6 to 13.4%), which reflects the supposed concentration in nodules transport.

3. Results and Discussion

Heterogeneous slurries may be defined as the flow with asymmetrical concentration and velocity distribution and a Coulombic friction contribution to the friction losses (Coulombic friction is slightly velocity-dependent). The threshold (deposition critical) velocity is a very important parameter for heterogeneous slurries; it is of the same importance as friction losses for design and operation.

For heterogeneous slurries many empirical correlations exist, which can be successfully used after calibration (Vlasak, P. & Chara, Z., 2009). The empirical model developed by Durand (1951) for the horizontal flow and monodisperse particle size distribution was constructed by the using of dimensional analysis. Based on the experimental results the following relationship was proposed for the slurry hydraulic gradient

$$\varphi = (i_s - i_o) / i_o . c_v = K \left[Fr / \sqrt{Fr_w (\rho_p / \rho_o - 1)} \right]^{-\alpha} = \beta . Fr^{-\alpha} \quad , \tag{1}$$

where i_o and i_s are the carrier liquid and slurry hydraulic gradient, respectively, c_v is the slurry concentration, $Fr = V_s^2 /gD$ and $Fr_w = w_{50}^2 /gD$ are the slurry and mean particle Froude numbers, D is the pipe diameter, ρ_o and ρ_p are water and the particle density, respectively, w_{50} is the fall velocity of a medium particle. The Durand model can be used to scale up the frictional pressure drops of the sand and gravel slurries at medium velocities, supposing the material parameters are determined experimentally (Vlasak & Chara, 2011). Its disadvantage is that it does not reflect different slurry flow patterns, especially fully stratified and fully suspended flow patterns.

For this reason the so-called two-layer model, which applies the conservation equations to a large control volume of slurry, was developed. In the chosen volume (e.g. a pipe cross sectional area of a unit length with approximately uniform concentration of solids) the conservation equations are formulated using averaged quantities over the control volume. Wilson (1976) considered a fully stratified flow in which all particles are concentrated in the lower portion of the pipe (concentration in the layer near the bottom approaches the loose-packed value) and the Coulombic contribution to particle-wall friction is dominant. The RSC two-layer model (Shook & Roco, 1991, Saskatchewan Research Council, Canada) is based upon force balance for the horizontal layers:

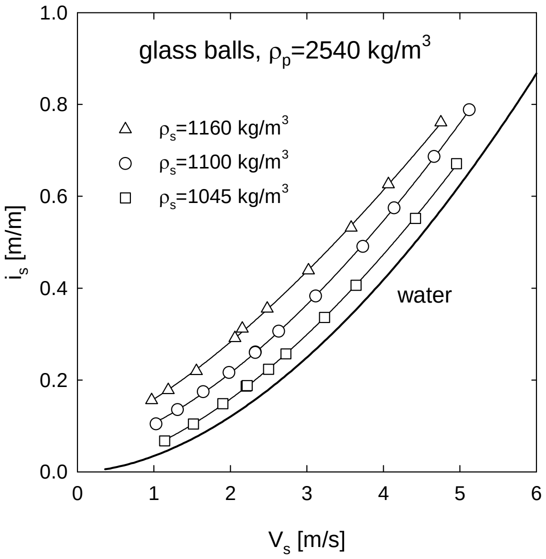
upper layer
$$- dP / d_z = (\tau_1 S_1 + \tau_{12} S_{12}) / A_1 \, , \tag{2}$$

lower layer
$$- dP / d_z = (\tau_2 S_2 + \tau_{12} S_{12} + F_2) / A_2 \, , \tag{3}$$

where τ_1, τ_2 and τ_{12} are kinematical stresses, S_i is responsible partial perimeter and A_i is responsible cross-sectional area, F_2 is Coulombic force. The model satisfied the material balance constraints on total flow and solids transport rate for V_i as bulk velocity in the respective layer or total in situ solids concentration C_i is related to the partial concentrations by

$$AV = A_1 V_1 + A_2 V_2 \text{ and } C_v AV = C_1 A_1 V_1 + C_2 A_2 V_2 \text{ or } C_v A = C_1 A_1 + C_2 A_2 \tag{4}$$

All above mentioned quantities, including Reynolds number, friction factor, and Coulombic friction are defined for each layer as well as the interfacial friction factor f_{12} and the flow parameters could be determined. The model may be used for description of the stratified flow and prediction of the deposition-limit velocity, pressure drop due to friction, thickness and translational velocity of the sliding-bed, and also the value of the mean slip between the solid and liquid phases (Matousek, 1997; Matousek, 2007).



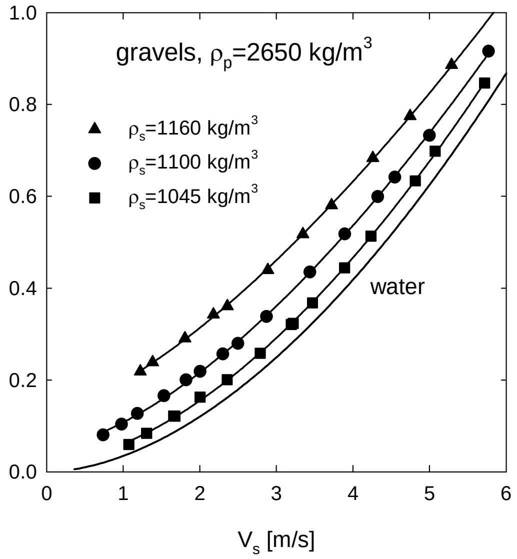
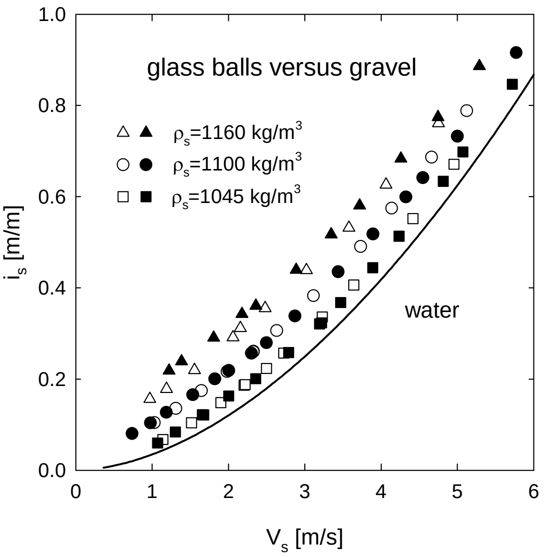


Fig. 1: Hydraulic gradient i_s vs. average slurry velocity V_s for glass slurries.

Fig. 2: Hydraulic gradient i_s vs. average slurry velocity V_s for gravel slurries.



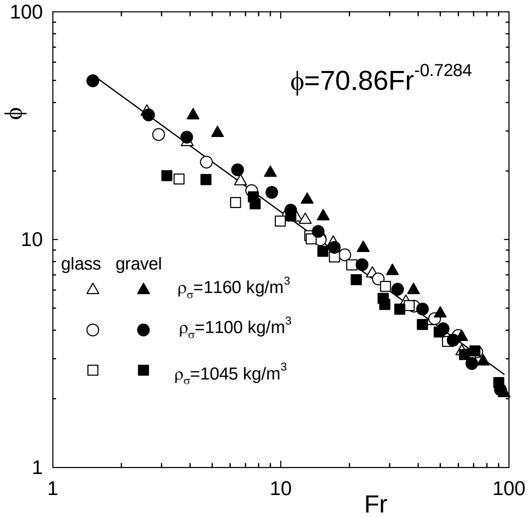


Fig. 3: Comparison of i_s/V_s relationship for glass balls and gravel slurries.

Fig. 4: Plot of Durand function φ versus slurry Froude number Fr.

The effect of solids concentration and slurry average velocity on the hydraulic gradient ratio i_s vs. the slurry velocity V_s relationship of glass balls and pebble gravel slurries is illustrated in Figs. 1 and 2. The effect of particle concentration depends on the slurry velocity, i.e. it slightly increases with increasing velocity. This behavior can be described by a model of equivalent liquid

$$i_s = i_o + B\,(\rho_s/\rho_o - 1), \tag{5}$$

where B is a coefficient, which gives the proportion of suspended solids that contribute to the viscous shear stress at the pipe wall. Because density of both solid materials slightly differs the densities were used for comparison of the slurries instead of volumetric concentration, which is for gravel slurries with the same density as glass balls slurry slightly lower.

It follows from Fig. 3, that the effect of particle shape is negligible, pressure drops for measured slurries of densities ρ_s = 1 045 and ρ_s = 1 100 kg/m^3 are practically the same. A slight difference was found out for the higher slurry density ρ_s = 1 160 kg/m^3, the difference increases with decreasing slurry average velocity. For lower slurry velocities can play a role that gravel particles are slightly different size and the bigger particles slide along the pipe bottom as against the glass balls, which move in rolling patterns even for low flow velocities.

Interesting is that even for the studied very coarse particles (compared with pipe) the Durand model describes well the hydraulic gradient for slurries of density ρ_s > 1 100 kg/m^3 (i.e. concentration c_v > 5%). For lower concentrations it is valid when Fr > 8 (i.e. V_s > 1.7 m/s). It can be explained by the visually confirmed fact that glass particles similarly as gravel particles do not move in a continuous layer along the pipe bottom. Probably with regard to their size they originated significant eddies in the bottom layer of pipe, mainly for higher flow velocities. They influence motion of individual particles, help them to reach a saltation pattern or in some case even to move fully suspended in the carrier liquid.

4. Conclusions

The Durand model or two-layer model approximated well the flow behavior of coarse-grained slurries in the turbulent region. Accuracy of the models is influenced by the model parameters, which should be verified or determined experimentally.

The Durand model can be used for prediction of the frictional pressure drops, better for higher velocities. For fully stratified heterogeneous slurries, the two-layer model provided a good approximation. The glass balls slurry reaches nearly the same hydraulic gradient as the narrow-sized pebble gravel slurry of the same size of particle mean diameter, the difference decreases with decreasing concentration.

The study revealed that coarse particles moved in the pipe in a layer close to the pipe bottom, however for higher flow velocities and concentration saltation of particles was observed and particles moved also in the central area of the pipe.

Acknowledgement

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