International Journal of Multiphase Flow 65 (2014) 31–37

Contents lists available at ScienceDirect

International Journal of Multiphase Flow

journal homepage: www.elsevier.com/locate/ijmulflow

Modelling the critical velocity for heterogeneous flow of mineral slurries

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ARTICLE INFO

Article history:
Received 25 June 2013
Received in revised form 7 March 2014
Accepted 20 May 2014
Available online 29 May 2014

Keywords:
Critical deposition velocity
Pipeline
Coarse particles
Shape factor

ABSTRACT

This paper reports and discusses results from pumping experiments conducted with heterogeneous slurries containing coarse particles of apatite and hematite industrial concentrates and quartz, clustered in two ranges of particles size (d): Class 1 ($0.210\ \text{mm} < d < 0.297\ \text{mm}$), and Class 2 ($0.105\ \text{mm} < d < 0.149\ \text{mm}$). Using two recirculating pipeline testing loops of pipe diameter (D) of 25 mm and 50 mm and mineral slurries with volumetric concentrations ranging from 8% to 27%, it was possible to vary bulk flow velocity (V) and measure the horizontal pipe pressure gradient ($\Delta P/L$). The results were depicted by curves $\Delta P/L$ versus V. The limit of particle deposition in the pipe was addressed as a *critical velocity* (V_C) of slurry flow at which a moving bed of particles started to form on the bottom of the pipe. Based on the experimental results, a model was proposed to predict V_C using process variables, yielding a deviation of less than 10% from the predicted versus observed data. The sensitivity of the input variables can be evaluated from the magnitude of the powers term of any process variable.

1. Introduction

The hydraulic transport of slurries containing coarse particles ($d > 0.105$ mm) poses an important challenge for pipeline design and operation because it is usually conducted under flow conditions which are very close to the limit of particle deposition (Jacobs, 1991). Conversely, particles of diameter smaller than 0.105 mm are poorly influenced by inertial effects and eventually form homogeneous slurries, where the particles are well distributed across the cross sectional area of the pipe and the inertial effects do not exert a major influence on the bulk slurry velocity (Wasp et al., 1977; Wilson et al., 2006).

Regarding heterogeneous slurries, where the inertial effects present an important role on the slurry velocity and the particles are not well distributed over the cross sectional area of pipe, to achieve stable operation of a pipeline, bulk slurry velocity (V) must be equal to or greater than a particular value at which a moving bed of particles starts to form at the bottom of the pipe and turbulent suspension still exists in its upper part. Wasp and Slatter (2004) called it *deposition velocity* (V_D), but other authors have also addressed the limits of particle deposition to another term named *critical velocity of deposition* (V_C), which has been used rather loosely in the literature because there is a lack of a common basis to define it. Therefore, although literature reports several models attempting to correlate the limits of particle deposition (V_C or V_D) to system variables (pipe diameter, particle size and density, concentration of solids in the slurry, amongst others), it has been particularly difficult to benchmark them (Wasp et al., 1977; Wasp and Slatter, 2004; Wilson et al., 2006).

Regardless of using V_C or V_D to characterize the limit of particle deposition in a pipeline, its realistic prediction constitutes an essential assessment for correct pipeline design and stable operation (Wasp et al., 1977). Gillies et al. (2000) reviewed numerous correlations attempting to predict bulk flow velocity at which particle deposition occurs in pipes. The models proposed by Wilson and Judge (1976), and also by Thomas (1979), are particularly interesting because they address theoretical concepts to an empirical approach and its application embraces a broad spectrum of fluid properties and pipe diameters. Approaching fine particles in homogeneous slurries, Wasp and Slatter (2004), considered V_D and V_C as the same limit condition for particle deposition and proposed a model to correlate V_C with system variables (pipe diameter, solids volumetric concentration, particle size and density, slurry viscosity). As a complement for the latter model, this paper approaches the critical deposition velocity (V_C) of coarse particles of minerals (apatite, hematite and quartz) which are largely exploited, processed and transported around the world. Unlike

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http://dx.doi.org/10.1016/j.ijmultiphaseflow.2014.05.013
0301-9322/

other models found in current literature, this paper probes the influence of the shape of coarse particles on V_C by including the sphericity function (Ψ).

2. Background

The limit of deposition (V_D or V_C) of coarse particles in a pipe plays a major role in the formation of an undesirable stationary bed of solids on its bottom. Because of this, pipeline designers usually aim at deposition free flow by favouring the dominance of turbulent forces over gravity, maintaining the bulk slurry velocity (V) well above V_C. However, several reasons (mainly economical) have led the operation of industrial pipelines at lower values of V, and unable to avoid the formation of a particle bed on the bottom of the pipe (Matousek, 2009).

A method for predicting the limit slurry flow velocity (V_C) which allows the occurrence of a moving bed of particles on the bottom of a pipeline was deduced from a two-layer model developed by Wilson and Judge (1976), as depicted in Eq. (1). The results were also presented in nomographic form (Wilson, 1976) which has its application for particles ($d > 0.15$ mm) and pipe diameter (D) greater than 100 mm.

$$V_D = 2.0 + 0.3\log\left(\frac{d}{D \cdot C_D}\right) \cdot [2 \cdot g \cdot D(S-1)]^{0.5} \tag{1}$$

where V_D – deposition velocity, m/s; D – pipe diameter, m; d – particle diameter, m; g – gravitational acceleration, m/s^2; C_D – drag coefficient; S – relative density of solid/fluid.

Considering as fine those particles which exhibit a diameter smaller than the thickness (δ) of the viscous sub layer, as shown by Eq. (2), Thomas (1979) maintained that they exert a significant effect on the deposition velocity (V_D), as depicted by Eq. (3). The shear velocity is given by Eq. (4).

$$\delta = \frac{5\mu}{\rho_f V^*} \tag{2}$$

$$\frac{V_D}{V^*} = 0.068 \cdot \left(\frac{d \cdot V^* \rho_f}{\mu_f}\right)^2 \tag{3}$$

$$V^* = \sqrt{\frac{\tau_o}{\rho}} \tag{4}$$

where δ – thickness of the viscous sub layer, m; V^* – shear velocity, m/s; μ and μ_f – fluid viscosity, Pa s; ρ_f – fluid density, kg/m^3, τ_o – shear stress at the flow boundary, Pa; ρ fluid density, kg/m^3.

Based on the assumptions of Thomas (1979), Wasp and Slatter (2004) developed a predictive model for deposition velocities for slurries composed of fine particles. However, it included coal slurries that bear heterogeneous characteristics at low velocities. The proposed model is described by Eq. (5), which is based on industrial pipes whose diameter lay in the range of 203–458 mm. Reasonable agreement between predicted versus experimental data was achieved.

$$V_D = 0.18 \cdot (S-1)^{0.5} \cdot \left(\frac{d_{95} \cdot \rho_s \cdot \sqrt{gD}}{\mu_f}\right)^{0.22} e^{4.34 \cdot C_V} \tag{5}$$

where ρ_s – solid density, kg/m^3, d_{95} – diameter of 95% of particles are passing, m; C_V – volumetric concentration.

Many other correlations have been proposed to predict V_D or V_C for slurries containing both fine and coarse particles. Table 1 depicts some of them (Durand, 1952; Wasp et al., 1977; Turian et al., 1987; Schiller and Herbich, 1991; Shook and Daniel, 1965). On the other hand, there are some mineral concentrates, such as hematite sinter feed, which call for models based solely on the behaviour of coarse particles. This paper attempts to contribute in this field.

Table 1
Correlations for predicting deposition velocity.

Researcher	Correlation
Durand (1952)	$V_D = F_L \cdot [2gD(S-1)]^{0.5}$
Wasp et al. (1977)	$V_D = 4 \cdot \left(\frac{d}{D}\right)^{\frac{1}{16}} \cdot (C_V)^{\frac{1}{5}}\sqrt{2gD(S-1))}$
Turian et al. (1987)	$V_D = 1.7951 \cdot C_V^{0.1087}(1-C_V)^{0.2401} \cdot \left(\frac{d_{95} \cdot \rho_F\sqrt{gD}(S-1)}{\mu_f}\right)^{0.00179} \cdot \left(\frac{d}{D}\right)^{0.06623} \cdot \sqrt{2gD(S-1)}$
Schiller and Herbich (1991)	$V_D = 1.3C_V^{0.125}[1-e^{-6.9 \cdot d}] \cdot \sqrt{2gD(S-1)}$
Shook and Daniel (1965)	$V_D = 2.43C_V^{0.33}\frac{\sqrt{2gD(S-1)}}{C_D^{0.25}}$

3. Materials and methods

Pumping experiments were conducted in two recirculating pipeline test rigs, with pipe diameters (D) of 25 mm and 50 mm with transparent sections to observe the slurry flowing inside the pipe. The curve of pressure gradient ($\Delta P/L$) versus bulk flow velocity (V) was obtained by varying the pump speed with a variable frequency driver and measuring the pressure drop in 1 m horizontal pipe for each experimental condition.

Any pumping test approached a particular mineral sample (characterized by its specific gravity and sphericity), particle size, solids concentration and pipe diameter. It started with a slurry flow velocity under which no settled particles were observed at the bottom of the pipe. Flow velocity was gradually decreased until a critical value at which particles started to form a moving bed. This particular value of flow velocity was visually observed and named *critical velocity* (V_C). Flow velocity lower than V_C were also explored. They led to a clear observation of a stationary bed. For any particular value of flow velocity (V), the pressure gradient ($\Delta P/L$) was measured and associated to its respective V. This way, any pumping test yielded a curve $\Delta P/L$ versus V. Appropriate lighting was installed over the pipe for a better visualization of the slurry flow, in particular allowing the visual identification of V_C through the transparent pipes.

Mean flow velocities were measured by collecting samples from the exit gutter, at the end of pipeline versus time. These samples were weighed and dried to accurately determine delivered concentration. The slurry flow velocity was obtained from the volumetric flow rate and the continuity equation. The pressure tapping were located at a distance of 20 pipe diameters from the pipe bend, to ensure fully developed flow. Fig. 1 depicts the schematic of the both experimental apparatus. Static pressure taps and an inverted U-tube water manometer were used for pressure measurements, aiming at determining the pressure drop (ΔP) experienced by the slurry in a 1-m length of horizontal pipe (L). Valves were installed in the U-tube water manometer to allow water injection for flushing, in order to avoid the ingress of solids into the manometer during the pumping runs. Plots of $\Delta P/L$ versus V resembled the shape of typical curves which characterize the flow of heterogeneous slurries through pipes (Wilson et al., 2006; Wasp et al., 1977; Jacobs, 1991).

Samples of concentrates of apatite (from Cajati-SP-Brazil), hematite (Itabira-MG-Brazil) and quartz (Descalvado-SP-Brazil) were obtained from their respective mineral processing plants. They were sized by wet screening and clustered in two size classes: Class-1 (0.210 mm < d < 0.297 mm) and Class-2 (105 mm < d < 149 mm). After drying the samples, the specific gravity of solids was measured by pycnometry (Table 2). Particle shape was evaluated by the sphericity function (Ψ) which was determined by percolation of air through a bed of particles of known porosity (ε), as shown by Eq. (6) (Souza Pinto et al., 2009).

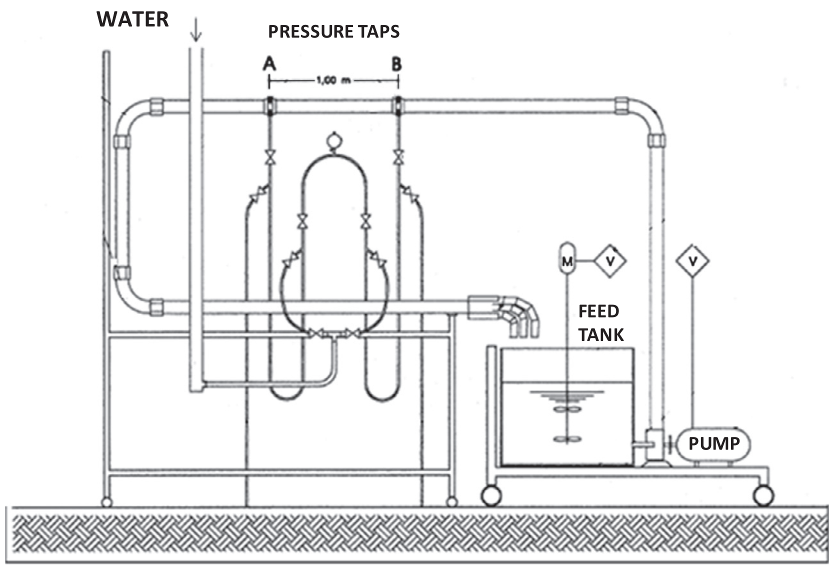

Fig. 1. Schematic of recirculating pipeline test rig.

Table 2
Information on mineral samples used in the model.

Sample	Sauter mean diameter (μm)		Specific gravity	Sphericity function (Ψ)	
	Class-1	Class-2		Class-1	Class-2
Quartz	265	132	2.620	0.80	0.81
Apatite	295	151	3.130	0.63	0.64
Hematite	336	163	4.900	0.39	0.37

$$K = \frac{(d_S \cdot \Psi)^2 \varepsilon^3}{150 \cdot (1-\varepsilon)^2} \quad (6)$$

where K – permeability constant; d_S – particle Sauter mean diameter, m; ε – bed porosity; Ψ – particle sphericity.

As the variable d_S in Eq. (6) is the mean diameter of a sphere having the same volume of the particle (volumetric mean diameter), to account for actual particle size, the Sauter mean diameter ($D_{3,2}$) may be adopted (McCabe et al., 1985). The $D_{3,2}$ of all approached mineral samples was determined by laser diffraction via Malvern Mastersize S-2.19. Results are depicted in Table 2. Accordingly, particles of apatite, hematite and quartz exhibited sphericity function (Ψ) values of 0.64, 0.38 and 0.81, respectively. Because the hematite concentrate used in the pumping experiments is typically composed of rounded ($\Psi \sim 0.5$) plus slabbed ($\Psi \sim 0.2$) particles, the magnitude of sphericity function ($\Psi \sim 0.38$) depicted in Table 2 must be regarded as an averaged value of both types of shape (Souza Pinto, 2012).

Mineral concentrates were mixed with tap water in order to prepare slurries with a desired volumetric concentration of solids (C_V), which varied in the range of 8–27%. Accordingly, slurry densities were in the range 1226 kg/m^3 and 1661 kg/m^3, as presented in Table 3.

Table 3
Solids volumetric concentration and density of slurries.

Slurry	Solids volumetric concentration (%)			Slurry density (kg/m^3)		
Quartz	14	20	27	1226	1326	1444
Apatite	12	18	24	1257	1374	1516
Hematite	8	12	17	1314	1467	1661

4. Results and discussion

Pumping experiments yielded plots of pressure drop per meter of horizontal pipe ($\Delta P/L$) versus bulk flow velocity (V) of slurry (Figs. 2–7), resembling the typical curve which characterizes heterogeneous flow (Wilson et al., 2006; Wasp et al., 1977; Jacobs, 1991). In this kind of curve, a minimum value of $\Delta P/L$ occurs at a critical value of bulk flow velocity (V_C) which represents the limits of particle deposition. This way, the condition $V < V_C$ favours particle deposition on the bottom of the pipe, whereas $V > V_C$ creates turbulent suspension to avoid solids stratification in the pipe. Moreover, increasing values of V promotes a more uniform particle distribution across the pipe diameter (Doron et al., 1987). In this study, the identification of a particular value of slurry flow rate (Q) at which a moving bed of particles started to form on the bottom of the pipes (visually observed) allowed the determination of V_C, once the cross sectional area of pipes was known (Table 4). At this specific point ($V = V_C$), the head loss per meter of horizontal pipe ($\Delta P/L$) reached its minimum measured value. It is important to note that Figs. 2–7 show results obtained with a 50 mm pipe diameter. In the interests of avoiding repetition, results obtained from pumping experiments conducted with pipes of diameter ($D = 25$ mm) are not presented here. However they showed the same behaviour exhibited by the pipes of diameter ($D = 50$ mm), yielding values of V_C which were used in the proposed modelling.

Regarding the influence of particle size (Class-1 versus Class-2) on V_C in pumping experiments conducted in pipes of $D = 50$ mm, it is possible to observe that values of V_C related to particles of smaller diameter (Class 2 = 0.105 mm < d < 149 mm) of a single mineral are lower than those values obtained with particles of greater diameter (Class 1 = 0.210 mm < d < 0.297 mm). Because the settling rate exhibited by particles of Class-1 is higher than particles of Class-2, the latter requires less turbulence to be transported than the former, resulting in lower values of V_C.

Taking into account the influence of solids concentration (C_V) on V_C obtained from pumping experiments conducted with slurries of apatite (Figs. 2 and 3), hematite (Figs. 4 and 5) and quartz (Figs. 6 and 7), it is possible to observe a slight increase in the magnitude of V_C as C_V increases. According to Gillies et al. (2000), a decrease in deposition velocity is usually observed for solids concentration greater than 35% by volume. For lower concentrations an increase in deposition velocity can be observed. Thomas (1979) also found

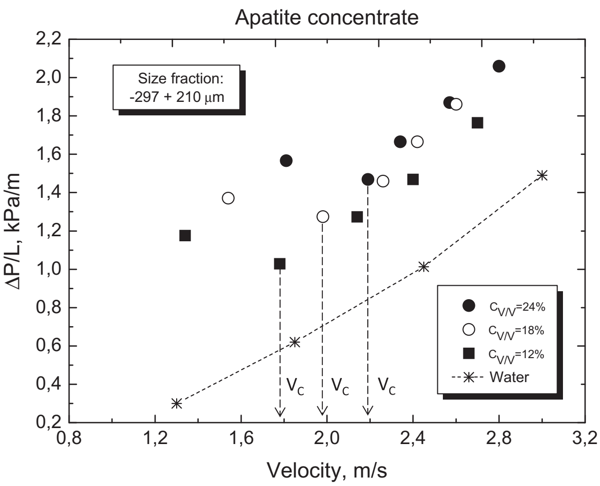

Fig. 2. Pressure drop as function of slurry flow velocity for apatite particles in a pipe diameter of 50 mm.

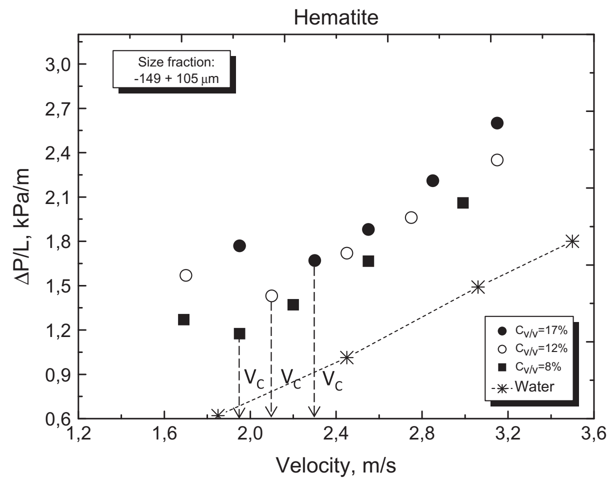

Fig. 5. Pressure drop as function of slurry flow velocity of hematite concentrate for a pipe diameter of 50 mm.

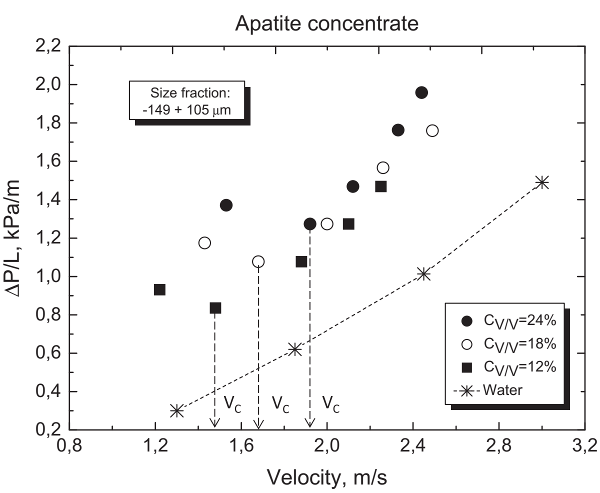

Fig. 3. Pressure drop as function of slurry flow velocity for pipe diameter of 50 mm.

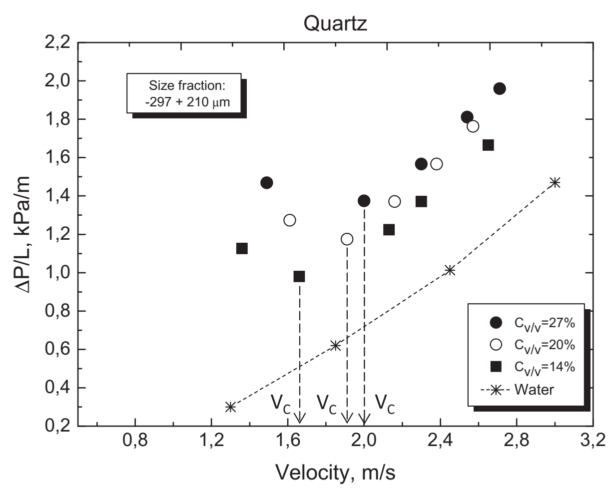

Fig. 6. Pressure drop as function of slurry flow velocity for quartz in a 50 mm pipe diameter.

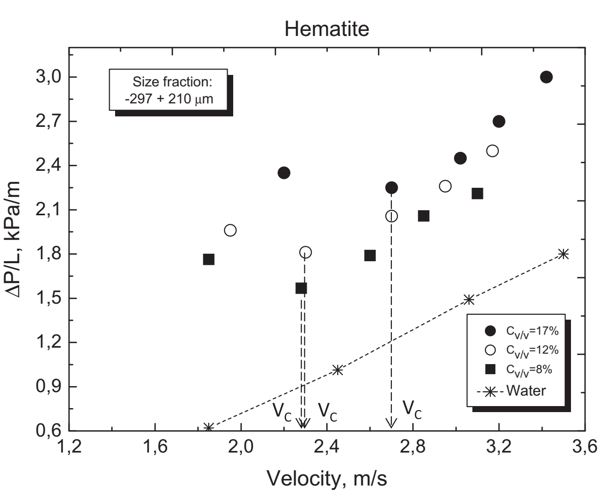

Fig. 4. Pressure drop as function of slurry flow velocity for hematite concentrate in a 50 mm pipe diameter.

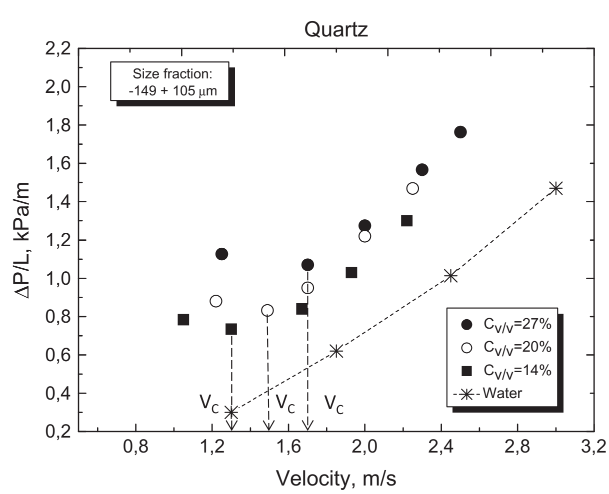

Fig. 7. Pressure drop as function of slurry flow velocity for quartz in a 50 mm pipe diameter.

Table 4
Observed critical velocity (Vc).

Mineral concentrate	Pipe diameter (mm)	Particle size	Volumetric concentration (%)	Observed V_C (m/s)
Quartz	50	Class 1	14	1.7
			20	1.9
			27	2.0
		Class 2	14	1.3
			20	1.5
			27	1.7
Apatite		Class 1	12	1.8
			18	2.0
			24	2.2
		Class 2	12	1.5
			18	1.7
			24	1.9
Hematite		Class 1	8	2.3
			12	2.3
			17	2.7
		Class 2	8	1.9
			12	2.1
			17	2.3

that for solids volumetric concentrations in the range of 5–20% no great variation on deposition velocity was observed. The investigation on pressure drop presented smaller values for the $D = 50$ mm pipe as compared with the $D = 25$ mm pipe. Therefore V_C presents lower values for the small pipe diameter as the height of the bed of particles is higher and demands higher velocities to flow (Doron and Barnea, 1995).

4.1. Modelling critical velocity (V_C)

For the effect of density, we follow the work of Durand (1952), Wilson et al. (2006), Schaan et al. (2000) and Wasp and Slatter (2004), taking the exponent of the ratio of density $(S-1)$ as 0.5.

The effect of the modified Reynolds group (Eq. (7)) is depicted in Fig. 8, presenting a slope of 0.37. The viscosity of water was taken based on the low slurry concentration flowing above the moving bed of solids particles.

$$R_E = \left(\frac{d_S \cdot \rho_m \cdot \sqrt{g \cdot D}}{\mu_f}\right) \tag{7}$$

where ρ_m – slurry density, kg/m^3; d_S – particle Sauter mean diameter, m; μ_f – fluid viscosity, Pa s; D – pipe diameter, m; g – gravitational acceleration, m/s^2.

The two layer model of Wilson (1976) is considered to be applicable for coarse particles, larger than 0.1 mm, thus including the particle sizes of interest of this work. Wilson's work present the drag coefficient, introducing the effect of the particle shape associated with the ratio of particle and pipe diameter (d/DC_D).

The introduction of a shape factor in the modelling of V_C is based on the sphericity function (Ψ) as depicted in Fig. 9. The effect of the sphericity showed a relatively minor effect on the critical velocity. Gillies et al. (2000) discusses the particles shape effect on velocity and concludes that it has a minor effect, leading to suitable increasing on the velocity as particle shape tends to spherical. They discuss the shape effect through the circularity of particles, taking into account the axes of the particles. Gillies et al. (2010) determined the sphericity through image analysis of 20–30 particles on microscope and, for particles diameter of magnitude 28 μm, the authors conclude to be a size too small for this analysis, pointing out a weakness of this method. According to Schaan et al. (2000), the deposition velocity is qualitatively similar for different conditions of shape factor, culminating in a minor effect on V_C. Many correlations (Wilson and Judge, 1976; Shook and Daniel, 1965; Zandi and Govatos, 1967) discuss the particle shape effect through the drag coefficient. Thus, there is a gap in the literature to analyse the effect of particle shape through the sphericity function determined by pressure gradient in a porous media. Fig. 10 presents the particles shape image in an electronic microscope micrograph (MeV).

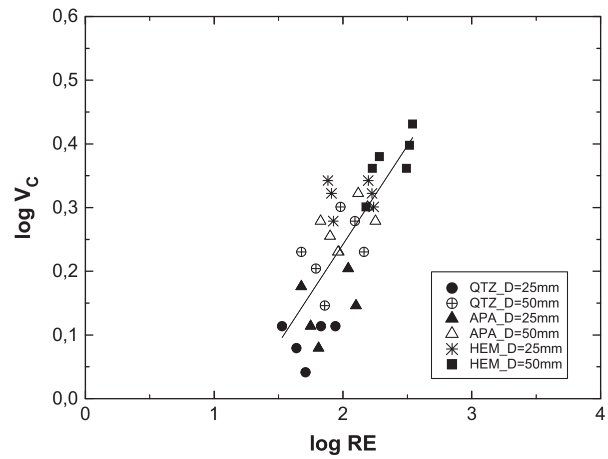

Fig. 8. Reynolds effect on the critical velocity.

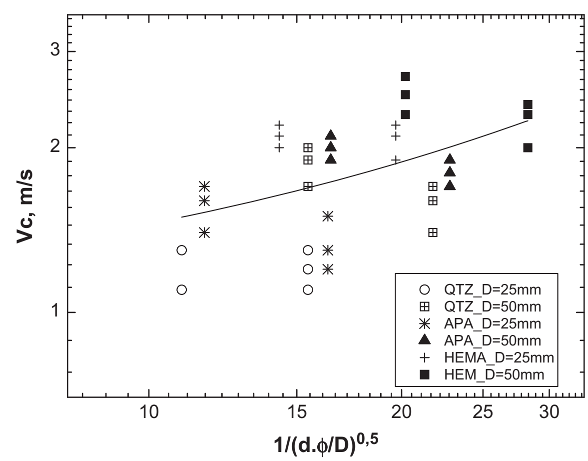

Fig. 9. Particle shape effect through the sphericity function.

Wasp and Slatter (2004) developed the effect of concentration as an exponential function. Regarding their work, a good fit of the concentration effect on the experimental data of critical velocity (V_C), obtained by a least squares regression of the exponential fit, is depicted by Eq. (8).

$$F(C_V) = 0.124e^{3.10 \cdot C_V} \tag{8}$$

The new suggested model for predicting the critical velocity was based on the work of Wasp and Slatter (2004) and it is shown in Eq. (9). All the exponents of Eq. (9) were improved by the method of least squares, for the best adjustment of the proposed modelling to the observed V_C. A good agreement was achieved yielding a deviation less than 10% with the measured experimental critical velocities, as depicted in Fig. 11.

$$V_C = 0.124(S_S - 1)^{0.5}\left(\frac{d_S \cdot \rho_m \cdot \sqrt{g \cdot D}}{\mu_f}\right)^{0.37} \cdot \left(\frac{d_S \cdot \Psi}{D}\right)^{-0.007} e^{3.10 \cdot C_V} \tag{9}$$

where V_C – critical deposition velocity, m/s; S_S – relative density of solid and slurry (ρ_s/ρ_m); d_S – particle Sauter mean diameter, m; ρ_m

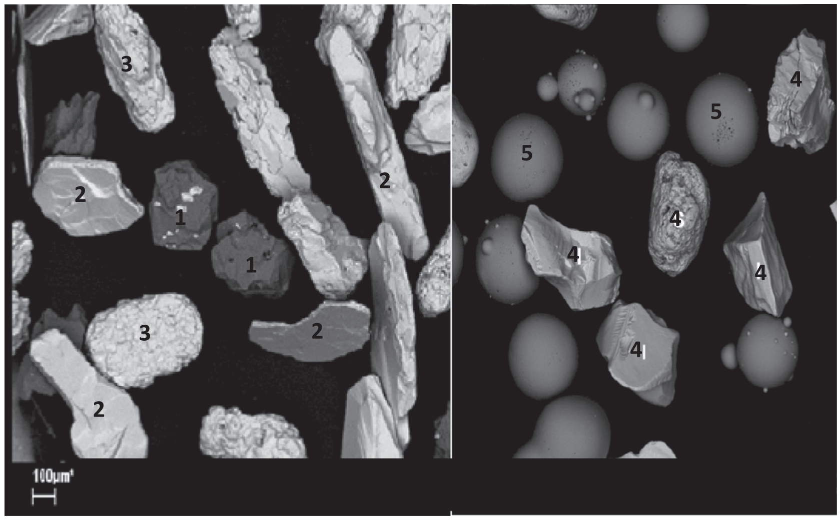

Fig. 10. Electronic microscope image of particles: (1) quartz; (2) slabbed hematite; (3) rounded hematite; (4) apatite, (5) spherical glass beads.

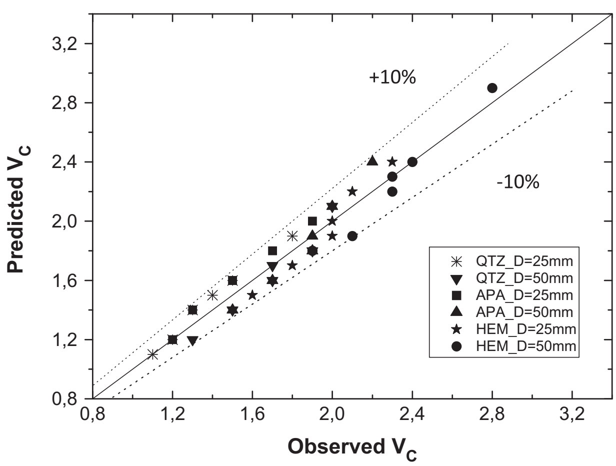

Fig. 11. Observed versus predicted critical velocity, m/s.

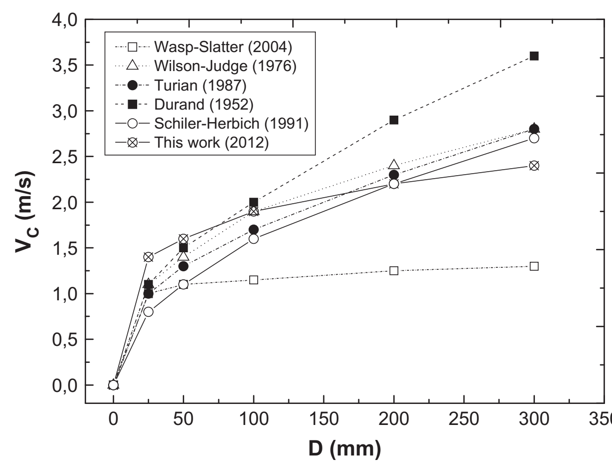

Fig. 12. Comparison of predictive models of critical velocity for quartz slurry, volumetric concentration of 14% and particles diameter of 0.265 mm.

– slurry density, kg/m^3; μ_f – fluid viscosity, Pa s; D – pipe diameter, m; g – gravity constant, m/s^2; C_V – volumetric concentration; Ψ – particle sphericity.

This new suggested model of V_C is based on the following conditions: particle diameter (d) of 0.105–0.297 mm; pipe diameter (D) of 25–50 mm; slurry volumetric concentration (C_V) of 8–27%, slurry density (ρ_m) of 1226–1661 kg/m^3; sphericity function (Ψ) of 0.38–0.81 and solids density (ρ_s) of 2600–5100 kg/m^3.

A comparison of some predictive models for critical/deposition velocity in function of pipe diameter (D) were applied for quartz slurry, with 14% volumetric concentration and particles mean diameter of 0.265 mm, and the results are depicted in Fig. 12. It could be observed a considerable disagreement between them. The extrapolation of pipe diameter is also presented by Wasp and Slatter (2004) and according to them one of the reasons for that is the bounds of applicability to each correlation is not well defined. In Fig. 13, the experimental observed V_C was compared with the same predictive models of Fig. 12 regarding the analysis of the behaviour of each model on predicting V_C. It is important to highlight that the critical velocity (V_C), experimentally observed in this work, still present turbulent effects and a solid gradient concentration along the cross sectional area of the pipe could be visually identified. Comparing Figs. 12 and 13 it is possible to observe that the values of critical velocity based on proposed model of this

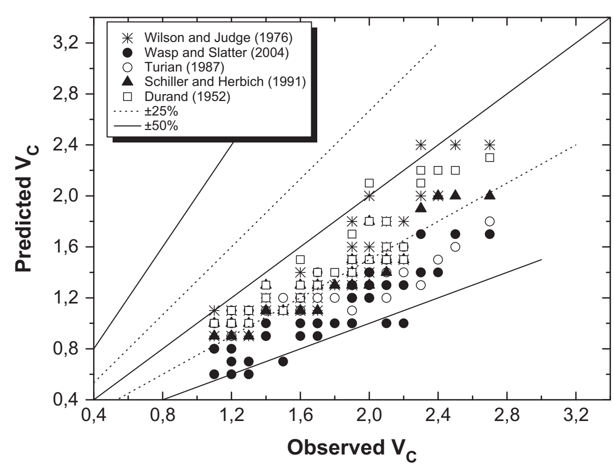

Fig. 13. Comparison of predictive models in the literature with the observed V_C.

work presented magnitude greater than the others for the applied conditions as the proposed model aimed to predict the critical velocity with a moving bed of particles at the pipe bottom. Therefore, the bounds of each correlation should be well defined to have more accuracy between the predictive results for V_C. The model of Wilson and Judge (1976) achieved the best accuracy with the observed V_C followed by Durand (1952). The most conservative model was the Wasp and Slatter (2004), given the lowest values to the predicted V_C, reaching a deviation, for some cases, greater than 50%. As each correlation has their own conditions of applicability, Fig. 13 contributes bringing the behaviour of each one for a given condition and illustrates how they work on predicting V_C for pipe diameter up to 50 mm. It is important to know the behaviour of each predictive model for an applied condition as V_C is a fundamental parameter for pipeline design and it could vary depending on the model used to predict it.

5. Conclusion

Many correlations have been developed to predict the deposition velocity and we are far from reasonable agreement amongst them. The semi-empirical correlation used in the foregoing work has presented a satisfactory prediction of critical velocity of deposition (V_C), slightly above the deposition (V_D), for the applied conditions. The results yielded a deviation less than 10% for the experimental conditions. The particle shape effect was introduced through the sphericity function presenting a minor effect on V_C. Further investigations with larger pipe diameters and concentrations are justified.

Acknowledgments

CAPES is fully acknowledged for providing scholarships to one of the authors.

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