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The influence of hematite particle shape on stratification in pipe flow

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ABSTRACT

This paper discusses the influence of hematite particle shape factor, through the sphericity function, on the concentration distributions of solids over the cross sectional area of the pipe for the hydraulic transportation of hematite industrial mineral concentrates. The results are depicted by figures of solids distribution along three sectors of the pipe cross sectional area of the pipe and the sphericity function of particles from each section were evaluated using the permeametry method. A recirculating pipeline testing loop with a transparent section and pipe diameter (D) of 50 mm, with a special gutter device installed at the discharge of the test loop, was employed. The hematite mineral concentrate used is composed exclusively of coarse particles clustered in two particle size (d) ranges: 0.210 mm < d < 0.297 mm and 0.105 mm < d < 0.149 mm. The results of solids distribution profiles indicated that the coarser particle class yielded a more heterogeneous concentration profile over the cross sectional area flowing at the critical deposition velocity (V_C). The slurry stratification inside the pipe was influenced by the particle shape factor evaluated by the sphericity function according to each pipe section. The higher the particle sphericity the more these particles were found at the bottom of the pipe. It was also observed that < 6% of the bulk particles flowed in the top section of the pipe (0.8D from the bottom to the top) for any given condition.

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1. Introduction

Brazil is a global supplier of hematite concentrates as sinter feed and pellet feed products, which are widely used as raw material in steel production. Because mines and mineral processing plants in Brazil are not located close to the harbours from where concentrates are exported, hydraulic transportation instead of railway may be an attractive option to reduce costs and environmental issues. The main advantages of hydraulic transportation can be stated as: lower pollution (noise, dust and carbon dioxide emission), technically feasible even in remote areas, low maintenance requirement, cost-effective over long distances, higher reliability and continuous operation [9,14].

Unlike pellet feed slurry, which is widely conveyed by pipelines around the world without significant problems, sinter feed slurry poses a challenge of great importance because coarse (particle diameter > 100 μm) and very dense (specific gravity = 5100 kg/m^3) particles of hematite must be transported hundreds of kilometres without obstructing the pipe. In addition, although actual hematite particles exhibit either flat or rounded shape, most papers dealing with slurry transport regard solid particles as spheres. To contribute towards a better understanding of the behaviour of coarse hematite particles along pipelines, Vale Institute of Technology (ITV) has associated to the University of São Paulo (USP) aiming at studying the fundamentals of the hydraulic transport of coarse hematite particles. To address these issues, this paper investigates the influence of hematite particle shape, utilising the sphericity factor, on the cross sectional concentration distributions of solids over the cross sectional area of pipe for hematite concentrates. Furthermore, a novel gutter delivery at the discharge of the system enabled the collection of data at three different pipe sections: top, medium and bottom.

The relationship between slurry velocity, head losses, bulk slurry volumetric concentration and also solids cross sectional distribution has been widely addressed for heterogeneous flow [12,20,27].

2. Theoretical background

The design procedure for the hydraulic transportation of slurries composed of coarse particles (d > 100 μm) is very complex. Some important parameters for slurry pipelines are pressure drop, deposition velocity and solids concentration profile across the pipe cross sectional area, where experimental data is commonly used to predict these parameters [2,5,7,23,25]. For slurries with settling characteristics, such as those which transport coarse hematite particles (ρ_s = 5100 kg/m^3), the solids are conveyed and suspended by two mechanisms in which one is the turbulence of the system and the other is the contact load of

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Table 1
Correction factors for settling velocity based on the sphericity and density, from Concha and Barrientos [3].

Factor	Description
f_A	$(5.42-4.75\psi)/0.67$
f_B	$\left[\frac{(5.42-4.75\psi)}{0.795}, \log\frac{\psi}{0.065}\right]^{-0.5}$
f_C	$\lambda^{-0.0145}; \lambda=\frac{\rho_p}{\rho_f}$
f_D	$\lambda^{0.00725}$
$\alpha\ (\alpha\psi)$	${f_B}^2(\psi)$
$\beta\ (\alpha\psi)$	$\left[{f_A}^{\frac{1}{2}}(\alpha\psi){f_B}^2(\alpha\psi)\right]^{-1}$
$\gamma\ (\lambda)$	${f_D}^2(\lambda)$
$\eta\ (\lambda)$	$\left[{f_C}^2(\lambda){f_D}^2\right]^{-1}$

the particles, as discussed by Wilson et al. [26] and Gillies et al. [7]. For flow velocities close to the limit of deposition and especially for coarse particles, the contact load of grains becomes predominant on the particles transport and also increases the friction due to the contact of the bed of particles with the pipe wall. For heterogeneous slurries in partially stratified flow, the lifting forces raised from the turbulence diffusion on the turbulent part of flow are partially responsible for particle suspension and eventual transport [25]. The lifting force is a function of the kinetic energy of the carrier fluid with density (ρ_f) and of the projected area of a particle of diameter (d). The gravity effect depends mostly on the particle volume and the submerged density of the remaining particles would be function of the relative density of the particle-fluid mixture ($\frac{\rho_p-\rho_f}{\rho_f}$) and gravity (g). This leads to the famous Durand's parameter, referred as modified Froude number [1,8,15]. This modified Froude number represents the ratio of inertial to gravitational effects and it must be greater than unity for particles transport, as depicted by Eq. (1).

$$\frac{V}{\left[2gd\left(\frac{\rho_p-\rho_f}{\rho_f}\right)\right]^{0.5}}>1 \tag{1}$$

The other contribution to the particle transport in partially stratified flow comes from the contact load of the particles. As the solids concentration increases, the space between particles is smaller and the effect of hindered settling becomes more pronounced. Consequently, the transport by granular contact becomes predominant over the turbulence effects and the solids concentration at the pipe bottom also increases, as described by Wilson et al. [25] and Gillies et al. [7]. The effect of solids concentration on the stratification inside the pipes was first described by Newitt et al. [16] to be inversely proportional to the stratification ratio (R) as presented in Eq. (2).

$$R=\frac{(i_m-i_f)}{\left[\left(\frac{\rho_p-\rho_f}{\rho_f}\right)\cdot C\right]} \tag{2}$$

As depicted by Newitt et al. [16], the smaller the volumetric concentration (C), the higher the stratification ratio (R). Wilson et al. [26] highlight that for fully stratified flow the stratification ratio tends to the unity. Therefore, the turbulence effects associated with the slurry transport volumetric concentration need to be able to overcome the gravity effects to suspend and transport the particles. The fraction of the particles flowing along the bottom of the pipe (moving bed of particles) is transported as a non-suspended stratified flow and the remaining particles flowing above this moving bed are considered to be transported by turbulent suspension. This way, slurries presenting coarse particles and flowing close to the limit of deposition mandatorily present stratification inside the pipes. Many authors have presented a discussion on the limit deposition velocity based on the terminal settling velocity and drag coefficient of the particle and most of the theory in this field has been developed for spherical particles [1,16,22,24,26].

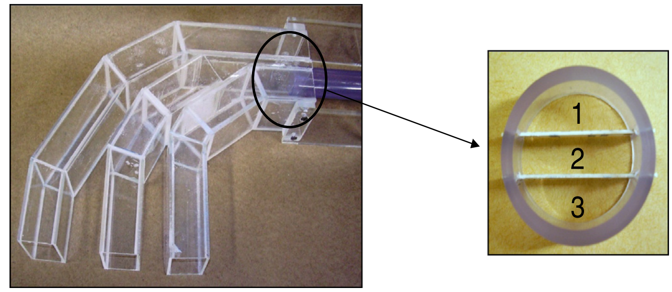

Fig. 1. Gutter delivery at the pipe discharge (3-bottom; 2 centre; 1 top of pipe diameter).

Particle shape affects both solid properties (superficial area, volume and settling velocity) and fluid properties (rheology, friction factor and drag). It also influences the performance of many mineral processing unit operations such as flow in pipes, stirred tanks, fluidized beds, flotation cells, and others [13] (in modeling, particle shape can be represented by sphericity factor (ψ) [17,18]).

Haider and Levenspiel [10] developed equations for spherical and non-spherical particles for different drag coefficients and settling terminal velocities. Taking into account the particle size, they used the equivalent spherical diameter, defined as the diameter of a sphere having the same volume of the particle. They plotted curves of Drag coefficient versus Reynolds number and concluded that the particles undergo higher drag as the sphericity drops from unity (perfect sphere), and so the higher the drag the lower the settling velocity. Similarly, as particles deviate from the spherical shape ($\psi<1$), transport by turbulent eddies is favoured. The concept of sphericity was first introduced by Wadell [21] and is defined by Eq. (3).

$$\psi=\frac{s}{S_p} \tag{3}$$

Tran-Cong et al. [19] described the sphericity factor as being an appropriate dimensionless number for characterizing the shape of non-isometric particles, although they highlight the difficulty of determining the sphericity, as this requires the measurements of the surface area and also the diameter of the particles, which is not an easy task. An alternative for evaluating the sphericity factor is the permeametry method. It is based on the percolation of a fluid, such as air, at laminar regime

Table 2
Particle and slurry properties for hematite industrial concentrate.

Sauter mean diameter (μm)	Bulk sphericity	Slurry density (kg/m^3)	Volumetric concentration (%)	Critical deposition velocity[a] (m/s)	
				336 μm	163 μm
336 (0.210 mm < d < 0.297 mm)	0.37	1314	8	2.3	1.9
		1467	12	2.3	2.1
163 (0.105 mm < d < 0.149 mm)	0.39	1661	17	2.7	2.3

[a] Presented by Souza Pinto et al. (2014) [18].

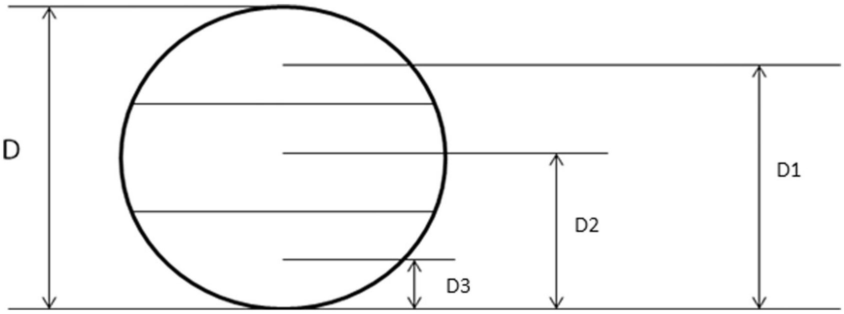

Fig. 2. The representative distance of the centre of each section to the pipe diameter.

through a bed of particles, as presented by Ergun [6]. As a fluid percolates the packed bed, the pressure drop over the length L of the bed (ΔP/L) and volumetric air flow rate (Q_f) are measured. Darcy's law is then used to determine the permeability constant (k) of the porous medium leading to the sphericity factor, as presented in Eq. (4). A more detailed discussion on the permeametry method applied to the evaluation of the sphericity function for mineral particles is described by Souza Pinto et al. [17].

$$-\frac{\Delta P}{L}\cdot\frac{(d_p\psi)^2}{v_f\mu}\cdot\frac{\varepsilon^3}{(1-\varepsilon)^2}=150 \quad (4)$$

Settling rates of non-spherical particles are more affected by rotation and oscillation than spheres. To account for these differences, Concha and Barrientos [3] developed correction parameters (Table 1) to extend classical equations used for predicting the settling behaviour of non-spherical and isometric particles (Eq. (5)), where parameters (α and β) are function of ψ. Young et al. [28] describe the influence of particle shape on the distribution of drag and lift forces along the particle surface and how difficult is to predict them precisely. Moreover the influence of the ratio of particle-fluid density and the sphericity factor on the correction parameters of Concha and Barrientos [3] presented a minor error (~12%) for Reynolds number $Re < 10^4$.

$$u_p^* = 20.52\cdot\frac{\alpha(\psi)\gamma(\lambda)}{d_E^*}\left\{\left[1+0.09132\beta(\psi)\eta(\lambda)d_E^{*\frac{3}{2}}\right]^{\frac{1}{2}}-1\right\}^2 \quad (5)$$

3. Materials and methods

3.1. Materials

Hematite concentrate used in this study was sampled at a mineral processing plant (Brucutu mine-Brazil). The sample was sized by wet screening which yielded two classes of size range: 0.210 mm < d < 0.297 mm and 0.105 mm < d < 0.149 mm. The size fractions were mixed with tap water, yielding slurries of volumetric concentration varying from 8% to 17%. Information on the solid particles and slurries is presented in Table 2. The particle Sauter mean diameter (d_s) was determined by laser diffraction with a Malvern Mastersizer S-2.19.

A laboratory unit test loop with a 50 mm diameter pipe (D) made of Perspex was employed for slurry transportation tests. A more detailed description of the experimental set up and discussion on the curves of head losses versus flow velocity plus critical deposition velocity for hematite are found elsewhere [18].

A gutter delivery was installed at the discharge of the pipeline test loop, which splits the cross sectional area of the pipe into three different sections of equal area (~6.5cm^2) enabling the observation of the solid particles flowing inside the pipe at different heights (Fig. 1). This device is useful for determining the heterogeneity of the slurries flowing inside the pipes. Kaushal [12] has also used a sampling tube in a 4 × 6 mm rectangular slot, varying the height along the vertical pipe diameter to measure the solids cross sectional distribution. The gutter device splits the pipe cross sectional area at the centre of each section in the ratio of 0.2D, 0.5D and 0.8D from the bottom to the top of the pipe, respectively, as depicted by Fig. 2.

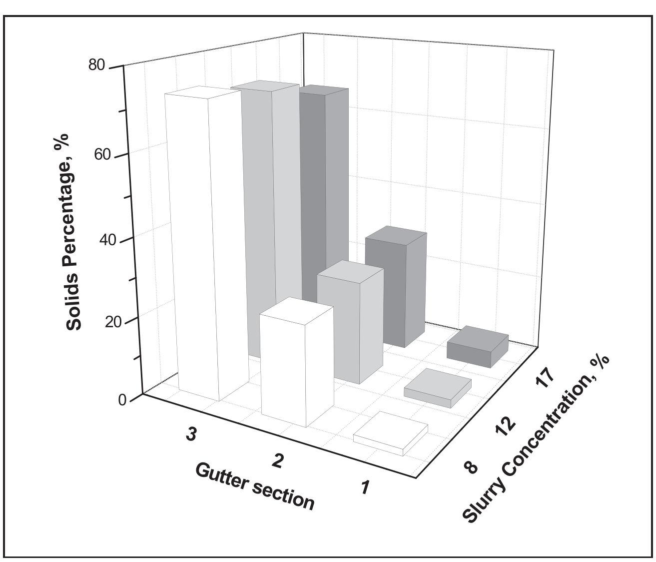

Fig. 3. Solids distribution profiles across the cross-sectional area of the pipe (hematite concentrate - 0.210 mm < d < 0.297 mm).

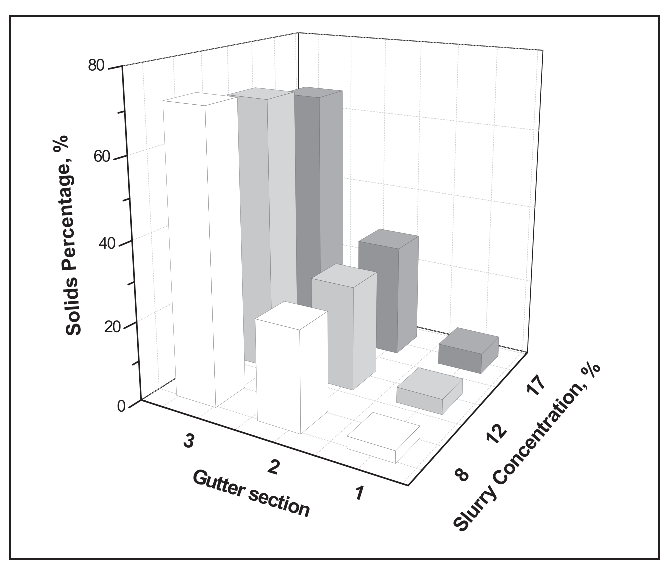

Fig. 4. Solids distribution profiles across the cross-sectional area of the pipe (hematite concentrate - 0.105 mm < d < 0.149 mm).

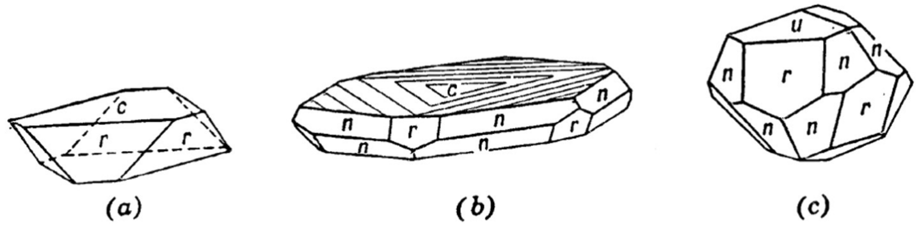

Fig. 5. Hematite particle shapes (from Dana [4]).

3.2. Methods

The measurement of the concentration profile along the pipeline cross sectional area was carried out using the delivery gutter at the discharge of the system, by dividing the cross-sectional area of the pipe into 3 sectors (Figs. 1 and 2). Samples from each sector were collected simultaneously at the critical deposition velocity (V_C) that is the velocity at which a moving bed of particles starts to form on the pipe invert. The critical deposition velocities, as discussed by Souza Pinto et al. [18], were visually determined within the transparent section of the Perspex pipe. For the evaluation of the sphericity function of hematite particles from the industrial concentrate, the permeametry method as described by the work of Souza Pinto et al. [17] was followed.

The terminal settling velocities of each class of particles (0.210 mm < d < 0.297 mm and 0.105 mm < d < 0.149 mm) for the data from each gutter delivery section (1; 2; 3) were measured in a glass tube of diameter ($d_{GT} = 0{,}045$ m). A very small amount of particles were poured into the tube filled up with distilled water, to avoid the hindered settling effects of batch sedimentation. The time was monitored over a given distance (0.20 m).

4. Results and discussion

Profiles of solids distribution along the cross sectional area of the pipe for slurry flow at the critical deposition velocity (V) are presented in Fig. 3 (0.210 mm < d < 0.297 mm) and Fig. 4 (0.105 mm < d < 0.149 mm). Under the most cost-effective flow condition for heterogeneous flow in pipelines (at Vc), it can be observed that the solids volumetric concentration (Cv) is higher at the bottom of the pipe (Cv > 65% at 0.2D), for any given experimental condition, and decreases from the bottom to the top of the pipe: (Cv < 6% at 0.8D), These results indicate the occurrence of slurry stratification over the cross sectional area of the pipe, clearly characterizing the heterogeneity of the flow. A more even distribution was observed for 0.105 mm < d < 0.149 mm at the highest volumetric concentration (17%), highlighting the effect of particle size and slurry volumetric concentration on the solids distribution over the cross-sectional area of the pipe. As the contact load of solids promotes a hindered settling of particles within the pipe, these findings compare well with the influence of the solids volumetric concentration on the pipe stratification, e.g., the higher the solid concentration the less pronounced is the stratification and thus a tendency to the solids being better distributed across the cross sectional area of pipe [13,16,22,26].

The dominance of inertial effects over the gravity effects is clear when the Froude number (*Fr*) is examined presenting a magnitude around 6.0 ($Fr = \frac{v^2}{D \cdot g} \gg 1$). Even with the inertial effect being dominant, the turbulence effect was not able to prevent solids stratification at Vc. As mentioned in Section 2, partially stratified flow (slurry containing coarse particles of hematite) presents a moving bed of particles at the bottom of the pipe that are kept flowing due to the turbulent conditions although the bulk flow velocity is close to the limit of deposition (Vc). In this case, the inter-particle contact still dominates, leading to stratification inside the pipe.

As maintained by Dana [4], particles of hematite may exhibit different shapes which are influenced by its crystallography (Fig. 5) and genesis. Some particles may be flat-shaped (Fig. 5-b), others are more rounded (Fig. 5-c), whereas intermediate shape could also be found (Fig. 5a). Because the sphericity factor (Ψ) drops from $\Psi = 1$ (for a perfect sphere) to $\Psi = 0$ (for a thin plate or disk), rounded particles of hematite are expected to exhibit higher values for the sphericity factor than flat-shaped particles. For a population composed of several shapes, as a concentrate of hematite yielded by a mineral processing plant, intermediate values of Ψ are expected to occur.

Values of Ψ determined for hematite particles sampled at the three different pipe sections (gutters 1–3) are displayed in Fig. 6 and Fig. 7, illustrating the pipe split cross sectional area. It could be observed that particles flowing close to the bottom of the pipe (section 3) show higher values for Ψ than those particles which flow close to the top of the pipe (section 1). This finding was observed for all experimental conditions, regardless of the class of the particle size: 0.210 mm < d < 0.297 mm or 0.105 mm < d < 0.149 mm.

Taking into account the particle size, which is split into two classes of narrow size range, the finer class (0.105 mm < d < 0.149 mm) presented higher values for sphericity factor flowing at the top section of the pipe than the coarser class (0.210 mm < d < 0.297 mm), leading to a rationale that as the particle size is decreased the suspended fraction of particles is less dependent on the shape factor for the action of turbulent suspension forces. The finer class size also presented a higher quantity of particles flowing at the top section of pipe (5.4%) than the coarser class of size (4.5%).

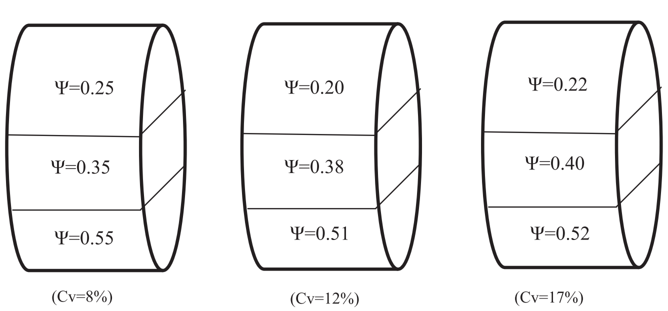

Fig. 6. Sphericity function according to the gutter pipe section for hematite concentrate (0.210 mm < d < 0.297 mm).

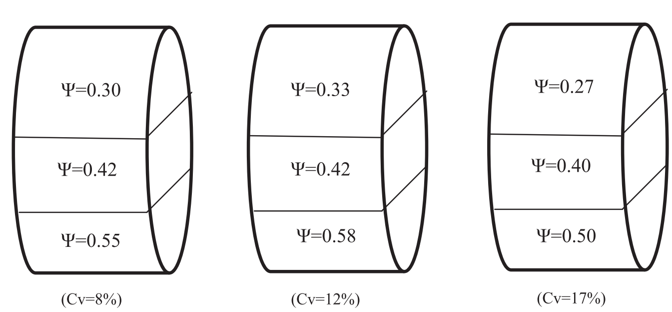

Fig. 7. Sphericity function according to the gutter pipe section for hematite concentrate (0.105 mm < d < 0.149 mm).

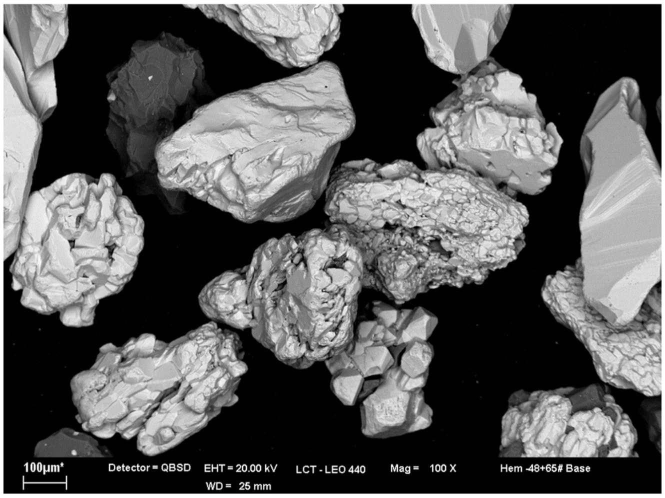

Fig. 8. Hematite particles from the bottom of the pipe (gutter section 3).

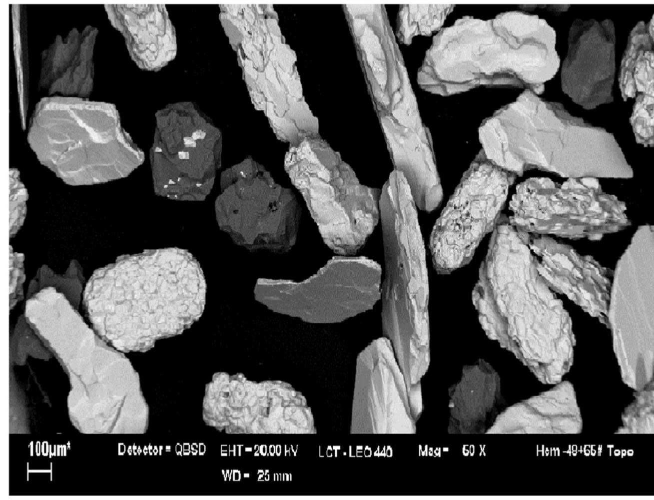

Fig. 10. Hematite particles from the top of the pipe (gutter section 1).

The image of the particles from each section of the pipe is presented in an electronic microscope micrograph (MeV) in the Figs. 8–10. It is important to remark that the figures show a different magnification scale, e.g., Fig. 10 presents a magnification of 60× and the others (Figs. 8 and 9) 100×. The particles flowing at the bottom of the pipe (section 3 of the gutter) show a preponderance of more rounded hematite as the sphericity factor evaluated for these particles was ($\Psi = 0.54 \pm 0.03$). For particles flowing in the intermediate region of the pipe (section 2 of the gutter) the sphericity factor achieved the magnitude of ($\Psi = 0.40 \pm 0.03$). Finally, particles from the Gutter at section 1 (top of the pipe) clearly presented a dominance of flat hematite with sphericity factor of ($\Psi = 0.26 \pm 0.05$). Because the sample of hematite used in this study is an industrial concentrate yielded by a mineral processing plant it contains impurities, mainly quartz. This way, quartz particles are supposed to appear in the three sections of the gutter.

Wilson et al. [26] present a discussion for the stratification ratio (R) and state that for a narrow particle size distribution, the slurry flow velocity must be equal or greater than the flow velocity at threshold of turbulent lift to attend the partially stratified flow, otherwise the flow is fully stratified. They take into account as the key parameters the particle diameter and fall velocity. To observe the particle shape effect on the terminal settling velocity of the hematite particles for both class size range used in this study, the Concha and Barriento's model was used to predict the fall velocities and the results were compared to those obtained experimentally (Table 3). Fig. 11 brings the parity chart comparing the observed versus predicted results.

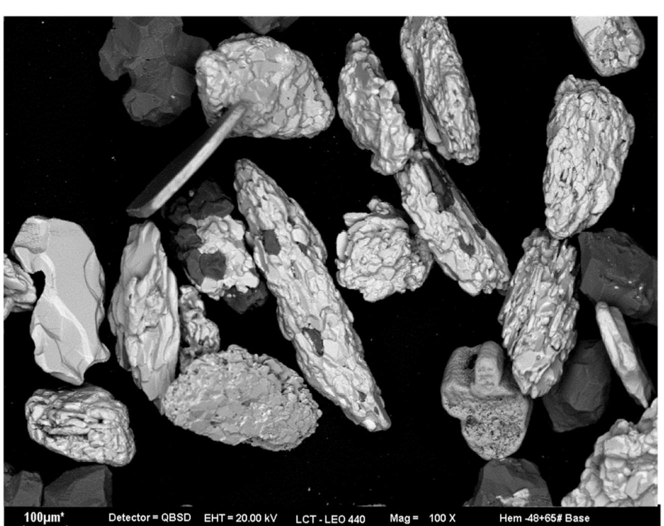

Fig. 9. Hematite particles from the centre of the pipe (gutter section 2).

According to Fig. 11, experimental values of terminal settling velocities are lower than those predicted by Concha and Barrientos` model. This difference may be due to the fact that the model approached isometric particles showing sphericity factor lying in the range of $0.67 < \Psi < 1$, whereas this study deals with non-isometric particles exhibiting very much lower sphericity factor: $0.20 < \Psi < 0.58$. This way, hematite particles are likely to be more affected by drag along the settling path, justifying its lower values for the terminal settling velocity. The particle Reynolds number (Re_p) for 0.210 mm < d < 0.297 mm and 0.105 mm < d < 0.149 mm lay in the range of $3.2 < Re_p < 3.5$ and $13.3 < Re_p < 16.5$ respectively, matching the Transitional regime. These values of Re_p fall within the range covered by Concha and Barrientos model [3] ($0.005 < Re_p < 2 \cdot 10^4$). According to Heiskanen [11] shape does not affect the settling velocity of particles at very low Re_p ($Re_p < 1$), but its influence starts to increases the transitional regime is approached.

5. Conclusion

Slurries containing coarse particles of hematite concentrate (0.210 mm < d < 0.297 mm and 0.105 mm < d < 0.149 mm) at volumetric solids concentration of 8%–17% flowing in a pipe of diameter of 50 mm exhibited partial stratification along the cross sectional area of the pipe under Vc condition. The most homogeneous particle distribution within the cross sectional area of the pipe was found for the particles from 0.105 mm < d < 0.149 mm at the highest solids concentration (17% by volume), clearly exhibiting the effect that slurry concentration and particle size exert on solids distribution over the pipe cross sectional area. It was also possible to observe that <6% of the total solids were found flowing at the top region of the pipe, at the V_C point. The particle shape evaluated through the sphericity factor presented a clear effect on

Table 3
Settling velocities for particles at the different pipe sections.

Particle size	Gutter section	Experimental settling velocity (cm/s)	Predicted settling velocity (cm/s)
(0.210 mm < d < 0.297 mm)	1	3.96 ± 0.26	3.77
	2	4.56 ± 0.30	3.91
	3	4.89 ± 0.26	4.27
(0.105 mm < d < 0.149 mm)	1	1.92 ± 0.14	1.53
	2	2.01 ± 0.16	1.64
	3	2.15 ± 0.14	1.81

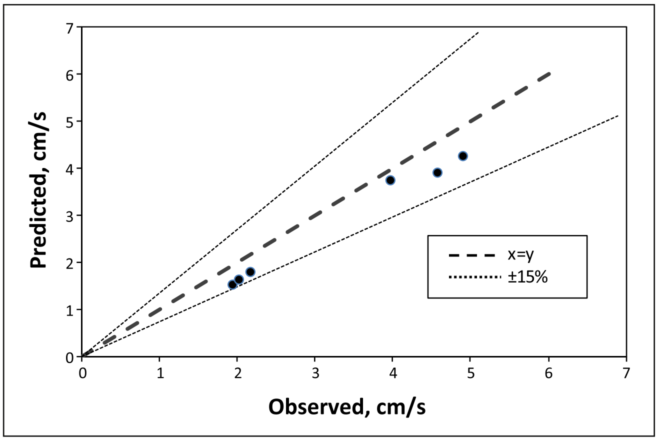

Fig. 11. Predicted versus observed terminal settling velocities for hematite particles.

the slurry stratification as it was possible to observe that particles conveyed in the bottom section of the pipe presented a higher value for the sphericity factor ($\Psi = 0.54 \pm 0.03$) than those found flowing at the top section ($\Psi = 0{,}26 \pm 0{,}05$). The magnitude of the terminal settling velocities were experimentally evaluated and compared with those predicted by Concha and Barrientos [3] for all tested conditions. A higher deviation was observed for particles from 0.105 mm < d < 0.149 mm and the lowest sphericity factor values. As the sphericity range maintained by Concha and Barrientos is higher than the range used in this work, it is expected that the later experience a higher drag along the settling path justifying its lower values for the terminal velocity.

Nomenclature

C	solids concentration (fraction)
D	particle size (m)
d_{GT}	glass tube diameter (m)
d_e^*	equivalent volume diameter of a non-spherical particle (from Concha and Barrientos [3])
D	pipe diameter (m)
F	correction factors (from Concha and Barrientos [3])
Fr	Froude Number
G	gravitational acceleration (m/s^2)
i	hydraulic gradient (m/m)
Q	volumetric flow rate (m^3/s)
Re	Reynolds number (–)
s	surface area of a sphere with the same volume as the particle (m^2)
S	surface area (m^2)
u^*	dimensionless settling velocity (from Concha and Barrientos [3])
V	slurry flow velocity (m/s)
v	particle velocity (m/s)
ΔP/L	pressure drop through packed bed (Pa/m)
ε	porosity (–)
ψ	sphericity function (–)
ρ	density (kg/m^3)
μ	dynamic viscosity (Pa·s)
α, β, γ, η	parameters (from Concha and Barrientos [3])

Subscripts

c	critical
f	fluid
m	slurry
p	particle
s	Sauter mean diameter
t	terminal velocity

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.powtec.2016.08.015.

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