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Impact of flotation operational parameters on the optimization of fine and coarse Itabirite iron ore beneficiation

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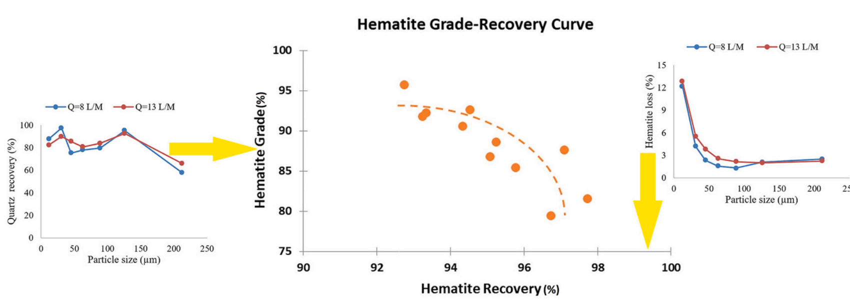
HIGHLIGHTS

- Evaluation of the reverse flotation of hematite in a pneumatic flotation cell.
- Quartz recovery and hematite loss decreases with increasing depressant dosage.
- Coarse quartz recovery increases with increasing Jg to an optimum.
- Fine hematite loss decreases significantly with decreasing solids concentration.
- Physical parameters had the largest effect on the flotation performance (grade and recovery).

GRAPHICAL ABSTRACT



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ABSTRACT

This paper investigates the impact of operational parameters on the reverse flotation of Timbopeba itabirite iron ore in a pneumatic (MBE Pneuflot) flotation cell. To this end, the effects of physical and chemical parameters (i.e., collector and depressant dosage, superficial gas velocity (J_g), solids concentration, and feed rate) on the reverse flotation of iron ore are investigated in detail. Results show that increasing collector dosage increases quartz recovery, particularly for the coarser quartz where recovery increases by nearly 30%. Increasing depressant dosage results in a decrease in both quartz recovery and hematite loss, for the coarser hematite particles. In addition, increasing the feed rate does not affect quartz recovery or hematite loss, suggesting that the pneumatic flotation cell is not constrained by residence time. Furthermore, increasing the superficial gas velocity results in an increases in quartz recovery to an optimum at a J_g of around 0.6 cm/s after which it decreases significantly, particularly for the coarser particles where recovery decreases by 50%. Decreasing the solids concentration does not affect quartz recovery but results in a significant reduction in hematite loss. Here, fine and coarse hematite loss decrease from around 25% to 12% and 10% to 2%, respectively. Solids concentration and J_g are operating parameters that have the largest effect on the flotation performance of the pneumatic flotation cell. Overall, the obtained results suggest that this flotation cell should be operated at relatively low superficial gas velocities and solids concentrations. However, these findings are for a pilot scale and would need to be examined at larger scale (e.g., an industrial scale) where different operating conditions may be optimal.

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1. Introduction

Flotation is a selective separation method that contributes to upgrading at least two billion tons of different minerals per annum. The process of flotation selectively separates minerals by exploiting differences in the physical and chemical properties of the various species. The efficiency of flotation separation relies on the chemical and physical variables inside the flotation cell [1–9]. In the iron ore industry, cationic reverse flotation is a regular separation method for removing quartz as main impurity [10–12]. Some big challenges in the iron ore production process, specifically in the hematite reverse flotation, are recovering coarser quartz particles by flotation and preventing the losses of finer hematite particles by entrainment [13,14]. Normally, due to the inefficiency of the existing processes, the coarser quartz particles appear in tailings and fine hematite particles appear in in concentrate.

The process chemical parameters and flotation cell hydrodynamic conditions including type and concentration of chemical reagents, solid percentage, superficial gas velocity, and feed rate have significant effects on the selectivity of flotation process. The coarse particles recovery is more sensitive to the chemical conditions, compared to the fine particles recovery which is more sensitive to the hydrodynamic conditions. The aggregates stability formed during the process controlled the flotation kinetic of coarse particles. This stability relies on the optimum chemical and hydrodynamic conditions. The suitable collector type and its optimum concentration can create the stronger attractive forces for attachment coarse particle onto the bubble surface [14]. Starch as a common depressant in iron flotation effectively depresses the iron particles and has slight effect on the quartz particles. In the optimum starch concentration, the successful separation of quarte from hematite could be achieved [15]. The physical parameters have as significant role in the flotation process as the chemical parameters [1]. Increasing the solid percentage leads to a decrease in the iron flotation efficiency due to decrease of bubble numbers in the pulp and increase particles detachment from bubble surface [16]. On the other hand, the optimum hydrodynamic conditions including superficial gas velocity can reduce rupture forces in the process [15]. The detachment forces decreased with decreasing superficial gas velocity.

The correlation between the flotation performance and particle size is established well in the literature [17,18]. The particle size distribution is one of the physical parameters in a flotation regarding its significant influence on flotation performance where coarse and fine particles have contrasting flotation behavior [19–25]. The flotation recovery versus particle size curve is a useful diagnostic technique for determining optimal chemical and physical conditions for the flotation of particles of various sizes. Coarse particles have large settling velocities and high detachment rates, making them more difficult to recover [18,26,27]. Generally, due to the lack of inertia in fine particles, it is hard and unlikely to overcome the streamlines around bubbles and collide with nearby bubbles [28–30]. Large number of fine particles also increases the collector consumption and reduces the selectivity. These issues are particularly noticed in separating quartz and hematite using ether amine, where the predominant mechanism is electrostatic adsorption [11]. In addition, the entrainment of fine particles cannot be negligible due to the water recovery, which leads to the poor selectivity of fine and ultrafine particles [12,31–37].

Some excellent iron ore flotation works into the effect of physical and chemical conditions have been carried out in conventional flotation cells [10,13,38–49]. In 2016, Lima et al. [50] showed that although conventional flotation cells can efficiently recover quartz particles below 150 μm, the flotation efficiency is low for larger particle sizes. Currently, pneumatic flotation cells are considered the main beneficiation unit in different countries for some iron ore industrial operations. In particular, some encouraging results have been detected from industrial-pilot scale pneumatic flotation cell trials by Vale Iron Ore Project Developments department. According to this research, these cells may have higher efficiency for coarse quartz flotation than conventional flotation cells. In the present study, we investigate the effect of operational parameters, including physical and chemical parameters such as collector dosage, depressant dosage, superficial gas velocity, solids concentration, and feed rate on the reverse flotation of Timbopeba itabirite sample in a pilot-scale pneumatic flotation cell.

2. Material, reagents, and methods

The hematite sample was received from the Timbopeba iron ore in Brazil. The sample was from the flotation rougher feed of the Vale Itabirite iron ore concentrator. The ore sample was collected directly from the feed before any chemical adding to the flotation circuit. The received sample was blended properly in a few different stages using some sample dividers. This operation is performed to ensure that all samples are divided to separate samples to be used as a feed for the flotation experiments. After preparations, samples were sealed and properly stored. Based on Inductively Coupled Plasma spectroscopy (ICP) and X-Ray powder Diffraction analysis (XRD) of the feed sample, its elemental composition was containing 64.4% hematite (Fe_2O_3) and 34.9% quartz (SiO_2) as major elements. Ether dodecyl amine (EDA) was received in liquid form (supplied by Clariant) and used as collector. No Frother was used in this study as the collector itself has frothing properties. Corn Starch was received in powder form and used as a depressant (obtained from Sigma-Aldrich). Reagents were prepared on a daily basis using deionized water and adjusted to the appropriate pH by HCl and NaOH. The pH modifier reagents were of analytical grade quality and obtained from Sigma-Aldrich. The parameters for the flotation experiments are presented in Table 1. Fig. 1 shows the pneumatic flotation cell used in the study.

Flotation tests were carried out using the MBE Pneuflot flotation cell at a pilot scale. MBE Coal and Minerals Technology supplied the pneumatic flotation cell. The flotation cell has a 25-l capacity. The air and feed flow rate, as cell variables, could be changed from 5 l/min to 15 l/min. The flotation cell setup can operate under semi-batch or continuous mode. The pulp was conditioned sequentially with a pH regulator (1 min), depressant (5 min), collector (2 min), and frother (1 min). Five to seven concentrates were collected over 10 min at specified times during the flotation test. Multiple flotation experiments were performed on a pilot scale in some selected conditions to determine repeatability. For mineral recovery calculation, the concentration and tails samples were properly filtered and dried before the screening process to seven fractions (sizes below 212 μm). The elemental composition (mainly Fe and SiO_2) of the concentrate and tails samples was determined by ICP and XRD analysis.

3. Result and discussion

This section discusses and presents results for the effect of chemical and physical parameters on flotation performance. The effect of chemical parameters and physical parameters is investigated in Sections 3.1 and 3.2, respectively. The overall separation efficiency results, which are a combined effect of chemical and physical parameters on hematite grade-recovery, are presented in Section 3.3. The terms "quartz recovery" and "hematite loss" in this section refer to quartz and hematite particles recovered to the flotation froth, respectively. Although they are

Table 1
Flotation parameters.

Parameter/Reagent	Value/Unit
pH	10.5
Feed Mass (Iron Ore)	7–15 kg
Solid Concentration (%wt)	25, 50 %
Depressant Dosage (Corn Starch)	500–1000 g/t
Collector Dosage (Flotigam EDA)	100–200 g/t
Superficial Gas Velocity (Jg)	0.3, 0.6, 0.9, 1.2 cm/s

Fig. 1. Pneumatic flotation cell used in the study. (1) Pneumatic reactor; (2) Feed tank; (3) Froth height adjustment; (4) Concentrate collector; (5) Pump.

termed concentrate for conventional flotation, but tailings for reverse flotation as the concentrate remains in the flotation cell (cationic reverse iron ore flotation).

3.1. Effect of chemical parameters

This section discusses and presents results for the effect of collector and depressant dosage on flotation performance. Ether dodecyl amine and starch were used as a collector and depressant, respectively, as these are commonly employed in the cationic reverse flotation of iron ore [10]. Finally, the flotation results were obtained for fixed physical conditions (i.e., $J_g = 0.9$ cm/s and solids concentration = 25%).

3.1.1. Effect of collector concentration (dosage)

The collector dosage effect on the total water recovery and mass recovery is shown in Fig. 2. As can be seen, water and mass recovery increase with increasing collector concentration. Also, this figure presents the effect of collector dosage on the hematite loss and quartz recovery as a function of collector dosage. As expected, hematite loss and quartz recovery increase with increasing collector concentration. The increase in the recovery of quartz is higher than the corresponding increase in hematite loss. This increment is because increasing collector dosage results in a more remarkable increase in mass recovery than the corresponding water recovery, as quartz recovery is due to flotation while hematite loss is primarily due to entrainment [51]. The recovery of quartz is relatively constant up to around 150 μm. After this point, it decreases significantly, as commonly observed in the literature. The loss of fine hematite decreases substantially up to 100 μm, which is also commonly observed. However, increasing collector dosage significantly affects both the coarser quartz and hematite particles, with coarse quartz recovery increasing by 30%. This outcome is probably due to the increased hydrophobicity of quartz for coarser particles (resulting in less bubble particle detachment) and the presence of coarse floatable hematite and/or composite quartz-hematite particles.

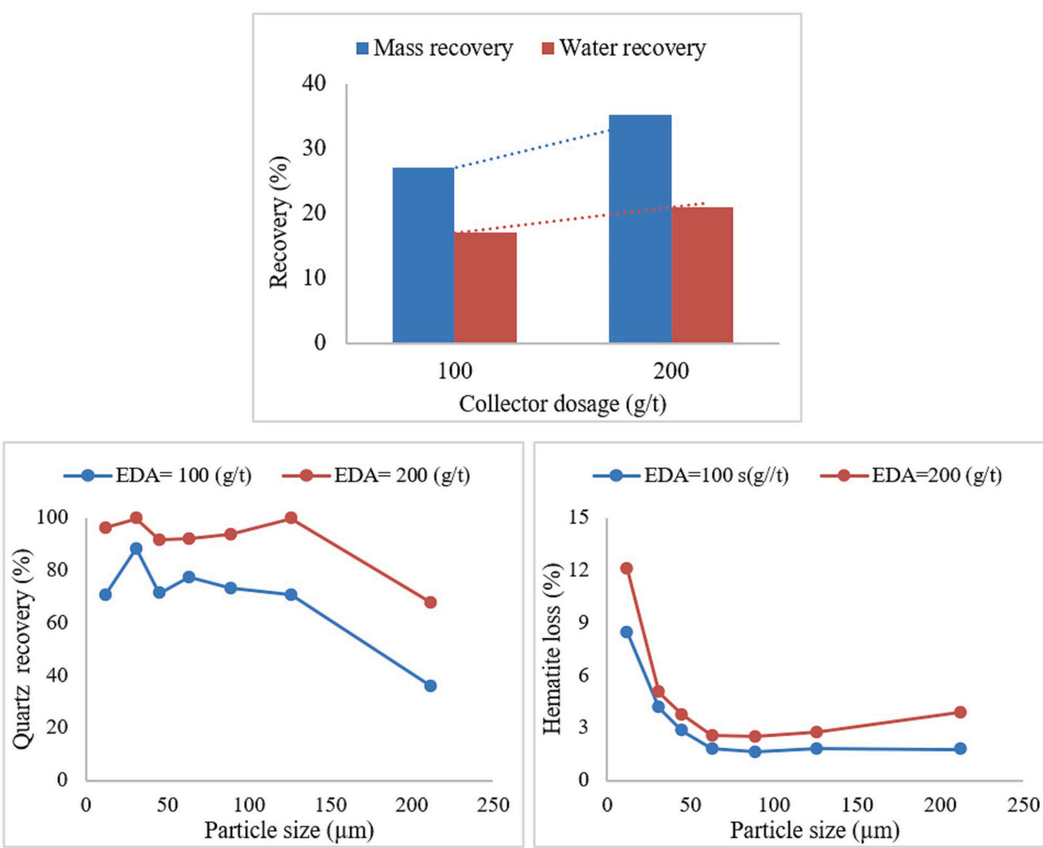

Fig. 2. Effect of collector dosage on the recovery of quartz and hematite particles.

3.1.2. Effect of depressant dosage

Fig. 3 presents the effect of depressant dosage on the total water recovery and mass recovery, hematite loss, and quartz recovery. Mass and quartz recovery decrease significantly with increasing depressant dosage, particularly for the coarser quartz particles. This reduction may be due to unselective depression of quartz at higher dosages or destabilization of the froth, resulting in lower froth recoveries for coarser particles [52]. Although increasing depressant dosage does not affect water recovery and fine hematite loss, but the loss of coarser hematite is reduced. This result may also be due to the froth's destabilization or the depression of coarse floatable hematite or composite quartz-hematite particles. As the adsorption mechanism is mainly due to electrostatic interaction, the lack of depressant can also promote the flotation of hematite coarse particles [53].

3.2. Effect of physical parameters

This section discusses and presents results for the impact of feed rate, solids concentration, and superficial gas velocity on flotation performance. Flotation results are for fixed chemical conditions at standard plant reagent dosages of 500 and 200 g/t for depressant and collector, respectively.

3.2.1. Effect of feed rate

Fig. 4 represents the correlation between quartz recovery and hematite loss as a function of feed rate. Increasing feed rate does not affect either quartz recovery or hematite loss. This result suggests that the pilot-scale pneumatic flotation cell is not constrained by residence time and can increase throughput without affecting either quartz recovery or hematite loss regardless of particle size. The presented results are pilot-scale observations and would need to be examined at a larger scale, such as an industrial scale, where the feed rate may need to be optimized.

3.2.2. Effect of superficial gas velocity

Fig. 5 shows the correlation between total water, mass and quartz recovery, and hematite loss as a function of superficial gas velocity (J_g). Mass recovery increases with increasing Jg (Jg = 0.6–0.9 cm/s) to a maximum. Water recovery continuously increased with increasing J_g. Higher J_g results in both an increase in water transported into the froth and a decrease in the froth residence time. It reduces the drainage of water to the pulp phase, resulting in higher water recovery and higher entrainment rates [4,12,54].

Quartz recovery increases with increasing superficial gas velocity to an optimum at a J_g of around 0.6 cm/s, after which it decreases significantly. This reduction is particularly noticed for the coarser particles where recovery decreases by as much as 50%. In general, recovery should increase with increasing Jg as it increases the bubble surface area flux (S_b), with a corresponding increase in the flotation rate constant [25]. However, higher airflow rates also result in larger bubbles that may result in an optimum airflow rate where the Sb is at a maximum. More importantly, perhaps, higher air flow rates may also lower froth stability, which will have a significant effect on coarse particle recovery. In general, there is an optimum airflow rate that results in a peak in the air recovery and a corresponding maximum in both froth stability and mineral recovery [55].

Fine hematite loss increases significantly with increasing Jg, as this simply follows the water recovery, which drives the mechanical entrainment of particles [12]. It is interesting to note that the loss of coarse hematite particles increases with increasing Jg to a maximum and decreases thereafter, probably due to decreased froth stability. This result again suggests presents of coarse floatable hematite or composite quartz-hematite particles.

3.2.3. Effect of solids percentage

Fig. 6 shows the correlation between total water and mass recovery,

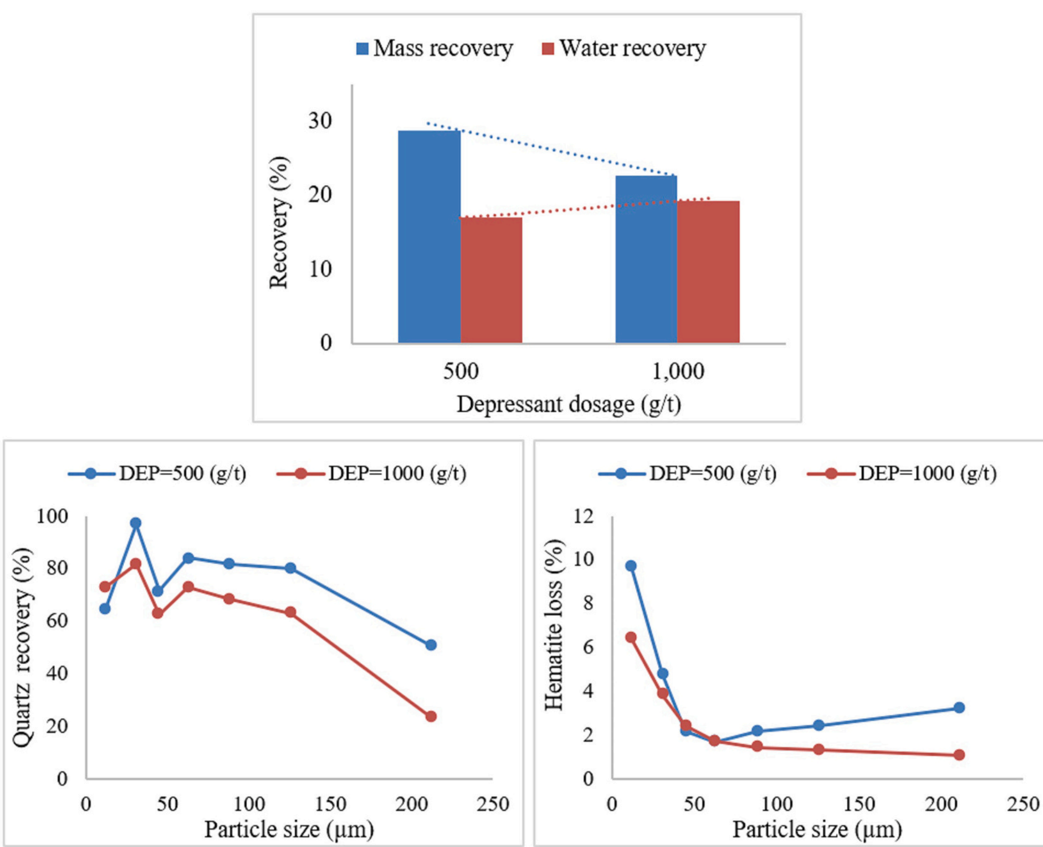

Fig. 3. Effect of depressant dosage on the hematite and quartz particles recovery.

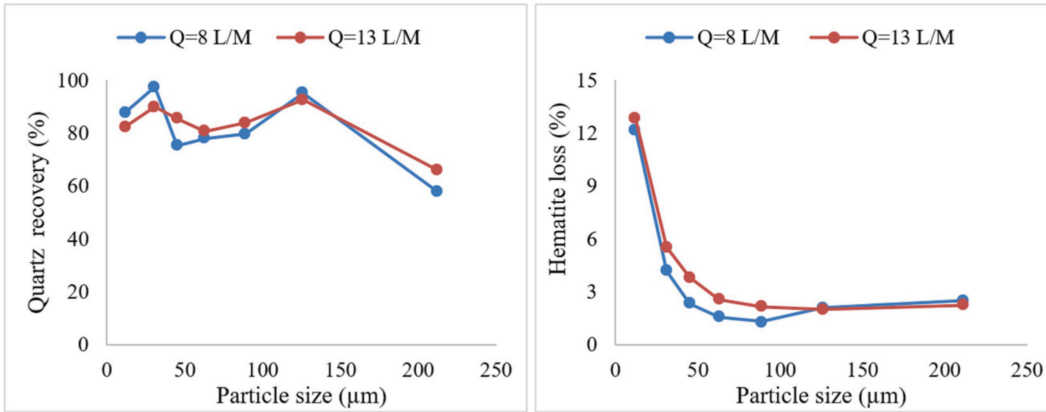

Fig. 4. Effect of feed rate on the hematite and quartz particles recovery.

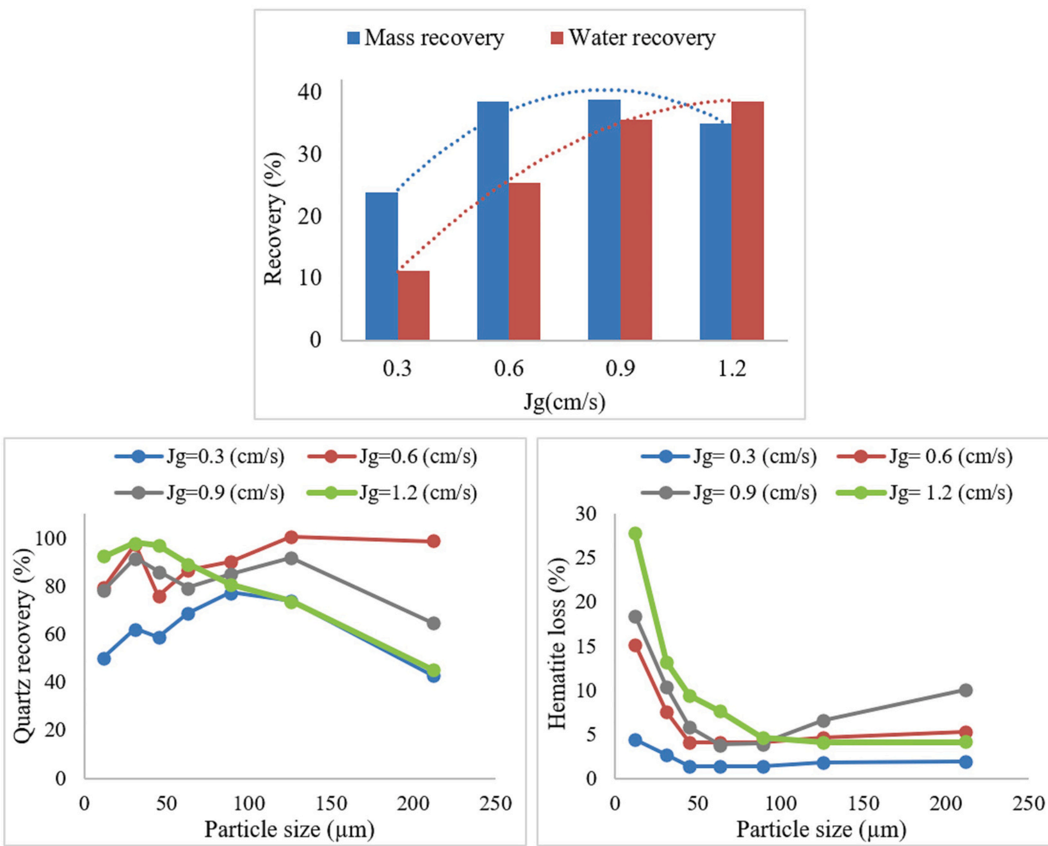

Fig. 5. Effect of superficial gas velocity (Jg) on the hematite and quartz particles recovery.

recovery of quartz particles in the coarse fraction, and hematite loss as a function of solids concentration. As expected, water and mass recovery both increased while solid concentration increased. However, the increase in water recovery was more significant when solids concentration increased, reaching almost 35% at the higher solid concentration. Increasing solids concentration did not affect quartz recovery, but hematite loss increased significantly due to the increased water recovery.

The performance of the pneumatic cell is considerably higher when flotation experiments run with lower pulp density (concentration of solids). The recovery of quartz remains approximately constant, while both fine and coarse hematite loss decrease significantly from 25% to 12% and 10% to 2%, respectively. The effect of pulp density (concentration of solids) on flotation performance is very complicated as it affects suspension of solids, hydrodynamics of cell, dispersion of gas, characteristics of froth, and particle bubble contacting [56]. A low solids concentration could decrease froth recovery due to low stability in froth structure. On the other hand, a high solids concentration could significantly increase froth recovery because of very high stability in froth structure due to complex pulp and froth rheology. Research has shown that the percentage solid reduction in flotation tank could affect positively or negatively the flotation performance [16,56,57].

It is clear that the superficial gas velocity and solids concentration are operating parameters with a large impact on the flotation recovery and grade of the pilot-scale pneumatic flotation cell. Results suggest that this flotation cell should be operated at relatively low superficial gas velocities and solids concentrations, which may be counterintuitive for flotation concentrators' operators. However, there will likely be an optimum in these operational parameters that will vary between cells/

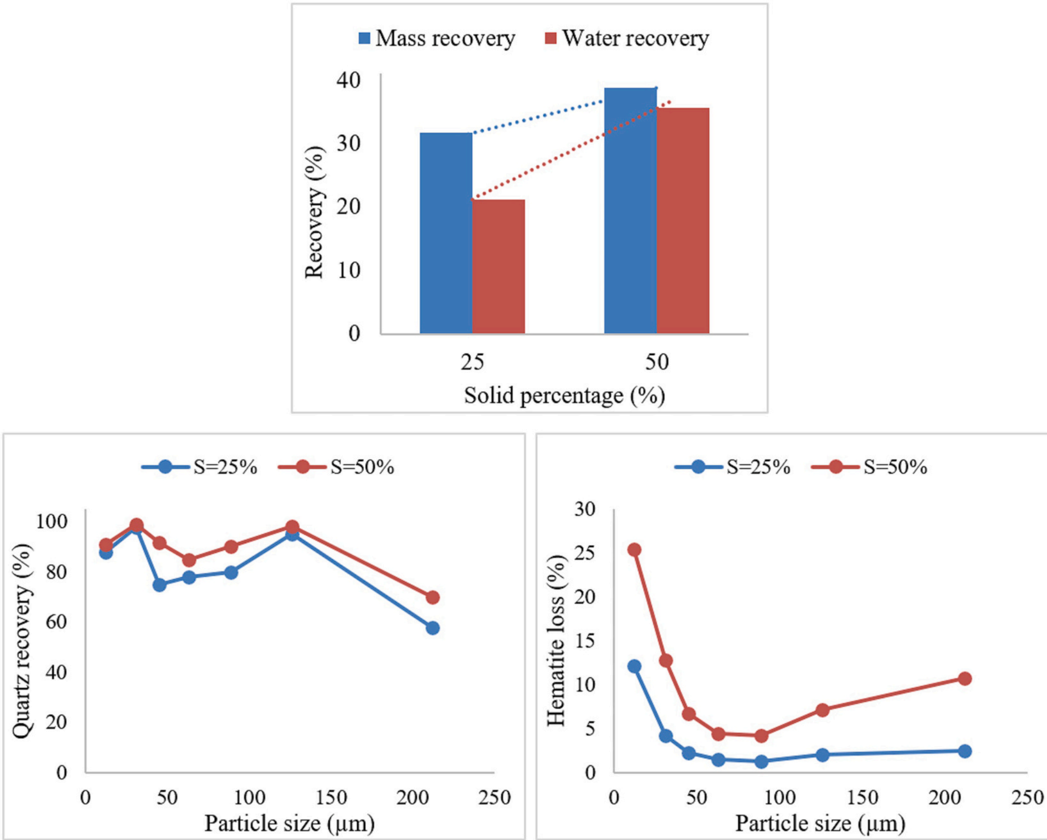

Fig. 6. Effect of solids concentration on the hematite and quartz particles recovery.

concentrators and depend on some characteristics such as ore mineralogy, pulp chemistry, reagents, particle size, size, and type of flotation cell and its duty in the flotation circuit. These findings are based on a pilot scale study and need to be examined at larger scales (e.g., an industrial scale). Based on conditions in industrial flotation cells, the availability of extra residence time in the circuit or/and lower stability of froth may be an overriding consideration.

3.3. *Overall separation efficiency*

The effects of chemical and physical parameters were investigated and presented in previous sections. As a combined effect of chemical and physical parameters on grade-recovery of hematite, the overall separation efficiency results are shown in Fig. 7. The figure shows the overall separation efficiency for the pneumatic flotation cell by observing flotation results for various testing conditions. Based on different conditions of the flotation cell, some scatter plots are presented in flotation results; however, all data follow the grade-recovery curve. It was observed from overall recovery data that over 93% hematite recovery was achieved while testing different operational conditions. The best condition based on metal recovery was achieved at 97.73% hematite recovery; however, hematite grade was around 82%. Also, the best condition based on concentrate quality was achieved at 95.75% hematite grade, while hematite recovery was 92.74%. The solids concentration and superficial gas velocity (both are physical parameters) were found as operating parameters with the largest impact on the pneumatic flotation cell's flotation performance (recovery-grade).

The chemical parameters and physical parameters had a huge effect on the performance of flotation in terms of water recovery in the pneumatic cell. These factors were the main reason for entrainment and loss of hematite in fine fractions. Therefore, the water recovery and loss of hematite can be minimized by having the correct chemical and physical conditions. On the other hand, results show that by controlling the hydrodynamic condition in the pneumatic cell, the coarser quartz recovery increases rapidly due to lower detachment rates [58,59]. The overall results were accurate enough based on the pneumatic flotation cell's recovery and grade curve data. The best conditions were selected based on the metal recovery-grade curve. The results showed that increasing the feed rate does not affect quartz recovery or hematite loss, suggesting that cell residence time is not constrained in the pneumatic flotation due to the high kinetics of quartz particles flotation. The overall flotation rates of quartz particles were high in various testing conditions. This result is expected and observed in the industry for reactor-separator-type flotation cells designed on process intensification [60–62].

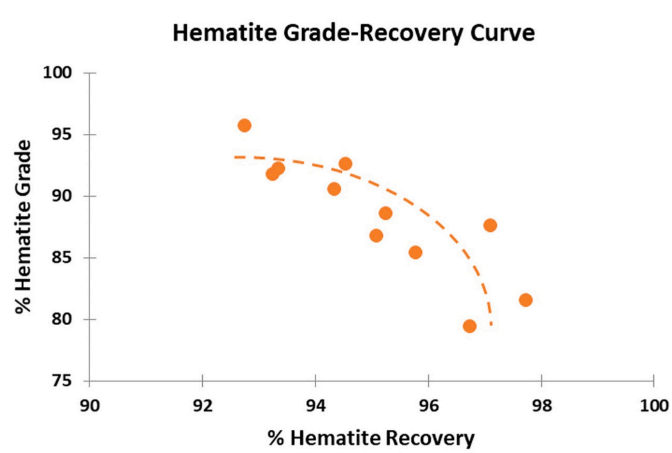

Fig. 7. Overall separation efficiency for the pneumatic flotation cell.

4. Conclusions

This work investigated the effect of collector dosage, depressant dosage, feed rate, solids concentration and superficial gas velocity on the reverse flotation of Timbopeba iron ore in a pilot scale pneumatic flotation cell. The main conclusions of this study are outlined as follows:

- Reagent Dosage: Increasing collector dosage results in an increase in quartz recovery, particularly for the coarser quartz where recovery increases by nearly 30%. Increasing depressant dosage results in a decrease in both quartz recovery and hematite loss, for the coarser hematite particles.
- Feed Rate: Increasing the feed rate does not affect quartz recovery or hematite loss, suggesting that the pneumatic flotation cell is not constrained by residence time.
- Superficial Gas Velocity: Increasing the J_g results in an increase in quartz recovery to an optimum at a J_g of around 0.6 cm/s. Afterward, this recovery decreases significantly, particularly for the coarser particles where recovery decreases by as much as 50%.
- Solids Concentration: Decreasing the solids concentration does not affect quartz recovery but significantly declines the hematite loss. Also, fine and coarse hematite loss decreased from around 25% to 12% and 10% to 2% respectively.
- Pneumatic Flotation Cell: Solid's concentration and superficial gas velocity are operating parameters with the largest effect on the flotation performance of the pneumatic flotation cell. Results suggest that this flotation cell should be operated at relatively low superficial gas velocities and solids concentrations. It is worth to noting that these results are pilot scale observations and need to be examined at larger scale, such as an industrial scale where different operating conditions may be optimal.

Author contributions

All of the authors contributed to analyzing the results and writing the paper.

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All of the authors contributed to analyzing the results and writing the paper.

CRediT authorship contribution statement

M. Safari: Conceptualization, Validation, Investigation, Resources, Writing – original draft, Writing – review & editing, Visualization, Supervision. **F.S. Hoseinian:** Validation, Investigation, Resources, Writing – review & editing. **D. Deglon:** Conceptualization, Validation, Investigation, Resources, Writing – review & editing, Supervision. **L. Leal Filho:** Conceptualization, Validation, Resources, Writing – review & editing. **T.C. Souza Pinto:** Validation, Resources, Writing – review & editing.

Declaration of Competing Interest

The authors declare they have no conflict of interest.

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