Mining
Mineração

Comparative evaluation between mechanical and pneumatic cells for quartz flotation in the iron ore industry

http://dx.doi.org/10.1590/0370-44672016710179

Neymayer Pereira Lima
Engenheiro de Minas, Dsc
Diretoria de Planejamento e Desenvolvimento de Ferrosos, Vale S.A.
Belo Horizonte – Minas Gerais - Brasil
neymayer.lima@vale.com

Antônio Eduardo Clark Peres
Professor Emérito
Universidade Federal de Minas Gerais – UFMG
Escola de Engenharia
Departamento de Engenharia Metalúrgica e de Materiais (UFMG – DEMET)
Belo Horizonte – Minas Gerais - Brasil
aecperes@demet.ufmg.br

Tatiane Aparecida Rocha Gonçalves
Engenheira de Minas, Msc
Diretoria de Planejamento e Desenvolvimento de Ferrosos, Vale S.A.
Mariana - Minas Gerais - Brasil
tatiane.rocha@vale.com

Abstract

Flotation plays a relevant role in the concentration of iron ores. Conventional flotation technology employing mechanical machines and columns and also circuits combining both types of cells have been utilized in the iron ore industry. The top size of particles in the flotation circuit feed is 150 µm and the slimes below 10 µm are removed as overflow in hydrocyclone classification. The conventional flotation technology faces difficulties in achieving tailings with iron grades lower than 12% and concentrates with SiO_2 grades lower than 1%, and requires long residence times, resulting in large volume machines and huge footprints. The pneumatic flotation technology was evaluated in the reverse flotation of quartz from an iron ore sample of the Iron Quadrangle, Brazil. Bench and industrial scale tests were conducted in pneumatic flotation machines at low residence time. Both tests were carried out in open circuit stages with the objective of comparison with mechanical cells. The bench scale tests were carried out in three stages (rougher, cleaner and recleaner) in an 11 L pneumatic cell aiming at final concentrate with maximum 2% SiO_2 while the industrial tests were carried out in a 25 m^3 pneumatic cell in the rougher stage aiming at comparison with a circuit of five 14 m^3 cells in the rougher stage and four 14 m^3 cells in the scavenger stage. The collision and particle-bubble adhesion occur in a step before the pulp reaches the pneumatic cell vessel. The results indicate the possibility of achieving concentrates with a SiO_2 content of approximately 1% and tailings with iron contents lower than 10% with three stages (rougher, cleaner and recleaner) without the need of scavenger stages. Furthermore, the residence time was three times shorter than that required for conventional mechanical cells. The speed of the pulp at the entrance of the pneumatic cell strongly affects the quality of the concentrate.

Keywords: froth flotation, pneumatic flotation, iron ore.

1. Introduction

The flotation of iron ores is performed in circuits consisting of mechanical cells, columns, or a combination of both types of machines. The feed consists of particles in the size range between 10 µm and 150 µm. The slimes (fraction < 10 µm) are removed in hydrocyclones and the top size is limited to 5% to 10% > 150 µm. This wide range of particles size impairs process selectivity due to the possible differences in behavior concerning properties such as hydrophobicity, specific surface area, weight, etc. (Lima *et al*., 2013).

The flotation mechanism was investigated by Tomlinson and Fleming (1963), using a probabilistic concept between the probabilities of collision (Pc), adhesion (Pa) and a stable aggregate formation (Ps):

$$Pf = Pc \times Pa \times Ps \quad \text{eq. 1}$$

Different probability parameters are associated with different particle sizes in the flotation pulp. Thus, coarse particles have a high Pc and a low Pa, which helps to explain the difficulty of collecting these particles in the flotation process. Studies carried out by Hewitt *et al*. (1994) showed that the Pa increases with decreasing particle size and with increasing degree of hydrophobicity, the latter being achieved with increased collector dosage. Furthermore, fine particles have a low Pc and adhesion and high probability of retaining the bubble.

Current flotation systems utilized in the iron ore industry (mechanical cells and columns) are not effective for collecting quartz particles larger than 150 µm and smaller than 45 µm, and the loss of fine particles of iron minerals in the tailings fraction is high. Furthermore, these systems require multiple stages and long residence times to produce concentrates with maximum 2% of SiO_2 within market specifications and with minimal loss of iron in the tailings. Entrainment of particles into the froth phase is an important factor in the performance of the flotation process, especially concerning fine particle recovery. It has been observed that the entrained gangue recovery is often proportional to the water recovery (Trahar, 1981, Neethling and Cilliers, 2009), although there is sometimes a non-linear relationship at low water recoveries, followed by a linear increase at higher water recoveries (Engelbrecht and Woodburn, 1975; Zheng *et al.*, 2006, Neethling and Cilliers, 2009).

A simplified model was proposed by Neethling and Cilliers (2002) to predict the entrainment factor as a function of the water recovery and the froth height. This investigation confirmed the experimentally observed relationship between gangue and water recovery, including its dependence on particle size, by using physics-based models for the liquid and solids behavior in the froth. It was concluded that there is a significant particle size effect on entrainment, in agreement with experimental observation (Neethling and Cilliers, 2009). Equation 2 was used as a simplified model for the calculation of entrainment.

$$Ent \approx \exp\left(\frac{-2\nu_{set}^{1,5}\, h_{froth}}{D_{axial}\sqrt{J_g}}\right) \quad \text{eq. 2}$$

Where: Ent : Entrainment; V_{set} : Particle settling velocity, h_{frot}: Froth height, D_{Axial}: Axial dispersion coefficient (particle dispersion), J_g: Superficial gas velocity.

The entrainment of fine iron mineral particles (<45 μm) into the froth can be one of the reasons for the difficulty in achieving tailings with low iron content (<12%) in traditional machines (mechanical and column cells) in the quartz reverse flotation of iron ores. The pneumatic flotation system was introduced in 1987, with the first operation in Pennsylvania for coal flotation. Since then, the technology has been widely used for fine coal slurries, industrial minerals, ferrous ores, non-ferrous metal-bearing ores such as copper, lead, nickel and zinc, for the precious metals platinum, gold, and silver. The pneumatic machines have been used in a wide range of particle sizes, from 80% passing 45 μm to 80% passing 1000 μm (Ören *et al.*, 2012).

Figure 1 illustrates a pneumatic flotation machine, where the pulp must be pumped at high pressure (2.5 to 3.0 bar) to promote the suction of air (self-aerated air) and the collision between mineral particles and bubbles under high energy.

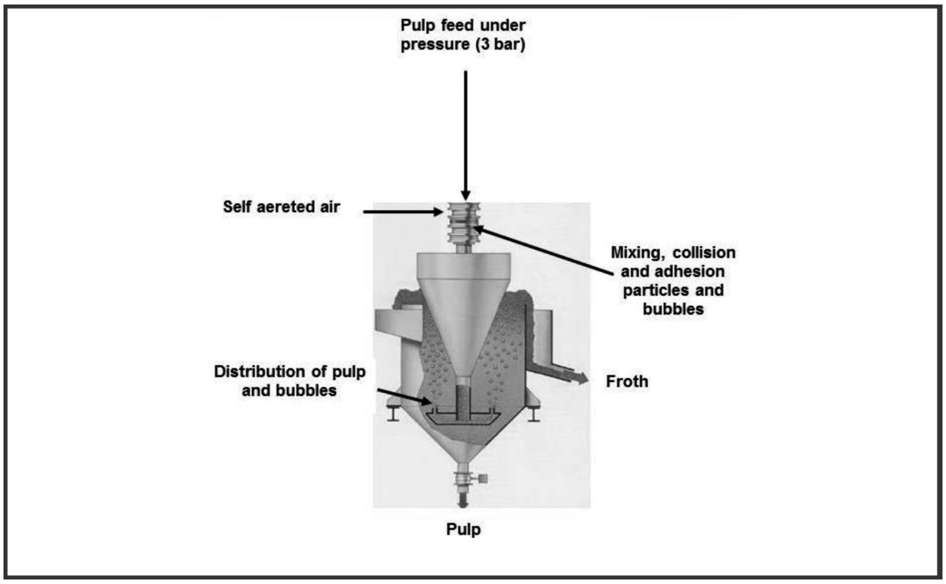

Figure 1
Pneumatic flotation machine
(adapted from Imhof *et al.*, 2002).

The pressurized conditioned pulp feed to the pneumatic machine shown in Figure 1 promotes the self-aeration to the feed pipe: when the air mixes with the pulp, small diameter bubbles are created. Collision and adhesion with particles take place ahead of the distributor and the hydrophobic particles adhered to bubbles immediately migrate to the froth phase, while the hydrophilic particles follow the pulp phase to the underflow. The residence time is very low, not requiring probabilistic effects between particles and bubbles in the cell as in conventional machines (Imhof *et al.*, 2002).

The main features of the pneumatic flotation are (Imhof *et al.*, 2002; Uliana *et al.*, 2013):

• the mechanisms of collision and adhesion between particles and bubbles which occur with high efficiency, before the pulp reaches the cell vessel, reducing the required residence times;

• low turbulence, reducing the likelihood of detachment of coarse particles, leading to concentrates with low SiO_2 content;

• low drag of fine iron mineral particles to the froth, resulting in tailings fraction with low iron content;

• generation of small diameter bubbles with high collection efficiency;

• simplicity of operation and maintenance due to the absence of moving parts.

This paper reports the results and discussion of an investigation into the pneumatic machine used in the reverse flotation of quartz for in comparison with the conventional machines.

2. Materials and methods

2.1 Bench scale tests

Bench scale tests were carried out in a pneumatic flotation machine of 11 L in the rougher, cleaner and recleaner continuous stages aiming to produce the final product (iron concentrate) with SiO_2 content below 2% and final tailings with maximum 10% of Fe. The tests were conducted in open circuit, where the first concentrate was used to feed the next stage. The recleaner concentrate was the final product, the combination of rougher, cleaner and recleaner tailings were the final tailings. The gas flowrate was controlled by a compressor.

The following conditions were used in the pneumatic flotation machine tests based on preliminary tests to define the best conditions for reagents dosages, pH, and physical operating conditions:

- pulp solids concentration: 50% by weight;
- pulp flowrate: 376 litres/hour;
- residence time: 2.5 minutes in each stage, 7.5 minutes total. The residence time was calculated dividing the pulp flowrate by the cell net volume;
- cornstarch dosage: 500g/t, added during the pulp conditioning for 3 minutes;
- collector (etheramine EDA-C by Clariant) dosage: 80g/t, added during the pulp conditioning after the cornstarch for 1 minute;
- pH: 10.5.

Feed, concentrates, and tailings were sampled for chemical analysis (Fe and SiO_2) and determination of size distribution and percent solids.

A representative iron ore sample from the Iron Quadrangle was used in the tests. Comparative tests in a 2600 mL conventional mechanical cell were conducted with the same sample and with the same reagents dosages and pH described above. Kinetic flotation tests were carried out in the mechanical bench scale machine, collecting tailings every two minutes for chemical analyses (Fe and SiO_2). All the tests, pneumatic and mechanical cells, were done in duplicate.

2.2 Industrial scale tests

Industrial scale tests were carried out to validate the bench scale results and the scale up. The tests were done in parallel with the conventional circuit: one pneumatic rougher cell of 25 m^3 was compared with nine mechanical cells of 14 m^3 each. Figure 2 shows the comparative circuits for the industrial tests.

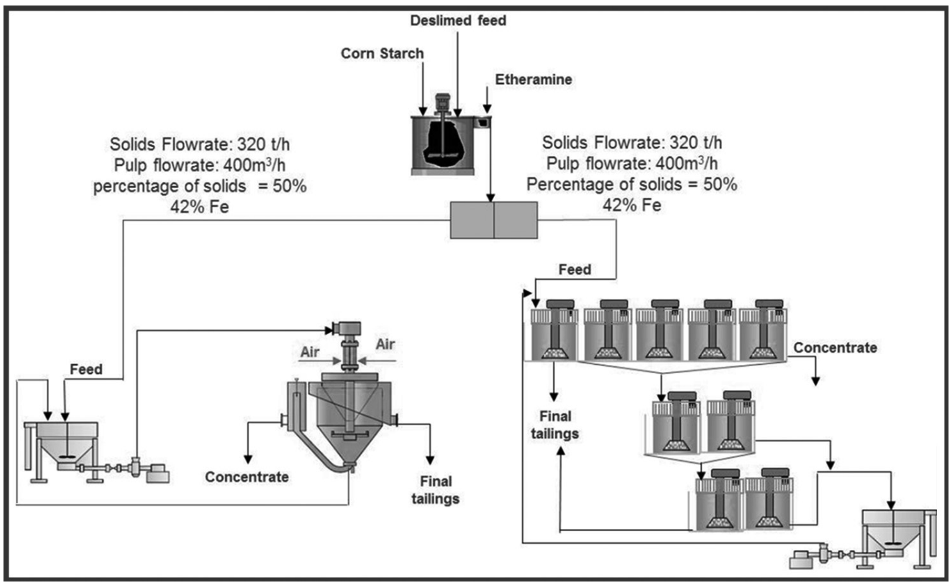

Figure 2
Comparative circuits
for the industrial tests.

3. Results and discussion

Figure 3 compares the Fe content in the rougher, cleaner and recleaner tailings for pneumatic and mechanical bench scale machines.

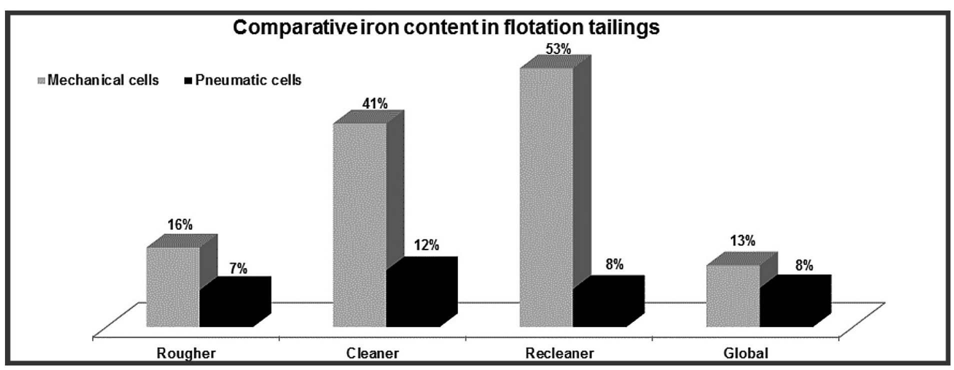

Figure 3
Comparative Fe content
in the tailings of the flotation stages.

The content of Fe in the pneumatic flotation tailings is almost stable in each stage. On the other hand, the Fe grades in the mechanical cells tailings are higher than those in the pneumatic cell, increasing from rougher to cleaner to recleaner. The higher grades of Fe in the tailings of the mechanical cell are related to the fractions of <45 µm, as shown in Figure 4. The entrainment is the main hypothesis for the higher losses of fine particles of iron bearing minerals in the tailings of the mechanical cell.

The loss of fine particles of iron minerals by entrainment can be related to the water recovery in the froth as stated by Neethling and Cilliers (2002). Figure 5 shows the water recovery in the froth for the different stages in the mechanical and pneumatic cells.

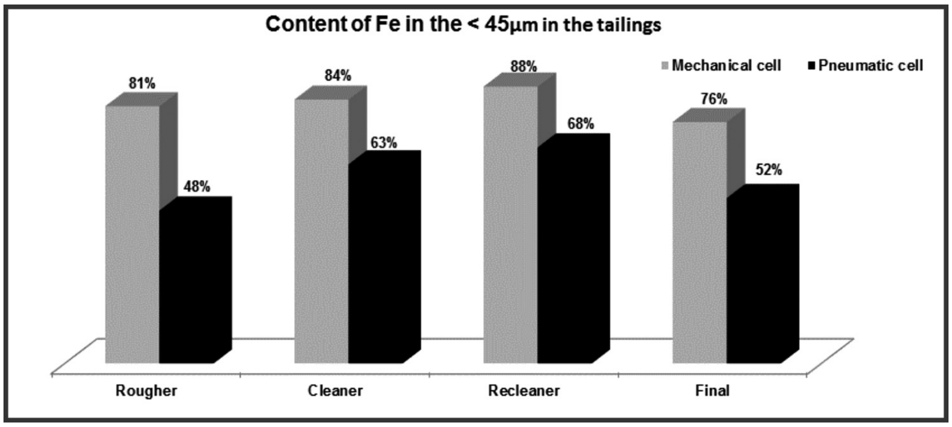

Figure 4
Content of Fe in the <45µm in the tailings.

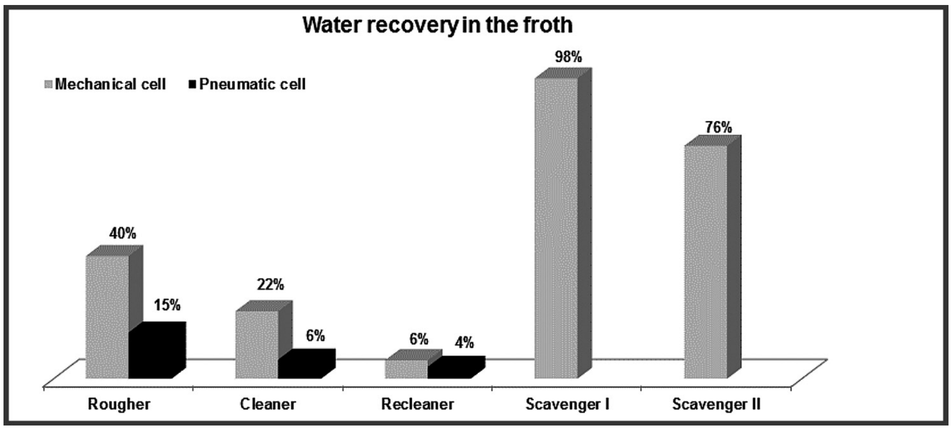

Figure 5
Water recovery in the froth.

The water recovery is lower in all stages of the pneumatic cell compared to those in the mechanical cell.

Figure 6 shows the correlation between water recovery and iron recovery in the froth for mechanical cell and pneumatic cells.

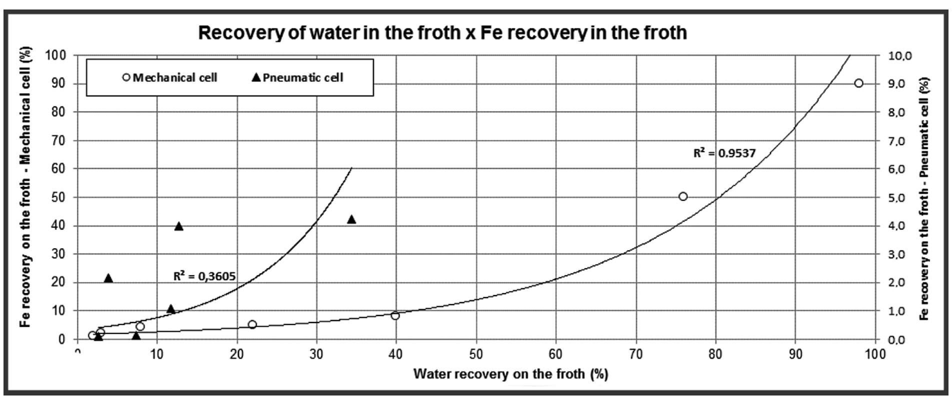

Figure 6
Water recovery in the froth vs Fe recovery in the froth – Mechanical and pneumatic cells.

Iron recovery in the froth strongly correlates (R^2 = 0.9537) with the water recovery in the froth for the mechanical cell. On the other hand, the correlation is weak (R^2 = 0.3605) for the pneumatic cell, indicating that entrainment is less relevant in this machine, regarding Fe recovery to the froth. The high water recovery on the froth for the mechanical cell is in agreement with the study of Lima et al (2016), where more than 96% of water in the froth and close to 90% of Fe recovery were observed in the scavenger stage.

Figure 7 compares the performance of the mechanical and pneumatic cells, over cumulative flotation time, in terms of grades of SiO_2 in the final concentrate and iron in the tailings. The Pneumatic cell produced an iron concentrate with 0.8% SiO_2 after 7.5 minutes while the mechanical cell produced an iron concentrate with 2% SiO_2 after 16 minutes. The grade of iron in the pneumatic cell tailings was close to 6% during the three stages while this grade increased to 9% to 30% in the mechanical cells.

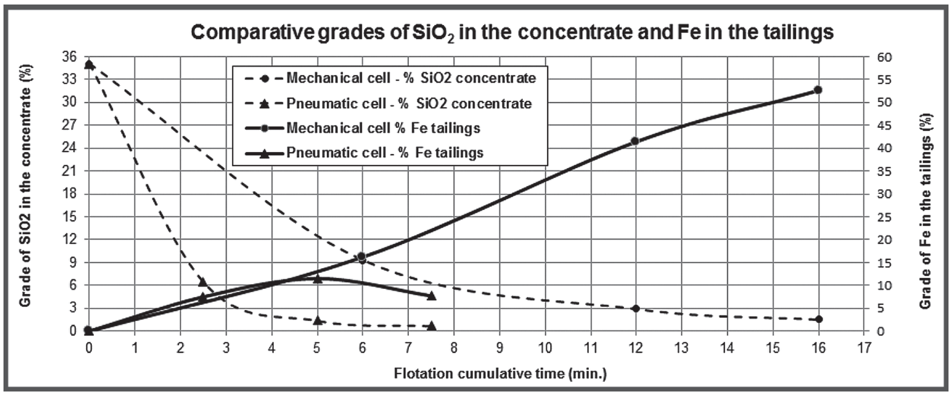

Figure 7
Comparative grades of SiO_2 in the concentrate and Fe in the tailings.

Figure 8 compares the results of the industrial flotation tests, regarding % of Fe in the froth, % of SiO_2 in the rougher concentrate, metallic recovery and Gaudin selectivity index. The most outstanding feature is the low iron grade in the froth (tailings), but the enhanced metallic recovery and higher value of Gaudin's selectivity index are also relevant. Gaudin´s selectivy index was used to compare the separation efficiency between the two flotation machines. Equation 3 was used to calculate this index.

$$Gaudin\acute{}selectivityindex = \sqrt{\frac{(\%\ Feconc \times \%\ SiO_2\ tails)}{(\%\ Fetails \times \%\ SiO_2\ conc)}} \quad \text{eq. 3}$$

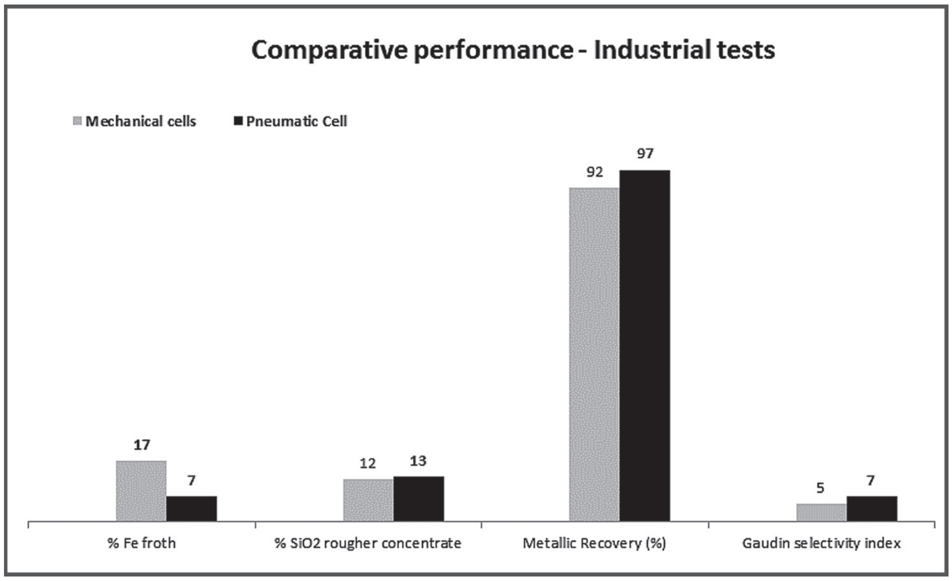

Figure 8
Comparative industrial performance between the pneumatic and mechanical cells.

The industrial tests showed that the froth depth is not so relevant in the pneumatic performance as is in the mechanical cells. Other physical parameters require better investigation regarding pneumatic flotation, such as the pulp density, pulp velocity, and ratio between air and pulp flow rates. These parameters seem to affect and control the pneumatic flotation performance.

4. Conclusions

The pneumatic cell has a great potential for quartz reverse flotation in the iron ore industry, with the possibility of reducing the flotation time and increasing the metallic recovery. One stage of pneumatic flotation can replace the rougher and scavenger stages of mechanical cells, with a strong decrease in the footprint and enhanced flotation performance for iron ore. The results of the investigation involving bench scale and industrial tests indicated that the entrainment of fine iron bearing mineral particles is lower in the pneumatic cell. Although there is greater operational simplicity, the effect of some parameters requires better investigation and understanding regarding the pneumatic cell, such as pulp density, pulp velocity, and the ratio between air and pulp flow rates. The bench scale pneumatic cell of 11 L of volume can be easily operated to estimate results for the industrial scale cell but the scaling up still requires investigation.

References

ENGELBRECHT, J.A., WOODBURN, E.T. The effects of froth height, aeration rate and gas precipitation on flotation. ***Journal South African Institute of Mining and Metallurgy,*** p.125-132, October, 1975.

IMHOF, R.M., BATTERSBY, M.J.G., CIERNIOCH, G. Pneumatic flotation – an innovative application in the processing of potash salts. In: SME ANNUAL MEETING, 2002.

HEWITT, D., FORNASIERO, D., RALSTON, J. Bubble particle attachment efficiency. ***Minerals Engineering,*** v.7, n.5/6, p. 657–665, 1994.

LIMA, NEYMAYER P., GEORGE E.S. VALADÃO; ANTÔNIO E.C. PERES. Effect of amine and starch dosages on the reverse cationic flotation of an iron ore. ***Minerals Engineering,*** 2013.

LIMA, NEYMAYER P. PINTO, THIAGO C.S., TAVARES, ALINE, C., SWEET, JENNI. The entrainment effect on the performance of iron ore reverse flotation. ***Minerals Engineering*** 96-97, 53-58, 2016.

NEETHLING, S.J., CILLIERS, J.J. The entrainment of gangue into a flotation froth. ***International Journal of Mineral Processing,*** v.64, p.123-134, 2002.

NEETHLING, S.J., CILLIERS, J.J. The entrainment factor in froth flotation: Model for particle size and other operating parameter effects. ***International Journal of Mineral Processing,*** v.93, p.141-148, 2009.

ÖREN, E., MARKWORTH, L., HEEVER, J.V.D. Pneumatic flotation challenges conventional technology. A wide range of bubble sizes, online control of froth level, turbulence-free operation and no need for a blower or compressor comprise a user- friendly system. ***Engineering and Mining Journal,*** p.60-61, November 2012.

TOMLINSON, H.S., FLEMING, M.G. Flotation rate studies. In: INTERNATIONAL MINERAL PROCESSING CONGRESS. ***Proceedings...*** Cannes, 1963, v.6, p. 563-579.

TRAHAR, W.J. A rational interpretation of the role of particle size in flotation. ***International Journal of Mineral Processing,*** v.8, p. 289-327, 1981.

ULIANA, A. JÚNIOR, L.C.A., QUINTÃO, A.O., CASTRO, G., ARAÚJO, V. Aplicação de células pneumáticas de flotação no processo de minério de ferro da Samarco Mineração S.A. ***Tecnol. Metal. Mater. Min.,*** São Paulo, v.10, n.4, p. 359-364, out/dez 2013.

ZHENG, X., JOHNSON, N.W., FRANZIDIS, J.P. Modelling of entrainment in industrial flotation cells: water recovery and degree of entrainment. ***Minerals Engineering,*** v.19, n.11, p. 1191-1203, 2006.

Received: 28 March 2017 - Accepted: 18 April 2017.