Minerals Engineering 118 (2018) 1–8

Contents lists available at ScienceDirect

Minerals Engineering

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

A new approach to measure gas holdup in industrial flotation machines part I: Demonstration of working principle

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ARTICLE INFO

Keywords:
Gas holdup measurement
Gas-exclusion cell
Collection zone
Flotation machines
Sensor

ABSTRACT

A new approach for continuous measurement of gas holdup, based on the generation and measurement of a bubble-free pulp flow using a gas-exclusion cell immersed in the collection zone of industrial flotation machines is introduced and demonstrated. The gas-exclusion cell, a device that works exclusively on hydrodynamics effects caused by its design, prevents the entrance of bubbles and fills continuously only with mineral pulp; the higher density of the fluid inside the cell originates a circulating pulp flow through the unit that is proportional to the gas holdup. Continuous tracking of the pulp flow velocity, using a magnetic flowmeter connected to the gas-exclusion cell, allows online calculation of the gas holdup using an equation derived from a mechanical energy balance. Design constraints and results of the hydrodynamic characterization of demonstration units are discussed. The results of two-phase prototype testing demonstrated that the approach is robust and provides reliable gas holdup measurements and tracking.

1. Introduction

The selective separation of mineral particles in flotation proceeds in two interactive zones where different and simultaneous phenomena take place. In the collection zone, the valuable particles are separated by collection on the surface of bubbles, while in the froth zone, the bubble-particle aggregates are gathered, drained, and directed into the concentrate stream. The flotation cell overall recovery, which is determined from proper stream sampling under steady-state conditions, is a function of the recoveries in the individual zones. Flotation process optimization consists of finding and maintaining operating conditions in both zones that maximize metallurgical performance (recovery and grade). Progress in the independent measurement or assessment of zone recoveries has been slow because on line and reliable sensors to measure properties of the significantly different dispersions existing in both zones are not available.

In the case of the collection zone, it has been demonstrated that the recovery of hydrophobic particles captured on the surface of bubbles (true flotation), considered as a process with first-order kinetics, correlates with the bubble surface area flux (Finch et al., 2000; Hernandez, et al., 2003; Lopez-Saucedo et al., 2012). Bubble surface area flux (bubble area generated per unit time and cell cross-sectional area), is a variable affected by gas flow rate and the resulting bubble size distribution, which mainly depends on frother concentration and the technology used by the flotation machine to disperse air into bubbles. Gas holdup (volumetric fraction of gas dispersed in the slurry) is also affected by the same variables, and as such, carries information on the interacting variables that define the performance of the process. Therefore, a correlation between gas holdup and bubble surface area flux was expected and demonstrated (Finch et al, 2000; Lopez-Saucedo et al., 2012), and since gas holdup is easier to measure as no bubble size is required, it has the potential to be the basis of a cell control and optimization strategy if a continuous sensor is available (Wills and Finch, 2016).

Several methods have been proposed to measure collection-zone gas holdup in flotation cells. Efforts to develop continuous methods include measurement of pressure differences at different depths (Finch and Dobby, 1990), light (Schweitzer et al., 2001) and sound propagation through the aerated fluid (óKeefe et al., 2007), tomography (Patel and Thorat, 2008), and changes in the electrical conductivity of a liquid with a non-conducting dispersed phase (Sigrist et al., 1980; Uribe Salas et al., 1994; Tavera et al., 1996; Gomez et al., 2003). These methods, however, have found little application at industrial scale except for the conductivity-based gas holdup sensor, which has been widely used at the lab and industrial scale for diagnostic purposes (Gomez and Finch, 2007).

The objective of this communication is to introduce a new submersible online sensor to measure, in real-time, the gas holdup in the

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https://doi.org/10.1016/j.mineng.2018.01.001
Received 3 November 2017; Received in revised form 29 December 2017; Accepted 2 January 2018

collection zone of industrial flotation machines. The working principle, its main components, and the theory behind the measurement are described. Design and construction details of prototypes are discussed, and the results of its lab testing in a two-phase system are included. The effect of fluid characteristics on the discharge coefficient and testing on a three-phase system will be addressed in a future communication.

The approach is based on the generation and measurement of a bubble-free pulp flow using a gas-exclusion cell immersed in the aerated pulp. The gas-exclusion cell creates hydrodynamic conditions that, when vertically immersed in the collection zone, prevents the entrance of bubbles and fills it only with mineral pulp. The density difference between the fluids inside and outside the device originates a downward pulp flow through the unit that is proportional to the external gas holdup. Therefore, continuous tracking of the pulp flowrate through the gas-exclusion cell allows online calculation of the gas holdup using an equation derived from an energy balance, knowing the geometry of the cell and the conditions and characteristics of the pulp.

2. Theoretical considerations

2.1. Gas-exclusion cell hydrodynamics

The gas-exclusion cell is a device designed in our case, as our interest is in flotation, to continuously generate a flow of fluid with no bubbles present when immersed in the aerated fluid. The device works exclusively on hydrodynamics effects caused by its design: a variable-area cylindrical tube, vertically installed, open at both ends and with a larger diameter at the top than at the bottom. This geometry initially reduces the entrance of rising bubbles into the unit; the higher density of the fluid within the cell generates a downward flow that completes the exclusion of bubbles, providing that no entrainment in the circulating fluid takes place.

A schematic of a gas-exclusion cell indicating relevant dimensions is shown in Fig. 1: a total length L, and top and bottom sections of internal diameter D and d, respectively, connected by a truncated inverted cone. Our application involves a stationary flow of an incompressible fluid between the top (t) and bottom (b) planes, with no work done by or on the fluid. If friction losses are not considered, a balance of mechanical-energy contributions is the following (Geankoplis, 1993):

$$gZ_t + \frac{v_t^2}{2} + \frac{P_t}{\rho_{fluid}} = gZ_b + \frac{v_b^2}{2} + \frac{P_b}{\rho_{fluid}} \quad (1)$$

where

- Z_t, Z_b : elevations of top and bottom planes (m)
- v_t, v_b : fluid velocity at the top and bottom sections (m/s)
- P_t, P_b : hydrostatic pressure at top and bottom planes (Pa)
- g : gravity acceleration (m/s^2)
- ρ_{fluid} : fluid density (kg/m^3)

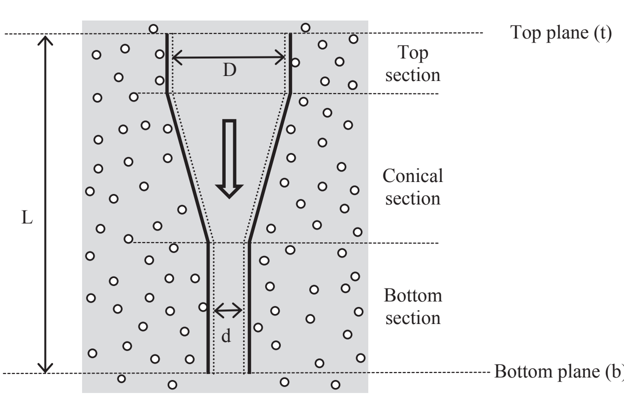

Fig. 1. Schematics of gas-exclusion cell immersed in an aerated liquid.

The hydrostatic pressure difference between the bottom and top planes is equal to the weight of the aerated fluid per unit area between the two planes, which depends on the density of the aerated fluid (ρ_{bulk}), the gas holdup (ε_g), defined as the gas fraction in the aerated fluid, and the total length L of the cell. Neglecting the gas contribution (Finch and Dobby, 1990):

$$\Delta P = P_b - P_t = \rho_{bulk} gL = \rho_{fluid} gL(1-\varepsilon_g) \quad (2)$$

For an incompressible fluid, pulp velocities and cross-sectional areas at the top (A_t) and bottom(A_b) planes, respectively, are related through a mass balance as follows:

$$v_t \cdot A_t = v_b \cdot A_b \quad (3)$$

Replacing Eqs. (2) and (3) in Eq. (1), with $L = Z_t - Z_b$, the following equation is obtained, which indicates a direct relationship between the velocity of the fluid leaving the exclusion cell (v_b) and the surrounding gas holdup:

$$v_b = \sqrt{\frac{2gL\varepsilon_g}{1-\beta^4}} \quad (4)$$

This velocity, which corresponds to the ideal case when no friction losses are considered, is the maximum possible that can be induced in a gas-exclusion cell of length L and contraction coefficient β (defined as the ratio of the bottom to the top section diameters d/D), operating under a gas holdup ε_g.

In practical applications, friction losses are expected at the entrance, exit, and in every section of the exclusion cell. The effect of these losses is a reduction of the velocity predicted by this equation, which is accounted for in the form of a discharge coefficient (C_d), a dimensionless parameter with a value less than one and defined as:

$$C_d = \frac{v'_b}{v_b} \quad (5)$$

Where v'_b is the fluid velocity leaving the exclusion cell. Combining Eqs. (4) and (5), a relationship between the discharge velocityv'_b and the gas holdup ε_g can be demonstrated:

$$v'_b = C_d\sqrt{\frac{2gL\varepsilon_g}{1-\beta^4}} \quad (6)$$

or

$$\varepsilon_g = \frac{(1-\beta^4)}{2gL}\left(\frac{v'_b}{C_d}\right)^2 \quad (7)$$

Our interest is to use this equation as the basis for a new approach to determine gas holdup in flotation from measurements of the fluid discharge velocity. The determination requires exclusion-cell dimensions and values of the discharge coefficient, which depends on the discharge velocity.

The discharge coefficient of devices such as Venturi tubes, flow nozzles and orifices has been successfully modeled, for turbulent flow, as follows (Miller, 1996):

$$C_d = C_\infty + \frac{b}{(\beta Re_b)^n} \quad (8)$$

where the parameters C_∞ (discharge coefficient at an infinite Reynolds number), b and n must be determined experimentally. The Reynolds number (Re_b) corresponds to that for the fluid flow through the bottom section of the gas-exclusion cell, calculated as:

$$Re_b = \frac{\rho_{fluid} v'_b d}{\mu_{fluid}} = \frac{v'_b d}{\nu_{fluid}} \quad (9)$$

with μ_{fluid} and ν_{fluid} as viscosity and kinematic viscosity (μ_{fluid}/ρ_{fluid}), respectively.