



Gas holdup estimation using Maxwell equation in flotation systems: Revisited



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ABSTRACT

Estimation of gas holdup from electrical conductivity measurements has been used in lab and industrial installations. The approach is based on the application of Maxwell's model, which relates the concentration of a dispersed phase in a continuous medium to measurements of the electrical conductivity of the dispersed phase, continuous medium and the resulting mixture (dispersion). When applied to inferring the collection zone gas holdup in a three phase system and to facilitate real-time on-line measurement, the slurry is assumed to behave as the continuous medium and gas bubbles as a non-conducting dispersed phase. This article derives an equation for estimating gas holdup in a three phase system, eliminating the assumption that the slurry behaves as a continuous medium but rather as a dispersion of non-conducting solid particles in water. In this formulation only water behaves as the continuous medium in the sense of Maxwell, and gas holdup in a three phase system is then calculated from the application of the Maxwell model twice: (1) to determine solid content in a two-phase system, and (2) to determine solid plus gas holdup in a three phase system. To validate the new equation and quantify the errors incurred by assuming slurry is the continuous phase a laboratory flotation cell was instrumented to continuously measure the conductivity of two and three phase dispersions with known solids contents. As the amount of gas in a lab flotation machine is difficult to measure directly or by another indirect technique such as using pressure signals, 2.5 mm dielectric plastic spheres having a density of ca. 1.3 g/cm³ were used instead of air bubbles for validation. Experimental results demonstrated that the continuous medium assumption underestimates gas holdup and that the resulting bias error increases linearly with the solid content and decreases with the magnitude of gas holdup.

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1. Introduction

Optimizing the metallurgical performance of the flotation process is challenging and demands, among others, reliable sensors to provide real-time information about the current state of the process. The collection (or pulp) zone gas holdup, the volumetric fraction of gas dispersed as bubbles in the slurry, is a potential variable to be incorporated in a control and optimization system as it carries important information about the process state. Indeed, gas holdup has been correlated to the bubble surface area flux, a variable directly related to the collection zone performance (Hernandez et al., 2003; Lopez-Saucedo et al., 2012) and to the froth performance through the water overflow (Finch et al., 2006). Recently, collection zone gas holdup measured in flotation columns of a Zn circuit was found to correlate directly to Zn

recovery and inversely to the enrichment ratio (Lopez-Saucedo et al., 2012).

Gas hold up sensor based on conductivity measurements developed at McGill University has been widely used at the lab and industrial scale mainly for diagnostic purposes (Gomez and Finch, 2007). The sensor device consists of two tubes called flow cells: an open cell that allows the free flow of slurry and a syphon cell that retains slurry only. Both the open and syphon cells are equipped with metal rings flush-mounted inside the tubes forming electrical conductivity cells that allow the measurement of the conductivity of the aerated slurry (open cell) and the slurry only (syphon cell). Gas holdup is then calculated by applying Maxwell equation that relates the volumetric fraction of a phase dispersed in a continuous phase to the conductivity of the dispersion and continuous phases (Maxwell, 1873). In this case the slurry is assumed to behave as a continuous phase in the Maxwell sense. This study derives a new equation for gas holdup estimation in a three phase system eliminating this assumption and quantifies the impact of this assumption on the estimation of gas holdup.

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The article is organized as follows: next section introduces the Maxwell model and derives an equation to calculate gas holdup in a three phase system considering liquid as the only (and true) continuous phase present. Then the experimental set-up is described. After that, experimental results are presented followed by a discussion section. Finally, the main conclusions are provided.

2. Gas holdup estimation using maxwell equation revisited

Maxwell (1873) derived an equation that relates the apparent conductivity k_m of an arrangement of same-size small spheres uniformly dispersed in a continuous medium to the electrical conductivity of the dispersed (spheres) and continuous phase, k_d and k_c , respectively, and the volumetric fraction of the dispersed spheres ε :

$$k_m = \left(\frac{1 + 2 \cdot \beta \cdot \varepsilon}{1 - \beta \cdot \varepsilon} \right) \cdot k_c \quad (1a)$$

where

$$\beta = \frac{k_d - k_c}{k_d + 2 \cdot k_c} \quad (1b)$$

when the electrical conductivity of the dispersed phase is negligible compared to that of the continuous medium (i.e., $k_d \ll k_c$), which is the case of bubbles and particles in an electrolyte solution, $\beta \approx -0.5$ and Eq. (1) simplifies to:

$$k_m = \left(\frac{1 - \varepsilon}{1 + 0.5 \cdot \varepsilon} \right) \cdot k_c \quad (2)$$

The dispersed phase volumetric fraction can then be calculated from the following equation:

$$\varepsilon = \left(\frac{1 - \frac{k_m}{k_c}}{1 + 0.5 \cdot \frac{k_m}{k_c}} \right) \quad (3)$$

Although Maxwell assumed that the spheres were separated by distances large enough not to disturb the flow of electric current, a condition limiting the approach to low volume fractions of dispersed phase, later studies showed that the Maxwell equation works over a wide range, up to values of 60% for solid spheres (Turner, 1976) and gas bubbles (Sigrist et al., 1980). Beyond this range, conduction path tortuosity must be taken into account as described in (Yianatos et al., 1985). In the case of flotation, which occurs in a continuous liquid (water) phase, the following Maxwell equations can be applied to (a) calculate the solid holdup in a two phase system ($\varepsilon_{s/sl}$), i.e., solids content in the slurry:

$$\varepsilon_{s/sl} = \left(\frac{1 - \frac{k_{sl}}{k_l}}{1 + 0.5 \cdot \frac{k_{sl}}{k_l}} \right) \quad (4)$$

and (b) the total solid plus gas holdup in a three phase system ($\varepsilon_{sg/slg}$), that is, the case of aerated slurry in flotation machines:

$$\varepsilon_{sg/slg} = \left(\frac{1 - \frac{k_{slg}}{k_l}}{1 + 0.5 \cdot \frac{k_{slg}}{k_l}} \right) \quad (5)$$

where k_l , k_{sl} and k_{slg} are, respectively, the electrical conductivities of the liquid phase, of the slurry (solid-liquid), and of the aerated slurry (solid-liquid-gas).

The total solid-gas holdup is the sum of the volumetric fractions of solid (particles) and gas (bubbles) in the three-phase suspension:

$$\varepsilon_{sg/slg} = \varepsilon_{s/sl} + \varepsilon_{g/slg} \quad (6)$$

The volumetric fraction of solids in an aerated slurry ($\varepsilon_{s/slg}$), which is a three-phase suspension, can be calculated from the fraction of solids in the slurry ($\varepsilon_{s/sl}$), a two-phase suspension, and the gas holdup in the three-phase suspension as follows:

$$\varepsilon_{s/slg} = \varepsilon_{s/sl} \cdot (1 - \varepsilon_{g/slg}) \quad (7)$$

Substituting Eq. (7) into Eq. (6), the following is obtained:

$$\varepsilon_{g/slg} = \frac{\varepsilon_{sg/slg} - \varepsilon_{s/sl}}{1 - \varepsilon_{s/sl}} \quad (8)$$

Now, substituting Eqs. (4) and (5) into Eq. (8), an equation for calculating gas holdup in three-phase systems is obtained:

$$\varepsilon_{g/slg} = \left(\frac{1 - \frac{k_{slg}}{k_l}}{1 + 0.5 \cdot \frac{k_{slg}}{k_l}} \right) \quad (9)$$

which requires measurements of the electrical conductivity of the liquid, of the slurry, and of the aerated pulp.

In previous work the slurry was assumed to behave as a continuous homogeneous medium resulting in the following equation for gas holdup:

$$\hat{\varepsilon}_{g/slg} = \left(\frac{1 - \frac{k_{slg}}{k_{sl}}}{1 + 0.5 \cdot \frac{k_{slg}}{k_{sl}}} \right) \quad (10)$$

Compared to Eq. (9), in Eq. (10) the electrical conductivity of the liquid only, k_l , is no longer required. Since $k_l > k_{sl}$, by inspection it can be determined that Eq. (10) underestimates the true value of gas holdup (Eq. (9)) by assuming the slurry to behave as a continuous phase in the sense of Maxwell. This also suggests that deviations of Eq. (10) from Eq. (9) depends on the solid fraction as it determines the difference in the electrical conductivity between k_l and k_{sl} .

The relative error (E) in gas holdup incurred when assuming the slurry to be the continuous medium can be calculated from one of the following equations:

$$E(\%) = 100 \cdot \left(\frac{\varepsilon_{g/slg} - \hat{\varepsilon}_{g/slg}}{\varepsilon_{g/slg}} \right) \quad (11a)$$

$$= 50 \cdot (1 - \hat{\varepsilon}_{g/slg}) \cdot \left(\frac{\varepsilon_{s/sl}}{1 + 0.5 \cdot \varepsilon_{s/sl}} \right) \quad (11b)$$

$$\approx 46.3 \cdot (1 - \hat{\varepsilon}_{g/slg}) \cdot \varepsilon_{s/sl} \quad (11c)$$

The last term in parenthesis in Eq. (11b) can be very well approximated, in the range of interest for flotation, i.e., $\varepsilon_{s/sl} \leq 0.2$, by a linear equation in $\varepsilon_{s/sl}$ resulting in Eq. (11c). This suggests that the measurement error is of a type of offset or bias error and that it increases linearly as solid content increases and decreases with the magnitude of gas holdup, here represented by its estimation $\hat{\varepsilon}_{g/slg}$.

3. Experimental setup

The setup to evaluate the new Eq. (9) is shown in Fig. 1. It comprises a 2.5 L Denver flotation cell equipped with a stainless steel hollow tube inserted in the shaft that, in conjunction with the metallic vessel, forms a conductivity cell that allows the conductivity of the dispersion inside the vessel to be measured, as shown in Fig. 2. During the experiments the temperature of the fluid inside the vessel increased as a result of the agitation. To keep the temperature constant a peristaltic pump (Masterflex model IP 7591-22) was used to pass the fluid through a glass heat exchanger immersed in a liquid-ice bath and the pump speed adjusted to regulate the fluid temperature at 25 ± 0.1 °C. A RTD probe was installed inside the cell to monitor the temperature of the solution. The process signals were centralized to I/O modules equipped with Ethernet I/P communication protocol (STB Advantys Schneider Electric). A HMI was developed using iFIX 5.3 (General Electric) to supervise and interact with the process.

To calibrate the conductivity cell, a two-point calibration procedure was followed using Metler Toledo M300 conductivity

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