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Optimisation of air rate and froth depth in flotation using a CCRD factorial design – PGM case study

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ABSTRACT

Air rate and froth depth are the most commonly adjusted levers in PGM flotation plants. The optimisation of these levers on each flotation cell has traditionally been done by varying either air rate at a fixed froth depth or vice versa. This approach does not consider the interaction relationship between air rate and froth depth and this effect on flotation performance.

Factorial type experimental designs are best suited for investigating interaction effects between variables. This paper presents the use of a factorial type of experimental design being the (CCRD) Central Composite Rotatable Design for plant scale flotation optimisation of air and froth depth. The results obtained include three dimensional response surfaces and models of flotation response variables such as 4E PGM recovery and grade as a function of air rate and cell level. This paper illustrates the experimental methodology and discusses the results for normalised 4E PGM grade and recovery for a rougher cell treating a Platreef ore.

These results indicate that interaction effects of air and froth depth are significant and are more pronounced at conditions of higher air and shallower froth depth. In addition, indices which are based on an optimisation objective such as grade multiplied by recovery and/or grade multiplied by recovery squared allows application of this technique as an optimisation tool. These indices can be used to determine an optimum operating range for air and level with the consideration of interaction effects.

1. Introduction

Anglo American Platinum (AAP) is the world's largest primary producer of platinum group metals. AAP mines different ore bodies which include UG2 reef, Merensky Reef, Platreef and the Main Sulphide Zone of the Great Dyke. Run of mine ore is transported to concentrator plants where it undergoes comminution and flotation to liberate and upgrade the mineral content prior to smelting.

In controlling the flotation process, air rate and froth depth are the most commonly used levers . In recent years, mass pull controllers have been introduced onto flotation banks in order to improve process stability and the achievement of plant mass pull targets. Mass pull controllers manipulate air and froth depth to achieve a target mass pull. A critical role of the metallurgist in this system is to define operating limits for the air rate and froth depth of each flotation cell as well as setting sensible mass pull targets for the bank.

Optimisation of air and level on individual flotation cells has traditionally been performed by fixing air and changing level or vice versa. This methodology ignores interaction effects between air rate and level. Factorial type experiments are designed to investigate the main effects of variables and to determine interaction effects between variables. The Central Composite Rotatable Design (CCRD) is a factorial type of experimental design which enables the investigation of the effects of multiple variables simultaneously. The CCRD design has the added benefit of requiring fewer experimental runs. The results of the experiment allow for 3D response surfaces and empirical mathematical models to be determined for each response variable.

The current paper describes a methodology that has been developed for performing a CCRD for air rate and froth depth on an industrial scale flotation cell. It demonstrates how the CCRD can be used as a tool for deciding on optimum air and froth depth ranges.

2. Theory

2.1. Importance of air and froth depth in PGM flotation

The overall 1st order flotation rate constant can be described as (Gorain et al., 1998):

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$$k = \underbrace{PS_b}_{\text{Pulp Phase effect}}\underbrace{R_f}_{\text{Froth Phase effect}} \quad (1)$$

where k is the overall flotation rate constant (s^{-1}), P is the floatability of the PGM minerals, S_b is the bubble surface area flux (s^{-1}), R_f is the froth recovery.

The bubble surface area flux can be defined as (Gorain et al., 1998):

$$S_b = \frac{6J_g}{d_{32}}$$

where J_g is the superficial gas velocity or air rate (cm/s), d_{32} is the sauter mean bubble diameter (cm).

Air rate and froth depth are very important variables which affect flotation performance. The effect of air rate can be described by the bubble surface area flux which is defined as the total surface area of bubbles rising up the cell per unit cross sectional area per unit time (Gorain et al., 1998). Gorain et al. (1995) also showed that the flotation rate constant in an industrial flotation cell increases almost linearly with bubble surface area flux.

Vera et al. (1999) investigated the relationship between the overall flotation rate constant and froth depth treating a copper ore on a mechanical flotation cell for a series of different cell operating conditions. It was shown that there is a linear relationship of negative slope between overall flotation rate constant and froth depth, i.e. increasing froth depth decreases the overall rate constant. It was further shown that this was a result of the decrease in the froth recovery of valuable minerals with increasing froth depth. Similarly it was shown that increasing air rate increases the flotation rate in the pulp phase, but this is detrimental to the froth phase because it reduces froth recovery (Harris et al., 2013; Vera et al., 1999). Hence there is an interaction between the air in the pulp phase and the effect on the froth phase.

Hadler and Cilliers (2009) used a concept of air recovery which is defined as the fraction of the air that overflows as unburst bubbles in the concentrate as an approximation of froth stability. It was shown that air recovery varied with air rate and there existed an optimum air recovery or peak air recovery which correlated closely to the optimum flotation performance. This was done at fixed level whilst varying the air rate. Hadler et al. (2012) found that the peak in air recovery for a cell varied with froth depth. Hence Hadler's results implied that there was an interaction effect between air and level. As the froth depth increased, the air rate needed to increase in order to reach the peak air recovery. This indicates that there are combinations of froth depth and air rate which result in optimum flotation performance.

Furthermore, Harris et al. (2013) observed that increasing air rate increased the froth velocity but also decreased the froth height above the lip of the cell and hence the total froth depth. This phenomenon further illustrates the interaction effect between air and froth depth.

2.2. Effect of Air and froth depth on entrainment

In PGM flotation, the majority of the mass recovered in the concentrate is gangue. Gangue enters the flotation concentrate by two mechanisms: true flotation (attached to the bubble lamellae) and entrainment (recovered in water held in the bubble plateau boundaries). Hence the gangue portion of the concentrate is a combination of floatable gangue and entrained gangue. Both types of gangue dilute the concentrate grade but entrainment is a significant problem with UG2 ore where non-floatable chromite forms a large proportion of the entrained gangue (Hay and Roy, 2010). Because chromite is non-flotable, recovery of chromite can be used as an indication of entrainment. High chromite concentrates present a range of challenges to smelters and result in increased energy consumption and decreased maintenance intervals. Zheng et al. (2006) showed that increasing air rate increased entrainment because of the increase in water reporting to the concentrate. Similarly it was shown that increasing froth depth (defined as the distance between the pulp-froth interface and the flotation cell lip) decreased entrainment mainly as a result of higher froth retention time and more drainage of hydrophilic particles. It was also observed that air and froth depth strongly interact with each other and influence entrainment by altering froth residence time, froth structure, and froth properties.

2.3. Central Composite Rotatable Design (CCRD)

Air rate and froth depth are important flotation variables because they affect both the recovery of valuable minerals and the sub-processes which drive recovery of gangue through entrainment. Interaction effects between air rate and froth depth are important in understanding the combined overall effect and for optimisation. In order to optimise air and froth depth with consideration of interaction effects, a suitable experimental design is required. The experimental design should also be able to measure the non-linear effects of air and level on flotation performance.

Commonly used experimental designs for process analysis and modelling are the full factorial, partial factorial and central composite rotatable designs (Obeng et al., 2005). Factorial designs are typically good for measuring main effects and interactions between variables. However, in order to quantify quadratic and non-linear relationships, a full factorial requires at least 3 levels per variable (Box and Wilson, 1951). In addition, 3^k factorial designs predicts the quadratic terms with little precision (Box and Wilson, 1951). A partial factorial requires fewer runs than a full factorial, but the former is more useful if variables tested are known to have no interaction effects (Obeng et al., 2005). This is not the case for air rate and froth depth which have interaction effects.

The Central Composite Rotatable Design (CCRD) is an effective alternative to factorial designs (Aslan, 2008; Obeng et al., 2005). The number of tests required for the CCRD are 2^k standard factorial points with its origin at the centre, $2k$ points fixed axially at distance β from the centre to generate the quadratic terms, replicate tests at the centre, where k refers to the number of variables to be tested (Aslan, 2008; Obeng et al., 2005). The axial points are chosen for rotability of the design, which ensures that the variance in the model prediction is constant at all points equidistant from the centre point (Box and Hunter, 1957; Obeng et al., 2005). The replicate measurements allow for an independent estimate of error to be obtained for the experiment (Aslan, 2008; Obeng et al., 2005). For the case of this experiment, SCADA air rate and cell level were the two variables tested, hence there were 4 factorial points, 4 axial points and 4 replicate runs were used to quantify experimental error. The model equation to be fitted can be described as:

$$Response = C_0 + C_1 \times Level + C_2 \times Air + C_3 \times Level^2 + C_4 \times Air^2 + C_5 \times Level \times Air$$

where C_0–C_5 are fitted coefficients of the quadratic relationship.

These coefficients and their significance in the model can be obtained using a statistical software package like Statistica.