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Determining the significance of flotation variables on froth rheology using a central composite rotatable design

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ABSTRACT

Froth performance in a flotation cell is expected to be affected by froth rheology due to change in the froth transportation rate. However, very little study has been performed to investigate how froth rheology responds to flotation variables. This paper presents an experimental program performed to study the effects of flotation variables (i.e. feed grade, feed particle size, froth height, superficial gas velocity and impeller speed) on the froth rheology. These conditions were varied using a central composite rotatable design (CCRD).

Froth rheology was found to change significantly with a variation in flotation conditions and exhibited shear-thinning behaviour. Assuming the froth moving towards the flotation lip is an open channel flow, the shear rate in the froth was calculated to be less than 4 s^{-1}. Results of the CCRD experiments showed that the flotation variables have different effects on the froth rheology. The interactions between these flotation variables in determining froth rheology were also analysed. A shear rate specific empirical model was developed to relate froth rheology to the flotation variables and their interactions.

1. Introduction

Flotation is a process to separate valuable mineral from gangue to produce a concentrated mineral product. Flotation consists of pulp and froth phases. The hydrophobic particles are attached to the bubble surface in the pulp phase and then transported to the pulp surface. The mineralized air bubbles are accumulated at the pulp surface and form the froth phase. The froth phase is a complex system in which valuable minerals are further concentrated. Upgrading occurs as hydrophilic and weakly hydrophobic particles which were entrained into the froth drop back with the water into the pulp resulting in an increase in mineral grade. As the froth moves upwards and is transported towards the concentrate launder, bubbles coalesce and burst and valuable minerals are also lost back to the pulp phase. The froth transportation characteristics (and thus froth rheology) will affect the time the froth takes to reach the launder and thus the degree of drainage and bubble bursting that occurs. This affects the amount of valuable mineral particles that are recovered and the resulting concentrate grade.

Several methods have been proposed to model froth transportation [1]. For example, Zheng et al. [2] and Contreras et al. [3] divided the froth into two zones — below the launder lip where the froth rises vertically and above the launder lip where the froth moves horizontally towards the lip. Zheng et al. [2] have mentioned that their model poorly predicts froth transportation time at deep froth depth and this was attributed to changes in froth viscosity which was not considered in their model. Harris [4] has recently proposed a different type of froth transportation model which predicts the height of the froth zone above the cell launder lip by minimising the energy of the system taking into account both froth stability and froth rheology effects. However, this model is yet to be validated in flotation systems.

In addition to the recognition that froth rheology is an important parameter that should be incorporated into a froth transportation model, the importance of froth rheology and its effects on flotation performance have been directly demonstrated by many researchers. Farrokhpay [5,6] and Shi and Zheng [7] have highlighted that froth rheology can affect froth mobility, as well as froth stability, and ultimately influence the flotation performance. Shi and Zheng [7] reported a correlation between froth rheology and grade of hydrophobic and hydrophilic minerals (chalcopyrite and quartz, respectively). Moudgil [8] observed a direct correlation between froth viscosity and flotation recovery and, on the other hand, an inverse correlation between froth viscosity and the phosphate mineral grade. Moolman et al. [9] also observed a correlation between froth viscosity and mineral recovery in phosphate flotation. Neethling and Cilliers [10] have simulated the effect of froth washing on flotation performance by incorporating the viscosity of the fluid in the froth as a variable.

Rheology is a measure of the flow characteristics of a substance. It is usually represented by a rheogram which is a measure of the shear stress of a fluid when subject to different shear rates [11]. In general, the substance can either exhibit Newtonian or non-Newtonian behaviour, with the latter including dilatant, plastic, pseudo-plastic and Bingham behaviours. Various types of rheograms are illustrated in Fig. 1 [12]. Apparent viscosity is the ratio of shear stress to the shear

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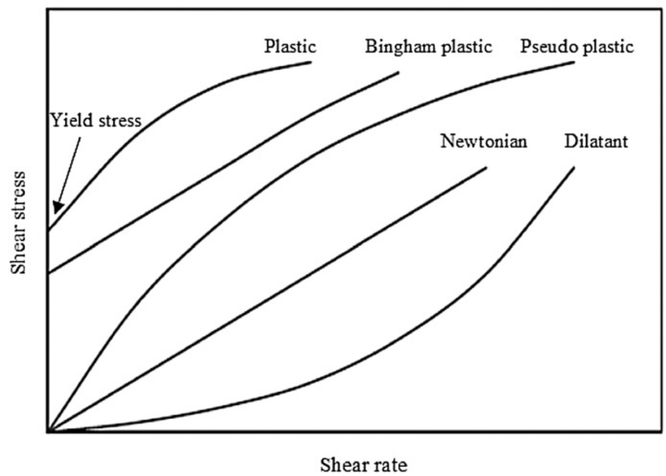

Fig. 1. Schematic diagram of shear rate as a function of shear stress for different types of fluid.
After Mewis and Wagner [12].

rate, which is constant in a Newtonian flow, but it is shear rate dependent in a non-Newtonian flow. Shear rate is the rate at which a progressive shearing deformation is applied to a material. The shear rate for a fluid between two parallel plates, one moving at a constant speed and the other one stationary, is defined by the ratio of the relative velocity between the two plates to the distance between the two parallel plates. Shear stress is a measurement of the force of friction from a fluid acting on a body in the path of that flow. A flotation froth flow moving towards the launder lip in a flotation machine can be considered as similar to an open channel flow. Shear stress in this case is the force of the moving fluid against the bed of the channel.

Rheology of flotation pulps is usually measured by a cup and bob style rheometer (Fig. 2a) but the authors [13] demonstrated that the rheology of flotation froth can be better measured using a vane head encapsulated in a tube (Fig. 2b). The vane is rotated at a set speed, and the resulting torque that arises due to the drag force of the froth is measured. The speed and measured torque of the vane can be converted into shear and strain parameters using a series of equations. The surrounding tube is required to remove adverse effects on the measurement caused by turbulence arising from horizontal flow of the froth.

It should be noted that two phase system (e.g. gas–liquid foam and solid–liquid suspension) have been the subject of many studies. Foam structure and rheology has been well reported by Bikerman in his milestone book [14]. The fluid behaviour of liquid foam has been reviewed by Höhler and Cohen-Addad [15]. Mewis and Wagner [12] introduced the effect of solid concentration and particle shape on the suspension rheology. However, there is very little information available about the rheological behaviour of three phase flotation froth. Researchers have reported pseudo-plastic for two-phase foam systems [16,17]. As a flotation froth is a three-phase system (liquid–gas–solid), its rheological behaviour may be different to that of foam. Shi and Zheng [7] concluded from their measurements performed using a vane rheometer that flotation froth has pseudo-plastic characteristics. The validity of their results, however, could be questioned because they did not perform their measurements with the vane surrounded by a tube and therefore the horizontal flow of the froth is likely to have affected their rheology measurements. In addition, they used a rheometer with relatively low sensitivity with a mechanical bearing which was suitable for measurement only in the relatively high shear rate range (above 2.5 s^{-1}). Therefore, it was difficult to perform measurements at low shear rate and investigate whether the froth has a yield stress or not. An improved approach to measure froth rheology in-situ using a more sensitive air-bearing rheometer has recently confirmed that froth has a pseudo-plastic nature with a minor yield stress [13]. Therefore, it is expected that viscosity of the froth will change as the froth velocity (and thus the shear rate imparted to the froth) varies.

The aim of the current work is to investigate how changes in flotation operating variables such as air rate, froth height and impeller speed as well as flotation feed properties such as feed grade and particle size can influence the froth rheology. The results will assist to develop more conclusive prediction for froth transportation models in order to optimise froth phase performance, and ultimately improving flotation performance.

2. Experimental design, setup and materials

2.1. Central composite rotatable design (CCRD) of the experiments

After careful consideration of which parameters could potentially affect the characteristics of a flotation froth (as well as practical limitations) five parameters were chosen for investigation. These included the froth height, gas rate, impeller speed, particle size, and feed grade.

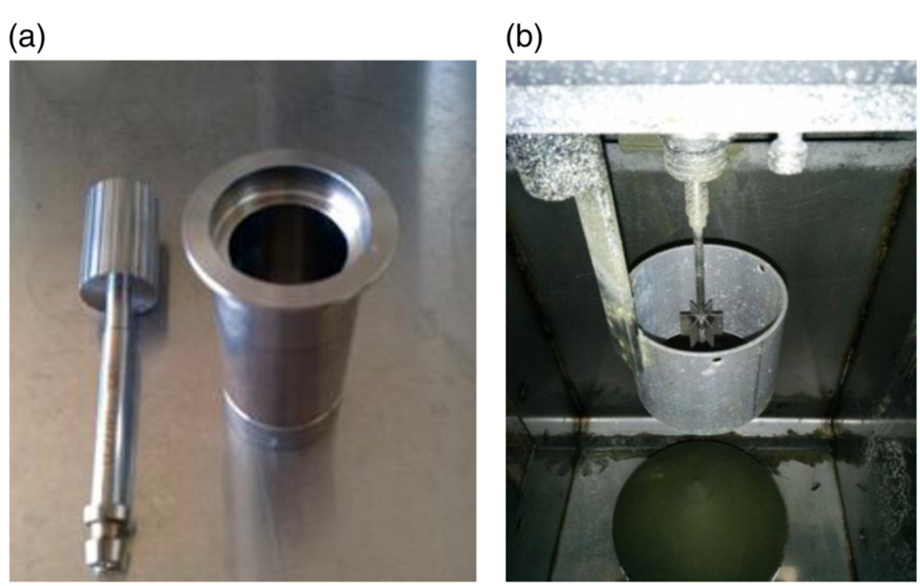

Fig. 2. Example of (a) 'bobbin and cup' and (b) 'vane' rheology measuring heads [13].