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A novel approach to measure froth rheology in flotation

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ABSTRACT

The current study involves a novel approach to measure froth rheology in-situ using vane. The results showed that the horizontal flow of froth towards the flotation launder interferes with the rheology measurement. A tube encircling the vane was used to minimize the effects of the horizontal flow. In order to convert the rheology raw data to rheograms, shear stress is only a function of the vane geometry and the torque values. However, it was shown that calculation of the shear rate from the vane speed depends on whether froth is fully or partially sheared.

The froth characterised in this study exhibited a pseudo-plastic nature with a minor yield stress using Casson model. Therefore, froth viscosity which potentially affects froth transportation is not constant throughout the whole froth phase and it depends on the local shear rate. The suitability of the vane system to measure rheology of fluids with low shear stress was examined using a Newtonian silicone oil. It was found that the vane head should not be run in speeds above a certain range which needs to be determined. Measurements above such a speed range may not be accurate.

1. Introduction

Understanding and modelling flotation process to optimise its performance has been the ultimate aim of many flotation studies. A robust model should be capable of predicting flotation performance and also be a function of operating conditions. To develop models of this type, there is a need to better understand the mechanisms and the sub-processes occurring in froth flotation. At present, the ability to predict and evaluate the effect of froth performance on the recovery of minerals is limited (Franzidis and Harris, 2010). Thus, model improvement in this regard continues to be of significant importance, and developing a model to better predict froth efficiency is still an on-going research topic.

Froth recovery, the fraction of valuable mineral reporting to the froth which survives into the concentrate (Finch and Dobby, 1990), is usually used to represent the efficiency of the froth. Several researchers have demonstrated that froth recovery is related to the time that particles spend in the froth (froth residence time) and the rate at which bubbles burst (froth stability) (Gorain et al., 1998; Mathe et al., 2000). Froth residence time is determined by the froth transportation distance, which includes the vertical motion of froth from the pulp-froth interface towards the surface and the horizontal motion towards the concentrate lip, and also the froth transportation characteristics which are related to froth stability. Several techniques have been proposed to model froth transportation (Moys, 1984; Ross, 1998; Zheng et al., 2004; Contreras et al., 2013).

Rheology is the science related to the deformation and flow of matter. Rheological behaviour of a substance is often presented by plotting the shear stress against the shear rate ('flow curve' or 'rheogram') measured by a rheometer. Various types of rheograms are illustrated in Fig. 1. In general, the substance can either exhibit Newtonian or non-Newtonian behaviour, with the latter including dilatant, plastic, pseudo-plastic and Bingham behaviours. A Newtonian fluid exhibits a linear increase of the shear stress as a function of the shear rate. Two important rheological terms which are often associated with rheology studies are 'yield stress', which is the intercept of the flow curve on the shear stress axis at zero shear rates, and 'viscosity' which is the slope of the line connecting the origin and a point on the flow curve at a particular shear rate. As shown in Fig. 1, the viscosity is constant throughout the entire shear rate range for Newtonian fluids. However, it does change as a function of shear rate for non-Newtonian fluids. Therefore, the viscosity of a non-Newtonian fluid at a specified point is referred to as 'apparent viscosity'. It has been also shown that the material flow is significantly different below and above the yield stress (Barnes, 1999).

The importance of froth rheology in evaluating flotation performance and modelling froth transportation zone has been previously recognised (Farrokhpay, 2012a). Moudgil (1993) observed a direct correlation between froth viscosity and flotation

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recovery and, on the other hand, an inverse correlation between froth viscosity and the phosphate mineral grade (in a Denver laboratory flotation cell). Moolman et al. (1996) also observed a correlation between froth viscosity and mineral recovery in phosphate flotation. A correlation between froth rheology and grade of hydrophobic and hydrophilic minerals (chalcopyrite and quartz, respectively) has also been reported (Shi and Zheng, 2003). Zheng et al. (2004) highlighted the importance of froth rheology in modelling froth transportation. The poor prediction of froth transportation by their model at deep froth depths was attributed to the change in froth viscosity which was not considered in their model. Recently, Harris (2013) proposed a model to predict the froth height above the cell launder lip by taking into account froth rheology in terms of viscosity and yield stress. However, this model has not been fully validated in flotation systems due to the absence of a reliable method to measure froth rheology.

Rheology of flotation pulps and mineral slurries is usually measured by a 'bob and cup' style rheometer (Fig. 2a) (e.g. Farrokhpay and Zanin (2012), Genc et al. (2012) and Farrokhpay et al. (2004)). It consists of a rotating inner cylinder (bob), within an outer cylinder (cup). The bob is rotated at a pre-set speed creating a strain on the pulp. The drag force (or torque) on the surrounding cylinder caused by this strain is measured and converted to the shear stress. It should be noted that it is difficult to perform this style of traditional rheology measurement in flotation froth. As froth is an unstable three-phase system (gas–liquid–solid), froth structure will be destroyed by the rotating bob. In addition, the froth bubble size may be much larger than the clearance between the bob and cup (Shi and Zheng, 2003). To overcome these problems, Shi and Zheng (2003) employed a vane rheometer to measure froth viscosity (Fig. 2b). Vane consists of a small number (usually 2–8) of thin blades arranged at equal angles around a small cylindrical shaft. It was initially developed with the aim of determining yield stress (Nguyen and Boger, 1983). Recently, 'vane and cup' system has been used to measure the yield stress of mineral slurries (Patra et al., 2010).

It should be noted that little work has been done to measure froth rheology. This may be due to the fact that froth bursts and collapses if left for any length of time because of water and solids draining from the bubble surfaces. The vane system used by Shi and Zheng (2003) to measure froth rheology in a 3 m^3 Outokumpu cell sounds promising but requires further investigation to assess its suitability in a system where froth is continually moving towards the lip. Froth movement and turbulence may interfere with the froth rheology measurement, masking any changes in froth rheology as a consequence of operational conditions and ore properties.

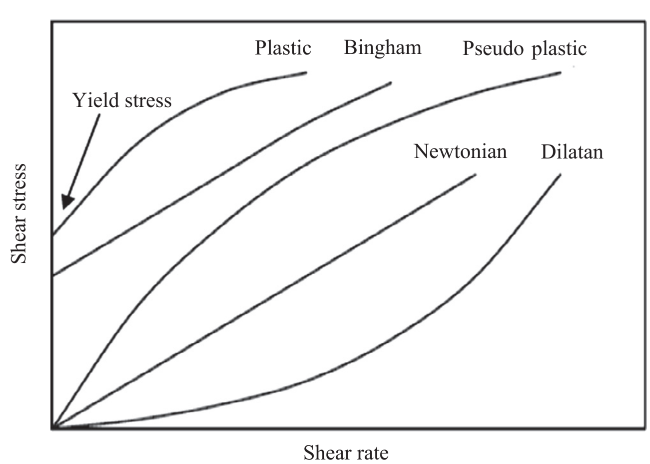

Fig. 1. Schematic diagram of shear rate as a function of shear stress for different types of fluid (Farrokhpay, 2012a).

In this study, froth rheology measurements were performed using a vane head in a continuously operated flotation cell. The modifications to the vane method to make it suitable for froth rheology measurement are discussed in this paper.

2. Materials and experimental methods

The tests described in this paper were performed in a 20 L pilot scale flotation cell with cross sectional dimensions of 30 by 30 cm. The cell was run continuously with the feed provided from a 60 L tank and the feeding rate was controlled by a peristaltic pump. The concentrate and the tailing were returned back to the tank and recombined to recycle back as the feed. The froth rheology measurement was conducted using an air-bearing rheometer, Anton Paar DSR301 capable of detecting the torque from 0.1 μN m to 100.0 mN m with a resolution of 0.001 μN m. The rheometer was connected to a computer running the measurement software which controlled the vane rotating speed. A 6-blade vane of 22 mm diameter and 16 mm height was attached to the rheometer to conduct the measurement. The system configuration is shown in Fig. 3. As the system used in this study was not the standard measurement configuration for the rheometer, the rheological parameters in terms of shear rate and shear stress could not be directly obtained. Therefore, only the vane rotating speed and the torque required to drive the spinning vane were measured. The method required to convert the vane rotating speed and the torque to shear rate and shear stress values are discussed in this paper. The measuring head was fixed to a bracket which was able to be precisely moved in three dimensions to measure the froth rheology at different horizontal and vertical positions in the flotation cell. The vane was lowered fully into the froth during measurements.

Initial tests were performed using a 5 wt% bentonite slurry at 26.5 °C to investigate the effect of flow on the rheology measurement. The bentonite used in this work had a particle size of P80 = 11 μm. Later tests were performed in flotation froth at 26.8 °C. The flotation feed was a mixture of pure chalcopyrite (P80 = 60 μm) and silica (P80 = 73 μm) combined to produce a 0.8% Cu grade. The superficial gas velocity during flotation test was 0.68 cm/s and the cell impeller speed was set at 800 rpm. Potassium Amyl Xanthate (PAX) and Huntsman H57 (an alcohol frother) were used as the collector and the frother at a dosage of 20 g/t and 38.6 ppm, respectively. The developed method was validated in a Brookfield silicon oil with viscosity and density of 95.9 cP and 9.59 g/cm^3, respectively, at 25.0 °C.

3. Results and discussion

3.1. Effect of horizontal flow on the rheology measurement

There is a concern that froth flow may affect the froth rheology results during in-situ measurements. In order to evaluate the effect of the flow on the rheology measurement it is necessary to perform the measurement in both flowing and non-flowing environments and compare the results. However, it was found impossible to perform the rheology measurement in a non-flowing froth. Therefore, it was decided to conduct this type of comparison using bentonite slurry in a flotation cell to produce different flow rates of pulp over the cell lip. The full analysis of the rheology of bentonite suspension was beyond the scope of the current study as bentonite slurry was merely used to compare the rheology measurements with and without flow, as discussed. However, it is expected that any flow effect on the rheology measurement that occurs in