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Convective–dispersive gangue transport in flotation froth

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Abstract

The transport of gangue through flotation froth has been described by solving the convection–diffusion equation. Gangue recovery is predicted to be proportional to liquid recovery, which is consistent with experimental observation. In addition, it is seen that the dependency of gangue recovery upon particle size is due to processes within the pulp phase rather than the froth, insofar as the transport of particles in a given froth is approximately independent of size. The importance of maintenance of positive bias in column flotation, previously stressed by other workers, is reinforced. This model utilises a simplified representation of the froth and, as a consequence, it does not necessarily give accurate gangue recovery estimates for practical flotation processes. However, the convective–diffusive model does illuminate the physical processes behind gangue recovery in the concentrate which will aid the development of automatic control strategies.

Keywords: Flotation; Gangue; Foam; Convection; Dispersion

1. Introduction

It has been noted by Ata et al. (2002) that, no matter how hard the froth phase is washed in column flotation, there is always some unwanted recovery of gangue material in the concentrate stream. This observation has a profound influence on the design of flotation circuits since a number of flotation operations are required in series to achieve the desired product recovery and selectivity.

Kirjavainen (1996) asserted that there are two principal mechanisms by which gangue particles are recovered in the concentrate stream in flotation. Entrainment is caused by convection of liquid from the pulp to the froth, entrapment occurs when particles become ‘wedged’ between bubbles. In this article we will consider the former mechanism.

There have been a number of published models for the entrainment of gangue into the concentrate stream. It has long been recognised that gangue entrainment rate approximately scales with the rate of water recovery (Engelbrecht and Woodburn, 1975), and this observation has recently been reaffirmed by Zheng et al. (2006). Kirjavainen (1992) presented an empirical expression for this scaling factor as a function of water recovery rate, particle density, slurry viscosity and a particle shape factor. However, the expression is dimensionally inconsistent and is therefore only strictly effective for the system on which the data was taken (Stevenson and Galvin, 2007). Neethling and Cilliers (2002a) developed a numerical model for two-dimensional gangue entrainment and presented results of simulations. Their model was dependent upon a dispersion coefficient, but no indication of how this should be calculated was given, with an arbitrary selection made for the benefit of the simulations. A similar approach was taken by Neethling and Cilliers (2002b). In addition, the channel-dominated foam drainage equation of Verbist et al. (1996) was assumed; all published foam drainage data investigated by Stevenson (2007a) suggest that this model under-predicts liquid drainage rate by a factor of at least 10. Moreover, Neethling and Cilliers (2002a, b) did not explicitly give boundary conditions for their model making it difficult to be replicated by other researchers.

It is apparent that the transport of gangue through the froth due to entrainment is as a result of two processes: (1) convection of particles due to net transport of liquid through the froth, and (2) dispersion of particles within the froth. Thus, if simplifying assumptions are made about the state of the

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froth, the transport of gangue can be predicted by solving the convection–dispersion equation for the gangue particles. Such analyses are very common, especially in the modelling of environmental transport of contaminants; for an example please see Nguyen et al. (1999). However, in order to construct the appropriate convection–dispersion equation the liquid drainage rate and dispersion coefficient must be known, and these are estimated using previously published empirical correlations. By adopting such a semi-empirical approach we will show what the underlying physical factors govern gangue entrainment in flotation are. Such knowledge of the principal governing factors will enable the development of more effective strategies for automatic control of the flotation process. In addition, this model is the first to provide estimates of the effect of washwater rate upon gangue entrainment. We are fully aware that our work lacks experimental verification. Previous work of Neethling and Cilliers (2002b, 2003a) suffered similarly, and this reflects the complexity of the flotation system. However, the liquid drainage rates and dispersion coefficients used herein have been experimentally verified.

Both Xu and Finch (1991) and Mavros (1993) have studied axial dispersion in the pulp phase in flotation (known as the collection zone in column flotation), whereas we specifically study the froth phase (known as the cleaning zone in column flotation) as it is the transport of gangue through the froth that interests us. The theory that we will present is general to both column flotation devices as well as mechanical cells. The relevant differences between the two types of flotation are:

1. Mechanical agitation is provided to the pulp phase of a mechanical cell, whereas mixing of the gangue in the collection zone must come from the turbulence of the bubbly mixture in column flotation.
2. The addition of washwater to the froth of mechanical cells is rare, but washwater addition to the surface of the froth in column flotation is universal.
3. The depth of the froth in mechanical flotation is often small (i.e., a few centimetres in depth in rougher cells), whereas cleaning zone depths in column flotation are typically around one metre (Finch and Dobby, 1990).

The theory presented applies to the transport of gangue through the froth phase in new generation flotation cells, such as the Jameson Cell, too.

A note on nomenclature: We will adhere where possible to conventional nomenclature, but it is appropriate to explicitly define the direction of fluxes. Gas and liquid flux in the froth, j_g and j_f, are measured positive *upwards*. However, bias rate, j_B, is given as positive *downwards* by Finch and Dobby (1990), and we maintain this convention herein. In addition we define the liquid drainage superficial velocity, j_d, and added washwater superficial velocity, j_W, as positive *downwards*.

2. Hydrodynamics of rising foam: the convection term

Before we can begin to consider the behaviour of particles within a pneumatic froth, we must first understand its

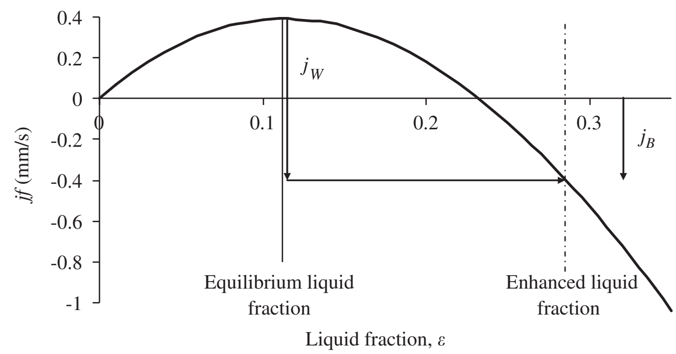

Fig. 1. j_f versus ε for a pneumatic foam showing the graphical calculation of equilibrium liquid fraction, enhanced liquid fraction due to washwater rate j_W and the definition of bias rate, j_B (after Stevenson, 2007b).

hydrodynamic condition. Stevenson (2006a) showed that the liquid superficial drainage rate from a stationary column of foam, j_d, could be non-dimensionalised as a Stokes-type number, Sk, where

$$Sk = \frac{\mu j_d}{\rho g r_b^2} \tag{1}$$

(ρ is the liquid density, μ is the liquid dynamic viscosity, g is the acceleration due to gravity and r_b is the harmonic mean bubble radius) and, for a temporally and spatially invariant froth, could be expressed as a power-law function of the volumetric liquid fraction, ε, only:

$$Sk = m\varepsilon^n, \tag{2}$$

where m and n are adjustable dimensionless constants specific to a certain surfactant system. Two adjustable constants are the minimum required to describe this system since we cannot quantify the viscous losses at the nodes (Koehler et al., 1999) and we cannot measure the surface shear viscosity (Stevenson, 2005). Stevenson et al. (2007) have shown that, for foam stabilised by $2.92\,\mathrm{g\,l^{-1}}$ SDS, $m = 0.016$ and $n = 2$.

Now, this simple equation for the liquid drainage rate from a stationary foam may be readily adapted to describe the hydrodynamics of a rising foam. Stevenson (2006b) showed that the liquid superficial rate, j_f, rising in the foam could be expressed as

$$j_f = \frac{\varepsilon j_g}{(1-\varepsilon)} - \frac{\rho g r_b^2}{\mu} m\varepsilon^n, \tag{3}$$

where j_g is the superficial velocity of gas sparged to the flotation machine. The dependency of j_f upon ε is shown in Fig. 1 assuming $r_b = 0.5$ mm, $\rho = 1000\,\mathrm{kg\,m^{-3}}$, $\mu = 1$ cP, $j_g = 7\,\mathrm{mm\,s^{-1}}$ and using the drainage parameters, m and n, of Stevenson et al. (2007). Stevenson (2006b) showed that the maximum of the curve in Fig. 1 represented the equilibrium condition. The implication is that a pneumatic foam adjusts its liquid fraction to maximise the liquid rate. The equilibrium volume fraction may be calculated through numerical solution of

$$\frac{\mu j_g}{mn\rho g r_b^2} = \varepsilon^{n-1}(1-\varepsilon)^2 \tag{4}$$