Chemical Engineering Science 101 (2013) 554–564

Contents lists available at ScienceDirect

Chemical Engineering Science

journal homepage: www.elsevier.com/locate/ces

Convective mixing in a wet planar foam

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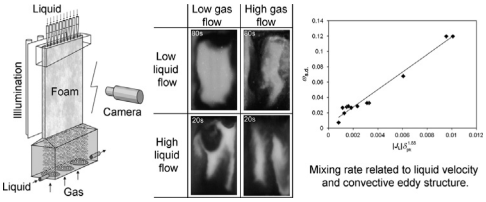
HIGHLIGHTS

- Experimental study of convective patterns in wet planar foam under forced drainage.
- Dye tracer introduced to forcing liquid to image mixing flows.
- Convective eddy structure had complex relationship with gas and liquid velocities.
- Mixing times had a close relationship with both liquid velocity and eddy structure.
- Important insights into wash water application to flotation froths.

GRAPHICAL ABSTRACT



Mixing rate related to liquid velocity and convective eddy structure.

ARTICLE INFO

Article history:
Received 16 March 2013
Received in revised form
1 July 2013
Accepted 15 July 2013
Available online 23 July 2013

Keywords:
Foam
Flotation
Convection
Bubble columns
Mixing

ABSTRACT

Buoyancy-driven convective flows have a substantial effect on the performance of the froth layer in flotation cells, particularly when wash water is applied, but are relatively poorly understood. This study presents some experiments on convective flows in a foam undergoing forced drainage. A flat cell was used to create a planar foam, and a dye tracer was used to reveal the flow patterns, which were digitally imaged. The eddy scales and mixing behaviour of the flows are assessed using several different metrics, and their dependence on liquid and gas flow rates in the foam is assessed and compared. Finally, the implications of these findings for the effectiveness of wash water in flotation froths are discussed.

1. Introduction

In froth flotation, air bubbles are introduced to a 'pulp', or suspension of particles in water. The bubbles capture the valuable hydrophobic particles and carry them upwards into the froth layer, which then flows over the lip of the vessel as the 'concentrate'. Ideally, the hydrophilic 'gangue' particles remain in the pulp, and are not lifted into the concentrate. In the case of a simple rising froth, however, some liquid is always present in the overflow. Since particles of the sizes separated by flotation typically have settling velocities much smaller than the velocity of the entrained liquid in the froth, some gangue inevitably finds its way into the concentrate (Engelbrecht and Woodburn, 1975; Jowett, 1966; Smith and Warren, 1989; Zheng et al., 2006). To reduce contamination of the concentrate by gangue, clean wash water is commonly applied to the froth layer, to impose a 'negative bias' (a net downward flow of liquid) on the flotation cell (Finch and Dobby, 1991). This can be either applied to the top of the froth or injected into its midst. To be effective, the wash water must infiltrate as much of the froth below the injection position as possible. At the same time, it must also drain down uniformly through the froth, clearing all the interstitial spaces ('Plateau borders') of gangue. Unfortunately, the application of wash water to the froth raises its liquid fraction and lowers its yield stress and

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http://dx.doi.org/10.1016/j.ces.2013.07.023

effective viscosity. It also creates what is effectively a density inversion, with a region of very wet dense froth near the wash water injection site overlying less dense froth beneath. Buoyancy forces give the wet, dense froth a tendency to sink relative to the dry, less dense froth. Under these conditions, in certain circumstances, convective instabilities have the potential to form. This phenomenon has been described as *column drainage* to distinguish it from the aforementioned interstitial or *film drainage* (Cutting et al., 1986, 1981). There is the possibility that these convective flows could cause the wash water to bypass the main body of the froth, reducing its efficacy, and transferring material from lower, gangue-rich parts of the cell to higher, relatively gangue-free regions.

Given the potential importance of foam convection to the performance of flotation cells, it is perhaps surprising how little it has been studied in its own right. This may be explained by the difficulty of modelling convective flows in foams, particularly as many of the ingredients required for a coherent theory are not understood in detail – foam rheology in the wet limit, for example. Two main experimental systems have previously been studied: 'convective rolls' in tilted cylindrical tubes; and convection in foam generated in a planar cell. In both cases, a 'forced drainage' configuration has invariably been adopted. This corresponds closely with the concept of wash water addition in flotation cells – liquid is added to the top or in the midst of the foam. A 'convective roll' is the term used for a very simple convective rotation in which wet material sinks on one side of a cell and dry material rises on the other. The type of convective rolls observed in the tilted tube system (Cox et al., 2006; Hutzler et al., 2007; Hutzler et al., 1998) might be described as 'geometry-induced', in the sense that the direction of liquid drainage has a component normal to the axis of the tube. This results in a density gradient that is also normal to the tube axis, producing a convective roll. The liquid fraction gradient is maintained by addition of liquid to the top of the tube. Cox et al. (2006) were able to provide a theoretical expression relating the tilt angle to the critical forcing liquid flow rate at which a convective roll formed. At this point, it is also worth mentioning the work of Embley and Grassia (2006) in providing several alternatives for a generalised model of the onset of convective instability in foams.

In the planar cell experiments, a foam cell was used whose *x*- and *z*- dimensions were much larger than its *y*-dimension. The result was a planar foam which could be easily observed in its entirety. Hutzler et al. (2007) reported double convective rolls in a planar foam when the liquid injection was concentrated at a single point midway along the top of the cell. The liquid fraction was not reported. Vera et al. (2000) used a planar cell with even application of liquid across the entire top to investigate transient convective patterns prior to achievement of steady-state forced drainage. The mean bubble size was very small indeed (55 μm), and liquid fractions of up to 0.5 were achieved. A complex series of convective phenomena, including convective rolls at one stage, were observed as the applied liquid flow rate was increased. Vera et al. (2000) explained these convective instabilities in the following terms: '*It seems natural that such an instability exists: if a portion of the front becomes wetter by fluctuation, then the Plateau borders necessarily become thicker and the flow should increase at the expense of the rest of the front.*' Horizontal buoyancy gradients associated with density fluctuations are not mentioned explicitly. Ireland et al. (2007) reported accumulation of liquid from a relatively uniform wetted upper layer to form what appeared to be a buoyancy-driven inverted plume or 'spike' penetrating the layer of drier foam beneath. Flows of this type are inherently dynamic, in the sense that individual bubbles and elements of fluid are not at equilibrium, and inertia plays an important role. In this study, we have used a flat cell to image planar foams during forced drainage at steady-state. These foams were wet (liquid fractions 0.22–0.54), and the convective flows were buoyancy driven and highly dynamic. The 'forcing liquid' or 'wash water' was applied evenly across the top of the cell, as in Vera et al. (2000). However, the bubbles were much larger (700–900 μm), and a very different set of convective phenomena were observed. In keeping with the origins of the study in application of wash water to flotation froths, we investigated the rate and manner of mixing of the forcing liquid into the foam. This was achieved by dyeing the forcing liquid but not the liquid supplied to the reservoir at the bottom of the cell, which was entrained by the bubbles at the liquid-foam interface, and taking sequences of images of the foam. The mixing rate was assessed using two different statistical metrics, and the convective patterns were characterised using the fractal dimension of the images in *x*-*z*-luminosity space.

2. Experimental methods

Observations were made in a planar rectangular foam cell, 190 mm wide, 12 mm deep and 490 mm high, Fig. 1. The column was mounted atop a 3.3 L reservoir containing a porous sparger, through which air was passed via a rotameter into an aqueous solution of tap water at 22–25 °C containing 100 ppm Triton-X100 non-ionic surfactant, producing bubbles of diameter 700–900 μm. The resulting foam layer rose to the top of the cell and overflowed along the back edge of the cell into a launder. No measurable bubble coalescence occurred with this bubble size and concentration of surfactant. An adjustable-length U-tube controller was used to position the liquid/foam interface just above the base of the planar section of the column. The forcing liquid was identical to that in the lower reservoir, including surfactant, and was injected into the foam as shown in Fig. 1, using a constant-head manifold consisting of ten outlets spaced evenly across the top of the cell. Plastic pipette heads were used as manifold outlet nozzles. These ensured an identical nozzle geometry for all of

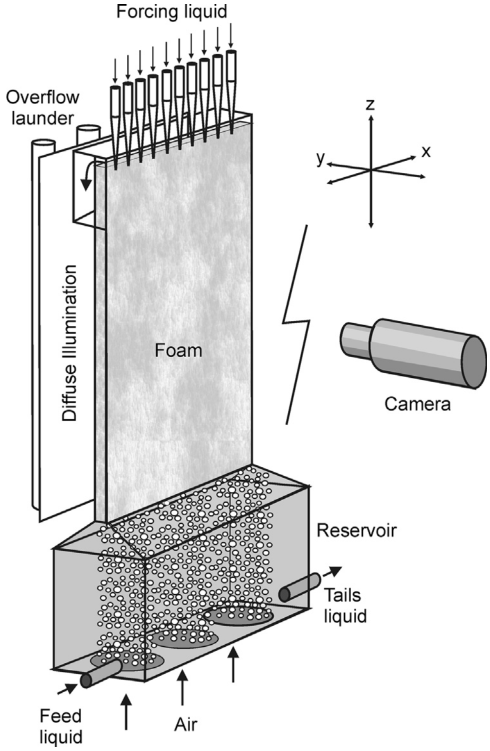

Fig. 1. Schematic of the experimental apparatus.