Measuring Flowing Foam Density Distributions Using ERT

J.J. Cilliers, M. Wang and S.J. Neethling

Froth and Foam Research Group, Department of Chemical Engineering,
UMIST, P.O. Box 88 Manchester, M60 1QD, U.K.
E-mail: j.j.cilliers@umist.ac.uk

Abstract *- In process industries where froth flotation is used, such as mineral production and paper de-inking, the froth structure required for effective particle separation is very specific. The froth structure is different at various heights in a flotation column and influences the separation achieved. In all of these systems, the fragility and opacity of the system and the associated process conditions make the use of non-intrusive characterisation techniques a necessity.*

Three techniques are described; firstly image analysis of the surface of the froth, and secondly visual modelling of a cross-section through a flowing foam. Finally, the use of ERT for exploring the internal structure of a foam column is described. This shows that zones of coalescence within the column can be detected and which can subsequently be used to compliment the surface characterisation and verify the visual model. Other potential application of this measurement technology to foams are discussed.

1. INTRODUCTION

The formation of stable foams is a significant industrial problem in industries as diverse as North Sea oil and gas production and biological fermentation systems. These foams are conventionally broken up by the addition of chemical anti-foaming agents, by mechanic means or, recently, using ultrasound. In cases where the foam is the product, such as foods, the structure is of paramount interest.

In other process industries, such as mineral production and paper de-inking, the foam is a desirable phase, and the structure required for effective particle separation is very specific. The froth structure at various heights in flotation columns influence the separation achieved. In all of these systems, the fragility and opacity of the system and the associated process conditions make the use of non-intrusive characterisation techniques a necessity.

Three approached will be discussed. Firstly, the characterisation of the surfaces of flotation froths using image analysis will be described. Secondly, a visual model of a cross-section through a flowing foam will be presented. Finally, the use of ERT for measuring the internal structure of foams will be illustrated. The ERT results can be used to compliment the surface characterisation and verify the visual models.

2. IMAGE PROCESSING OF THE SURFACE OF FLOTATION FROTHS

It is known that the froth structure plays an important role in the flotation separation achieved. The appearance of the upper bubble surface is indicative of the internal froth structure, and can be used quantitatively as a basis for control in industrial flotation cells [1]. The appearance includes froth properties such as the bubble size and shape, the solids loading and the froth mobility.

The accurate and rapid detection of the bubble size and shape distribution on the surface of flotation froths is therefore important if it is to be used for process control or fault diagnosis. The bubble size distribution is further indicative of the sub-processes occurring within the froth, and may be used to estimate coalescence and bursting rates.

A successful methodology for bubble edge detection under a wide range of conditions has been developed [2]. The segmentation algorithm, sing reconstruction and the watershed as the critical steps, can be generally applied to flotation froths from a variety of systems (see Figure 1).

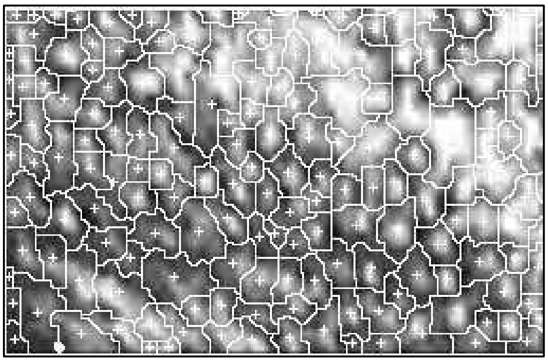

Figure 1: Detection of bubble edges on a froth surface.

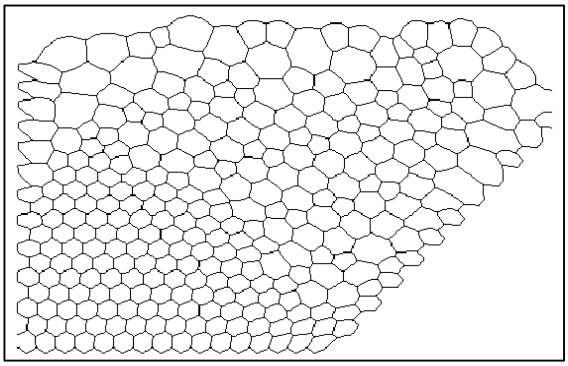

Figure 2: Foam coalescence in a widening channel.

3. VISUAL MODELLING OF INTERNAL FOAM STRUCTURE

Visualisation is widely used for the analysis and understanding of fluid flow in complex configurations. Flow modelling and visualisation of the structure of foams, however, requires considerably more detailed calculations. To observe changes in the foam structure, each bubble in the foam, its edges and the vertices where edges meet must be tracked in conjunction with the flow model itself. Furthermore, the sub-processes occurring within the foam; coalescence, relative motion of Plateau borders and edges, drainage and bursting must be allowed for. One of the most significant benefits of such models is that their outputs are visually verifiable.

A visual model of flowing foams, based on the fundamental equations of motion and the physics of bubble equilibrium and which incorporates bubble coalescence, has been developed [3]. This provides a dynamic, visual simulation of the motion, deformation and coalescence of bubbles between the pulp froth interface and either bursting on the surface or overflowing the weir. The model combines the flow model of Murphy *et al.* [4,5] based on Laplace's equation and the visualisation techniques of Weire and Kermode [6]. A coalescence criterion was defined that determines the extent of bubble deformation required for coalescence. Comparison of experimental and predicted coalescence zones in a pseudo 2-D cell shows close agreement [7].

An example of a single image of a dynamic simulation is shown in Figure 2. Note that the foam is flowing upward and that the channel is widening. Bubbles either burst on the surface of the system, or overflow to the right.

In industrial systems, however, confirmation of the model predictions is difficult. In general, the materials of construction are not transparent and the froths are opaque. This means that beyond even the first layer of bubbles that coalescence cannot be observed. In cases such as those, the use of alternative methods is required. ERT is a potentially suitable technique for such systems as it is non-intrusive, industrially robust and has a rapid response.

4. ELECTRICAL RESISTANCE TOMOGRAPHY (ERT) FOR FOAM STRUCTURE MEASUREMENT

4.1 Internal foam structure visualisation

A number of methods have previously been used to visualise internal foam structure. In general, these have focussed on resolving individual bubbles in the foam, rather than zones of different bubble size or density. Early work used medical X-ray transmission to measure interfacial areas in foams [8]. This requires a radio-opaque liquid and is relatively slow. Magnetic resonance imaging has been used more recently [9, 10] to develop a full three-dimensional image of a stable liquid foam. High-resolution imaging using this technique requires slowly evolving foams that change structure primarily by diffusion of gas from smaller to larger bubbles. In addition, a relatively high liquid content (of the order of 10%) is preferred. This method is, however, able to identify individual bubbles and their change in size over time.

Thomas *et al.* [11] use optical axial tomography to visualise the Plateau borders in a stable, dry foam. They take a number of visual images of a static foam in a revolving column and re-construct the three-dimensional structure by back-projection, producing very clear images of individual bubbles.

Their more recent work [12] clearly describes a number of optical tomographic methods in addition to the axial system previously used. A second axial system develops wire frame models of the foam structure while a third uses confocal imaging. Here images of the foam are taken at a number of focal planes and combined to give the three-dimensional structure.

All of the methods described have relatively long acquisition times and therefore are only suitable for highly stable foam systems. In contrast, for process control or the measurement of the structure of flowing foams, high acquisition rates are required but the need for high resolution is less demanding. A method that can identify areas of coalescence, i.e. local regions having different bubble densities, is required in this case.

4.2 Electrical conductivity of foams

The conductive properties of foams have been previously investigated. Bikerman [13] notes that foam electrical resistance is considerable because of the low liquid content and its distribution. The ratio of electrical conductivity of a solution and its foam is approximately linearly proportional to the foam density and is largely independent of the surfactant system.

A number of experimental and theoretical studies [15,16,17] explored the distribution of liquid between the lamellae and Plateau borders and estimate [16] that in real, polyhedral foams, roughly 91% of the liquid is found in the Plateau borders. For foams in which all the liquid is situated in Plateau borders of a given area, the density is inversely proportional to the square of the bubble diameter [13].

The relationship between foam conductivity and density is thus well established. Since there is also a clear relationship between foam density and bubble size, the potential of ERT for detecting foam density distribution can therefore be evaluated by comparing visually observed regions of different bubble sizes in a foam to the reconstructed resistance map.

4.3 Experimental method

A cylindrical, plastic vessel fitted with a tomographic sensing ring with 16 electrodes was used for the experiments. The experimental equipment is shown below. The cross-sectional conductivity map of the foam was reconstructed using the 2-dimensional linear back projection algorithm [18]. The data generated is qualitative in that it indicates regions with different conductivities, but the results cannot be used to compare quantitatively the conductivities of these regions.

Figure 3: Experimental ERT foam column

Fine bubbles were generated by agitation of the liquid to entrain air, the coarse bubbles by blowing air through a tube that was removed before measurement.

The foaming liquid consisted of high conductivity salt brine (22mS/cm) and 10ml of commercial surfactant. Reference data were collected from the brine solution and pure water.

The surface of the foam was photographed using a digital camera and the images transferred directly to computer. The results generated allowed comparison of the conductivity map of a cross-section within the foam with visual observation of the surface of the froth.

4.4 Example of foam density measurement using ERT

Only a single set of results is shown below. It can be seen that the region of coarse bubbles toward the top of the cylinder corresponds closely to the region of low conductivity (dark area) in the reconstructed resistance map. Further results in which the regions of coalescence were positioned at different locations in the column have been published elsewhere [19]. Those results showed conclusively that ERT is a suitable method for the visualisation of non-uniform foam density due to differences in their bubble size distribution.

Figure 4: Foam column surface.

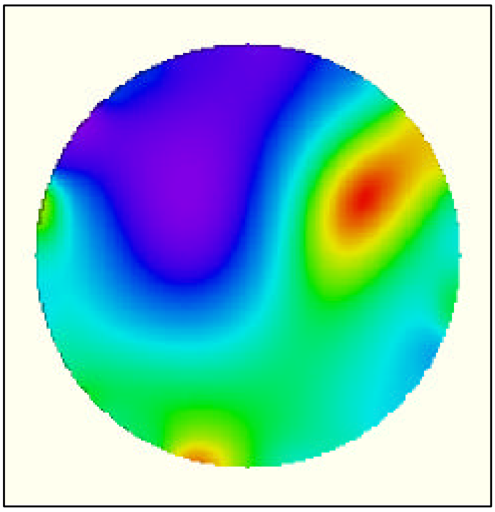

Figure 5: Corresponding ERT map
(Note: tube removed before imaging)

5. CONCLUSIONS

The measurement of internal foam structure, in particular zones of coalescence and relative foam densities is of particular significance in the process industries. In froth columns used for particle separation, such as minerals processing or paper de-inking, the froth structure largely determines the product purity and production rate.

Currently, these processes are controlled by visual observation of the froth by process operators. Image analysis techniques have been developed to detect individual bubbles on the surface of the froth. This information can subsequently be used for automatic control or fault diagnosis.

It is not known directly, however, how the observed froth surface properties are related to the sub-processes of drainage and coalescence occurring within the froth column. A visual model has been developed to examine how the column dimensions affect the flow and coalescence patterns.

ERT has been shown to be able to detect variations in the internal structure of foams which can be used both as a control measurement, complimenting the froth surface image analysis, and also allowing verification of the visual models developed.

It is believed that the combination of ERT and image analysis will yield a methodology for fault detection and process control of froth columns that was not previously possible.

In addition, ERT can be used as a tool for verifying the fundamentally-based, visual models developed for flowing foams. This can subsequently be used with confidence for the design of foam systems that will yield an appropriate froth structure for various applications. These may include both the breakdown of unwanted foams and the generation of foams with very specific structure and function.

ACKNOWLEDGEMENTS

The encouragement of Professor Reg Mann in bringing the tomographic work to publication is gratefully acknowledged.

The tomographic data was generated in collaboration with Dr Alec James and the image processing performed by Ms Naheed Sadr-kazemi and Mr Ben Wright.

REFERENCES

[1] Cilliers, J.J., Asplin, R.A. and Woodburn, E.T., 1998. Kinetic flotation modelling using froth imaging data. Chapter 10 in *Frothing and Flotation II* (Eds. Laskowski, J.S and Woodburn, E.T.), OPA, Amsterdam.

[2] Sadr-kazemi, N. and Cilliers, J.J., 1997, An image processing algorithm for measurement of flotation froth bubble size and shape distributions. *Minerals Engineering*, **10**, 10, 1075-1083.

[3] Neethling, S. and Cilliers, J.J., 1998, A visual model of flowing foams incorporating coalescence, *Powder Technology*, in press.

[4] Murphy, D.G., Woodburn, E.T. and Cilliers, J.J., 1998, Modelling of foam dynamics with implications for feed-back control. Chapter 7 in *Frothing and Flotation II* (Eds. Laskowski, J.S and Woodburn, E.T.), OPA, Amsterdam.

[5] Murphy, D.G., Zimmerman, W. and Woodburn, E.T., 1996, Kinematic model of bubble motion in a flotation froth. *Powder Technology*, **87**, 3-12.

[6] Weaire, D. and Kermode, J.P. 1983, Computer Simulation of a 2-D Soap Froth, *Phil. Mag*., **48**, 245-259

[7] Neethling, S. and Cilliers, J.J., 1998, The effect of weir angle of foam structure, *Minerals Engineering*, **11**, 11, 1035-1046.

[8] Morris, R.M. and Morris, A., (1965) The measurement of interfacial areas of foams and froths by a radiographic technique. *Chemistry and Industry*, November, 1902-1903.

[9] Gonatas, C.P., Leigh, J.S., Yodh, A.G., Glazier, J.A. and Prause, B. (1995). Magnetic resonance images of coarsening inside a foam. *Physical Review Letters*, **75**, 3, 573-576.

[10] Prause, B.A., Glazier, J.A., Gravina, S.J. and Montemagno, C.D. (1995). Three-dimensional magnetic resonance imaging of a liquid foam. *J. Physics Condensed Matter*, **7**, 40, L511-L516.

[11] Thomas, P.D., Darton, R.C. and Whalley, P.B. (1995) Liquid foam structure analysis by visible light tomography. *The Chemical Engineering Journal*, **56**, 187-192.

[12] Thomas, P.D., Darton, R.C. and Whalley, P.B. (1998) Resolving the structure of cellular foams by the use of optical tomography. *Industrial and Engineering Chemistry Research*, **37**, 3, 710-717.

[13] Bikerman, J.J. (1973) *Foams*. Springer-Verlag, New York.

[14] Clark, N.O. (1948) The electrical conductivity of foam. *Trans. Faraday Soc*., **44**, 13-15.

[15] Chang, K-S. and Lemlich, R. (1980) A study of the electrical conductivity of foam. *Journal of Colloid and Interface Science*, **73**, 1, 224-232.

[16] Agnihotri, A.K. and Lemlich, R. (1981) Electrical conductivity and the distribution of liquid in polyhedral foam. *Journal of Colloid and Interface Science*, **84**, 1, 42-46.

[17] Datye, A.K and Lemlich, R. (1983) Liquid distribution and electrical conductivity in foam. *Int. J. Multiphase Flow*, **9**, 6, 627-636.

[18] Wang, M., Dickin, F.J., and Beck, M.S. (1993), Improved electrical impedance tomography data collection system and measurement protocols, in *Tomography Techniques and Processes Design and Operation* (ed: Beck, M.S., Campogrande, E., Morris, M.A., Williams, R.A., and Waterfall, R.C.) Computational Mechanics Publications, pp 65-88.

[19] Wang, M. and Cilliers, J.J., 1998, Detection of non-uniform foam density using ERT. *Chemical Engineering Science*, in press.