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PEPT combined with high speed digital imaging for particle tracking in dynamic foams

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ABSTRACT

Positron emission particle tracking (PEPT) has been combined with high speed digital imaging to track a particle within a foam column. The tracer was sufficiently large (diameter 2.5 mm) to allow visual verification of the tracer trajectory recorded with PEPT. This enables validation of the technique for use with smaller, less visible, tracers in the future. A difference in recording rates of PEPT and the high speed camera necessitated the use of a weighting function to interpolate the discrete PEPT data set into a continuous function. A kernel width of 200 ms was used to ensure a confidence level of 95% that the tracer position calculated from PEPT and measured visually were the same, within error limits of ± 2.7 mm. The largest contribution to the error was the resolution of the images. Images of dynamic foam structure can now be paired with PEPT measurement to observe the tracer trajectory relative to individual bubbles.

1. Introduction

Foam has a distinctive structure, where gas cells are separated by film surfaces, and the film edges meet to form a network of channels called Plateau borders (Weaire and Hutzler, 1999). Froth shares its structure with foam; however the additional solid phase entrained in the Plateau borders and attached to the lamellae surfaces dominates the froth stability and also completely prevents inspection of the froth interior. Understanding of froth structure is particularly important for minerals processing which relies on froth flotation to separate and concentrate valuable mineral particles from a complex ore body. Events such as coalescence and bursting act to diminish flotation efficiency by reducing the recovery of valuable mineral particles. These particles, along with entrained water and gangue (waste particles), are released into the Plateau border network where they may move away freely. Since the extent of these processes cannot be observed in-froth as the mineral loaded bubbles are opaque, empirical research has focused on particle tracking in transparent foams to investigate the particle motion and internal flow dynamics.

The flow dynamics of the foam liquid network have already been measured by liquid dispersion in an individual Plateau border (Pitois et al., 2005); by particle dispersion in a foam under forced drainage (Lee et al., 2005), and also by particle dispersion in an overflowing foam with modified viscosity (Ata et al., 2006). Bennani et al. (2007) used particle tracking velocimetry (PTV) to track particles through individual Plateau borders and nodes of a quasi-2D rising foam. By combining the PTV data with digital images, their results showed important correlations between tracer velocity and foam structure. PTV is limited by the need for a transparent system and fluorescent particles.

Positron emission particle tracking (PEPT) utilises the pairs of back-to-back gamma-rays from positron-electron annihilation events, which can penetrate the opaque surfaces, to determine the location of a radioactive tracer particle by triangulation. PEPT was developed at the University of Birmingham as a variant of the medical positron emission tomography (PET) technique (Parker et al., 1993) and uses a "positron camera" consisting of a pair of gamma-ray detectors (Parker et al., 2002). The accuracy of the technique has been validated in two ways: in the first instance, Parker et al. (2002) placed a tracer on a turntable and compared visual observations to PEPT measurements. The root mean square of the deviation of the PEPT measurement from the true path, or the spread of the data, was 0.6 mm. In the z-direction between the detectors, there was approximately 2.5 times greater uncertainty in the PEPT measurement. Parker and Fan (2008) report that for

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steady-state mixing the time averaged flow pattern measured by PEPT agrees well with the instantaneous flow observed with PTV.

Barigou (2004) presents a review of successful application of PEPT to opaque mixing systems. More recently, Chan et al. (2009) observed solid particle motion in standpipes with PEPT and Guida et al. (2009) tracked particles with PEPT in a mechanically agitated solid–liquid suspension. Edwards et al. (2009) used PEPT concomitantly with Electrical Resistance Tomography, to understand aluminium hydroxide precipitation. PEPT is particularly useful for measuring foam and froth properties as the tracers can have defined surface characteristics such as size, density and hydrophobicity. It was applied to a dynamic froth by Waters et al. (2008) to show liquid mixing and bubble attachment and motion in the froth. The measured particle velocity behaviour could not be ascribed to froth structural changes as the froth and container material were completely opaque. This work develops a method to address this question.

This paper presents a technique developed to synchronise images of dynamic foam with PEPT data so that the tracer motion can be observed relative to individual bubble behaviour. In this way, small scale tracer velocity changes can be correlated to specific foam structures or events. This work employed a tracer large enough to verify the tracer location with image analysis. However, the true potential of the technique will be realised with smaller tracers which are more representative of the particles found in flotation, but which are too small to be optically tracked.

2. Experimental description

The experimental set-up is shown in Fig. 1. The foam column was composed of Perspex, with internal dimensions 12 mm (x), 425 mm (y), and 80 mm (z). Eight PVC capillaries of internal diameter 1.5 mm attached to an air compressor provided the aeration to the base of the column.

The foam column was placed centrally between the detectors, with the largest face perpendicular to the detectors to facilitate filming of the bubble profile. The PEPT scanner detectors were spaced at maximum separation (~800 mm). Full details of the PEPT technique can be found in Parker et al. (1993), Parker et al. (2002) and Parker and Fan (2008). The tracer fabrication and radionuclide labelling (usually with Fluorine-18), is detailed in Fan et al. (2006a, b).

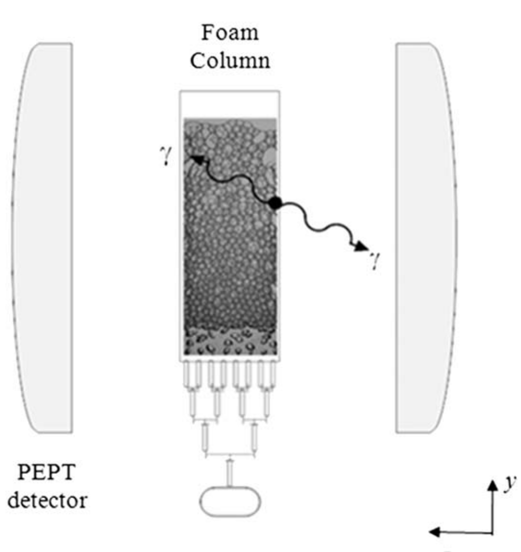

Fig. 1. The experimental set-up in the yz-plane with the PEPT detector containing the aerated foam column.

A high speed camera (Casio Exilim EX-FH20) video recorded the foam behaviour onto SD memory at 210 frames/s and 480 × 360 pixel resolution. A strong, diffuse light source was placed behind the column to enhance the Plateau borders at the front of the column. The entire experiment was performed under blackout material to prevent extraneous light degrading the image quality.

The column contained 20 ml of a solution containing deionised water, 2.5 g/l dodecyltrimethylammonium bromide and 70%$_{v/v}$ glycerol. The glycerol was included to increase the viscosity of the solution to make it comparable to that of an industrial froth, as suggested by Ata et al. (2006). The air rate was 1.6 l/min to create a rising foam of height 20 cm and bubble diameter range of 5–20 mm between the liquid level and the surface. The PEPT recording system and the high speed video capture were started manually at approximately the same time. However this could not ensure simultaneity, so a video camera (Panasonic NVGS37E) was used to capture and correct for small differences between the start of each recording system.

A hydrophilic tracer particle with an initial activity of 340 μCi was created by adsorbing the radionuclide ^{18}F from solution onto the surface of a 2.5 mm glass bead and then sealing the surface using cellulose paint. The tracer was added to the top of the column for capture with PEPT and the high speed camera. The PEPT system logged a tracer co-ordinate approximately every 18 ms, each co-ordinate being a triangulation of about 13 detection events.

3. PEPT data interpolation algorithm

A time weighting function was applied to interpolate and smooth the set of discrete PEPT data points into a continuous function; necessary due to a difference in recording frequency between PEPT (56 points/s) and the camera (210 frames/s). Cubic splines with a varying kernel width were used in the weighting function.

$$\text{If } (qi < 0.5),\ w_i = 1 - 6q_i^3 + 6q_i^3 \tag{1}$$

$$\text{If } (0.5 < q_i < 1.0),\ w_i = 2(1 - q_i)^3 \tag{2}$$

The weights are a function of q_i

$$q_i = \frac{|t_i - t|}{\Delta t} \tag{3}$$

where and Δt is the weighting function width, equal to half the kernel width.

For each final PEPT co-ordinate,

$$\hat{A} = \frac{\sum w_i \hat{A}_i}{w_i} \tag{4}$$

where $\hat{A}$ is one of the co-ordinates y or z, and $\hat{A}_i$ is the PEPT co-ordinate at time i. Two PEPT dimensions, y and z, were considered, corresponding to the vertical and horizontal dimensions of the camera images.

The kernel is shown in Fig. 2. Two important features of the weighting function relate to the kernel properties: compactness and the non-infinite value at the kernel centre. The function is compact such that points beyond the kernel width have zero importance. It is therefore more computationally efficient as the function does not search the entire data set to create each final value. In addition, the function does not tend to infinite importance at the centre of the kernel. The weighting therefore provides a combination of interpolation and smoothing, since even when the time corresponds to one of PEPT times, the calculated position includes an influence from neighbouring time