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Short communication

Neutron imaging of froth structure and particle motion

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ABSTRACT

This article reports on the simultaneous measurement of foam structure and attached particles employing neutron imaging. An aqueous foam sample is placed in the NEUTRA beamline at the Paul Scherrer Institut, enabling a spatial resolution of less than 200 μm to be achieved at a frame rate of more than 1 Hz. A forced drainage setup allows the liquid content of the foam to be controlled. The averaged attenuation of the neutrons is demonstrated to yield the liquid fraction of the foam. Hydrophobized gadolinium particles with a diameter of 200 μm are added to the foam. Using two surfactants, different levels of hydrophobicity are achieved. Depending on the drainage flow and the hydrophobicity, the particles are washed out of the foam at different rates. An avalanche-like motion of particle clusters is observed. Neutron radiography is demonstrated to yield unique insights into the unsteady froth flotation process.

1. Introduction

Froth flotation, exploiting differences in surface properties of mineral particles, is the most important process in ore beneficiation in mineral processing. In the froth zone, the bubble-particle aggregates, crossing the pulp-froth interface, move upwards towards the concentrate launder (Nguyen and Schulze, 2003; Ata, 2012). Additionally, hydrophilic particles are non-selectively entrained into the froth, driven by the turbulence in the pulp. Counterflowing wash water sprayed on top of the froth is able to reduce the transport of these undesired fractions into the concentrate. It is obvious that improving the recovery and the grade of the flotation concentrate requires a refined understanding of the froth dynamics, including drainage, the bursting and coalescence of bubbles and the respective impact on particle motion. This also requires the availability of reliable experimental data. However, local measurements and detection of particles in flotation froths are challenging due to their opaqueness. Phosphorescent tracer particles were applied to determine the dispersion of hydrophilic particles in the froth in Ata et al. (2006). Particle tracking velocimetry was used in Bennani et al. (2007) to analyse particle sedimentation in dependence on the foam structure. The rheology of froth, coupled to optical inspection, was studied in Li et al. (2016). However, the applications of these optical techniques is limited to transparent foams of low thickness. To overcome these restrictions, positron emission particle tracking (PEPT) has been established as an attractive technique to analyse particle paths in the froth (Waters et al., 2008; Cole et al., 2010). However, high-speed imaging of the froth is required to be able to correlate particle trajectories with the foam and froth structure. By applying neutron imaging, we introduce a promising technique for froth studies which overcomes the limitations of all previously mentioned techniques. Recently, Neutron scattering has been applied to foam in order to explore foam structure properties (Mikhailovskaya et al., 2017) without directly imaging it. Neutron imaging now is capable of tracking the motion of selected particles, both hydrophilic and hydrophobic, and of characterizing the local foam structure and liquid fraction. Compared to optical measurement techniques, neutron imaging allows the investigation of thicker froth samples and higher liquid fractions, because the neutrons are not refracted by the gas-liquid interfaces. The main advantage over X-ray imaging is, that water has a roughly 30 times higher attenuation coefficient for neutrons (25 meV) than for X-rays (150 keV) (Hubbell and Seltzer, 1995; Sears, 1992), yielding high-contrast images of the thin foam structure at reasonable frame rates.

2. Experimental setup

2.1. Measuring configuration

Measurements were carried out at the Paul Scherrer Institut (PSI) in

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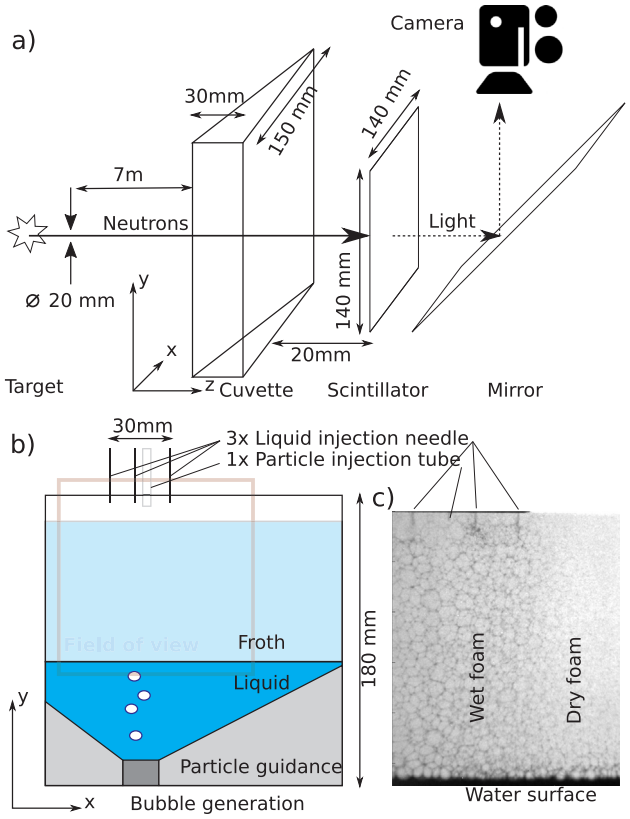

Fig. 1. Setup of neutron imaging arrangement (a), foaming inside the vessel (b) and foam image (c).

Villigen, Switzerland. The NEUTRA beam line of the neutron spallation source SINQ was employed (P.S. Institut, 2016), providing approximately $1.0 \times 10^7\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ of thermal neutron flux at 25 meV. The distance between measurement position 2 and the beam defining aperture (Ø20 mm) equals 7000 mm. Similarly to X-rays, the neutrons penetrate matter and are attenuated at the contained elements. In contrast to X-rays, neutrons are attenuated at the atomic nucleus rather than at the electrons. Therefore, the attenuation coefficient does not increase in line with the atomic number, but is also high for some light atoms, e.g. hydrogen and boron. The measurement object is placed inside the neutron beam (see Fig. 1a). The unattenuated neutrons hit a scintillator screen of $14 \times 14\,\mathrm{cm}^2$ area, generating visible light. This light is captured by means of a sCMOS camera with 2048×2048 px at 5 fps, yielding a radiographic image of the measurement object. More details on the beam line are given in Lehmann and Vontobel (2007).

The measurement object is a glass vessel with a triangular cross section, partially filled with liquid (see Fig. 1). The triangular shape is chosen to carry out experiments at different container thicknesses simultaneously. Blowing air through four nozzles at the bottom of the vessel, bubbles of a diameter $D_b = (5 \pm 1)$ mm are injected, filling the vessel with foam. Using three needles positioned at the top, a steady flow of liquid is applied, draining downward through the foam. Wetted gadolinium (Gd) particles (Section 2.2) are introduced via an additional tube between the needles. After each run, visual checks are carried out to ensure that no particle clusters are stuck at the glass wall.

2.2. Particle selection and image contrast

The measurements are carried out using a dispersion of hydrophobic, irregularly shaped Gd particles (Section 2.3) in aqueous liquid. The Gd particles are assumed to exhibit a thin oxidized surface (Gd_2O_3) with negligible influence on the neutron attenuation. Gadolinium has the largest neutron attenuation coefficient ($\sigma_{Gd} = 1479.04\,\mathrm{cm}^{-1}$) of all

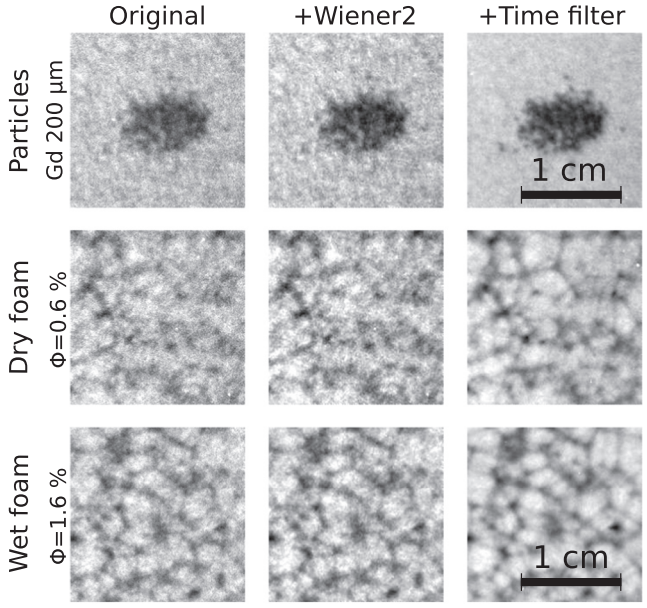

Fig. 2. Image processing by means of Wiener2 noise reduction and subsequent time filtering. Result of cluster of particles, dry foam and more wet foam is shown.

the elements (Sears, 1992). Even small Gd particles of 200 µm diameter attenuate all but 1×10^{-11}% of the neutrons. Fig. 2 shows a sample image of a large cluster of such particles. The attenuation coefficient of pure water equals $\sigma_{H2O} = 3.74\,\mathrm{cm}^{-1}$. The dissolved surfactants have a negligible influence of less than 1% on this value. A water structure with a thickness of 1 mm attenuates approximately 31% of the beam intensity. However, the low neutron rate per pixel causes a low signal-to-noise ratio (SNR). A Wiener2 noise reduction (Lim et al., 1990) and subsequent Gaussian filtering in time ($\sigma_t = 200$ ms) are applied to visualize the foam structure. Fig. 2 demonstrates the filtering outcome on a particle cluster attached at a fixed position at the container wall and on dry and more wet foam (middle and bottom rows) The foam has a thickness of 25 mm and about $\Phi = 0.6\%$ and $\Phi = 1.6\%$ liquid content, respectively.

2.3. Particle treatment

To mimic a flotation process, the Gd particles are hydrophobized. To that end, 2.5 g particles are added to 100 ml of deionized water with 0.01 M KCl and 0.002 M sodium oleate (NaOl), and stirred for 15 min. The level of hydrophobicity is evaluated in a prestudy by submerging a 0.25 µl air bubble for 1 s in the sediment bed, then pulling it out and taking a picture of the attached particles (Fig. 3). Treated particles show much greater hydrophobicity (Fig. 3b) than untreated particles in pure water (Fig. 3a). However, adding 0.0087 M sodium dodecyl sulfate (SDS) again reduces the hydrophobicity (Fig. 3c), rendering the particles hydrophilic again.

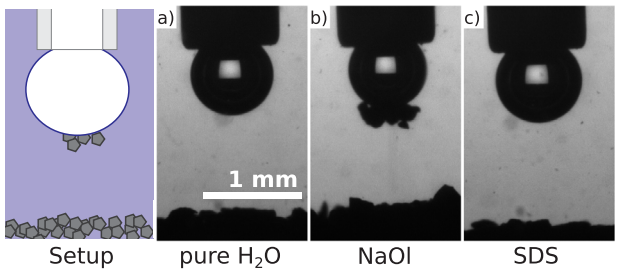

Fig. 3. Hydrophobicity of Gd particles in pure water (a), treated with KCl + NaOl (b) and treated with KCl + NaOl in SDS (c).