In situ ultrasonic measurement of the local liquid fraction of froth for flotation processes

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Receiving in situ information of multi-phase mixtures is an ongoing interest of the industry to optimize processes. Controlling process parameters in froth flotation, as the liquid fraction or the bubble size, opens up potential to save resources, to reduce energy consumption and to increase the process yield and grade. Using ultrasound in the low kilohertz range, we are able to receive backscattered ultrasound signals from the inside of froth. Based on these echo signals and the assumption that Plateau borders cause the backscattering, we employ an one dimensional model of the sound propagation through the foam. Regarding dry foam (liquid fraction < 0.8 %) the calculated backscattering coefficient shows a proportional relation to the liquid fraction and increases with rising liquid fraction. By time gating the echo signal, we achieve an axial spatial resolution of 3.9 mm with a measurement uncertainty of σ_Φ = 0.094 %. With these measurements for calibration, we demonstrated a time-resolved measurement of a sudden change of the liquid fraction. We therefore demonstrated a first possible approach to gather in situ information of foam's liquid fraction and set up the way for mass flow measurements in strongly attenuating suspensions with possible applications in froth flotation.

Keywords: Froth, In situ, Liquid fraction, Backscattering coefficient

1. Introduction

To extract copper minerals from ore it is grinded to particles and put in a flotation cell. Surfactant containing solutions selectively render the mineral particles hydrophobic. Thus they attach to rising bubbles and move to the top-lying froth overflowing the vessel and extracting the mineral in high purity.

44 million tons of water are used every year in only one conventional froth flotation circuit for copper [1]. Regarding this massive amount of resources needed to carry out this process, a closed loop-control is essential for a potential save of resources, energy and an increase of the yield.

However, gathering in situ information of strongly damping materials is a metrological challenge. Optical measurements hardly enter the inner of a multiple phase solution as froth [2]. The same problem occurs with high frequency ultrasound. Especially suspension like compounds as water air mixtures additionally cause a high acoustic impedance jump and a lot of scatter. However, using ultrasound in the low kilohertz range enables a penetration of some centimeters into the froth [3]. Parameters such as bubble size, liquid fraction Φ and particle flow could be controlled, if one is able to measure them in situ with a robust measurement system. We therefore investigate the possible deduction of the local liquid fraction Φ from ultrasound backscattering for dry foam (Φ < 0.8 %).

2. Experimental setup

A scheme of the experimental setup, seen in Figure 1, illustrates the build of an acrylic glass cylinder. The liquid at the bottom consists of deionized water with additional 10 g/l sodium dodecyl sulfate (SDS) and 0.75 g/l potassium chloride (KCl). Air enters the cylinder with a constant flow rate through a drilled smaller tube at the bottom. The tenside solution foams up until the acrylic cylinder is filled up completely. The airflow is then terminated. The determined bubble diameter amounts to 2 ±1.7 mm. During that time a double syringe pump (Harvard Apparatus - Model 33) pumps up the tenside solution from the bottom of the cylinder to a sprinkler at the top with a volume flow of 20 ml/min. The water enters the foam and drains downward, yielding a steady and homogeneous liquid fraction distribution [4]. After three minutes, the liquid flow rate is turned off as well and the foam begins to dry. Now the measurement is started, observing the drying phase of the foam.

Two ultrasound transducers (multicomp-MCUSD19A175B11.5RS) are mounted at the same height of the cylinder, with direct contact to the foam. Due to a long ringing of the emitting transducer, a second transducer had to be used for receiving. The transducers with a diameter of 19 mm and a center frequency of 175 kHz have been used to send/ receive a logarithmic chirp from 165…185 kHz. An in house developed generic ultrasound research platform "Phased array Doppler velocimeter" (PAUDV) [5] was used for the electrical activation and data acquisition (see Table 1).

Two electrodes, connected to a digital oscilloscope (PicoScope) are covered in foam and measure the reference liquid fraction according to Feitosa et al. [6] via an electrical impedance measurement. The electrodes are one resistor in a voltage divider, whereas the other resistor is constant and has 1 kΩ.

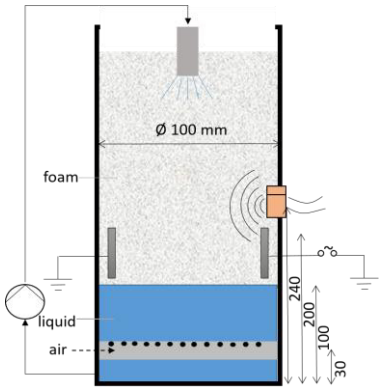

Figure 1: Scheme of experimental setup to determine a local liquid fraction in foam with ultrasonic echo measurements.

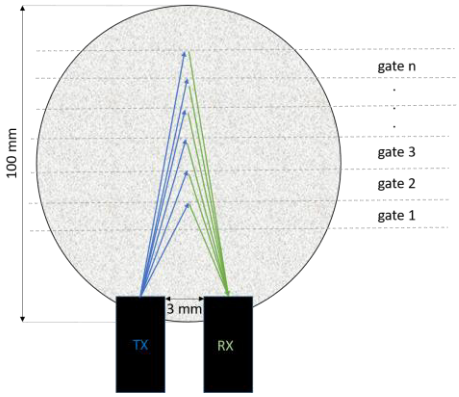

Figure 2: Scheme of the time gated equivalent spatial gates for a local liquid fraction measurement with two ultrasound transducers.

Table 1: Parameter of data acquisition

pulse repetition frequency	50 Hz
number of pulses to average	10
measurement frequency of impedance reference	0.33 Hz
sample frequency	5 MHz

3. Calibration measurement

The drying foam was measured not longer than 5 minutes to prevent bubble coarsening [7] and the measurement was repeated four times. An approximate liquid fraction range from 0.1 % < Φ < 0.8 % is achieved. Acquired echo data could only be investigated between 300…437.4 µs after the transducer excitation. Talk-over, transducer ringing and backwall echo of the cylinder, therefore minimize the regarded spatial area to 23.7 mm close to the backwall. The received signal is transformed into an analytical signal by Hilbert transformation and the envelope is time-gated to achieve a spatial resolution. As foam is holding the liquid in the Plateau borders and vertices between the bubbles we aim at a local resolution of about twice the bubble diameter (e.g. ~ 4 mm). To achieve the highest possible spatial resolution, the analyzed part of the signal has been divided into 6 equally sized time gates. This equals λ/4 of the whole sent pulse and corresponds to a spatial resolution of 3.9 mm (regarding the speed of sound in air $c_{air} = 345\ m/s$). A general scheme to illustrate the spatial equivalent to the time gates is shown in Figure 2.

The backscattering coefficient r_n can be determined by Equation 1 and 2, where RX_n is the integrated amplitude envelope for the specific time gate n and I_0 is the total backscattered energy after talk-over and transducer ringing.

$$r_0 = \frac{RX_0}{I_0} \tag{1}$$

$$r_\mathrm{n} = \frac{RX_n}{I_0 \prod_{i=1}^{n}(1 - r_{\mathrm{i}-1})^2} \tag{2}$$

Two of 2400 backscattering coefficients exceeded the maximal physically possible backscattering coefficient of r = 1 (total reflection) and therefore have been set to one. Regarding all backscattering coefficients r_n for the drying foam, a linear regression has been derived to show the dependency of the backscattering coefficient r_n on the liquid fraction Φ. Figure 3 illustrates this dependency. A proportional relation is visible, where the backscattering coefficient increases for a rising liquid fraction. Presumably, thicker Plateau borders increase the amount of backscattered energy and hypothetically establish our physical effect. These measurements are used to calibrate the measurement system. The deviation of the backscattering coefficient increases for higher liquid fractions and penetration depth.

The residuals between the predicted and the actual liquid fraction serve to calculate the measurement uncertainty according to the *Guide to the Expression of Uncertainty in Measurement* (GUM [8]) considering the unknown systematic and the random error and add up to σ_Φ = 0.094 %.

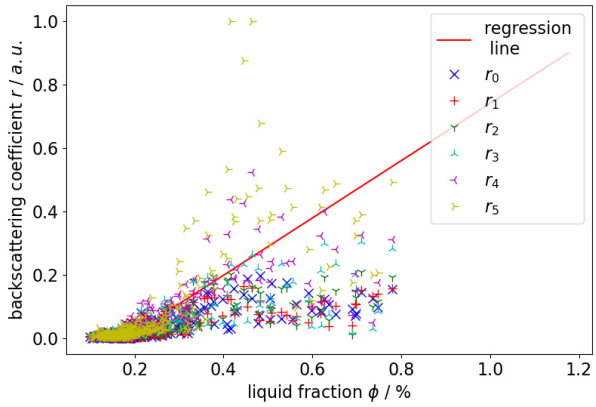

Figure 3: Backscattering coefficients r of the six time gates of the analyzed echo signal over a varying liquid fraction during a drying process of foam. Presumably a higher attenuation for a higher liquid fraction leads to an increased deviation in the section Φ > 0.4 %.

4. Results of model experiment

As a validation of our measurement system, we conducted a model experiment with a sudden change of liquid fraction. Therefore, the sprinkler was pulled of its hose and the loose end of the hose was attached in the foam to the backwall of the cylinder, 5 cm above the transducer height. Approx. 23 s after the measurement started, the tenside liquid was pumped from the bottom of the acrylic cylinder towards the loose end of the hose and therefore to the backwall of the cylinder, with a volume flow of 60 ml/min. Due to capillary pressure, this liquid does not accumulate at the wall but is sucked into the foam near the wall. This forms a wetting front that moves downward through the foam.

Figure 4 displays the temporal change of the liquid fraction in the different gates. Backscattering coefficients exceeding the calibration range have been excluded as outliers. After approximately 30 seconds the wetting front reaches the measurement position and the liquid fraction in all measurement positions increases. With gate 6 as the closest gate to the backwall of the cylinder (epicenter of the change of the liquid fraction) and gate 1 as the closest gate to the transducers, a significant higher increase of the liquid fraction in the gates closer to the backwall is observed.

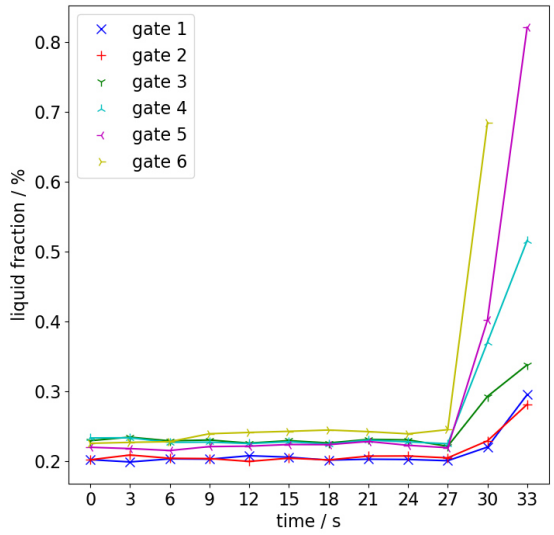

Figure 4: Model experiment: Sudden local change of liquid fraction allows a spatio-temporally resolution and validates the measurement system.

5. Summary

Drying foam has been analyzed by the means of ultrasound echo measurements and a calibration of the measurement system has been achieved with a measurement uncertainty less than 0.1 % (σ_Φ= 0.094 %). A model experiment with a sudden local change of liquid fraction has been conducted to validate our measurement system. We therefore showed a spatially and temporally resolved measurement of the liquid fraction in foam. Future work aims to decrease the deviation for higher liquid fractions by the use of transducers, that introduce more energy into the medium. Additionally, Doppler measurements will be conducted to build up the mass flow measurement. A local reference for the local liquid fraction will be derived by neutron imaging [9].

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