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On the design of electrical conductance probes for foam drainage applications
Assessment of ring electrodes performance and bubble size effects on measurements

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Abstract

This work examines critical design aspects of electrical conductance probes for measuring the liquid fraction in foams. These include the electrodes' size, shape, separation distance and intrusiveness as well as issues such as the excitation current frequency, multiplexing, data reduction to liquid fraction, etc. Measurements are performed with ring type electrodes, flush mounted on a test vessel wall at different heights to provide a measure of the longitudinal variation of liquid fraction in the foam. Runs are also performed with traditional disk and rod type electrodes immersed in the foam. The electrically determined local liquid fraction is compared with the photographically determined local bubble size distribution at the wall as well as with the volumetrically determined global liquid fraction in the entire vessel. For the examined protein-polysaccharide stabilized wet foam, drainage is negligible for a substantial initial period of time and only later a liquid fraction gradient emerges. In this no-drainage period, comparison of the local electrical signal with the local bubble size distributions reveals that the bubble size affects the liquid fraction. Moreover, a strong correlation is found between bubble size and onset of drainage.

Keywords: Impedance probe; Foam stability; Foam electrical conductivity; Bubble size effects; Ring electrodes

1. Introduction

There are quite a few techniques available for foam drainage measurement. Early studies usually referred to global measurement of the volumes of the foam and of the drained liquid versus time. Although this was sufficient from a technological point of view [1], it was soon understood that in a draining foam the liquid fraction is not only a function of time but also of foam height. In subsequent years, magnetic resonance imaging (MRI), γ-ray and X-ray techniques were applied to measure density profiles in draining foams [2–4]. Despite their high potential, these are expensive techniques that allow measurements only on small volumes and require highly skilled personnel. With regard to simplicity and fast response, electrical measurements offer a tempting alternative for determining the longitudinal liquid content profile in draining foams. This is implemented by placing several small electrodes along the vertical direction of the foam and scanning them at a rate faster than the time scale of drainage [2,3] (usually a scan through all electrodes in less than a second is enough). Another important advantage is the possibility of using non-intrusive electrodes that can be attached to the wall of test vessels of virtually any size.

Draining profiles in electrically non-conducting foams have been studied by Hutzler et al. [5] using a segmented capacitance probe. Difficulties associated with calibration and parasitic effects due to the no-direct contact of capacitance electrodes with the foam are serious drawbacks diminishing the reproducibility of results. On the contrary, measuring the conductance of electrically conducting foams do not suffer from these effects and, thus, has been exploited by several authors for investigating various properties of drainage (e.g. [6–9]). Technology oriented

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authors often used single point electrical conductivity measurements as a means to compare and characterize the drainage rate in their foams without worrying about the relationship between foam conductivity and liquid content, [10–14]. Recently, even technology oriented authors have started to care about reducing their measurements to liquid fraction values through appropriate existing theoretical relations, e.g. [15].

Since the first multi-segment conductivity measurement system of Weaire et al. [2] others have also tried such systems. Varley and co-workers [16,17] have developed multi-point measuring systems for characterization and control of foams in process equipment where foams are not easily visualized, e.g. in fermenters. Again, no reduction to liquid content was attempted. Multi-point systems were employed also by Barigou et al. [3], Fournel et al. [4], Saint-Jalmes and Langevin [18] and Maurdev et al. [19]. These authors, however, realized the importance of correctly transforming their electrical measurements to proper liquid content values and so either conducted independent calibration tests or employed existing theoretical relations to do the work.

A far more challenging application is electrical resistance tomography (ERT) which involves several conductivity sensors across a measuring volume to determine the distribution of the conducting regions inside a foam from electrical signals taken from all possible views of the sensing electrodes. An ERT device consists of electrodes which alternate role in applying a constant current and reading the resultant voltage pattern in the measuring volume. Suitable image reconstruction algorithms determine the conductivity distribution combining signals from all pairs of the sensing electrodes. Such a device has been developed by Wang and Cilliers [20] and Cilliers et al. [21] to investigate non-uniformities in dry foam systems. Difficulties in obtaining an accurate image reconstruction are usually attributed to the limited spatial resolution which is affected by the number of sensing electrodes, their size and the presence of electrical noise. The proper range of excitation frequencies is an additional matter of concern as it seems to depend on the value of the impedance of the conducting phase [22].

Flush mounted ring electrodes has been used first by Asali et al. [23] for measuring the average film thickness in annular flow. Andreussi and Bendiksen [24] and Tsochatzidis et al. [25] elaborated further on their use and also presented a theoretical treatment for measuring the liquid fraction in two phase flows in pipes and packed beds. Recently, Karapantsios and co-workers [26–30] have examined the possibility to use ring electrodes as electrical resistance tomography probes for foam and emulsion stability measurements and also for characterizing dense bubbly flows during the degassing of liquid solutions.

A first objective of this work is to present a comprehensive list of issues that need be considered when performing electrical conductance measurements of liquid fraction in foams. A second objective is to explore the use of flush mounted ring electrodes for measuring the instantaneous, cross-sectionally averaged, liquid fraction in draining foams and compare it to measurements from traditional rod and disk electrodes. Several ring electrodes placed at various heights along a foam, are energized successively in pairs to provide a measure of the variation of liquid fraction along the foam. Local electrical conductance measurements are compared with global volumetrically determined liquid fractions and local bubble size distributions at the wall derived from high resolution close-up photos. In pursuing these goals, a protein-polysaccharide stabilized wet foam (liquid fraction ~0.25) is produced, typical for food applications [31], in which drainage is negligible for a substantial initial period of time. It has been argued that for very wet foams the drainage behavior does not fit with any of the known theoretical predictions and remains puzzling [18]. The initial no-drainage period of our stable foam permits to study the effect of bubble size distribution independently from liquid drainage regarding the electrical response of the foam. In most publications that we know, foam decay starts right after its formation, e.g. [13,14] and so this was not possible. In addition, our foam is prepared with de-ionized water and not with buffer solutions as many authors did in the past to regulate the ionic strength. This is because we and others, e.g. [13,32], observed that the ions present in buffer solutions can have a strong effect on the stability of low ionic strength foams.

In the following section, considerations pertinent to electrical conductance measurements for foam drainage are reviewed and assessed. The main features and advantages related to the use of ring electrodes are also presented. In the next section, the experimental setup is outlined along with the employed measuring techniques. A section follows on experimental results and discussion on the performance of ring electrodes.

2. Design and operation considerations

Despite the significant effort devoted in measuring the effective electrical conductivity of multiphase dispersions, the role of the shape and size, separation distance, relative position in the container and frequency of the excitation electrical current has received little attention. These parameters dictate the current density distribution between electrodes and so determine the true effective measuring volume. Ceccio and George [22] reviewed many different arrangements of electrodes for gas/liquid fraction measurements in multiphase systems. For such systems the objective is the electrodes not to disturb the distribution of phases while maintaining uniform electrical (potential and current) fields across the electrode surfaces. In foam applications, the most popular electrodes are two parallel opposite-facing plates inserted in the wall of the container, e.g. [7,8,10]. This configuration resembles the ideal *rectangular* cell consisting of two electrodes e.g. platinized plates, covering the entire cross sectional area of the cell [33]. However, often the lateral distance between electrodes, i.e. diameter of test vessel, is different than the dimensions of the plates so electric fields through the dispersion volume are not uniform and lead to incorrect estimation of its effective conductivity [34]. For opposite-facing electrodes, this problem is more acute the smaller the size of the electrodes, e.g. partly stripped wires [9], since then electrical lines are much denser in the neighborhood of the electrodes and so measurements reflect more what occurs in these regions and not across the entire measuring volume [33]. This is also the case when a large and a small electrode are combined in a probe; measure-