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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.

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### 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),  $\gamma$ -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  $\sim 0.25$ ) 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-

ments are representative more of the neighborhood of the small electrode. In general, the size of the electrode should be larger than the average size of bubbles to diminish sensitivity in small perturbations due to individual bubbles.

The shape of electrodes dictates the orientation of the electric field between them with a direct consequence to the linearity of their response. For electrodes facing each other in the same horizontal plane, the electric field is oriented mainly horizontally. On the contrary, for electrodes spaced apart in the axial (longitudinal) direction, the electric field is oriented mainly along the vertical axis. During foam drainage the main liquid flow is through the nearly vertical intra-bubble channels which soon accommodate the largest portion of the descending liquid. A horizontal electric field passes chiefly through the horizontal intra-bubble channels, so it misses a large part of the draining liquid. On the other hand, a vertical electric field can capture the draining liquid but one should avoid using electrodes intruding the foam as for instance parallel grid electrodes covering the cross-section of the test vessel [34,35]. The ideal would be to have an electric field which would evenly span the measuring volume in both the horizontal and vertical directions.

The separation distance between electrodes must be carefully selected in order to obtain meaningful data. Criteria for such a selection may be based on the volume-averaging approach of modeling porous media [36]. The size of the probe averaging volume, i.e. the required minimum volume of a dispersion surrounding a probe, must be large enough to average porosity/tortuosity undulations (due to the finite bubble size) yet small enough to preserve the local character of the measurements. Celmins [37] while working with gas-particle mixtures showed that the above “representative elementary volume” criteria are satisfied if the averaging volume contains at least 60–150 particles. Of course, this value must be viewed with reservation since particle/bubble size may play a role.

Special attention is required when all the parts of the electrodes are not at the same distance from each other. For instance, with horse-shoe or half-ring electrodes opposite-facing one another at the same plane, the distance between the edges of the electrodes is much shorter than the distance between the centers of the electrodes. So, more current flows through the edges and the measurement is not representative of the entire volume surrounded by the electrodes.

During drainage of a foam column, a substantial liquid layer may form on the walls of the foam container [3,4,29]. This is a serious problem if the container walls are hydrophilic, e.g. glass, and the foam under investigation is dry, i.e. liquid fraction below 0.1. In such cases, the risk arises that the wall liquid layer may shunt the measurement since the electrical resistance of the foam is higher than the resistance of the liquid layer and so electric current flows through this layer rather than through the core of the foam. To circumvent this problem, Barigou et al. [3] proposed a new electrode arrangement where a stainless steel ring mounted flush with the inner walls of the container serves as the “outer” electrode and an “inner” electrode is positioned along the central axis of the foam column. Results of these authors demonstrate that this arrangement is superior to traditional electrodes regarding effects due to a liquid layer on the wall. Yet,

the immersed inner electrode inevitably disturbs the foam and affects drainage rates. If in order to avoid this effect one reduces the electrodes size then the other risk (described above) may arise of getting measurements chiefly from the region around this small electrode and not across the core of the foam. Fournel et al. [4] dealt with this problem by employing a non-intrusive electrode arrangement where auxiliary guard electrodes collect the counterfeit electric current flowing through the wall liquid layer. Their set-up could measure directly not only the liquid fraction in the foam but also the layer thickness running down the wall.

A very important aspect when performing electrical conductance measurements in dispersions is to assure that the electrical impedance across an electrode pair is essentially resistive [38]. It has been shown, [4,39], that this impedance depends on the excitation current amplitude and frequency and is greatly affected by the interfacial impedance between the conducting liquid and the surface of the electrodes. If the active (for electrical flow) surface area of the electrode varies with time then this interfacial impedance varies accordingly giving spurious measurements. This is important if the surface area of the electrodes is small so coalescence and collapse of the bubbles touching the electrodes may change drastically the electrodes active surface. Moreover, the interfacial impedance is affected by the chemical nature of the electrode material and the conducting liquid as well as by the intensity of the electric field. For all these reasons, the excitation frequency must be selected at a sufficiently high value (for stainless steel electrodes and tap water  $\sim 10$ – $100$  kHz) but not much higher; for frequencies above  $\sim 1$  MHz strong capacitive effects appear in tap water. In the  $10$ – $100$  kHz region the phase shift of the applied signal is essentially close to zero and the amplitude is that of the real part of the complex impedance. It is interesting that many earlier studies employed alternating currents of lower frequency ([3] 50 Hz; [6] 1 kHz; [7,8] 1 and 3 kHz; [9] 1 kHz; [40] 1 kHz). Unfortunately, many other authors used commercial conductivity meters (usually operating around or below 1 kHz) without even bothering to mention the excitation frequency [10–14,16–19]. To our knowledge, the only work on foams that elaborated about the proper choice of the excitation frequency was that of Fournel et al. [4] who eventually employed 50 kHz. Using a frequency around 1 kHz is adequate to suppress electrode polarization but to eliminate capacitive impedance is usually not enough if accuracy is a concern. For air-water multiphase flows which are either stratified and annular flows (existence of thick liquid layers) or dispersed flows at high liquid fractions (usually above 0.6), the frequency of operation found in literature ranges from 5 kHz to 5 MHz [22]. This again was not always the outcome of serious investigation.

Electrodes of very small surface areas operating at high frequencies may be prone to errors due to the impedance of the cables carrying the signal. For most practical systems this is insignificant if the system measures liquid resistances of the order of a few k $\Omega$  or below. The same effect concerns also electrodes placed far apart but the distances that can create serious problems are usually unrealistically large for applications where the local character of measurements is an important issue.

When using multiple electrodes for a multi-point detection of liquid content along the foam height it is imperative to discard the cross-talk between electrode pairs. Some authors, e.g. [3], claimed that they have minimized electrode pair's interference by simply feeding each pair by an isolated power supply and by recording signals on isolated channels of a data-logger. Our experience is that for really simultaneous readings, the cross talk is strongly dependent on the intensity of the electric field and the distance between neighboring electrode pairs. Thus, for the electrodes configuration of [3] (horizontal electric filed) and the employed distance between electrode pairs (four times the electrodes size) it is not surprising that electronic cross-talk was not so important. Nevertheless, one should always check for this effect on every new electrodes configuration or, alternatively, use multiplexer technology [2,17]. The latter is a cheap and easy solution for intra-channel multiplexing intervals of the order of 1 ms and/or multiplexing full cycles of the order of 10 ms which is sufficient for pseudo-simultaneous measurements in draining foams.

As far as is known, Maxwell [41] was the first to investigate the problem of the effective electrical conductivity of two-phase dispersions. He considered uniformly sized spheres as the dispersed phase in a sufficiently dilute dispersion to ignore interactions between spheres. For a non-conducting dispersed phase (as air bubbles in foam) the dispersion conductivity  $\sigma_{\text{dis}}$ , was given by

$$\frac{\sigma_{\text{dis}}}{\sigma_{\text{liq}}} = \left( \frac{2\varepsilon}{3 - \varepsilon} \right) \quad (1)$$

where  $\sigma_{\text{liq}}$  is the conductivity and  $\varepsilon$  the volume fraction of the continuous liquid phase. This equation is expected to hold for very wet foams where gas bubbles are widely separated. On the other hand, for a situation of closely spaced polyhedral bubbles, i.e., for very dry foams, Lemlich [42] proposed the following relation:

$$\frac{\sigma_{\text{dis}}}{\sigma_{\text{liq}}} = \left( \frac{1}{3} \right) \varepsilon \quad (2)$$

Recently, Feitosa et al. [40] in a very useful reappraisal of widely cited prior data and performing also new measurements verified that indeed these two models describe adequately the two extreme limits. Furthermore, they proposed an empirical formula which effectively describes dispersions over the entire range of liquid fraction from 0 to 1. Their relation is:

$$\frac{\sigma_{\text{dis}}}{\sigma_{\text{liq}}} = 2\varepsilon \left( \frac{1 + 12\varepsilon}{6 + 29\varepsilon - 9\varepsilon^2} \right) \quad (3)$$

In a different approach, Yianatos et al. [43] introduced the concept of using the tortuosity of a dispersion for estimating the liquid fraction from conductivity measurements. They proposed the relation:

$$\frac{\sigma_{\text{dis}}}{\sigma_{\text{liq}}} = \left( \frac{\varepsilon}{\xi} \right) \quad (4)$$

where  $\xi = L_{\text{dis}}/L_{\text{liq}}$  is the tortuosity of the dispersion with  $L$  being the length of the conductive path between the measuring electrodes. These authors used an existing tortuosity model

originally developed to describe diffusion inside homogeneous suspensions of randomly situated spheres [44]. The employed tortuosity model is:

$$\xi = 1 - 0.5 \ln \varepsilon \quad (5)$$

This relation describes tortuosity only as a function of liquid fraction (independent from bubble size). This approximation is valid for an ideal fully homogeneous dispersion but in a polydisperse foam severe non-uniformities in the bubble size distribution with time are expected to occur and this may bring about a dependence of tortuosity on the bubble size.

Yianatos et al., showed that Eqs. (4) and (5) are capable of describing successfully gas–liquid systems with liquid fractions between 0.05 and 1. Later, other authors verified this behavior, e.g. Cents et al. [45]. The above tortuosity model (at its present form) fails to describe very dry foams (liquid fractions less than 0.05). If one compares predictions from Eq. (3) with those from Eqs. (4) and (5) there is an average deviation of  $\sim 3\%$  over the whole range of liquid fractions (essentially within the scatter of data used by Feitosa et al. to derive Eq. (3)). This deviation is less than half of the deviation between Eq. (3) and a formula communicated by Curtayne [46] which was also claimed to hold for all liquid fractions.

For a uniformly distributed liquid phase (as in foam), the ratio of conductivities is equal to the ratio of the apparent conductances (the inverse of the apparent resistances):

$$\frac{\sigma_{\text{dis}}}{\sigma_{\text{liq}}} = \left( \frac{K_{\text{dis}}^{\text{app}}}{K_{\text{liq}}^{\text{app}}} \right) \quad (6)$$

where  $K_{\text{dis}}^{\text{app}}$  denotes the apparent conductance of the dispersion (for simplicity henceforth denoted as  $K_{\text{app}}$ ) and  $K_{\text{liq}}^{\text{app}}$  denotes the apparent conductance of the liquid (for simplicity henceforth denoted as  $K_{\text{liq}}$ ).

Therefore, to present and compare experimental data with theory it is advisable to normalize conductance measurements with the conductance of the liquid constituting the foam. This normalization also eliminates errors owing to variations of liquid conductivity because of temperature or ionic strength changes.

### 2.1. Flush mounted ring electrodes

The use of flush mounted probes in two phase systems is based on the electrical potential field theory. Coney [47] was the first to treat theoretically the electrical behavior of a liquid layer covering a pair of two parallel strip electrodes at constant potential. Andreussi et al. [24] showed that the solution of Coney holds for circular electrodes covering the entire circumference of a pipe and for any height of a liquid layer above them if simply the distance between electrodes is sufficiently large with respect to the liquid height. Tsochatzidis et al. [25] extended the use of flush mounted ring electrodes for measuring the liquid fraction in uniformly distributed liquid patterns inside packed beds. Those authors conducted a detailed parametric study on the performance of ring electrodes and developed an analytical solution for their response by solving the Laplace equation in cylindrical coordinates. Their analysis showed that increas-

ing the electrodes width or decreasing their separation distance disturbs the uniform distribution of current density at neighboring electrode edges. So, for cases where the electrodes width is larger than half the electrodes separation distance, it is a better approximation to consider a linear current density distribution on each electrode with zero value at the outer electrode edge.

The sensitivity of ring electrodes to angular, radial and axial non-uniformities was examined thoroughly by Tsochatzidis et al. [25]. What is relevant to measurements in foams is the axial sensitivity of the technique (edge effects). In other words, one should be concerned about the spread of the electric field above and below the electrodes which would increase the measuring volume lowering the local character of measurement. Indeed, with ring electrodes the electric field is not entirely confined between the two electrodes [25]. However, by proper choice of the electrodes width and separation distance with respect to the diameter of the foam column one can suppress edge effects. An interesting choice of electrode parameters is to take their width equal to 5% of their separation distance and their separation distance equal to the column radius. For this configuration, edge effects constitute less than 4% of the measured conductance and are confined within a distance (above and below electrodes) of less than 9% of the separation distance. What is of greater significance, though, is that for this configuration the electric field approaches the ideal uniform spanning of the foam volume between the electrodes in both the horizontal and vertical directions. This is critical if radial non-uniformities are expected to occur across the cross-section of the foam column. On the other hand, if the foam is radially homogeneous then one can reduce the separation distance in favor of the local character of measurements. Devia and Fossa [48] working with dispersed flows over a broad range of void fractions showed that there is a small dependence ( $\sim 4\%$ ) of probe response on electrodes' distance. Such small effects may be attributed to the different confinement (size and shape) of the electric field at different electrode distances but also to minor imperfections of the electrodes geometry or/and electrodes misalignment but, in any case, they are within the overall experimental uncertainty.

Another issue is the sensitivity of ring electrodes to different bubble sizes. In principle, as the dispersed phase mean diameter increases, the tortuosity of the electric field decreases and therefore the conductance of the dispersion increases. Such size effects have been reported for bubbles and particles in the range 1–5 mm, for liquid fractions between 0.75 and 1 and for a 21 kHz excitation signal [48]. For foams where the liquid fraction is below 0.35 and the tortuosity is always high, the sensitivity to bubble dimensions is a serious matter of concern. This is confirmed in this study.

### 3. Experimental setup and procedures

Soya protein isolate (SPI, PRO FAM<sup>®</sup> 974) purchased from VIOTREK is used as the foaming agent without any further purification. The isoelectric point of protein is 5. Xanthan gum (XG) purchased from SIGMA is used to increase the viscosity of the liquid phase since most high molecular weight polysaccharides are hydrophilic and so do not have a high ten-

dency to adsorb at the air water interface. Solutions of SPI are prepared in de-ionized water at 1% (w/v) by gentle stirring for one hour. De-ionized water is selected instead of buffer solutions because we noticed that the high salinity of buffer solutions (so widely employed by other authors to control the foam pH) had stronger effects in our foam behavior than the protein and the polysaccharide together. The insoluble SPI fraction ( $\sim 50\%$ ) is removed by centrifugation at 10,000 rpm for 15 min (ROTINA 35, HETTICH) and the supernatant is refrigerated for 24 h at 4 °C. The soluble fraction is used to prepare the protein/polysaccharide mixed solution by gradually adding 0.1% (w/v) xanthan gum and further gentle stirring for another hour. The resulting liquid serum has viscosity 12 cP (Covette DV-II Viscometer, Brookfield), natural pH 6.9 (MP 220, Mettler Toledo), electrical specific conductivity 0.52 mS/cm (ECM, Dr. Lange) and equilibrium surface tension 44.5 mN/m (ring method, Sigma 70, KSV); all properties measured at 25 °C. This serum is then left in the fridge at 4 °C for additional 24 h.

The natural pH of the solution is above the isoelectric point of protein where limited thermodynamic incompatibility may be expected between the protein and the polysaccharide because of repulsive electrostatic interactions and different affinities towards the solvent making these macromolecules to exclude one another and segregate into different phases [49]. However, recent evidence supports an additional role for polysaccharides which may interact with proteins at the interface affecting the interfacial rheological properties of the system, e.g. increase the dilatational viscosity [50].

Foams are prepared by whipping air into 300 ml of the above solution using a Sunbeam Mixmaster mixer for 10 min at 900 rpm. This intense production rate, apart from being technologically more realistic than the bubbling method (e.g. in terms of polydispersity), also allows creating large volumes of initially uniform and homogeneous foam columns [51]. Part of the produced foam is then decanted to fill a Plexiglas test tube up to its top and is allowed to drain.

The Plexiglas test tube has 70 mm internal diameter and 170 mm height. The conductance gauge consists of six parallel stainless-steel rings that are placed at various heights along the tube, flush with its inner surface (Fig. 1). The electrodes are 2 mm wide. The electrodes of the gauge are combined in pairs to give several conductance probes. Assuming a radially uniform foam at all times during drainage, the separation distance between electrodes (dictating the measuring volume also in the radial direction) is not a matter of concern and the selection of pairs is solely based on their relative position along the foam height. Thus, for obtaining data at different heights the four electrode pairs (probes) shown in Fig. 1 are selected.

Apart from the ring electrodes, a pair of disc-like and a pair of rod-like electrodes are manufactured, each one having the same active (for electrical flow) surface area with a ring electrode, Fig. 2. Each disc electrode has available for electrical current flow only its front plane surface ( $d = 23.7$  mm) whereas each rod electrode only its side cylindrical surface ( $d = 5.9$  mm,  $l = 23.7$  mm), respectively. For all pairs, the electrodes separation distance is large enough to average bubble size undulations yet small enough to preserve the local character of measurements.

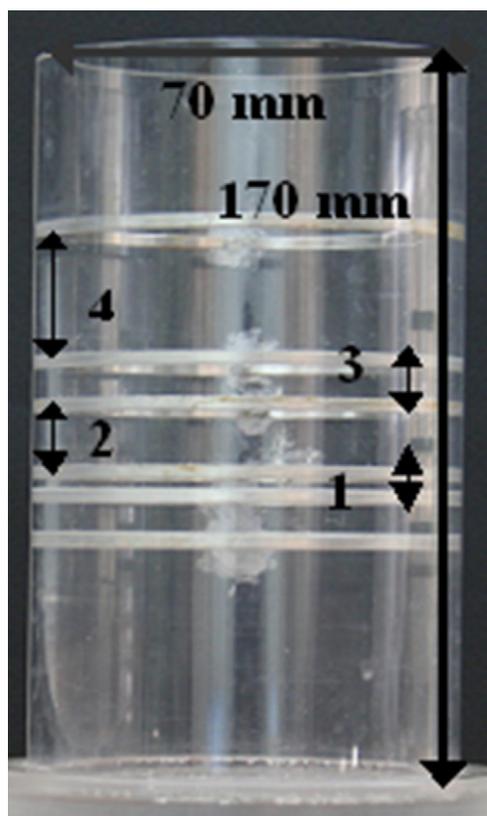


Fig. 1. Experimental test tube with flush mounted ring electrodes. Tube ID: 70 mm, height: 170 mm. Electrode pairs (probes) are from bottom to top: probe 1 (separation distance 5 mm), probe 2 (separation distance 15 mm), probe 3 (separation distance 10 mm) and probe 4 (separation distance 30 mm).

An a.c. carrier voltage of 1.0 V (peak-to-peak) is applied across each electrode pair at a frequency of 25 kHz. The selection of the frequency is made by inspecting both the amplitude and the phase shift of the applied voltage under various frequencies to assure the resistive behavior of the foam. The response of the probe is fed to a special electronic analyzer, similar to that employed by Karapantsios and co-workers [25,38,39]. Particular attention is given to achieve a satisfactory sensitivity over all the examined foam liquid fractions. For this, a special demodulation circuitry is included in the analyzer. This circuit acts to demodulate the peaks of the output signal in a synchronous fashion using the source oscillator to create square pulses of

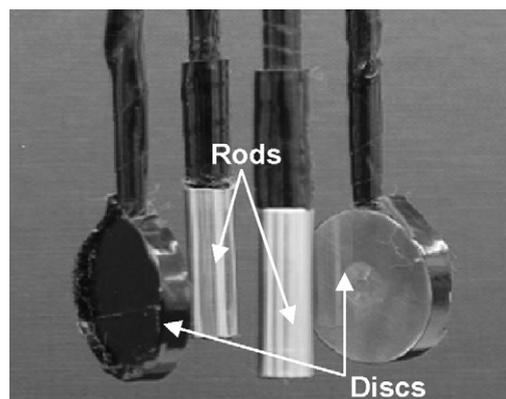


Fig. 2. Disc electrodes ( $d=23.7$  mm) and rod electrodes ( $d=5.9$  mm,  $l=23.7$  mm).

the same frequency as the reference. A two stage cascade phase adjustment permits the pulses to scroll about and intersect the carrier signal at any point along its cycle thus converting it to an analog d.c. voltage signal.

The good performance of the electronic analyzer is supervised by monitoring the carrier signal and the pulse signal by a dual band oscilloscope. A multiplexer is programmed to scan channels with an intrachannel delay of 5 ms allowing for virtually simultaneous measurements from all four probes, with only one probe being activated at a time in order to avoid electronic interference. A multiplexer cycle (loop delay) is executed once in 5 s. The d.c. signals from electrode pairs are collected and stored in a microcomputer. These analog d.c. signals are converted to equivalent conductance  $K_{app}$  of the foam using a calibration curve based on precision resistors. The reported data are means of at least three replicates with an average variance (standard deviation/mean) less than 0.1.

Close-up photographs of the foam are taken every 10 min between electrodes of probe 2 using a still camera (Canon, EOS 350D, 8 Mp) equipped with proper magnification lenses (Pentax, FA100 macro, F2.8). A dual probe fiber optic system (HAISER Macrospot 1500) supplemented with thin fiber extensions is employed to illuminate the foam uniformly from the back. The useful field of view is 13 mm  $\times$  10 mm (Fig. 3; orthogonal frame in the center of photos) which assures that several bubbles is contained in the image even at long times after foam formation when bubbles become excessively large ( $d > 1$  mm). Bubble sizes and

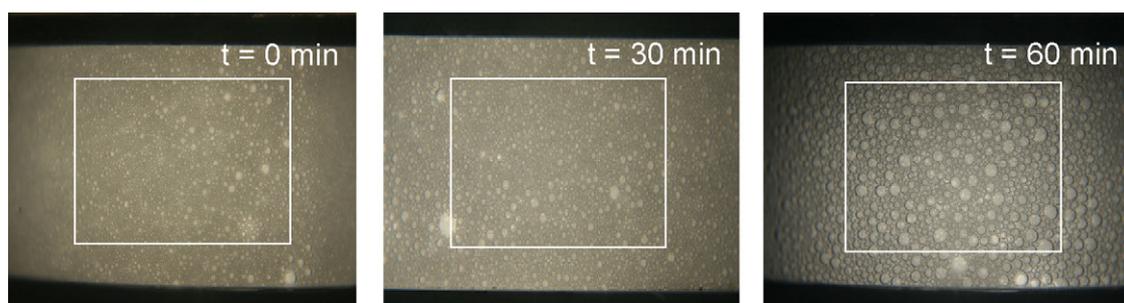


Fig. 3. Bubble size distributions during foam decay. The black horizontal regions at the top and bottom are the upper and lower electrodes of probe 2. The orthogonal frame (13 mm  $\times$  10 mm) in the center of the photos denotes the field of view for images analysis.

bubble size distribution are determined from the images using a custom made software based on a template matching technique which is capable of analyzing densely dispersed spherical bubbles in digital images [52]. The software selects only sharp focus/clear edge bubbles from the population of each image for the analysis. The selected bubbles span evenly across images and always include above 80% of the entire population. This represents more than 1700 and 400 bubbles for short and long times, respectively.

Another still camera (SONY, DSC-F717) is used to take photographs of the whole Plexiglas tube at the moments when the close-up photos are taken. These images are used to determine the instantaneous heights of the foam and of the drained liquid inside the test tube and from them estimate the quantities  $V_{Ft}/V_{Fo}$ ,  $V_{Lt}/V_{Lo}$  and  $V_{Lt}/V_{Ft}$  (global liquid fraction of the foam).

#### 4. Results and discussion

Although our foams continue to drain for several hours we have decided for practical reasons to present here results only for the first hour after their formation. It is instructive to begin with the results from global volumetric measurements. Fig. 4, shows how the global liquid fraction changes with time along with the respective global variations in the volume of the liquid contained in the foam and the volume of the foam. In the figure,  $V_{Lt}$  denotes the liquid volume contained in the foam at time  $t$ ,  $V_{Lo}$  the initial liquid volume contained in the foam,  $V_{Ft}$  the foam volume at time  $t$  and  $V_{Fo}$  the initial foam volume. Repeatability checks from different runs give an initial liquid fraction variation of less than 3%.

It is apparent that the foam remains wet (liquid fraction above 0.2) during the entire first hour of draining. Moreover, the foam is so stable that for about the first 20 min there is virtually no sign of drainage. For wet foams met typically in food applications this is a good sign from a technological point of view. Capillary hold-up effects at the bottom of the foam column may be blamed for the initial delay in drainage. After 20 min, the liquid starts to drain out while at the same time a small change is also noticed in the volume of the foam. Following the onset of drainage, the

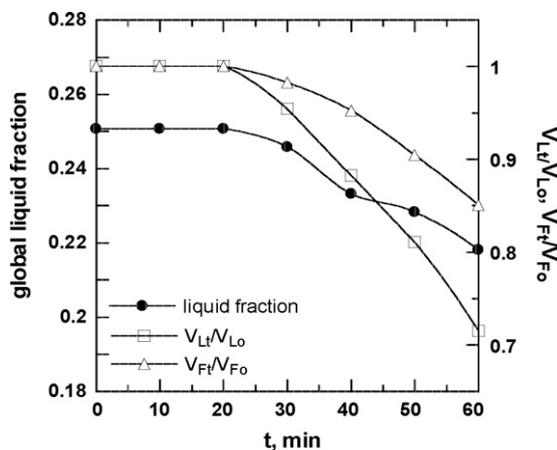


Fig. 4. Global volumetric measurements: evolution of liquid fraction, liquid content and foam volume with time.

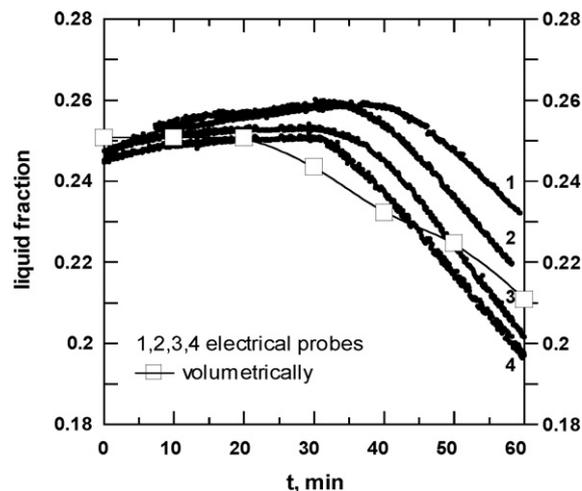


Fig. 5. Local electrical conductance measurements: evolution of liquid fraction with time at different heights (probes).

rate of liquid withdrawal is much higher than the rate of decay of the foam volume so the liquid fraction follows a slow but steady decline.

Volumetric measurements in our initially uniform and homogeneous foam yield an independent check of electrical data reduction to liquid fraction values. The volumetrically determined initial liquid fraction is 0.25. The deviation from theoretical predictions is: 16.2% from Eq. (1), 46% from Eq. (2), 2.4% from Eq. (3) and 4.3% from Eqs. (4) and (5). So, the equation of Feitosa et al. [4] is used here for deducing liquid fractions from electrical measurements. However, given the reasonable success of the model of Yianatos et al. [43] we think that the concept of tortuosity deserves further attention in the sense that it is not purely empirical but there is a theoretical foundation.

Fig. 5 presents data obtained from the four measuring probes along the foam column. Global volumetric measurements are also presented for comparison. The four probes give qualitatively similar results. However, both the time for drainage onset (moment when curves start to decline) and the liquid fraction variation with time show a monotonous trend among probes: the lower a probe is located in the foam the later the drainage starts and the slower the drainage rate. This is normal and is due to hydrostatic effects in the foam.

Interestingly, a slight gradual rise of the electrical signal is observed from time zero until the moment (different for each probe) that the liquid starts to leak out of the measuring volume. This rise corresponds to a liquid fraction increase of about 0.01. This is just a small difference which in terms of accuracy is out of the capacity of determination but in terms of resolution it can be safely sensed. Inasmuch as capillary hold-up effects are restricted to low heights (the capillary length at our bottom foam-liquid interface is estimated around 1 cm) they can not be blamed for the liquid fraction rise with time. Such signal rise could be explained by a slight temperature increase during the experiment but our temperature recordings at the wall do not confirm this. Nor the ionic strength of the solution has changed with time as conductivity measurements show. Another possi-

ble explanation is a bubble size effect (through tortuosity) as bubbles get larger with time. Datye and Lemlich [8] observed a similar small bubble size effect on the conductivity of dry foams ( $\varepsilon < 0.06$ ). Although qualitatively correct, this remains to be seen from the analysis of the close-up photos. To our knowledge, this is the first time that such a feature is reported regarding electrical signals in foams. This is because one needs very stable foams to see this effect, otherwise drainage masks it completely.

Local electrical measurements differ from global volumetric ones. The shorter delay for the onset of drainage observed in volumetric measurements is because there is yet an additional foam volume above probe 4 and up to the top of the tube where drainage starts first. For the same reason, the global volumetric drainage rates measured after the initial delay is a bit different than the electrically measured ones.

The role of the electrode geometry and intrusiveness is examined next. Fig. 6a and b shows the electrical and volumetric measurements, respectively, obtained by employing ring, rod and disc electrodes simultaneously. For comparison, the data

obtained when using just the ring electrodes are shown. Beside their different shape, rod and disc electrodes have a much longer vertical surface exposed to the foam compared to the narrow (2 mm) ring electrodes and one may have concerns whether this may enhance drainage. It must be also stressed that rod and disc electrodes are immersion electrodes while ring electrodes are flush mounted at the wall of the container.

The signals obtained by the three simultaneous electrode pairs roughly coincide for about 40 min after foam formation. This is a period of a rather stable foam where the geometrically different electrical fields deployed between the different electrode pairs (different measuring volumes) and the longer vertical surfaces of the rod and disc electrodes do not seem to influence the measured signal. However, the response of the three probes starts to diverge after these 40 min with the ring electrodes showing the lowest and the disc electrodes the highest drainage rate. It is probable that once drainage has started the geometry of the electrodes can affect the drainage rates.

What is perhaps more interesting is that the signal of the ring electrodes when they are used alone is pretty close to simultaneous measurements, if one takes into account the variance among runs. Therefore, one may be tempted to argue that not only the geometry of the electrodes but also the intrusive or non-intrusive character of electrodes do not affect dramatically the response of the system. Nevertheless, the full truth is revealed in Fig. 6b. Both the volume of the remaining liquid in the foam as well as the volume of the foam decrease faster during simultaneous measurements than during ring-alone measurements. That is, the presence of intrusive electrodes affects the system. Interestingly, the relative changes in liquid volume and foam volume are such that the instantaneous liquid fraction does not vary significantly between simultaneous and ring-alone measurements. In view of this it is evident that information on liquid fraction alone is misleading in appraising the behavior of foam.

Fig. 7 shows the variation of bubble size distribution with respect to time as determined from the analysis of close-up photos. For clarity, bubble sizes are divided into four distinct classes

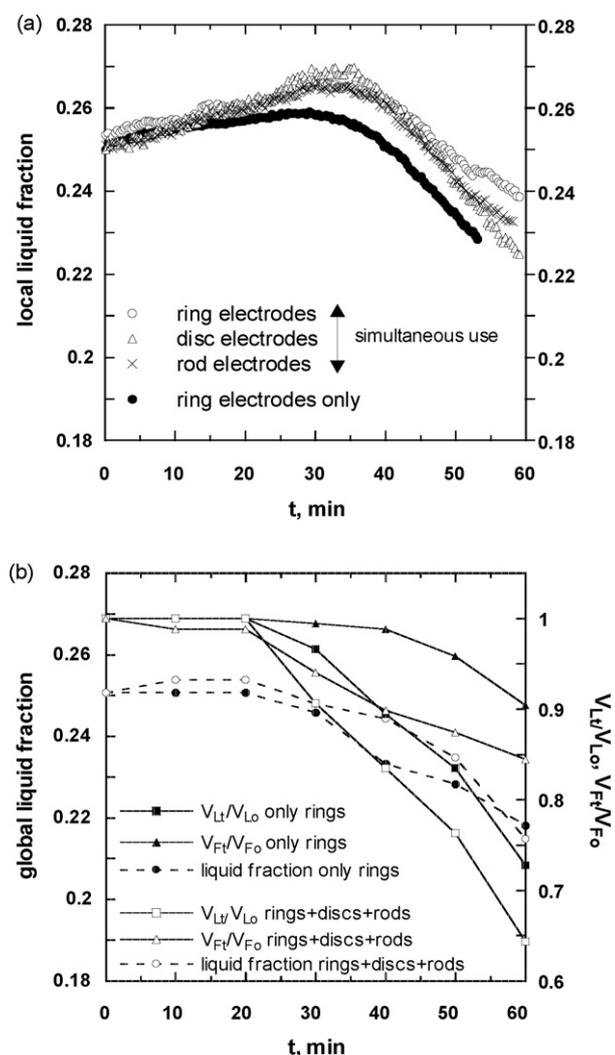


Fig. 6. Comparison between ring, disk and rod electrodes: (a) evolution of local liquid fractions with time and (b) evolution of global liquid fraction, liquid content and foam volume with time.

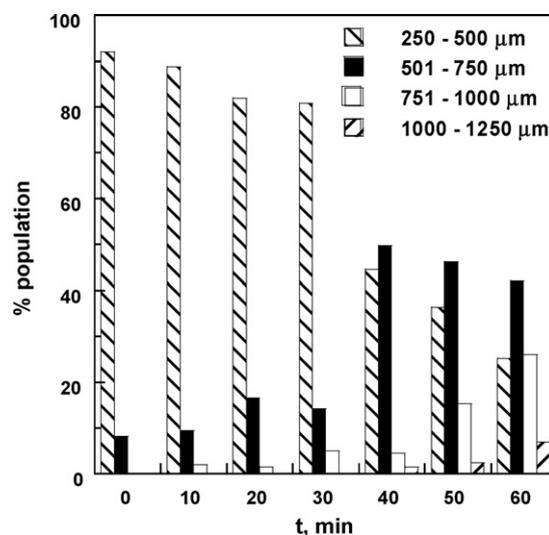


Fig. 7. Evolution of bubble size distribution (bars) with time.

(bins) spanning between 250 and 1250  $\mu\text{m}$ . In fact, there are also a few bubbles below and above these limits but their number is small and do not affect the distribution. Initially the foam is quite homogeneous with more than  $\approx 90\%$  of the detected bubble population between 250 and 500  $\mu\text{m}$ . The situation does not change much for the first 10 min. Sometime between 10 and 20 min, a small but clear alteration occurs with the smaller bubbles to partially vanish in favor of larger ones while still remaining the dominant population ( $> \approx 80\%$ ) in the foam. After that moment and up to 30 min, again no drastic activity is observed. Suddenly, at some instant between 30 and 40 min a large size redistribution takes place. This is manifested by the great reduction of the smaller bubbles (250–500  $\mu\text{m}$ ) and the sound increase of the second class of bubbles (500–750  $\mu\text{m}$ ). In addition, very large bubbles (1000–1250  $\mu\text{m}$ ) appear for the first time. From that moment on, there is a gradual reduction of the two smaller size-classes and a progressive increase of the two larger ones.

The comparison between bubble size distributions in Fig. 7 and variations of electrical signal from probe 2 in Fig. 5 is revealing. Both bubble size distribution and electrical signal change dramatically between 30 and 40 min indicating a strong correlation between bubble size and liquid drainage. This is interesting if one notes that the photos depict the bubbles in contact with wall while the electrical signal spans the cross section of the foam. So, we can assume that the foam is pretty homogeneous. It is noteworthy that the change of bubble size during the first 30 min, although small in terms of % population, it is appreciable in terms of bubble surface area as expressed by the  $\sim 25\%$  rise of the Sauter mean diameter  $d_{3,2}$  from 0 to 30 min. The Sauter mean diameter is most appropriate for correlation with conductance measurements since in theory, electrical conductivity is a function of the interfacial area of the foam [53]. Furthermore, if one considers that 3D non-uniformities can affect tortuosity beyond what is predicted by Eq. (5) then small changes in bubble size distribution may lead to even larger path differences between the electrodes. In other words, it is quite probable that the observed changes of bubble size can yield the small gradual rise of electrical signals observed in the first 30 min of the experiments, a period during which there is no liquid withdrawal to shadow this effect. Apparently, more work is needed to elucidate this issue.

## 5. Conclusions

Several important aspects of the performance of electrical conductance probes for foam drainage measurements are assessed. It is shown how the electrodes' size, shape, separation distance, relative placement inside the foam dictate the geometry of the generated electric field and thus affect the measurement of liquid fraction in the foam. The largely underestimated and often overlooked issue of the frequency of the excitation carrier signal is discussed and an appropriate range of operation is proposed. Matters such as the role of electrodes intrusiveness, use of simultaneous multiple probes and/or multiplexing and proper reduction of electrical data to liquid fraction values are discussed in detail and practical solutions are provided.

In this work, electrical measurements are performed with flush-mounted ring electrodes placed at several heights along

the foam column. It is the first time that such electrodes are used in foam drainage measurements. Comparisons are made with traditional rod type and disk type electrodes that are immersed in the foam. In addition, the global liquid fraction of the foam is measured volumetrically and the bubble size distribution is deduced from close-up photos of the foam. It is shown that the global volumetric determinations differ from the local electrical measurements. Moreover, it is seen that the local liquid fraction alone may not be a safe indicator of foam behavior since the liquid fraction combines information on the evolution of both the drained liquid and the foam volume and these quantities may vary in such a way that the liquid fraction is slightly affected while the foam itself has changed dramatically. The electrically determined evolution of the local liquid fraction appears to be related to the evolution of the bubble size distribution obtained at the same height in the foam. This was observed during the initial period that drainage was negligible in our very stable foam where changes in the bubble size distribution (tortuosity) affected electrical measurements.

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