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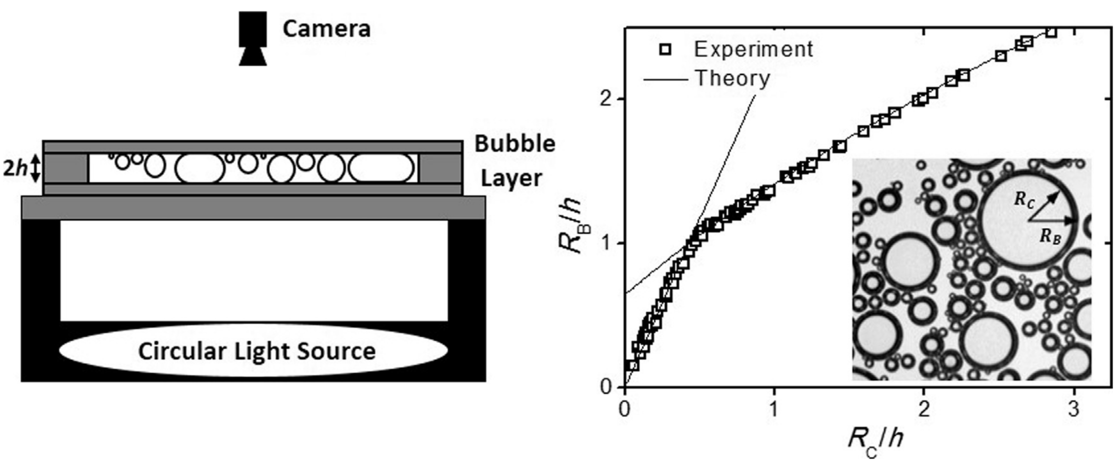
A simple technique for the automation of bubble size measurements

T. Gaillard[a,*], C. Honorez[a], M. Jumeau[a], F. Elias[b,c], W. Drenckhan[a]

[a] Laboratoire de Physique des Solides, UMR8502–Université Paris Sud, Orsay, France
[b] Laboratoire Matière et Système Complexes, UMR7057-Université Paris Diderot, Paris, France
[c] Université Pierre et Marie Curie, Paris, France

GRAPHICAL ABSTRACT



HIGHLIGHTS

- We propose two simple setups to measure bubble size distributions of foams using the lensing properties of bubbles.
- Simple optical modelling captures very well the experimental data.
- Image treatment of small and large bubbles can hence be fully automated without the need of calibration.

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ABSTRACT

An increasing number of research topics and applications ask for a precise measurement of the size distribution of small bubbles in a liquid—and hence for reliable and automated image analysis. However, due to the strong mismatch between the refractive index of a liquid and a gas, bubbles deform strongly the path of light rays, rendering automated bubble size analysis a challenging task. We show here how this challenge can be met using the fact that bubbles act like inverted, spherical lenses with a curvature which is the inverse of the bubble radius. The imaging properties of each bubble can then be used to accurately determine the radius of the bubble upon imaging an object which can be filtered easily by a computer. When bubbles are large enough to be deformed under the influence of gravity, it is more appropriate to measure their size after squeezing them between two narrowly spaced glass plates. We therefore show here, how the analysis can be extended to this case; and how both approaches can be combined to measure the size distributions of strongly polydisperse foams containing simultaneously small (several 10s of micrometres) and large bubbles (several 100s of micrometres).

* Corresponding author. Tel.: +33 169155399.
E-mail address: thibaut.gaillard@u-psud.fr (T. Gaillard).

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1. Introduction

Bubbles of sub-millimetric dimensions play an important role in an increasing number of applications such as foam flotation [1], foam fractionation [2] or bubble column reactors [3]. They also play an important role in many geophysical problems [4]. The bubble sizes as well as the size distributions play an important role in determining the final properties of the fluid/bubble mixture and therefore need to be known with sufficient precision. For this purpose, numerous techniques have been developed in the past, including liquid scattering [5], acoustic methods, or laser scanning techniques (see introductory review in [6]). These techniques are efficient, but generally suffer from a lack in precision when reliable information about the size distribution is required. Due to their simplicity and low cost, classic photographic techniques making use of white light are the preferred tool for precise bubble size measurements. However, due to the strong mismatch of the refractive indices between the gas and the liquid, and the curved surfaces of the bubbles, they interfere strongly with the light paths and therefore render quantitative imaging a challenging task [7]. This is even more the case when automated image analysis is required with the desire to obtain reasonably reliable statistical measures on averages and distributions.

In order to overcome this challenge, we propose here two simple approaches. The first (Section 3) considers freely floating bubbles which are small enough not to be deformed by gravity (for example several 10s of micrometres in water). To measure their size, a simple approach can be used which exploits the fact that a bubble in a liquid acts like an inverse, spherical lens which creates a virtual image which can be photographed by a camera. The relationship between the size of the final image and the imaged object is directly related to the curvature of the bubble and hence its radius. By exploiting the curvature of the bubble, the image treatment does not need to look for the boundary of the bubble which tends to be ill-defined in most lighting conditions [7]. The geometry of the imaged object needs to be defined in a manner that it can be picked up easily by a computer program amongst other objects (reflections, space between bubbles) in the overall image. The simplest shape is a circle–which is what we use here in order to illustrate the approach. The second approach (Section 4) deals with bubbles which are large enough to be deformed under gravity (several 100s of micrometres). In this case it is more adapted to squeeze them between two narrowly spaced glass plates, creating so-called bubble "pancakes". Using surface evolver simulations [8] (http://www.susqu.edu/brakke/evolver/evolver.html) of such squeezed bubbles, we show how their undeformed sizes can be determined from simple photographs using the same experimental set-up as for the small bubbles. I.e. both, small and large bubbles of a strongly polydisperse bubble mixture or foam can be measured simultaneously and in a fully automated manner.

2. Imaging properties of a bubble

A spherical bubble of radius R_B surrounded by a liquid acts like an inverse, spherical lens, i.e. like a diverging lens. As indicated in Fig. 1a (scheme not drawn to scale), an object of size R_L creates a smaller, virtual image of size R_C and of the same orientation between the lens and the focal point "f" of the bubble lens. Fig. 1b illustrates this effect by showing the example of the letter "R" on a bright, square-shaped background, imaged through three air bubbles in water (left image). On the right of Fig. 1b, the image of the same letter "R" is shown through three water drops in air. These images are created using the ray tracing software Studio Max (http://www.autodesk.com/, as explained in detail in [7]).

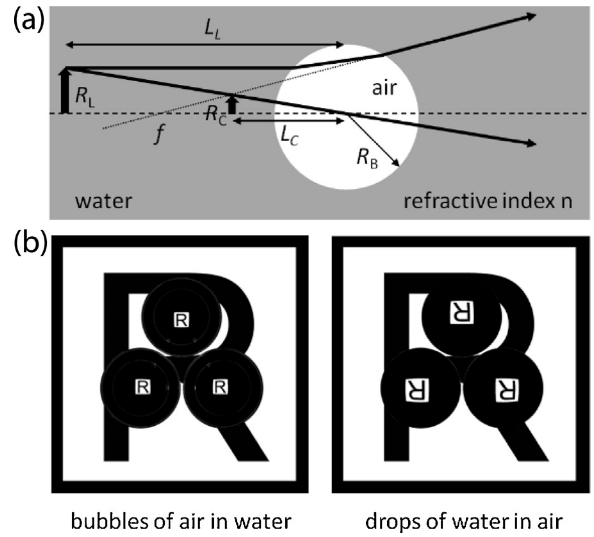

Fig. 1. A bubble in water creates virtual image of an object with the same orientation. (a) Image construction of an air bubble in water (scheme not drawn to scale). (b) Images of the letter "R" on a square background taken through three bubbles of air in water (left) or three drops of water in air (right).

The focal length f of a thick lens is given by

$$\frac{1}{f} = \frac{n-n'}{n'}\left(\frac{1}{R_1} - \frac{1}{R_2}\right) + \frac{(n-n')^2}{n'n}\frac{d}{R_1R_2}, \quad (1)$$

where R_1 and R_2 are the radii of curvature of either side of the lens and d is the thickness of the lens. n' is the refractive index of the lens, while n is the refractive index of the medium surrounding the lens. In the case of a spherical bubble $R_1 = -R_2 = R_B$, $d = 2R_B$ and $n' \approx 1$. Eq. (1) therefore simplifies to

$$\frac{1}{f} = 2(n-1)\frac{1}{R_B}. \quad (2)$$

This means, for example, that a bubble with radius $R_B = 100\ \mu m$ has a focal length of $f = 150\ \mu m$ for $n = 1.33$. Hence, the virtual image is generated very close to the bubble, which is practical for imaging purposes.

The relationship between the distance L_L (distance between the object and the centre of the bubble) and L_C (distance between the virtual image and the centre of the bubble) is related to the focal length f of the bubble by simple optics

$$\frac{1}{f} = \frac{1}{L_C} - \frac{1}{L_L}. \quad (3)$$

Moreover, we can relate those distances to the object and image size via simple geometry

$$\frac{L_L}{L_C} = \frac{R_L}{R_C}. \quad (4)$$

Equating Eqs. (2) and (3), and using Eq. (4) one finds the relationship

$$R_B = 2(n-1)L_L\frac{R_C}{R_L - R_C}. \quad (5)$$

Hence, knowing L_L and R_L, and measuring R_C, one can obtain R_B. One notices that if R_L is much larger than R_C (in our experiments $R_L \approx 1000R_c$), the relationship between R_B and R_C can be approximated by

$$R_B = 2(n-1)\frac{L_L}{R_L}R_C. \quad (6)$$