Colloids and Surfaces A: Physicochem. Eng. Aspects 509 (2016) 334–340

Contents lists available at ScienceDirect

Colloids and Surfaces A: Physicochemical and Engineering Aspects

journal homepage: www.elsevier.com/locate/colsurfa

Formation of antibubbles and multilayer antibubbles

Lixin Bai[a,*], Weilin Xu[b], Pengfei Wu[a], Weijun Lin[a], Chao Li[a], Delong Xu[a]

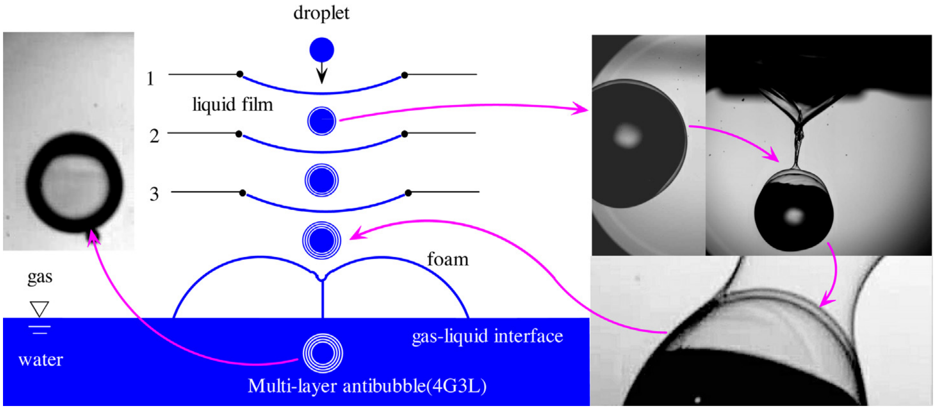
[a] Institute of Acoustics, Chinese Academy of Sciences, Beijing 100190, China
[b] State Key Laboratory of Hydraulics and mountain river Engineering, Sichuan University, Chengdu 610065, China

HIGHLIGHTS

- Multilayer antibubbles with 3 gas films and 2 liquid films were formed by liquid films and foams for the first time.
- The multilayer droplet on the gas-liquid interface can sink into the liquid becoming an antibubble.
- The authenticity of the existence of the multilayer antibubbles was verified.

GRAPHICAL ABSTRACT

By adding soap films between a falling droplet and a liquid pool, a multilayer antibubble can be generated. The complex hydrodynamic behavior was recorded by high-speed photography. The authenticity of the existence of the multilayer antibubble was verified.



ARTICLE INFO

Article history:
Received 4 May 2016
Received in revised form 5 September 2016
Accepted 11 September 2016
Available online 12 September 2016

Keywords:
Antibubbles
Foams
Bubbles
Liquid films
Drops

ABSTRACT

Soap bubbles and antibubbles are reversed-phase fluidic objects. A series of experiments were conducted in this paper to establish a link between soap bubbles and antibubbles. A new method was proposed to form antibubbles with the assistance of soap bubbles. The complex hydrodynamic behavior was recorded by high-speed photography. Multilayer antibubbles were formed by liquid films and foams for the first time. The authenticity of the existence of the multilayer antibubbles was verified.

1. Introduction

The soap bubble, as is well known to us all, is a thin spherical liquid shell with gas inside and outside. The soap bubbles floating in the air show brilliant colors in the sun because of interference of liquid film [1]. It is not so well known that a reverse phase construction may exist: the antibubble – a thin spherical gas shell containing liquid inside and surrounded by liquid outside. The antibubble floating in the water shows a thick black rim because of total reflection at the liquid – air interface [2]. Antibubble phenomenon was first reported by Hughes and Hughes [3] in 1932 and the term antibubble was coined by Stong [4] in 1974. Though several decades have

---

[*] Corresponding author.
E-mail address: blx@mail.ioa.ac.cn (L. Bai).

http://dx.doi.org/10.1016/j.colsurfa.2016.09.032
0927-7757/

passed since the antibubble was first reported and designated, few researches were conducted until this century on the formation [5–9], aging [10–13], collapse [14,15], stabilization [2,13,16,17], optical properties [18] and control [19,20] of antibubbles.

The formation of antibubbles is an important part and indispensable precondition of antibubble research and antibubble application (Many possible areas of their applications have been suggested [21]). An ordinary way to generate antibubbles is to gently drip or pour a small amount of the same liquid over the gas-liquid surface [14]. A gas film is formed around the liquid flow when separating the external liquid from the existing liquid. The liquid flow may break up due to the Rayleigh – Plateau instability. An antibubble will be formed from the breaking liquid flow under the effect of surface tension. This method was used by most researchers of antibubbles. Some minor improvements were also made to generate antibubbles, such as vibrating the nozzle and creating an oscillation in the incident jet [22], adding an electrical connection to prevent electrical potential difference due to triboelectric effects [2], and rationalizing several aspects of the optimal window in parameter space for creating antibubbles [8]. Other researchers developed totally different methods to generate antibubbles, such as bubbling method: to generate micron-sized antibubbles by capillary flow focusing [5], or generate millimeter-sized antibubbles by the coalescence between two bubbles [6]; and freeze-drying method: to produce antibubbles by first making a particle-stabilized water-in-oil-in-water emulsion, then freeze-drying to remove both the water and the oil, and finally reconstitute the resulting powder in water [20]; ultrasound method: in the ultrasonic field, oscillating contrast agent microbubbles may create a surface instability, and the re-entrant jet protrude into the gas bubble, leaving a droplet inside the bubble [7,9]. All of the above methods can not generate multilayer antibubbles. We coin the term 'multilayer antibubbles' to describe an antibubble with several gas films and several liquid films in the outer shell. Indeed there were reports of liquid onion (a droplet with several liquid films in the outer shell) [23], in which a liquid phase replaces the gas film. So the liquid onion is not antibubble. The major result of our paper is to propose a new method to form antibubbles and multilayer antibubbles. The generation of multilayer antibubbles will open up an interesting new area in the study of antibubbles.

2. Experimental

The experimental setup consists of the faucet, liquid films, foams, the high-speed imaging and illumination system, opto-electric switch, fixing and adjusting devices. We inserted liquid films and/or foam between the faucet and the gas-liquid interface. Droplets falling down from the faucet will hit through the liquid films and/or foam before sinking into the water and becoming antibubbles. The faucet and liquid films were mounted to the fixing and adjusting devices. Droplets falling down from the faucet will trigger the opto-electric switch, and then the high-speed photographer (Photron Fastcam SA-1, Photron Ltd., Japan) will record the process of antibubble formation. A rectangular plexiglass container (220 mm × 150 mm × 170 mm) is used to hold a mixture of tap water and linear alkylbenzenesulfonate (LAS) (about 10 times the critical micellar concentration (2.2 mM)). The liquid mixture and laboratory temperature are maintained at about 20 °C.

3. Results and discussion

Soap bubbles and antibubbles are present in the gas phase and liquid phase respectively, the thin shell is incompressible liquid and compressible gas respectively, and the orientation of surfactant molecules (hydrophilic head and their hydrophobic tail) is also the opposite. Few relationships were discussioned between the two fluidic objects except the reversation of physical properties and the similarity of structures. In fact, soap bubble and antibubble can transform into each other under certain condition (as shown in Fig. 1(a)). When the liquid film of a soap bubble (A) collapse, droplets (B) will be formed (surface energy of soap bubble converts into the kinetic energy of the liquid). When a droplet (B) drops on the gas-liquid interface, a globule (C) will be formed (potential energy converted into kinetic energy, then into surface energy). If the kinetic energy of the falling droplet (B) is large enough, the globule (C) will sink into the liquid and transform into an antibubble (D). The antibubble (D) may collapse due to the drainage of the gas and action of van der Waals forces [12], and bubbles (E) will be formed (surface energy of antibubble convert into the kinetic energy of the fluid). Bubbles (E) float to the interface and become foams (F) (potential energy converted into surface energy). The foams (F) can break away from surface under certain forces and become soap bubble (A) again. This is indeed a cycle, though some transformation needs additional energy and the volume will become smaller.

Soap bubble and antibubble exist in different phases; however, they still can interact with each other. Soap bubble is not spherically symmetric, but cylindrically symmetric. The lower part of the liquid shell is thicker than the upper because of gravity [1]. Imagine, if the lower part of the liquid shell infinite thickening, a soap bubble (A) will become foam (F). For the liquid film, there is no essential difference between them. Antibubble is not spherically symmetric, but cylindrically symmetric. The upper part of the gas shell is thicker than the lower because of buoyancy [2]. Imagine, if the upper part of the gas shell infinite thickening, an antibubble (D) will become a globule (C). For the gas film, there is no essential difference between them. So, the interaction at the contact point between foam (F) and globule (C) is actually the interaction between soap bubble (A) and antibubble (D). It is found that there is a multilayer structure at the contact point (1G1L, i.e. one gas film one liquid film, as shown in Fig. 1(b)). We introduce soap bubble (A) or foam (F) to the transformation process of droplet (B) to globule (C) (as shown the dotted curve with arrow in Fig. 1(a)). With the help of multilayer structure, we can generate antibubble and multilayer antibubble very easily.

3.1. Foam

When we generate antibubbles with traditional method (pouring liquid over the gas-liquid interface), it is required that no foam should appear on the surface [8]. As a result, overflow is used to keep the surface clean. A foam layer was produced on the surface deliberately in our experiment to generate antibubbles (as shown in Fig. 2(e); the diameter of the droplet is 0.8 mm–1.6 mm; the impact velocity of droplet is about 1.1 m/s.). As far as we know, this is the first report on the formation of antibubbles by foams. The formation process was recorded by high-speed photography.

It is found in our experiment that a multilayer structure (1G1L, i.e. one gas film plus one liquid film, as shown in Fig. 2(b)) is formed between the droplet and the foam when the droplet passes through the foam layer. The liquid film of foam bubbles is stretched, and the foam bubbles deformed slightly. The multilayer structure is well preserved without breaking up during the impact in most cases. Antibubbles are most likely to be formed when the droplets drop on the interface of two foam bubbles or on the plateau border.

Fig. 2(a–d) shows the schematic diagram of the process of a droplet passing through foams and generating an antibubble. Fig. 3 shows the high-speed photos of this process (the diameter of the droplet is 3.3 mm). It is found that the droplet is pushed toward the interface of two foam bubbles or plateau border by the foam bubbles when the droplet hits the foam (the impact velocity of the droplet is about 0.9 m/s, as shown point A in Fig. 3(d)) because foam bubbles tend to minimize the surface energy [24]. When the droplet