Chemical Engineering Science 116 (2014) 849–856

Contents lists available at ScienceDirect

Chemical Engineering Science

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

Mechanisms of fluidic microbubble generation Part II: Suppressing the conjunctions

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HIGHLIGHTS

- Microbubbles generated by percolation through an aerator grow in size by conjunctions.
- Conjunctions may be suppressed by oscillating the gas inlet flow.
- Suppression involves returning the bubble into aerator exit for a part of the cycle.

ARTICLE INFO

Article history:
Received 12 February 2014
Received in revised form
12 May 2014
Accepted 1 June 2014
Available online 12 June 2014

Keywords:
Bubble coalescence
Bubble conjunction
Fluidic oscillator
Flow reversal
Hybrid-synthetic jet

ABSTRACT

In the first part of this paper was demonstrated fact that microbubbles, because of their low ascent velocity, grow by repeated mutual conjunctions while they are still near their aerator exits. In this second part of the paper is shown that this undesirable growth may be avoided by a fluidic oscillator in the gas supply into the aerator. The oscillation leads to periodic sucking in and then expelling out water from the aerator channel during the two halves of the oscillation cycle—and moves back into the aerator exit during the suction half-cycle also the newly generated microbubble. This return prevents it from conjunction with the previously generated microbubble. In the subsequent half-cycle the inertia of water carries the microbubble (with surrounding water) sufficiently far away, out of the influence of the subsequent suction. As a result of the different motion directions, the two bubbles generated one after the other cannot get into a mutual contact—and thus remain small.

1. Introduction

1.1. Importance of microbubbles

Availability of efficiently generated microbubbles – bubbles of gas in a liquid of diameter less than 1 mm (but larger than 1 nm so that they are not confused with differently behaving nanobubbles Zimmerman et al., 2011; Prevenslik, 2014) – have recently led to developments in several areas of engineering that have been sometimes described as almost revolutionary.

(a) One such area is that part of chemical engineering, including biochemistry, in which operations depend on diffusion transport of gas into liquid. The large total collective surface of small microbubbles, together with slow ascent velocity (rapidly decreasing with size), can intensify the transfer rate substantially. Example that benefited from the use of microbubbles is transfer of oxygen into processed waste water (Terasaka et al., 2011) or delivering to unicellular algae in a bioreactor the carbon dioxide (Zimmerman et al., 2011) they need for photosynthesis.

(b) Important increase in effectiveness is offered by microbubbles also to separation of substances by flotation. By their strong clinging to contaminants like oil or grease they made possible their environmentally friendly removal from processed water. Microbubbles also exhibit a remarkable washing effect (Wataneabe et al., 2013) without chemical detergents. Xi (2012) discusses use of microbubbles to de-contamination of silicon wafers. Their yield losses over 50% are currently caused by micro-contamination removable by microbubbles. In fact, microbubbles were demonstrated (Tsuge et al., 2009) to even perform disinfection.

(c) In food industry microbubbles can extend shelf-life of products of foamy character – whipped cream, ice-cream, sorbets and mousses – in addition giving them interesting taste properties. Microbubble foam was demonstrated to remain stable for up to a year. Also of interest for food industry is water evaporation ability of microbubbles (Zimmerman et al., 2013) without the heat reaching the dried product.

(d) Hydrodynamic resistance of ships and boats may be reduced by air microbubbles. McCormick and Bhattacharyya demonstrated

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http://dx.doi.org/10.1016/j.ces.2014.06.006
0009-2509/

already in 1973 a 30% reduction in the frictional resistance (McCormick and Bhattacharyya, 1973). Lack of further progress was due to their method of generation of hydrogen microbubbles by electrolyzing, needing more energy than was saved. The problem of suitable microbubble generation at the required large scale plagued also other attempts, including those able to show reductions up to 80%—i.e. decrease to one fifth of original value (Bogdevich et al., 1977; Madavan et al., 1984). Recent ship tests with microbubbles are now already made with very large models (Madavan et al., 1984; Watanabe et al., 1998; Moriguchi and Kato, 2002), very near to practical use (such as Indonesian Navy fast patrol boat in Yanuar et al. (2012)). For process engineers may be interesting the analogous decrease of friction factor of flow in tubes (Pang et al., 2014; Shams et al., 2014).

(e) A wide spectrum of microbubble uses has been found in medicine. Microbubbles can convert energy of the ultrasonic vibration into a local thermal therapeutic effect (Kanagawa, 2013). Streaming effect on microbubbles in ultrasonic field can destroy cells (Kooiman et al., 2011) and can cause permeabilisation their membranes for drugs (Oh et al., 2014) in particular anti-cancer ones (Watanabe et al., 2008). Microbubbles also make possible measuring absolute blood pressure (Tremblay-Darveau et al., 2014).

(f) Many currently developed techniques of using microbubbles aim at microfluidic scale. A use was found in gene manipulation (Sun et al., 2014), biosensors (Kuznetsova and Coakley, 2007), mixing of reactants (Lee et al., 2012) or sorting (Wang, 2012). Important progress is expected in optofluidics, where ordered arrays of microbubbles can create tuneable optical components (Hashimoto et al., 2006; Allouch et al., 2014).

1.2. The task of microbubble generation

In view of this list of potential uses, there is no wonder that interest in microbubbles has been growing rapidly. This is demonstrated by the growth of annual output of scientific publications presented in Fig. 1—based on search in database provided by Scopus. Until recently, the progress was slowed down by low efficiency of available methods of microbubble generation, especially when demanded in large quantities. The critical requirements, as usual,

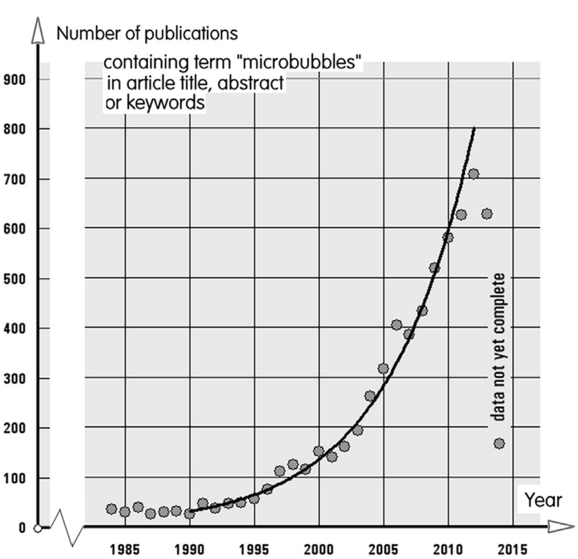

Fig. 1. Importance of microbubbles reflected in the exponential growth of interest. Until ~1990 the term was mentioned in publication titles at a constant rate of on average 30-times per year. Then the potential advantages became recognised and the papers on the subject now appear with doubling time 4.66 years.

are low const and reliability of microbubble generators. In many applications it is also desirable – considering the operation in humid environments and water presence – to avoid driving the bubble generators by electricity.

What seemed to be the simplest generation method – a direct continuation the standard method of percolating the gas through an aerator having a large number of parallel exit channels – was making the aerator exits small. This, however, was a failure. The bubbles obviously tend to grow far beyond the size of aerator exits. In tests of the applications listed in Section. 1.1 the microbubbles were mostly produced by ultrasonic generators. These are not particularly efficient and thus are likely to remain in use only in the medical and similar applications handling relatively small amounts of the two-phase mixture.

A promising new solution was recently found (Zimmerman et al., 2008) in using the aerator approach – but pulsating the supplied gas flow into the aerator. Especially promising is to use for the purpose a fluidic oscillator, with its many advantageous properties like robustness, low cost, long life, reliability, and operation without driving electric current – just using a small part of the supplied gas pressure. The main obstacle in designing the corresponding fluidic microbubble generation system has been the lack of understanding the mechanism of pulsatile microbubble formation. Without this knowledge was not possible e.g. a decision concerning the proper frequency and perhaps other properties of applied oscillation. There were some success cases but interspersed with disappointing generation of bubbles of no particularly small size. Initially, there were attempts at explaining the small size in the successful cases by bubble fragmentation caused by the pulsation. This was seen to be analogous to atomisation of droplets, well demonstrated in James et al., (2003). Closer studies, however, have shown the low effectiveness of such a mechanism – under the conditions prevailing in microbubble-producing demonstrations – made it quite unlikely. In particular, operating in the resonant frequency of the excrescences on the initial bubble surface would require a very high fluidic oscillator frequencies, of the order of kilohertzs. No such conditions were there in the cases of successful demonstrations. Also the size considerations opposed the explanation by fragmentation: the resultant fragment bubbles should be significantly smaller than the aerator exits, which also has not been the case.

In the Part I of the present paper are described author's recent experimental investigations the results of which have clearly shown that the reason for the generated microbubbles being much larger than they should have been is they are the result of a series of repeated conjunctions (phenomena sometimes known as "binary coalescence," a term actually an oxymoron, because in opposition to conjunction of two entities term "coalescence" is characterised by involving a growth from more than two objects).

1.3. Structure of the paper and its objectives

The growth of freshly made microbubbles by conjunctions at very small, sub-millimetre distances from the aerator exits was actually observed even with operating fluidic oscillator if the latter was imperfectly adjusted. The question thus remained what made so special those cases in which the microbubbles were demonstrably produced, either by the author himself or by other researchers, e.g. (Zimmerman et al., 2011, 2013). The obvious idea was that the oscillation generated by the fluidic oscillator somehow prevented the conjunctions to take place—at least avoiding some of the conjunctions that occur in the series.

The search for the mechanism suppressing the conjunctions is the main objective of the present paper. The method used was recording the microbubbles immediately after their formation by a high-speed camera. The following Section 2 discusses the origin of