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Minimising microbubble size through oscillation frequency control

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ABSTRACT

Microbubbles are bubbles below 1 mm in size and have been extensively deployed in industrial settings to improve gaseous exchange between gas and liquid phases. The high surface to volume ratio offered by microbubbles enables them to enhance transport phenomena and therefore can be used to reduce energy demands in many applications including, waste water aeration, froth flotation, oil emulsion separations and evaporation dynamics. Microbubbles can be produced by passing a gas stream through a micro-porous diffuser placed at the gas–liquid interface. Previous work has shown that oscillating this gas steam can reduce the bubble size and therefore increase energy savings. In this work we show that it is possible to further reduce microbubble size (and consequently maximise the number of bubbles) by varying the frequency of the oscillating gas supply. Three different microbubble generation systems have been investigated; an acoustic oscillation system and a mesh membrane, a fluidic oscillator coupled to a single orifice membrane and a fluidic oscillator coupled to a commercially available ceramic diffuser. In all three bubble generation methods there is an optimum oscillation frequency at which the bubble size is minimised and the number of microbubbles maximised. In some cases a reduction in bubble size of up to 73% was achieved compared with non-optimal operating frequencies. The frequency at which this optimum occurs is dependent on the bubble generation system; more specifically the geometry of the system, the type micro-porous diffuser and the gas flow rate. This work proves that by tuning industrial microbubble generators to their optimal oscillation frequency will result in a reduction of microbubble size and increase their number density. This will further improve gaseous exchange rates and therefore improve the efficiency of the industrial processes where they are being employed to produce bubbles, leading to a reduction in associated energy costs and an increase in the overall economic and energetic feasibility of these processes.

1. Introduction

Bubbling systems have regularly been employed in industrial processes in order to achieve gaseous exchange of both mass and heat from gaseous phases to the liquid phase and vice versa. More recently microbubbles have been shown to improve the efficiency of these gaseous exchange processes due to their higher surface area to volume ratio (Zimmerman et al., 2011a,b). Microbubbles can be generated by passing gas through a microporous diffuser at the gas–liquid interface or

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through other methods discussed in Zimmerman et al. (2011a). It has been shown that the gas pressure (and therefore energy input) required to do this can be significantly reduced if an oscillation is applied to the flowing gas stream prior to passing through the diffuser. Previous studies using oscillatory flow have shown improvement in topics such as microflotation (Hanotu et al., 2012), algal growth (Ying et al., 2013), wastewater aeration and treatment (Rehman et al., 2015) and oil-emulsion separations (Hanotu et al., 2013). Hanotu et al., used oscillated and non-oscillated air which showed a significant size reduction using oscillated air. This study reported reduction in bubble size from 1059 μm, using a steady air flow system, to 84 μm, with an oscillated air mechanism, using a diffuser with an average pore size of 38 μm (Hanotu et al., 2012).

Surface area to volume ratio has been long understood to be extremely relevant in processes involving heat and mass transfer (Bird et al., 2007). The higher the ratio, the better the performance of the system. If the radius of a bubble is halved bubble volume will be reduced to 1/8 its original value and the surface area reduced to 1/4 its original value. Therefore the transfer coefficients which are proportional to the surface area to volume ratio will be increased by a factor of 2. Therefore if bubble sizes are reduced, in turn the process efficiency is improved due to better heat or mass transfer (Zimmerman et al., 2008).

Microbubbles provide unique opportunities due to their ability to be manipulated photo-acoustically therefore providing manoeuvrability (Ashkin, 1997; Lauterborn and Kurz, 2010), lower rise velocity meaning greater residence time (Zimmerman et al., 2013) and have their ability to be used as sensors (Darveau, 2011). Small (<8 μm) microbubbles have other potential applications in medicine such as theranostics (Liu et al., 2006). The reduced buoyancy and size of microbubbles <8 μm means that they will not cause blockages in capillaries associated with larger bubbles. For most of these applications it is desirable to have a narrow size distribution. For example when applying photo-acoustic tweezing the microbubble manoeuvrability is size dependent, so having a narrow size distribution is hugely beneficial. For medical applications if a wider size distribution is generated the bubbles must be differentially centrifuged to select the desired size. This adds an additional process thereby increasing costs (Brodkey, 2004; Feshitan et al., 2009). Therefore there is considerable interest in being able to control and therefore reduce the size of microbubbles. In general being able to provide a narrow distribution of very small bubbles will result in increased efficiency and economics of the various processes that use microbubbles.

The first of the microbubble generating methods investigated here uses an acoustic speaker to oscillate the airstream before it flows through the diffuser. With this system it is very easy to explore a wide range of oscillation frequencies as the frequency is defined by the waveform played through the speaker. The two other microbubble generation systems use microfluidic devices known as a Tesar–Zimmerman fluidic oscillator (Jilek, 2013; Tesař, 2012; Tesař and Bandalusena, 2011; Zimmerman et al., 2011a,b, 2010) to generate the oscillation before the gas stream passes through two different diffusers, one with a single orifice and another with multiple orifices (mesoporous diffusers). The latter is most typical of the large scale microbubble generators being used in industry.

The Tesar–Zimmerman fluidic oscillator is a microfluidic device with no moving parts that creates a dynamic jet which alternates between two exit ports at a frequency determined by the feedback characteristics of the oscillator. This oscillatory flow is generated due to the adherence of the jet to one wall, caused by the Coanda effect, and its subsequent detachment and adherence to the opposite wall due to a switchover caused by pressure changes in the feedback loop. The gas stream from either or both of the exits can be passed through porous diffusers in order to engender microbubbles in an economical fashion. In this work a control loop has been used so that the operating frequency of the fluidic oscillator can be altered using this technique, which has been adequately described in Tesař and Bandalusena (2011). Clearly the orifice size in the microporous diffuser will play a significant role in determining the size of the bubbles produced (Clift et al., 1978). However, reducing the orifice size increases the pressure required to push the gas through the diffuser and therefore increases the energy requirements of the system. This shows that minimising the bubble size for a fixed diffuser geometry is of industrial relevance and highly beneficial if this results at no additional expenditure in energetics.

The motivation of this work was to investigate how bubble size varies as a function of oscillation frequency. From previous work (Zimmerman et al., 2011a,b, 2010, 2008) it is clear that applying an oscillation to the gas stream can help reduce bubble size and this was attributed to an increased rate of bubble ‘pinch off’ due to the oscillation. Three different microbubble generators are studied, exploring the size of the microbubbles generated as a function of the oscillation frequency when producing air bubbles in water. Exploring this relationship deepens the understanding of how to control microbubble production and therefore enables the required bubble sizes for their various industrial applications to be easily targeted economically. This work investigates if improvement is possible using three bubble generation systems all utilising oscillated gas flow streams. It is important to know how the frequency of the oscillating gas stream affects the size of the bubbles produced in order to further increase the impact of the oscillator on energy cost. This work investigates how frequency control affects microbubble generation using three different bubble generation systems.

2. Experimental methods

Three techniques to create bubbles using an oscillating airflow are used in this study. The oscillation mechanism and the diffuser type i.e. mesh, single orifice membrane or multi-orifice diffuser (at the air water interface) are varied in these 3 methods.

I. An acoustic oscillation system and a metal mesh membrane.
II. The fluidic oscillator coupled to a single orifice membrane via a bespoke visualisation rig.
III. The fluidic oscillator and a commercially available diffuser with an average pore size of 20 μm.

For each of these techniques the oscillation frequency is controlled and the effect on the bubble size is observed.