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Analysis of the velocity and displacement of a condensing bubble in a liquid solution

Philip Donnellan*, Edmond Byrne, Kevin Cronin

Department of Process and Chemical Engineering, University College Cork, Cork, Ireland

HIGHLIGHTS

- The absorption of steam bubbles in a hotter lithium bromide solution is tracked.
- A model is developed to describe the vertical translation of the collapsing bubbles.
- The developed model incorporates both deterministic and random bubble behaviour.
- The added mass force is the dominant force causing upward vertical motion.
- The model adequately describes the observed displacement randomness.

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ABSTRACT

The absorption of steam bubbles in a hot aqueous solution of Lithium Bromide is a key process that occurs in the absorber vessel of a heat transformer system. During the condensation process, their size and shape changes dynamically with time as they rise up through the column of liquid. An understanding of the factors that control the vertical upwards motion of the bubbles is necessary to enable proper design of such units. However, the exact vertical displacement of a bubble moving through a liquid is difficult to predict and becomes much more complex if the bubble is simultaneously collapsing. In this paper, the displacement of steam bubbles collapsing in a concentrated aqueous lithium bromide solution (LiBr–H_2O) has been quantified experimentally. A simple kinetic model predicting the vertical displacement as a function of time was then developed from elementary force–balance considerations. A key feature of the system is the large variability in the motion of the bubbles arising from extreme fluctuations in their size and shape. Bubble dynamic morphology was modelled with stochastic techniques and the output from this was used in the kinetic model to predict dispersion in bubble displacement with time. While the uncertainty predicted by the stochastic model is shown to be less than that observed experimentally, it nonetheless highlights the importance of this random behaviour during the design of such an absorption column.

1. Introduction

Absorption heat transformers and absorption chillers are devices primarily based upon the interaction between saturated water vapour (the dispersed phase) and a concentrated liquid salt solution such as aqueous lithium bromide (LiBr–H_2O) (Donnellan et al., 2013, 2014a, 2014b). This interaction is can potentially be achieved using bubble columns. In a previous study conducted by Donnellan et al. (2014c), the heat and mass transfer rates of such steam bubbles being absorbed in a LiBr–H_2O solution were examined experimentally. The paper developed a model describing the heat and mass transfer process, and demonstrated that these bubbles are prone to shape oscillations and deformations, leading to significant amounts of random behaviour. This unpredictability implies that significant variability exists within the system. In a design scenario, it is very important to be able to quantify this unpredictability, especially that associated with the vertical displacement of the bubbles as it impacts directly upon the required height of the bubble column.

The two phase flow of vapour bubbles moving through a liquid is a complex phenomenon that is encountered in many different areas of chemical engineering such as in biological reactors or in absorption columns. Often other phenomena may be connected to the bubble rise, such as a simultaneous chemical reaction or heat and mass transfer. Two conventional approaches to examine bubble motion are either theoretical analysis or numerical CFD techniques. Developing analytical solutions of such flow scenarios

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* Corresponding author. Tel.: +353 214903096.
E-mail address: p.donnellan@umail.ucc.ie (P. Donnellan).

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is extremely difficult however and generally relies upon assumptions such as negligible liquid viscosity or creeping flow conditions ($Re \rightarrow 0$) (Clift et al., 1978). While detailed analytical formulae developed under such assumptions are extremely useful from the perspective of gaining a better understanding of underlying principles, they do not generally apply to real world situations in which liquid viscosities or Reynolds numbers may be significant. More recently much work has been conducted examining such situations using detailed CFD simulation techniques (Krishna and Van Baten, 2003; Campos and Lage, 2000a, 2000b). CFD enables parameters such as the mass transfer rate, bubble size, velocity fields and gas hold-up to be investigated in addition to pure flow phenomena (Darmana et al., 2007; Wang and Wang, 2007; Lau et al., 2012). CFD also has the advantage of permitting detailed analysis of the influence of turbulence on bubble motion (Ekambara and Dhotre, 2010; Silva et al., 2012). Such detailed CFD approaches are extremely beneficial as they allow an insight into the complex processes which are taking place at the vapour–liquid interface and in the bubble wake.

The objective of this paper is to develop a model of the motion (velocity and displacement) of condensing steam bubbles in an aqueous LiBr solution. A large focus is on the randomness associated with this motion so that the mean and variance in displacement versus time can be predicted. As the system is very complex, a standard deterministic model of bubble motion is selected by making simplifying assumptions which allow basic but adequate descriptions of the process. Correct identification and quantification of the forces acting on a bubble is a prerequisite. Drag (Roghair et al., 2011) and lift (Dijkhuizen et al., 2010) force equations have been examined using DNS (Direct Numerical Simulation) techniques, while the importance of including the added mass, wake and history forces was demonstrated by Zhang and Fan (2003). To the authors' best knowledge no previous studies exist which examine the random behaviour of collapsing bubbles and therefore this paper investigates the unpredictability associated with the vertical displacement of steam bubbles being absorbed into a concentrated LiBr–H_2O solution. The model developed in this paper utilises probabilistic methods to predict the vertical displacement of the bubble as it collapses under the action of heat and mass transfer.

2. Theory

2.1. Bubble shape model

Solution of the differential equation of motion for bubbles requires prior knowledge of their size and shape (as both these parameters affect bubble inertia and bubble interaction with the continuous phase) and their dynamic evolution with time. The real bubbles of this study have a very complex morphology that does not conform to any standard geometry and moreover changes very significantly with time. They emanate from a sparger pipe, at the base of the column of liquid, with an approximately spherical shape, then, they become pronouncedly non-spherical before returning to an approximately spherical shape just before extinction. One approach to model the dynamic change in size and shape is to treat the bubble as being an oblate spheroid (Clift et al., 1978) which is an ellipsoid where two of the axes are the same length with semi-major axis, (a), while the third is shorter than the other two with semi-minor axis length, (b) (Fig. 1). For a bubble, the shortened axis is parallel to the motion direction. This approach permits shape variation to be explored without an excessive number of unknown degrees of freedom. A small residual amount of air is contained in these bubbles however which causes the collapse rate to decrease towards the end of the bubble's lifetime as discussed by Donnellan et al. (2014c). Once the bubble's volume reduces to a certain level, the volumetric fraction of air in the bubble begins to increase rapidly, decreasing the water concentration at the vapour–liquid interface and essentially causing mass transfer from the bubble to cease. This means that the bubble continues to travel at (almost) constant volume without any further absorption. As this study is examining the vertical displacement of a collapsing bubble, experimental data is used only up the point at which this air fraction becomes dominant (a_∞). In this context, a_∞ is the semi-major axis which remains constant with respect to time once the bubble collapse has effectively ceased. An example of a_∞ and its use in this study is given in Fig. 2. In this figure it can be seen that a_∞ is the final steady state bubble semi-major axis and that experimental data is used up to the point where the regressed line intersects a_∞.

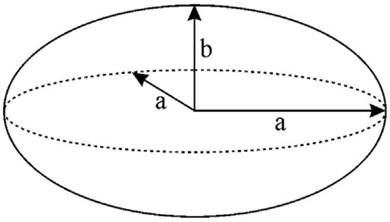

Fig. 1. Oblate spheroid bubble shape approximation.

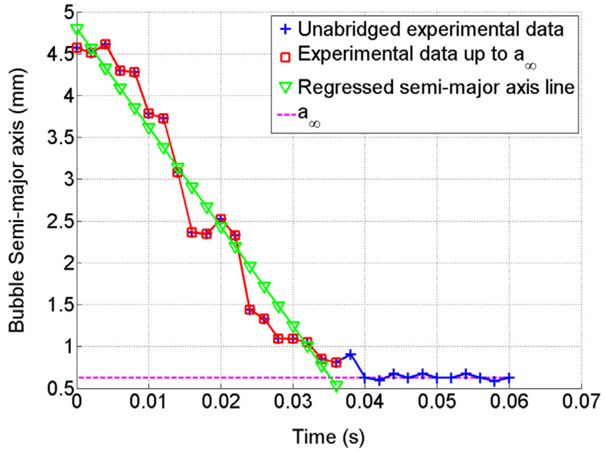

Fig. 2. Experimental bubble semi-major axis versus time for a bubble, highlighting the transition point at which the volumetric fraction of air in the bubble effectively causes mass transfer from the bubble to cease.

The aspect ratio, ρ, volume and vertically projected cross sectional area of the ellipsoid are

$$\rho = \frac{b}{a} \quad V = \frac{4\pi a^2 b}{3} \quad A_p = \pi a^2 \tag{1}$$

The steam bubbles are being absorbed into the lithium bromide solution as they flow vertically upwards, and therefore the magnitude of the bubble's semi-major axis is dependent upon the rate of heat and mass transfer from the bubble. Initially the bubbles have a characteristic dimension of between 4 and 5 mm and this falls down to 1 mm within ~0.1 s. For the purpose of this analysis (and as indicated by measured experimental data), it is assumed that the average rate of bubble collapse with time is approximately linear and therefore, a regression line can be drawn through the experimental data with slope, β_a (Fig. 2). This assumption of a linear rate of bubble collapse is made primarily based upon the collected experimental data, however it has also been demonstrated previously using a comprehensive theoretical approach by Donnellan et al. (2014c). The residual can be treated