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Evaporation dynamics of microbubbles ☆

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HIGHLIGHTS

- Direct contact microbubble evaporation always achieves 100% relative humidity.
- Vapour temperature *reduction* with contact time increase.
- Absolute humidity *decrease* with contact time increase.
- Practically isothermal operation with low contact times.
- Greater than 95% selectivity for vaporization over sensible heat transfer achievable.

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ABSTRACT

Until recently, generating clouds of microbubbles was a relatively expensive proposition, with the smallest bubbles requiring high energy density from either the saturation–nucleation mechanism or Venturi effect. Due to the expense of processing with microbubbles, exploration of the acceleration effects of microbubbles for physico-chemical processes are largely unstudied, particularly those that are combined effects. In this paper, the trade-off between heat transfer and evaporation on the microbubble interface are explored, largely by computational modelling but supported by some experimental evidence. The hypothesis is that both processes are inherently transient, but that during short residence times, vaporization is favoured, while at longer residence times, sensible heat transfer dominates and results in re-condensation of the initially vaporized liquid. The computational model address how thin a layer thickness will result in the maximum absolute vaporization, after which sensible heat transfer condenses the vapour as the bubble cools. This maximum vaporization layer thickness is estimated to be a few hundred microns, on the order of a few microbubble diameters at most. If the maximum vaporization estimate and the contact time necessary to achieve it are accurately estimated, these are engineering design features needed to design a vaporizing system to achieve maximum removal of vapour with minimum heat transfer. The modelling work presented here should be considered in light of the humidification experiments also conducted which showed the exit air at 100% saturation, but increasing gas temperature with decreasing layer height, and decreasing water temperature with decreasing layer height, all of which are consistent with the predictions of the computational model.

1. Introduction

Why do we boil liquid to create water vapour? There are three effects achieved by boiling: (i) provision of the latent heat of vaporization, (ii) raising the temperature of the liquid so that the temperature of the vapour that is in equilibrium rises, hence raising the saturation pressure of water vapor or the absolute humidity achievable, (iii) increasing the gas–liquid interfacial area so as to increase the rate of evaporation. So if the aim is vaporization, most of the applied heat is actually used to raise the water temperature, rather than to "pay" for the latent heat of vaporization and to raise the absolute level of humidity achievable. This is an unavoidable consequence of equilibrium.

Direct contact evaporators (DCE) using superheated bubbles sparged into bubble columns have been known for many years, with the first English patent in 1887, and have recently been reviewed by Ribeiro and Lage (2005). Commonly, DCE is industrially implemented with spargers made from perforated plates generating fine (1–2 mm diameter) to coarse (~1 cm diameter) bubbles in turbulent flow. One of the major advantages for DCE is sensible heat transfer, which is reported to achieve 95% efficiencies and only a 2–5 °C difference in temperature between the bubble

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phase and the liquid. DCE is widely adopted for concentration of aqueous solutions, but does have a well known issue with potential foaming to contend with.

This article addresses the question whether a radically different approach can achieve more vaporization by conducting the process far from equilibrium. Can the same objectives of boiling be achieved without heating the liquid to equilibrium? Rather than heat the liquid, why not heat the gas phase? Since $\rho\, c_p$ for water is 3 orders of magnitude larger than that for gas, it is possible to raise the gas temperature very high with the same quanta of heat energy. Introducing the gas phase as a uniform cloud of microbubbles (Zimmerman et al., 2008, 2009, 2011) which are nearly monodisperse, and hence non-convergent (see Fig. 1), should increase the gas–liquid interfacial area which is expected to accelerate both sensible heat transfer and evaporation rates, as the typical models for rate laws for these processes are proportional to gas–liquid surface area. But which molecular mechanism – sensible heat transfer or evaporation – is favoured with microbubble dynamics? Even if they are equally important, there should be an exploitable effect: with heating of the liquid phase in traditional, equilibrium based vaporization, very little temperature rise is achieved due to the ratios of liquid to gas densities and heat capacities, hence practically no vaporization will be achieved by a quanta of heat transferred to the liquid. If half of the quanta of heat is used for vaporization and half for sensible heat transfer to the liquid, substantially more vaporization is achieved. Given the three orders of magnitude greater $\rho\, c_p$ for water than gas, it is clear that even a few percent of the heat used for vaporization will achieve more than an order of magnitude more vaporization than that same quanta of heat transmitted to the liquid at equilibrium.

We have conducted preliminary experiments with microbubble heat transfer and vaporization that indicate that the absolute level of humidification is a controllable parameter, and varies significantly with the layer depth that the bubble rises through. Intuitively, one would think that the longer the residence time, the greater the vaporization achieved, as well as the greater the sensible heat transfer. This article addresses that "straw man" hypothesis and explains why the experiments achieve counter-intuitive control by varying the layer depth. The computational model is inherently transient, and demonstrates that transient operation, far from equilibrium, permits the selection for preferentially high absolute vaporization levels. It should be stressed that the purpose of the modelling is to characterize the contact time needed to achieve evaporation and heat transfer within the microbubble regime for design purposes, given that this is the first approach to the subject.

To our knowledge, these are the first experiments on humidification–dehumidification cycling by bubbles. However, two recent studies have considered coarse bubbles humidification–dehumidification dynamics: Narayan et al. (2013) builds on earlier experimental work (Narayan et al., 2011) but with bubbles of greater than 3 mm in size with heat transfer coefficients treated by correlation.

This paper is organized as follows. In Section 2, the numerical analysis is presented, along with computational modelling predictions for maximum humidification rates and residence times with maximum humidity. In Section 3, the only unknown modelling parameter, the microbubble heat transfer coefficient, is analyzed in respect of bubble column heat transfer/humidification experiments which motivated the numerical analysis. Section 4 holds the discussion and interpretation. In Section 5, conclusions are drawn and recommendations are proposed.

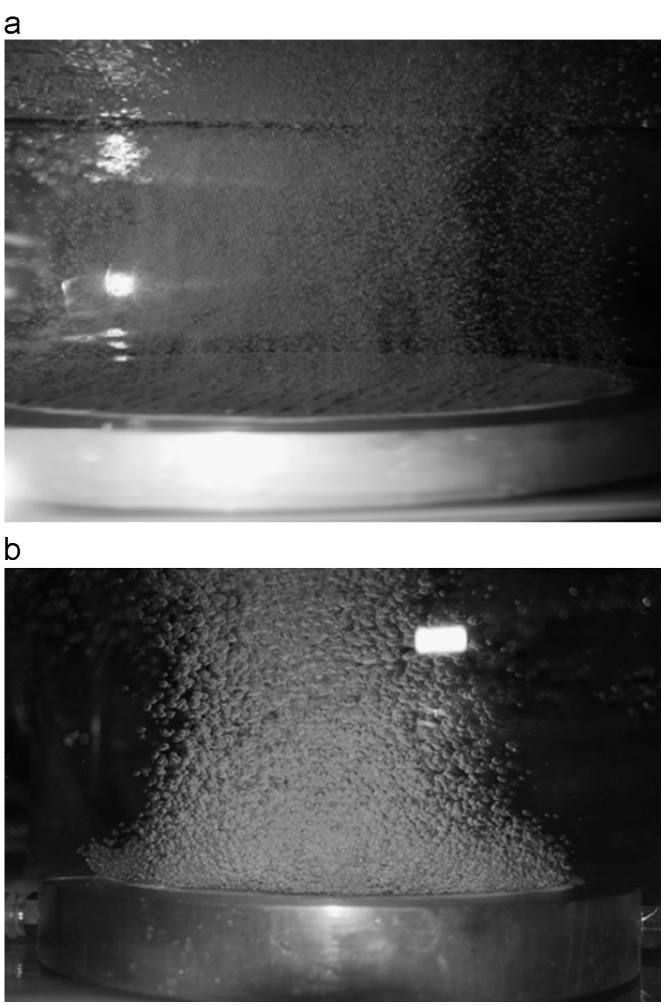

Fig. 1. Microporous diffuser with fluidic oscillation (a) and without (b) with nominally the same volumetric flow rate. The microbubbles are uniformly spaced and emerge at approximately the pore size with appropriately tuned oscillation frequency, and are therefore practically non-convergent. With steady flow, the bubbles emerge much larger and then, due to random release, coalesce with neighboring bubbles.

2. Model for evaporation from a rising microbubble

In this section we propose an idealized model based on imposed internal bubble flow with interfacial dynamics for heat and mass transfer treated phenomenologically, i.e. no external dynamics, which is appropriate for an isolated bubble or a dilute volume fraction of bubbles that are uniformly sized and spaced. This is intended as a single bubble model for the dynamics of fluidic oscillator induced microbubbles such as in Fig. 1(a). The previous models of superheated bubbles formed and rising in a direct contact evaporator by Campos and Lage (2000a, 2000b, 2001) do not take into account the internal gas dynamics of the bubble, so the model presented here can be considered complementary, as it uses phenomenological approaches to external dynamics and distributed system partial differential equations for heat and mass transport internally, with convection imposed. Ribeiro and Lage (2004a, 2004b) measured bubble size distributions in agreement with their formation and ascension model, demonstrating distributions larger than fine bubbles and into the coarse bubble regime. This model aims to treat submillimeter bubbles primarily.

2.1. Model equations

The modelling approach adopted here is to assume that all bubbles are sufficiently small that surface tension opposes deformation from a spherical shape, and that the time to achieve fully developed laminar flow is infinitesimally short after bubble