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The electrically induced bubble behaviors considering different bubble injection directions

Qinggong Wang *, Guang Zhang, Chao Wang, Rong Ma, Wei Yao *

Energy Conversion Research Center, Qian Xuesen Laboratory of Space Technology, China Academy of Space Technology, Beijing 100094, China

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ABSTRACT

The electrohydrodynamic (EHD) is an effective method to enhance boiling heat transfer in the terrestrial and space applications. To simplify the coupling effect of hydrodynamics and heat transfer processes, a varieties of adiabatic researches have been carried out recently, mainly for the upward surfaces. Actually, in industrial application, the boiling heat surface can be in any direction. The EHD effects on bubble dynamics on vertical surfaces and downward surfaces should be paid particular attention. In this work, a systematic experimental research was performed to study the effect of EHD on bubble behaviors considering the different bubble injection directions. A uniform DC electric field was applied to the testing zone with coarse bubbles generated from an orifice of 1.5 mm. Both the positive and negative directions of the electric field were considered in the measurement. The retarding effect of EHD on bubble detachment was demonstrated from the experimental results. This phenomenon was confirmed in all the three bubble injection conditions and was proved to be related to the bubble size by an extra experimental case. To explain the mechanism of the influence of electric field on the bubble dynamics, the main forces acting on the single bubble were analyzed qualitatively based on the evolution characteristics of the bubbles. The force distribution around the coarse bubble was proved to be in imbalance and the net force inhabited the bubble growth, prolonging the bubble detaching time.

1. Introduction

Heat transfer enhancement has been a hot topic due to the increasing requirement for large scale energy transportation loads and compact heat exchangers [1]. Over the past century, a series of enhancement technologies have been proposed, including passive methods [2–5] and active methods [6–8], depending on whether an extra power source is needed. Among the active methods, applying an electric field to a dielectric fluid has been proved an effective technique for enhancing heat transfer in nucleate boiling [9–13]. To explain the underlying mechanism of electrohydrodynamic (EHD) effect on heat transfer, a varieties of studies have been performed to demonstrate the influence of electric field on bubble behaviors in adiabatic condition [14–17]. Generally, the EHD effect on bubble behavior relates to the electrical force experienced by a dielectric fluid in the electrical field [18]. The electric force can be expressed by:

$$\boldsymbol{F}_{\mathrm{e}} = q\boldsymbol{E} - \frac{1}{2}E^2\nabla\varepsilon + \frac{1}{2}\nabla\left[E^2\left(\frac{\partial\varepsilon}{\partial\rho}\right)_{\mathrm{t}}\rho\right] \tag{1}$$

where q is the free charge density, ρ is the fluid density, E is the electric field intensity and ε is the dielectric permittivity of the fluid. The first term on the right-hand side of Eq. (1) is the electrophoretic force. This force originates from the net free charge within the fluid and can be ignored when the q is low. The second term is the dielectrophoretic force resulting from the non-uniform distribution of the dielectric permittivity in the electric field, e.g. at the interface of vapor phase and liquid phase. The third term is electrostrictive force caused by inhomogeneous electric field strength and variation of the electric permittivity.

As commonly reported in literature, the electric force affects both bubble deformation and detaching dynamics. Bubbles are elongated in the direction parallel to the applied electric field due to the non-uniform distribution of the electric force at the bubble surface [14–17]. On the aspects of bubble departure characteristics, Danti et al. [15] used a small orifice of 0.13 mm to generate adiabatic bubbles in the fluorinert liquid and found that the bubble detachment frequency was increased and the equivalent bubble diameter decreased with an increase of the electric voltage. Dong et al. [16] tested different sizes of the orifice and found that under

* Corresponding authors.
E-mail addresses: wangqinggong@qxslab.cn (Q. Wang), yaowei@qxslab.cn (W. Yao).

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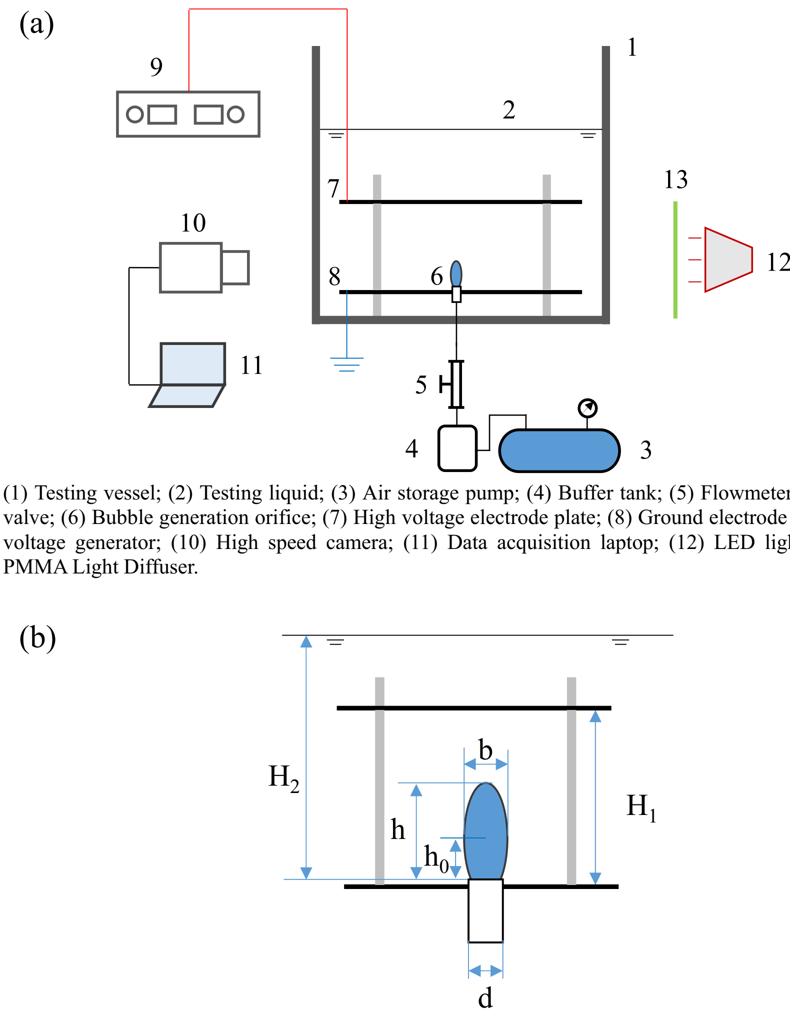

(1) Testing vessel; (2) Testing liquid; (3) Air storage pump; (4) Buffer tank; (5) Flowmeter with a control valve; (6) Bubble generation orifice; (7) High voltage electrode plate; (8) Ground electrode plate; (9) High voltage generator; (10) High speed camera; (11) Data acquisition laptop; (12) LED light source; (13) PMMA Light Diffuser.

H_1– Height between the two electrode plates; H_2– Height between the bubble generation surface and the liquid free surface; h– Visualized bubble height; b- bubble width.

Fig. 1. Schematic drawing of the experimental system. (a) Testing facility; (b) geometrical parameters used to describe the bubble dynamics.

Table 1
The liquid properties used in the experiment.

Parameters	Value
Density	960 kg/m^3
Viscosity	50 mm^2/s
Viscosity-temperature coefficient	0.59
Relative permittivity	2.7
Thermal conductivity	0.15 W/m K
Surface tension	20.8 mN/m
Dielectric Strength	>50 kV

the action of electric field, large bubbles break into smaller bubbles. The breakage and non-uniformity of the electric field induced local convection and turbulence underneath of the bubble. Bari and Robinson [17] examined the bubble growth from a 1.0 mm orifice in uniform DC electric fields using a finite element analysis, and found that the notable bubble deformation occurred when the EHD stress was close to the magnitude of the Young–Laplace stress.

Due to the positive action of EHD on bubble detachment as proved above, the electric field is seen to be a possible method to provide a force to replace buoyancy in microgravity. To demonstrate the EHD effect on bubble dynamics under the microgravity condition, Di Macro et al. [19] performed tests to study the detachment and motion of gas bubbles through an orifice of 0.1 mm using a dropshaft. It was found that the detachment volume was observed to be insensitive to the level of gravity for high electric field strengths. Under these conditions, the electric field can entirely replace the influence of gravity. But differently, Herman et al. [20] performed similar experiments using a larger orifice of 1.5 mm. They found that even if the electric field managed to detach the bubble in microgravity, the bubble volume was still ten times larger than that at earth gravity. They concluded that the electrically induced forces were not strong enough to completely substitute the buoyancy force.

As is evident above, the existing experiments are mainly performed for small bubbles generated from orifices no large than 1.0 mm. These small bubbles are found to be promoted to detach from the wall. However, researchers have also observed the retarding effect of EHD on bubble departure, leading to the controversy of promoting, retarding and having little effects on the bubble behaviors. Unfortunately, there is no studies clearly verify how the retarding effect occurs in detail. To the knowledge of the authors, the controversy may originate from the experimental observation on the big bubbles. Since the variation of bubble sizes are seldom