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An investigation of behaviours of a single bubble in a uniform electric field

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Abstract

The effects of a d.c. electric field on bubble behaviours such as bubble growth, deformation and detachment are investigated. The bubble behaviours are simulated experimentally and the electric force acting on bubble is calculated numerically. The results indicate that bubbles are compressed intensely by the horizontal component of the electric stress and elongated by the vertical component, thus prolate spherical bubbles in the direction of electric field are formed. The investigation shows that both the rate of bubble deformation and the contact angle increase with electric field strength. Under the action of the electric field at a certain voltage, a larger bubble normally breaks into smaller ones while departing from the wall. In addition, the effects of the EHD induced bubble behaviours on boiling heat transfer are discussed.

Keywords: Electrohydrodynamic (EHD); Bubble; Uniform electric field; Electric stress

1. Introduction

In recent years, many works on electrohydrodynamic (EHD) enhancement of boiling heat transfer have been carried out; the attractiveness of the EHD technique has been increasingly recognized by the heat transfer society [1]. In order to explain the mechanism of EHD-enhanced boiling heat transfer, much effort has been made to study bubble behaviours of nucleate boiling in the presence of an electric field [2–12]. Ogata and Yabe [2,3] carried out experimental and numerical studies of the EHD effect on nucleate bubbles; typically, in their numerical simulation [2], they defined the boundary condition of the electric field at the two-phase interface as $\mathbf{n}\cdot\nabla\phi = 0$. Cho et al. [4,5] performed numerical simulations and experiments to investigate the effect of uniform and non-uniform electric fields on a single bubble, respectively, and made the same assumption as Ogata and Yabe [2] did. However, as Karayiannis and Xu pointed out in [6,7], it is not reasonable to set the electric field strength E in the direction of normal to the sphere surface to be zero; an improved boundary condition was then applied in their papers [6,7]. On experimental visualisation, Madadnia and Koosha [8] demonstrated the behaviours of isolated bubbles in pool nucleate boiling in the presence of an electric field; and based on the visualisation, such parameters as bubble departure diameter, nucleation rate, and density of nucleation sites were studied. By applying a wire–wire electrode, a phenomenon that the bubble size was reduced by the imposing electric field was observed. Similar phenomenon has also been reported by Kweon et al. [9] and Marco and co-workers [10], respectively. The above studies suggested that a mutual interaction between the boiling fluid and the electric field leads to a change of the bubble dynamics on the heating surface and more fundamental studies on the mechanism of EHD-enhancement of nucleate boiling should be carried out.

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Nomenclature

a	major axis, m
b	minor axis, m
D	bubble deformation
E	electric field strength, MV m^{-1}
n	normal direction
r	length in radial direction, m
R	radius, m
T	electric stress, N m^{-2}
U_0	applied voltage, kV
z	length in axial direction, m

Greek symbols

γ	surface tension, N cm^{-1}
ε	permittivity, F m^{-1}
ε_0	permittivity in space, F m^{-1}
θ	angle, °
κ	relative permittivity
λ	thermal conductivity, W m^{-1} K^{-1}
μ	dynamic viscosity, Pa s
ρ	density, kg m^{-3}
ϕ	electric potential, kV

Subscripts

l	liquid
b	bubble
n	normal direction
x	horizontal direction
y	vertical direction

In the present study, we first focus on identifying the pure mechanical effect of applying the electric field on bubble apart from the general heat and mass transfer effects. Inert air bubbles are injected through an orifice into dielectric bulk liquid to establish an adiabatic two-phase condition. In such a way, visualisations for the effects of the electric field on bubbles' growth, deformation and detachment are realised experimentally. Moreover, in parallel with numerical analysis, the EHD effects of the bubble behaviours on boiling are discussed.

2. The experimental system and the procedure

A schematic diagram of the experimental system is shown in Fig. 1. The system consists of a test chamber made of tempered glass for visual observation, a high-voltage d.c. supply for maintaining the electric potential between the two parallel plate-electrodes immersed in the liquid, and a bubble generator.

The experiments are conducted in a rectangular glass chamber (540 mm × 400 mm × 300 mm) where the working fluid of tetrachloride (CCl_4) is filled. A high-voltage d.c. generator (Model EH50P2, Glassman Corp.) is connected to the flat copper electrode with positive polarity. The other copper plate is placed 8 mm apart from the upper surface served as the counter electrode and is connected to electrical ground. The two plate-electrodes have the same dimension of 400 mm × 280 mm. With this configuration, a uniform electric field is produced between the parallel electrodes.

Bubbles are formed from the orifices on the lower electrode. The orifices with different diameters of 0.5 mm, 1.0 mm, 1.5 mm, and 2.0 mm, respectively, are connected to a syringe through the silicon tubes. By screwing the lifter, the air in the syringe is injected into the bulk fluid to form a bubble. Since the flow rate of the air injected into the bulk fluid is sufficiently low, the pressure variations, inertia and viscous effects can be negligible.

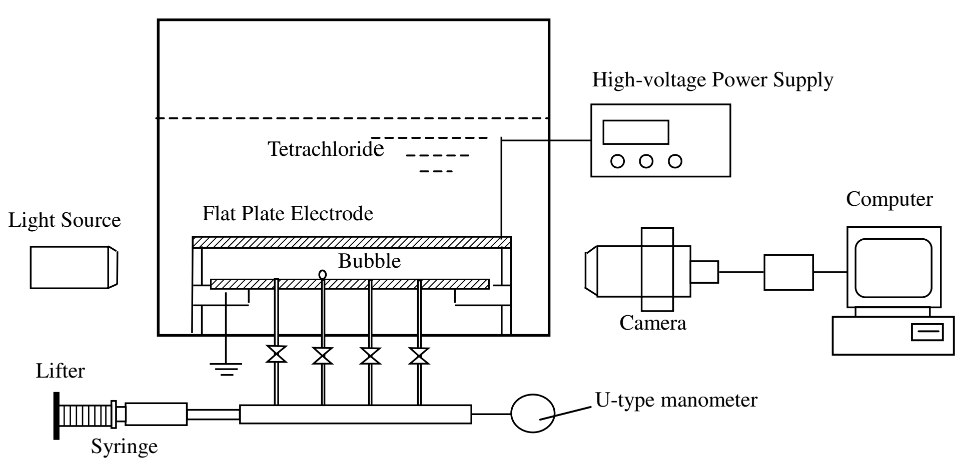

Fig. 1. Schematic diagram of the experimental apparatus.