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Lateral coalescence of bubbles in the presence of a DC electric field☆

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ABSTRACT

In this work, the influence of electrohydrodynamic forces on lateral bubble coalescence during nucleate pool boiling is investigated. An experimental pool boiling test facility was used with *n*-pentane as the working fluid. Boiling took place atop a polished copper surface on which two artificial nucleation sites were fabricated. The nucleation sites were 180 μm in diameter and 500 μm deep with a centre-to-centre spacing of 660 μm. Two diametrically opposed windows allowed for illumination and high speed videography of the bubble growth process from the two nucleation sites. For the saturated boiling tests considered here, bubbles only formed at the two artificial nucleation sites allowing their coalescence behaviour to be scrutinized. A screen electrode above the boiling surface and a high voltage DC power supply facilitated the establishment of the electric field which was varied between 0 and 34.5 kVcm^{-1}. Observation of the high speed videos has revealed that bubble coalescence is influenced in such a way that it is delayed in the presence of the electric field to such an extent that, at the highest electric field strength tested, it is avoided all together. To help explain the observed results, a simple numerical model is solved showing that bubbles in close proximity to one another create an electric field distribution with high intensity between them. The overall result is net polarization forces that push the bubbles apart, and the closer they are together the larger this repulsive force becomes.

1. Introduction

Electrohydrodynamics involves the interaction of electric fields with fluid flows and fluid structures. In the presence of an electric field, coulombic and/or polarization forces can be strong enough to influence the fluid mechanics in such a way as to significantly modify heat and mass transport properties. This is particularly true for two-phase systems where the near step change in thermodynamic and electrical properties across the interface can induce very strong EHD forces. This being the case, EHD has been considered as a technology to augment two-phase heat transfer [1,2].

Recent work has demonstrated the feasibility of EHD as a means of enhancement for both nucleate pool [3] and convective [4] boiling scenarios. These studies, amongst many others, demonstrate that the EHD forces interact with the growing and departing bubbles in such a way as to have a positive influence on heat transfer. Regardless, these boiling systems are complex to the extent that it is not possible to discern the exact mechanisms responsible for the augmented bubble dynamics and subsequent heat transfer purely by observation.

In efforts to better understand the EHD influence on bubble dynamics, some recent research has focussed on EHD on single isolated bubbles both in adiabatic [5–7] and diabatic [8,9] scenarios. Invariably, single bubbles are observed to be elongated in electric fields primarily due to inwardly acting compressive EHD forces caused by the presence of the bubble altering the electric field distribution in such a way that large electric field gradients exist in the region of the bubble equator [5–7, 9]. The change of shape of the bubble then alters the bubble dynamics by changing the nature of other mechanical forces acting on it [6] and, for boiling scenarios, changing the heat and mass transfer characteristics driving bubble growth and departure [8].

In most boiling systems of practical interest, bubbles grow and depart from naturally occurring nucleation sites distributed over the heated surface. Bubbles can thus interact with one another, whether by influencing each other's flow and thermal environment or by vertical and lateral coalescence. Regarding the latter, there has been a growing number of studies in the recent literature aimed at gaining a deeper understanding of the mechanics and heat transfer associated with lateral bubble coalescence [10–13]. Using spatially resolved thermal measurements, refs [12,13] have shown that bubble coalescence events have very unique heat transfer characteristics compared with those associated with isolated bubbles. This would then suggest that any technique that can influence bubble coalescence would also influence the heat and mass transport characteristics of nucleate pool boiling.

As discussed, EHD forces are known to affect the growth dynamics of single bubbles since their physical presence changes the electric field distribution in such a way as to create regions of high electric field intensity at their interfaces. It would stand to reason that the growth and coalescence behaviour of neighbouring bubbles will also

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Nomenclature

d	Distance between bubbles, m
E	Electric field intensity, Vm^{-1}
E_o	Uniform electric field intensity, Vm^{-1}
f_s	Surface electric stress, Nm^{-2}
H	Height, m
h	Height of centre of curvature, m
n	Unit normal vector, –
R	Radius, m
t	Time, s
ΔT_w	Wall superheat, K
U	Voltage, V
x	Lateral horizontal coordinate, m
y	Transverse horizontal coordinate, m
z	Vertical coordinate, m
ε_o	Permittivity in vacuum, Fm^{-1}
ε_r	Relative permittivity, –

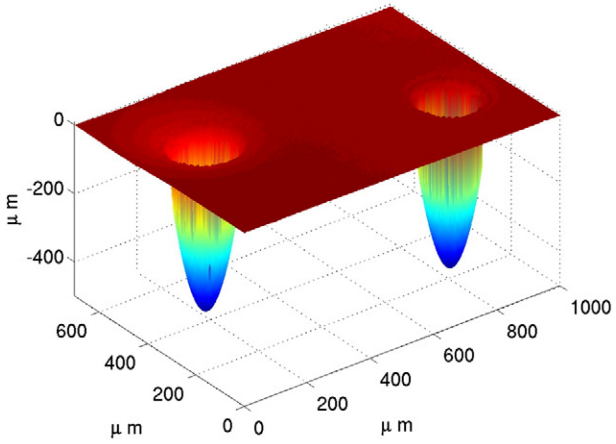


Fig. 2. Geometry of nucleation sites obtained by measured with a confocal microscope.

be affected in the presence of electric fields due to their combined influence on the electric field distribution. However, to the best of our knowledge there does not at present exist a study in the open literature aimed at understanding the influence of electric fields on neighbouring bubble growth dynamics.

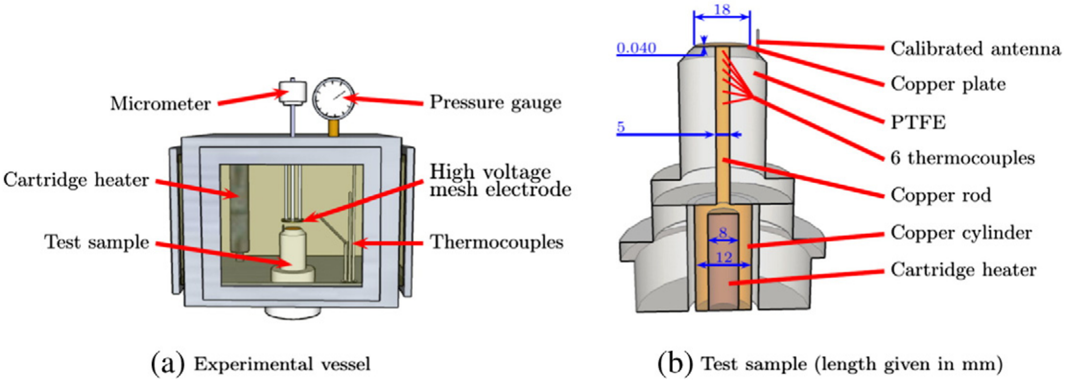
The above being said, the overarching objective of this investigation is to provide a preliminary understanding of the influence of electric fields on the dynamics of bubbles growing in close proximity to one another during nucleate pool boiling. Specifically, the study aims to perform experiments that facilitate the observation of neighbouring bubble dynamics during field-free nucleate boiling as well as boiling within electric fields of increasing field strength. Following this, a straightforward theoretical analysis is performed to elucidate the influence of EHD on neighbouring bubbles with the aim of providing a physical explanation for the behaviour observed in the experiments.

2. Experimental apparatus

The experimental apparatus used in this investigation is shown in Fig. 1. It has been described in earlier studies [8–10] so only the salient features will be discussed here for conciseness. The apparatus, shown in Fig. 1a, consists of a sealed 250 mm × 250 mm × 180 mm vessel containing 99% pure *n*-pentane. To facilitate observation and high speed videography within the vessel, the vertical faces of the vessel were equipped with rectangular windows which were sealed to the main housing of the tank. Pressure and temperature gauges along with an immersed heater controlled the thermodynamic state such that experiments were performed at saturation conditions at atmospheric pressure.

Boiling took place atop the metered heater element illustrated in Fig. 1b. The heater element was situated in the centre of the vessel with the upper surface nominally 100 mm below the vapour–liquid free surface. The heater element was constructed from a 12 mm diameter solid copper cylinder with the lower end machined to receive a 300 W cartridge heater. In order to increase the axial heat flux as well as reduce the overall heat transfer area at the exposed end of the heater element, the upper portion of the copper rod was reduced to a diameter of 5 mm. The upper portion of the thinner copper pin section was equipped with six K-type thermocouples to monitor the axial temperature distribution such that the heat flux and wall superheat could be measured. The boiling surface consisted of a 40 μm thin and 18 mm diameter copper sheet which was soldered to the top surface of the copper pin section. The plate was mirror polished to eliminate potential nucleation sites on its surface. Two artificial nucleation sites were then created by mechanical indentation of a tungsten carbide needle. The geometry of the nucleation sites have been measured with a confocal white light microscope and are depicted in Fig. 2. As shown, the indentations are nearly identical in shape and form 500 μm deep parabolic cavities with diameters of 180 μm. The centre-to-centre spacing of the nucleation sites was 660 μm.

In order to generate strong DC electric fields in the vicinity of the boiling surface, a brass screen mesh electrode was fixed 8.7 mm above the boiling surface and arranged parallel to the surface, as depicted in Fig. 1a. The electric field within the working fluid was generated by placing a voltage potential between the electrode and the boiling



(a) Experimental vessel (b) Test sample (length given in mm)

Fig. 1. Experimental facility.