Aqueous ionic liquid solutions for boiling heat transfer enhancement in the absence of buoyancy induced bubble departure

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ABSTRACT

Advantage of high heat transfer during boiling is lost due to the absence of buoyancy induced bubble departure in space. Absence of bubble departure with pure water on an inverted heater in earth gravity ($-1g$) resembles boiling behavior in space and is often used to mimic zero-gravity ($0g$) boiling experiments on earth. Here we perform experiments on an inverted heater to show that unlike water, the aqueous solution of surface active ionic liquid (IL) avoids coalescence to form multiple small bubbles with significantly large wet area on the heater surface. The force of repulsion due to the interaction of ILs adsorbed at the liquid–vapor interface of neighboring bubbles induces a completely passive bubble departure away from the inverted heater surface against the combined effect of buoyancy and surface-tension. Resulting rewetting of the heater surface increases the critical heat flux (CHF) to $\approx 950 \, \text{kW/m}^2$, which is an enhancement of $\approx 4.5\times$ in comparison to pure water. Effect of bulk liquid sub-cooling and concentration on pool boiling CHF are extensively investigated. The mechanism of CHF is explained with the help of the adsorption dynamics of IL at the solid–liquid and liquid–vapor interface of bubbles.

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1. Introduction

Boiling heat transfer is fundamental to many household processes and industrial applications such as cooking, water purification, chemical processing, thermal management of electronics, refrigeration and air conditioning, and cryogenic fuel storage [1–4]. The relatively high heat transfer during boiling is usually attributed to the ebullition cycle which comprises of bubble nucleation, growth, buoyancy-induced bubble departure, and rewetting of the heater surface in a cyclic manner (Fig. 1a) [5,6]. Ebullition cycle, which strongly depends on gravity, is absent in space ($g \approx 0$) [7–12], and, on an inverted heater in earth gravity ($-1g$) [13–15] where buoyancy opposes bubble departure. In the absence of bubble departure, nucleating bubbles coalesce together to form a big primary bubble and cover the entire heater surface (dry patch in Fig. 1b and c) which abruptly increases the heater surface temperature and results in a premature critical heat flux (CHF).

A summary of the studies in literature with pool boiling data in microgravity ($g \approx 0$) and on an inverted heater in earth gravity ($-1g$) is shown in Table 1. The CHF data in $0g$ and $-1g$ are compa-

rable and significantly lower than the CHF ($\geqslant 1000 \, \text{kW/m}^2$ [1]) in earth gravity ($1g$). Accordingly, much of the research in this field is focused on devising innovative strategies to induce the bubble departure to resemble the typical ebullition cycle in $1g$ and improve boiling heat transfer in $0g$ and $-1g$. For example, use of active approaches such as acoustic field [16] and electric field [17] have been proposed in the literature to facilitate the bubble departure by applying external body forces on the bubble. However, such strategies make the overall system complex, energy intensive, and less reliable. It is probably due to these limitations that despite the high latent heat of vaporization, thermal management of spacecraft, except for the heat pipe [18], is usually based on the single-phase cooling systems which rely on the low sensible heat of the fluid. However, the size and power requirements of typical space platforms are on an ever-increasing trend and the need for developing advanced cooling strategies based on boiling are increasingly realized [19].

We recently demonstrated (S.N. 6, Table 1) a completely passive mechanism of bubble departure against buoyancy on an inverted heater setup where both surface-tension and buoyancy forces act upwards ($\uparrow$) and push bubbles towards the heater surface [15]. In comparison to water where bubbles gradually coalesce together to form a large dry patch on the heater surface, surfactant additives were shown to avoid bubble coalescence and form multiple smal-

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Nomenclature

C	concentration (mol/l)
D	bubble diameter (m)
D^*	diffusion coefficient (m^2/s)
F_B	buoyancy force (N)
F_S	surface-tension force (N)
h	heat transfer coefficient (kW/m^2 K)
q''	heat flux (kW/m^2)
T	temperature (°C)

Greek symbols

σ	surface-tension (N/m)
Γ	surface concentration (mol/m^2)
τ_D	time-scale of diffusion (ms)

Subscripts

sat	saturation
sub	subcooling
sup	superheat

Abbreviation

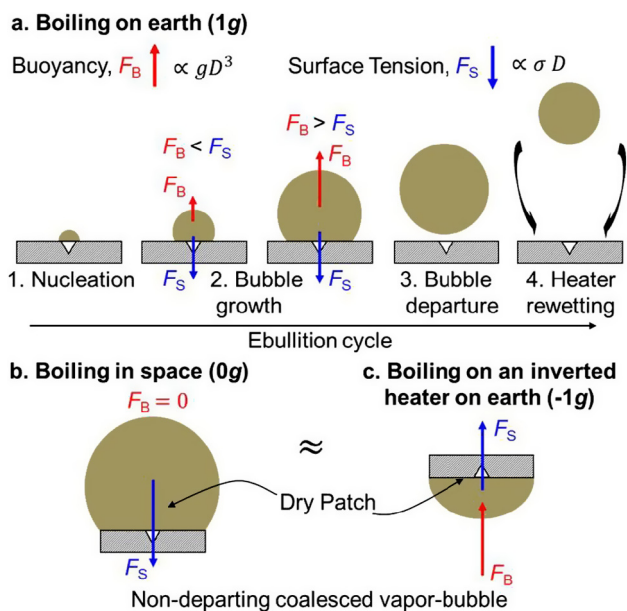|	
CHF	critical heat flux
HTC	heat transfer coefficient
IL	ionic liquid
ppm	parts per million
SAIL	surface active ionic liquid

Fig. 1. (a) Boiling with water in earth gravity (1g). Buoyancy induced bubble departure is observed. Ebullition cycle is present. (b) Boiling with water in space (0g), (c) Boiling with water on an inverted heater in earth gravity (−1g). Ebullition cycle is absent, in the absence of buoyancy induced bubble departure, coalesced big vapor-bubble covered the entire heater area.

ler non-coalescing bubbles. These bubbles not only reduced the dry patches on the heater surface but were also observed to depart downwards away from the inverted heater surface (↓), even against the combined effect of buoyancy (↑) and surface-tension force (↑). Bubble departure frequency of $\approx 15-16$ Hz resulted in $\approx 2.4\times$ enhancement in both the CHF and the heat transfer coefficient (HTC), in comparison to the pure water.

In this work, we use surface active ionic liquid (SAIL) 1-butyl-3-methylimidazolium octyl sulfate ([BMIM][OS]) as additive in the base fluid (water) for further heat transfer enhancements in the absence of buoyancy induced bubble departure. Ionic liquids (ILs) are mostly non-volatile, non-flammable, and thermally stable organic salts entirely composed of ions. Some ILs are also biodegradable [20,21]. Molten potassium chloride is an IL; whereas a solution of potassium chloride in water is an ionic solution. These salts (e.g. KCl or NaCl) need to heat to several hundred degrees to melt. The term 'ionic liquid' was selected with due care since the phrase 'molten salt' made an imperfect image of these solvents

as being high temperature and corrosive media. However, in reality, ILs show wide liquidous temperature range [21,22]. They have many applications in areas of science and technology, such as, in the absorption refrigeration system [23,24], heat exchangers [25], lubrication [26], space propulsion [27], stabilization of metal nanoparticles [28,29], chemical industry [21], electrochemistry [30,31], nanotribology [32], and in separation science [33,34], among others.

ILs with surface active properties are called SAILs. Many of these SAIL molecules are generally amphiphilic in nature and researched as a suitable alternative to surfactants for various applications [35]. For example, bubbles in an aqueous solution of such ILs avoid coalescence to form vapor foam, very similar to the aqueous surfactant solutions. Here we use an amphiphilic SAIL as an additive in water to avoid bubble coalescence and improve the boiling heat transfer performance in the absence of bubble departure during pool boiling on an inverted heater in earth gravity. Subcooled pool boiling experiments were performed with aqueous IL ([BMIM][OS]) solution, aqueous surfactant (SDS) solutions, and pure water on an inverted heater in earth gravity. We illustrate that [BMIM][OS] avoids coalescence significantly to induce bubble departure in excess of 30 Hz which is almost twice in comparison to SDS. The twofold enhancement in departure frequency is attributed to the relatively small value of the time-scale of diffusion in comparison to aqueous SDS solution. Experimental results on the effect of concentration of IL/surfactant on CHF reveal that the mechanism of CHF is dictated by the adsorption dynamics at both, the solid–liquid, and, the liquid–vapor interfaces. A maximum heat flux of ≈ 950 kW/m^2 was dissipated at an optimum concentration of CMC/64 of [BMIM][OS].

2. Experimental facility

2.1. Solution preparation

As received SAIL 1-butyl-3-methylimidazolium octyl sulfate ([BMIM][OS]) (Sigma Aldrich, purity $\geqslant 95\%$) and surfactant Sodium Dodecyl Sulphate (SDS) (Sigma Aldrich, purity $\geqslant 98.5\%$) were used in this work. The critical micelle concentration (CMC) of [BMIM][OS] and SDS are $\approx 10,000$ ppm and ≈ 2500 ppm, respectively. The test fluids (aqueous solution of [BMIM][OS] and aqueous solution of SDS) were prepared in a separate container (other than the test container) by adding the required concentration of [BMIM][OS] and SDS in pure water (Milli-Q, Merck). The test fluids were then stirred properly with the help of a magnetic stirrer for two hours to allow proper mixing of [BMIM][OS]/SDS in water.