



Surfactant aided bubble departure during pool boiling

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ARTICLE INFO

Keywords:
Surfactants
Pool boiling
Bubble departure
Orientation

ABSTRACT

The cyclic process of bubble nucleation, growth, departure, and rewetting of the heater surface is a typical sight during boiling. Early bubble departure at smaller sizes is known to improve boiling heat transfer. The passive strategy of addition of small amount of surfactant additives in water is a widely used technique in this regard. While several bubble departure models for pure fluid are present in the literature, they overestimate the bubble sizes during boiling with aqueous surfactant solutions. In this work, we perform pool boiling experiments at various heater orientations to elucidate the role of a lesser-known force of repulsion on bubble departure diameter. The same force was recently shown to facilitate bubble departure away from an inverted heater surface, even against the combined effect of surface tension and buoyancy. We perform a simple force balance analysis to demonstrate that this force originates from the repulsion between the surfactants adsorbed at the liquid-vapor interfaces of the thin liquid-film contained between neighboring bubbles. We show that this force is strong enough to facilitate early bubble departure from an upward facing heater, even at very small bubble sizes where buoyancy is negligible in comparison to the opposing forces of surface tension and drag. We further confirm the importance of this force during near-saturated boiling on vertical facing heaters, where surfactant-laden bubbles depart horizontally away from the heater surface, unlike boiling with pure water, where buoyancy simply slides the bubbles up along the heater surface. We believe that the new physical insights on bubble dynamics provided in this study are critical for heat transfer enhancements during boiling with aqueous surfactant solutions.

1. Introduction

Boiling is a liquid-vapor phase change phenomenon which utilizes latent heat of vaporization to dissipate large heat fluxes within small temperature differences. It is an efficient mode of heat transfer and is widely used in various applications such as cooling of electronic components, thermal and nuclear power plants, chemical and petrochemical industries, cryogenic fuel storage, and refrigeration and air conditioning [1–4]. The combination of bubble nucleation, growth, departure/removal, and rewetting of the heater surface in a cyclic manner is known as ebullition cycle and primarily governs the heat transfer during boiling [5]. Faster ebullition cycle, i.e., early bubble departure at smaller bubble sizes, is known to improve boiling heat transfer coefficient (HTC) [6].

Several enhancement strategies (both active and passive) have been investigated to improve the boiling heat transfer performance beyond the conventional limits. The active techniques such as ultrasonic vibrations [7], electric field [8], and acoustic field [9], among others, require external power to enhance the heat transfer, thus making the overall system bulky and energy inefficient, and are not suitable for high energy-to-mass ratio applications [10]. Techniques such as

wettability improvements via heater surface modifications [11], extended surfaces [12], treated surfaces [13], and additives in fluid [14] are other widely used passive strategies for boiling heat transfer enhancement. Among these, use of surfactant additives in water is a relatively easy approach to enhance nucleate pool boiling HTC in comparison to pure water [15–27] (Table 1).

Addition of small amount of surfactants in water is primarily known to reduce the surface tension and facilitate early bubble departure. In addition, surfactant monomers also adsorb at the solid-liquid interface (heater surface) to increase the nucleation site density. While both of these mechanisms are known to improve the HTC [15–18], the increase in HTCs are often so large that they cannot be attributed to these mechanisms alone [19–22] (Table 1). Furthermore, while many studies often report that the bubble departure during boiling with aqueous surfactant solutions happen at much smaller sizes [17,24,25], simple force balance analysis shows that even after accounting for the reduction in surface tension due to the adsorption of surfactants at the liquid-vapor interface, and the increase in contact angle due to the adsorption of surfactants at the solid-liquid interface, buoyancy is insufficient to overcome the opposing force of surface tension at such smaller sizes.

We recently [26,27] (S. N. 12, Table 1) reported the use of aqueous

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Nomenclature			
C	concentration (mol/l)	σ	surface tension (N/m)
C_p	specific heat (J/kgK)	α	thermal diffusivity (m ² /s)
C_D	coefficient of drag	θ	contact angle (°)
D	bubble diameter (m)	Π	disjoining pressure (Pa)
D^*	diffusion coefficient (m ² /s)	Γ	surface concentration (mol/m ²)
F_B	buoyancy force (N)	τ_D	time-scale of diffusion (ms)
F_D	drag force (N)	<i>Subscripts</i>	
F_I	inertia force (N)	avg	average
F_{Net}	net departure force (N)	d	departure
F_R	force of repulsion (N)	l	liquid
F_S	surface tension force (N)	max	maximum
f	bubble departure frequency (Hz)	min	minimum
H	liquid-film thickness (nm)	sat	saturated
h	heat transfer coefficient (kW/m ² K)	sub	subcooling
h_{lv}	latent heat of vaporization (J/kg)	sup	superheat
k	thermal conductivity (W/mK)	v	vapor
m	mass of the vapor bubble (kg)	w	surface
q''	heat flux (kW/m ²)	<i>Abbreviation</i>	
R	bubble radius (m)	CHF	critical heat flux
T	temperature (°C)	DF	downward facing
x	horizontal distance from the heater (m)	HTC	heat transfer coefficient
<i>Greek symbols</i>		ppm	parts per million
ρ	density (kg/m ³)	UF	upward facing
μ	dynamic viscosity (Ns/m ²)	VF	vertical facing

surfactant solution as a robust passive technique to depart bubbles away from a downward facing heater surface. We also developed a model to demonstrate that the force of repulsion resulting from the interaction of surfactants adsorbed at the neighboring liquid-vapor interfaces of the thin liquid-film contained between bubbles overcomes the combined effect of buoyancy and surface tension to aid bubble departure. This repulsive force is fundamentally similar in nature to that responsible for the stability of foams against coalescence, and is only dependent on the type of aqueous surfactant solution used. Hence, this force should be present during boiling at other heater surface orientations as well, and may explain the puzzling trends of bubble departure diameter and HTC during boiling with aqueous surfactant solutions on upward facing heaters. However, we could not find any reference to such a repulsive force in the existing literature on boiling with aqueous surfactant solutions.

In this work, we investigate the role of this lesser-known force of repulsion on bubble departure during pool boiling with aqueous surfactant solutions on upward facing heaters. The significance of this repulsive force in comparison to buoyancy, which also aids bubble departure on an upward facing heater, is estimated and compared with those during boiling on a downward facing heater [26]. Using a simple force balance, we show that this force of repulsion is strong enough to induce bubble departure at very small sizes where buoyancy alone is not sufficient to remove bubbles away from the heater surface. The presence of this force is further confirmed by the fact that while water vapor bubbles slide up (due to buoyancy) along the heater surface on a vertical facing heater, bubbles in aqueous surfactant solutions depart perpendicularly away from the heater surface, and that too at much smaller sizes where buoyancy is significantly smaller than the surface tension. Maximum bubble departure frequency of the order of ≈ 25 Hz and HTC enhancement of $\approx 30\%$ in comparison to pure water was observed on upward and vertical facing heater orientations. We believe that the inability to account for this force in the models are primarily responsible for unexplained bubble departure diameter and HTC trends in literature [19,20] (Table 1).

2. Experimental facility

2.1. Solution preparation

As received water soluble surfactants (Sigma-Aldrich), namely, Sodium Dodecyl Sulphate (SDS, CAS Number 151-21-3) and Dodecyltrimethylammonium Bromide (DTAB, CAS Number 1119-94-4) were used in this work. SDS is anionic whereas DTAB is cationic in nature. The critical micelle concentration (CMC) of SDS and DTAB at room temperature were ≈ 2500 ppm and ≈ 4620 ppm, respectively. The beaker was cleaned with acetone and properly rinsed with water before preparing the aqueous surfactant solution. The test fluids were prepared by adding required weight of SDS and DTAB in deionised (DI) water. The test fluids were stirred properly with the help of a magnetic stirrer for two hours and stored for one day prior to each run. Please note that the physical properties of pure water (except for the surface tension) are not altered significantly by surfactant additives used in this work [20,28–30].

2.2. Experimental setup

The sectional view of the three-dimensional computer-aided design model of the experimental setup used for performing pool boiling experiments on the upward facing heater configuration is shown in Fig. 1. Experimental setup consists of a transparent cylindrical glass enclosure which contains the test fluid and the heater assembly. Silicon cloth heater was wrapped around the enclosure to maintain the subcooling of the bulk fluid with the help of a thermocouple T_1 and a PID (proportional integral derivative) temperature controller. The enclosure was kept open to ambient resulting in gas saturated condition.

While a similar setup was used in our previous work [26], here we used a stepped aluminium block with a flat circular boiling surface (13.7 mm in diameter). The aluminium block was insulated with a Teflon bush of 40 mm outer diameter with a collar at one end. Same heater assembly along with the help of appropriate fixtures was also

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