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Research Paper

Boiling heat transfer enhancement with surfactant on the tip of a submerged hypodermic needle as nucleation site

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HIGHLIGHTS

- Effect of addition of 2-Ethyl-1-Hexanol into pure water on boiling was studied.
- Addition of 2-Ethyl-1-Hexanol into pure water reduces its surface tension.
- Effect of heat flux on bubble growth in aq. solutions was also studied.
- Changes in departure dia. and release frequency were observed in aq. solution.
- Heat transfer coefficient was found to be increased with heat flux in aq. solution.

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ABSTRACT

The addition of small concentration surfactant additive in pure water decreases the surface tension of aqueous solution considerably, and, critical micelle concentration (cmc) decides the limit of reduction in surface tension with increasing additive concentration. The objective of the present investigation is to study bubble growth in aqueous 2-Ethyl-1-Hexanol solution, and compare it with pure water experimentally. The bubble growth was studied at 880 pmm concentration of 2-Ethyl-1-Hexanol which is critical micelle concentration (cmc). A single bubble was generated using the right angle tip of a hypodermic needle as a nucleation site. Bubble growth was studied using high speed camera operating at 1000 frames per second. The investigation was conducted at two values of heat fluxes to check the effect of heat flux on bubble growth. At low heat flux ($q = 20\ kW/m^2$), the bubble departure diameter was found to be almost equal for both water and aqueous surfactant solution. At high heat flux ($q = 100\ kW/m^2$), bubble departure diameter increases in water, but, decreases significantly in aqueous surfactant solution. The bubble release frequency was nearly equivalent for both solutions at low heat flux, but, increases for aq. surfactant solution at high heat flux, which indicates augmentation in boiling heat transfer.

1. Introduction

Boiling has been found in a wide range of applications such as power generation, refrigeration, and air-conditioning, chemical, and thermal processes, cooling of electronic components, microfluidic system, thermal control of aerospace station, material processing etc. Most of the industrial applications operate in nucleate boiling regime. It is very difficult to analyze the boiling regimes, and hence till date boiling is dependent on large amount of empirical relations. Over the past decades, a great amount of research on pool boiling and flow boiling has been carried out to understand the fundamental aspect of boiling phenomena, and to provide practical knowledge for the engineering design requirements in various industries.

An active nucleation site features a periodic process of bubble formation, growth and departure. The generation of a bubble from its inception to departure is termed as Bubble Dynamics, which is featured by three parameters: growth period, departure size and release frequency. The forces acting on bubble growing on a heated wall are buoyancy force, surface tension force, liquid inertia force, viscous drag etc. When a bubble grows on a heated surface, buoyancy force acts as the main upward force, and surface tension force as a main countering force. The surface tension force generally tries to keep bubble attached to the heated surface. Other forces (lift, drag, and inertia etc.) try to push bubble away from the heated surface. Generally, when bubble is small capillary forces

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Nomenclature

D	bubble diameter (mm)
D_d	bubble departure diameter (mm)
f	bubble release frequency (Hz)
h_c	heat transfer coefficient determined from co-relations (W/m^2 K)
h_e	heat transfer coefficient determined from experimentation (W/m^2 K)
q	boiling heat flux (W/m^2)
R	bubble radius (mm)
t	bubble growth period (ms)

Greek symbols

ϕ	contact angle (degree)
ρ	mass density (kg/m^3)
σ	surface tension (N/m)

Subscripts

l	liquid
v	vapor

are strong. When the bubble is larger, other forces will strong or large. So, when bubble grows, other forces start dominating, and the bubble departs. After this, repetition of a cycle takes place. It is necessary to understand bubble dynamics in order to gain an understanding of the nucleate boiling heat transfer, developing mechanistic models of boiling heat transfer, and designing bubble driven micro-devices.

Several researchers have studied the bubble growth rate during pool boiling heat transfer theoretically. Jakob [1] studied pool boiling theoretically, and derived a relation between frequency of bubble formation at favor point on the heated surface and bubble departure diameter. Fritz [2] derived correlation for bubble departure diameter at low pressure by balancing buoyancy with surface tension force.

Rohsenow [3] developed relation between heat transfers to the bubbles while attached to the heated surface.

Researchers have extensively investigated bubble growth dynamics in nucleate pool boiling experimentally. Han and Griffith [4], Van Stralen [5], Cole and Shulman [6], Mimik et al. [7] presented a criterion for bubble growth rate from a gas filled cavity from a surface in contact with a superheated layer of pure liquid. A constant heat flux was applied at heating surface. The time dependence of bubble radius was $R \sim t^{0.5}$. Wong et al. [8] studied expansion and contraction of bubble pinned at submerged tube tip at low Reynolds number. They suggested a bubble departure criterion in terms of Bond number. Mori and Baines [9] carried out experimental and numerical investigation on growth and departure of bubbles from artificial nucleation sites. The effect of surface tension on bubble departure diameter was found to assist departure by formation of a bubble neck. Robinson and Judd [10] focused their investigation on dynamics of spherical bubble growth, and observed that the bubble growth remains in thermally controlled regime. Gerlach et al. [11] studied quasi-static bubble formation on submerged orifice empirically, and found out the importance of maximum bubble height to develop bubble detachment criteria using Capillary equation. Siedel et al. [12] investigated the bubble growth, departure, and interactions during pool boiling on artificial nucleation sites experimentally. Bubble departure diameter, and departure volume being independent of wall superheat, whereas the growth period is dependent on the superheat. Bari and Robinson [13] empirically developed a correlation for quasi-static adiabatic gas injected bubble departure. Lesage and Marois [14] used four hypodermic needles of varying diameters and depths to analyse quasi-static bubble size and shape characteristics at detachment.

Amid the different enhancement techniques probed, the use of surfactant additives in water has been found to be very effective [16–23,25]. Surfactant additive change the boiling phenomenon significantly. The addition of small concentration surfactant additive in pure water decreases the surface tension of aqueous solution at the liquid vapor interface considerably, and, critical micelle concentration (cmc) decides the asymptotic limit of reduction in surface tension with increasing additive concentration. The critical micelle concentration (cmc) indicates effectiveness of a surfactant to reduce surface tension of the solution. After critical micelle concentration (cmc), the surface tension will not reduce. Anionic and non-ionic surfactants fulfill most of industrial surfactant requirements. Because of their low concentration, presence of surfactants in water causes no significant change in the solvent physical properties except for surface tension, and, in some cases, the viscosity. Boiling with surfactant additive is generally an exceedingly complex process, and it is influenced by the large number of variables like the phase change process of pure water, surface tension of aqueous solution, the concentration of surfactant additive, kinematic and dynamic viscosity of aqueous solution, surface roughness of heated surface, the presence of electric field etc.

The effect of surfactant additives on pool boiling heat transfer were reported as a means of heat transfer enhancement. Wu et al. [15] listed the literature of researchers who carried out work using different surfactants, and under different conditions, such as pool or flow boiling as shown in Table 1. Yuan and Herold [16] measured surface tension of pure water, and aqueous Lithium bromide with 2-Ethyl-1-Hexanol using drop weight method. It was observed that surface tension of aqueous 2-Ethyl-1Hexanol decreases significantly within range 790 ppm (Parts per Million) to 880 ppm, after 880 ppm concentration, no significant reduction in surface tension takes place. Manglik et al. [17] used Sodium Dodecyl Sulphate (SDS), Sodium Lauryl Ether Sulphate (SLES), Octylphenol Ethoxylates (TRITON™ X-100, TRITON™ X-305), Hydroxyethyl Cellulose (CELLOSIZE™ QP) and Polyacrylate Polymer (Carbopol® 934) to study dynamics, and equilibrium surface tension of aqueous surfactant, and polymeric solutions. Yang and Maa [18] concluded in their study that for a highly soluble surfactant, boiling heat transfer is enhanced by the depression of equilibrium surface tension but suppressed by the depression of equilibrium contact angle. Wasekar and Manglik [19] considered the influence of additive molecular weight, and ionic nature on pool boiling performance of aqueous surfactant solution. They concluded that boiling performance characterized by an early onset of nucleate boiling is significantly enhanced, and the maximum enhancement is increasing with decreasing surfactant molecular weight. Inoue et al. [20] observed in their experiment that, boiling heat transfer coefficients were enhanced in a lower ethanol fraction. Also, the enhancement due to the surfactant disappears over 1000 ppm. Hetsroni et al. [21] investigated the effect of surfactants on bubble growth in saturated water, and aqueous surfactant solution using alkyl glucoside as a surfactant in pool boiling experimentally. Cheng et al. [22] presented a state of the art review on boiling phenomenon with surfactant and polymeric additives. It was suggested that experimental work be done to explore this