



# Effect of Marangoni flow on subcooled pool boiling on micro-scale and macro-scale heaters in water and surfactant solutions



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## ARTICLE INFO

### Article history:

Received 29 January 2015

Received in revised form 10 May 2015

Accepted 18 May 2015

### Keywords:

Subcooled boiling

Micro-scale

Macro-scale heaters

Surfactant

Marangoni convection

## ABSTRACT

Experiments were conducted on subcooled boiling at 30 °C on a heated wire of  $d = 50 \mu\text{m}$  in diameter and a heated tube of  $d = 1.5 \text{ mm}$  in diameter considered as micro-scale and macro-scale heaters, respectively. For boiling on the wire of  $d = 50 \mu\text{m}$  submerged in water, jet flow due to surface tension gradient played an important role in promoting heat transfer from the wire to the liquid. For subcooled boiling on the wire of  $d = 50 \mu\text{m}$  submerged in surfactant solutions, jet flow was not observed. The adsorption of surfactants at the vapor–liquid interface of the bubble creates a surface excess concentration gradient, which acts in the opposite direction to the imposed temperature gradient and it results in the reduction of thermo-capillary convection around the bubble.

The experimental data obtained under conditions of boiling on the wire of  $d = 50 \mu\text{m}$  in surfactant solutions showed different behavior of boiling curves compared to those obtained for macro-scale boiling. The boiling curves obtained during boiling on micro-scale heater are not dependent on surfactant concentration. When surfactants are present in water, there is generally a reduction of the overall or combined thermo-capillary and diffuse-capillary Marangoni convection.

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## 1. Introduction

With new developments in technology the need for more accurate prediction of boiling heat transfer requires more investigations. Drastic changes in inter-phase hydrodynamics should be studied, especially for micro-scale and microgravity conditions, Sitter et al. [1]. In saturated pool boiling the bubble interface is at saturation temperature and shows no temperature gradients, except for the interface in the region of the micro wedge. Up to now, no thermo-capillary convection could be observed in saturated boiling under micro-gravity. On the contrary, thermo-capillary convection is an important heat transfer mechanism in subcooled boiling Marek and Straub [2].

Subcooled nucleate boiling is characterized by high heat transfer rates. For water systems at near atmospheric pressure the heat fluxes of  $10 \text{ MW/m}^2$  and higher can be achieved, (Inoue et al. [3], Fukuda and Sakurai [4], Lu et al. [5]). Full utilization of this mode of heat transfer requires reliable knowledge of its limitations such as heated surface geometry and the properties of the fluid. In subcooled nucleate boiling, evaporation and condensation are coupled in a very complex manner as shown by Marek and Straub [2] for conventional size heaters. If the top of a growing bubble reaches

into the subcooled region, vapor starts to condense. The bubble dynamics in subcooled nucleate boiling was studied i.a. by Hsu [6], Robin and Snyder [7], Takagi et al. [8], Wu et al. [9], Marek and Straub [2], Lu and Peng [10]. It was shown that, in general, the surface tension  $\sigma$  depends on both the temperature and chemical composition at the interface. A flow induced by surface tension gradients is termed Marangoni convection; consequently Marangoni flows may be generated by gradients in either temperature or chemical concentration at the interface. For most fluids the temperature gradient of surface tension  $d\sigma/dT$  is negative, i.e. regions of higher temperature exhibit a reduced surface tension. Boiling on macro-scale heaters in surfactant solutions, generally, leads to enhancement of heat transfer, Hetsroni et al. [11–13].

For very small heaters the ratio of buoyant forces to surface tension forces becomes small and the equilibrium radius of the bubble depends on the heater size. It takes place as the ratio of  $R' < 0.15$ , (Bakhrin and Lienhard [14]). With the advancement of micro-scale technologies, experimental findings and computational predictions that shed more lights towards effect of heater size on nucleate boiling phenomena were conducted. The micro-heater array system was first adopted by the Rule and Kim [15] for boiling heat transfer study on micro-heaters. The system featured micro-heaters with a size of  $0.27 \times 0.27 \text{ mm}$ . In the present study we also assign the heaters of size  $\leq 0.27 \text{ mm}$  as micro scale heaters. Wang et al. [16,17], Hetsroni et al. [18] observed nucleation jet and

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## Nomenclature

$a$	thermal diffusivity
$C$	concentration
$d$	diameter
$g$	acceleration due to gravity
$h$	heat transfer coefficient
$I$	current
$L$	length
$Ma_S = \frac{\partial \sigma}{\partial C} \frac{\Delta C \cdot r}{D \cdot \mu}$	diffuse capillary Marangoni number
$Ma_T = -\frac{\partial \sigma}{\partial T} \frac{\Delta T \cdot r}{a \cdot \mu}$	thermo-capillary Marangoni number
$q$	heat flux
$r$	radius of a cylindrical wire
$R' = r[g(\rho_L - \rho_G)/\sigma]^{0.5} < 0.15$	dimensionless characteristic of the heater
$Ra = \frac{g \rho \beta r^3 \Delta T}{a \mu}$	Rayleigh number
$T$	temperature

## Greek symbols.

$\beta$	thermal expansion coefficient
$\Delta T$	temperature difference between the heated surface and subcooled water
$\mu$	dynamic viscosity
$\rho$	density
$\sigma$	surface tension
$\Omega$	electrical resistance

## Subscripts.

$b$	bubble
$G$	vapor
$in$	inner
$L$	liquid
$out$	outer
$s$	saturation
$w$	wall

bubble-top jet flow in a sequence of subcooled boiling experiments on small wires. In general, the bubble jet flow phenomena can significantly enhance the heat and mass transport between the bubble and bulk liquid, and were considered as important complements to nucleate boiling heat transfer. As noted in many investigations, (Marek and Straub [2], Wang et al. [16], Lu and Peng [19], Marangoni flow driven by interfacial tension gradient was expected to play a principal role in bubble jet flow phenomena. The bubble jet phenomena and associated Marangoni flow was investigated during boiling in water. Relatively few studies have considered the effects of surfactant additives on Marangoni convection.

Surfactants are molecules that have an affinity for interfaces. Their presence reduces the surface tension  $\sigma$ ; consequently gradients in surfactant concentration  $C$  result in surface tension gradients. Boiling with surfactant additives is generally an exceedingly complex process, and it is influenced by a larger set of variables than the phase-change process of pure water. Besides the wall heat flux (or wall excess temperature), heating surface geometry, and bulk concentration of additives, the boiling behavior is also dependent upon interfacial properties, the nature of the additive, its chemistry, foaming etc. The subcooled pool boiling of environmentally acceptable surfactant solutions at various concentrations on macro-scale heaters was studied by Hetsroni et al. [12]. It was found that the subcooled nucleate boiling of surfactants could not be described by a single curve, in contrast to water. They also noted a significant enhancement of the heat transfer and showed drastic change in the bubble structure next to the heated tube wall. The effect of varying initial liquid–solid contact angle on the evaporation of single droplets of water deposited on a stainless steel surface was studied. Contact angle was controlled in experiments by adding varying amounts of surfactant to water. The evolution of contact angle and liquid–solid contact diameter was measured from a video record of droplet evaporation. Reducing contact angle increases contact area between the droplet and solid surface, and also reduces droplet thickness, enhancing heat conduction through the droplet. Both effects increase droplet evaporation rate. Decreasing the initial contact angle from  $90^\circ$  to  $20^\circ$  reduces droplet evaporation time by approximately 50%. Reducing contact angle was shown to enhance surface cooling. For a wide range of common surfactants, surface tension is a monotonically decreasing function of  $C$  until a critical concentration is achieved, beyond which  $\sigma$  remains constant. Surfactants thus generate a special class

of Marangoni flows. The effect of surfactant concentration on the Marangoni convection around boiling nuclei in aqueous solutions was computationally investigated by Wasekar and Manglik [20]. It was shown that the Marangoni effect is the most important factor in the heat transfer based on the pumping effect of the jet flow. However, there is a paucity of experimental measurements. The goal of the present work is to present the experimental observation and analyses for understanding some special boiling phenomena concerning different micro-scale and macro-scale boiling modes, their characteristics, and associated heat transfer phenomena during boiling of water and surfactant solutions at very high subcooling.

## 2. Experimental facility and methodology

### 2.1. Rheological properties of surfactant solutions

We used Alkyl (8–16) Glucoside (Plantacare 818 UP) with molecular weight of 390 g/mol for our experiments. This product is produced by the Company BASF Care Creations and has a liquid appearance with an active substrate constant 51–53%. All kinds of surfactants are normally marketed as a mixture that contains an active substrate constant 51–53%. The solutions of different concentrations used in the present study were prepared by dissolving the surfactant (52% active substance and 48% water) in deionized water, with gentle stirring over a period of one-day. The measurements of the physical properties were carried out at the Department of Chemical Engineering, Ohio State University (Hetsroni et al., [12]). The surface tension data were obtained by using a SensaDyne PC500-LV Surface Tensiometer System. This system measures the surface tension within the body of a test fluid by blowing a bubble of gas through two probes of different diameters inside the fluid. The measurements of surface tension were carried out for different concentrations of surfactant solutions over a range of temperature from 300 to 368 K with standard deviation of 2%. In Fig. 1 the equilibrium surface tension,  $\sigma$ , is plotted vs. the concentration of the surfactant solution at different temperatures. All surfactant–solvent systems have a characteristic surfactant concentration referred to a critical micelle concentration, which differentiates the presence of surfactant in the solution either as individual monomer or associated groups as micelles. A micelle is an aggregation of a large number of monomers and can have different types of structures depending upon the nature of surfactant.

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