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# Effects of surfactant additive on flow boiling over a microheater under pulse heating

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An experimental investigation has been carried out to study effects of surfactant additive on microscale boiling under pulse heating over a Pt microheater ($140 \times 100\ \mu m^2$) fabricated in a trapezoidal microchannel (600 μm in width and 150 μm in depth). Experiments are carried out for six different surfactant concentrations of Triton X-100 ranging from 47 ppm to 2103 ppm, for mass flux in the range from 45 $kg/m^2$ s to 225 $kg/m^2$ s, pulse width in the range from 50 μs to 2 ms, and heat flux in the range from 3 $MW/m^2$ to 65 $MW/m^2$. As in existing work on pool boiling under steady heating, it is found that nucleate boiling becomes more vigorous and heat transfer is enhanced greatly with the addition of surfactant with maximum boiling heat transfer occurs at the critical micelle concentration (cmc). Furthermore, these maximum values of boiling heat transfer coefficient increase with decreasing pulse width. When concentration is below cmc, the heat flux needed for nucleation increases with increasing concentration and the nucleation temperature is reduced. When concentration is higher than cmc, the boiling heat transfer coefficient decreases and nucleation temperature is higher than that of pure water.



## 1. Introduction

It is well known that the addition of surfactants and polymers in a phase-change liquid can enhance nucleate boiling heat transfer rate. If a surfactant is added in a solution, the surface tension usually decreases with increasing concentration and approaches to a constant value at a critical micelle concentration [1,2]. As the rate of vapor nuclei formation is proportional to surface tension as $N \propto \exp(-\sigma^3)$ [3], the change in surface tension will affect boiling heat transfer process. Wasekar and Manglik [4] performed an experimental investigation on effects of an anionic surfactant solutions (SDS or SLS) on saturated nucleate pool boiling on a horizontal cylindrical heater, and found that boiling heat transfer was enhanced significantly by the presence of SDS. An optimum enhancement was observed in solutions at the critical micelle concentration (cmc). Zhang and Manglik [5,6] pointed out that the surface molecules form a bilayer on the surface and make it strongly hydrophilic as the cmc is approached, making boiling inception more difficult. From the existing literature on pool boiling, it appears that the main effects of surfactants on boiling heat transfer are: (i) When the concentration is smaller than cmc, the decrease in surface tension of the solution results in increased number of nuclei and nucleate pool boiling heat transfer rate, and reduces the force required to rupture a liquid in tension [3]. (ii) When the concentration is higher than cmc, the adsorption of surfactants on the heating surface leads to a decrease of contact angle affecting the delay of boiling inception, and the increase of viscosity results in the decrease of boiling heat transfer rate [6].

On the other hand, many experiments have been carried out for microscale boiling over a microheater under pulse heating during the past several years [7–9]. In particular, Varlamov et al. [7] and Wiesche et al. [8] found that boiling inception time decreases with heat flux. Chen and Cheng [9] investigated experimentally effects of heat flux and mass flux on boiling regimes and microbubble dynamics of water on a Pt microheater ($60 \times 100\ \mu m^2$) with pulse width under 2 ms. They found that nucleate boiling and film boiling began to appear on the microheater successively with increasing heat flux at a given mass flux and a fixed pulse width. It should be noted that most of microscale boiling experiments under pulse heating were performed with pure water.

In this paper, we focus our attention on the effect of surfactant additive of Triton X-100 on flow boiling regimes and boiling inception for subcooled flow boiling over a Pt microheater ($140 \times 100\ \mu m^2$) under pulse heating. Since the cmc of Triton X-100 is about 100–200 ppm at room temperature [1,2], surfactant solutions of Triton X-100 with six concentrations (47 ppm, 133 ppm, 257 ppm, 553 ppm, 1042 ppm and 2103 ppm) were selected for this experiment to cover concentrations below, near and above cmc. Experiments for flow boiling of these solutions were carried out for different pulse widths, mass fluxes, and heat fluxes. The use of a Pt microheater enables instantaneous and accurate temperature measurements of the heater surface. With the aid of a microscope and a high-speed data acquisition system, the instantaneous temperature data can be used to identify nucleation temperature and inception time during the pulse heating process.

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The effects of surfactant additive on boiling flow regimes, boiling heat transfer coefficient, nucleation temperature and boiling inception time during microscale boiling over a microheater under pulse heating are analyzed.

## 2. Experimental setup and procedure

### 2.1. Test section and experimental procedure

A trapezoidal microchannel, with the top width and depth of 600 μm and 150 μm respectively, was etched through a <1 0 0> Silicon wafer by wet etching, and then bonded with two glass wafers (Pyrex7740). The Pt microheater, $140 \times 100\ \mu m^2$, was fabricated on one of the two glass substrates. The test section and the experimental setup (including a microscope, a high-speed CCD, a syringe pump, a pulse generator and a control circuit) used in this experiment were similar to those in our previous work [9] except that a new high-speed data acquisition card was installed in the data acquisition system.

### 2.2. Calibration of Pt microheater

Before performing experiment, the Pt microheater was calibrated to give its resistance–temperature characteristic. After fitting the experimental data, the resistance as a linear function of temperature can be correlated as:

$$R_c = 3.5358 + 0.01008T \quad (1)$$

where $R_c$ is the resistance of microheater circuit, including the resistances of Pt microheater, connecting wire and contact. The temperature of the Pt microheater can be calculated from Eq. (1),

$$T_{pt} = (R_c - 3.5358)/0.01008 \quad (2)$$

where $R_c$ can be calculated through recorded voltages of microheater circuit and standard resistance.

## 3. Results and discussion

### 3.1. Boiling flow regimes

At fixed values of mass flux and pulse width, it was observed that four flow regimes appeared sequentially with increasing heat flux: single phase, nucleate boiling, film boiling and dry out. Fig. 1 shows the effects of concentration on heat flux required for transition of the four flow regimes at pulse widths of 0.2 ms, 0.6 ms and 1 ms and at a mass flux of $45\ kg/m^2\ s$. The heat flux needed for nucleation is *increased* with increasing concentration at low concentration until cmc (about 100–200 ppm) is reached. This effect may be associated with the adsorbance of surfactant molecules to the microheater [5,6] making the microheater surface more hydrophilic and therefore boiling inception is more difficult, while the adsorption becomes independent of the concentration as the cmc is approached. On the other hand, it can also be seen from Fig. 1 that the heat fluxes required for transition from nucleate boiling to film boiling and from film boiling to dry out *decrease* with increasing concentration and approach constant values after cmc is reached. This effect may due to much more nucleation sites with surfactant additives, making vapor film easier to form.

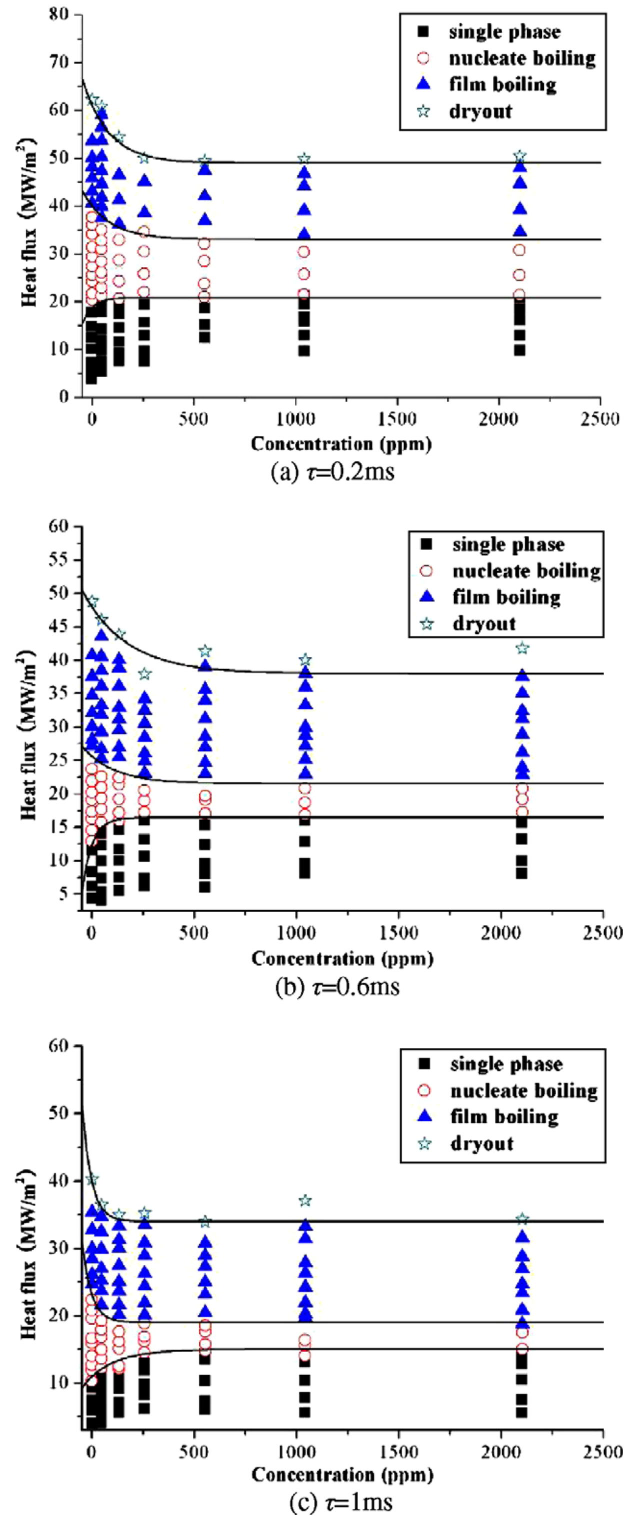


**Fig. 1.** Effects of surfactant on boiling regime at $G = 45\ kg/m^2\ s$.

As mentioned previously, the cmc of Triton X-100 solution is about 100–200 ppm. For this reason, three concentrations of 0 ppm, 133 ppm and 553 ppm (corresponding to below, near and higher than cmc) are selected to illustrate the effect of surfactant concentration on temperature variation and boiling phenomenon under fixed heat flux, pulse width and mass flux. Fig. 2 shows the temperature variations and photos of nucleation processes at different times on the Pt heater, heated at $17\ MW/m^2$ with a pulse width of 0.6 ms and a mass flux of $45\ kg/m^2\ s$ for three different concentrations. The nucleation inception was identified from the photos and is marked on each of the temperature variation curve. From the initial temperature rise, the initial heating rate ($dT/dt$) was calculated to be in the order of $10^7$–$10^8\ K^{-1}$. From the photos, it can be seen that the number of nuclei is increased when the concentration of surfactant is increased because of the decrease