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# Bubble explosion in pool boiling around a heated wire in surfactant solution

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## ABSTRACT

This paper reports a new pool boiling phenomenon of bubble explosion in a surfactant solution. The working fluid was an aqueous solution of cetyltrimethyl ammonium chloride (CTAC) with addition of sodium salicylate (NaSal) at the same mass concentration. A platinum wire was horizontally placed in the fluid for heating. The boiling heat transfer performances of the tested fluid at fluid temperature (288.15 K) and different concentrations of CTAC/NaSal solution (0–400 ppm) have been presented. It's found that the tested surfactant solution significantly augmented boiling heat transfer as compared with water, and the best heat transfer performance was found at the concentration ranging from 5 to 100 ppm. With a high-speed camera and an inverted microscope, the nucleation boiling process on the heated wire was recorded. For the first time, we observed a new bubble explosion phenomenon around the heated wire in CTAC/NaSal solutions (at concentration beyond 0.1 ppm), which is apparently different from the previously reported boiling explosion due to homogeneous nucleation. Together with the observed strong jet-flow behaviors, bubble explosion strengthened the local disturbance and enhanced the boiling heat transfer. It was conjectured that the strong jet-flow phenomenon is essentially the traces of small bubbles and bubble explosion is a failed coalescence of unstable bubbles, which leads to the disturbance and boiling heat transfer enhancement.

## 1. Introduction

Due to its high efficiency of heat transfer, boiling process was widely encountered in industrial applications such as steam generators, heat pipe, air-conditioning, and so forth. With the increase of power density and the miniaturization of electronic packages, heat transfer enhancement was need to meet the cooling demand. And the methods include surface modification, microchannel sink and adopting surfactant solution in boiling, etc. [1–3].

One of the earliest studies on nucleate pool boiling with surfactant additives was done by Morgan et al. [3] in 1949. They performed nucleate pool boiling of aqueous solutions of Drene and sodium lauryl sulfonate (SLS), and found that the heat transfer coefficients of nucleate pool boiling increased with the decrease in surface tension of the liquid before the critical situation. Chou and Yang also studied the surfactant effect on the temperature profile and found that the maximum heat transfer coefficient of Octadecylamine solution was increased by 150% compared with that of water [4]. However, Hetsroni et al. claimed that for various surfactant concentration in nucleate pool boiling, the heat transfer rate decreased at higher surfactant concentrations, which is possibly due to the increase of viscosity. High viscosity delayed the convection of heated fluid [5]. For Habon G solutions, the best concentration for boiling heat transfer was about 530 ppm. The similar value (600 ppm) for HEC-QP300 and Carbopol 934 solutions was got by Zhang and Manglik [6]. This implies that the best concentration should be a balance between the decreasing surface tension and increasing viscosity. Also, Frost and Kippenhan clarified that when the surface tension decreased, the bubble size decreased and the bubble population increased, and that was responsible for the enhancement of the boiling heat transfer [7].

In addition, the critical heat flux (CHF) is a crucial parameter which is related to the safe operation of the heater. Wu et al. [8] conducted the pool boiling in water with SLS, although the heat transfer was enhanced, the CHF of water was decreased by the surfactant. Inoue et al. [9] found that surfactant (Perfluoroalkyl compound) has little effect on CHF of water. However, other researchers have different conclusion. Hu et al. carried out pool boiling experiments on the CHF of self-rewetting fluid (dilute heptanol aqueous solution) around a horizontal heated wire under atmospheric pressure [10]. The self-rewetting fluids are non-azeotropic solutions featured with an increased surface tension gradient with increasing temperature. They found that the CHF

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**Nomenclature**

| | |
|---|---|
| $C$ | concentration, [ppm] |
| $h$ | heat transfer coefficient, [$W \cdot m^{-2} \cdot K^{-1}$] |
| $l$ | wire length, [mm] |
| $T_f$ | fluid temperature, [K] |
| $T_S$ | saturation temperature, [K] |
| $T_{out}$ | outlet temperature, [K] |
| $\eta$ | dynamic viscosity, [Pa·s] |
| $\sigma$ | surface tension, [$N \cdot m^{-1}$] |
| $d$ | wire diameter, [mm] |
| $I$ | current, [A] |
| $q$ | heat flux, [$W \cdot m^{-2}$] |
| $T_W$ | wire temperature, [K] |
| $T_{in}$ | inlet temperature, [K] |
| $U$ | voltage, [V] |
| $\lambda$ | thermal conductivity, [$W \cdot m^{-1} \cdot K^{-1}$] |
| $\Delta$ | absolute error |

in the self-rewetting fluid (0.1 wt% heptanol solution) increased up to 2.52 times of that in water. So, decreasing the surface tension has obvious influence on the CHF. Thus it's necessary to further research the CHF of surfactant solution.

In this paper, we made efforts in investigating the characteristics of pool boiling in an aqueous solution of surfactant additives. The purpose of this study is to seek a superior working fluid and find out the mechanism of surfactant enhancing heat transfer. The boiling performance of an aqueous solution of cetyltrimethyl ammonium chloride (CTAC) with addition of sodium salicylate (NaSal) at different concentrations and the same fluid temperature (288.15 K) have been demonstrated. The aqueous solution of CTAC/NaSal has been utilized as drag-reducing fluid [11–13]. Such kind of working fluid might be used in some circulation systems, of which turbulent drag reduction effect can be realized in some parts and boiling heat transfer enhancement can be also realized in other parts locally. In this work, in order to investigate the boiling behaviors and explore the boiling heat transfer enhancement mechanism in the surfactant solution, nucleate boiling processes have been visualized at different concentrations. And for the first time, bubble explosion phenomena together with strong jet flow phenomena were discovered, indicating a new reason enhancing the heat transfer performance.

## 2. Experimental procedures

### 2.1. Physical properties of tested fluid

The working fluid was an aqueous solution of CTAC with addition of NaSal at the same mass concentration. The solution was stirred about 8 h to dissolve solute and made another 8 h standing before using. For the fluids, surface tension, viscosity and thermal conductivity are three important physical properties of working fluid affecting the boiling heat transfer performance. The surface tension of CTAC/NaSal solution was measured with the Wilhelmy plate method (BZY-2, HengPing, Shanghai, China). The measurement procedure is briefed as follows. The temperatures of the samples remained stable through a temperature control system, and the maximum temperature deviation was less than ±0.5 K. After repeated measurements for at least three times, the surface tension values were obtained for surfactant solutions at different concentrations. For each surface tension value, the standard deviation was about ±0.1 $mN \cdot m^{-1}$. Fig. 1 shows the measured surface tensions of surfactant solution at different concentrations taken at a constant temperature of 288.15 K. It can be seen that, when the concentration of CTAC/NaSal solution is larger than 50 ppm, the surface tension becomes nearly constant and only about 30% of that of water. To make a comparison, the surface tensions of CTAC solutions without addition of NaSal were also provided, which was nearly the same as that of CTAC/NaSal solution, indicating that NaSal has little effect on the surface tension of CTAC/NaSal solution. As mentioned previously [3–9], low surface tension is advantageous to nucleate boiling and the surface tension is related to the surfactant solution concentration. So the tested surfactant solution at concentration beyond 50 ppm should have the similar effect on enhancing boiling heat transfer enhancement.

Rheology measurements by Kawaguchi et al. [14] and Li et al. [15,16] showed that the shear viscosity of dilute aqueous solution of CTAC/NaSal below 50 ppm was almost the same as that of water at different shear rate. Above 50 ppm, the shear viscosity of CTAC/NaSal solution becomes increasingly higher than that of water with the increase of concentration. Fig. 2a shows that the CTAC/NaSal solution is shear-thinning in a large range of shear rate. However, for the zero-shear-viscosity, they tend to Newtonian fluids behaviors as the temperature increasing (Fig. 2b). Also, the higher the concentration is, the more viscous the solution becomes, which should influence the convection of heated fluid. Herein, we need a typical viscosity characterizing the working fluid, and the zero-shear viscosity was chosen to represent the viscosity of fluid since it's nearly at rest in the experiments. Fig. 2b shows the measured zero-shear viscosity of CTAC/NaSal solution at different concentrations. The zero-shear viscosity of CTAC/NaSal solution is about 2.5 times (100 ppm) of that of water and 6.0 times (200 ppm) of that of water.

Thermal conductivity of CTAC/NaSal solution at different concentrations was measured through transient hot-wire method (XIA-TC-THW-L01, Xiaxi, Xi'an, China). The uncertainty of measurement is less than 3%. As shown in Fig. 3. Surfactant has little effect on the thermal conductivity of solution. For other physical properties of the aqueous solution of CTAC/NaSal including

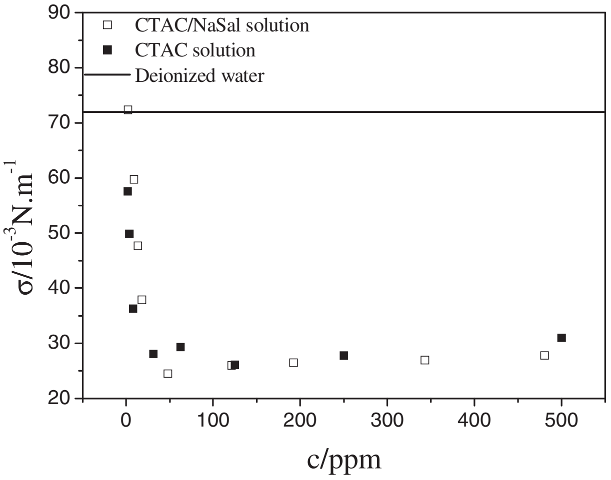

**Fig. 1.** Measured surface tensions of aqueous solution of CTAC/NaSal at different concentrations at 288.15 K.