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Heat transfer and CHF in subcooled flow boiling of aqueous surfactant solutions

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ABSTRACT

Flow boiling heat transfer characteristics of surfactant solution was studied and compared to that of pure water. The tested fluid was an aqueous solution of cetyltrimethyl ammonium chloride (CTAC) with addition of sodium salicylate (NaSal) at the same mass concentration. Tests were performed with 6.0 × 3.5 mm cross-section channel over flow rate range of 192–403 ml/min, at inlet temperature of 80 °C and an outlet pressure of 101.3 kPa. Liquid column method and resistance method of temperature determination were adopted to obtain accurate experimental data. The present experimental results show that, the flow boiling in CTAC/NaSal solutions at an appropriate concentration (100 ppm, ppm refers to part per million) behaved a good flow boiling performance. The heat transfer coefficient of 100 ppm CTAC/NaSal solution at the critical heat flux (CHF) was increased to 1.36 times compared to that of pure water. Besides, the CHF of 0.08 mm thick Nickel foil was increased to about 126% by surfactant addition when the concentration was beyond 100 ppm. The addition of CATC/NaSal increased the nucleation site density and inhibits bubble coalescence which were likely to be causes of enhancing the boiling heat transfer coefficient and CHF of subcooled flow boiling of CATC/NaSal aqueous solutions.

1. Introduction

There have been a large number of studies to investigate effects of surfactant additives on boiling heat transfer and critical heat flux (CHF) in pool boiling of water (e.g. [1–10]). According to those studies, the heat transfer coefficient in fully developed nucleate boiling region is generally enhanced [1–8] and the CHF is hardly affected or decreased slightly [8–10] by addition of a small amount of surfactants to water.

As for the studies on flow boiling conditions with aqueous surfactant solutions, Stroebe et al. [11] carried out experiments of flow boiling through a heated vertical tube with length of 6.1 m and inner diameter of 44.7 mm. They reduced the surface tension of water by about 50% with addition of a small amount of SDS, and obtained the result where the heat transfer coefficient of SDS aqueous solution were 2–4 times larger than that of water. Frost and Kippenham [12] carried out experiments of subcooled flow boiling in an inner tube heated vertical annular channel with inner diameter of 4.76 mm and outer diameter of 38.1 mm. They varied the surface tension of water in a wide range by addition of surfactant (Ultra Wet 60L) and measured the boiling curves from low heat fluxes to the CHF. They found that the heat transfer in nucleate boiling region is enhanced similarly to the results by Stoebe et al., and the CHF decreases with the decreasing surface tension. Different from Frost and Kippenhan, Jeong et al. [13] found that the CHF of surfactant solution increased at low mass flux (100–400 kg/m^2s) and decreased at high mass flux (500 kg/m^2s). The surfactant was Tri-sodium phosphate. They proposed that the increasing CHF was due to an increasing wettability of the heater surface and promoted liquid supply under bubbly or churn flow conditions. The effect of surfactant on the CHF was not clear which needed further research. Hetsroni et al. [14] conducted experiments with a vertical upward flow through an inner tube heated annular passage having an inner diameter of 3.2 mm, an outer diameter of 12 mm, and a heated length of 290 mm. They used Alkyl (8–16) Glycoside aqueous solution with a concentration of 300 ppm (ppm: part per million), and found that the boiling heat transfer coefficient was enhanced up to 4 times compared to that of water. In this experiment, the data were measured at very small mass fluxes $G = 3.2–7.7\ kg/m^2s$, which correspond to the inlet flow velocities of 3.4–8 mm/s, and therefore, the experimental condition is close to that in pool boiling. In addition to the above studies using a single flow passage, Klein et al. [15] carried out an experiment with alkyl-poly-glycoside (APG) aqueous solutions in a microchannel heat sink, where 26 parallel channels with triangular cross section (base length is

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Nomenclature

A_f	cross-section of flow channel [mm^2]
Bo	boiling number, $q/G \cdot H_{fg}$
C_i	numerical constants in Eq. (4), i = 1, 2, 3, 4, 5
D	diameter [mm]
D_h	heated equivalent diameter defined by Eq. (5) [mm]
G	mass flow rate [kg/m^2 s]
H_f	height of fluid in water tank [mm]
H	height of rectangular channel [mm]
h	heat transfer coefficient [W/m^2 K]
H_{fg}	latent heat of vaporization [J/kg]
L	heated length [mm]
P_h	heated perimeter [mm]
Re	Reynolds number
T_f	fluid temperature [°C]
T_{sat}	saturation temperature [°C]
T_w	surface temperature averaged over the heating surface [°C]
P	exit pressure [kPa]
q	heat flux [W/m^2]
q_{CHF}	critical heat flux [W/m^2]
W	width of rectangular channel [mm]
W_e	Weber number, $G^2D/\rho_f \cdot \sigma$
W_h	width of heating surface [mm]
x_i^*	inlet quality defined by the saturated physical properties at the exit pressure
x_{in}	inlet quality

Greek symbols

σ	surface tension [mN mm^{-1}]
ΔT_{sat}	superheat $T_w - T_{sat}$ [K]
$\Delta T_{sub,in}$	inlet subcooling [K]
ρ_f	density of liquid [kg/m^3]
ρ_g	density of vapor [kg/m^3]

210 μm) are provided on a 15 mm × 15 mm silicon substrate. They conducted the measurements of single phase and boiling heat transfer in the range of mass flux, G = 38–172 kg/m^{2}s, and APG concentration from 0 to 300 ppm, and concluded that there are the optimal values of mass flux and the APG concentration at which the heat removal rate from the microchannel heat sink reaches the maximum value.

As mentioned above, there are much less studies for flow boiling with aqueous surfactant solutions compared to those for pool boiling, and further research is necessary to elucidate the effects of surfactant additives on the heat transfer and CHF for flow boiling of water.

When a small amount of CATC/NaSal (the equimolar mixture of cetyltrimethyl ammonium chloride (CATC) and sodium salicylate (NaSal)) is added to water, the frictional resistance of single phase turbulent flow is often greatly reduced. Various researchers have experimentally investigated the reduction of frictional resistance using CATC/NaSal aqueous solution [16–18 among others] and obtained excellent turbulent drag-reducing effect. When CATC/NaSal aqueous solution is used as a working fluid for a forced circulation closed loop cooling system using phase change phenomena, it is possible to achieve great reduction in pressure drop in non-boiling section of the cooling system. However, in order to evaluate the heat removal characteristics of the cooling system, it is necessary to examine the characteristics of heat transfer and CHF in flow boiling of CATC/NaSal aqueous solutions.

This paper conducted experiments of flow boiling of CATC/NaSal aqueous solutions. A vertically oriented rectangular channel with one side heated was used and the heat transfer coefficients and CHF were measured by varying the concentration of CATC/NaSal from 0 to 600 ppm. Further, the boiling behaviors on the heating surface were observed by a high speed camera and effects of surfactant additives on boiling behaviors were examined.

2. Experiment

2.1. Thermo-physical properties of CATC/NaSal aqueous solutions

For the working fluids, surface tension, thermal conductivity, and viscosity are three important physical properties affecting the boiling heat transfer. Table 1 shows the thermo-physical properties of CATC/NaSal aqueous solutions at different temperatures. The surface tension and thermal conductivity of CTAC/NaSal aqueous solutions were measured in previous studies [19,20]. The critical micelle concentration (CMC) of CTAC/NaSal aqueous solution is about 50 ppm at 20 °C while it is about 100 ppm at 80 °C. The surface tension drastically decreases with the increase in the concentration and takes almost constant value around 28 mN/m, when the concentration is beyond CMC. The thermal conductivity was measured in the temperature range of 20–50 °C, and has little dependency from the concentration. The viscosity was measured by Kawaguchi et al. [21]. According to these measurements, the shear viscosity of CTAC/NaSal solution at 80 °C is almost the same as that of water over concentration range of 0–600 ppm.

2.2. Experimental apparatus

Fig. 1 shows a schematic of the experimental facility. It consists of an upper tank containing immersion heaters and cooling pipes, a flow control valve, a test section (one side heated vertical channel), a lower tank and a circulation pump. The working fluid flows through the test section by a difference in hydraulic head between the upper and lower tanks. Liquid column method was used in the paper. The pressure ($p = \rho g H$) drove the fluid pass through the channel while the pump drew the fluid in reservoir (7) into the water tank (2) to hold the height

Table 1
Thermo-physical properties of CATC/NaSal aqueous solutions.

Concentration	Shear viscosity (η) [10^{-3} Pa s] (γ = 10 L/s)			Thermal conductivity(λ) [W m^{-1} K^{-1}]			Surface tension (σ) [N m^{-1}]	
	20 °C	30 °C	40 °C	20 °C	30 °C	40 °C	20 °C	80 °C
0 (reference)	1.01 (1.004)	0.788 (0.8015)	0.652 (0.6533)	0.6 (0.599)	0.614 (0.618)	0.633 (0.635)	71.99 (72.58)	63.5 (63.4)
20				0.605	0.615	0.637	33.08	38.02
50	1.45	1.25	0.688	0.602	0.618	0.638	24.47 (CMC)	34.46
100	3.69	6.48	0.578	0.605	0.620	0.639	25.96	29.79 (CMC)
200	17.84	0.947	0.746	0.606	0.618	0.635	26.46	28.64
400				0.603	0.617	0.635	26.94	28.6
600				0.601	0.617	0.631	28.44	28.4