Pergamon

Int. J. Heat Mass Transfer. Vol. 37, No. 15, pp. 2377–2379, 1994

0017–9310/94 $7.00+0.00

TECHNICAL NOTE

Critical heat flux in pool boiling of aqueous surfactant solutions as determined by the quenching method

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(*Received* 21 *October* 1993 *and in final form* 24 *February* 1994)

INTRODUCTION

SMALL amounts of certain surfactants in aqueous solution have been known to enhance the rate of nucleate boiling heat transfer of water significantly [1]. Wu and Yang [2] listed chronologically some investigations of the surfactant effect on boiling water from the literature. It is evident that nucleate boiling is the intriguing heat transfer process that has been the subject of most investigations on the surfactant effect in the literature. The surfactant effect on the critical heat flux (CHF, q_c), however, has received relatively less attention. Two papers available in the literature are reviewed briefly as follows.

Frost and Kippenhan [3] studied forced convection boiling of water and aqueous surfactant (Ultra Wet 60L, an anionic surfactant) solutions in a vertical annulus. The annular test section was jacketed with a transparent 1.5-in. I.D. Pyrex glass tube and the inner (electrically heated) surface was made of $\frac{3}{16}$ in. O.D. stainless steel tube. Different energy transfer processes which control the bubble growth were proposed for boiling of water with and without surfactant additive. It was concluded that latent heat transport contributes approximately 50% of the measured heat flux in water and significantly more in water having reduced surface tension by surfactant additive. They also reported the measured CHF data, as shown in Fig. 1, but failed to provide any explanation of the results. Yang and Maa [4] investigated the surfactant effect of sodium lauryl sulfate (SLS) and sodium lauryl benzene sulfonate (SLBS) on the CHF of water by using a heating element made of 0.116-mm nickel wire. As also shown in Fig. 1, CHF was increased rather than decreased by the addition of small amount of surfactants. They attributed the increased CHF data to the inhibition of vapor bubble coalescence over the boiling surface by the Marangoni effect, which is a result of slowness of migration of surfactant molecules from the bulk to the adsorption layer at the extending vapor/liquid interface during bubble coalescence. This effect bestows the elasticity on a thin liquid film between two adjacent vapor bubbles, and the coalescence of the bubbles is therefore inhibited. If critical heat flux (q_c) is correlated with surface tension (σ) so that $q_c \propto \sigma^m$, m values were evaluated by them to approximately be -0.6 and -1.22 for the aqueous solutions of SLS and SLBS, respectively.

It is obvious from above review that the surfactant effect on CHF is contradictory in the literature. However, it is worth noting that the heating surfaces used by Frost and Kippenhan [3] and by Yang and Maa [4] differ widely in their dimensions. The contradictory results may suffer from the fact that the influential roles of geometry and/or geometric scale on CHF had not yet been identified or properly diagnosed.

The objective of this work is to report the experimental results of the surfactant (sodium lauryl sulfate, SLS) effect on the pool boiling CHF in saturated water over a relatively wide range of concentration (0–1200 ppm) on a quenching sphere of 12.7 mm diameter, which differs from the ones of previous investigations in geometry and dimension and begins to approximate industrial-size elements.

EXPERIMENTAL

The use of quenching techniques to determine boiling curves has been proved to be a more rapid and easier method than traditional steady-state methods. However, the boiling curve from a quenching test depends on the dimensions of the quenching solid, its material of construction, the dimensions of the enclosing vessel, and sometimes the location of the thermocouple used to get the time vs temperature data.

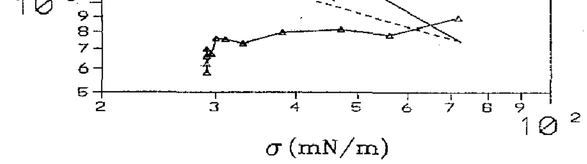

FIG. 1. Effect of surface tension on the critical heat flux of aqueous surfactant solutions. ○, Ultra Wet 60L, annulus, flow, inlet temp. = 100°F, velocity = 4 ft s^{-1}, Frost and Kippenhan [3]; □, Ultra Wet 60L, annulus, flow, inlet temp. = 170°F, velocity = 0.8 ft s^{-1}, Frost and Kippenhan [3]; ——, SLBS, wire, pool, Yang and Maa [4]; – – –, SLS, wire, pool, Yang and Maa [4]; △, SLS, sphere, pool, this work.

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NOMENCLATURE

C	concentration [ppm]
g	gravitational acceleration [m s^{-2}]
h_{fg}	latent heat of evaporization [J kg^{-1}]
q	heat flux [W m^{-2}]
$q_{c,Zuber}$	q_c predicted by Zuber, equation (4)
R	radius of sphere [m]
R'	dimensionless radius, equation (3)
T	temperature [°C]

Greek symbols

ρ	density [kg m^{-3}]
σ	surface tension [mN m^{-1}].

Subscripts

c	critical
f	liquid
g	vapor
w	wall
sat	saturation.

These factors can be standardized so that the resulting data are applicable to commercial equipment [5]. The pool boiling apparatus used in this work was basically that which was constructed by Chen *et al.* [6], and was also designed mainly according to their suggestions.

Saturated boiling took place on the outer surface of a quenching copper sphere of 12.7 mm diameter with two K-type sheathed thermocouples silver-soldered at the center and near the surface. Two liters of water or aqueous surfactant solutions were contained in a 14-cm I.D. stainless steel tank. The test sphere was inductively heated in a high frequency coil to 550 ± 10°C. When a uniform temperature was reached, a data acquisition process was started and then the sphere was plunged into the saturated liquid pool with 6 cm depth of immersion. The signal from thermocouples was amplified and fed to the interfaced personal computer through analog-to-digital converter. The sampling time was adjusted to 5 ms and the sampling always lasted for 64 s in this work. In this quenching experiment, the record is that of time vs temperature at known locations inside the sphere being quenched. What is desired is the heat flux at the surface of the sphere vs superheat for boiling. The details of quenching apparatus and the data reduction and analysis for the estimation of the surface heat fux from interior temperature measurements, the so-called inverse heat conduction problem, were given else where [6].

Surface tensions of the aqueous surfactant solution were measured at a controlled temperature (25.0 ± 0.2°C) with a commercial equipment (CBVP-A3 Type, Kyowa Interface Science Co. Ltd., Japan) by the Wilhelmy plate method.

EXPERIMENTAL RESULTS AND DISCUSSION

Figure 2 shows samples of the quenching curve (surface temperature vs time) for SLS surfactant solutions. Conventional boiling curves can then be obtained, as shown in Fig. 3, and critical heat fluxes were determined from boiling curves as the peak heat fluxes. It is worth noting that nine runs of the quenching experiment in pure water have been conducted for the purpose of evaluating experimental uncertainty. The critical heat fluxes were determined to be as follows: 787, 792, 838, 833, 800, 836, 827, 898, 779 (kW m^{-2}). The average and standard deviation of these data are 821 and 37 (kW m^{-2}), respectively. From these results we can confidently estimate that the uncertainty for CHF was well within 5%. Even smaller uncertainty was found for the temperature data. As shown in Fig. 4, the experimental results reveal that CHF is decreased by the addition of surfactant. Figure 4 also shows the measured surface tension data. Because changes in physical properties, such as viscosity and density, are usually too slight for significance except that the surface tension is depressed considerably by the addition of small amounts of surfactant, CHF has been correlated with surface tension alone and this has been demonstrated in Fig. 1. It is interesting to find that exactly the same surfactant additive (SLS) does exhibit a reversal effect on the CHF results for a thin wire of 0.116 mm diameter and a sphere of 12.7 mm diameter. These experimental results of CHF in surfactant solutions give strong evidence of the influential effects exerted by geometry and geometric scale. Chen *et al.* [6] reached a similar conclusion for the dilemma of CHF in binary systems, such as acetone–water and n-propanol–water, that the increased or decreased CHF may be due to the extent of the contribution from convective heat transfer caused by the bubble motion on different boiling surfaces of different geometry and geometric scale.

Ded and Lienhard [7] formulated a hydrodynamic prediction for pool boiling CHF of pure liquids on a sphere:

$$\frac{q_c}{q_{c,Zuber}} = \frac{1.734}{\sqrt{R'}}, \quad 0.1 \leqslant R' \leqslant 4.26 \tag{1}$$

and

$$\frac{q_c}{q_{c,Zuber}} = 0.84, \quad R' \geqslant 4.26. \tag{2}$$

In equation (1), R' is a dimensionless radius, the Laplace number, defined by

$$R' = R\left[\frac{g(\rho_f - \rho_g)}{\sigma}\right]^{1/2} \tag{3}$$

where R is the radius of the sphere and ρ_f and ρ_g are saturated liquid and vapor densities, respectively. And $q_{c,Zuber}$ is the

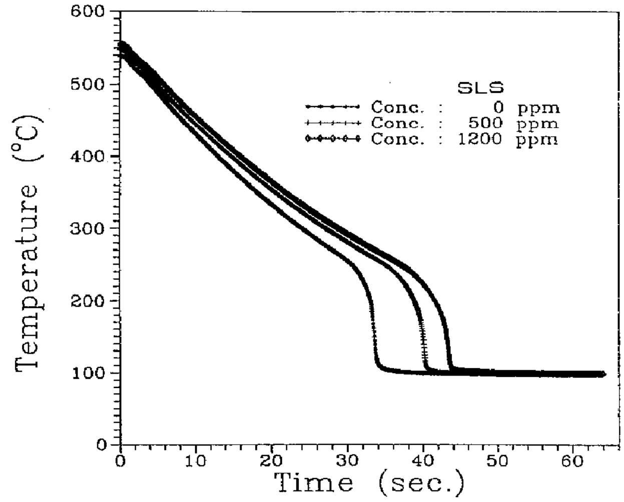

FIG. 2. Quenching curves (surface temperature vs time) for aqueous SLS solutions.

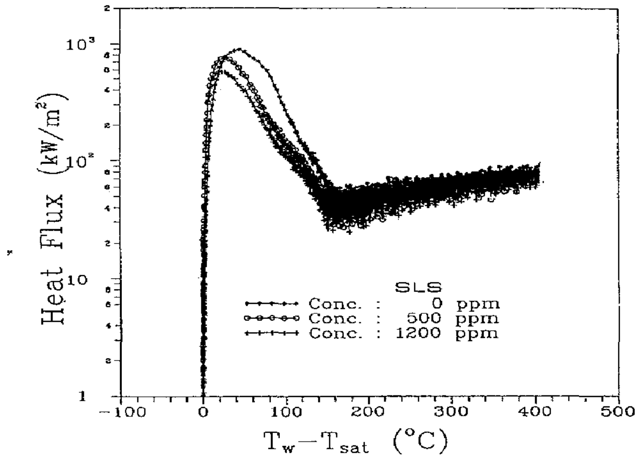

FIG. 3. Saturated boiling curves for aqueous SLS solutions.

CHF predicted by Zuber [8] based on a hydrodynamic instability model for pure liquids on flat-plate heaters:

$$q_{c,\mathrm{Zuber}} = \frac{\pi}{24} \rho_g^{1/2} h_{fg} [\sigma g(\rho_f - \rho_g)]^{1/4} \tag{4}$$

in which h_{fg}, σ, and g are latent heat of vaporization, surface tension and gravitational acceleration, respectively.

The dimensionless radius, R', and predicted CHF by equation (1) are 2.49 and 1206 kW m^{-2}, respectively, for water. With the postulations that Ded and Lienhard's formulation can also apply to surfactant solutions and the degree of surface tension depression by surfactant additive in solutions at boiling point is the same as that at 25°C, CHF values were evaluated by using equation (1), and are shown in Fig. 4. It is obvious that Ded and Lienhard's correlation predicts the decreased CHF but overpredicts CHF values for SLS solutions. Moreover, it fails to predict the still decreasing CHF for a solution with level-off surface tension at higher concentrations.

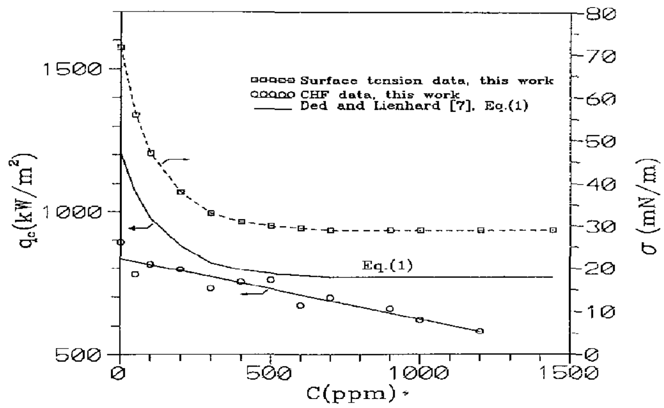

FIG. 4. Variations of critical heat flux (experimental and predicted) and surface tension (25°C) with SLS concentration.

CONCLUSIONS

Saturated pool boiling critical heat flux values for pure water and aqueous SLS solutions (0–1200 ppm) were measured by the quenching method. The quenching sphere of 12.7 mm diameter differs from the elements used by previous investigators [3, 4] in geometry and dimensions. The experimental results show that CHF of water is decreased by the surfactant additive. This trend of surfactant effect is similar to that found by Frost and Kippenhan [3], but contrary to that found by Yang and Maa [4]. It is noticeable that exactly the same surfactant (SLS) does exhibit a reversal effect on the CHF for a thin wire of 0.116 mm diameter and a sphere of this work.

The bewildering status of CHF in aqueous surfactant solutions and binary mixtures is discussed and is due to the extent of the contribution from convective heat transfer caused by the bubble motion on different boiling surfaces of different geometry and geometric scale.

Ded and Lienhard's prediction, equation (1), was tried to correlate the experimental results but with less success in that, while it predicts asymptotic decreased CHF for a solution with level-off surface tension at higher concentration, the CHF data still decrease with increase of concentration.

Acknowledgement—This study was supported by the National Science Council of the Republic of China through grant No. NSC 79-0402-E006-19.

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