



Effects of surface wettability on nucleate pool boiling heat transfer for surfactant solutions

D.S. Wen^a, B.X. Wang^{b,*}

^a Department of Engineering Science, Oxford University, Parks Road, Oxford OX1 3PJ, UK

^b Department of Thermal Engineering, Tsinghua University, Beijing 100084, China

Received 5 March 2001

Abstract

Experiments for pool boiling of deionised water and acetone with different surfactant, 95% sodium dodecyl sulfate (SDS), Triton X-100 and octadecylamine, have been conducted under atmospheric pressure to investigate the effect of surface wettability. The boiling curves for different concentrations of surfactant solution on both smooth and roughened surfaces were obtained. The results show that the addition of surfactant can enhance the water boiling heat transfer, and the enhancement is more obvious for SDS solution; but has little influence on the acetone boiling curve. While the roughened surface enhanced the heat transfer for Triton X-100 solution, it also decreased the heat transfer coefficient for SDS solution. All these can be explained by including the changing of surface wettability, which has been neglected for a long time and should be an important parameter influencing boiling heat transfer. By incorporating such effects, the modified Mikic–Rohsenow pool boiling model, we proposed, can predict these experimental data well. © 2002 Published by Elsevier Science Ltd.

Keywords: Surfactant; Pool boiling; Surface wettability; Rough surface

1. Introduction

It would be desirable to transfer much more heat flux with limited temperature difference between the heating surface and the boiling liquid. Various means have been developed with this aim in mind, including the use of additives to modify the liquid's properties. Small amounts of certain surfactant additives are known to change drastically the boiling phenomena [1,2]. Such boiling phenomena have received continuous interest for a long time. One interesting application of surfactant boiling and evaporation is in dissipating high heat flux from micro-electronic devices. It was shown by Qiao and Chandra [3] that, by the addition of surfactant to water, the spray cooling coefficient was enhanced even up to 300%, and also, the surface temperature required to

initiate vapour bubble nucleation was reduced from 118 to 103 °C.

The concentrations are usually low enough that, the addition of surfactant to water causes no significant change in saturation temperature and most other physical properties, except viscosity and surface tension. The presence of surfactant in the solution can be expressed as either individual monomer or micelles, which is an aggregation of a large number of monomers and can have spherical, cylindrical or lamellar type structure depending upon the nature of surfactant. The transition point from monomers to micelles is referred as critical micelle concentration (CMC). The presence of large number of micelles is to be believed as to increase the fluid viscosity and reduce heat transfer coefficient. Small concentrations of surfactant additives can also reduce the solution's surface tension considerably, and its level of reduction depends on the amount and type of surfactant presented in solution. The reduction of surface tension will influence the activation of nucleate sites, bubble growth and dynamics, thus influence the boiling heat transfer coefficient. Different mechanisms were so far

* Corresponding author. Tel.: +1-86-10-6278-4530; fax: +1-86-10-6277-0209.

E-mail addresses: dongsheng.wen@eng.ox.ac.uk (D.S. Wen), bxwang@tsinghua.edu.cn (B.X. Wang).

Nomenclature	
A	heating surface area
c_p	specific heat capacity
D_d	bubble departure diameter
f	bubble departure frequency
h	boiling heat transfer coefficient
h_{fg}	latent heat of vaporization
I	electric current
n_a	active nucleate site density
q	heating surface heat flux
q_n	heat flux on nucleate site
r	radius
t	time
T	temperature
T_s	saturated temperature
U	electric voltage
<i>Greeks symbols</i>	
α	thermal diffusivity
β	cavity mouth angle
λ	thermal conductivity
ρ	density
θ	contact angle
σ	surface tension, N/m
<i>Subscripts</i>	
l	liquid
v	vapor
w	wall surface

proposed with emphasis on either surface tension or viscosity.

It is generally believed that small amount of surfactant can increase boiling heat transfer. The extent of enhancement has been found to be dependent on additive concentrations, its type and chemistry, wall heat flux, and the heater geometry, as reviewed recently by Wasekar and Manglik [1]. Although many investigators have conducted experiments to determine the boiling enhancement mechanisms caused by addition of surfactants to water, the effects of surfactant on boiling heat transfer are still unclear. Effects of surface tension and viscosity have been extensively investigated for a long time. Kotchaphakdee and Williams [4] investigated nucleate pool boiling heat transfer with dilute aqueous polymer solutions and found significant differences in bubble size and dynamics between polymeric and non-polymeric liquids. They attribute such phenomena to the effects of changing viscosity. Bang et al. [5] studied vapour explosions (Fuel–Coolant Interactions, CFIs) phenomena with both surfactant and dilute polymer solutions which can greatly increase viscosity. They found that the minimum film boiling temperature was firstly decreased drastically with the increasing of polymer concentration, and then maintain constant with further increasing of the concentration. However, the tests with surfactant solutions do not show an appreciable reduction in the minimum film boiling temperature. The tests show the importance of the viscosity in changing minimum film boiling temperature. During nucleate pool boiling of pure water and water with cationic surfactant, Hetsroni et al. [6] recorded the motion of bubbles and the temperature of the heated surface with a high-speed video camera and an infrared radiometer, they found that heat transfer coefficient depend both on the surface tension and the kinematic viscosity; the increase of the heat transfer coefficient at low concentration was attributed to the decreasing of

surface tension, while for high concentration, the increase in kinematic viscosity decreased the heat transfer coefficient. On the other hand, many studies have reported the importance of surface tension decreased by adding additives on the boiling heat transfer coefficient. Frost and Kipperhan [7] investigated boiling of water with various concentrations of surfactant “Ultra Wet 60L” and found the increase of heat transfer being related to the reduced surface tension. Wu and Yang, with their co-workers [8–10], conducted a series of systematic investigations on surfactant boiling with different surfactants and different concentrations. They mainly concentrated on the effects of surface tension. But neither equilibrium nor dynamic surface tension alone can explain the experiments, no unified correlations exist between surface tension and heat transfer coefficient. Different types and concentrations of the surfactant may have different effects on the boiling heat transfer. In their earlier experiments [8], they reported that addition of SDS can significantly decrease the incipient superheat and shorten waiting period, which can be reasonably explained by taking into account the equilibrium surface tension and contact angle changed due to the surfactant. But their later experiments [10] showed that such conclusions cannot be extended to the addition of Aerosol-22, Triton X-100 and DTMAC on water boiling and no convincing conclusion can be drawn. Neither the viscosity theory nor the surface tension effects can explain the results.

Besides changing the kinematic viscosity and surface tension as mentioned above, the wettability of the fluid may change greatly also in some types of surfactant as illustrated in Fig. 1 [10], where the contact angle of water decreased by the addition of Triton X-100. The fluid's wettability was believed to have obvious influence on boiling heat transfer coefficient [11]. Wang and Dhir [12] studied the effects of surface wettability on active nucleation site density during pool boiling of water on a

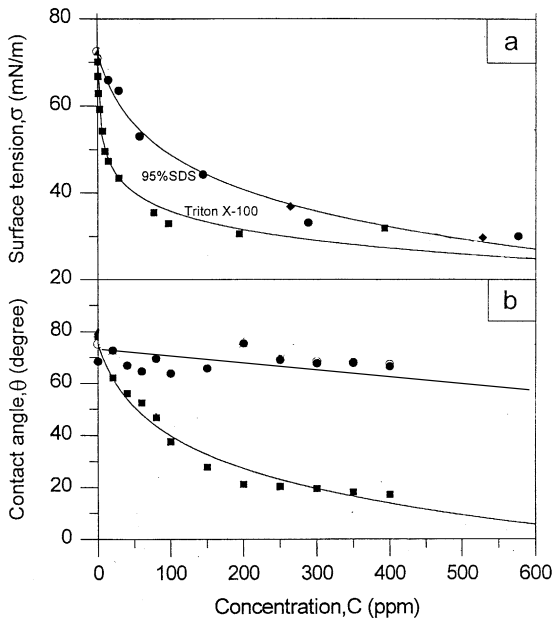


Fig. 1. Surface tension and contact angle vary with concentration (from Wu et al. [10]).

vertical surface. In their experiments, the nucleate site density was reduced more than 20 times when the equilibrium contact angle of water was changed from 90° to 18° . Wang et al. [11] studied the effects of wettability on boiling crisis and found that the CHF increased with improving of surface wettability. It is well known that, the nucleate site density will definitely influence the boiling heat transfer coefficient. But so far, the effects of wettability on surfactant boiling heat transfer have not been noticed and analysed in the open literature.

In the present work, boiling heat transfer experiments of water with three kinds of surfactant, 95% sodium dodecyl sulfate (SDS), Triton X-100 and octadecylamine, were conducted. Both smooth surface and rough surface rubbed by emery papers with different grits, were tested. The purpose is to examine the influence of fluid wettability on pool boiling heat transfer with surfactant solution.

2. Experiments

The experimental setup is shown in Fig. 2. It is composed of three parts: the heating system, the data processing system and the boiling vessel. A flat heater, supplied directly from electric power and adjusted by an electric transformer, was soldered on the back of the boiling surface to provide heat flux. The boiling surface was $50 \times 50 \text{ mm}^2$ rectangular, with depth of 5 mm. Both copper and aluminium surfaces were used in the pre-

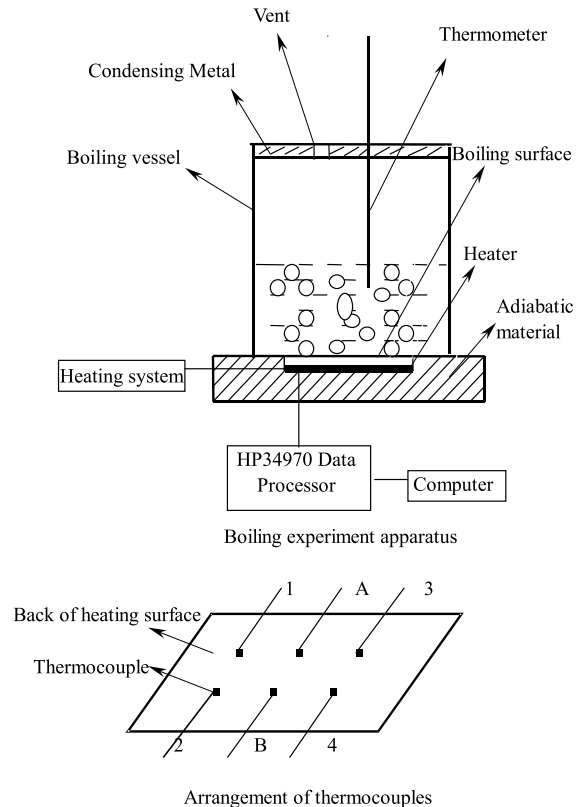


Fig. 2. Experiment setup.

liminary tests, but little difference was found between heating surface materials. When exposed to higher temperature, the copper ages easily, so aluminium surface was selected in the following experiments. At the back of the boiling surface, three $0.5 \times 0.5 \text{ mm}^2$ channels were machined where six T-type thermocouples were hidden. The signals of the thermocouples were collected by a HP 34970 data processor and stored in a computer for future analysis. The boiling vessel was made of organic glass for observation, the top of which was covered by a metal lid to condense the vapour, within which a vent was machined for safety. Thermometer was used to inspect the boiling liquid temperature.

All experiments were performed under atmospheric pressure. Before being filled into the vessel, boiling liquid was pre-heated to saturated temperature in a separate vessel. The inner surface of the boiling vessel was rinsed several times with the same concentration of surfactant solution before each surfactant experiment.

2.1. Data deduction

The voltage, U , and electric current, I , supplying to the heater were used to compute the heat flux as:

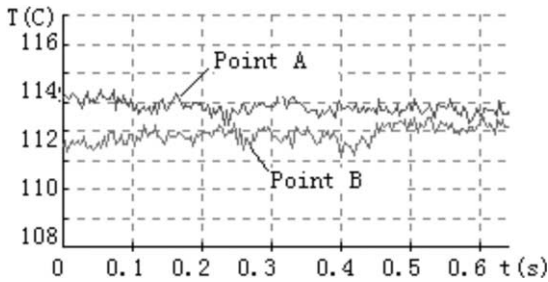


Fig. 3. Typical temperature signal.

$$q = \frac{UI}{A}, \tag{1}$$

where q is the heat flux and A is the heating surface area.

The signals of six thermocouples were recorded simultaneously by the data processor. Typical variation of the temperature signal with time is illustrated in Fig. 3. It can be clearly seen that the temperature distribution on the boiling surface is non-uniform, and around 2 °C temperature difference exists between points A and B . Even at the same point, an obvious temperature fluctuation with time was observed. For the computation of heat transfer coefficient, the time-space averaged temperature was used, i.e.

$$T = \frac{1}{At} \int_A \int_t T dA dt. \tag{2}$$

One-dimensional conduction equation was adopted to compute the boiling surface temperature, or

$$T_w = T - qb/\lambda, \tag{3}$$

where b is the thickness of the heated plate.

The superheat and averaged boiling heat transfer coefficient were defined, respectively, as:

$$\Delta T_w = T_w - T_s, \tag{4}$$

$$h = q/\Delta T_w. \tag{5}$$

2.2. Uncertainty analysis

The thermocouples were provided by OMEGA Company and have an accuracy of 0.1 K. In most of the experiments, the temperature difference was more than 5 °C, so the uncertainty of temperature measurement was $\delta(\Delta T)/\Delta T \leq 2\%$. The uncertainty of voltage and current measurement was $\delta U/U \leq 2\%$, $\delta I/I \leq 2\%$, respectively. Contact resistance between heater and boiling surface and convection heat transfer between boiling vessel and environment are the main sources of heat loss. Both convection and conduction equations were used to estimate heat loss; the result shows that uncertainty $\varphi \leq 5\%$. The heat imbalance inaccuracy was estimated as $\varepsilon \leq 4\%$. So, the estimated total heat flux uncertainty in this experiment was

$$\frac{\delta q}{q} = \sqrt{\left(\frac{\delta I}{I}\right)^2 + \left(\frac{\delta U}{U}\right)^2 + \varepsilon^2 + \varphi^2} \leq 8\% \tag{6}$$

and the estimated uncertainty of the heat transfer coefficient was

$$\frac{\delta h}{h} = \sqrt{\left(\frac{\delta q}{q}\right)^2 + \left(\frac{\delta \Delta T}{\Delta T}\right)^2} \leq 8\%. \tag{7}$$

3. Experimental results and discussion

General observations show that more bubbles were activated in surfactant boiling solutions compared with boiling of pure water. The bubbles nucleated uniformly on the aluminium surface and grow up rapidly, accompanied by decreased bubble departure diameters and increased departure frequency.

Experimental data were plotted in Figs. 4–9.

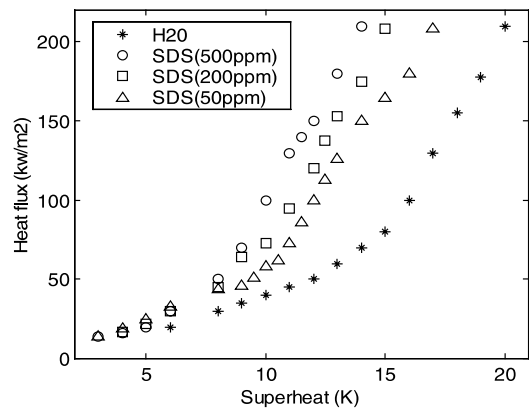


Fig. 4. Concentration effects.

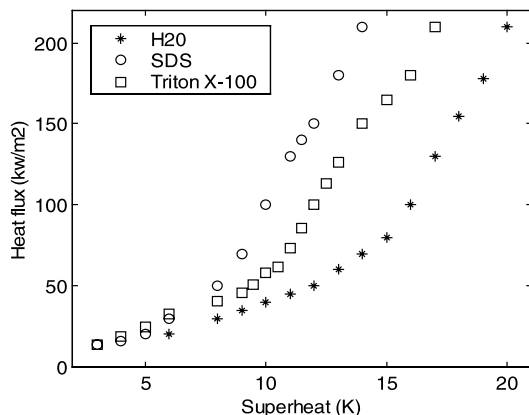


Fig. 5. Comparison of additives SDS and Triton X-100.

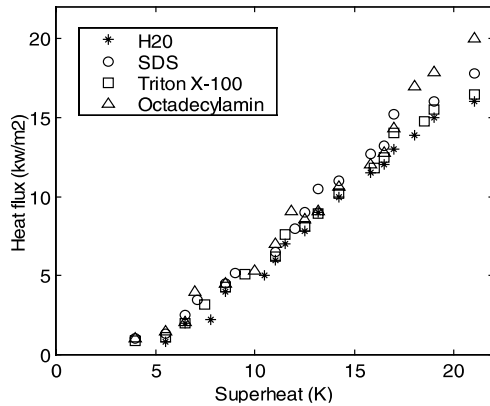


Fig. 6. Surfactant effects on acetone boiling.

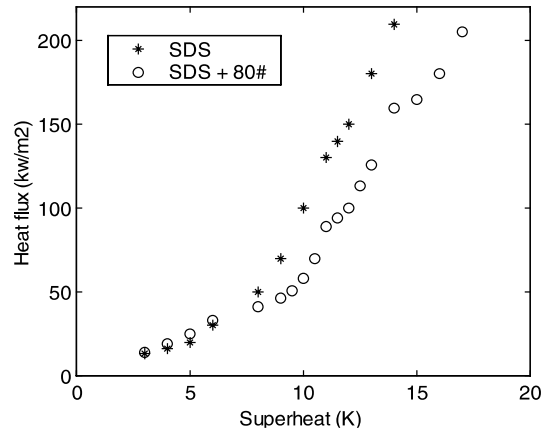


Fig. 9. Effects of roughness on SDS solution.

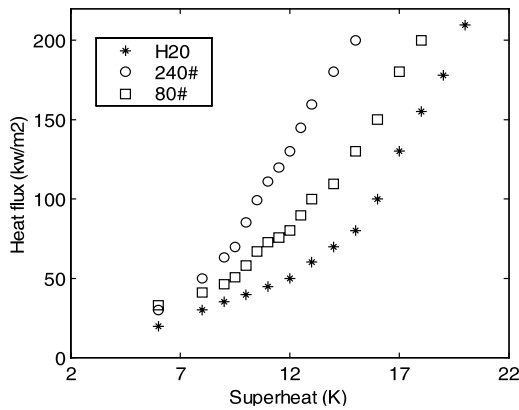


Fig. 7. Effects of roughness on distilled water.

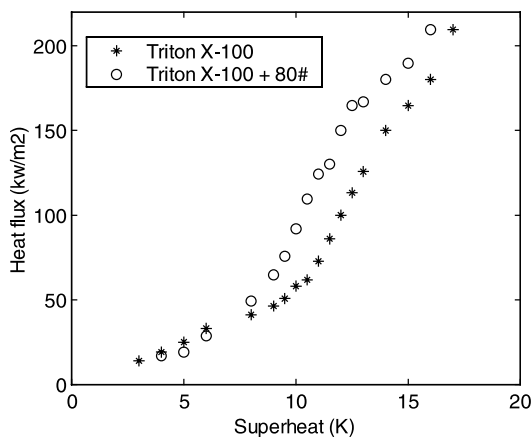


Fig. 8. Effects of roughness on Triton X-100.

3.1. Effects of surfactant solution concentration on boiling heat transfer

It can be seen from Fig. 4 that the boiling heat transfer coefficient was greatly increased by adding SDS.

Different concentrations of SDS solution display different degrees of increase in heat transfer coefficient. This agrees qualitatively with the experimental results of Wu et al. [8], except when stated otherwise for the surfactant solution with concentration of 500 ppm for Figs. 4–9.

3.2. Effects of different surfactant solutions on boiling heat transfer

Figs. 5 and 6 illustrate the effect of different types of surfactant on the boiling curve of water and acetone, respectively. The addition of both SDS and Triton X-100 caused the water boiling curve to shift to the left, i.e. improving the pool nucleate boiling heat transfer. Compared with that for Triton X-100 solution, the heat transfer coefficient was increased more obviously by SDS solution at the same concentration. But for boiling with the organic liquid, acetone, little difference was found among the three surfactant solutions as illustrated in Fig. 6.

3.3. Effects of surface roughness on boiling heat transfer

The surface roughness was controlled by rubbing the smooth surfaces with 80# and 240# emery paper, the larger the paper number, the more roughened the surface. Boiling experiments with pure water were first conducted on the roughened surface; then 500 ppm SDS and Triton X-100 surfactant solutions were heated both on the smooth surface and roughened surface. The results were illustrated in Figs. 7–9. For boiling of water without adding surfactant, the boiling heat transfer coefficient increased with increasing surface roughness, which is also the same trend as Triton X-100 solution as illustrated in Fig. 8. But for SDS solutions in Fig. 9, rather than enhancement of boiling heat transfer, decreased boiling heat transfer was observed on roughened surface.

4. Discussion

It is hard to analyze the influence of one parameter while maintain others constant in experiments. The change of one parameter will always change other related properties. Due to the constriction of the present experiments, the interfacial properties and kinematic viscosity were not measured specially.

For a boiling bubble in saturated water as well as in surfactant solutions, typical bubble growth times are in the range of 25–30 ms, and the characteristic surfactant diffusion timescale is of the order of 10–15 ms. The comparable bubble growth and surfactant diffusion timescale suggest that the dynamic surface tension at boiling temperature should be employed in the analysis. But due to the difficulties in measuring, big diversities have been found in public literatures. Wasekar and Manglik [2] have measured and compared dynamic and equilibrium surface tension at the temperature of both 23 and 80 °C. Since the dynamic surface tension is always greater than the equilibrium surface tension and the surface tension decreases with increasing temperature, the equilibrium surface tension at room temperature is indeed comparable to the dynamic surface tension at boiling temperature. So, the stable interfacial parameters for water at room temperature illustrated in Fig. 1 [10] were used here as a first estimation.

The solution viscosity increases obviously when the surfactant concentration exceeds the CMC and large number of micelles have been formed. As pointed by Wasekar and Manglik [2], the CMC of SDS solution is in the order of 2500 ppm, which is far beyond our experimental conditions. The viscosity seems to have no salient influence on the results. So the difference between water boiling with surfactant solution SDS and Triton X-100 lies in the interfacial properties, i.e. surface tension and contact angle. As illustrated in Fig. 1, the solutions' surface tension decreases with the increasing surfactant concentration, which can qualitatively explain the observed phenomena thereby. The lowered surface tension can reduce the critical nucleation radius, as expressed by Eq. (13), thus proceeding more active nucleation sites. It can also allow the departures of smaller sized bubbles due to the reduction in surface tension force at the heater surface that counters the buoyancy force trying to pull the bubble away from the surface. The bubble growth time could be expected consequently as being reduced, and hence, leads to an increase the bubble departure frequency accordingly.

As illustrated from Fig. 1, although both 500 ppm SDS and Triton X-100 solution display nearly the same surface tension, approximately 30 mN/m, the difference between contact angles is salient. The contact angle formed by SDS solution is insensitive to the change of concentration, but for Triton X-100, when concentra-

tion is increased to 500 ppm, the contact angle decreases from 76 to 17 °C. So, the different enhancements of boiling heat transfer between 500 ppm solution of SDS and Triton X-100 should be caused by different contact angles. This means, the reduced contact angle, or improving the surface wettability, may explain why the measured boiling heat transfer coefficient for surfactant solution of SDS differs from that for surfactant Triton X-100.

The surface roughness was believed to increase the boiling heat transfer coefficient by increasing the nucleation site density as many investigators have proposed. But as pointed out by Wang et al. [11], besides providing more nucleate sites, the roughness can also change the surface wettability to a great extent. Based on the equilibrium analysis of changing free energy, the apparent contact angle for a roughed surface, θ_R , can be expressed as [13]:

$$\cos \theta_R = \frac{\sigma_{sv} - \sigma_{sl}}{\sigma_{lv}} \gamma = \gamma \cos \theta, \quad (8)$$

where γ is the area ratio of roughness surface to smooth surface, or

$$\gamma = A_r/A_s. \quad (9)$$

Obviously, the area ratio is greater than 1, so the apparent contact angle will be smaller for roughed surface than that for smooth surface.

Surface wettability would have great influence on the activation of nucleate sites, as illustrated in Fig. 10. The criterion for activation of cavity is $\theta \geq \beta$. Theoretically, the density of active nucleation site's, n_a , as proposed by Yang and Kim [14], can be integrated as:

$$n_a = n_s \int_{r_{\min}}^{r_{\max}} \varphi(r) dr \int_0^\theta \phi(\beta) d\beta, \quad (10)$$

where n_s is cavity density, r_{\max} and r_{\min} are the maximum and minimum active radius, respectively, $\varphi(r)$ is the cavity radius distribution function and $\phi(\beta)$ is the distribution of cavity mouth angle. Hence, it would be clear that, decreased contact angle will decrease the number of active nucleate sites.

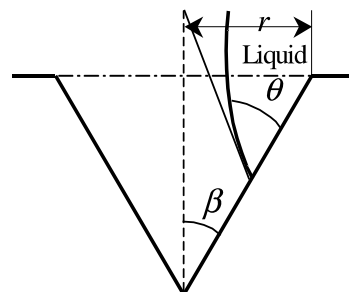


Fig. 10. Illustration of wettability effects.

For the same concentration of surfactant solution, boiling experiment, both the surface tension and viscosity are kept the same, the different experimental results on smooth surface and on roughened surface will be attributed to the differences in nucleate site density and apparent contact angle. The increase in nucleate site density for rough surface will enhance the boiling heat transfer, generally, however, the decreased apparent contact angle will cause nucleate sites more difficult to be activated. The actual effect of roughness on boiling heat transfer will depend on these two factor's dual influence. It can be inferred from Fig. 9 with special consideration of Fig. 1, that the dominant influencing factor for surfactant boiling of SDS is the apparent contact angle. Although the surface rubbed by the emery paper will provide more nucleate sites compared with the smooth surface, the decreased apparent contact angle, or improved surface wettability, may cause more sites being activated, which in turn, decreased the boiling heat transfer coefficient. For Triton X-100, the dominant factor is the increase of nucleate sites. From Fig. 1, the contact angle for SDS solution at 500 ppm is already quite low, around 17 °C, so the further decrease of contact angle by roughened surface was not important for the activation of nucleation site and the influence of apparent contact angle becomes smaller therefore.

5. Modification of the Mikic–Rohsenow pool boiling model

Although the mechanism of surfactant pool nucleate boiling heat transfer is still not clear, the application of surfactant boiling in industries calls for the prediction of heat transfer coefficient. There are large numbers of nucleate pool boiling heat transfer correlations based on different view of mechanism, but so far, no suitable heat transfer correlations directly related to the surfactant solution boiling. Due to the great change of surface properties, possibly the kinematics viscosity, it should be cautious to directly apply ordinary pool boiling heat transfer correlations to surfactant solution boiling. The effects of wettability should be also included into the correlation to verify its role in surfactant boiling.

Nearly all the traditional correlations depend mainly on the nucleate site density and superheat, which can be concluded as the following form:

$$q'' \sim (n_a)^{a_1} (T_w - T_s)^{a_2}, \quad (11)$$

where a_1, a_2 are experimental constants, a_1 ranges from 1/3 to 4/3 and a_2 ranges from 1 to 1.5. n_a is the active nucleate site density and can be expressed as

$$n_a = C(1/r_c)^m, \quad (12)$$

where r_c is the critical site radius for nucleation, mainly influenced by surface tension and superheat as

$$r_c = \frac{2T_s\sigma}{h_{fg}\rho_v\Delta T_s}, \quad (13)$$

where C and m are experimental constants, where m ranges from 3 to 7 depending on different situations. According to Eq. (12), when the surface tension was half decreased, the active nucleation sites should increase $2^3 - 2^7$ times. Although obvious increase of nucleate sites were observed in the experiments and other public literatures, the degree of enhancement is not so intensive. As pointed by Wu et al. [10], neither equilibrium nor dynamic surface tension alone can predict active nucleate sites well, no unified correlations between surface tension and heat transfer coefficient exist. Based on above discussions, surface wettability would be an important parameter in surfactant boiling and should be included in the modelling.

Among the traditional models, the important one is Mikic–Rohsenow (M–R) model [15], which assumes the main mechanism of heat transfer in nucleate boiling being transient heat conduction, that is:

$$q = -k_l \left(\frac{\partial T}{\partial y} \right)_{y=0} = \frac{K_1(T_w - T_s)}{(\pi\alpha_l\tau)^{1/2}}. \quad (14)$$

By neglecting the convection effects, the heat flux for one nucleate site can be expressed by,

$$q_n = f \int_0^{1/f} q_b d\tau = \left(\frac{4k_l\rho_l c_{pl}}{\pi} \right)^{1/2} (T_w - T_s) f^{1/2} \quad (15)$$

and the averaged heat flux is,

$$q = \frac{\pi D_d^2}{4} n_a q_b. \quad (16)$$

So,

$$q = \frac{1}{2} (\pi k_l \rho_l c_{pl})^{1/2} f^{1/2} D_d^2 n_a (T_w - T_s), \quad (17)$$

where D_d is the departure diameter and f is the departure frequency, or

$$D_d = A_1 \left[\frac{\sigma}{(\rho_l - \rho_v)} \right]^{1/2} \left(\frac{\rho_l C_{pl} T_s}{\rho_v h_{fg}} \right)^{5/4}, \quad (18)$$

$$f D_d = A_2 [\sigma(\rho_l - \rho_v)/\rho_v^2]^{1/4}, \quad (19)$$

where A_1 and A_2 are experimental constants: $A_2 = 0.6$; $A_1 = 1.5 \times 10^{-4}$ for water, and $A_1 = 4.65 \times 10^{-4}$ for other fluid.

The comparison of Eq. (17) with experimental data is shown in Fig. 11. Only at very lower superheat, the predicted value fits experiment; with the increase of superheat, the Mikic–Rohsenow model [15] overpredicts the heat transfer coefficient for both SDS and Triton X-100. Nearly 100% overprediction exists at superheat of

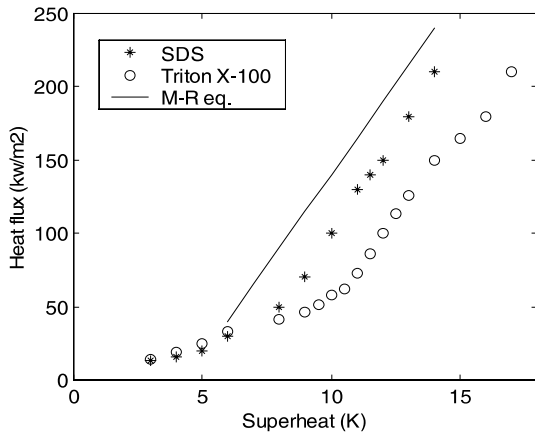


Fig. 11. Comparison of M-R (Mikic-Rohsenow) equation with experiment.

12 °C for Triton X-100 solution. Apparently, the Mikic-Rohsenow model [15] cannot be used to predict the surfactant pool boiling heat transfer coefficient without being modified.

The active nucleate site correlation of Wang and Dhir [12] was adopted here to incorporate the effects of surface wettability,

$$n_a = C \left(\frac{1}{r_c} \right)^m (1 - \cos \theta), \quad (20)$$

where $C = 5 \times 10^5$ and $m = 6$. Hence, we have

$$q = B[\phi(T_w - T_s)]^{m+1} C(1 - \cos \theta) \mu_l h_{lv} \left[\frac{\sigma}{(\rho_l - \rho_v)} \right]^{-1/2} \quad (21)$$

with

$$\phi^{m+1} = \left(\frac{k_l^{1/2} \rho_l^{17/8} C_{pl}^{19/8} h_{lv}^{m-23/8} \rho_v^{m-15/8}}{\mu_l (\rho_l - \rho_v)^{9/8} \sigma^{m-11/8} T_s^{m-15/8}} \right), \quad (22)$$

$$B = A_1^{2/3} A_2^{1/2} \left(\frac{2}{\pi^{1/2} g^{9/8}} \right), \quad (23)$$

where B is the experimental constant in Mikic-Rohsenow's model [15].

The modification here, Eq. (21), is temporary only to include the wettability effect on the existing correlation. Comparisons of this modified equation with present experimental data are shown in Figs. 12 and 13. For boiling with SDS solution, the modified equation slightly underestimates the experiment. For Triton X-100, it overpredicts the experimental value. Much progress was achieved as compared with original Mikic-Rohsenow correlation. The experimental data of Wu et al. [10] were used here to examine the modified model as illustrated in Fig. 14, good agreement is obtained by

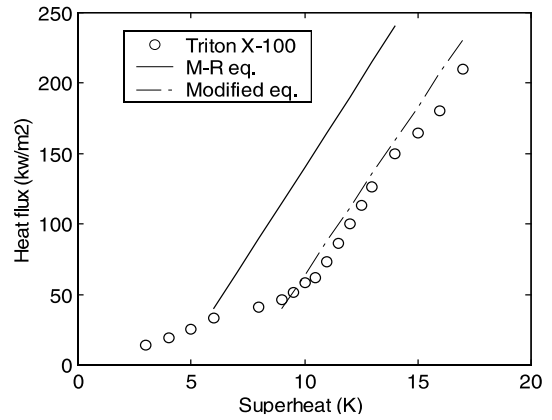


Fig. 12. Comparison with Triton X-100 solution.

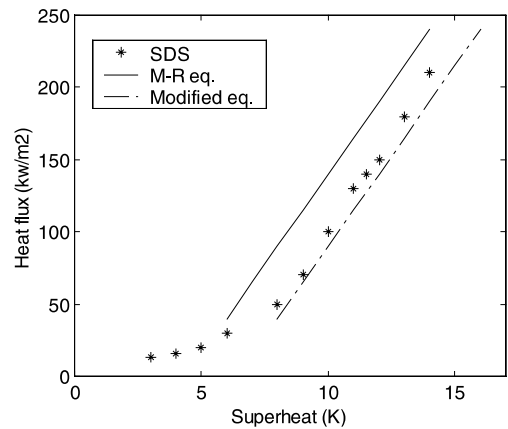


Fig. 13. Comparison with SDS solution.

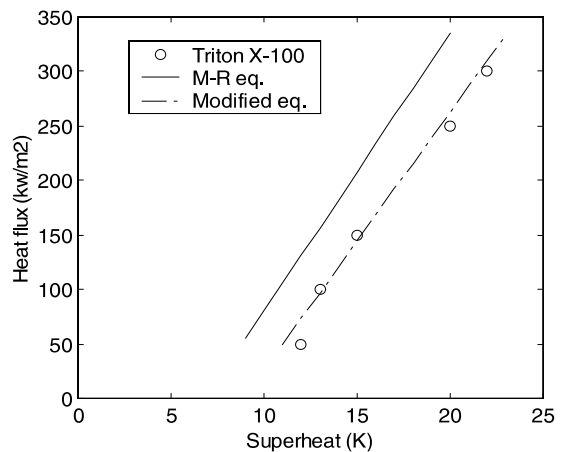


Fig. 14. Comparison with Wu et al.'s experiments [10].

including the effects of surface wettability into the modelling of pool boiling heat transfer in surfactant solutions.

6. Conclusion

Due to lack of experimental data on surface tension, kinematics viscosity and wettability, the results of this paper are preliminary, more detailed experiments should be conducted before unified conclusion can be drawn. But with regard to the mechanism of boiling in surfactant solutions, neither kinematic viscosity theory nor surface tension theory alone can give a persuasive explanation. This paper shows that wettability is an important parameter in surfactant boiling and should be taken into consideration. Following conclusions can be drawn based on experiments and discussions:

1. Both SDS and Triton X-100 solution can increase the water boiling heat transfer coefficient but have little influence in acetone boiling curve. The enhancement of heat transfer is more obvious for SDS solution.
2. While the roughened surface enhanced heat transfer for Triton X-100 solution, it decreased the heat transfer coefficient for SDS solution.
3. These interesting phenomena can be explained by considering the changing of surface wettability, which was neglected in open literature for a long time and should be an important parameter influencing boiling heat transfer in surfactant solution.
4. By incorporating the effect of surface wettability, the modified Mikic–Rohsenow pool boiling heat transfer correlation can predict surfactant solution boiling experimental data well.

Acknowledgements

The project financially supported by the National Natural Science Foundation of China with Contract Number #59995550.

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