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Technical Note

Pool boiling incipience and vapor bubble growth dynamics in surfactant solutions

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1. Introduction

Small amounts of certain surfactant additives are known to significantly enhance the nucleate boiling heat transfer of water. Because the concentrations are usually low, addition of the surfactant to water causes no significant change in physical properties, except for the surface tension, which is greatly reduced. In fact, this important variable has been consistently subjected to study for its relationship to boiling heat transfer in the past. If the nucleate boiling heat transfer coefficient (h) is related to the equilibrium surface tension (σ) of the aqueous surfactant solution by the following equation

$$h \propto \sigma^n \tag{1}$$

the values of constant n were found to range from 0 to -3.3.

Wu et al. [1] discussed the role of surface tension in boiling phenomena. On nucleation theoretical grounds, they concluded that a decrease in surface tension by surfactant additive may have no effect or it may increase the rate of boiling heat transfer. It cannot decrease the heat flow. They also carried out systematic experiments in the exactly same apparatus to determine the effect of nine different surfactant additives on nucleate boiling heat transfer of water. The diversity of experimental results, revealed that the effect of equilibrium surface tension on nucleate boiling heat transfer is still unproved. The possibility of the existence of a universal correlation such as equation (1) should be excluded.

The situation thus comes out to be: while surfactant additives generally depress surface tension, the primary effect of them on boiling heat transfer is due to factors that may be at best only indirectly related to changes in surface tension. We are still far from a systematic theory or explanation for the enhancement of boiling heat transfer caused by surfactant additives. It seems that some more fundamental boiling phenomena should be studied before the problems can be elucidated and the practical application of surfactant additives in commercial plants is possible.

The objective of this work is to report the new systematically obtained experimental data of boiling incipience and vapor bubble growth dynamics on target cavities for four additives—including anionic, cationic, and nonionic surfactants. One of the surfactants studied in this work, i.e. sodium dodecyl sulfate (SDS), is exactly the same as that used in the previous work (Wu et al. [2]). The results were also subjected to examining by the possible theoretical explanations. It aims at generalizing the conclusions drawn previously for SDS.

2. Theoretical background

2.1. Surfactant effect on boiling incipience

By considering a cavity with mouth radius r_c on a heated surface, Hsu [3] postulated that the criterion for the bubble embryo to grow is the condition in which the liquid temperature at the bubble cap is equal to or greater than the bubble interior temperature. The liquid temperature can be represented by the temperature profile in a thermal boundary layer. Because of turbulence in the bulk of the liquid, thermal boundary layer cannot grow beyond a limiting thickness δ. The incipience of boiling thus occurs at an incipient superheat

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$$\Delta T_{\mathrm{incip}} = \frac{\dfrac{2T_{\mathrm{sat}}\sigma}{h_{\mathrm{fg}}\rho_{\mathrm{v}}r_{\mathrm{c}}}}{C_2(1-\dfrac{C_1 r_{\mathrm{c}}}{\delta})} \tag{2}$$

where T_{sat}, h_{fg}, and ρ_{v} are saturation temperature, latent heat of vaporization, and vapor density, correspondingly; $C_1 = (1+\cos\theta)/\sin\theta$ and $C_2 = 1/\sin\theta$.

By assuming that Hsu's nucleation criterion for boiling is also valid, the incipient superheats in surfactant solutions over a cavity with mouth radius r_{c} can then be calculated by equation (2) if data of surface tension, contact angle, and thickness of thermal boundary layer can be collected.

2.2. *Surfactant effect on ebullition cycle in nucleate boiling*

As the cavities on a heating surface are activated, ebullition over them takes place thereafter.

2.2.1. *Waiting period*

Following the general postulation of Hsu [3] as mentioned above, an explicit form of waiting period can be obtained

$$t_{\mathrm{w}} = \frac{1}{\pi\alpha}\left(C_1 r_{\mathrm{c}} + \frac{2kT_{\mathrm{sat}}\sigma}{C_2 h_{\mathrm{fg}}\rho_{\mathrm{v}} r_{\mathrm{c}} q}\right)^2 \tag{3}$$

where α, k and q are liquid thermal diffusivity, thermal conductivity, and heat flux, correspondingly. Substituting surface tension and contact angle data in equation (3), the waiting period for a bubble to grow in surfactant solution over a cavity under a heat flux is then determined.

2.2.2. *Vapor bubble growth rate and vapor bubble departure diameter*

The basis for the majority of pool boiling vapor bubble departure correlations is the supposition that at the point of departure the net force acting on the bubble is zero. Zeng et al., [4] proposed that the buoyancy force and growth force are the only two forces that should not be neglected at the point of departure. In their analysis, the vapor bubble growth rate $r(t)$ is required. For vapor bubbles growing in a nonuniform temperature field, the theoretical determination of $r(t)$ is too complex, and the determination of $r(t)$ based on empiricism is usually used instead. In general the vapor bubble growth rate follows a power law

$$r(t) = Kt^n \tag{4}$$

where constants K and n may be determined from the measured vapor bubble growth data based on a least squares regression analysis.

The balancing of buoyancy force by growth force then results in

$$d = 2\left\{\frac{3}{4}\frac{K^{\frac{2}{n}}}{g}\left[\frac{3}{2}C_s n^2 + n(n-1)\right]\right\}^{\frac{n}{(2-n)}} \tag{5}$$

where d is the departure diameter and $\rho_{\mathrm{v}}/\rho_{\mathrm{l}} \ll 1$ has been assumed. The value of C_{s} is determined from the best fit to the data of the measured bubble departure diameter based on a least squares regression analysis.

3. Experimental

The pool boiling apparatus and the method used in this work is basically the same with that used by Wu et al. [1, 2]. These two references may be consulted for the details of the apparatus and the experimental data uncertainty.

A suitable site is desirable for studying the surfactant effect on boiling incipience and vapor bubble growth dynamics from it. The stable target site can be chosen by alternatively raising and reducing the heat flux. Once this determination has been made, the tubular heater was subjected to turning so that the target site was at the uppermost position of the tube so as to get the best view of bubble. Taking advantage of this opportunity is actually one of the reasons why a tubular heater is chosen in this study as the heating surface. The water soluble surfactants used in this work are sodium dodecyl sulfate (SDS), n-octadecyl tetrasodium 1,2 dicarboxyethyl sulfosuccinamate (Aerosol-22), dodecyl trimethyl ammonium chloride (DTMAC), and polyoxyethylated *t*-octylphenol (Triton X-100).

Surface tensions of the aqueous surfactant solutions were measured at room temperature ($25 \pm 1^{\circ}$C) with commercial equipment (CBVP-A3 Type, Kyowa Interface Science Co. Ltd., Japan) by the Wilhelmy plate method. On the other hand, contact angles were also measured on a stainless steel flat plate with another commercial equipment (CA-A type, Kyowa Interface Science Co. Ltd., Japan).

4. Results and discussion

4.1. *Interfacial properties of surfactant solutions*

The equilibrium surface tensions and contact angles for various surfactant solutions are shown in Fig. 1. It was found that the depression of equilibrium surface tension increases in the order: Triton X-100 > SDS > Aerosol-22 > DTMAC. And all surfactants except Triton X-100, which drastically decreases the contact angle, have insignificant effect on contact angle. In this situation, the contact angle for aqueous surfactant solutions on stainless steel flat plate is constantly about 75°.

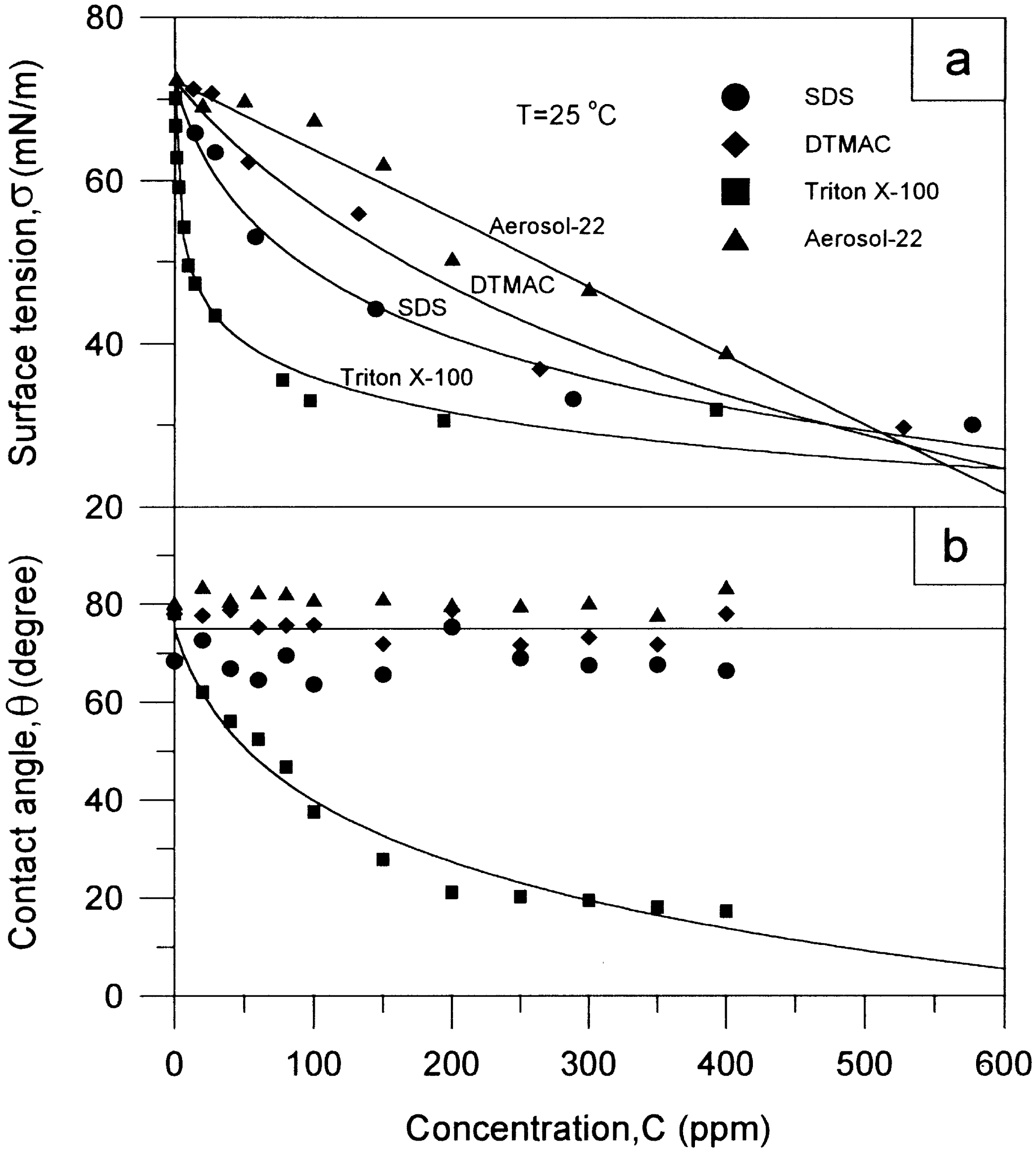

Fig. 1. (a) Equilibrium surface tensions of surfactant solutions, (b) Equilibrium contact angles of surfactant solutions over stainless steel flat plate.

4.2. Boiling incipience

It is desirable that the surfactant effects on boiling incipience can be examined at the exactly same cavity on the heating surface for all surfactants under studying. Unfortunately the identified target cavity for the previous experiment usually ceased re-nucleating after the cleansing procedure has been completed and the system got ready for the next experiment in the series of runs for all surfactants except SDS. In these situations, some other cavities near the original one may nucleate instead. Therefore, the effect of a specific surfactant on boiling incipience can only be examined by comparing the incipient superheats to that of pure water and SDS solutions at the same cavity. A comparison between the measured and predicted incipient superheats using equation (2) by taking the variations of equilibrium surface tension σ and contact angle θ into consideration is shown in Fig. 2. The thickness of the superheated boundary layer, δ, is approximately assumed to be 380 μm as measured by Chou and Yang [5] for aqueous SDS solutions at the onset of nucleate boiling. It should be noted that the

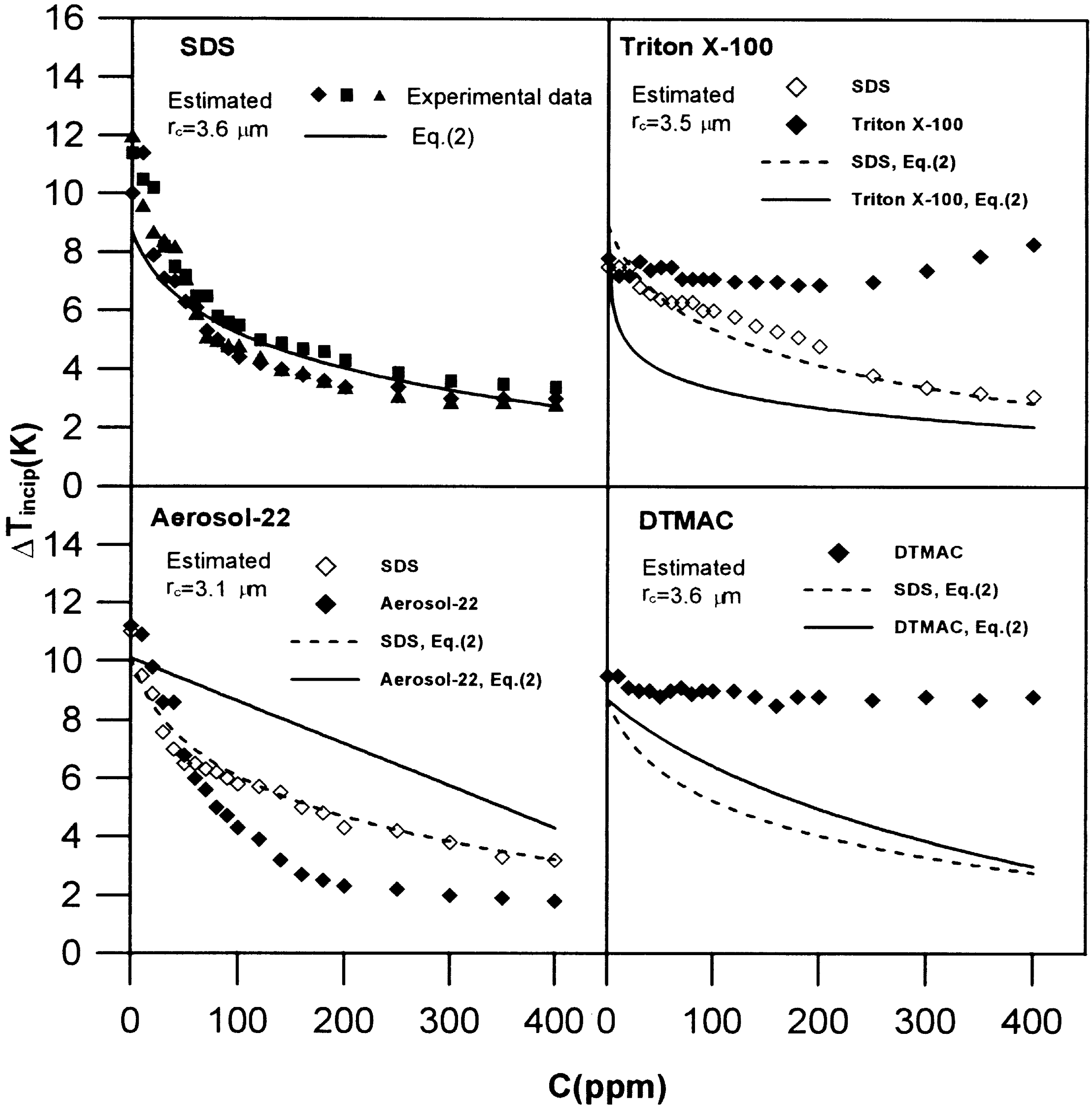

Fig. 2. Boiling incipient superheats in surfactant solutions under atmospheric pressure.

experimental data of pure water and SDS solutions at the survived target cavity have been used to estimate the radius of the cavity mouth, which is needed for predicting the incipient superheats in solutions of other surfactants, by best fitting. The experimental results show that the addition of SDS and Aerosol-22 causes a significant decrease in incipient superheat as predicted by the theory although the measured and predicted results are not in very good quantitative agreement. On the other hand, while the theory predicts a decrease in incipient superheat, the addition of Triton X-100 and DTMAC causes nearly no change in incipient superheat. The promotion of boiling incipience by the addition of a surfactant, as previously evidenced for SDS [2], seems not to be a universal phenomenon.

4.3. *Vapor bubble ebullition cycle*

It is obvious that the bubbles do not grow at the same rate—even for successive bubbles from the same cavity.

Statistical samples of experimentally determined waiting periods, growth rates, and departure diameters were collected and are shown in Table 1. The radii of cavity mouth were estimated by equation (3) based on the average waiting period data of pure water.

4.3.1. *Waiting period*

By considering the variations in equilibrium surface tension and contact angle, the waiting periods in surfactant solutions can be predicted by equation (3). The experimental results show that while the addition of SDS drastically shortens the waiting period as also evidenced previously [2], the addition of Aerosol-22, Triton X-100, and DTMAC causes insignificant change in waiting period in view of the scattering of data. The theory, however, is found to ill-describe the surfactant effect of Triton X-100 on waiting period.

4.3.2. *Vapor bubble growth rate*

Bubble growth rate equations in the form of equation (4) were determined from the experimental data based on a least squares regression analysis. Effect of various surfactants on bubble growth rate can then be evaluated. Except for SDS and DTMAC, other surfactants seem to cause insignificant influence on the average bubble growth rate in the range of concentrations studied in view of the scattering of data.

4.3.3. *Departure diameter*

Besides K and n, the value of C_s in equation (5) is required for estimating the bubble diameter at departure. The C_s values were determined from the best fit to the data of the measured bubble departure diameter in water based on a least squares repression analysis. By assuming that the same C_s value is valid for the same cavity, the comparison between the measured and the predicted departure diameters in surfactant solutions can then be made. The addition of SDS caused bubble departure diameter to become smaller as also evidenced previously [2]. The average bubble departure diameter is reasonably estimated by the dynamic vapor bubble growth model. However, in view of data scattering, convincing conclusion for effect of other surfactants on bubble departure diameter cannot be drawn.

5. Conclusions

Surfactant effects on boiling incipience and single vapor bubble growth dynamics were systematically studied in a pool boiling apparatus for SDS, Aerosol-22, DTMAC, and Triton X-100. The values of incipient superheat ΔT_{incip} can be determined by measuring the incipient wall temperatures over the identified target cavities on a tubular heater. By analyzing the films, in which

Table 1
Experimental data of vapor bubble growth dynamics. $q = 28$ kW/m^2. Film speed = 1720 frames/sec

	SDS			Triton X-100			Aerosol-22			DTMAC
	0 ppm	50 ppm	100 ppm	0 ppm	50 ppm	100 ppm	0 ppm	50 ppm	100 ppm	100 ppm
Estimated r_c (μm)	5.0			6.6			10.3			
Wall superheat (ΔT_{sat}, K)	7.0	6.5	6.3	9.0	8.5	8.2	8.7	8.4	7.3	7.5
Bubble cycles	15	39	75	21	49	50	67	10	46	38
Waiting period ($t_w \times 10^3$, s)										
ave.	47.6	5.9	3.6	29.2	23.9	23.3	14.5	19.9	15.8	28.6
std.	8.7	7.9	4.7	11.5	7.0	8.7	9.0	8.7	9.6	14.4
Growth period ($t_g \times 10^3$, s)										
ave.	7.0	12.0	10.7	4.1	7.5	5.5	6.9	5.4	4.9	3.5
std.	2.0	5.8	6.4	1.9	2.0	1.6	2.0	1.7	2.2	0.7
Period ($t_c \times 10^3$, s)										
ave.	54.6	17.9	14.3	33.3	31.4	28.8	21.4	25.3	20.7	32.1
std.	8.8	7.0	6.9	12.2	8.3	8.6	10.1	8.3	10.9	14.6
Departure diameter ($d \times 10^3$, m)										
ave.	3.6	2.8	2.4	2.0	3.0	2.2	2.8	1.9	1.9	1.6
std.	0.9	0.6	0.7	0.7	0.6	0.4	0.8	0.5	0.8	0.2
K in equation (4)	0.00888	0.00521	0.004128	0.01347	0.01350	0.00830	0.01175	0.00841	0.01276	0.001886
n in equation (4)	0.2997	0.2855	0.2591	0.4398	0.4228	0.3706	0.4102	0.4013	0.4546	0.1407
C_s in equation (5)	2.7824			1.1735			2.0617			

ave.: average value; std.: standard deviation.

ebullition cycles over identified target cavities at a low heat flux were photographed by using a high speed camera, frame by frame, the values of waiting period t_w, growth rate dr/dt, and departure diameter d can then be evaluated. The experimental results of SDS obtained in this work reconfirm the conclusions drawn previously [2] for itself, that is,

- the addition of SDS will significantly decrease the incipient superheat and shorten the waiting period;
- the occurrence of boiling incipience and the shorter waiting period would be reasonably explained by taking the equilibrium surface tension depression and contact angle change into consideration in Hsu's model [3];
- the addition of SDS will also influence the average bubble growth rate and cause vapor bubble departure diameter to become considerably smaller. The average bubble departure diameter is reasonably estimated by the dynamic vapor bubble growth model.

The experimental results of other surfactants, however, reveal the surfactant effects as follows.

1. The addition of Aerosol-22 also causes significant decrease in incipient superheat as predicted by the theory although the measured and predicted results are not in very good quantitative agreement. On the other hand, while the theory predicts decrease in incipient superheat, the addition of Triton X-100 and DTMAC causes nearly no change in incipient superheat.
2. The addition of Aerosol-22, Triton X-100, and DTMAC causes insignificant change in the waiting period in view of data scattering. The theory is found to be ineffective at describing the surfactant effect of Triton X-100 on waiting period.
3. In view of data scattering, the surfactants seem to cause insignificant influence on the average vapor bubble growth rate and the departure diameter. Convincing conclusions cannot be drawn.

Therefore, while surfactant effects on boiling incipience and single vapor bubble growth dynamics are evidenced once again for SDS, it is wise to suspend a hasty generalization.

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