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Urquiola, Erwin

Department of Mechanical Engineering Science : Graduate Student

Fujita, Yasunobu

Department of Mechanical Engineering Science : Professor

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Contact Angle Effects in Boiling Heat Transfer

by

Erwin URQUIOLA* and Yasunobu FUJITA**

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Abstract

This paper reports boiling experiments with pure water and surfactant solutions of SDS on horizontal heating surface. The static contact angle, rather than the surface tension value, was found to be the leading factor for the results and probably its previous determination could be useful for predicting experimental boiling characteristics. The influence of the contact angle and the importance of accounting for the experimental method when working with both pure water and surfactant substance solutions are shown.

Keywords: Boiling heat transfer, Contact angle, Surface tension value, Surfactant

1. Introduction

The addition of surfactants to water has been known to reduce the surface tension value and enhance the rate of boiling heat transfer. Many investigators have studied the role of surface tension reporting variable results. Among those, Jondtz and Myers¹⁾ developed a model for explaining how surface tension changes are reflected by changes in the waiting time, growth time and volume of the bubbles. Westwater²⁾ measured heat transfer coefficient and summarized his results in terms of the value assigned to the exponent term n in an assumed exponential relationship:

$$h \propto \sigma^n \quad (1)$$

The values he reported range from 2.5 to -1.275 and as he pointed out, surface tension value must be considered an important variable in boiling heat transfer. This led other investigators to attempt experimental measurements of relationship (1), among those Wu et. al³⁾ reported the constant n ranging from 0 to -3.3 .

Theoretically, a reduction in interfacial pressure decreases the pressure required within a vapor bubble, as indicated by the Young-Laplace equation. This decrease in vapor pressure translates into a corresponding decrease in heater surface temperature, resulting in boiling

*Graduate Student, Department of Mechanical Engineering Science

**Professor, Department of Mechanical Engineering Science

enhancement, as indicated by Ammerman⁴).

Because the formation of bubbles in a boiling system is an extremely rapid process, other variables rather than the static surface tension value could be more important. Jontz and Myers investigated the influence of the dynamic surface tension. Hsu⁵) modeled the size of the active nucleation cavities and Harrison and Levine⁶) investigated the effect of liquid-surface wettability. Furthermore, Huplik and Raithby⁷) changed the geometry of the experimental conditions and reported on nucleate boiling from a downward-facing surface.

In this work is shown the influence of the static contact angle and it is hoped that the results of the present investigation will lead to an increased understanding of the role of physical variables in boiling heat transfer.

Nomenclature

h	: heat transfer coefficient, [kW/m ² K]	sur	: surface
n	: exponent value	T	: temperature, [K]
sat	: saturation	σ	: Surface tension value, [mN/m]

2. Experimental Apparatus and Procedure

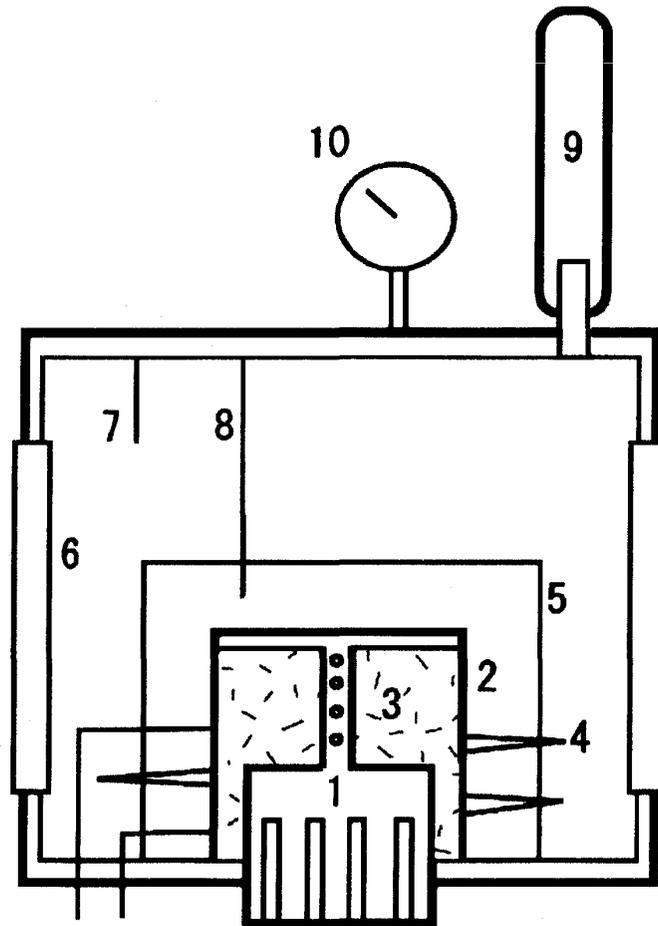
The experimental apparatus used in our work, **Figure 1**, is similar to the one built by Yang and Maa⁸). In our case, a digital manometer allows to determine atmospheric pressure within ± 1 mm Hg of accuracy. Vapor temperature is constantly controlled by means of a calibrated thermocouple. This double control makes easier to adjust the capacity of the reflux condenser placed on the top of the vessel, provided for condensing the vapor generated in the pool.

Boiling occurs at the center portion of the top surface of a copper block placed into a stainless steel pipe section. The block is heated by mean of nickel-chrome resistances inserted on its base and is enlarged at the top section forming the boiling surface. This enlarged top surface is thin enough for radial heat losses to be considered negligible. The temperature of the center portion of the heating surface is determined by extrapolating the readings of four thermocouples placed in the rod shaped middle section, these were inserted through holes drilled on the radial direction. Boiling on the polished top surface can be illuminated, observed and photographed through view windows placed at the sides of the apparatus. Heat conduction from the copper block in the radial direction is reduced to a minimum by mean of proper insulation.

A supplementary heater is installed on the bottom of the vessel for the purposes of bringing up the temperature of the liquid pool to boiling point and maintaining it during the period of operation.

Prior each operation, the center-top surface of the heating block is carefully polished with No 2000 sandpaper. Surfactant solutions are prepared using the anionic surfactant Sodium dodecyl sulfate ($\text{CH}_3(\text{CH}_2)_{10}\text{C}_6\text{H}_4\text{OSO}_3\text{Na}$) and pure water. The vessel is filled up with the solution to be tested and then this liquid pool is brought up to boiling point. The test liquid is allowed to remain at saturation temperature for about 1 to 2 hours in order to remove dissolved gases.

The heat flux released from the heating surface to the surrounding liquid is increased starting from zero and controlled by adjusting the current supplied by a rectifier. Pool temperature and vapor temperatures over the pool are measured with calibrated thermocouples. The reflux condenser was installed on a corner of the top cover, far enough from the



1 Cooper block 2 Steel pipe section 3 Insulation
 4 Auxiliary heater 5 Glass pipe section 6 Viewing windows
 7 Thermocouple for vapor temperature 8 Thermocouple for pool temperature
 9 Reflux condenser 10 Pressure gauge

Fig. 1 Experimental apparatus

center, in order that condensed drops would not affect the pool's core temperature.

Surface tensions of the aqueous surfactant were measured at room temperature with commercial equipment (Itoh Seisakusho Ltd. Japan) by the Du Noüy tension-meter method. Standard error of ± 2 [mN/m] must be accounted for the surface tension values shown in the following sections of this work. In most cases, decimal scale is used in graphs in order to highlight the boiling paths.

3. Experimental Results

In accordance to **Figure 2**, a period of four hours seemed to be enough for the surface tension value of a given concentration solution to reach a near minimum. We have called to this span of time *waiting period*. Although no change in the surface tension value occurs after much longer periods, experimental results were disperse, as shown in **Figure 3a**, and the heat transfer coefficient enhancement was poor, as averaged in **Figure 3b**.

It was also observed that solutions which had been kept inside the experimental vessel during the *waiting period* tended to show better enhancement characteristics if compared with those prepared and kept in an auxiliary plastic container. The following situation was

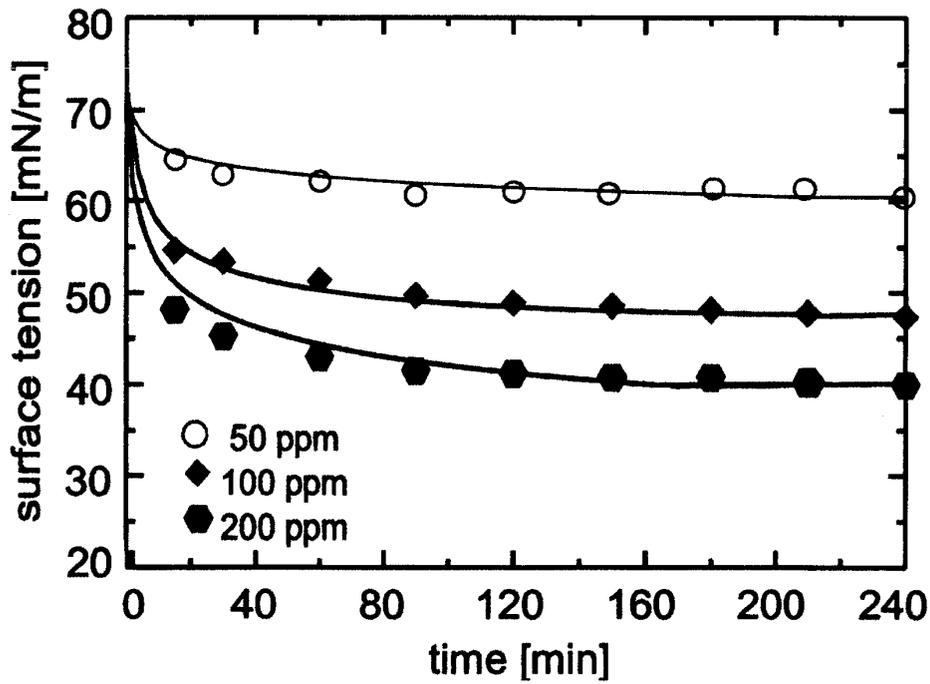


Fig. 2 Surface tension variation for different SDS solutions

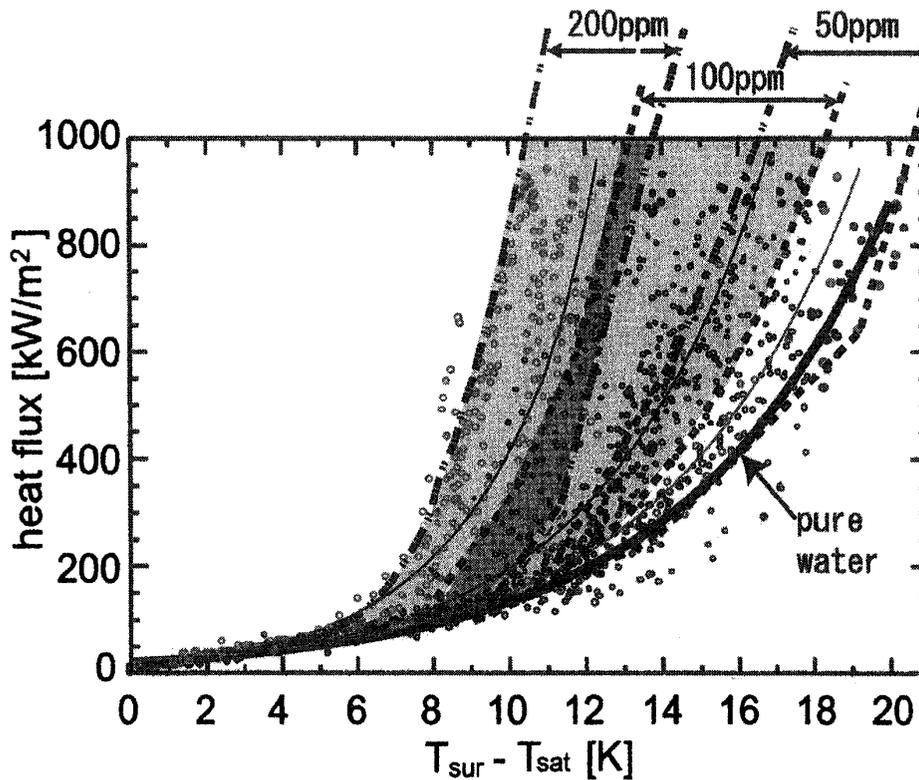


Fig. 3a Preliminary results for SDS solutions and pure water

investigated: A 200 ppm surfactant solution is prepared and kept for a 20h period in a separated container to allow its surface tension to drop to a minimum. After it is poured into the experimental-set vessel, pool temperature is brought up and trapped gases remove process is completed as usual. Experimental results have showed that the heat transfer enhancement effect of the dissolved surfactant is poor (or in some opportunities almost null) compared with the results of that procedures in which same concentration solutions were kept *all the time inside the experimental vessel* and for similar period of time. In both cases, measurement of the surface tension values found them to be around 42 ± 2 [mN/m]. **Figure**

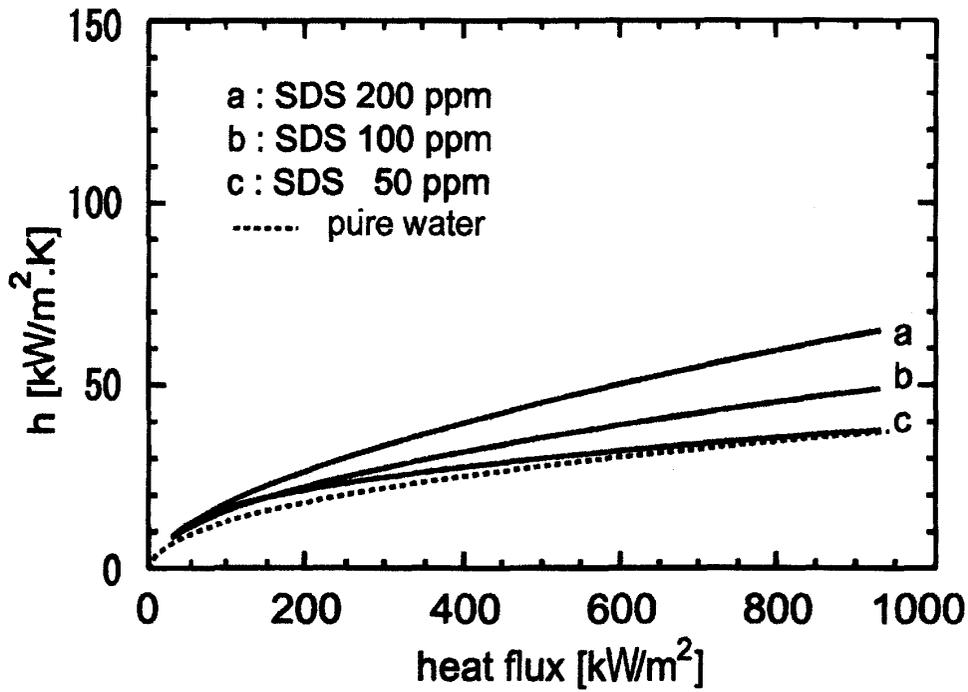


Fig. 3b Average heat transfer coefficient. for the solutions of Fig. 3a

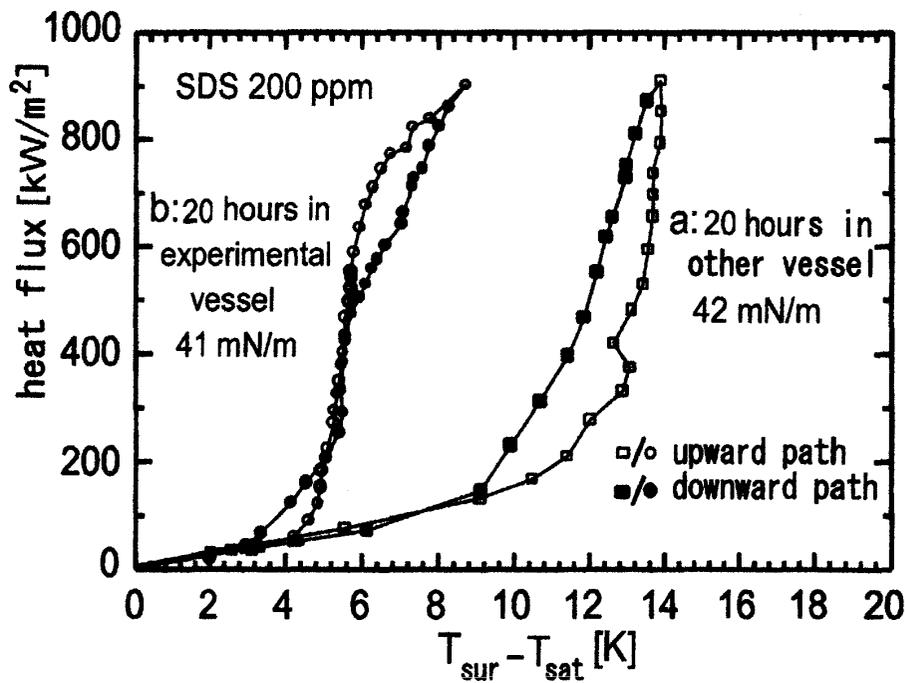


Fig. 4 Procedure comparison

4 shows the boiling curves of the two cases described above.

These facts led us to consider long *waiting* periods. Therefore, the *waiting time* period was made five times longer and solutions were kept inside the experimental-set vessel for a 20h period prior experiment. That span of time was adopted as a minimum and from now on will be referred as "*standard*". Results became more uniform and additional enhancement of the heat transfer coefficient was observed. **Figure 5** shows the averaged heat transfer coefficient of the previous procedure **curve a** vs. the *standard* one, **curve b**, which accounts for the 20h period.

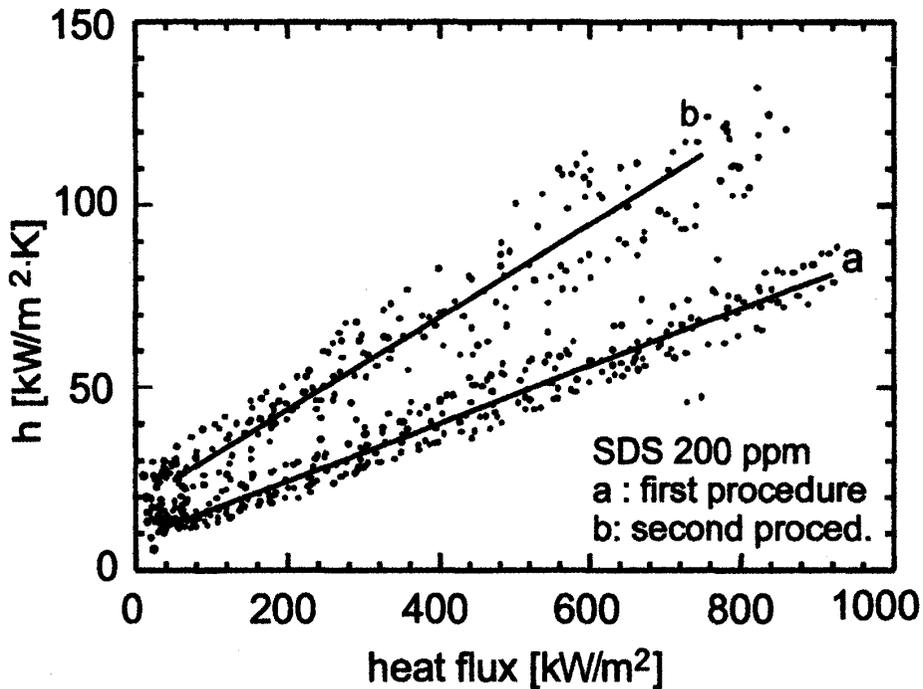


Fig. 5 Heat transfer enhancement for different procedures

3.1 Re-using a Solution

After a solution is tested, this is, heated and then cooled back to room temperature, the dissolved surfactant is expected to have lost some quantity of its original properties. In our experiments it was observed to have lost some transparency becoming opaque, a sign that a dissociation process took place. If this solution is tested again, the new experimental boiling curve varies in two ways depending on the type of the original test. If a no *standard* type solution (i.e. like the one of curve **a** on **Figure 4**) is re-used, tests show enhancement of the heat transferring capacity despite the fact the surface tension value stays unchanged or has increased, as is shown in **Figure 6**. In this particular case, original surface tension value was found to be 44 [mN/m], which in the subsequent tests increased as is detailed. Unexpectedly, the boiling curves moved to the left of the graphic (a, b, c, and d) which contrarily means

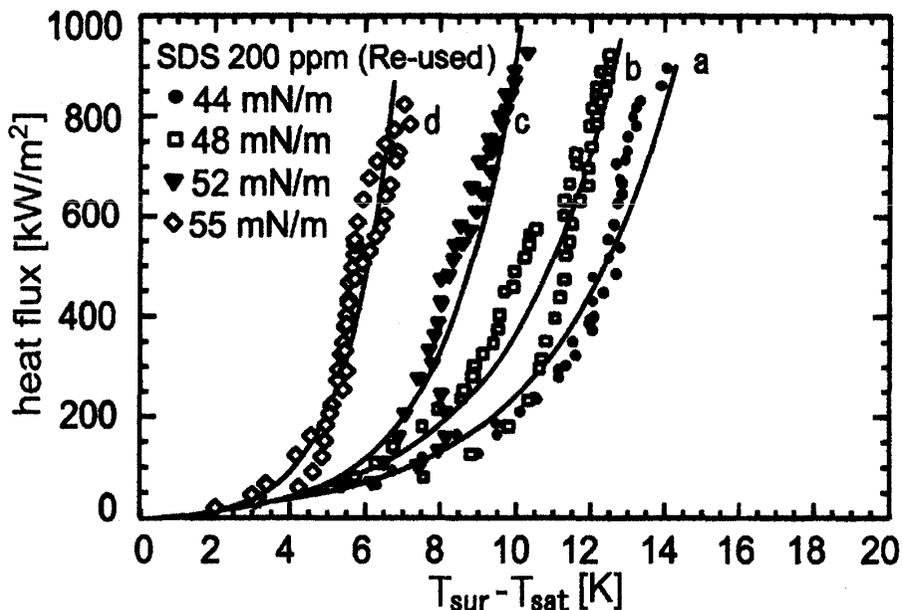


Fig. 6 Re-using a solution originally kept in other vessel

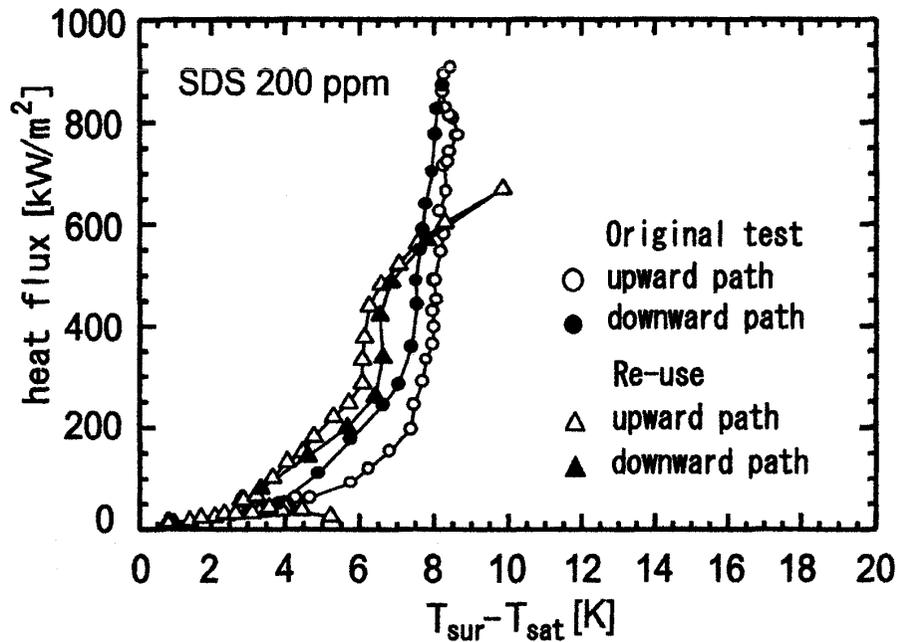


Fig. 7 Re-using a solution originally kept in the experimental vessel

improve of the heat transfer characteristics. Each test took around 12h to be completed and tests were carried out every 24h. Surface tension values were measured before each re-use.

A second type case occurs experimenting with *standard* type solutions. In these, the upward path will nearly follow the original up and downward paths but will be separating from them halfway. Minimum or null enhancement of the heat transfer characteristics is obtained. For the particular experiment showed in **Figure 7** surface tension was found to be 41 [mN/m] on the original solution, 38 [mN/m] before re-use and [53mN/m] after it. ONB occurs as a sudden eruption of bubbles in many nucleation sites and covering rapidly most of the heating surface. This causes a momentary but remarkable decrease of the temperature difference $T_{\text{sup}}-T_{\text{sat}}$.

3.2 Contact Angle Role

The observations described above led us to investigate into the solid-liquid interaction. A simple procedure, the *drip drop method*, was used to measure the contact angles for the studied cases.

If a solution is kept into the experimental vessel, the heating surface-liquid contact angle was observed to increase with time. If pure water is tested, the same phenomenon is observable, however increase is small. The empty box in **Figure 8**, first from the right, describes the contact angle interval value of a solution just poured into the experimental set after been kept 20h in other vessel. Its value nearly matches the interval box of a just mixed solution, first darkened box from the left. After 20h inside the experimental vessel, its contact angle value increases gradually to the value given by the fifth darkened box.

The contact angle variation explains the notable heat enhancement difference found for two surfactant solutions with similar surface tension value. The case illustrated in **Figure 6**, for what we have called non-standard solution, is somehow significant. In this, although surface tension value increases there was also improvement of the heat transfer characteristics. As the contact angle was investigated it was found to be growing gradually and according to the heat transfer characteristics improvement, **Figure 9**.

At this stage it must be pointed out that contact angle variation certainly takes place due the quality worsening of the heating surface. In tests carried on with pure water change of

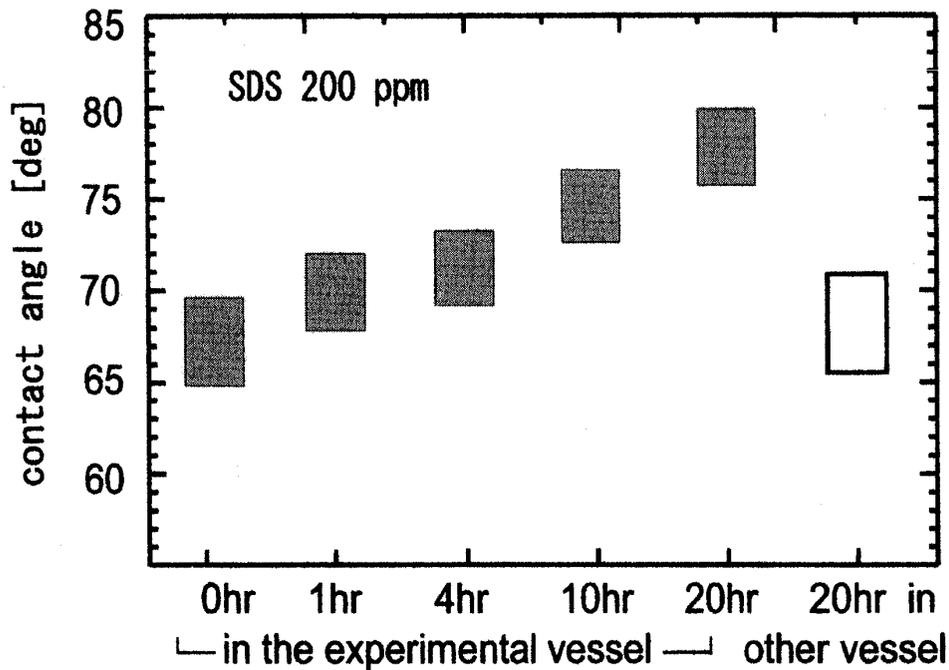


Fig. 8 Variation of contact angle with time and situation

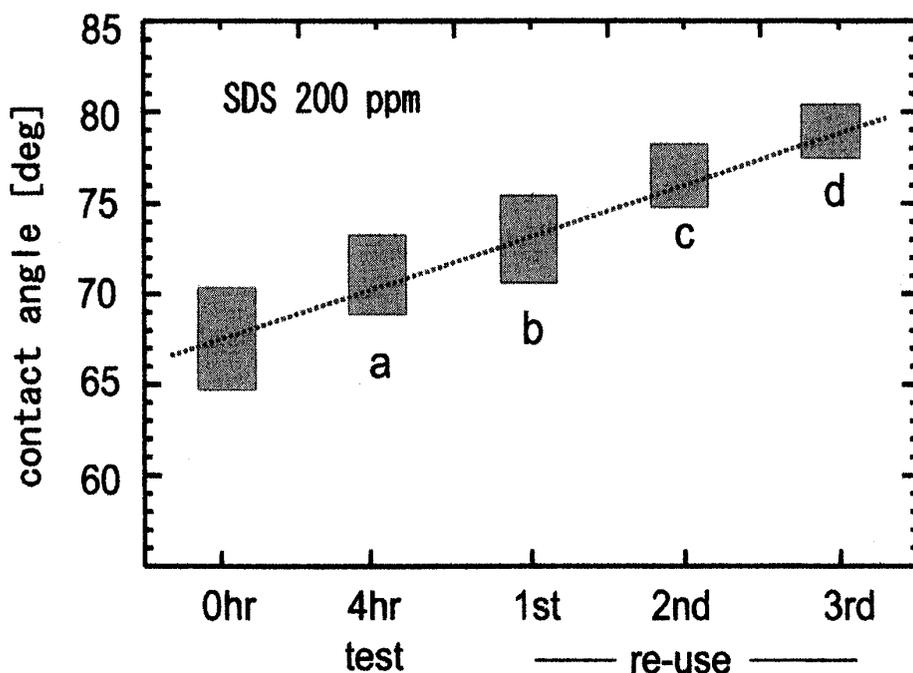


Fig. 9 Variation of contact angle for each of the test of Figure 6

the contact angle was small, this was not more than 3 degrees over a period of 20h. Additional boiling tests carried on with pure water showed also a similar result. It has been found that if the surface-liquid contact angle is 84 degrees, the pure water-boiling curve overlaps the Rosehnow correlation. On the other hand, if the contact angle is just 60 degrees, boiling curve approaches better to the Stephan-Abdelsalam correlation, especially at high heat fluxes. **Figure 10** shows four of a series of eight experiments in which the static contact angle was measured prior test. The resulting variation on the heat transfer coefficient is detailed for various fluxes in **Figure 11**.

A theoretical explanation for these experimental results is likely found on the "vapor trapping" model of Lorentz⁹, and fully explained by Carey¹⁰. In accordance with this, the number of nucleation sites should increase along contact angle increment. In **Figure 12** is

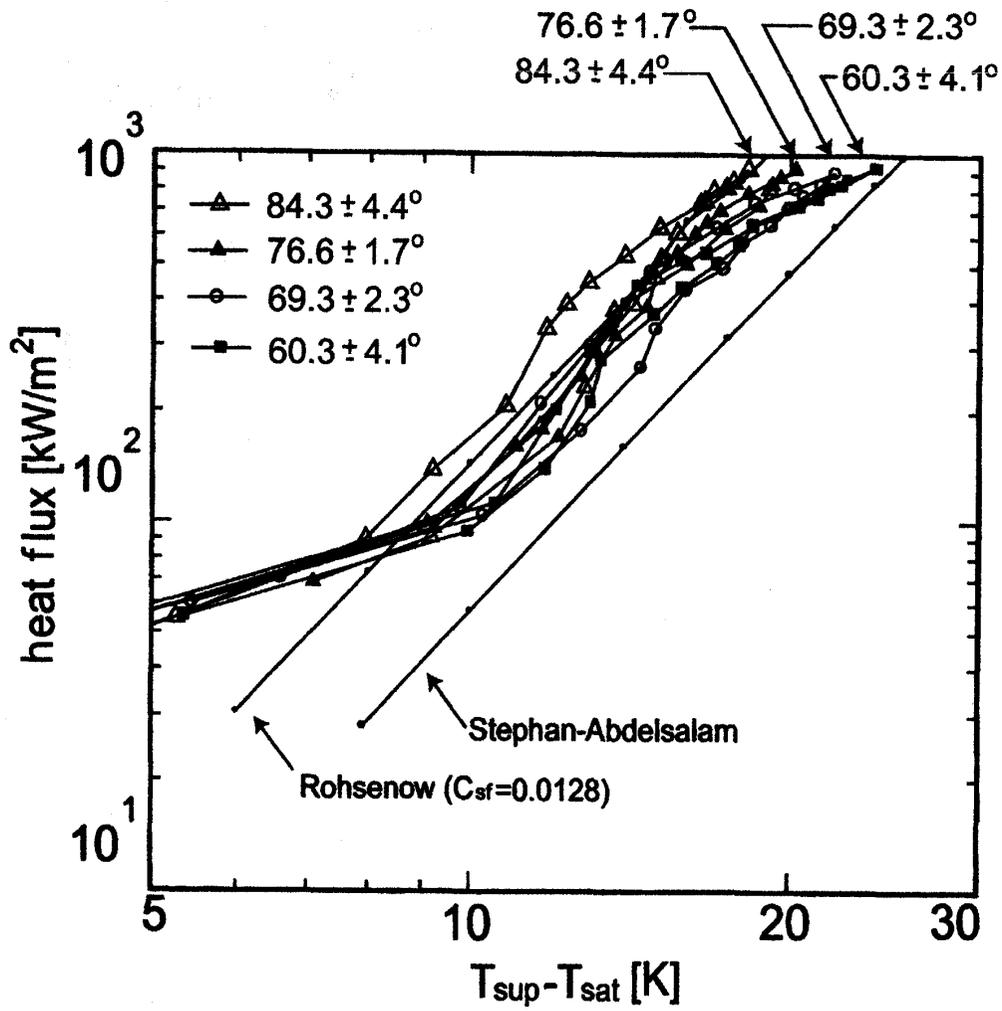


Fig. 10 Contact angle and pure water boiling curve

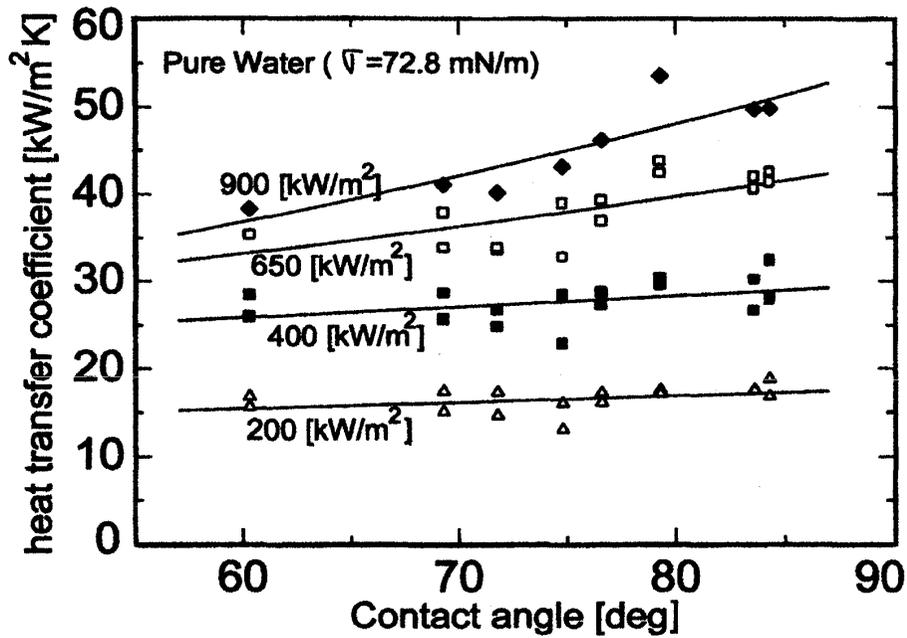


Fig. 11 Variation of heat transfer coefficient and contact angle

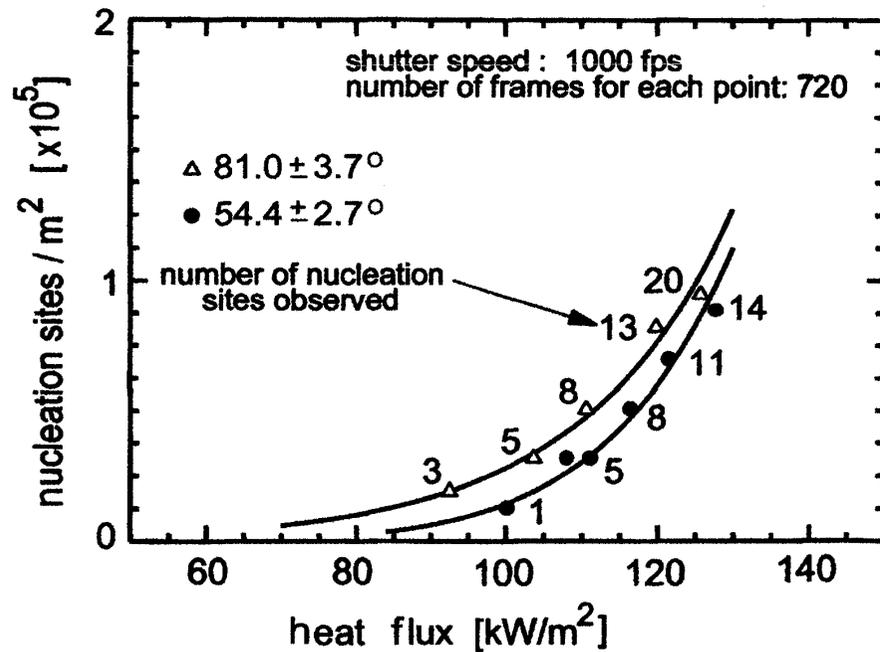


Fig. 12 Number of nucleation sites and contact angle.

shown the number of nucleation sites found for two different contact angles. Each point of the graphic was determined by direct analysis of a photographic sequence of 720 frames over 0.72 s. Each point was set over the downward path, starting from approximately 135 [kW/m²]. At higher heat fluxes coalescence of bubbles avoids fine counting of sites.

4. Conclusions

- It has been found that variations of the path of boiling curves of both pure water and surfactant solutions are directly related with the surface conditions, specifically the contact angle. Higher contact angle leads the boiling and contact angle curve of a specific liquid or solution to show better heat transfer characteristics.
- Experiments also show that the time both liquid and heater surface interact with each other is an important factor to consider at the time of experimenting with surfactant solutions. Long interactions lead to the increase of contact angle value and heat transfer characteristics.
- Above conclusions and experimental results lead us to consider that the existence of a prediction correlation like (1) is doubtful and should be better ruled out. On the other hand, the static contact angle seems to apply much better for such a kind of correlation.

References

- 1) Jontz P. D. Myers J. E. 1960, The effect of Dynamic Surface tension on Nucleate Boiling Coefficients. A. I. Ch. E. Journal, Vol.6, No 1 pp.33
- 2) Westwater, J. W. 1956, *Advances in Chemical Engineering*, Vol.1, Chapter 1. Academic Press, New York.
- 3) Wu Wuu-Tsann, Yang Yu-Min and Maa Jer-Ru, 1997. *Pool Boiling Incipience and Vapor Bubble Growth Dynamics in Surfactant Solutions*. Thesis. Department of Chemical Engineering, National Cheng Kung University, Tainan, Taiwan.
- 4) Ammerman, C. N., You S. M. 1996, Determination of the Boiling Enhancement Mecha-

nism caused by Surfactant Addition to Water, *Journal of Heat Transfer*, Vol.118, pp.429-435.

- 5) Hsu, Y. Y. 1962,. On the size range of Active Nucleation Cavities on a Heating Surface, *ASME Journal of Heat Transfer*, Vol.84, pp.207-212.
- 6) Harrison W. B., Levine Z., 1957, Wetting Effects in Boiling Heat Transfer – The Cooper-Stearic Acid System. Paper No 57 HT-29, AIChE-ASME Heat Transfer Conference, State College, Pa., August '57.
- 7) Huplick V., Raithby G. D. 1972, Surface-Tension Effects in Boiling from a Downward-facing Surface. *Journal of Heat Transfer*, Vol.98, pp.403-409.
- 8) Yang, Yu-Min, Maa Jer-Ru, 1983, “Pool Boiling in Dilute Surfactant Solutions” , *ASME Journal of Heat Transfer*, Vol.105, pp.190-193.
- 9) Carey, V. P. 1992, Liquid-Vapor Phase-Change Phenomena. pp.176-184. Hemisphere Publishers. N.Y.
- 10) Lorentz, J. J., Mikic, B. B. and Rohsenow, W. M., Proceedings Fifth International Heat Transfer Conference, Vol.IV, p.35, 1974.