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Natural convection boiling of water and surfactants in narrow horizontal annular channels

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Abstract

Natural convection boiling of water and surfactants at atmospheric pressure in narrow horizontal annular channels was studied experimentally in the range of Bond numbers $Bo = 0.185–1.52$. The flow pattern was visualized by high-speed video recording to identify the different regimes of boiling of water and surfactants. The channel length was 24 mm and 36 mm, the gap size was 0.45, 1.2, 2.2, and 3.7 mm. The heat flux was in the range of 20–500 kW/m^2, the concentration of surfactant solutions was varied from 10 to 600 ppm. For water boiling at Bond numbers $Bo < 1$ the CHF in restricted space is lower than that in unconfined space. This effect increases with increasing the channel length. For water at Bond number $Bo = 1.52$, boiling can almost be considered as unconfined. Additive of surfactant led to enhancement of heat transfer compared to water boiling in the same gap size, however, this effect decreased with decreasing gap size. For the same gap size, CHF in surfactant solutions was significantly lower than that in water. Hysteresis was observed for boiling in degraded surfactant solutions.

Keywords: Annular channel; Restricted space; Boiling; Flow pattern; Heat transfer; Critical heat flux; Boiling hysteresis

1. Introduction

Boiling heat transfer of water and refrigerants in a confined space have been studied experimentally by a number of investigators. When one dimension of the space in which boiling takes place is narrow enough the hydrodynamic characteristics of boiling and heat transfer are very different from those observed in pool boiling, Katto et al. (1966), Ishibashi and Nishikawa (1969), Monde et al. (1982), Yao and Chang (1983a,b), Chang and Yao (1985), Fujita et al. (1988), Nishikawa et al. (1984), Zhao et al. (2002), Bonjour and Lallemand (1998). These studies showed that confined boiling causes a heat transfer enhancement as compared with unconfined boiling. The effect of gap size on boiling was studied by Chulin (1994) and Long et al. (2004).

It was shown by Tzan and Yang (1990), Wu and Yang (1992), Wu et al. (1995), Ammerman and You (1996), Kandlikar and Alves (1999), Yang and Maa (1983, 2003), Wasekar and Manglik (1999, 2000,

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2002), Yang et al. (2002), Hetsroni et al. (2001, 2002, 2004), Sher and Hetsroni (2002), Zhang and Manglik (2005) that addition of a small amount of surfactant significantly increases heat transfer in saturated boiling. Yang and Maa (1983) showed that the surface tension of the surfactant solution had significant influence on the heat transfer coefficient at boiling of a dilute sodium lauryl benzene sulfonate and sodium lauryl sulfate solution. Pool boiling experiments were carried out by Tzan and Yang (1990) for a wide range of surfactant concentrations and heat fluxes. The results verify again that a small amount of surface-active additive makes the nucleate boiling heat transfer coefficient considerably higher. It was also found, that for some additives, the heat transfer increases at low concentration of surfactant, reaches a maximum and decreases with further increase in the concentration. Wu et al. (1995) reported experimental data on the effect of surfactants on nucleate boiling heat transfer in water with nine different additives. Anionic, cationic, and nonionic surfactants were studied at concentration up to 400 ppm.

The enhancement of heat transfer was related to the depression of the static surface tension. Boiling heat transfer coefficients were measured by Ammerman and You (1996) for an electrically heated platinum wire immersed in saturated water, and in water mixed with three different concentrations of sodium dodecyl sulfate (an anionic surfactant). Their results showed that addition of an anionic surfactant to water caused an increase in the convection component and a corresponding reduction in the latent heat component of the heat flux in the fully developed boiling region. The comprehensive reviews on the heat transfer in nucleate pool boiling of aqueous surfactants and polymeric solutions have been published by Kandlikar and Alves (1999) and by Wasekar and Manglik (1999). It was shown that surfactant additives at low concentrations could enhance the nucleate boiling heat transfer significantly. The subcooled pool boiling of cationic surfactant solution at various concentrations was studied by Hetsroni et al. (2002). It was found that the subcooled nucleate boiling of surfactants could not be described by a single curve, in contrast to water. They also noted a significant enhancement of the heat transfer and showed drastic change in the bubble structure next to the heated tube wall.

Boiling incipience and vapor bubble growth dynamics in aqueous surfactant solutions were studied using high speed photography by Wu and Yang (1992). The bubble growth period was observed to increase slightly, while the waiting period and the time interval between two consecutive bubbles were reduced drastically. The experimental results of bubble dynamics for pure water and 100 ppm SDS solution at relatively low heat flux of 23 $\mathrm{kW/m^2}$ were presented by Yang and Maa (2003). It was shown that the departure diameter decreases considerably with an addition of surfactant. Zhang and Manglik (2004) reported that the heat transfer in saturated boiling of aqueous cationic surfactant solutions was enhanced considerably, and it generally increased with increasing heat flux. However, they observed that bubble dynamics is different in boiling of CTAB and Ethoquard 18/25 surfactant solutions. They assumed that such a contrastingly different behavior may be attributed to surface wet ability characteristics (the measured contact angle is different for CTAB and Ethoquard 18/25 surfactant solutions).

We have used some other kind of surfactant in our previous study (Hetsroni et al., 2001) for the boiling enhancement. It was the cationic surfactant Habon G of molecular weight 500 g/mol. The cation of this surfactant is hexadecyldimethyl hydroxyethyl ammonium and the counter-ion is 3-hydroxy-2-naphthoate. The kinetics of surfactant adsorption and desorption, associated with its diffusion in the bulk fluid and the vapor–liquid interface, might be altered by the different electrostatic interactions induced by its ionic nature. These interactions also tend to govern the development of the interfacial concentration sublayer, thereby influencing the boiling behavior. No studies were found of effect of confined space on pool boiling of surfactant solutions.

The main objective of the present investigation is to study the effect of restricted space on two-phase flow pattern and on natural convective boiling heat transfer for surfactant solutions at various concentrations. A comparison of the results of this study with the ones obtained at the same experimental conditions for water provides information on new methods of heat transfer enhancement in pool boiling. Unfortunately, most of surfactants are not suited for industrial systems because of degradation and because of their environmental impact. That is why we have begun to study an enhancement of boiling by alkyl polyglucosides. They are nonionic surfactants with negligible environmental impact (Von Rybinski and Hill, 1998). Their production from the renewable resources glucose and fatty alcohol and their ultimate biodegradation is an example for a closed cycle. We used alkyl(8–16) Glucoside (Plantacare 818 UP) with molecular weight of 390 g/mol for our experiments.

2. Experimental

2.1. Rheological properties of surfactant solutions

The solution was prepared by dissolving the surfactant (52% active substance and 48% water) in deionized water, with gentle stirring over a period of a one-day. The measurements of the physical properties were carried out at the Department of Chemical Engineering, Ohio State University (Hetsroni et al., 2004).

The surface tension data were obtained by using a Surface Tensiometer System, which measures the surface tension within the body of a test fluid by blowing a bubble of gas through two probes of different diameters inside the fluid. The measurements of surface tension were carried out for different concentrations of surfactant solutions over a range of temperature from 300 K to 368 K with standard deviation of 2%.

In Fig. 1 the equilibrium surface tension, σ, is plotted vs. the concentration of the surfactant solution at different temperatures. An increase in the surfactant concentration up to $C = 300$ ppm (parts per million weight) leads to significant decrease in the surface tension, whereas the surface tension is almost independent of concentration in the range $300 \leqslant C \leqslant 1200$ ppm. In all cases an increase in a liquid temperature leads to a decrease in the surface tension.

The σ–T characteristics at different concentration of surfactant solutions were used to obtain the critical micelle concentration (c.m.c.). At low concentration, surfactant molecules arrange themselves at the interface in the form of monomers with their hydrophilic part inside water and the hydrophobic part away from the interface. This results in an appreciable reduction in the surface tension at the interface. This process continues with increasing concentrations till c.m.c. is reached, at which point no more molecules can be arranged at the interface, Rosen (1989). In all cases an increase in a liquid temperature leads to a decrease in the surface tension. The standard methods of measurement of surface tension cannot be used when the temperature of surfactant solution reaches the saturation temperature, T_s. That is why the c.m.c. point was obtained at temperatures less than T_s. For example the c.m.c. values of surfactants considered in study by Manglik et al. (2001) were obtained at $T = 298$ K. Our results showed that in the range of solutions temperature from 300 K to 368 K the c.m.c. point was reached at $C = 300$ ppm.

2.2. Apparatus

The experimental facility is shown in Fig. 2a and b. It consists of a rectangular vessel (140 mm long, 90 mm wide and 100 mm deep) with transparent walls, a thermostat to regulate the bulk fluid temperature, the heated stainless steel tube, two copper bars and electric contacts. The heated part of the tube ($d_{\text{out}} = 1.60$ mm, $d_{\text{in}} = 1.10$ mm) was 40 mm long. It was fixed in a horizontal position along the longitudinal centerline of the pool at a distance of 40 mm from the bottom. Electric current was supplied to the heated tube through copper bars from a DC power supply. A calibrated, Teflon coated, T-type thermocouple of diameter 0.3 mm was inserted inside the heated tube. The temperature on the heated wall of the test section was

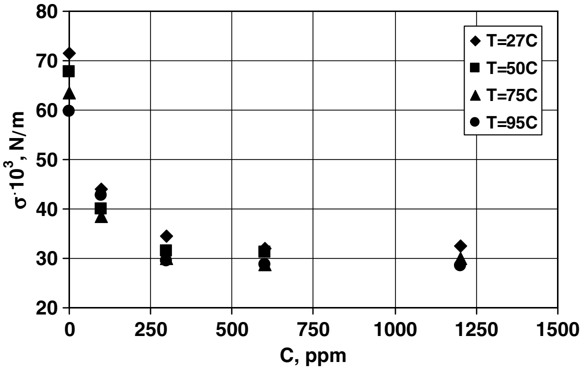

Fig. 1. Surface tension of surfactant solutions.

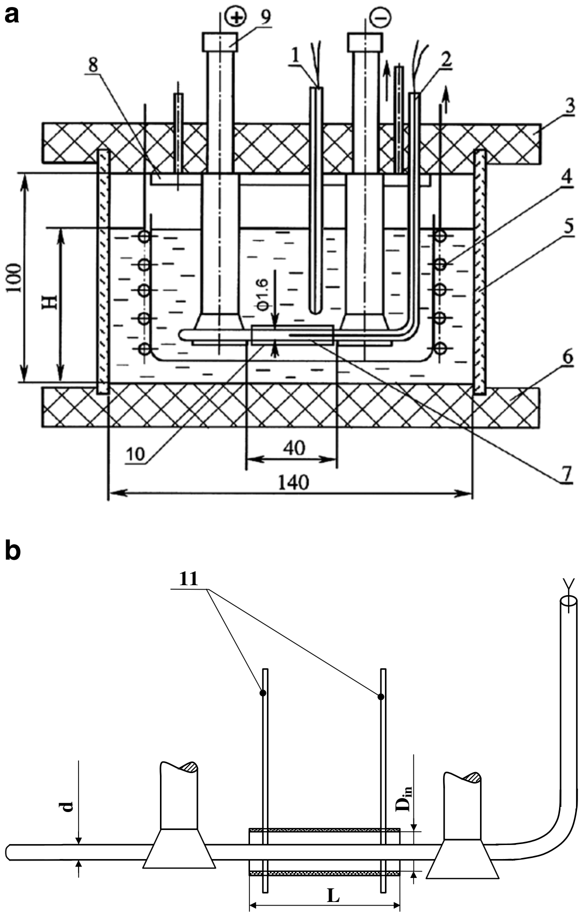

Fig. 2. Experimental facility (a) configuration of the test section to observe the side views of bubble structure and (b) annular channel. 1, 2 thermocouple; 3 upper plate; 4 thermostat; 5 glass wall; 6 bottom of the pool; 7 heated tube; 8 condenser; 9 electrical contact; 10 glass tube; 11 traverse mechanism.

measured by a radiation equilibrium thermocouple, Hetsroni et al. (2004). The thermocouple could be adjusted exactly to any desired position in the heated tube. The temperature of the outer surface of the heated tube was calculated from the power dissipation per unit volume of the tube. The saturation temperature of water or surfactant solutions was measured by a thermocouple as well as by a thermometer. The restriction of the boiling space was formed using unheated glass tubes as it is shown in Fig. 2b. The inner diameter of the glass tubes was in the range from 9 mm to 2.5 mm, the length was 24 mm and 36 mm for water boiling and 24 mm for boiling of surfactants. This length corresponds to the typical length of micro-channel heat exchangers. The glass tube position was controlled by a traverse mechanism with a position resolution of 0.02 mm. The vapor generated rises up through annular channel between the heated stainless steel tube and the glass tube to the free interface and condenses in a water-cooled condenser. An auxiliary heater (thermostat) was used to keep the fluid at saturation temperature independently of the power supplied to the heated tube.

2.3. Procedure

The heating surface was cleaned routinely before and after each set of three data points with a sequence of operations involving application of constantan cleaner and washing with hot tap water and deionized water. Only a soft sponge and absorbent paper tissues contacted the stainless steel foil, which remained smooth and

Table 1
Uncertainty of the measurements

Item	Designation	Bias limit B	Precision limit P (%)
Heat flux	q	1 kW/m^2	2.0
Wall temperature	T_{w}	0.3 K	1.0
Saturation temperature	T_{S}	0.1 K	0.2

completely wettable. During a typical run, the vessel was loaded with 1500 ml of liquid to bring the surface to a level 40–50 mm above the heater. Steady state boiling was achieved in 10–20 min after the supplementary heater was turned on. This was determined by monitoring the temperature of the solution. It should be noted that desorption of the dissolved gases forms bubbles of gases and a limited amount of bubbles containing gas–water vapor mixture. As a result boiling incipience occurred at the wall temperature below that of saturation temperature. As the surface temperature approaches the saturation temperature, the effect of dissolved gases vanishes. Degassed water and surfactant solution were used in the present study. The results discussed in the present study were obtained when the wall temperature exceeded the saturation temperature. To avoid effect of dissolved gases on bubble formation experiments were carried out after 1 h, when the saturated pool boiling began. Heat flux was increased stepwise and experiments were conducted up to conditions at which the CHF regime occurred. The beginning of CHF was characterized by sharp increase of the heated tube temperature. In this case the color of the heated tube can turn red. Although the CHF may initiate at particular location, different from the measuring position, the appearance of red color was usually very slow. The power was shut off before the temperature reached 140 °C. In this paper the highest point of each boiling curve denotes the condition of CHF.

Surfactant solutions were replaced with fresh samples after three runs. This precaution was taken in order to minimize changes in solution properties, which might have occurred at high temperature due to evaporation over long periods of time. While renewing the liquid, the heater surface was examined. No visible deposits formed under the test conditions, based on observations in the test runs and after draining the boiler. We also carried out experiments using degraded solutions, i.e. solutions which undergo more than ten repeated heating and cooling.

2.4. Uncertainty analysis

The electrical power was determined with an accuracy of 0.5%. The surface heat flux was calculated by measuring the power delivered to the heated surface and by determination of heat losses. The temperature of the heated surface and of the working fluid was measured by 0.3 mm type-T thermocouple. The thermocouple and the data acquisition system were calibrated at the steam point and ambient water temperature, and yield uncertainty values within 0.3 K at these two conditions. The estimated accuracy in the calculation of the saturation temperature is 0.1 K. In order to calculate the deviations associated with the measurement of various quantities, readings were taken for a few runs every 2 min over a period of 20 min. The uncertainty analysis was performed according to the ASME Policy on Reporting Uncertainties in Experimental Measurements and Results. The bias contribution and precision limit (95% confidence level) were calculated by means of following the equations (Kline and McClintoc, 1953). The results of the uncertainty analysis are given in Table 1, where the bias limit is an estimate of the magnitude of the fixed constant error. The precision limit is an estimate of the lack of repeatability caused by random errors and unsteadiness.

3. Experimental results and discussion

An experimental study has been carried out to identify the different regimes of natural convective boiling of water and surfactant solutions in narrow annular horizontal channels at atmospheric pressure. The channel length was 24 mm and 36 mm, the gap size was 0.45, 1.2, 2.2, and 3.7 mm. The heat flux was $q =$ 20–500 kW/m^2, the concentration of surfactant solutions was $C =$ 10–600 ppm.

3.1. Visualization of flow pattern

3.1.1. Bubble behavior at low heat flux

Fig. 3a–h shows the growth of the water bubble in annular horizontal channel of the length 24 mm and gap size of 2.2 mm. In this figure the inner heated tube appears as a dark horizontal line, the walls of the glass tube

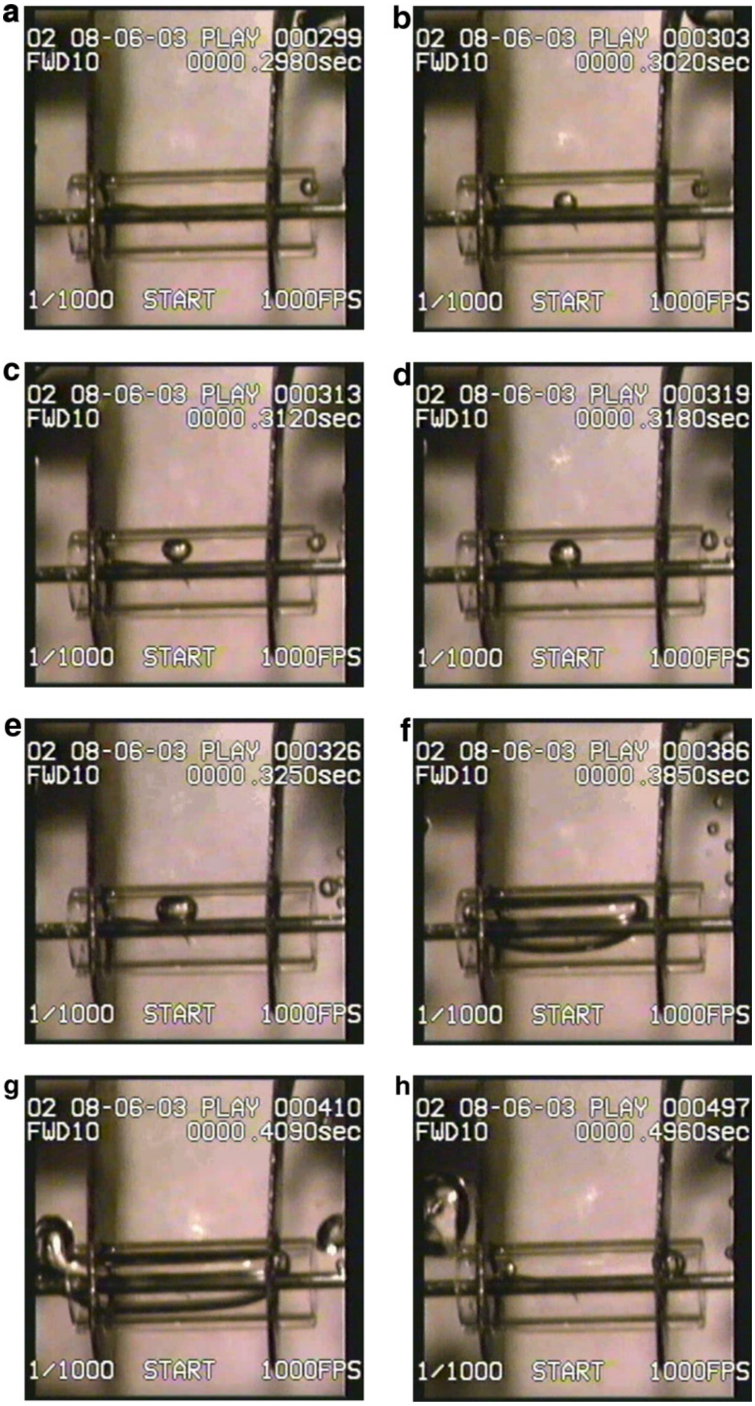

Fig. 3. Growth of the water bubble at low heat flux, $q = 80\ \mathrm{kW/m^2}$, $Bo = 0.9$.

appear as horizontal grey lines, the traverse mechanism appears as two vertical lines. The heat flux is $q = 80\ \mathrm{kW/m^2}$, the water in the vessel is at saturation temperature. Fig. 1a shows no bubbles at the center of the heated tube. Once nucleation begins, the heat flux causes a sudden release of energy into the vapor bubble, which grows rapidly and occupies the top part of annular channel, Fig. 3b–d. Then the growth of an elongate bubble was observed, Fig. 3e–f. The rapid bubble growth pushes the liquid–vapor interface on both sides of the channel and vapor leaves the channel through one or two open sides, Fig. 3g, and during some time the greater part of heated tube is immersed in water, Fig. 3h. When a bubble departs from a nucleus cavity, its cavity is then re-covered by liquid, and the next bubble will appear on the heated tube after a certain time interval. The behavior of the long vapor bubbles occurring in small size annular channels is not similar to annular flow with intermitted slugs of liquid between two vapor trains.

A different situation arises with the bubble growth in surfactant solution. Fig. 4a–d shows boiling of surfactant alkyl(8–16) of concentration $C = 600$ ppm at the same values of gap size and heat flux. The figure presents a cluster of small bubbles. Boiling in surfactant solution, when compared with that in pure water, was observed to be more vigorous. Surfactant solution promotes activation of nucleation sites in a clustered mode. The cluster contains a number of small bubbles, the location of nucleation sites and time behavior of each cannot be traced exactly. From the observation by the high-speed camera with the speed of 1000 frames/s, it was clarified that the outer glass tube may keep the bubbles within the confined space but does not lead them to form a coalescence bubble. In lower heat flux region ($q < 100\ \mathrm{kW/m^2}$) almost no coalescence bubble was formed in confined space and the bubbles leaved the channel through the open sides. However, at higher heat flux region the behavior of vapor bubbles changes.

3.1.2. Bubble behavior at moderate values of heat flux

Fig. 5a and b shows boiling of water and surfactant solution in the gap size of 2.2 mm at $q = 180\ \mathrm{kW/m^2}$. For water boiling in the range of heat flux $100 < q < 250\ \mathrm{kW/m^2}$, bubble coalescence occurred. Although the vapor left the channel through open sides, the heated tube was remained covered by elongated bubble, Fig. 5a. According to Zhao et al. (2002) the enhancement mechanism of heat transfer may be related to the bubble coalescence process within the confined space and the easier escape of the coalescence bubble through the open

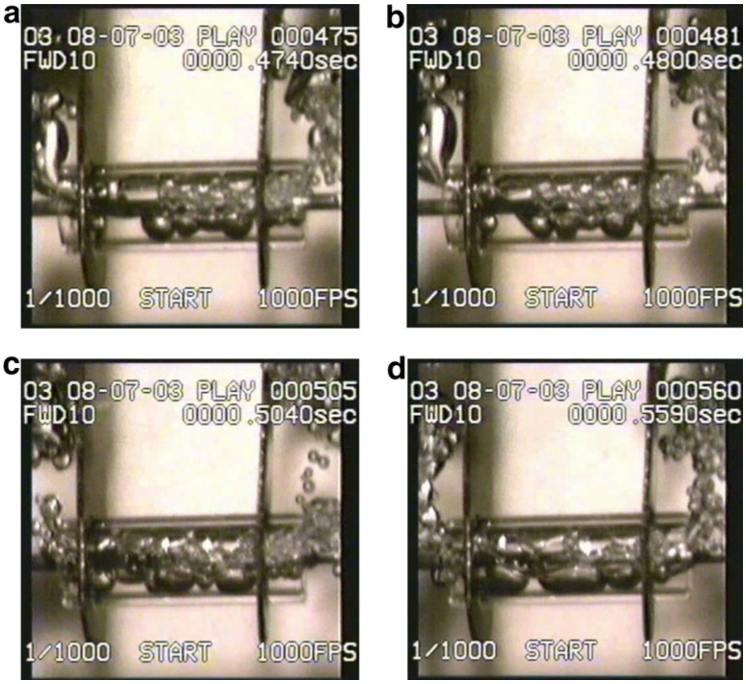

Fig. 4. Boiling of surfactant solution at low heat flux, $q = 80\ \mathrm{kW/m^2}$, $Bo = 1.26$.

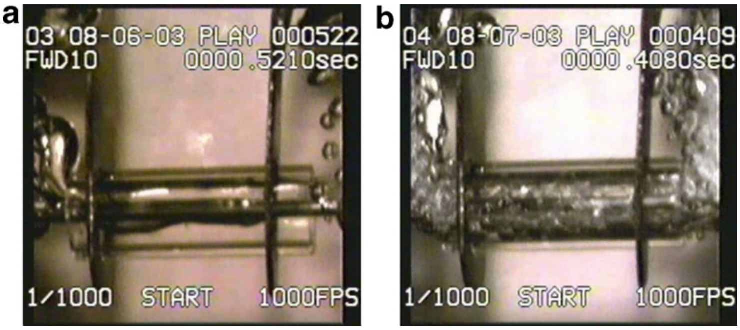

Fig. 5. Boiling at moderate values of heat flux (a) water boiling, $q = 180\ \mathrm{kW/m^2}$, $Bo = 0.9$ and (b) boiling of surfactant solution, $q = 180\ \mathrm{kW/m^2}$, $Bo = 1.26$.

channel sizes. For boiling of surfactant solution as the heat flux increased the departure frequency increased. When a bubble just departed from the nucleation site its size grew. The second bubble at the nucleation site also grew. It was observed in the images that coalescence, almost without exception, did not occur, Fig. 5b.

Yao and Chang (1983a) observed four regimes for confined boiling of water, acetone and R-113 in an annular vertical space ($H = 25.4$ mm or 76.2 mm and $0.32\ \mathrm{mm} < \delta < 2.58\ \mathrm{mm}$) whose bottom was closed. The regime of isolated deformed bubbles occurred for small gaps and low heat fluxes. For moderate heat fluxes coalesced deformed bubbles were observed. These two flow patterns were also observed in the present study for water boiling. When the heat flux was close to CHF, Yao and Chang (1983a) described the dryout regime. For very large gap sizes and high heat fluxes, nucleate boiling with slightly deformed bubbles took place. This last regime is a mixed condition of pool boiling, characterized by small bubbles, and confined boiling, with coalesced or deformed bubbles. However, the boiling flow pattern depends not only on gap-sizes but also on the kind of the fluid.

3.1.3. *Critical heat flux*

The CHF in a confined space is always of much concern due to its importance in practice, Zhao et al. (2002).When the heat flux is sufficiently high, suddenly at some point on the heating surface a dry area is not wetted and starts growing, leading to burnout. Fig. 6a, shows boiling of water at heat flux $q = 280\ \mathrm{kW/m^2}$ that corresponds to value of $q/q_{\mathrm{CHF}} = 0.65$, where q_{CHF} is the CHF. From the figure one can see that the whole heated surface is covered by a long vapor bubble. For unconfined boiling long bubbles (vapor mushrooms defined by Gaertner (1965) at $q/q_{\mathrm{cr}} \geqslant 0.7$) were in the majority (about 80%). However, in the present study contrary to unconfined space the contribution of long bubbles tends to 100%. Our results agree with those reported by Bonjour and Lallemand (1998). They concluded that such flow pattern characterizes beginning of dryout.

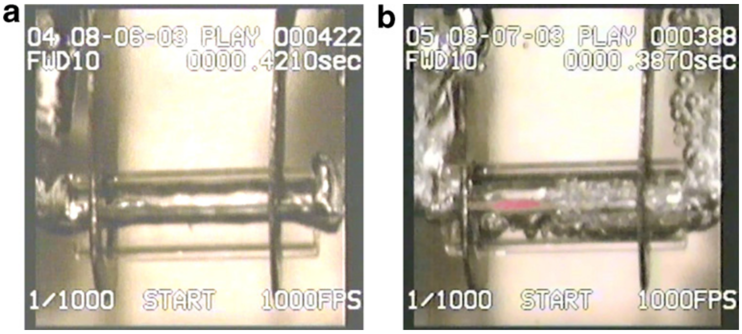

Fig. 6. Flow pattern at high heat flux (a) water boiling, $q = 280\ \mathrm{kW/m^2}$, $Bo = 0.9$ and (b) boiling of surfactant solution, $q = 280\ \mathrm{kW/m^2}$, $Bo = 1.26$.

For boiling at heat flux $q = 280\,\text{kW/m}^2$ of surfactant solution ($C = 600$ ppm) the heated surface was not completely covered by a vapor and only the part of the heated surface was covered by small deformed bubbles, Fig. 6b. One can see that under condition of the present experiment dryout occurred at the left side of the tube and led to CHF (the red region shown in Fig. 6b). Comparison between images shown in Fig. 6a and b reveals that at the same values of the gap-size CHF of surfactant solution is less than that of water.

3.1.4. Incipience of boiling of degraded solutions

For degraded alkyl(8–16) solutions boiling occurred at wall superheat higher than that observed in fresh solutions and water. Incipience of boiling in both water and fresh surfactant solutions was accompanied by formation of small bubbles on the heated surface. However, there was observed a significant difference in the behavior of boiling patterns. The formation of big vapor clusters took place before boiling incipience in degraded alkyl(8–16) solutions in the range of concentrations $C = 10$–600 ppm. This process is shown in Fig. 7a–c. The burst of such cluster is shown in Fig. 7d. The cluster formation was accompanied by high wall superheat (T_W–T_S) in heat flux controlled experiments, where T_W is the temperature measured on the heated wall, T_S is the saturation temperature measured in the vessel. It should be stressed that these clusters were not gas (air) bubbles. The desorption of the dissolved gases formed bubbles of gas and a limited amount of bubbles containing gas–water vapor mixture. As a result, boiling incipience occurred at heated wall temperature below that of saturation temperature. In the present study such a phenomenon was not observed. We also measured fluid temperature, T_f, in the annular space between the heated tube and the inner wall of glass tube by thermocouple. This temperature exceeded over 4–12 K saturation temperature depending on solution concentration. Finally, the collapse of the cluster led to reduction in wall superheat and saturated boiling regime occurred. For water boiling we did not observe the bubble coalescence at very small scales. For pool boiling of surfactant solutions bubble coalescence was observed by Hetsroni et al. (2004). There were clusters of small bubbles, which rose from the cavity. These bubbles were adjacent to each other and the cluster neck was not observed. The bursting of vapor clusters before boiling incipience of degraded cationic surfactant Habon G solution was also observed by Hetsroni et al. (2002).

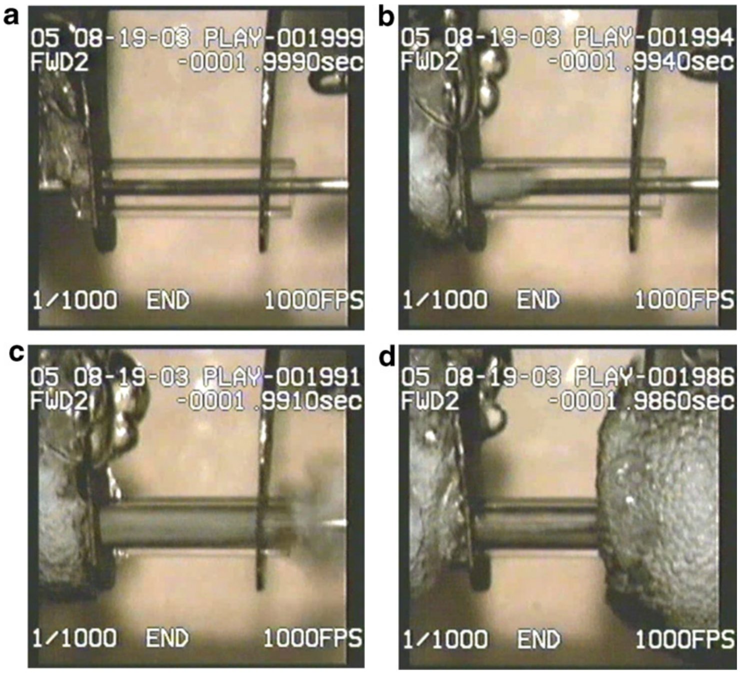

Fig. 7. Boiling incipience in degraded solutions.

3.2. Boiling curves

Data were taken for both increasing and decreasing heat fluxes. The total mass of the liquid in the test facility remained constant, thus no fresh liquid was introduced to "top off" the system. For water boiling in the gap sizes of 0.45, 1.2, 2.2, and 3.7 mm, the Bond numbers, $Bo = \delta(\sigma/g(\rho_L - \rho_G))^{-0.5}$, were 0.185, 0.493, 0.9 and 1.52, respectively, where δ is the gap size, σ is the surface tension, g is the acceleration due to gravity, ρ_L and ρ_G are the liquid and the vapor densities. Boiling of surfactant solutions was investigated in gap size of 0.45 and 2.2 mm in the range of Bond numbers $Bo = 0.26$–1.26.

3.2.1. Boiling of water

3.2.1.1. Low and moderate values of heat flux. Fig. 8 shows boiling curves obtained in annular channel with length of 24 mm and different values of gap size. The heat flux, q, is plotted vs. the wall excess temperature T_W–T_S (the natural convection data are not shown). Each point in Fig. 8 represents an average value obtained from the measurements. The vertical arrows mean critical heat flux. In these experiments we did not observe any signs of a hysteresis. The wall superheat was reduced as the gap size decreased. From visualization of flow pattern shown in Figs. 4 and 5, one can see, when bubbles grow in the narrow channel, the layer of liquid between the wall and the base of the bubble was enlarged. It facilitates evaporation and increases latent heat transfer. It was also noted by Bonjour and Lallemand (1998) that, because of the presence of the confinement wall, the liquid in the channel is warmed-up more efficiently than in unconfined boiling. Yao and Chang (1983a) showed that the squeezing effect of a bubble due to the confinement may be described by the Bond number. For low Bond numbers (of the order of unity or less), the squeezing effect is important since bubbles cannot grow naturally because the channel is narrower than the bubble diameter. In Fig. 8 boiling curves 1, 2, and 3 were obtained under condition of Bond numbers 0.185, 0.493, 0.9, respectively. For high Bond numbers, boiling can almost be considered as unconfined. The boiling curve obtained in the present study at $Bo = 1.52$ did not differ significantly from that obtained by Hetsroni et al. (2002, 2004) in pool boiling (unconfined space). For example, at $q = 450\ \mathrm{W/m^2}$ the difference (T_W–T_S) is close to 21 K for boiling at $Bo = 1.52$ and pool boiling. However when the gap size decreased a noticeable decrease in CHF occurred.

3.2.1.2. Critical heat flux. The experimental values of CHF are plotted in Fig. 9 as dependence q_{CNF}/q^0_{CHF} on Bond number, where q^0_{CHF} is the CHF in unconfined pool boiling as the space is large enough ($Bo > 1.5$). The data presented by Hetsroni et al. were used to calculate the value of q^0_{CHF}. Confined narrow space greatly degraded the CHF because the vapor bubbles are difficult to escape from the narrow space especially for larger length of the heater surfaces. For confined space vapor bubbles can escape from the heater surface only at the exit of the confined space. The larger is the length of the heater surface the lower is critical heat flux. Such a behavior is in agreement with experimental results described by Katto et al. (1966), Fujita et al. (1988), Bonjour and Lallemand (1998) and Zhao et al. (2002).

Katto et al. (1966) investigated heat transfer in narrow space ($\delta < 1.4$ mm) between horizontal plates with the lower plate heated. The study was based on high speed photos of bubbles and showed that the evaporation

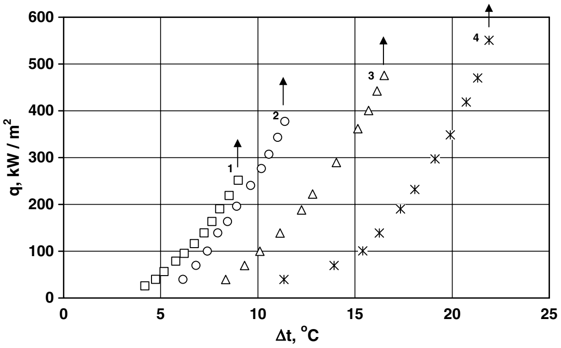

Fig. 8. Boiling curves of water in restricted space. (□) $Bo = 0.185$, (○) $Bo = 0.493$, (△) $Bo = 0.9$, (ж) $Bo = 1.52$.

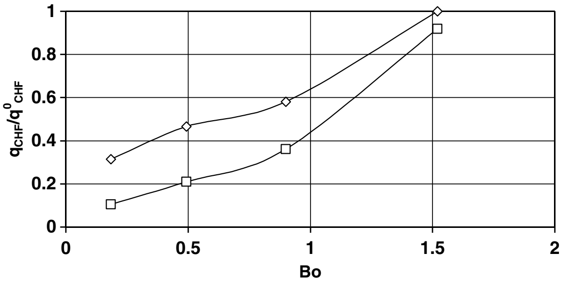

Fig. 9. Effect of restriction on CHF. Water boiling. (◇) $L = 24$ mm, (☐) $L = 36$ mm.

of liquid layer under bubbles plays the most important role in confined boiling. Fujita et al. (1988) carried out experiments on nucleate boiling and CHF in vertical/inclined narrow spaces which consisted of heated and unheated parallel rectangular plates. They investigated the effects of gap size, the periphery conditions of space, the size of the heating surface and surface orientation on heat transfer characteristics. Confined narrow space reduced CHF. An experimental study was carried out by Bonjour and Lallemand (1998) in order to identify the different regimes of natural convective boiling of R-113 in a narrow rectangular vertical channel. The reduced CHF was measured relative to unconfined conditions. Bonjour and Lallemand (1998) concluded that the reduced CHF is related to earlier dryout of micro-layer because the initial thickness of the micro-layer reduces with decrease of the space gap. In the present experiments we cannot directly observe micro-layer. We assume that a decrease in the channel gap leads to increasing the heated surface covered by vapor and increasing the time of the presence of the vapor blanket on it.

3.2.2. Boiling of surfactant solutions

3.2.2.1. Effect of gap size. Boiling curves of alkyl(8–16) solution of concentration $C = 600$ ppm obtained for the channel gap size of 1.2 mm ($Bo = 1.26$) and 0.45 mm ($Bo = 0.26$) are shown in Fig. 10a and b, respectively.

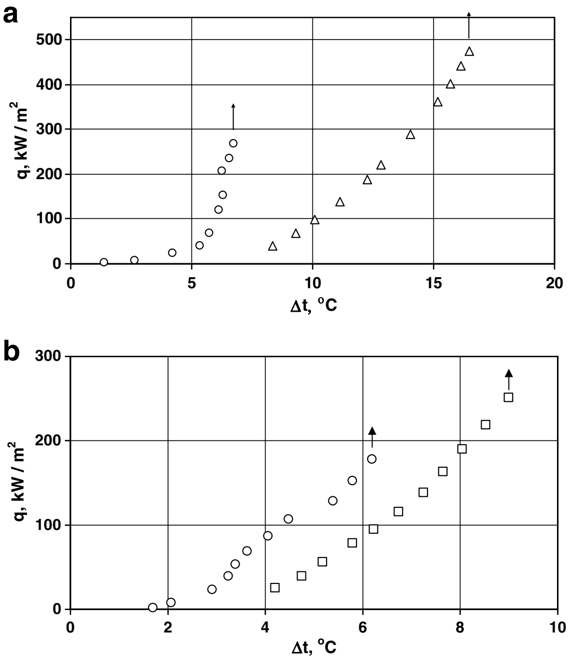

Fig. 10. Effect of gap size on boiling of surfactants: (a) $\delta = 1.2$ mm, (○) alkyl(8–16), $C = 600$ ppm, $Bo = 1.26$, (△) water, $Bo = 0.9$ and (b) $\delta = 0.45$ mm, (○) alkyl(8–16), $C = 600$ ppm, $Bo = 0.26$, (☐) water, $Bo = 0.185$.

In this figure the boiling curve of water, obtained at the same gap sizes, is also shown for comparison. The Bond number *Bo* depends on the values of the. gap size and the surface tension. The experiments were performed at fixed values of these parameters. At the same heat flux boiling of surfactant solution occurred at wall superheat less than boiling of water. For example, at $\delta = 1.2$ mm and $q = 100\ \text{kW/m}^2$ the wall superheat (T_W–T_S) was 6 K for boiling of surfactant solution, and 10 K for water boiling. At $q = 280\ \text{kW/m}^2$ and $\delta = 1.2$ mm the difference (T_W–T_S) was 14 K and 7 K for water and 600 ppm surfactant solution, respectively. This effect decreases with decreasing the channel gap size. For gap size of $\delta = 0.45$ mm and $q = 100\ \text{kW/m}^2$ the wall superheat was about 4 K and 6 K for surfactant and water boiling, respectively. Decrease in the wall superheat may be considered as enhancement of heat transfer. For pool boiling Wasekar and Manglik (2002) presented the results of a study that investigates the dependence of nucleate boiling heat transfer coefficients of aqueous surfactant solutions of different molecular weight and ionic nature. It was reported that the maximum enhancement increased with decreasing surfactant molecular weight. Criteria for nucleate boiling enhancement by surfactant additives were proposed by Yang and Maa (2003). As the first criterion, it was postulated that the surfactant should be soluble in water. As the second criterion, it was postulated that the surfactant should depress the equilibrium surface tension of solution significantly. As the third criterion, it was postulated that the surfactant should not depress the equilibrium contact angle significantly. According to Yang and Maa (2003), boiling heat transfer by addition of surfactant is enhanced by the depression of the equilibrium surface tension but suppressed by the depression of the equilibrium contact angle. Sher and Hetsroni (2002) developed a model of nucleate pool boiling with surfactant additives. Solid–vapor, solid–liquid and liquid–vapor surface tensions were assumed to be surfactant diffusion controlled, and the boiling curves were calculated. To the author's best knowledge no discussion on effect of channel gap size on natural convection boiling was found.

Addition of surfactant leads to enhancement of heat transfer compared to water boiling in the same gap size, however, this effect decreases with decreasing channel size. For the same gap size CHF in surfactant solutions is significantly lower than that in water. At high values of heat flux some foaming patches began to occur, this process increased with a decrease in gap size and led to decrease in CHF.

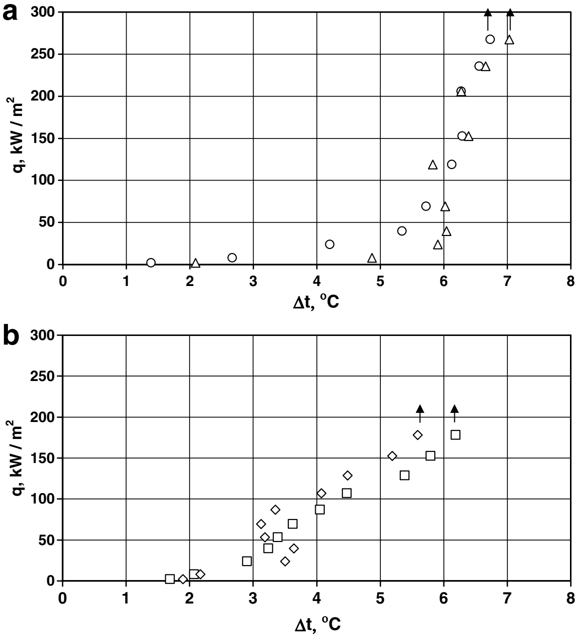

Fig. 11. Effect of concentration on boiling of surfactants: (a) $\delta = 1.2$ mm, $Bo = 1.26$ (○) alkyl(8–16), $C = 600$ ppm, (△) alkyl(8–16), $C = 200$ ppm and (b) $\delta = 0.45$ mm, $Bo = 0.26$, (□) alkyl(8–16), $C = 600$ ppm, (◇) alkyl(8–16), $C = 200$ ppm.

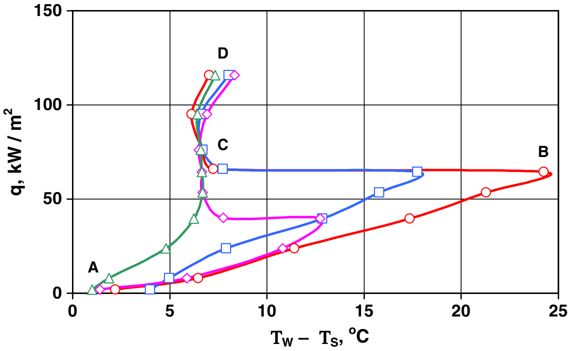

Fig. 12. Boiling hysteresis in degraded alkyl(8–16) solutions. (○) $C = 300$ ppm, (□) $C = 100$ ppm, (◊) $C = 25$ ppm, (△) $C = 10$ ppm.

3.2.2.2. Effect of concentration. Behavior of boiling curves in restricted space depending of concentration of surfactant solution also differs from that of pool boiling. In pool boiling as the solution concentration increased the boiling curves shifted towards the left (up to $C < C_{\mathrm{cmc}}$), where C_{cmc} is the critical micelle concentration, Hetsroni et al. (2001, 2002), Sher and Hetsroni (2002).

Fig. 11a and b shows boiling curves of alkyl(8–16) solution of concentration $C = 600$ ppm and $C = 200$ ppm obtained for the channel gap size of 1.2 mm ($Bo = 1.26$) and 0.45 mm ($Bo = 0.26$ mm), respectively. From this figure one may conclude that in restricted space the effect of solution concentration on behavior of boiling curve is insignificant.

3.2.2.3. Boiling hysteresis. The results obtained at $Bo = 1.26$ are presented in Fig. 12, for different concentrations of surfactant solutions. The onset of boiling corresponds to the curve ABCD for the runs with increasing heat flux. It follows the curve DCA for decreasing heat flux. The measurements were repeated several times and the same phenomena were observed. Point B stands for the condition at which the fluid starts to boil when the heat flux is increasing (The typical process is shown in Fig. 7a–d.). Zhang and Manglik (2005) concluded that hysteresis occurred due to high wet ability which takes place at very high concentrations ($C > C_{\mathrm{cmc}}$). It should be stressed that in the present study hysteresis was observed in restricted boiling of degraded solutions as for pre-cmc solutions ($C < 300$ ppm) as for post-cmc solutions. It is speculated that molecules of degraded surfactant are more amenable to formation of a surfactant monolayer, which renders the interface less flexible and results in the dampening of interfacial motion. For alkyl(8–16) hysteresis occurs only in degraded solutions.

4. Conclusions

The experimental results are summarized as follows:

4.1. Visualization of flow pattern

4.1.1. Low heat flux, $q < 100$ kW/m^2

For water boiling, when a bubble departs from a nucleus cavity, the cavity is then refilled by liquid, and the next bubble will appear on the heated tube, after a certain time interval. The behavior of the long vapor bubbles occurring in small size annular channels is not similar to annular flow with intermitted slugs of liquid between two vapor trains.

Boiling in surfactant solutions, when compared with that in pure water, was observed to be more vigorous. Surfactant solutions promoted activation of nucleation sites in a clustered mode. At lower heat flux region almost no coalescence bubble was formed in confined space and the bubbles leave the channel through the open sides. However, at higher heat flux region the behavior of vapor bubbles changed.

4.1.2. Bubble behavior at moderate values of heat flux

For water boiling in the range of heat flux $100 < q < 250$ kW/m^2 bubble coalescence occurred. Although the vapor left the channel through the open sides, the heated tube was remained covered by elongated bubble. For boiling of surfactant solution, as the heat flux increased the departure frequency increased. When a bubble just departed from the nucleation site its size grew. The second bubble at the nucleation site also grew. It was observed in the images that coalescence, almost without exception, did not occur.

4.1.3. Critical heat flux

For water boiling, when the heat flux was sufficiently high, suddenly at some point on the heating surface a dry area was not wetted and started growing, leading to burnout. Contrary to unconfined space, the contribution of long bubbles tends to be 100%.

For boiling of surfactant solution under CHF condition the heated surface was not completely covered by a vapor and only part of the heated surface was covered by small deformed bubbles.

4.2. Boiling curves

For water boiling at Bond numbers $Bo < 1$ the CHF in restricted space is lower than that in unconfined space. This effect increases with increasing the channel length. For high Bond numbers, boiling can almost be considered as unconfined.

Additive of surfactant led to enhancement of heat transfer compared to water boiling in the same gap size, however, this effect decreased with decreasing gap size. For the same gap size CHF in surfactant solutions was significantly lower than that in water.

Contrary to pool boiling the effect of solution concentration on behavior of boiling curve is insignificant in natural convection boiling of surfactants in narrow horizontal annular channels.

Hysteresis was observed in restricted boiling of degraded solutions for pre-cmc solutions ($C < 300$ ppm) and for post-cmc solutions. It is speculated that molecules of degraded surfactant are more amenable to formation of a surfactant monolayer, which renders the interface less flexible and results in the dampening of interfacial motion.

4.3. Enhancement of nucleate boiling heat transfer

Alkyl(8–16) glucoside used in the present study is nonionic surfactant. The experiments showed that addition of this surfactant to water caused an increase in heat transfer. The results are similar to those reported on the effect of anionic, Ammerman and You (1996), and cationic (Hetsroni et al. (2002, 2004) surfactants on boiling heat transfer.

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References

Ammerman, C.N., You, S.M., 1996. Determination of the boiling enhancement mechanism caused by surfactant addition to water. J. Heat Transfer 118, 429–435.

Bonjour, J., Lallemand, M., 1998. Flow patterns during boiling in a narrow space between two vertical surfaces. Int. J. Multiphase Flow 24, 947–960.

Chang, Y., Yao, S.C., 1985. Pool boiling heat transfer in a narrow horizontal crevices. J. Heat Transfer 107, 656–662.

Chulin, X., 1994. Mechanism of boiling in narrow spaces. J. Aviation 15, 774–779.

Fujita, Y., Ohta, H., Uchida, S., Nishikawa, K., 1988. Nucleate boiling heat transfer and critical heat flux in narrow space between rectangular surface. Int. J. Heat Mass Transfer 31, 229–239.

Gaertner, R.F., 1965. Photographic study of nucleate pool boiling on a horizontal surface. J. Heat Transfer 2, 17–29.

Hetsroni, G., Zakin, J.L., Lin, Z., Mosyak, A., Pancallo, E.A., Rozenblit, R., 2001. The effect of surfactants on bubble growth, wall thermal patterns and heat transfer in pool boiling. Int. J. Heat Mass Transfer 44, 485–497.

Hetsroni, G., Gurevich, M., Mosyak, A., Rozenblit, R., Yarin, L.P., 2002. Subcooled boiling of surfactant solutions. Int. J. Multiphase Flow 28, 347–361.

Hetsroni, G., Zakin, J.L., Gurevich, M., Mosyak, A., PogreBoyak, E., Rozenblit, R., 2004. Saturated flow boiling heat transfer of environmentally acceptable surfactants. Int. J. Multiphase Flow 30, 717–734.

Ishibashi, E., Nishikawa, K., 1969. Saturated boiling heat transfer in narrow space. Int. J. Heat Mass Transfer 12, 863–894.

Kandlikar, S.G., Alves, L., 1999. Effects of surface tension and binary diffusion on pool boiling of dilute solutions: an experimental assessment. J. Heat Transfer 121, 488–493.

Katto, Y., Yokoya, S., Teraoka, K., 1966. Experimental study of nucleate boiling in case of making interference-plate approach to the heating surface. In: Proc. 3th Int. Heat Transfer Conf., vol. 3, 1966, pp. 219–227.

Kline, S.J., McClintoc, F.A., 1953. Describing uncertainties in single-sample experiments. Mech. Eng. 75, 3–8.

Long, E., Xin, M., Wang, Y., 2004. Experimental research of pool boiling heat transfer in horizontal narrow spaces. Heat Transfer – Asian Res. 33 (5), 307–315.

Manglik, R.M., Wasekar, V.M., Zhang, J., 2001. Dynamic and equilibrium surface tension of aqueous surfactant and polymeric solutions. Exp. Thermal Fluid Sci. 25, 55–64.

Monde, M., Kusuda, H., Uehara, H., 1982. Critical heat flux during natural convective boiling in vertical rectangular channels submerged in saturated liquid. J. Heat Transfer 111, 731–738.

Nishikawa, K., Fujita, Y., Uchida, S., Ohta, H., 1984. Effect of surface configuration on nucleate boiling heat transfer. Int. J. Heat Mass Transfer 27, 1559–1571.

Rosen, M.J., 1989. Surfactants and Interfacial Phenomena, second ed. Wiley, New York.

Sher, I., Hetsroni, G., 2002. An analytical model for nucleate pool boiling with surfactant additives. Int. J. Multiphase Flow 28, 699–706.

Tzan, Y.L., Yang, Y.M., 1990. Experimental study of surfactant effects on pool boiling heat transfer. J. Heat Transfer 112, 207–212.

Von Rybinski, W., Hill, K., 1998. Alkyl polyglycosides – properties and applications of a new class of surfactants. Angew. Chem. Int. Ed. 37, 1328–1345.

Wasekar, V.M., Manglik, R.M., 1999. A review of enhanced heat transfer in nucleate pool boiling of aqueous surfactant and polymeric solutions. J. Enhanced Heat Transfer 6, 135–150.

Wasekar, V.M., Manglik, R.M., 2000. Pool boiling heat transfer in aqueous solutions of an anionic surfactant. J. Heat Transfer, Trans. ASME 122, 708–715.

Wasekar, V.M., Manglik, R.M., 2002. The influence of additive molecular weight and ionic nature on the pool boiling performance of aqueous surfactant solutions. Int. J. Heat Mass Transfer 45, 483–493.

Wu, W.T., Yang, Y.M., 1992. Enhanced boiling heat transfer by surfactant additives. In: Proc. Eng. Foundation Conf. on Pool and External Flow Boiling. Santa Barbara, California, pp. 361–366.

Wu, W.T., Yang, Y.M., Maa, J.R., 1995. Enhancement of nucleate boiling heat transfer and depression of surface tension by surfactant additives. J. Heat Transfer 117, 526–529.

Yang, Y.M., Maa, J.R., 1983. Pool boiling of a dilute surfactant solutions. J. Heat Transfer 105, 190–192.

Yang, Y.M., Maa, J.R., 2003. Boiling heat transfer enhancement by surfactant additives. In: Proc. 5th Int. Conf. Boiling Heat Transfer, ICBHT, Montego Bay, Jamaica, May 4–8, 2003.

Yang, Y.M., Lin, C.Y., Liu, M.H., Maa, J.R., 2002. Lower limit of the possible nucleate pool boiling enhancement by surfactant addition to water. J. Enhanced Heat Transfer 9, 153–160.

Yao, S.C., Chang, Y., 1983b. Critical heat flux of narrow vertical annuli with closed end and closed bottoms. Int. J. Heat Mass Transfer 105, 192–195.

Yao, S.C., Chang, Y., 1983a. Pool boiling heat transfer in a narrow space. Int. J. Heat Mass Transfer 26, 841–848.

Zhang, J., Manglik, R.M., 2004. Effect of ethoxylation and molecular weight of cationic surfactants on nucleate boiling in aqueous solutions. Int. J. Heat Mass Transfer 126, 34–42.

Zhang, J., Manglik, R.M., 2005. Additive absorption and interfacial characteristics of nucleate pool boiling in aqueous surfactant solutions. J. Heat Transfer 127, 684–691.

Zhao, Y.H., Masuoka, T., Tsuruta, T., 2002. Int. J. Heat Mass Transfer 45, 3189–3197.