

# Natural convection boiling of water and surfactant solutions having negligible environmental impact in vertical confined space

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## ABSTRACT

Natural convection boiling of water and surfactant solutions in a confined space between two vertical plates was studied experimentally in the range of heat flux 19–170 kW/m<sup>2</sup>. The surfactant used was Alkyl (8–16) Glucoside having negligible environmental impact. The gap size was changed in the range of  $s = 1$ –80 mm, the concentration of surfactant solutions was changed in the range of  $C = 200$ –600 ppm. Generally, an addition of surfactant leads to an enhancement of heat transfer compared to water boiling at the same gap size. Enhancement of the heat transfer depending on the solution concentration at fixed gap size yields maximum value at the solution concentration close to the critical micelle concentration. The effect of confined space on a bubble dynamic was studied. Temperature field on the heater was determined using the infrared thermography technique. Quasi periodic wall temperature fluctuations were observed in the regime of high heat flux. An increase in the Bond number leads to an increase in the dimensionless frequency of the heated wall temperature fluctuations. The correlation between the dimensionless parameter of heat transfer and the Bond number under condition of quasi periodic boiling was derived and discussed.

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## 1. Introduction

Boiling in confined narrow spaces becomes quite different from boiling process observed in a pool. This topic was studied experimentally by a number of researchers. Previous investigations (Katto et al., 1966; Ishibashi and Nishikawa, 1969; Yao and Chang, 1983; Fujita et al., 1988; Nishikawa et al., 1984; Bonjour and Lallemand, 1998; Zhao et al., 2002) showed that confinement of a space for boiling led to enhanced heat transfer coefficient compared to unconfined boiling, but led to a decrease in the critical heat flux (CHF).

In the study by Ishibashi and Nishikawa (1969) a series of experiments were conducted to clarify the space restriction effect on the saturated boiling heat-transfer phenomena. Through the experimental investigation, it was detected that with saturated boiling heat-transfer in a narrow space, there is a coalesced bubble region having remarkably different characteristics. Beside the isolated bubble region, the heat-transfer characteristics of which have already been confirmed by many researchers. The main purpose of this study is to detect and prove the heat-transfer characteristics of the coalesced bubble region. In the first half of this study, various characteristics of the coalesced bubble region and that of the isolated bubble region are compared, based on experimental findings, and coincidentally, a new type of correlating equation for the coa-

lesced bubble region is proposed. In the second half, a theoretical analysis based on a simple unsteady state thermal conduction model is described, and the verification to the correlating equation is demonstrated. Systematic experiments on heat transfer characteristics in pool boiling were carried out by Fujita et al., (1998) in a confined narrow space bounded by a rectangular heating surface and an opposed unheated plate. Experiments were performed on heating surfaces with a width of 30 mm, length of 30 and 120 mm, and gap sizes of 0.15–5 mm. Nucleate pool boiling of pure water and dilute aqueous sodium lauryl sulfate (SLS) solutions within a confined space between heated and unheated horizontal-parallel surfaces has been investigated under atmospheric pressure. The electrically heated lower surface is made of a sheet of stainless steel 304 with the dimension of 145 × 22 × 0.05 mm and the unheated upper plate is a stainless steel cylinder with a diameter of 20 mm. The periphery of the confined space is open and the size of the gap can be varied from 0 to 10 mm.

Experimental results for water boiling show that with the size of the gap between 0.3 and 3 mm, the heat transfer coefficient may increase to as much as 200 percent of those measured for conventional pool boiling. The addition of surfactant has no significant influence on the heat transfer coefficient in this case. Based on the experimental results, the microlayer evaporation with fluid flow driven by the gradient of disjoining pressure is discussed and considered as an important heat transfer mechanism for nucleate pool boiling in confined spaces.

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The frequency and time of bubble passages were measured by means of hot-wire anemometry by Bonjour and Lallemand (2001). It was shown that at high heat fluxes bubbles mainly remain on the wall and form large coalesced bubbles. The effect of gap size on boiling was studied by Lee et al. (1992), Chulin (1994), Long et al. (2004), Passos et al. (2004). They noted that a decrease in the gap size led to an enhancement in heat transfer, but this tendency was disrupted for very small gaps where heat transfer was deteriorated. Yao and Chang (1983) assumed that effect of confinement on boiling depends on the ratio of the channel gap size to the capillary length scale, the latter being proportional to the departure diameter of isolated bubbles. The latter one is proportional to the square root of the liquid surface tension and the may be connected to the Bond number  $Bo = s[g(\rho_L - \rho_G)/\sigma]^{0.5}$ , where  $s$  is the channel gap size,  $\sigma$  is the liquid surface tension,  $g$  is acceleration due to the gravity,  $\rho_L$  and  $\rho_G$  are density of the liquid and the vapor, respectively.

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 increases the nucleate boiling heat transfer coefficient considerably. It was also found, that for some additives, the heat transfer increases with increasing concentration of surfactant solutions, then reaches a maximum and decreases with further increase in the concentration. It was shown by Wu and Yang (1992), Wu et al. (1995), Ammerman and You (1996), Kandlikar and Alves (1999), Yang and Maa (2003), Wasekar and Manglik (1999, 2000, 2002), Yang et al. (2002), Hetsroni et al., (2001, 2004), Zhang and Manglik (2004, 2005) that addition of a small amount of surfactant significantly increases heat transfer in saturated pool boiling. Most of these researchers reported that the diameter of the bubbles was considerably smaller and the number of bubbles was considerably higher than that at boiling in the pure water.

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 reported on significant enhancement of the heat transfer and showed drastic change in a flow pattern near the heated tube wall.

Dynamics of boiling incipience and vapor bubble growth in aqueous surfactant solutions were studied using high-speed photography by Wu and Yang (1992), Manglik et al. (2001). 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  $23 \text{ kW/m}^2$  were presented by Yang and Maa (2003). It was shown that the departure diameter decreased considerably with an addition of surfactant.

The first study on simultaneous effect of the space confinement and surfactant additive was carried out by Hetsroni et al. (2007). Natural convection boiling of water and surfactants at atmospheric pressure in narrow horizontal annular channels was studied experimentally in the range of Bond numbers  $Bo = 0.185\text{--}1.52$ . The flow pattern was visualized by high-speed video recording to identify the different regimes of boiling of water and surfactants. The authors reported that the additive of surfactant led to enhancement of heat transfer compared to water boiling at the same gap size, however this effect decreased with decreasing gap size. Critical heat flux in surfactant solutions was significantly lower than that in water at the same gap size. Hysteresis was observed for boiling in degraded surfactant solutions.

The main objective of the present investigation is to study the joint effect of space confinement and surfactant additive of various concentrations on the natural convective boiling heat transfer between two vertical plates. 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 at boiling. Unfortunately, most surfactants are not suited for industrial systems because of their degradation and environmental impact. That is why we conducted this study using Alkyl polyglucosides. They are nonionic surfactants with negligible environmental impact (von Rybinski and Hill, 1998). We used Alkyl (8–16) Glucoside (Plantacare 818 UP) with molecular weight of  $390 \text{ g/mol}$  for our experiments.

## 2. Experimental apparatus and procedure

### 2.1. Experimental apparatus

The experimental facility is shown in Fig. 1. It consists of a rectangular vessel (1) of 140 mm long, 90 mm wide and 100 mm deep filled with liquid. The flow pattern was observed through three transparent side walls (2). The fourth side wall (3) was made of insulating material and was connected to the rectangular slot (4) of 14 mm height, 26 mm width, and 42 mm length. The horizontal centerline of this slot was at a distance of 35 mm from the bottom of the pool. The heater (5) was made of a stainless steel foil of  $50 \mu\text{m}$  thickness. It was of 50 mm width (the X direction), and 25 mm height (the Z direction). The temperature field on the heater was measured through a slot (4) by an IR camera. Electric current was supplied to the heated foil through stainless steel bars (6) from a DC power supply. The tested channels (7) were formed between the heater and the special glass plate (8) of 50 mm width and 25 mm height. The top, bottom and sides of these channels did not have any walls. Restriction of the boiling space was performed by moving the plate (8) towards to the heater (5). The gap size was controlled by calibrated plates. Fluid temperature was measured by T-type thermocouples of 0.3 mm diameter. Thermostat (9) was used to stabilize the bulk fluid temperature at a saturation point. The vapor bubbles were created on the heated foil into a channels (7). The field of the surface temperature on the air side of the foil, by the convective boiling, was measured by a high-speed infrared radiometer (10). Both the inside walls of the rectangular slot (4) and the part of stainless steel foil on air side were coated by a black paint of about  $20 \mu\text{m}$  thickness. The radiometer was placed on the side of the vessel at a distance of about 0.3 m from the heater. The recording frequency was chosen as 177 Hz. This frequency is an order of magnitude higher than the typical frequency of departure of large bubbles in a confined space between two vertical plates. The recording rate is the compromise between

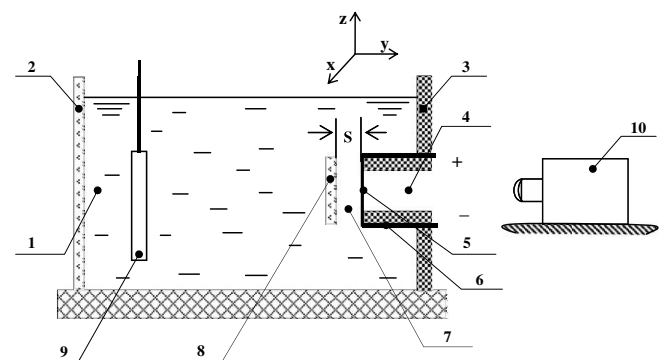


Fig. 1. Experimental facility (1) rectangular vessel; (2) transparent wall; (3) wall made of insulating material; (4) rectangular slot; (5) heater; (6) bars; (7) tested channel; (8) glass plate; (9) thermostat; (10) infrared radiometer.

the desire to record a thermal pattern on largest area and possible rate of recording at such frame size.

Preliminary calculations performed by Hetsroni and Rozenblit (1994) have shown that the maximal difference between the temperatures of the two sides of the foil is less than 0.24 °C at maximal value of heat flux. A detailed analysis of the time-response of the heat-foil infrared technique has been done by Hetsroni et al. (1996). It is estimated according to this analysis that signal with frequency of 40 Hz may be measured without significant distortion of its amplitude. This value is much higher than frequencies of temperature fluctuations recorded in the present study. The minimum detectable temperature difference of the radiometer is 0.1 °C at the surface temperature of 30 °C. The growth of the bubbles and the bubble motion near the heated surface were recorded by a high-speed video camera with recording rate up to 10,000 frames per second.

## 2.2. Properties of surfactant solutions

We used Alkyl (8–16) Glycoside nonionic surfactant solution of molecular weight 390 g/mol. The solutions were 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 surface tension were carried out for different concentrations of surfactant solutions over a range of temperature from 300 to 368 K (Hetsroni et al., 2004). In Fig. 2 the equilibrium surface tension,  $\sigma$ , is plotted vs. the concentration,  $C$ , of the surfactant solution at different temperatures. An increase in the surfactant concentration up to  $C = 300$  ppm (parts per million weight) leads to the significant decrease in the surface tension. In the range  $300 \leq C \leq 1200$  ppm the surface tension was almost independent of concentration. In all cases an increase in liquid temperature leads to a decrease in surface tension. Our results showed that in the range of the temperature of surfactant solutions from 300 to 368 K the CMC point was reached at concentration close to  $C = 300$  ppm.

## 2.3. Procedure

Before experimental runs the surface roughness of the heater, created during the boiling process, was examined by an atomic force microscope using such tools as the section analysis and line profiles. The results on boiling of water and surfactant solution of  $C = 200$  ppm after 10 h are presented in Fig. 3 and Fig. 4, respectively. As shown in these figures, the root-mean-square roughness of stainless steel heater was 422.92 nm in the case of water boiling whereas it was 617.67 nm in the case of surfactant boiling.

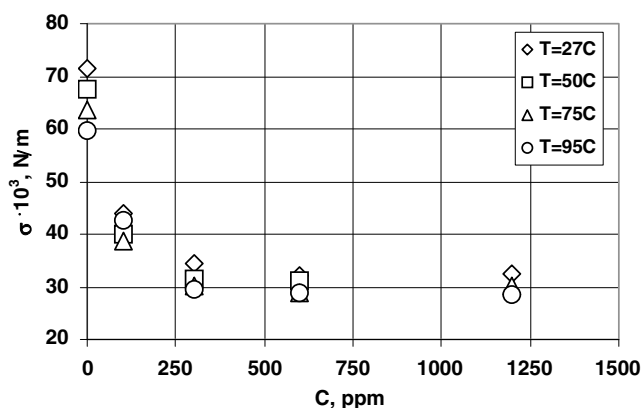


Fig. 2. Equilibrium surface tension of surfactant solutions.

The heating surface was cleaned routinely before and after each set of three data points. Only a soft sponge and absorbent paper tissues contacted the stainless steel foil, which remained smooth and completely wettable. No visible deposits formed under test conditions, based on observations in the test runs and after draining the test section.

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 heater was turned on. This was determined by monitoring the temperature of the solution. The degassing procedure was performed before the beginning and during the experiments. Fluid boiling was carried out before the experiments for 2 h at a pressure of 1 bar and then boiling over the period of the experiments was maintained.

All measurements were performed under steady state conditions. Each experiment was run for several minutes until the thermal regime became stabilized. Experiments were conducted under conditions at which the CHF regime did not occur. Thus, the heat flux did not exceed the value at which the heating surface temperature would rise suddenly.

We considered the results on heat transfer in solutions which undergo repeated heating and cooling. The following procedure was employed to test the effect of heating on the physical properties of surfactant solutions used in the present study. After a number of runs a small amount of the fluid sample was taken for measurement of the viscosity. After that the heating power was increased and the experimental runs started again. It was found that the viscosity of the fresh solution was stable for 3–5 runs, no more, then the viscosity began to change during 4–8 runs (boiling-cooling to ambient temperature) and afterwards did not change again (the relaxation time was about 30–40 h). Such solutions were defined as degraded.

We did not observe any change in surface tension and thermal conductivity, compared to the fresh solution. Boiling hysteresis occurred in degraded Alkyl (8–16) solutions. It should be stressed that after boiling incipience boiling curves in degraded solutions did not differ from those obtained in solutions after 1–3 runs. There is good reason to believe that Alkyl (8–16) surfactant solutions are suited for industrial use over a period at least of 40 h.

A fresh sample of surfactant solution was used after three runs. This precaution was taken to minimize changes in solution properties, which might have occurred at high temperature due to evaporation over a long period of time.

The heat flux was determined as:

$$q = (N - N_{\text{loss}})/A \quad (1)$$

where  $N$  is the electrical power supplied to the heated foil,  $N_{\text{loss}}$  is the heat losses by conduction to the electrical contacts and holding frame,  $A$  is the heater surface area on the liquid side. The heat losses were determined experimentally from energy balance when a given amount of single phase fluid was heated in the vessel under conditions of different electrical power supplied to the heated foil.

The average heat transfer coefficient is defined as

$$\alpha = \frac{q}{(\bar{T}_w - T_s)}, \quad (2)$$

where  $q$  is the heat flux,  $\bar{T}_w$  is the average wall temperature measured by the IR camera,  $T_s$  is the saturation temperature. The range of heat flux was  $19 \leq q \leq 170$  kW/m<sup>2</sup>.

## 2.4. Uncertainty analysis

The heat flux was calculated by measuring the power delivered to the heated surface and by determination of heat losses. The electrical power was determined with an accuracy of 0.5%. The heat

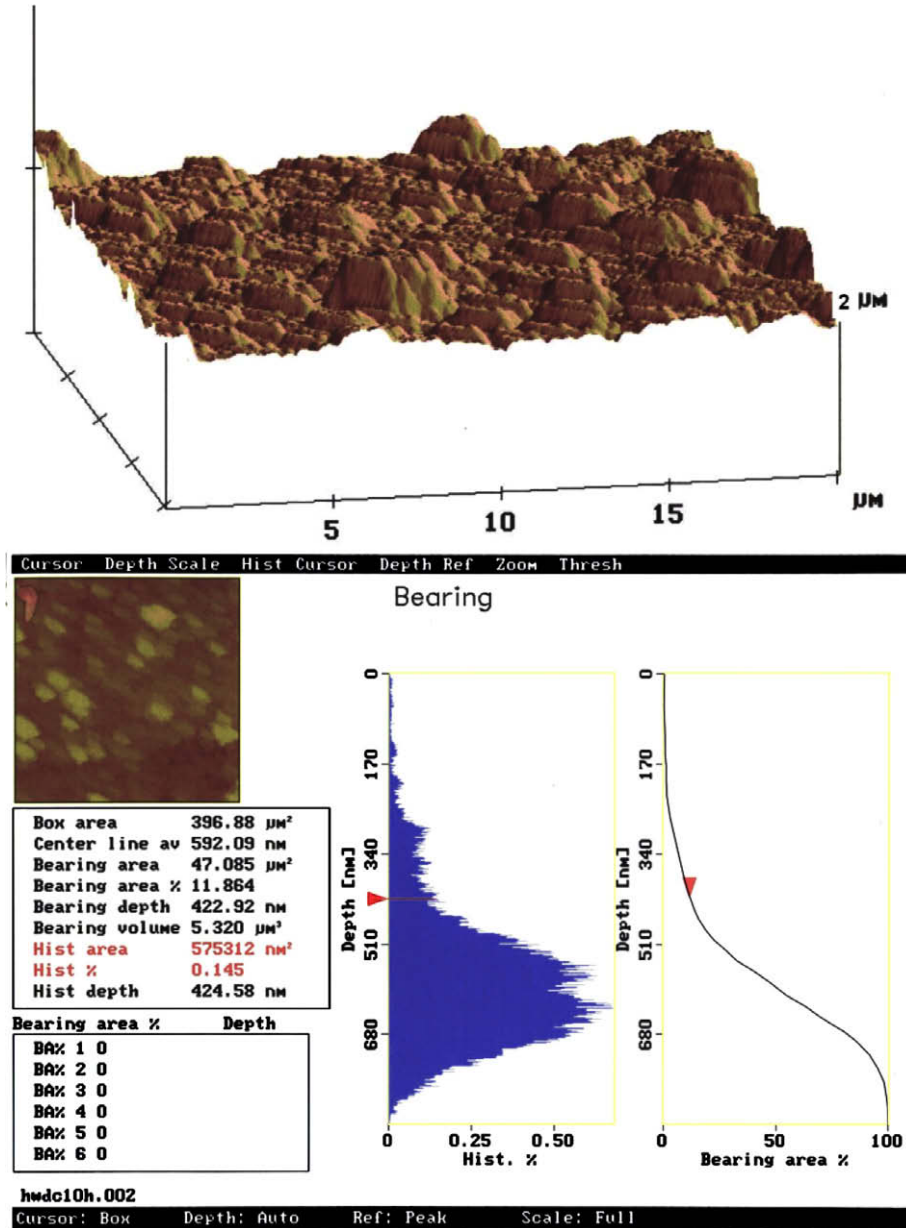


Fig. 3. Surface roughness after boiling of water during 10 h.

losses from the heated stainless film to electrical contacts and insulating frame did not exceed 0.2%. The estimated accuracy in the definition of heated area of stainless steel film is 0.28%. The thermocouple and the data acquisition system were calibrated at the steam point and ambient water temperature. The estimated accuracy in the definition of the saturation temperature was 0.1 K.

The IR camera was calibrated by measuring the temperature field of a heated surface in the temperature range close the saturation temperature. The estimated uncertainty of the average wall temperature measurement by the IR camera was within 0.2 K at the experimental conditions. The error in determining the conditional average heat transfer coefficient  $\alpha$ , according to Eqs. (1) and (2) is composed from an estimation of errors of measurements of the following values:  $q$  - heat flux;  $\bar{T}_w - T_s$  - difference between the averaged value of the wall and the saturation temperatures. The uncertainty is higher at the low values of heat flux due to the small temperature difference between the heater and fluid temperatures. Therefore, an uncertainty estimation of heat transfer

coefficient is done at the lowest value of heat flux. The results of the uncertainty analysis obtained according to the standard 1995 "Guide to the Expression of Uncertainty of the Measurements" are presented in Table 1. The heat transfer coefficient was determined with accuracy of 9.5% at 95% confidence level.

### 3. Experimental results and discussion

An experimental study has been carried out to investigate the heat transfer processes at natural convective boiling of water and surfactant solutions in narrow vertical channel at atmospheric pressure. The gap size of the vertical channel was 1.0, 2.0, 3.0, and 80 mm. The latter position of glass plate was considered by us as unconfined space. The heat flux was in the range  $q = 19$ – $170$  kW/m<sup>2</sup>, the concentration of surfactant solutions was in the range  $C = 0$ – $600$  ppm. Experimental conditions are given in Table 2.

Almost no coalescence of bubbles were formed in the confined space in the lower heat flux region ( $q < 40$  kW/m<sup>2</sup>). The bubbles left

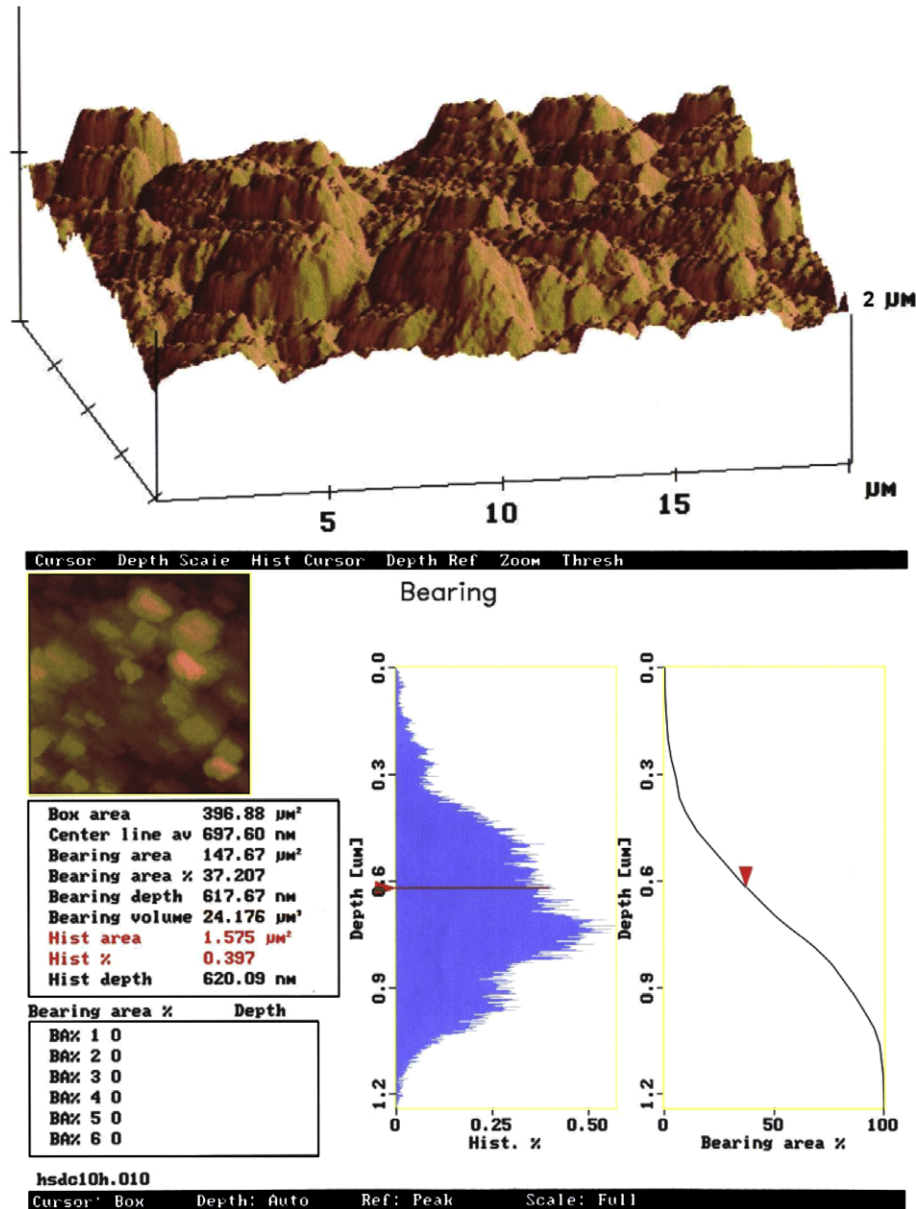


Fig. 4. Surface roughness of heater after boiling of surfactant solution of  $C = 200$  ppm during 10 h.

**Table 1**  
Summary of standard uncertainty components of heat transfer coefficient ( $q = 19 \cdot 10^3 \text{ W/m}^2$ ).

Standard uncertainty component $u(x_i)$	Source of uncertainty	Value of standard uncertainty $u(x_i)$	$c_i \equiv \partial\alpha/\partial x_i$	$\frac{u(x_i) c_i }{\alpha}$
$u(q)$	Heat flux	116 $\text{W/m}^2$	$\frac{1}{T_w - T_s}$	$6.1 \cdot 10^{-3}$
$u(T)$	Measured difference between wall and saturation temperatures	0.3 K	$\frac{1}{(T_w - T_s)^2}$	$4.4 \cdot 10^{-2}$
$u_c(\alpha)/\alpha = 4.45 \cdot 10^{-2}$ ; $\alpha = 2.81 \cdot 10^3 \text{ W/m}^2 \text{ K}$ ; degrees of freedom - 8; $\nu_{\text{eff}}(\alpha) = 15$ ; $k = 2.13$ ; $U_{95} = k u_c(\alpha)$ ; $U_{95}(\alpha)/\alpha = 0.095$				

the channel through the top of the channel. However, the behavior of vapor bubbles changed at higher heat fluxes. Bubble coalescence occurred for water boiling in the range of heat flux  $40 < q < 120 \text{ kW/m}^2$ . Analogous behavior reported early by Yao and Chang (1983) for confined boiling of water, acetone and R-113 in an annular vertical space ( $H = 25.4$  or  $76.2$  mm in the range of gap size of  $0.32\text{--}2.58$  mm) whose bottom was closed. They reported that the regime of isolated deformed bubbles occurred for small gaps and low heat fluxes. For moderate heat fluxes coalesced deformed bubbles were observed. Bonjour and Lallemand (1998) observed the boiling regimes at boiling of R-113 in the narrow

space between two vertical surfaces. They divided the boiling process into three regimes: (1) nucleate boiling with isolated deformed bubbles; (2) nucleate boiling with coalesced bubbles and (3) partial dryout. These flow patterns were also observed in the present study for water boiling.

When the heat flux was close to CHF, Yao and Chang (1983) described the dryout regime. If heat flux is sufficiently high, suddenly at some point on the heating surface, a part of the area becomes unwetted and the dry spot starts growing, leading to burnout. However, the boiling flow pattern depends not only on the gap sizes but also on the kind of the fluid.

**Table 2**  
Experimental conditions.

Spacing, $s$ , mm	$q$ , kW/m <sup>2</sup>	Water		Surfactant solution, ppm					
				200		300		600	
		$T_w$ , °C	$\alpha$ , kW/m <sup>2</sup> K	$T_w$ , °C	$\alpha$ , kW/m <sup>2</sup> K	$T_w$ , °C	$\alpha$ , kW/m <sup>2</sup> K	$T_w$ , °C	$\alpha$ , kW/m <sup>2</sup> K
80	19	106.8	2.81	104.3	4.47	103.4	5.6	103.5	5.39
	42	110.3	4.06	105.6	7.54	105.5	7.68	107.3	5.75
	75	112.4	6.05	109.3	8.03	108.6	8.68	109.3	8.06
	108	115.4	7.03	110.9	9.91	110.5	10.27	110.3	10.45
	137	117.4	7.88	111.7	11.74	110.6	12.92	111	12.51
	170	118.6	9.12	112	14.17	112.7	13.44	110.5	16.27
3	19	105.7	3.32	103.8	5.02	103.8	5.00	103.7	5.09
	42	109.4	4.46	105.2	7.54	106.8	6.18	107.1	5.34
	75	110.9	6.87	108.8	8.55	108.8	8.55	109.3	8.1
	108	112.2	8.84	111.4	9.46	110.5	10.27	111	9.84
	137	113.6	10.11	111.7	11.71	111.1	12.36	111.6	11.79
	170	114.2	11.95	111.4	14.95	112.2	13.98	111.5	14.78
2	19	106.7	2.84	103.1	6.08	104.1	4.63	103.7	5.2
	42	108.7	4.84	104.7	9.03	105.7	7.32	106.3	6.7
	75	110	7.43	106.2	12.06	106.2	12.13	106.8	11.04
	108	111.4	9.47	107.1	15.28	108	13.47	107.5	14.35
	137	112.2	11.26	107.5	18.32	108.1	16.83	108.4	16.3
	170	112.1	14.05	108.7	19.63	109.1	18.63	108.6	19.81
1	19	106.3	3.02	103.3	5.75	102.8	6.91	103.3	5.79
	42	108.7	4.83	104.1	10.36	103.7	11.5	103.7	11.48
	75	108.8	8.51	104.2	17.75	104.7	15.95	104.5	16.82
	108	108.3	13.01	105	21.37	106.2	17.41	105	21.78
	137	108.6	15.96	105.9	23.22	105.5	25	105.3	26.01
	170	109	18.85	105.7	29.57	106.3	26.94	105.5	30.89

### 3.1. Effect of gap size on bubble formation

The effect of the gap size appears qualitatively similar under visual observation, of boiling in both the water and the surfactant solution. However dynamic processes of a bubble rise are clearer in water since the water is optical more transparent medium than the surfactant solution. Therefore the qualitative analysis of the effect of the gap size on the bubble formation will be performed in water.

Fig. 5 shows the bubble behavior during boiling in water at  $q = 30$  kW/m<sup>2</sup> in an unconfined space. The field of view is  $10 \times 10$  mm. When the energy input from the heater reached a value needed for an onset of the bubble generation, single bubbles could be observed clearly, stably and repeatedly on the heated surface. Dimensions of bubbles and bubble displacement were measured by counting the number of pixels in the bubble image. A physical dimension of 1 mm corresponds to 30 pixels, i.e. 1 pixel in the image corresponds to 0.033 mm. The images were taken with the time resolution of 1 ms. From Fig. 5a–b, we can see that bubble diameter grew rapidly until reaching its final size, then the bubble began to move along the surface in a vertical direction, Fig. 5c–g. During such displacement along the surface a neck of the bubble attached to the surface (shown in Fig. 5 by an arrow pointing to the neck) was clearly observed. Under condition of the present experiment, the bubble displacement was in the range of 1.5–1.7 mm. The bubble is detached when the buoyant force just overcomes the surface tension, Fig. 5h.

Fig. 6 presents bubble behavior during boiling of water in the gap of 2 mm at  $q = 30$  kW/m<sup>2</sup>. It can be seen that the water bubble growth in confinement faster in the plan of the heater than that in an unconfined space.

### 3.2. Boiling curves and average heat transfer

Data were taken for both increasing and decreasing heat fluxes. The total mass of the liquid in the test facility remained constant; no fresh liquid was introduced to “top off” the system. The investigation was carried out in the range of the Bond numbers of  $0.4 \leq Bo \leq 47$ .

Figs. 7 and 8 show boiling curves obtained in vertical confined open channel at various values of the gap size for clear water and surfactant solutions of various concentrations. The heat flux,  $q$ , is plotted vs. the wall excess temperature  $\Delta T_s = T_w - T_s$ . Each point in Figs. 7 and 8 represents an average value obtained from the measurements. In these experiments we did not observe any signs of a hysteresis. It can be seen from Fig. 7 that the wall superheat in clear water was reduced at heat flux higher than 50 kW/m<sup>2</sup> as the gap size decreased.

Similar effect was observed in the solution of surfactants at concentrations of 200, 300 and 600 ppm, Fig. 8. The boiling curves for the boiling in surfactant solutions of the all concentrations in unconfined space shifted left relative to the boiling curve at the same conditions in the water. It should be noted that for the gap size of 3.0 mm the boiling curve was only slightly different from the one in unconfined space. This might have some validity since the bubbles in surfactant solutions were smaller in diameter than those in water. 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. For high Bond numbers, boiling can almost be considered as unconfined.

The decrease in the wall excess temperature may be considered as an enhancement of the heat transfer. According to Yang and Maa (2003), boiling heat transfer in surfactant solutions is enhanced by the depression of the equilibrium surface tension but suppressed by the depression of the equilibrium contact angle.

Effect of the confinement on water boiling is presented in Fig. 9 as the dependence of the relative heat transfer coefficient ( $\alpha/\alpha_{\text{wat,unconf}}^{-1}$ ) on the Bond number, where  $\alpha$  is the heat transfer coefficient in confined space,  $\alpha_{\text{wat,unconf}}$  is the heat transfer coefficient in unconfined space. Fig. 9 shows that under conditions of water boiling the decrease in the gap size lead to the enhancement of the heat transfer. This effect is more pronounced for  $Bo < 1$  (small gap sizes). As it was shown earlier (Figs. 5 and 6) the water bubble growth at confinement is more rapid than that in unconfined space. At a large gap,  $s = 80$  mm, a bubble is so small compared with the gap size that bubble behavior and the shape of boiling curves are similar to those in the unconfined boiling,

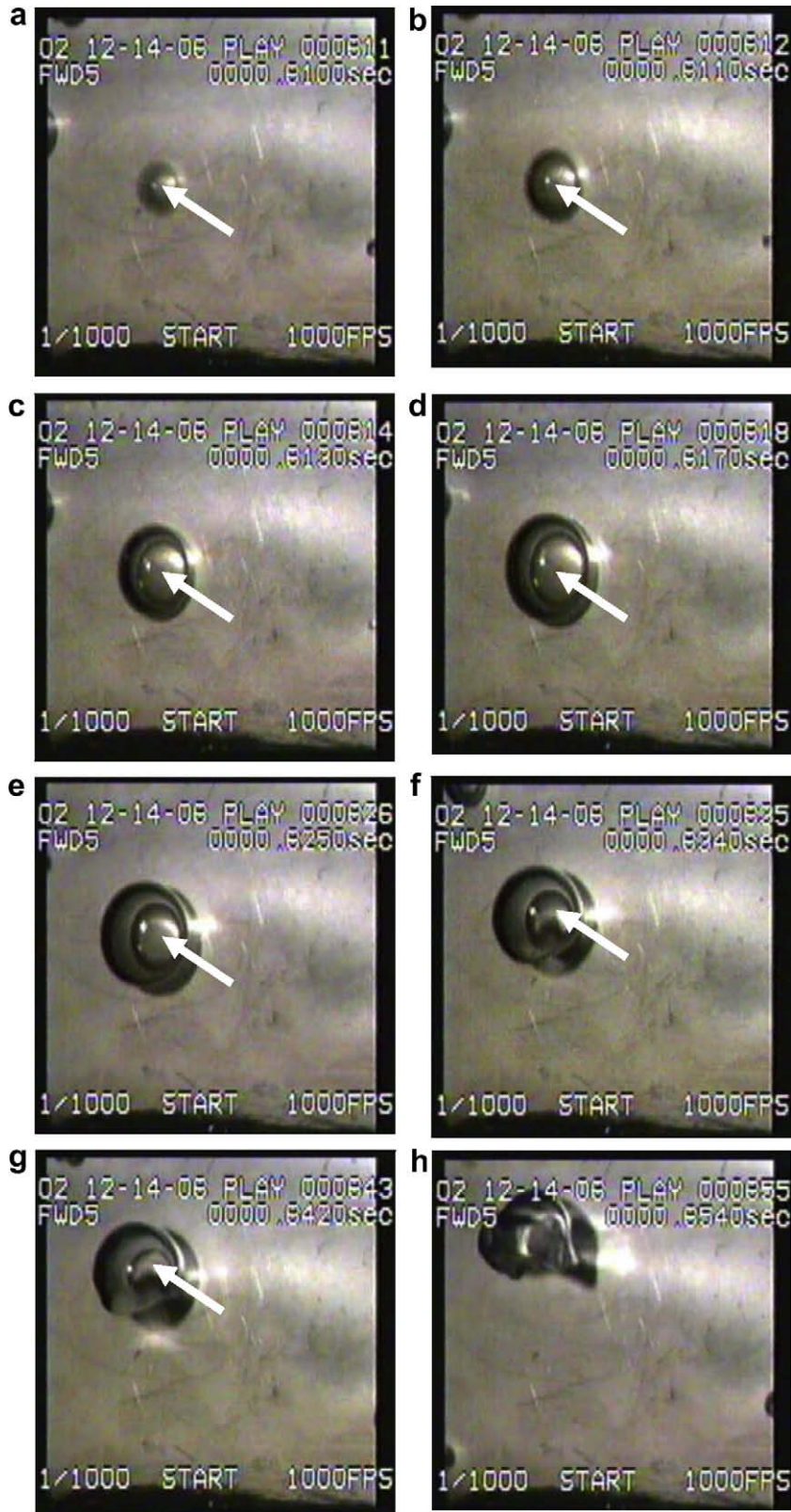


Fig. 5. Bubble behavior during water boiling in unconfined space at  $q = 30 \text{ kW/m}^2$ .

Hetsroni et al. (2004). But a higher heat transfer rate is achieved due to two-phase mixture agitation in a narrow space. Bubble formation is also responsible for lower effect of increase in heat transfer at the same gap size in the case of decrease in heat flux. That is

why the maximum values of the heat transfer enhancement were observed at low Bond numbers and high heat fluxes.

Though considerable light has been focused on the heat transfer problem through experimental studies on water boiling in

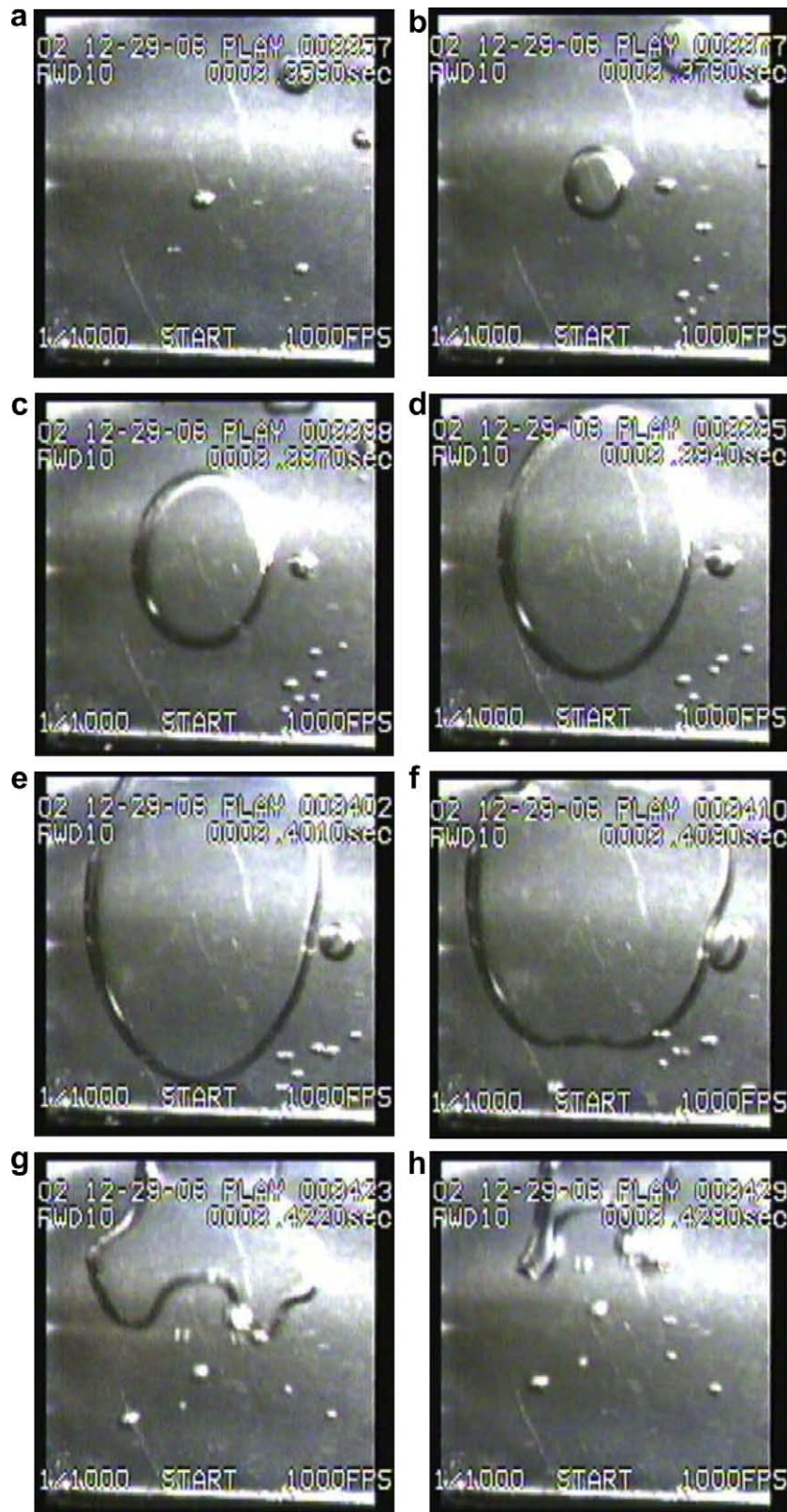


Fig. 6. Bubble behavior during water boiling in the gap of  $s = 2$  mm at  $q = 30$  kW/m<sup>2</sup>.

confined narrow spaces of various size and geometry under various peripheral conditions, there may still required data to elucidate the boiling of surfactant solutions in a confined narrow space.

In Fig. 10 the dependence of the relative heat transfer coefficient on the Bond number at different surfactant concentrations is presented. Fig. 11 shows the dependence of the relative heat transfer coefficient on the concentration of surfactant solutions.



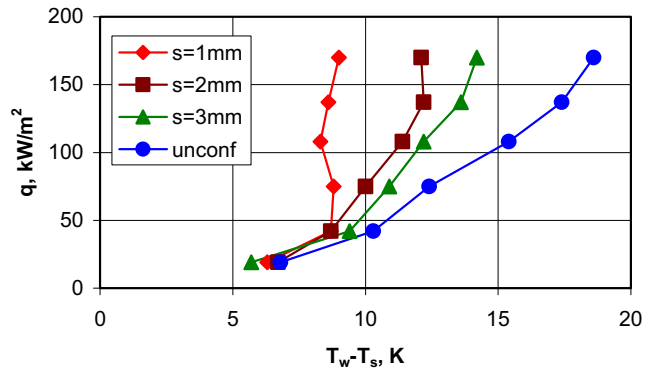


Fig. 7. Boiling curves obtained in vertical confined open channel in clear water at various values of gap size.

The gap size is  $s = 2mm$ . The dependence reaches the maximum at the solution concentration  $C = 200 ppm$ .

### 3.3. Variation of heat transfer in time and periodic boiling

Of special interest is the problem of identification of the boiling regime preceding full dryout and critical heat flux. An experimental study concerning this problem 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. The authors concluded that the reduced CHF is related to earlier dryout of micro-layer because the initial thickness of the micro-layer was reduced with a decrease in the space gap. We assume that a decrease in the channel gap leads to increasing the

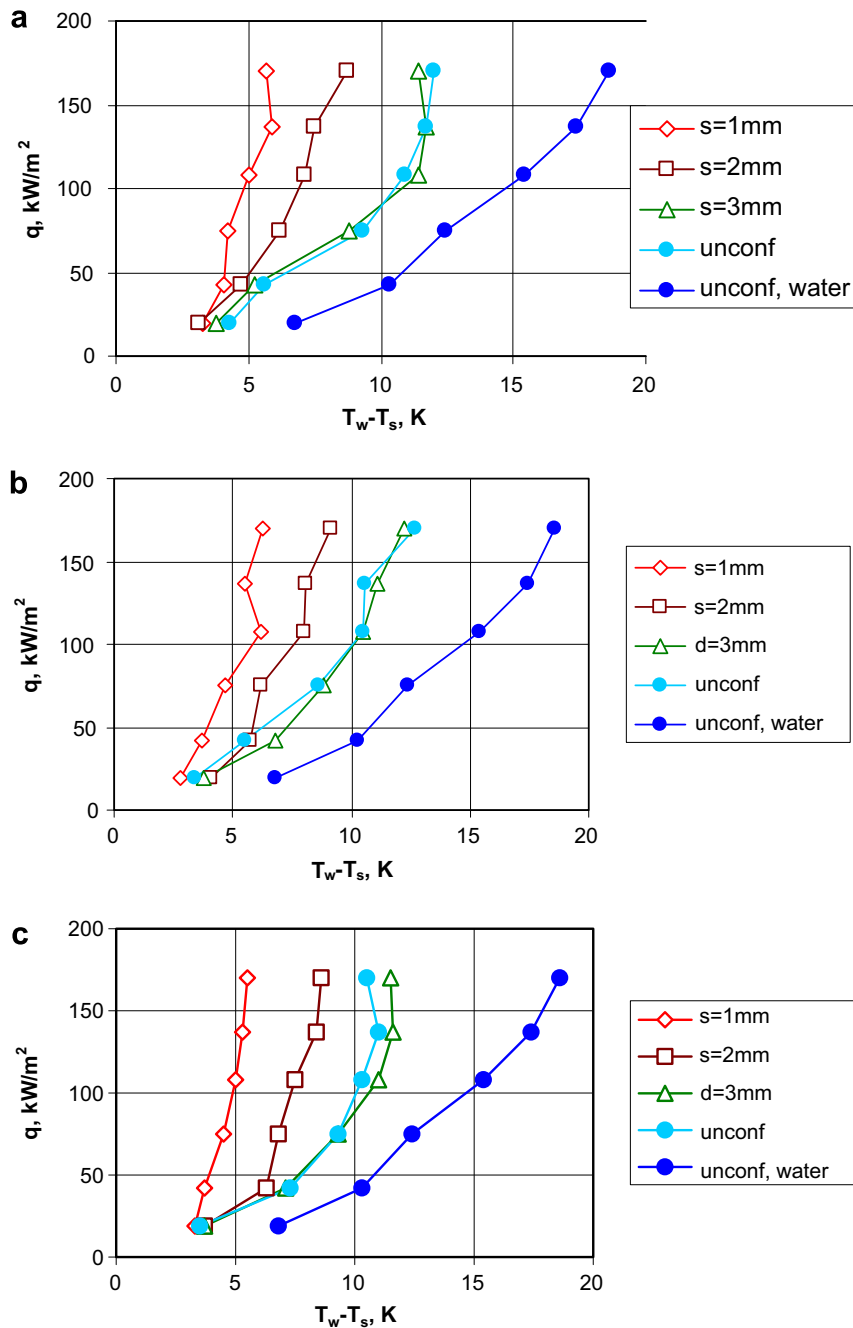


Fig. 8. Boiling curves obtained in vertical confined open channel in the surfactant solution of various concentrations at various values of gap size, (a)  $C = 200 ppm$ , (b)  $C = 300 ppm$ , (c)  $C = 600 ppm$ .

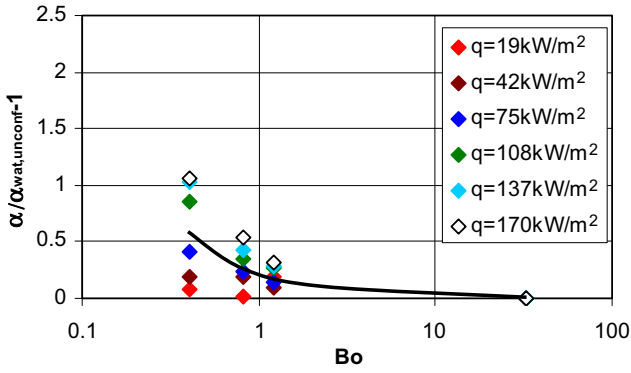


Fig. 9. Effect of confinement on water boiling.

heated surface which is covered by vapor, and increasing the time of the presence of the vapor blanket. We will analyze the temperature field on the heated foil as an instrument for identification of the boiling regimes, specially preceded the dryout.

The time variation of the mean heater temperature during boiling of water and surfactant solution of  $C = 300$  ppm in unconfined space is presented in Figs. 12 and 13, respectively. The mean heater temperature (i.e. average temperature of the whole heater) was higher for boiling in water than that in surfactant solution and for both liquids it changed in the range of  $\Delta T_{mean} = 1-2$  K. Figs. 14 and 15 illustrate the behavior of the mean heater temperature during boiling of water and surfactant solution of  $C = 300$  ppm in the gap of  $s = 2$  mm. Comparison between Figs. 14 and 15 shows that temperature fluctuations are higher in the case of water boiling.

Fig. 16 illustrates the behavior of the heater temperature during boiling of Alkyl (8–16),  $C = 300$  ppm in the gap of  $s = 3$  mm. Figs. 16a and c show instantaneous temperature distribution on the heater at  $q = 19$  kW/m<sup>2</sup> and  $q = 170$  kW/m<sup>2</sup>, respectively. Figs. 16b and d show variation of mean temperature on the heater vs. the frame number at  $q = 19$  kW/m<sup>2</sup> and  $q = 170$  kW/m<sup>2</sup>, respectively. The temperature field was recorded with the frequency of 177 Hz. Three curves are presented in Figs. 16b, d. The first of them, referred as 1, illustrates variation of mean temperature inside of the big rectangular area (over the whole heated surface shown in Figs. 16a, c). The two other curves, referred as 2 and 3, in Figs.

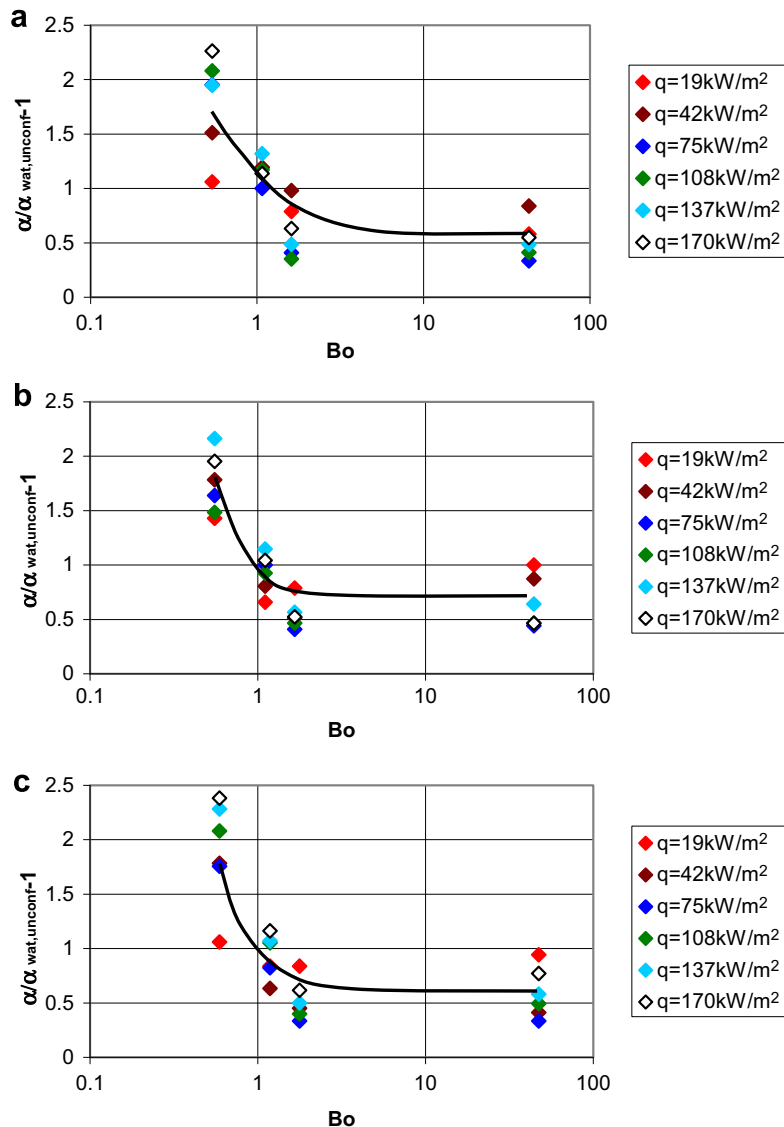


Fig. 10. Dependence of the relative heat transfer coefficient on Bond number, (a)  $C = 200$  ppm, (b)  $C = 300$  ppm, (c)  $C = 600$  ppm.

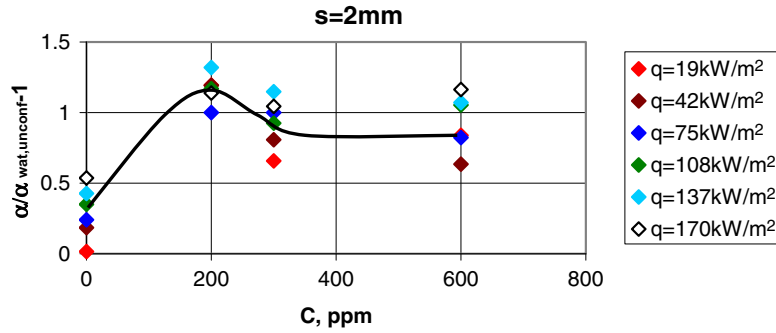


Fig. 11. Dependence of the relative heat transfer coefficient on concentration of the surfactant solutions. The gap is  $s = 2$  mm.

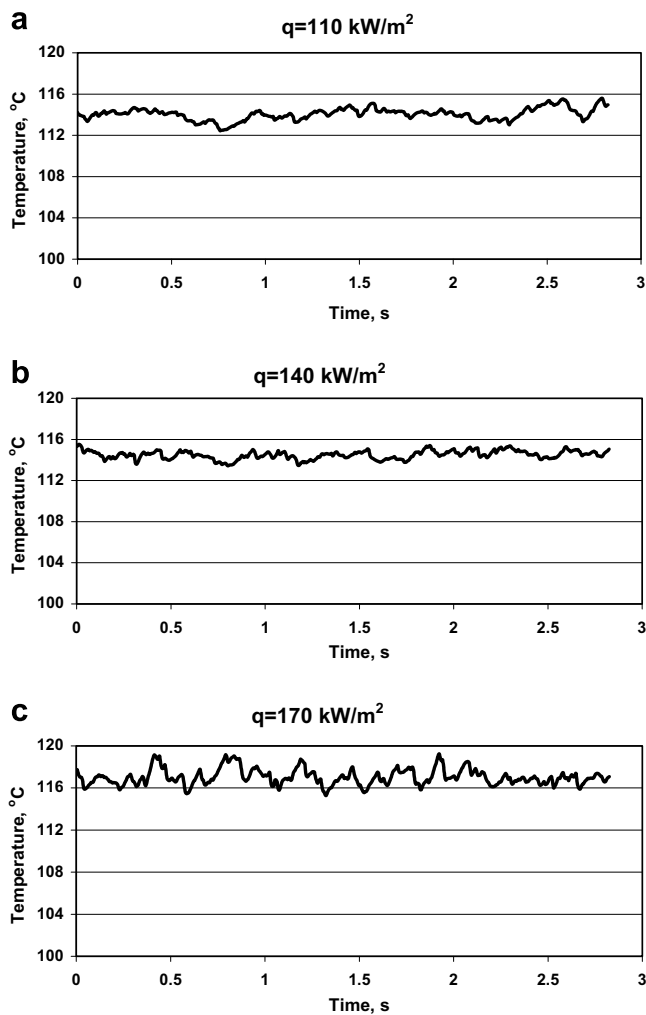


Fig. 12. Time variation of the mean heater temperature during water boiling in unconfined space.

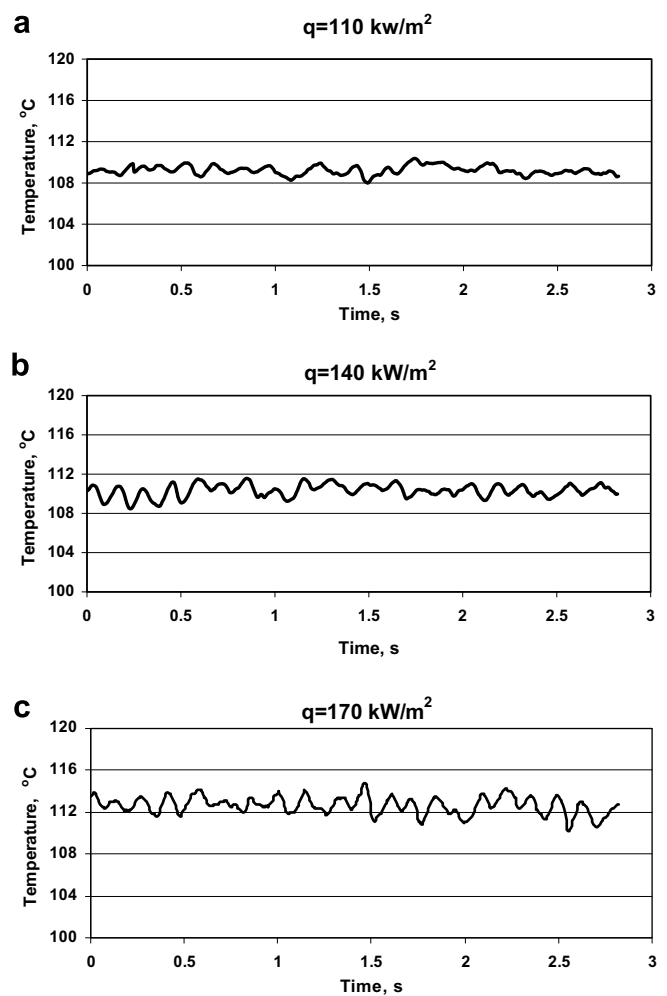


Fig. 13. Time variation of the mean heater temperature during boiling of surfactant solution of  $C = 300$  ppm in unconfined space.

16b, d show the mean temperature inside of the small rectangular areas 2 and 3 located at arbitrary points on the heated surface (Figs. 16a, c).

From Fig. 16b one can see that in the case of low heat flux,  $q = 19 \text{ kW/m}^2$ , the mean temperature fluctuations are not regular. Whereas fluctuations of mean temperature at high heat flux,  $q = 170 \text{ kW/m}^2$ , are almost regular. Fig. 16d shows that the fre-

quency of mean temperature fluctuations was the same for the whole surface as for different small areas located on the surface. Under this condition the whole heated surface was covered by a vapor blanket.

The curve of FFT shown in Fig. 17 has the clear peak at a frequency of about 5.5 Hz. It means that the mean temperature of the heated wall varied quasi periodically in time. Periodical variation of the mean temperature of the heater causes periodic change

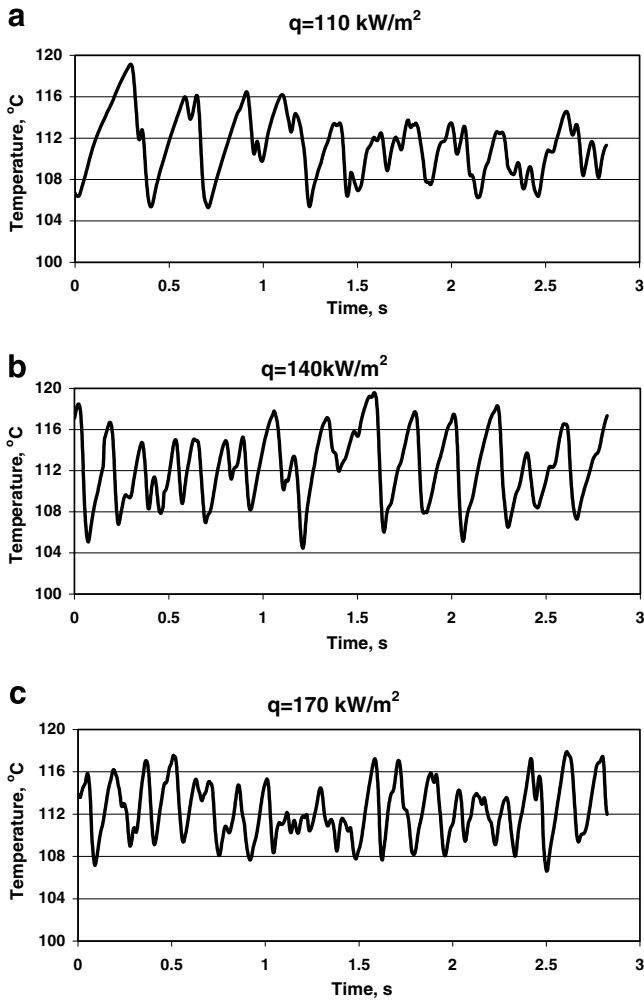


Fig. 14. Time variation of the mean heater temperature during water boiling in the gap of  $s = 2$  mm.

of the average heat transfer coefficient. Such quasi periodical fluctuations of temperature have been studied by Hetsroni et al. (2006), where periodic variations of pressure drop, fluid and heater temperatures were registered at the flow boiling of water and ethanol in parallel triangular microchannels of hydraulic diameter  $100\text{--}220\ \mu\text{m}$ . The authors concluded that the regime of quasi periodic boiling existed prior to CHF. Therefore such circumstance should be taken into account during at design of two-phase mini heat exchangers.

Analysis of experimental data makes it possible to determine the upper boundary of the heat transfer enhancement. Further decrease in the gap size or increase in the heat flux value led to drastic decrease in the heat transfer coefficient. The dependence of dimensionless frequency  $\bar{f} = fs^{0.5}/g^{0.5}$  of quasi periodic fluctuations on Bond number is presented in Fig. 18.

Fig. 19 shows the dependence of the dimensionless heat transfer parameter  $\bar{q} = qs/k\Delta T_s$  on the Bond number under conditions of quasi periodic boiling. This parameter may be considered as the heat flux during boiling, due to the heat flux transferred by thermal conductivity through the gap filled with steady motionless liquid and presents as:

$$\bar{q} = 44.9\text{Bo}^{0.95} \quad (3)$$

The correlation (3) may be used to determine the wall excess temperature at boiling in confined space for the regimes preceding partial dryout in the range of Bond numbers  $\text{Bo} = 0.40\text{--}47$ .

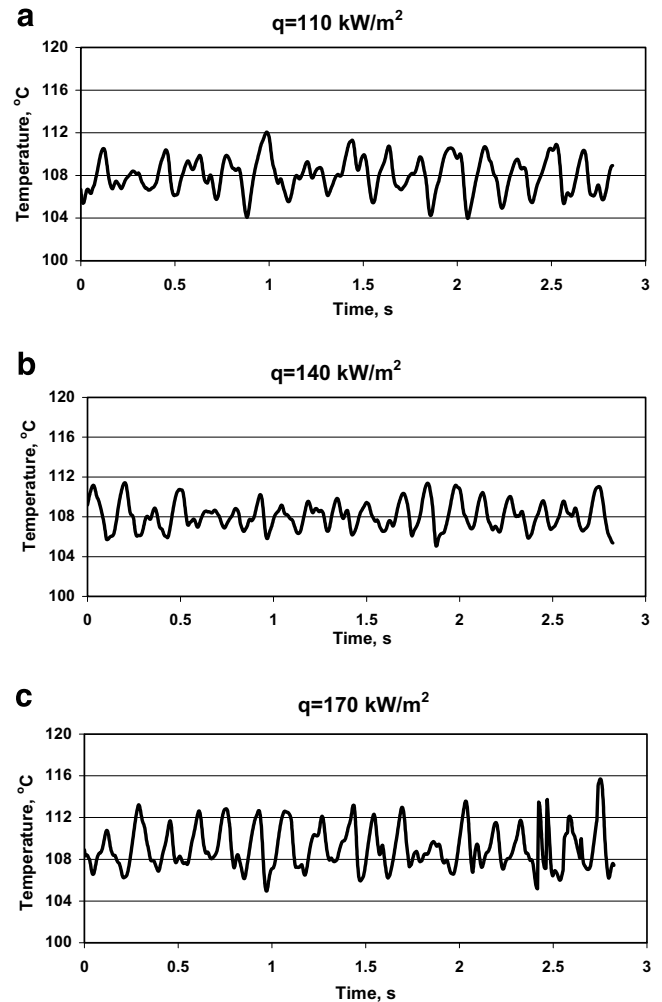


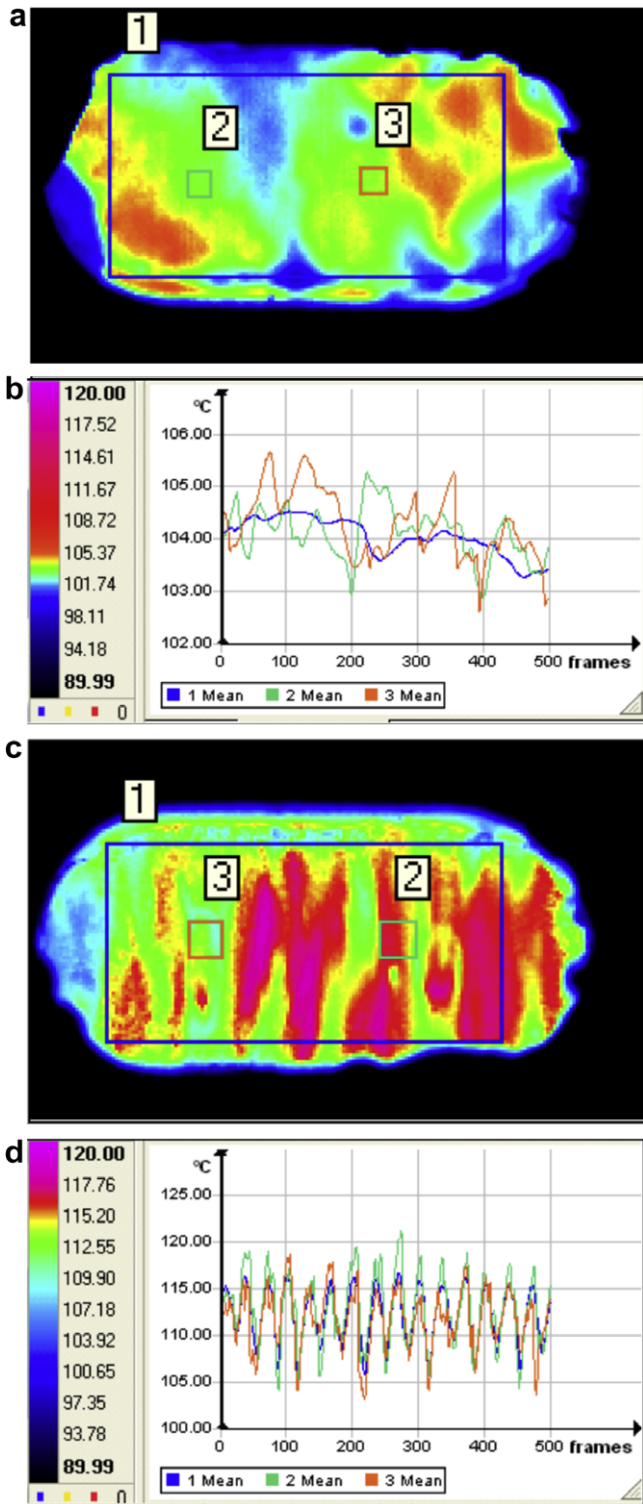
Fig. 15. Time variation of the mean heater temperature during boiling of surfactant solution of  $C = 300$  ppm in the gap of  $s = 2$  mm.

#### 4. Conclusions

Boiling heat transfer at boiling in a confined space between two vertical plates in the surfactant solution of various concentrations was studied experimentally. The surfactant used was Alkyl (8–16) Glucoside (Plantacare 818 UP), having negligible environmental impact. The gap size was changed in the range of  $1 \leq s \leq 80$  mm. The surfactant concentration was changed in the range of  $0 \leq C \leq 600$  ppm.

Visual observations showed that a decrease in gap space affected the bubble dynamics.

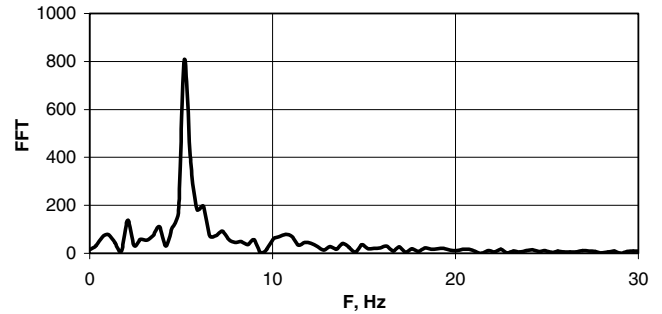
Generally, an addition of surfactant leads to an enhancement of heat transfer compared to water boiling at the same gap size. Enhancement of the heat transfer depending on the solution concentration at fixed gap size yields maximum value at the solution concentration close to the critical micelle concentration. Temperature field on the heater was determined using the infrared thermography technique. Quasi periodic wall temperature fluctuations were observed in the regime of high heat flux. An increase in the Bond number leads to an increase in the dimensionless frequency of the heated wall temperature fluctuations. The correlation between dimensionless parameter of heat transfer and the Bond number under condition of quasi periodic boiling was derived and discussed.



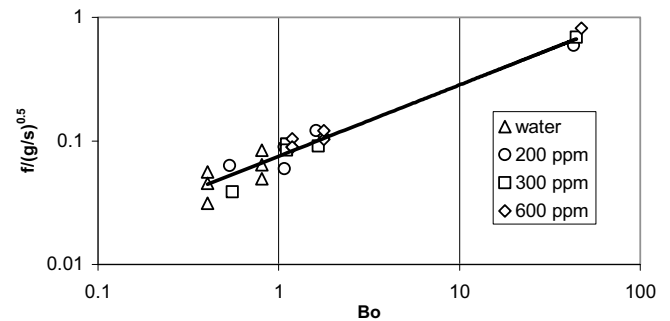
**Fig. 16.** Behavior of the heater temperature during boiling of Alkyl (8–16),  $C = 300$  ppm,  $s = 3$  mm. (a) Instantaneous temperature field on the heater,  $q = 19$  kW/m<sup>2</sup>, (b) variation of the mean heater temperature vs. frame number,  $q = 19$  kW/m<sup>2</sup>, (c) instantaneous temperature field on the heater,  $q = 170$  kW/m<sup>2</sup>, (d) variation of the mean heater temperature vs. frame number,  $q = 170$  kW/m<sup>2</sup>.

### Acknowledgements

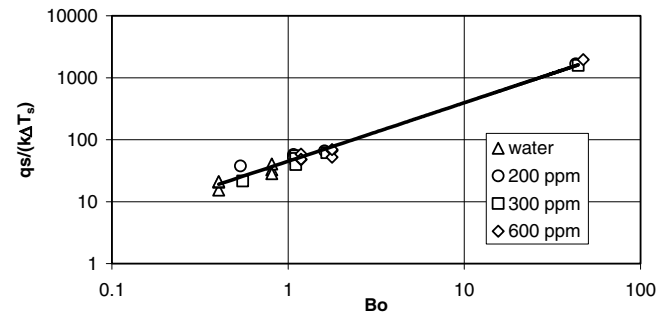
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**Fig. 17.** Power spectral density, K<sup>2</sup>/Hz of the mean temperature of the whole heater.



**Fig. 18.** Dependence of dimensionless frequency on the Bond number.



**Fig. 19.** Dependence of dimensionless parameter of heat transfer on the Bond number.

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