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THE INFLUENCE OF EXTERNAL ELECTRIC FIELD ON HEAT TRANSFER AT BOILING ON NON-UNIFORM SURFACES

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ABSTRACT

Characteristics of heat transfer and hydrodynamics of boiling of liquid nitrogen on the surfaces with different types of non-uniformities at the presence of external electric fields are experimentally investigated. It is shown that the formation of field traps is a major mechanism of heat transfer enhancement. And this effect result in noticeable change of two-phase hydrodynamics in vicinity of heated surface.

INTRODUCTION

Field trap effect at nucleate boiling of dielectric liquids in the presence of non-uniform electric fields was noticed in our works [1, 2]. The field trap is an area on a heated surface in which the electric field opposes a departure of a bubble growing on a heated surface. This results in the increase of growth time and departure diameter of a steam bubble and it results to appreciable increase of local heat transfer. And when applied electric field strength grows, the superheat of the heated surface (ΔT) corresponding to the boiling beginning decreases. Bubble nuclei originates at the sites of maximal electric field strength, at the top of non-uniformities of the heating surface, and their sizes is bigger that in case of absence of the electric field [4-6]. Then nuclei move to the areas of weaker electric field (to the field trap) under the influence of dielectrophoretic force. Size of the nucleus becomes overcritical and bubbles continue to grow in field-traps areas on heated surface while they is not reached the departure size. The bubble transfer mechanism to the field traps are described in [3]. Departure diameters of the bubbles on horizontal faced up non-uniform surfaces at the presence of non-uniform electric field R_0^E and corresponding time of bubble growth τ_0^E exceed those at the absence of the field R_0 and τ_0 [1]:

$$R_0^E = R_0 \left[1 - \frac{3}{2} \varepsilon_0 \frac{(\varepsilon_l - 1)}{(1 + 2\varepsilon_l)} \frac{\left(\nabla \boldsymbol{E}^2\right)_n}{g \Delta \rho} \right]^{-1/3} \qquad (1)$$

$$\tau_0^E = \tau_0 \left[1 - \frac{3}{2} \varepsilon_0 \frac{(\varepsilon_l - 1)}{(1 + 2\varepsilon_l)} \frac{\left(\nabla \boldsymbol{E}^2\right)_n}{g \Delta \rho} \right]^{-2/3} \qquad (2)$$

Here ε_0 is electric constant, ε_l is relative dielectric constant of the fluid in which there is the bubble, $\left(\nabla \boldsymbol{E}^2\right)_n$ - projection to the normal of vector $\nabla \boldsymbol{E}^2$, $\boldsymbol{E}$ is electric field strength, $\Delta \rho$ is phase density difference and g is acceleration of gravity.

As a result, the bigger volume of superheated microlayer of liquid evaporates, that leads to increase of local heat transfer from a surface in the given area.

Heat transfer at boiling on non-uniform surfaces at the presence of electric field are determined by two typical scales:

1. Sizes of the surface non-uniformities which create electric field non-uniformities that in turn cause dielectrophoretic forces acting on the bubble

2. Departure diameters of the bubbles which can change the pattern of the electric field distribution and change configuration of the field trap.

Therefore we can expect origination of scale effects at local and mean heat transfer process i.e. a dependence between local and mean heat transfer characteristics and typical scales mentioned above. The objective of the present work is the experimental research of such kind of effects.

SCALE EFFECTS AT THE LOCAL HEAT TRANSFER

Relations (1, 2) are valid at isothermic conditions in case when $\left(\nabla \boldsymbol{E}^2\right)_n$ is little varying on scales $\sim R_0$, i.e. in case of pins height $h \gg R_0$. It is clear, that at case $h \le R_0$, the electric field is essentially deformed due to bubble growth and it leads to occurrence of dimensional effects in local heat transfer in a pin vicinity, i.e. heat transfer coefficients change depending on pin height h at the preset voltage and surface superheat. The characteristic departure diameter of a bubble at boiling of liquid nitrogen on the nickel surface turned upwards at atmospheric pressure is about 0,6-0,9 mm.

The experimental setup consists of Dewar's vessel filled with liquid nitrogen at atmospheric pressure. The electrically grounded experimental sample is immersed into liquid nitrogen. Above the sample there is flat grid electrode where high positive potential is applied. The test sample is the Ni-Cr 8 mm width plate, rear side of which is heat-insulated. The plate is heated by AC current I, and the voltage drop value U_s of the sample is measured. Using measured values of I, U_s and the area of the plate S, it is simple to estimate heat flux density:

$$q = I \cdot U_s / S \qquad (3)$$

Plate surface superheat $\Delta T = T_W - T_L$ is measured by chromel-alumel thermocouples, hot junctions of thermocouples welded to down side of the heated plate while cold junctions are located in liquid nitrogen quite far away from area of boiling.

Experiments were carried out as follows. The test sample was located in nitrogen and within 10 minutes was heated up for activation of the possible centers of vaporization. Then the preset voltage on a mesh electrode was exposed and the boiling curve of nitrogen ($q(\Delta T)$ dependence) was measured in the electric field. Then the voltage was switched off and a boiling curve without the electric field was measured. Each point of a boiling curve was measured with respect to the waiting time necessary for the stabilization of a temperature after change of a heat load.

Boiling curve measurements is conducted for smooth surface and surface with pins of different heights ($h \le R_0$, $h \sim R_0$ and $h > R_0$) with and without electric field. On a smooth surface were welded three wire pins in diameter of *0.15* mm and various height: *0.5* mm, *1* mm, *1.5* mm. The scheme of an experimental sample is presented on fig. 1.

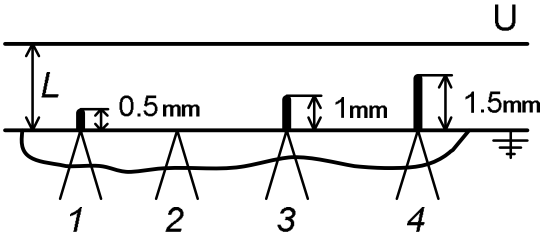

Fig. 1. Smooth surface with pins. The scheme of an experimental sample. 1 - 4 are thermocouples.

Distance between thermocouples: between 1 and 2 thermocouples - *5* mm, between 2 and 3 thermocouples - *4* mm, between 3 and 4 thermocouples - *9* mm. The distance between pins provided absence of their mutual influence. Distance between electrodes is *7* mm. Potential on the top electrode is *22.6* kV.

Experimental results are presented on fig. 2-5.

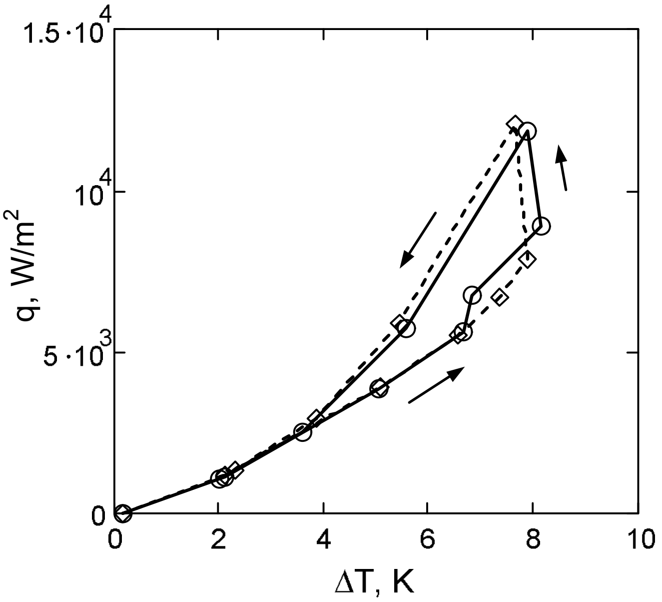

Fig. 2. Initial parts of boiling curves. 1st thermocouple. ◇-◇-◇ - with electric field, ⊖⊖⊖ - without electric field. The arrows indicate the direction of variation of the heat flux.

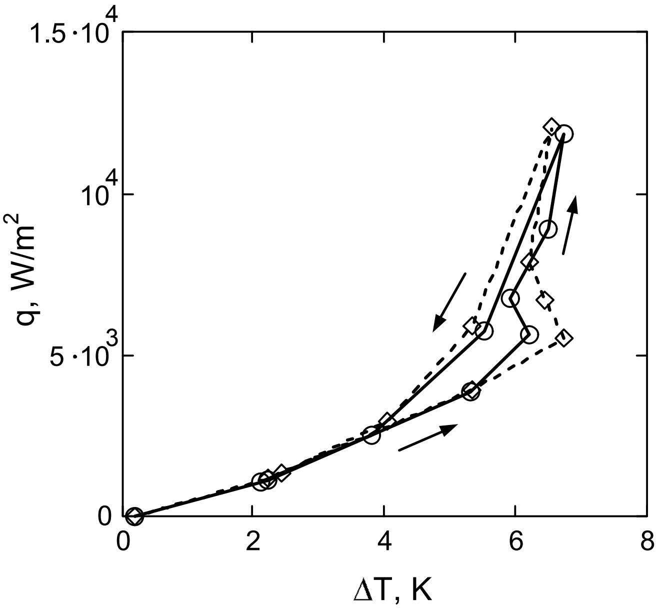

Fig. 3. Initial parts of boiling curves. 2nd thermocouple. -◇-◇-◇- - with electric field, -⊖-⊖-⊖- - without electric field. The arrows indicate the direction of variation of the heat flux.

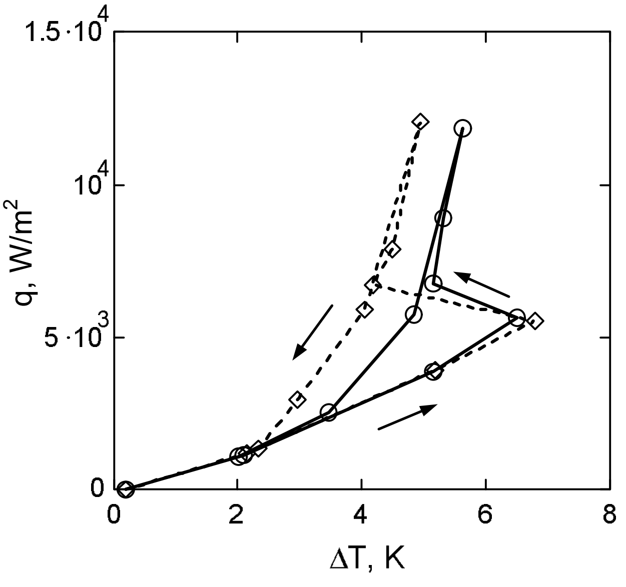

Fig. 4. Initial parts of boiling curves. 3rd thermocouple. -◇-◇-◇- - with electric field, -⊖-⊖-⊖- - without electric field. The arrows indicate the direction of variation of the heat flux.

From these figures one can see that for 3rd thermocouple, which is located directly under the 1 mm pin, there is shift of boiling curve towards lower surface superheats induced by electric field while for 2nd thermocouple, located under smooth area of the surface, there is no such a noticeable shift of heat transfer characteristics.

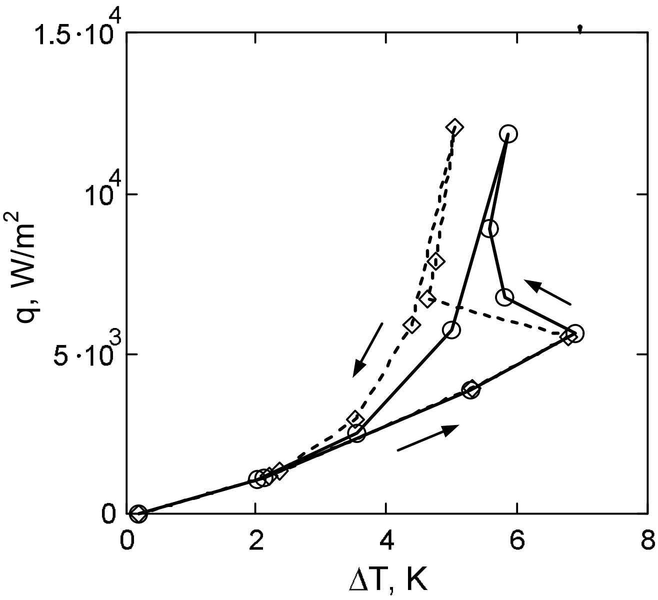

Fig. 5. Initial parts of boiling curves. 4th thermocouple. -◇-◇-◇- - with electric field, -⊖-⊖-⊖- - without electric field. The arrows indicate the direction of variation of the heat flux.

Estimation of relation of heat transfer coefficients α_E / α_0 shows that in the vicinity of field traps induced by 1 mm and 1,5 mm pins the application of electric field results in the rise of heat transfer coefficient for about 25 – 40 %, while in vicinity of 0,5 mm pin as well as for smooth surface there is no visible effect of electric field on heat transfer.

Basing on field trap phenomenon it is possible to develop arranged system of geometrical non-uniformities on heated surface with the aim of heat transfer intensification at initial part of boiling curve effected by external electric field. For that purpose the following part of experimental investigation was made.

MEASUREMENTS OF MEAN HEAT TRANSFER

The most cost-effective arranged field trap systems may be manufactured by groove milling with typical scales on the order of 1 – 3 of departure diameter of bubbles at given condition i.e. by finning the heated surface. Surfaces with rectangular and triangular fins are experimentally investigated.

The test section of the experimental setup (see fig. 6) consists of brass cylinder **I** with wire heater **III** on its bottom part. Six type L thermocouples are embedded into the cylinder. Test sample **IV** was solded to the top surface of the cylinder **I**. All the system was placed into cup from textolite **II**. The gap between the cup **II** and the brass cylinder **I** was filled with silicone sealant **V**.

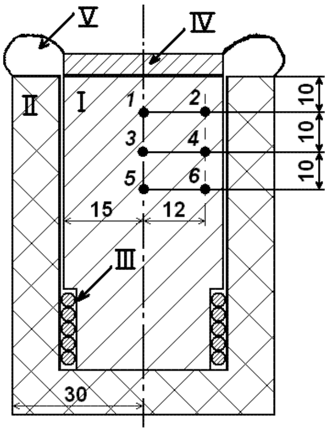

Fig. 6. The test section for mean heat transfer experiments.

The test section was immersed into Dewar's vessel containing liquid nitrogen at atmospheric pressure. All temperature data received via Keithley Model 2002 Multimeter and PC running LabView 7.1 software.

Triangular and rectangular surface non-uniformities were tested.

When a high voltage source turn on, the maximum of an electric field intensity is created in a vicinity of the fin top, and the minimum is created around the fin basis (see fig. 7)

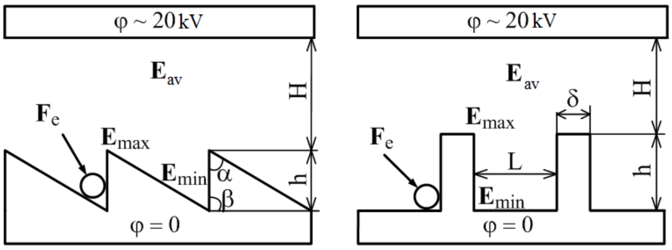

Fig. 7. Configuration of experimental samples.

Such non-uniform distribution of electric field strength induces dielectrophoretic forces (F_e) in dielectric fluid. These forces, first, press the bubbles being between fins to the bases of the fins, secondly, displaces bubbles from areas near the fin tops [1-3]. Moreover, the presence of electric field facilitates bubble nucleation [4-6], what leads to decrease of wall superheat corresponding initiation and termination of boiling. As a result it is possible to expect increase of surface average heat transfer coefficients at boiling dielectric liquids on initial part of boiling curve.

It is important to mention, that all measurements in this experiment was conducted at lowering heat inputs on boiling curve to avoid hysteresis, i.e. at decreasing heat load after achievement of developed bubble boiling. Since for liquid nitrogen at atmospheric pressure typical bubble departure diameter is ~0,7 mm the typical surface non-uniformities had the size of about 2-3 mm.

Experimental results

The experimental results for different samples with triangular fins are shown in fig. 8-10.

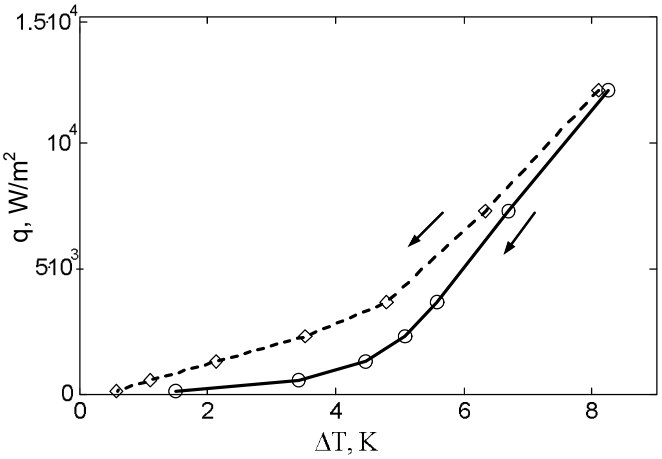

Fig. 8. Boiling curves on the sample with triangular fins: $\alpha = 60^\circ$, $\beta = 90^\circ$, **h = 3mm, H = 5mm, U=17.5kV.** $E_{\max} \sim 5.7\cdot 10^6\ V/m$, $E_{av} \sim 3.6\cdot 10^6\ V/m$, $E_{\min} \sim 10^5\ V/m$. **Lowering heat input. ◇-◇-◇ - with electric field, ○-○-○ - without electric field. The arrows indicate the direction of variation of the heat flux.**

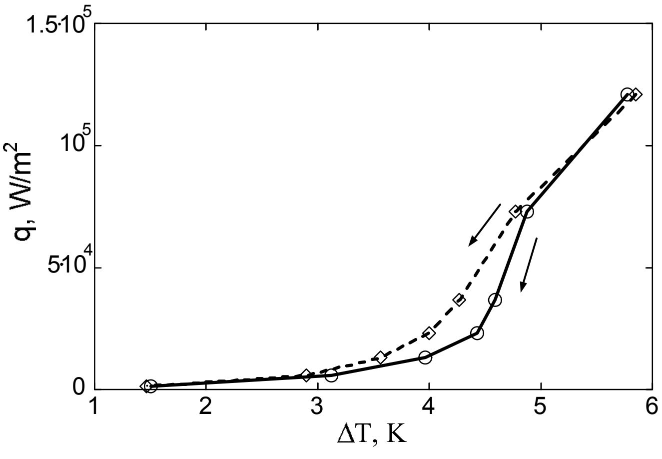

Fig. 9. Boiling curves on the sample with triangular fins: $\alpha = 45^\circ$, $\beta = 90^\circ$, **h = 2mm, H = 6mm, U=20kV.** $E_{\max} \sim 5.6\cdot 10^6\ V/m$, $E_{av} \sim 3.0\cdot 10^6\ V/m$, $E_{\min} \sim 10^5\ V/m$. **Lowering heat input. ◇-◇-◇ - with electric field, ○-○-○ - without electric field. The arrows indicate the direction of variation of the heat flux.**

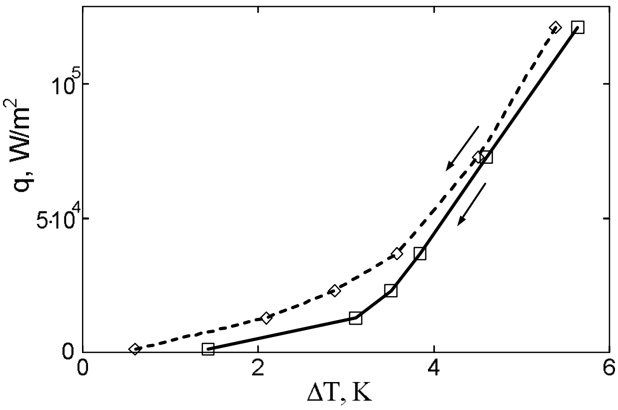

Fig. 10. Boiling curves on the sample with triangular fins: $\alpha = 45^\circ$, $\beta = 105^\circ$, **h = 2mm, H = 6mm, U=20kV.** $E_{\max} \sim 5.7 \cdot 10^6\ V/m$, $E_{av} \sim 3.7 \cdot 10^6\ V/m$, $E_{\min} \sim 10^5\ V/m$. **Lowering heat input. ◇◇◇ - with electric field, ○○○ - without electric field. The arrows indicate the direction of variation of the heat flux.**

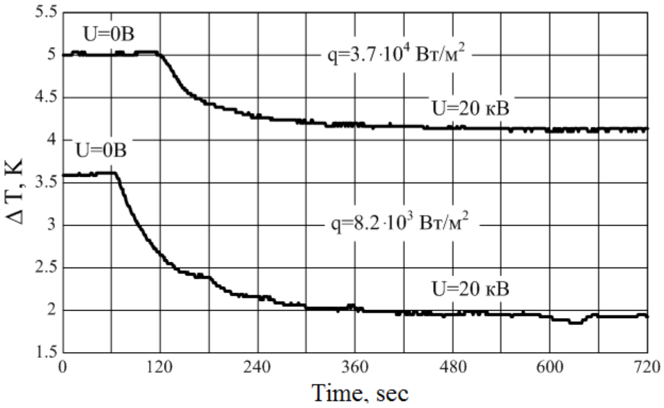

Fig. 11. Thermogram for different heat fluxes for sample with triangular fins: $\alpha = 45^\circ$, $\beta = 90^\circ$, **h = 2mm, H = 6mm.**

Thermograms for two values of heat flux at changing the top electrode potential from 0 to 20kV are shown on the fig.11.

As one can see from fig.8-10 the presence of non-uniform electric field in vicinity of heated surface results in significant enhancement of heat transfer at initial sections of boiling curve. At that as evident from fig.7 the mean surface heat transfer coefficient increases 1,75 times for initial boiling and 20% for developed boiling. On the fig.7 it is seen that typical hydrodynamic and heat relaxation time is about 200 sec., which is considerably longer than time of stabilizing of the top electrode potential which is of the order of 50 sec.

The role of electroconvection in increase of heat transfer coefficients at the presence of electric field can be estimated basing on two comparative experiments on two non-uniform surfaces of different geometry at similar field traps formation conditions but with different boundary conditions for convective flows at vicinity of the heated surfaces. Such experiments are conducted by us for rectangular-finned surfaces.

Results of the experiments on boiling on test samples with rectangular fins of different types are presented in fig.12-13.

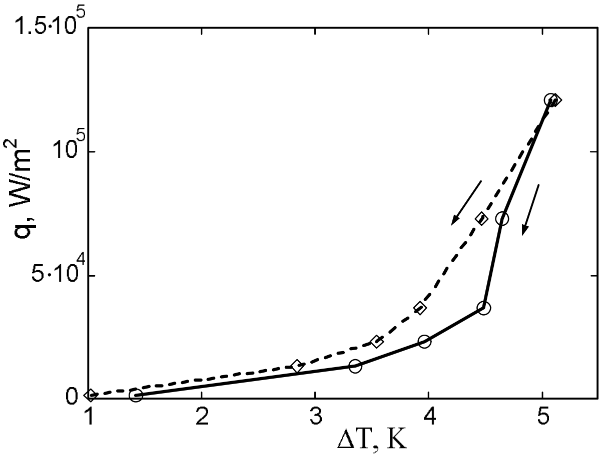

Fig. 12. Boiling curves on the sample with rectangular fins: $\delta = 1mm$, **h=2mm, L=4mm, H=4mm, U=23kV.** $E_{\max} \sim 6.5 \cdot 10^6\ V/m$, $E_{\min} \sim 10^5\ V/m$, $E_{av} \sim 3.5 \cdot 10^6\ V/m$. **Lowering heat input. ◇◇◇ – with electric field, ○○○– without electric field. The arrows indicate the direction of variation of the heat flux.**

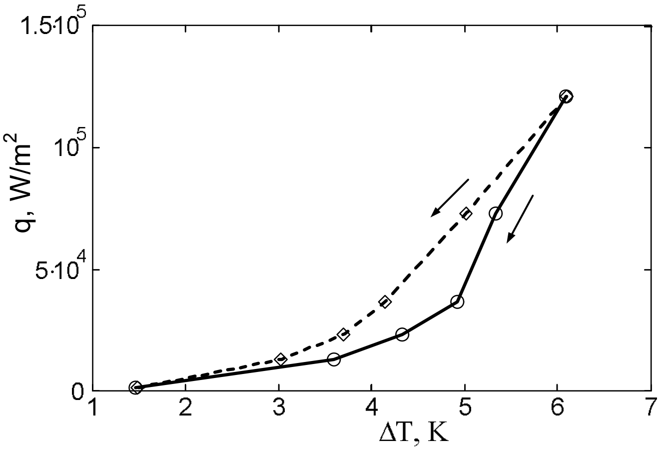

Fig. 13. Boiling curves on the sample with rectangular fins: $\delta = 1mm$, **h=1mm, L=4mm, H=4mm, U=23kV.** $E_{\max} \sim 5.4 \cdot 10^6\ V/m$, $E_{\min} \sim 2 \cdot 10^5\ V/m$, $E_{av} \sim 3.5 \cdot 10^6\ V/m$. **Lowering heat input. ◇◇◇ – with electric field, ○○○ – without electric field. The arrows indicate the direction of variation of the heat flux.**

Comparative analysis of experimental data in fig.8-10 and fig. 12-13 shows that at initial sections of boiling curves at presence of electric field the influence of an electric convection is weak and the major heat transfer enhancement mechanism is the field trap phenomenon. As a result on a surface there is an arranged system of intense heat sink spots allocated on the heated surface corresponding to surface artificial non-uniformities geometry. Naturally, that should result in the changes in of two-phase hydrodynamics at vicinity of the finned surface.

The visual observations of boiling process showed that hydrodynamics is cardinally changed by electric field. Vapor bubbles are quite evenly distributed over the sample surface and have quite small sizes at the absence of the field. At the presence of the field there are no departing bubbles in vicinity of the fin tops and all vaporization process is concentrated in between the fins from where strong vapor streams are pulled out, consisting of bubbles of bigger sizes than in a case of absence of a field (see fig. 14).

Boiling patterns in case of absence and in case of presence of an electric field are schematically depicted in fig. 15.

CONCLUSIONS

The experimental investigations of the effect of non-uniform electric field on local heat transfer show that field-trap phenomenon is more significant for single pins of height ranging $h \sim (1 \div 2) D_0$. At $h < D_0$ the local heat transfer at boiling is not considerably effected by electric field, i.e. in that case field configuration is hanging by growth bubble and forces acting on bubble do not form a field trap.

Experiments on mean heat transfer research show that non-uniform electric field significantly changed the hydrodynamics of the process by replacing evenly distributed bubble generation over the heated surface by vapor bubble streams originating only from the field traps.

Field trap effect on heat transfer consists in lowering of surface superheat and some reduction of boiling hysteresis. On test samples with field traps with sizes about 1-3 of bubble departure diameter, field trap effect depends weakly on the fin form.

Heat transfer at boiling on finned tubes is investigated in [7]. But in case of finned tubes there are two opposite effects: the field-trap effect when electric field prevents bubble departure and effect due to the radial field non-uniformity which in case of smooth tubes promote faster bubble departure and decrease of their sizes. In our experiments the field trap effect is investigated more evidently.

As it is known [4-6], electric field promotes bubble nucleation and in the area of maximum field it is possible to reach breakdown in liquid at lower field strengths [8] than predicted by uniform liquid breakdown theory. However, as it is shown in our experiments, at the boiling in electric field which results in formation of strong separate big bubble streams breakdown can occur at even lower electric field strengths.

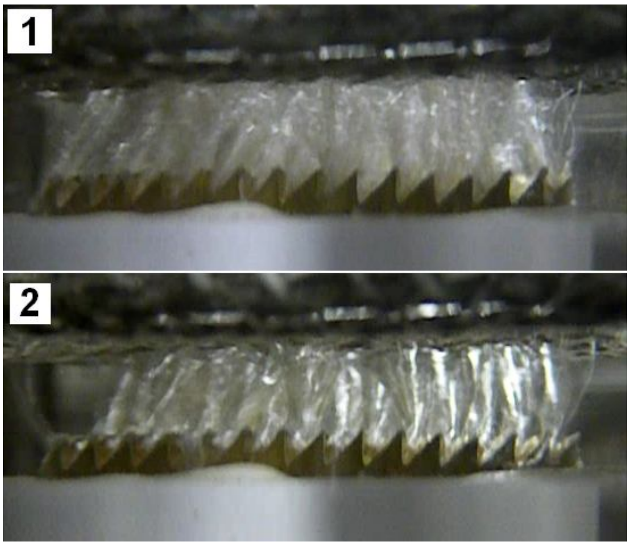

Fig. 14. Photography of the boiling process. 1 - in case of U=0, 2 - in case of top electrode potential U=20kV.

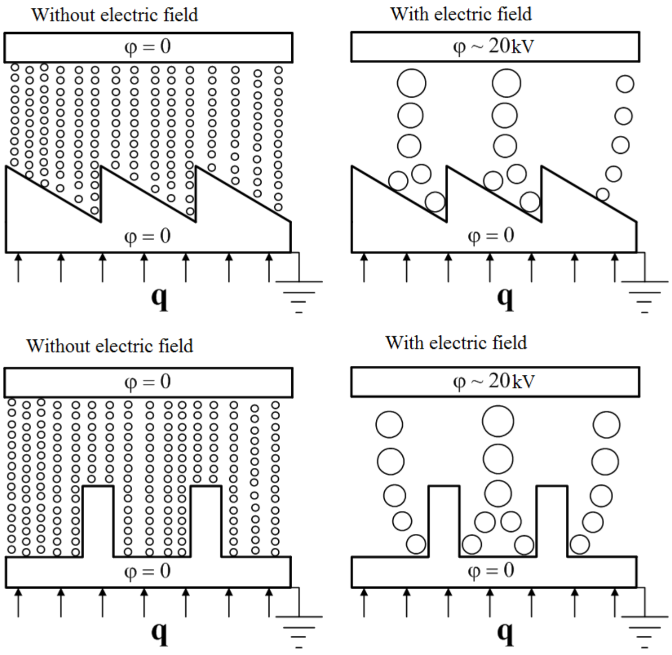

Fig. 15. Schematic depiction of bubble streams pattern on surfaces with triangular and rectangular fins in case of presence and in case of absence of electric field.

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