BOILING OF LIQUID NITROGEN ON GEOMETRICALLY MODIFIED SURFACES AT THE PRESENCE OF AN ELECTRIC FIELD.

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ABSTRACT

The influence of geometrical non-uniformities of heated surface on local heat transfer at boiling of liquid nitrogen at the presence of electric field was investigated. It is shown, that the creation of special areas on a heated surface - field traps - results in essential increase in local heat transfer coefficient. 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 that results in the increase of growth time and departure diameter of a steam bubble. The special configuration of an electric field is created by variation of the surface geometrical features. Theoretical explanation of field trap effect was given. Influence of an electric field on average heat transfer coefficient was investigated in experiments on boiling on various surfaces.

NOMENCLATURE

E – electric field intensity, V/m;

I – electric current, A;

L – distance between the electrodes, m;

S – area of heated surface, m^2;

T – temperature, K;

U – voltage, V;

h – pin height, m;

q – heat-flux density, W/m^2

n – vector of a normal on a heated surface;

α – heat transfer coefficient, W/m^{2}K;

ρ – mass density, kg/m^3;

ρ_e – free charge density, C/m^3;

ε_0 – electric constant, F/m;

ε – relative permittivity.

Subscripts

b – bubble;

CF1 – critical heat-flux density 1;

CF2 – critical heat-flux density 2;

sam – sample;

w – wall;

l – liquid;

o.b. – origination of boiling;

br – breakdown.

INTRODUCTION

Non-uniform external electric field leads to occurrence of the volumetric and surface forces in dielectric liquid. These forces strongly influence heat and mass transfer processes at boiling (see [1-10] and the literature quoted there). In the majority of researches such fields were created at a various relative positioning of a heated surface and external electrodes. When gradient of intensity of the electric field $\boldsymbol{E}$ is directed to a heated surface ($\nabla \boldsymbol{E}^2 \cdot \boldsymbol{n} < 0$), the following effects are experimentally observed: convective heat transfer due to electric convection on initial part of boiling curve increases, and accordingly heat-fluxes $q_{o.b.}$, corresponding to boiling origination, increase. The shape of departing vapor bubbles changes. Their size decreases, and departure frequency increases. Heat transfer coefficient α on initial part of boiling curve and in film boiling regime increases. Critical heat-flux q_{CF1} rises due to destabilization of vapor film on the heated surface. At $\nabla \boldsymbol{E}^2 \cdot \boldsymbol{n} > 0$ the increase of α on initial part of boiling curve was observed. It was due to "precipitation" of vapor bubbles on the heated surface. Also the decrease of q_{CF2} and the increase of vapor film stability were observed [10]. At $\nabla \boldsymbol{E}^2 \cdot \boldsymbol{n} < 0$ the hysteresis of boiling reduces or disappears and at $\nabla \boldsymbol{E}^2 \cdot \boldsymbol{n} > 0$ it is constant [1–10].

Thus, depending on a configuration of the external electrodes creating a non-uniform electric field on heated surfaces, the intensification of heat transfer at boiling of dielectric liquids in nucleation regimes of boiling was provided mainly in two ways: 1) due to growth of convection when evaporation heat transfer is suppressed (at $\nabla \boldsymbol{E}^2 \cdot \boldsymbol{n} < 0$); 2) due to evaporation (at $\nabla \boldsymbol{E}^2 \cdot \boldsymbol{n} > 0$), when the contribution of electric convection decreases, and critical heat flux decreases.

In the previous works we investigated the possibility of intensification of heat transfer at boiling of dielectric liquids in an external electric field by creation of a non-uniform electric field due to artificial geometrical non-uniformity on a heated surface [11-13]. The effect of significant increase of local heat transfer coefficient in the area of artificial non-uniformity on a heated surface, which we named “effect of field traps”, has been discovered. In the present work we study the influence of heated surface geometrical non-uniformities on the created “field trap’ and on heat transfer at boiling.

1. EFFECTS OF THE EXTERNAL FIELD AT BOILING ON NON-UNIFORM HEATED SURFACES

Influence of external field on heat transfer in liquid dielectrics is defined by occurrence of the volumetric forces depending on intensity of an electric field $\boldsymbol{E}$

$$\boldsymbol{f}_v = \rho_e \boldsymbol{E} - \frac{\varepsilon_0}{2}\boldsymbol{E}^2 \nabla\varepsilon + \frac{\varepsilon_0}{2}\nabla\left(\rho \boldsymbol{E}^2 \left(\frac{\partial\varepsilon}{\partial\rho}\right)_T\right). \tag{1}$$

At dielectric liquids boiling, time of a charge relaxation usually essentially exceeds time of growth and departure of the bubbles. Therefore, the first member in (1) is essential only on convective branch of a boiling curve. The second member is connected with non-uniformity of ε which depends on a gradient of temperature in a boundary layer. It partially compensates forces of buoyancy on a horizontal heated surfaces turned upwards that can lead to suppression of natural convection in uniformity fields. The second and third member in (1) define electrohydrodynamical effects at dielectric boiling in external fields.

Juts or cavities form a non-uniform electric field near to heated surfaces in a boundary layer. At the tops of juts the field has the maximal intensity, in the cavities it is minimal. In [14, 15] it is shown, that the external electric field initiates nucleation in superheated liquids, and these effects become significant at high strengths of electric field. Unlike boiling without electric field, at its presence, formation of viable vapor nuclei on a heated surface is the most probable not in cavities, but at tops of juts where intensity of electric field E is maximal, and the size of a critical nuclei increases when $\boldsymbol{E}$ increase. In this connection there is an opportunity of use of artificial juts as concentrators of intensity for initiation of vapor nucleation. In a non-uniform field the force acting on a bubble

$$\boldsymbol{F}_b = 2\pi R_b^3 \varepsilon_0 \frac{1-\varepsilon_l}{1+2\varepsilon_l}\nabla \boldsymbol{E}^2 . \tag{2}$$

This force is directed opposite to a vector $\nabla\boldsymbol{E}^2$. It is obvious, that, creating artificial nonuniformity on a heated surface, it is possible to realize such geometry of an electric field in which the critical nucleus formed on top of a jut will move along a surface under the action of electrophoretic forces to the area, where intensity of an electric field is minimal (a field trap), and stay there. Thus the size of nuclei becomes supercritical, that will cause its active growth, and also the increase of local heat transfer on the site of a surface near a field trap. At creation of the ordered system of concentrators of electric field intensity and field traps on a heated surface it is possible to provide an intensification of heat transfer at boiling on the average on all heated surface due to evaporation. Besides, the presence of nonuniformities on a heated surface will also promote the increase of convective heat-transfer. Realization of this method using an external electrode and the heated surface, parallel each other, is possible, for example, by creation of the system of pins on a heated surface with the characteristic sizes exceeding critical diameters of vapor nucleus and located on distances, greater them departure diameters (a rare brush), or by corrugating a surface as it has been made in our previous work.

The effect of a nonuniform field in a field trap on the departure sizes of bubbles may be estimated by analyzing the structure of semiempirical relations corresponding to the experimental data. This holds if we assume that the effect of external electric field is largely defined by the emergence of an additional force given by Eq. (2) which acts on the bubble and is proportional to its volume, i.e., assuming that the field causes a variation of only the buoyancy force acting on the bubble. The most reliable semiempirical relations for R_0 include the specific (per unit volume of the bubble) buoyancy force F_V in the form $R_0 \sim A\cdot F_V^{-1/3}$, where A is a function of the properties of liquid and Jacob numbers, and the form of the functions F_V is defined by the sum of the specific Archimedes force F_A and dielectrophoretic force F_b. For departure diameters on horizontal surfaces facing upwards under conditions of boiling that differ only by the absence R_0 or presence R_{0E} of an external electric field, we have

$$\frac{R_{0E}}{R_0} = \left(\frac{F_{VE}}{F_V}\right)^{-1/3} \tag{3}$$

For a spherical bubble in a gravity field $F_V = \frac{4}{3}\pi g \vartriangle\rho$, when an external electric field is initiated $F_{VE} = F_V - 2\pi\varepsilon_0 \frac{1-\varepsilon_l}{1+2\varepsilon_l}\left(\nabla\boldsymbol{E}^2\right)_n$, where $\left(\nabla\boldsymbol{E}^2\right)_n$ is the projection of the vector $\nabla\boldsymbol{E}^2$ on a vertical. We assume $\nabla\boldsymbol{E}^2$ to be weakly varying on scales of the order of R_0 and substitute F_V and F_{VE} into Eq. (3) to derive

$$\frac{R_{0E}}{R_0} = \left[1 - \frac{3}{2}\varepsilon_0 \frac{(\varepsilon_l - 1)}{(1+2\varepsilon_l)}\frac{\left(\nabla\boldsymbol{E}^2\right)_n}{g\vartriangle\rho}\right]^{-\frac{1}{3}} \tag{4}$$

and, accordingly, for the time of bubble growth to the departure size,

$$\frac{t_{0E}}{t_0} = \left(\frac{R_{0E}}{R_0}\right)^2 = \left[1 - \frac{3}{2}\varepsilon_0 \frac{(\varepsilon_l - 1)}{(1+2\varepsilon_l)}\frac{\left(\nabla\boldsymbol{E}^2\right)_n}{g\vartriangle\rho}\right]^{-\frac{2}{3}} \tag{5}$$

Relations (4) and (5) qualitatively define the bubble behavior in a field trap at the stage of its slow growth. It follows from these relations that the departure times and the times of delay of bubble departure from the heated surface increase significantly with increasing $\left(\nabla\boldsymbol{E}^2\right)_n$, which must result in an increase in the local coefficients of heat transfer in the field trap sites. It is obvious that the field-trap effects are most significant in the initial segment of the boiling curve and in the region of hysteresis of the start of boiling.

2. EXPERIMENTAL TECHNIQUE

Experimental installation consists of Dewar vessel filled with liquid nitrogen at atmospheric pressure. Experimental sample placed in liquid nitrogen is grounded. Above it there is a flat mesh electrode on which high positive potential is applied. Working sample represents a nichrome plate which is heat-insulated from the bottom and the sides. The plate is heated by AC *I*, at that voltage drop on the plate U_{sam} is measured. On measured values *I* and U_{sam} and the known area of the surface of the plate *S* the heat-flux is calculated as $q = I \cdot U_{sam} / S$. Temperature difference of $\Delta T = T_w - T_l$ is measured by differential type K thermocouples with hot junctions welded on the bottom side of a heated plate, and cold junctions in liquid nitrogen far below from area of boiling.

Experiments were carried out as follows. The working sample was located in nitrogen and within 10 minutes was heated up for activation of the possible centers of vaporization. Then the given voltage on a mesh electrode was exposed and the boiling curve of nitrogen in a electric field was taken. Then the field was switched off and a boiling curve without a field was taken. Each point of a boiling curve was taken with respect to the waiting time necessary for the stabilization of temperature after change of heat load.

3. RESULTES OF EXPERIMENTS

3.1. Influence of height of the pin on a boiling curve.

Experimental research of boiling on a smooth surface with 3 pins of various heights has been carried out.

On a smooth surface for local increase of intensity of an electric field and creation of a non-uniform electric field were welded three pins from a wire in diameter *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. 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.

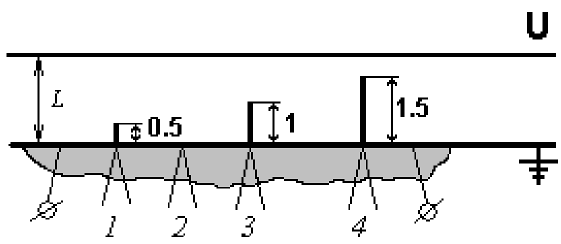

Fig. 1. Smooth surface with pins. The scheme of an experimental sample. 1 - 4 - thermocouples.

Experimental results are presented in figures 2 – 7.

From figures it is visible, that for the pin having the minimal size, acting of an electric field does not lead to change of parameters of heat transfer.

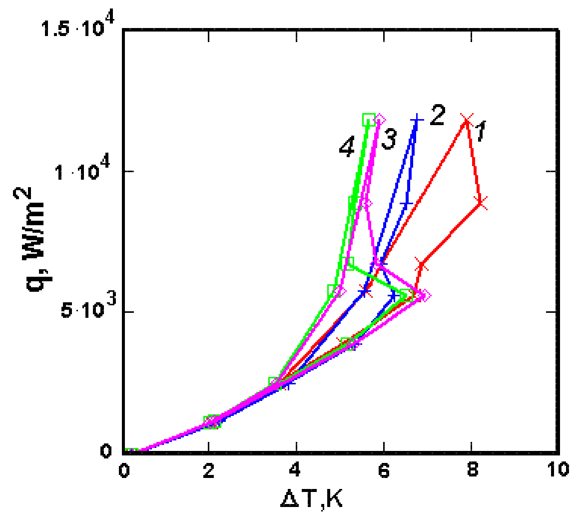

Fig. 2. Boiling curve for all thermocouples without a field. 1 – 4 thermocouples.

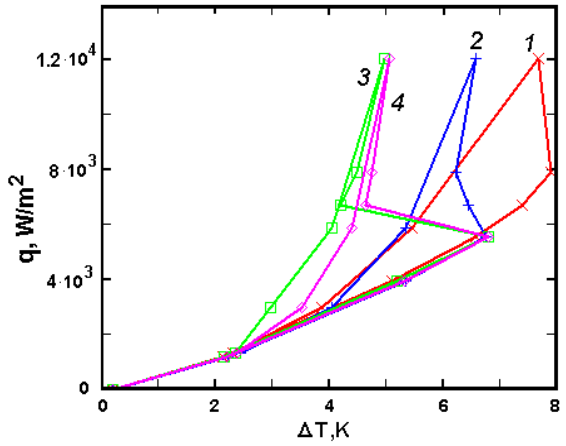

Fig. 3. Boiling curve for all thermocouples in a field. 1 – 4 thermocouples.

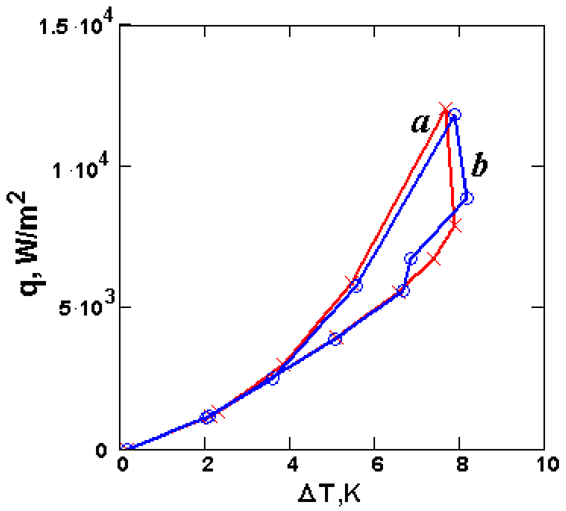

Fig. 4. Influence of electric field on origination of boiling curve. Thermocouple #**1**. **a** – in electric field, **b** – without electric field.

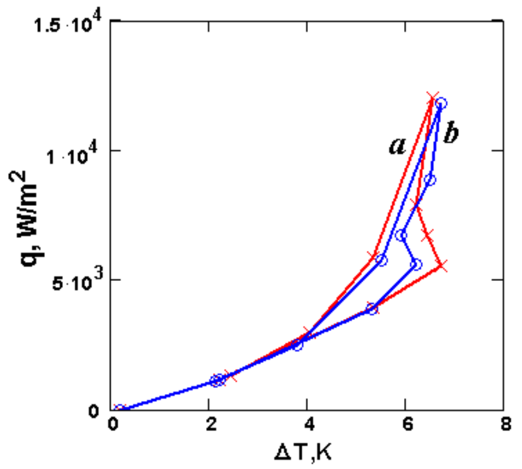

Fig. 5. Influence of electric field on origination of boiling curve. Thermocouple #**2**. **a** – in electric field, **b** – without electric field.

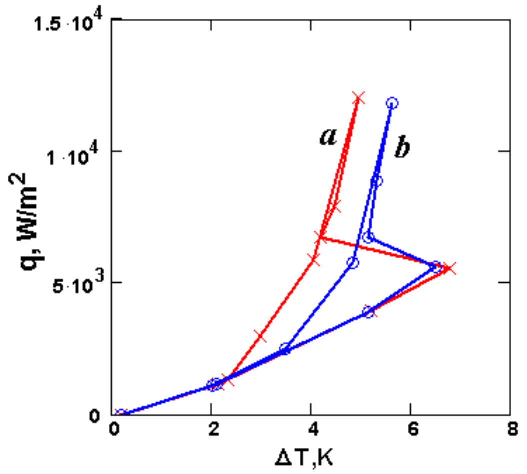

Fig. 6. Influence of electric field on origination of boiling curve. Termocouple #**3**. **a** – in electric field, **b** – without electric field.

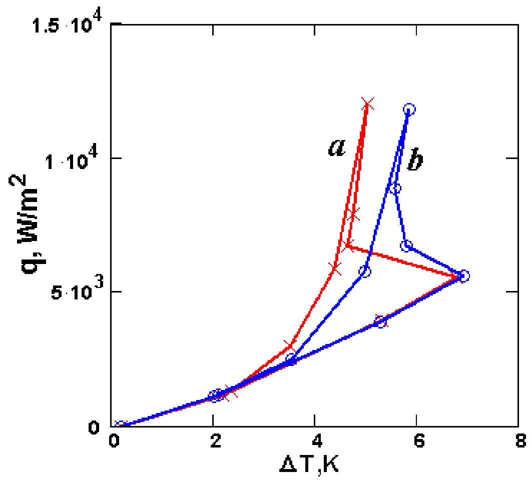

Fig. 7. Influence of electric field on origination of boiling curve. Termocouple #**4**. **a** – in electric field, **b** – without electric field.

3.2. The influence of an intensity of an electric field on the boiling curves.

A series of experiments by definition of influence of intensity of an electric field on a curve of boiling of liquid nitrogen is carried out. Experiments were carried out on a smooth sample with 4 welded pins: 2 pins in height of 1 mm and 2 pins in height 2мм. Temperature drop of a surface was measured by 8 thermocouples: 4 thermocouples under pins and 4 thermocouples under a smooth surface. Results of experiments are submitted in figures below.

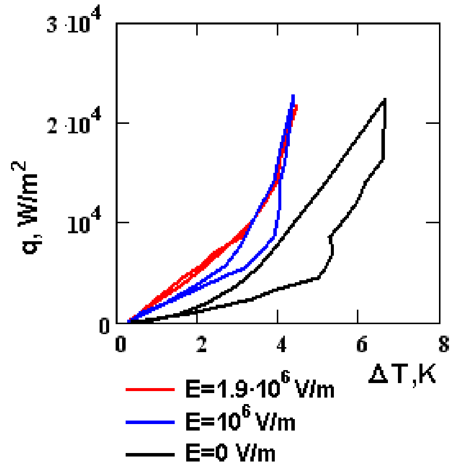

Fig. 8. The influence of an electric field on origination of the boiling curve. Termocouple #**2**.

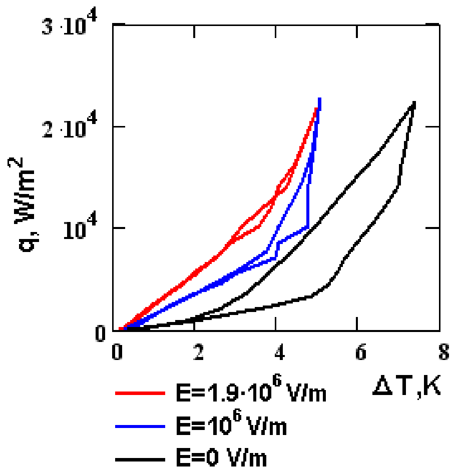

Fig. 9. The influence of an electric field on origination of the boiling curve. Termocouple #**4**.

It is clear from figures, that an electric field causes the curves of boiling to remove to the left, i.e. smaller superheats of surface corresponds bigger thermal heat fluxes. Also it is obviously visible, that the electric field results in disappearance of a hysteresis of boiling.

A series of experiments on porous surfaces in an electric field has been carried out. Porous samples, represented a nichrome substrate with a globular porous covering (porosity of 40 %), the received method of sintering from globules with the average size of the order *0.1* mm and thickness of a substrate *0.2 - 0.5* mm. Experiments have shown absence of influence of an electric field on heat transfer at boiling on porous surfaces.

4. CONCLUSION

Results of the given work allow to make some conclusions on ways of optimization of the geometrical non-uniformity sizes on a heated surface at boiling in an electric field. The electric force acting on growing vapor bubble presses it to area of the minimal value of an electric field, which is in the base of a pin. Due to it the most part of superheated microlayer of liquid evaporates, that leads to increase of heat transfer from a surface in the given area. Thus departure diameter of a bubble increases. It is obvious, that there should be some parity between distribution of an electric field in the area near a field trap and diameter of a departure bubble. The obtained results show existence of minimal geometrical non-uniformity sizes. When the non-uniformity is smaller the electric field does not render essential influence on heat transfer at boiling. This is due to the fact that the size of a growing bubble is comparable to geometrical non-uniformities on a surface. Therefore it brings strong distortion in an electric field and a new shape of electric field does not render essential influence on growing bubble.

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