The effect of electric field on heat transfer at boiling on porous surface

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Abstract. The influence of electric field, interelectrode spacing, and heat-release surface orientation on heat transfer at boiling on a porous surface is studied. With increase in heat flow density the influence of a field decreases up to degeneration. The local characteristics of the heat transfer coefficient indicate a significant heat transfer enhancement in the case of a permeable electrode in comparison with a solid electrode which increases with the growth in the field intensity. The influence of electric field on the dynamics of vapor bubble growth is investigated. There have been obtained the expressions for the vapor bubble diameter and heat flow density without and under electric field which agree satisfactorily with the experimental data.

1. Introduction

The influence of specific heat loads, the presence of an electric field in electronic and radio technical apparatus, reliability requirements, and keeping the prescribed thermal parameters call for the development and application of innovative evaporative cooling systems – closed electrohydrodynamic active control systems, thus it is important to continue the investigation of hydrodynamics and heat transfer in the electric field, including the case of phase transformations. For example, if the heat release source is within a confined space under a high electric potential and a dielectric liquid is used to insulate it from the surrounding walls, the method of the action of electric field on heat transfer is preferable. The fact that the Coulomb forces influence both the parameters of phase equilibrium and the thermodynamic stability boundary of the dielectric liquid is a peculiarity of the method of heat transfer enhancement at pool boiling. These effects can greatly affect the exchange processes within the boundary two-phase layer, and consequently, the heat transfer [1-6].

2. Experimental study of boiling process in the electric field

2.1. Brief description of experiments

The pool boiling under the influence of an electric field is studied, and certain results are presented in this report. A heating element was a tube of stainless steel 4 mm in diameter heated due to the electric current passage. The outer tube surface is bagged with the capillary-porous structure of caprolon 900 mesh in size. The high voltage electrode was placed parallel above the heating surface. An electrode with grooves for a free passage of vapor bubbles as well as a solid electrode were used in the experiments. The interelectrode spacing was varied from 0.75 to 5.00 mm for the solid electrode and from 0.50 to 6.00 for the permeable electrode. The voltage was changed step-like from 0 to 30 kV. Hexane is a heat carrier with a saturation temperature of 68.7 °C. Lateral survey was used to determine
the peculiar features of the vapor phase removal from the heating surface covered with a capillary-porous structure. The camera recording of the boiling process allowed to obtain reliable data on the internal characteristics of boiling. An important stage of the analysis internal characteristics of the boiling process is the comparison of experimental and calculated data on the growth dynamics of vapor bubbles at boiling in the non-uniform electrical field. External manifestation of the field effect on boiling is the change in both the vapor generation pattern on the heating surface and boiling process stages: the mode of single bubbles when in the experiments there was used a high voltage electrode with grooves for a free passage of vapor, and the mode of merged vapor bubbles when using a solid electrode that determines the external boiling characteristics of the hexane-type dielectric liquid.

2.2. Results and discussion

The visual observation of boiling process without field showed massive flowing of bubbles within the liquid bulk from the whole heating surface in the form of a brush of jets with the following jump through the electrode grooves. The camera recording, presented in figure 1, illustrates the conditions for vapor bubble nucleation in the active evaporation centers on the heating surface. The evaporation takes place inside the porous structure at the contact between the capronol thread and the heating surface. In the effective radius of the capillary structure 900 mech in size in the experiments without field there are observed the nuclei both in the cell center and in the contact capillary structure.

At the bubble boiling with the supply of high voltage there primarily stopped acting the evaporation centers which flow fine bubbles, there remain viable only the centers which generated big bubbles without field (figure 2). With the increase in the field intensity there is recorded the decrease in the vapor bubble departure diameter up to degeneration. The record of the boiling process showed that at the motion of a single bubble within the interelectrode spacing there is formed a moving liquid disk (figure 2). The authors suppose that the formation of a liquid disc on the bubble surface takes place as a result of the rotation of a bubble in the field of the nonuniform electric forces (figure 2b).

![Figure 1. Photos of boiling pool without electric field, \(q = 14000 \text{ W/m}^2\).](image1)

![Figure 2. Formation of a liquid disc on the vapor bubble surface, \(q = 7650 \text{ W/m}^2\).](image2)

The experimental results of camera recording of the boiling process in the case of the solid electrode made it possible to follow the vapor bubble nucleation in the evaporation centers growing at the initial moment when the spacing is 2.4 mm. It is found that when the bubble approaches the top high voltage electrode there begins its deformation with the following in-feeding by the growing bubbles and extension on the internal surface of the high voltage electrode. This happens till the interface
approaches the boundary of the neighboring bubble and the vapor bubble begins to go out of the interelectrode spacing. There is observed the simultaneous exit of several bubbles. The records show that due to the conditions of free exit of vapor cavity at the heat flows there is no confluence of them. A thin liquid intermediate layer is formed between the contact growing and emerging cavities. With the growth in the specific thermal load $q$ there increases the vapor content pulsation frequency that is associated with the enlargement in the number of evaporation centers. The reduction in the pulsation amplitude with the increase in the thermal load happens due to the mutual influence of the phases of growth and exit of vapor bubbles.

At atmospheric pressure and a gap height of 2.4 mm with the increase in $q$ without any field the average vapor content within the interelectrode spacing grows, and at $q > 10^4 \text{ W/m}^2$ its value is 65-70 %, then at the further increase in $q$ the dependence becomes less expressed. The comparison of the results in figure 3 and camera recording show that the influence of the field on heat transfer at boiling is associated with the qualitative changes in the boiling mechanism at the reduction in the gap and altered process modes, and the heat transfer rate is due to the suppression of little boiling centers, fragmentation of vapor phase and increase in its growth rate. Thus, in the interelectrode spacing at $q=10^4 \text{ W/m}^2$ the vapor content is 50-55 %.

At small values of field intensity $E<10^6 \text{ V/m}$ when there falls the number of acting evaporation centers the increasing electroconvection decreases the temperature difference for the existence of evaporation centers. The value of the heat flow component, removed by the vapor bubbles as a result of micro-layered evaporation of liquid into the bubble, is reduced due to a weak influence of field on heat transfer in the range of small values of the intensity (figure 3). With the growth in the heat flow density $q$ the number of boiling centers increases, the presence of bubbles retards the development of electroconvection, and a significant deformation of the thermal boundary layer occurs at higher voltage than in the mode of free convection (figure 3). The layer nonuniformity in the form of a wave is recorded on the heating surface. The generation of microwaves should be associated with the capillary forces of the heating element and the coating that hinders a steady motion of the interface (motion of liquid in the micro-layer). The comparative characteristics of the heat transfer coefficient values in the experiments with the grooved and solid high voltage electrodes are presented in figure 4. With the change in the heating surface slope there increases the movement rate of vapor bubbles, thus, the boundary layer near the heating surface becomes thinner, and boiling is shifted into the region of high values of heat transfer coefficients.

![Figure 3](image-url)

**Figure 3.** Influence of electric field on heat transfer at different heat flow densities: 1 – $q=1000 \text{ W/m}^2$; 2 – 3050; 3 – 4400; 4 – 8970; 5 – 13240.

![Figure 4](image-url)

**Figure 4.** Heat transfer of the impervious (1) and permeable (2) electrodes, $q = 63100 \text{ W/m}^2$. 


The influence of the interelectrode spacing on the heat transfer rate is multivalued (figure 5). There is a distinct heat transfer peak at a gap of 2 mm for the solid electrode and 1.5-1.6 mm for the permeable electrode, i.e., the spacings are commensurable with the departure diameter of bubbles. The influence of the gap width is determined by the hydrodynamical conditions of the evacuation of bubbles from the heating surface.

**Figure 5.** Heat transfer versus interelectrode spacing for the impervious (1) and permeable (2) electrodes, \( q = 9380\ \text{W/m}^2 \).

### 3. Calculation relation for a vapor bubble departure diameter

It is interesting to develop a calculating formula for a bubble departure diameter. This problem is poorly known as the dynamics of a vapor bubble is a very complicated phenomenon. Using the \( [\Pi] \) – theorem of the dimensional analysis we found:

\[
d_0 = C_1 \frac{\sigma}{\varepsilon\varepsilon_0 E^2} = C_1 \frac{\sigma}{\rho_s E},
\]

where \( C_1 \) is the dimensionless constant; \( \varepsilon \) is the relative dielectric permittivity of the medium; \( \varepsilon_0 \) is the absolute dielectric permittivity of vacuum, \( \text{V/m} \); \( E \) is the electrical field intensity, \( \text{V/m} \); and \( \rho_s = \varepsilon\varepsilon_0 E \) is the surface charge density at the phase interface, \( \text{C/m}^2 \). As formula (1) shows that two forces have the dominant effect on the vapor bubble size at the moment of departure from the heating surface – of electrostatic pressure \( f_e = \varepsilon\varepsilon_0 E^2 / 2 \) which aims for removing a bubble from the heating surface and of the surface tension \( \sigma \) which keeps it on the wall. It also follows from the obtained formula that the bubble departure diameter decreases with the increase in the electrical field intensity. This conclusion is confirmed by the test data.

When determining the density of electric forces it is necessary to take account of the relation between the lifetime \( t \) of vapor bubbles and the relaxation time \( \tau_p \) of electric field (time of accumulation of free electric charge at the interface) \([1, 2]\). With this correction formula (1) can be written as follows:

\[
d_0 = C_1 \frac{\sigma}{\varepsilon\varepsilon_0 E^2 \left(1 - e^{-\tau_p} \right)}. \tag{2}
\]

The comparison with experiment is shown in figure 6. Test data are approximated satisfactorily by formula (2) if we assume constant \( C_1 = 1 \) and introduce the additional correction being 0.6. Thus, relationship (2) becomes:
\[ d_0 = \frac{\sigma}{\varepsilon \varepsilon_0 E^2 \left(1 - e^{-1/r} \right)} + 0.6. \]  

Formula (3) can be used to calculate the bubble departure diameter at an electric field intensity of \( E > 10^6 \) V/m.

**Figure 6.** Comparison of formula (2) with experimental data.

4. Calculation relation for the heat flow density

Determining calculation relations for the heat flow density are of significant practical interest. Assuming (on the basis of general physical notions) that pool boiling without field depends on the heat flow density \( q \), heat conduction \( \lambda' \) and specific heat capacity \( c'_p \) of the liquid phase, surface tension \( \sigma \), density difference of the liquid and vapor phases \( \rho' - \rho'' \), and wall-saturation temperature difference \( T_w - T_s \), i.e.,

\[ q = f(\lambda', c'_p, \sigma, \rho' - \rho'', T_w - T_s), \]  

using the \( \Pi \)-theorem of the dimensional analysis we found:

\[ q = C \frac{c'_p^2 \sigma (\rho' - \rho'')}{\lambda'} (T_w - T_s). \]  

At the pool boiling under the action of electric field the formula for calculation of the heat flow density is written as:

\[ q = C_3 \frac{\lambda'^3 r E^2}{c'_p \sigma^3} (T_w - T_s), \]  

where \( r \) is the specific latent heat of evaporation, J/kg.

The distribution of the heat flow density calculated according to formulas (5) and (6) is presented in figure 7 at different field intensities. Higher values of the heat flow densities correspond to larger values of the field intensity. This result is confirmed by many measurements for the impervious electrode.

Comparison of the calculated values of the heat flow densities with the experimental results also presented in figure 7 shows that the latter are well approximated if the empiric constant with a value of \( 10^6 \) is introduced into formula (5) and a value of 0.25 into formula (6). With the allowance for the corrections relations (5) and (6) are as follows:
\[ q = \frac{c_p^2 \sigma (\rho' - \rho^*)}{\lambda'} \cdot (T_w - T_s) \cdot 10^{-6}; \]  
(7)

\[ q = \frac{\lambda^2 \rho E^2}{4c_p^2 \sigma^3} \cdot (T_w - T_s). \]  
(8)

Thus, formulas (7) and (8) reasonably reflect the main characteristics of boiling and agree well with the experimental data for hexane. The formulas can be used for other dielectric heat carriers, as well as for solution of engineering problems connected with the development and creation of a new highly effective equipment. Probably, in these cases the constants can have other values.

Figure 7. Comparison of calculated values of the heat flow densities with experimental data: line 1 – calculation according to (6); lines 2-5 – calculation according to (7).

5. Conclusion
Our investigations showed that the action of electric fields is an efficient method for enhancement of heat transfer at boiling. However, as there is no clear notions on the heat transfer enhancement at boiling in the field of electric forces and on the phenomena which occur in this case many results do not move beyond engineering solutions. The main attention must be paid to the study of the mechanism of vapor bubbles generation on the heating surface, the growth and movement of them, the development of the physical model of the boiling process in the field of electric forces.

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