Enhancement of heat transfer at boiling in electrohydrodynamic flow

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Abstract. The influence of the electric field strength and interelectrode spacing on the heat transfer intensity at boiling in an electrohydrodynamic flow was studied. It was stated that the heat transfer coefficient increases with the increasing of the field strength. The influence of the interelectrode spacing is ambiguous. The efficiency of the action of an electrohydrodynamic flow on the heat transfer intensity at boiling was evaluated using the ratio of the heat transfer coefficient at boiling in the field to the heat transfer coefficient at boiling without the field. The relationships for calculation were obtained that satisfactorily agree with the experimental data.

1. Introduction
The electrohydrodynamic (EHD) method of heat transfer enhancement has been investigated and tested mainly with regard to single-phase media [1, 2]. At the same time it attracts a growing interest since the experimental studies give evidence that the electric field exerts a more pronounced action both on the process and heat transfer at boiling of fluids in the conditions when a discrete system of local nonstationary intensifiers – evaporation centers – exist on the heating surface, and in the wall area emerge and form electrohydrodynamic swirling fluid flows [2-4]. The enhancement of heat transfer by the EHD method for engineering purposes attains an increasing recognition due to the results of investigations on one tube evaporators [2-6], evaporators of refrigerating machines [7], and heat pipes [8]. It is also expedient to perform these investigations in connection with the development and creation of evaporation and condensation systems of cooling and thermostating of a novel type – closed electrohydrodynamic systems with active control.

The influence of electric field on the heat transfer intensity at pool boiling is usually associated with electroconvective perturbations. The efficiency of the field is also defined by the thermal and electrophysical properties of the heat carrier, the shape and dimensions of electrodes, field intensity and the degree of its inhomogeneity. However, the electroconvective methods of cooling do not always ensure the specified thermal regimes of evaporation and condensation systems and thermostating with the increasing of thermal loads. Therefore, the investigation of heat transfer regularities at boiling in electroconvective flow remains an urgent problem.

2. Experimental methods
In the report the results are presented related to the investigations of heat transfer at boiling under the action of EHD flows generated by a high-voltage perforated electrode. The influence of the field
intensity and interelectrode spacing on the main characteristics of the pool boiling process is studied. The experimental data are generalized using the calculation relationships.

A stainless horizontally placed cylindrical tube 80 mm long with an outer diameter of 4 mm immersed in a relatively large volume of a liquid – hexane (boiling point of 68.7 °C, relative dielectric permeability $\varepsilon/\varepsilon_0 = 1.88$, and conductivity $\sigma = 10$ pSm$^{-1}$) – was used as a heating element. The high-voltage electrode was placed over the heating surface parallel to it; the electrode was made in the form of an isolated copper wire 1.5 mm in diameter with transverse notches facing the heating surface. The interelectrode spacing – the minimum distance between the outer surfaces of the electrodes - was varied from 0.5 to 4.5 mm. An electric circuit with a negative high-voltage electrode was used in the experiments. The electric field intensity was changed stepwise up to 12.5 kV. The measurements were performed in the range of the regime parameters $q = 500...150 \times 10^3$ Wm$^{-2}$, $\Delta T = T_w - T_s = 0.5...30$ K using the installation and method described in [9].

Before the experiments related to the determination of the main characteristic of the process under the action of the electric field $\alpha_e$ we performed experiments on the determination of the heat transfer coefficient at boiling without the field $\alpha_0$. Investigations were carried out at a constant heat flux generated via a direct heating of the heat transfer surface by a low voltage direct current.

For a system of parallel cylindrical electrodes the field intensity was determined using a simplified formula $E = \Phi / \delta$, where $\Phi$ is the electric field potential and $\delta$ is the interelectrode spacing.

The heat transfer coefficient was determined using the formula

$$\alpha = \frac{UI}{S(T_w - T_s)} \quad (1)$$

obtained when the relationship for the heat flux density $q = UI / S$ was substituted into the basic Newton law of convective heat exchange $\alpha = q/(T_w - T_s)$, i.e. the heat transfer intensity was determined as a result of indirect measurements of the current strength $I$, voltage $U$, the heating surface area $S$, wall temperature $T_w$, and saturation temperature $T_s$.

In the work the evaluation of the indirect measurement of the heat transfer coefficient, heat flux density, the temperature of the metal tube wall, and the fluid temperature was carried out. Since we had not other metrological measuring devices available we evaluated besides the grade of accuracy only the limits of the maximum permissible errors in accordance with the grade of accuracy and scale of the device. The limit of the permissible absolute error for determination of the heat transfer coefficient was calculated according to the known formula

$$\Delta \alpha = \sqrt{\left(\frac{\partial \alpha}{\partial I} \Delta I\right)^2 + \left(\frac{\partial \alpha}{\partial U} \Delta U\right)^2 + \left(\frac{\partial \alpha}{\partial S} \Delta S\right)^2 + \left(\frac{\partial \alpha}{\partial T_w} \Delta T_w\right)^2 + \left(\frac{\partial \alpha}{\partial T_s} \Delta T_s\right)^2} \quad (2)$$

The absolute error for the measurement of the heat flux density was determined according to the similar formula.

The relative error for the determination of the heat transfer coefficient did not exceed 1.99 % at low and 1.68 % at high heat loads. According to the evaluations, the error for determination of the heat flux density did not exceed 1.62 % for low heat fluxes and 1.41 % for greater heat fluxes. The temperatures of the metal tube and liquid were measured with an error of 0.54 °C.

3. Experimental results and discussion

The characteristic dependences $\alpha = f(q)$ at hexane boiling registered in a wide range of variation of the field intensity $E$ at an interelectrode spacing of $\delta = 2$ mm are shown in figure 1. These results as well as the published data [1, 3-12] give evidence that the formation of vapor bubbles and boiling of the fluid are more intensive for greater $q$ values; the value of the heat transfer coefficient is also greater. The heat transfer intensity increases with the increasing of the field intensity $E$, as well. The higher heat transfer coefficients correspond to the higher values of the field intensity at the same heat flux.
densities. The more pronounced influence of the field on the heat exchange intensity is observed at moderate heat flux densities. When $q$ increases the influence of the field on the heat transfer coefficient reduces. The similar results were obtained for other values of the interelectrode spacing.

The experimental data in figure 1 are approximated by straight lines. When the field is absent ($E = 0$) a usual for the area of developed boiling dependence of $\alpha$ versus $q$ persists within the entire studied range of variation of the heat flux $[13-17]$. However, when the boiling occurs in an electric field, the slope angle of the averaging straight lines markedly changes. The derivative $d\alpha/dq$ is lower for higher field intensities $E$. This gives evidence that the turbulent mixing generated by electroconvection is more intensive than the perturbations due to bubble vaporization. In these conditions the heat transfer enhances.

The investigations accomplished on the heat transfer at hexane boiling in an EHD flow have also found out the influence of the interelectrode spacing $\delta$ on the process characteristics. The results (figure 3) show that the maximum values of the heat transfer coefficient are obtained for the spacing between the heating surface and perforated electrode of $\delta = 3$ mm. The availability of the optimal interelectrode spacing can be explained by the fact that the heat exchange intensity in the interelectrode spacing is defined by the interaction of the pulse motion of the liquid due to vaporization and perturbations of the liquid flow induced by electroconvection $[9]$. At small interelectrode spacing (of the order of 3 mm) the electroconvection occurs within an overheated layer where the temperature of the liquid is approximately equal to the temperature of the wall of the
heating surface that is washed by hotter water in comparison with the bulk water. In such interelectrode spacing the bubbles are sufficiently well eliminated from the heating surface due to the difference of the dielectric permittivities of the liquid and vapor.

\[ \alpha \left[ \frac{W}{m^2 \cdot K} \right] = C_0 \frac{e^{3/2}}{\rho^{1/2}} \left( \frac{\rho_w - \rho_v}{\rho_w} \right) \left( T_w - T_v \right) \delta^3; \]

\[ \alpha = C_e \left( \frac{\lambda^{1/4}}{\sigma} \right) \frac{eE^2}{\varepsilon_0^{1/2}} \left( T_w - T_v \right) \delta^2. \]

Here \( C_0 \) and \( C_e \) are empirical constants that for hexane are as follows, \( C_0 = 15 \cdot 10^{-5} \) and \( C_e = 200 \).

The authors of [9, 12] have shown that Eqs. (3) and (4) satisfactorily agree with the experimental data for hexane. The main quantity of the experimental values of \( \alpha_0 \) follows the calculated curve.

**Figure 2.** Influence of electric field on the heat transfer intensity at boiling for various values, Wm\(^{-2}\): (1) 8920, (2) 12570, (3) 16510, (4) 19180, (5) 26030; (6) 33420.

**Figure 3.** Influence of the interelectrode spacing \( \delta \) on the dependence of \( \alpha \) versus \( q \); mm: (1) 3.0, (2) 4.2, (3) 2.0; (4) 1.5.

The electric field substantially changes the hydrodynamics of the boiling process. This is confirmed by the fact that at boiling without a field the vapor bubbles form and separate uniformly over the entire tube surface, whereas under the field action the vaporization is mainly located over the upper generatrix where the vapor separates in the form of jets consisting of bubbles with greater dimensions than at boiling without the field. The diameter of the bubbles separating from the lower tube generatrix is greater than the diameter of the bubbles separating from other generatrices. This is due to the fact that the electric field is inhomogeneous near the heating surface, and the influence of the field is more pronounced on the upper and lateral tube generatrices than on the lower one. In these conditions the law of the temperature distribution over the tube perimeter influences the local values of the heat transfer coefficient.

4. **Generalization of the experimental data**

On the basis of \( \Pi \)-method of dimensional theory the authors of [9, 12] proposed simple formulas for calculation of the heat transfer intensity at boiling in the presence of field and without it in conditions of natural convection.
defined by Eq. (3) with dispersion of ±25%. The accuracy of the approximation of the experimental data by the formula (4) amounts to ±30%.

To calculate the heat transfer coefficients $\alpha_0$ and $\alpha_e$ using the aforementioned formulas one should know the values of temperature drops $(T_w-T_s)_0$ and $(T_w-T_s)_e$ in the near wall layer. Since reliable instructions on this problem are not available it is not virtually possible to solve the formulated problem; hence, one need to modify Eqs. (3) and (4). For this it is sufficient to express the temperature drops via the heat flux densities $q_0$ and $q_e$ according to the basic Newton law of convective heat exchange

$$(T_w-T_s)_0 = \frac{q_0}{\alpha_0} \quad \text{and} \quad (T_w-T_s)_e = \frac{q_e}{\alpha_e}. $$

As a result we obtain

$$\alpha_0 = C_0^{1/3} \frac{c_p}{r^{1/2}} \left( \rho' - \rho^n \right)^{1/3} q_0^{2/3}, \quad (5)$$

$$\alpha_e = C_e^{4/3} \left( \frac{\lambda'}{\sigma} \right)^{4/3} \frac{e^{1/3} E^{2/3}}{c_p^{r^{1/6}}} q_e^{2/3}. \quad (6)$$

According to Eq. (5) the heat transfer coefficient $\alpha_0$ is proportional to the heat flux density $q_0$ in the power of 2/3, i.e.

$$\alpha_0 = K_0 q_0^{2/3}, \quad (7)$$

where $K_0 = C_0^{1/3} \frac{c_p}{r^{1/2}} \left( \rho' - \rho^n \right)^{1/3}$ is the proportionality coefficient that depends on the properties of the working fluid and heat transfer surface. This conclusion is confirmed by the published calculation formulas and measurements [14-17].

Taking into account Eq. (7) we can rewrite Eq. (6) in the form

$$\alpha_e = K_e (q_e E)^{2/3}, \quad (8)$$

where $K_e = C_e^{4/3} \left( \frac{\lambda'}{\sigma} \right)^{4/3} \frac{e^{1/3}}{c_p^{r^{1/6}}} \left( \rho' - \rho^n \right)^{1/3}$ is the proportionality coefficient depending on the type of the dielectric fluid. Thereby, the heat transfer coefficient at boiling in electrohydrodynamic flow $\alpha_e$ is proportional to the product of the heat flux density by the field intensity in the power of 2/3.

The efficiency of the action of the electrohydrodynamic flow on the heat transfer intensity is defined as a ratio of the heat transfer coefficients at boiling in the field $\alpha_e$ and without it $\alpha_0$ determined at the same heat flux density $q$. To find the required ratio it is sufficient to divide Eq. (8) by Eq. (7) taking into account the identity of the heat flux densities $q_0 \equiv q_e$ (ideal case) during the experiments. Then,

$$\frac{\alpha_e}{\alpha_0} = KE^{2/3}, \quad (9)$$

where $K = K_e / K_0 = \left( \frac{C_e}{C_0} \right)^{1/3} \left( \frac{\lambda'}{c_p \sigma} \right)^{4/3} \left( \frac{e^{r^{1/6}}}{\rho' - \rho^n} \right)^{1/3}$ is the proportionality coefficient.

As can be seen from Eq. (9), the relative heat transfer coefficient depends on the thermal and electrophysical properties of the dielectric liquid and field intensity $E$ in the power of 2/3.

Calculations according to Eq. (9) were accomplished taking into account the properties of saturated hexane at boiling point $T_i = 341.85$ K [18, 19]. Comparison of Eq. (9) with the experimental data is
shown in figure 4. For the field intensity of 12 kVcm⁻¹ a complete coincidence of the calculated and experimental values was observed. The main array of the experimental points is located below the calculated curve. Another peculiar feature was observed that the experimental values of the relative heat transfer coefficient are not invariant with respect to the heat flux density, this is more pronounced at high values of the field intensity. Hence, one should introduce into Eq. (9) a correction for the ratio of the heat flux densities \( q_e / q_0 \) (in fact, \( q_e \neq q_0 \)). With the noted correction Eq. (9) takes on the form

\[
\frac{\alpha_e}{\alpha_0} = K \left( \frac{q_e}{q_0} \right)^{2/3}.
\]

Comparison of the data calculated according Eq. (10) with the experimental data presented in figure 5 suggests that in the studied conditions Eq. (10) satisfactorily approximates the experimental data related to the heat transfer at boiling in the electrohydrodynamic flow. The obtained experimental values of the relative heat transfer coefficient are lower than the calculated ones by 20...30 % that is acceptable for this kind of studies.

Alongside with the aforementioned advantages Eq. (10) exhibits two substantial limitations. First, it follows from it that at the field intensity \( E = 0 \) the relative heat transfer coefficient takes on the value \( \alpha_e/\alpha_0 = 0 \). This disagrees with the experimental data to which corresponds the value \( \alpha_e/\alpha_0 = 1 \). Second, the relationship (10) is not linear, and the plot of the function exhibits a convexity directed upwards, though the convexity of the averaging curves for the experimental points is directed downwards.

5. Conclusions
The electrohydrodynamic action is an effective method of heat transfer enhancement at boiling and can be used for the development and adjustment of complex cooling systems and thermostating of heat exchange apparatuses. For its optimization more clear ideas are needed on the mechanism of liquid’s supply to the heating surface. In connection with this, the main attention should be paid to the investigation of the process hydrodynamics, the influence of the geometry and arrangement of electrodes, and the state of the heat transfer surface.

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