the working zone; u, rate of deposition of the aerosol particles in the water-vapor concentration gradient field; C_1 and C_2, relative concentrations of the vapor molecules (vapor content) and air; m_1 and m_2, masses of the vapor molecules and the air; I_1 and I_2, mass fluxes of water vapor and air; D_{12}, interdiffusion coefficient of the air—water vapor mixture.

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HEAT EXCHANGE AND BOILING CRISIS IN SLOT CHANNELS UNDER THE ACTION OF AN ELECTRIC FIELD

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The results of an experimental and analytical investigation of the effect of electric fields on the boiling of dielectric liquids with low thermal conductivity under constrained conditions are given.

Experimental and analytical investigations of heat transfer during boiling and condensation in an electric field [1-3] provide convincing evidence that, under certain conditions, its effect on the phase transition and the vapor—liquid flow causes considerable quantitative and qualitative changes in the thermal and hydrodynamic phenomena. The field-induced perturbations in a two-phase medium, which are accompanied by the development of large-amplitude electrodynamic waves, cause a restructuring of the flow. The development of electroconvection, changes in the structure of the two-phase medium, an increase in the interphase contact surface area, and reduction in the characteristic dimensions of films, drops, bubbles, etc., lead under certain conditions to vigorous intensification of the heat and mass exchange in an electric field. The specific features of the thermal and hydrodynamic phenomena in a two-phase flow resulting from the imposition of an electric field make it possible to devise highly efficient electrohydrodynamic heat transfer devices. However, the practical application of these features in designing closed electrohydrodynamic (EHD) heat-transfer devices (heat pipes or thermosiphons) is basically at the stage of technical proposals. The factors

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hindering this application are insufficient knowledge of the potentialities of EHD pumps capable of ensuring a closed coolant cycle, a lack of papers generalizing research data on the heat exchange in boiling and condensation in an electric field, and insufficient knowledge of the specifics of electric field action on the boiling and condensation under the various special conditions prevailing in gravitational and wick evaporation cooling systems (boiling and condensation in slot channels and capillary-porous structures, thin-film boiling, and condensation on liquid drops).

With regard to this, we performed comprehensive investigations of the heat exchange, the mechanism, and the intrinsic characteristics of the heat transfer crisis in boiling within narrow slot channels characterized by different geometries and three-dimensional orientations [4-6]. In particular, we have found that the highest level of heat exchange and the maximum intensification of heat transfer under electric field action occur during boiling in fairly long (70-140 mm) slot channels, while the maximum increase in the limiting heat flux occurs during boiling in short slots (20-30 mm) where the clearance is of the order of the capillary constant. However, the use of these results for developing compact EHD cooling systems is hindered by a lack of systematic experimental data and reliable theoretical relationships on the boiling crisis in electric fields and data on the way the heat transfer intensity is affected by various parameters, such as the pressure, the degree to which the slot channel is filled with the coolant, the wall thickness of the heater, and the velocities of the two-phase flow and the interphase boundaries. This prevented us from revealing fully the mechanism of the field action and elaborating suitable recommendations for heat transfer calculations, which made it necessary to undertake further investigations, the main results of which are given below.

We investigated the heat exchange and its crisis in boiling in flat and annular channels, immersed in a free coolant volume. The channel length varied from 20 to 70 mm, while the slot clearance varied from 4 to 0.5 mm. The temperature and the density of the thermal flux were measured by using the standard method. Glass plates or cylinders with a transparent, electrically conducting coating on their inner surfaces were used as high-voltage electrodes in investigating the mechanism and the intrinsic characteristics of the boiling process.

The experiments were performed in the thermal flux range of $2 \cdot 10^3$-$5 \cdot 10^5$ W/m^2. the following quantities were varied: the field strength in the interelectrode space, from 0 to 100 kV/cm; the saturation pressure, from 0.065 to 0.5 MPa; slot channel filling with the coolant, from 40 to 100%. Khladon-113, pentane, and diethyl ether were used as coolants.

Investigations of the effect of the coolant in the channel fill percentage on the heat exchange intensity indicate that a reduction of the filling (down to 40%) produces smaller critical thermal flux and a stronger intensifying effect of the field on heat transfer (Fig. 1). This effect, which manifests itself for all the coolants investigated, is connected with an increase in the actual volumetric vapor content. It occurs with a reduction in the slot clearance, an increase in the channel length, and changes in the three-dimensional orientation of the clearance and the channel [5]. The results of motion picture filming indicate that, regardless of the partial filling of the channel with a single-phase coolant (40%), the field action during the boiling process causes the two-phase flow to move to its upper part, the region occupied by vapor, and fill the entire interelectrode volume. However, the structure of the medium is similar to the structure of a two-phase flow in a slot channel when it is initially completely filled with the coolant, while the vapor content increases.

The increase in the actual volumetric vapor content continues to affect the heat transfer intensification by the electric field during boiling in slot channels until a vapor lock—emulsion flow structure is produced in the channel. In passing to the dispersed-annular flow conditions of a two-phase medium, the intensifying action of the field abates noticeably, regardless of the increase in the vapor content. Similar trends have also been observed in investigating the effect of pressure on the heat transfer intensity.

The motion picture data indicate that, in the $q > 1.4 \cdot 10^4$ W/m^2 range of thermal fluxes, dispersed—annular motion of the two-phase flow occurs in the upper part of a slot channel. An increase in pressure changes the structure of the two-phase medium (levels the section characterized by the dispersed—annular boiling conditions) and increases considerably (by a factor of 2-3) the heat transfer in boiling in an electric field (Fig. 2). The increase in heat exchange with pressure vatiation is basically unconnected with the suppression of dry areas, since the intensity of heat exchange increases insignificantly (by a factor of 1.2) in the absence of a field (Fig. 2, curve 1).

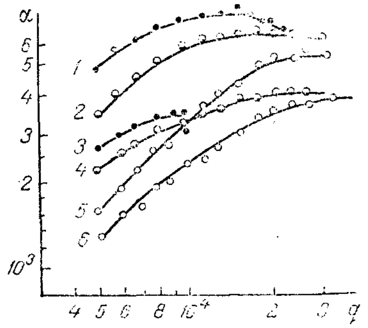


Fig. 1

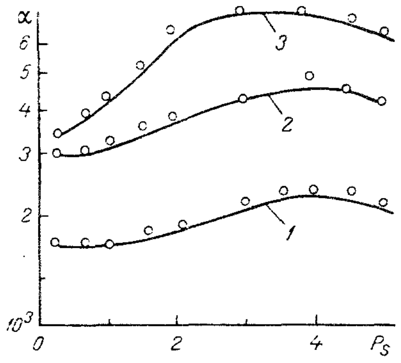


Fig. 2

Fig. 1. Effect of the fill factor for a single-phase coolant (pentane) in the slot channel on the heat transfer intensity in boiling under the action of an electric field; E (kV/cm): 0 (3, 4, and 6); 60 (1, 2, and 5). Fill factor (%): 40 (3 and 1); 60 (2 and 4); 90 (5 and 6); α is given in $W/m^2 \cdot deg$ units; q is given in W/m^2 units.

Fig. 2. Heat transfer coefficient as a function of the pressure and the field strength in Khladon-113 boiling in a vertical slot channel; E (kV/cm): 0 (1); 60 (2); 80 (3); $q = 1.4 \cdot 10^4$ W/m^2; P_s is given in 10^5 Pa units.

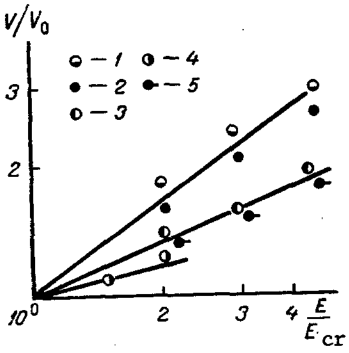
It was found earlier in studying boiling in horizontal slots [4] that the field action causes the breakup of vapor bubbles, strong suppression of dry spots, the onset of directional liquid and vapor flow in the slot, and the development of stream (transverse) coolant mixing in the interelectrode space. These peculiarities of field action also manifest themselves in long channels; however, the contribution of each factor causing heat exchange intensification to the over-all mechanism of heat transfer changes in this case. Motion picture filming indicates that, with an increase in the channel length ($\ell \geq 70$ mm), the directional motion of a two-phase flow in the field degenerates, which can be explained by the considerable increase in the hydraulic resistance of the channel.

It has been established experimentally that the actual volumetric vapor content does not vary with the imposition of a field, while the start of the boiling process is shifted with increasing channel length to the region of small thermal fluxes and is not accompanied by intensive development of dry spots at the heating surface. Consequently, the considerable intensification of the heat transfer (in excess of the corresponding value in boiling within short slots) is not connected with the suppression of dry spots. On the basis of the trends revealed, we can also assume that transverse mass transport in a slot channel hardly affects the heat exchange intensity. For instance, the heat exchange intensity increases with pressure (Fig. 2), while the dimensions of vapor cavities and, correspondingly, the heating surface area over which the stream mechanism of liquid transport occurs in an electric field diminish.

These results provide convincing evidence that the heat exchange in boiling in slot channels is most strongly affected by the field when the two-phase flow has a vapor lock—emulsion structure and a sufficiently developed interphase surface forms at the heater.

The above suggests that heat exchange intensification under electric field action is basically caused by a thinning of the liquid microlayer in the vapor bubble base due to an increase in the displacement rate of interphase boundaries and, in particular, the growth rate of vapor bubbles. Processing of the motion picture data has shown that the rate of random displacement of interphase boundaries increases considerably in an electric field (Fig. 3).

Moreover, we performed special investigations of the effect of a field on the behavior of the interphase boundary of a single vapor cavity, generated in a locally heated slot channel. The results suggest that, up to the breakup of the vapor phase, the field action accelerates considerably its growth within the heat-releasing area ($R \approx 3$ mm). The growth rate of the dry spot developing in the base of the vapor cavity in the liquid microlayer



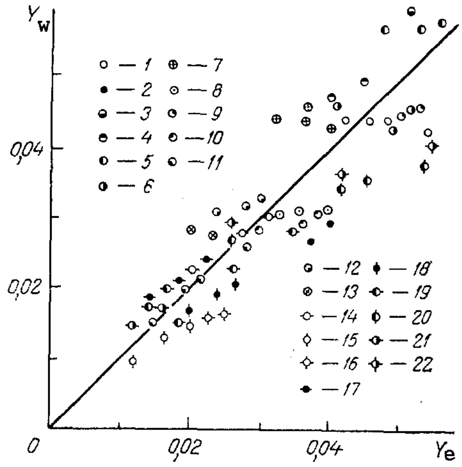


Fig. 3 Fig. 4

Fig. 3. Rate of displacement of interphase boundaries over the heating surface as a function of the field strength. S = 0.5 mm; $q(W/m^2)$: $2.5 \cdot 10^3$ (1); $6.3 \cdot 10^3$ (2, 3, and 4); $1.4 \cdot 10^4$ (5); Khladon-113 (1, 2, 3, and 5); pentane (4); horizontal channel orientation (1, 2, and 4); vertical channel orientation (3 and 5).

Fig. 4. Heat exchange in boiling within slot channels. Chennel length ℓ (mm): 20 (18); 70 (1-4, 18-13, 17, and 19-22); 140 (5 and 14); 210 (6, 15, and 16); slot clearance S (mm): 0.5 (1, 3, 5, 10, 12, 14, 18, and 20); 0.75 (2, 4, 6-9, 11, 13, 15, 16, 17, 19, and 22); horizontal orientation (3, 4, 12, 13, 16, and 18-20); vertical orientation (1, 2, 5-11, 14, 15, 21, 17, and 22); annular channel (1-17 and 19-22); flat channel (18); Khladon-113 (1-6, 8, and 10-20); pentane (7 and 21); diethyl ether (9 and 22); E (kV/cm): 0 (1-9), 40 (21 and 22), 60 (19 and 20), 90 (10-17), and 100 (18).

at the heating surface also increases considerably. The latter indicates that the higher growth rate of the vapor phase in an electric field causes the microlayer to become thinner and may be the cause of heat exchange intensification in boiling within slot channels.

The experimental data obtained can be explained by investigating analytically the initiation and development of electric convection in two-phase media and the growth dynamics of individual bubbles in an electric field and also by performing special experiments involving synchronous measurements of the microlayer thickness and the temperature profile in the vapor cavity base. Using empirical processing of the experimental results and the relationships found in the literature [7, 8], we shall consider here the effect of an electric field on the displacement rate of interphase boundaries and, correspondingly, the thickness of the microlayer formed at the base of vapor bubbles during their growth and motion. Without considering these factors, it was impossible in the past to generalize the experimental data on the heat exchange in boiling within slot channels under the action of an electric field in a wide range of operating, geometric, and physical parameters.

In accordance with the above, we reach the conclusion that the heat exchange in boiling within slot channels under the action of an electric field is determined by the following factors: microlayer evaporation inside large vapor cavities; contact heat exchange with the liquid entering the slot channel; overheating of the heat-exchange with the liquid entering the slot channel; overheating of the heat-exchange surface at locations where dry spots develop in the microlayer. The relationship generalizing the experimental data on heat exchange has the following form:

$$\frac{1}{\alpha} = \frac{\delta}{\lambda}(\varphi - \varphi_{ds}) + \varphi_{ds}\frac{\tau_{ds}}{\delta_h c_h \rho_h} + (1 - \varphi)\frac{\sqrt{\tau_\ell}}{\sqrt{\lambda' c' \rho'}}, \quad (1)$$

where the actual volumetric vapor content is determined from the conditions of two-phase flow filtration with an allowance for the action of capillary and electric forces, the effect of coolant inflow as the vapor lock emerges from the slot channel, and the two-phase flow circulation along the perimeter and the length of the heat-transfer elements:

$$\varphi = 0{,}29Z^{0,44};\ 1-\varphi = 0{,}8Z^{-0,39};$$
$$Z = \frac{\rho'}{\rho''}\frac{q}{r}\frac{l}{S}\sqrt{2\frac{B}{D}\frac{1}{\rho'}};\quad B = 1+\Sigma\xi + c_f\frac{l}{S};\tag{2}$$
$$D = \frac{2\sigma}{S} + \sqrt{2\sigma(\rho'-\rho'')g} + (\rho'-\rho'')g(l\sin\gamma + d_{\text{h}}\cos\gamma) + k\frac{S}{l}\frac{E^2\varepsilon_0(\varepsilon'-\varepsilon'')}{2}.$$

In relationship (1), the microlayer thickness in the vapor bubble base is determined according to the well-known expression [7]

$$\delta = k\nu(\rho' S/\sigma V_{\text{v}})^{1/3},\tag{3}$$

where the velocity of the interphase boundary in an electric field is found by processing the experimental data,

$$V_{\text{v}} = V_0(0{,}8+0{,}2\cos\gamma)\left(\frac{E}{E_{\text{cr}}}\right)^{0,3(1+0,67\cos\gamma)}(\varepsilon'-\varepsilon'').\tag{4}$$

In (4), the field strength capable of influencing the heat exchange and the velocity of the interphase boundary in the absence of a field are determined in correspondence with the recommendations given in [3, 8]:

$$E_{\text{cr}} = 2{,}6\cdot 10^2\left(\frac{\sigma}{\varepsilon_0\varepsilon''}\right)^{0,5}(\tau_{\text{r}}\nu)^{0,09},\tag{5}$$

$$V_0 = \frac{ql}{r\rho'' S}.\tag{6}$$

The duration of a dry spot at the heating surface is determined by the velocity of the two-phase flow and the breakup rate of vapor locks under the field action,

$$\tau_{\text{ds}} \sim R_{\max}/V_{\text{mi}},\tag{7}$$

where the limiting dimension of a vapor lock is defined as the length of the nonstationary wave at the interphase boundary in an electric field [9],

$$R_{\max} \sim 8\pi\sigma\varepsilon''^2/3(\varepsilon'-\varepsilon_{\text{mi}})^2\varepsilon_0 E^2,\tag{8}$$

while the mixture velocity is determined from the conditions of filtration of the vapor lock-emulsion flow from the channel,

$$V_{\text{mi}} = A^{-0,5}Z^{-0,39},\tag{9}$$

where $A = B/2D\rho'$.

Assuming that

$$\varphi_{\text{ds}} \sim \varphi;\ \tau_{\text{v}} \sim \frac{l}{V_{\text{mi}}};\ \tau_{\ell}/\tau_{\text{v}} \sim (1-\varphi)/\varphi\tag{10}$$

and substituting these values in (1) along with expressions (2)-(9), we obtain

$$Y = \frac{1}{\text{Nu}\,Z^{0,29}} = C_1\nu\left(\frac{r\rho'\rho''}{Sql\sigma(0{,}8+0{,}2\cos\gamma)\left(\frac{E}{E_{\text{cr}}}\right)^{0,3(1+0,67\cos\gamma)}(\varepsilon'-\varepsilon'')}\right)^{1/3} +$$
$$+ C_2\frac{\lambda}{S}Z^{0,54}A^{0,5}\frac{R_{\max}}{\delta_{\text{h}}c_{\text{h}}\rho_{\text{h}}} + C_3\frac{\lambda}{S}Z^{-0,9}A^{0,25}\left(\frac{l}{\lambda' c'\rho'}\right).\tag{11}$$

Figure 4 shows a generalization of experimental data on the heat exchange in boiling within narrow slot channels with different geometries and orientations in space, based on expression (11), for the following coefficient values: $C_1 = 12$; $C_2 = 0.4$; $C_3 = 0.1$.

Studies in the field effect on the heat transfer crisis in the case of direct electric heating of the heat-transfer elements have shown that reduction of the slot clearance di-

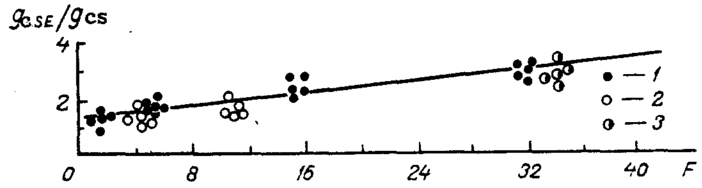


Fig. 5. Generalization of experimental data on the heat exchange crisis during boiling in horizontal slot channels under the action of an electric field; E (kV/cm): 0 – 100; S (mm): 0.5 – 4; Khladon-113 (1); pentane (2); diethyl ether (3); $F = \varepsilon_0\ (\varepsilon^1 - 1E^2 f(\varepsilon'))/(\varepsilon' g(\rho' - \rho''))10^3$.

minishes the limiting thermal fluxes, which is especially strongly pronounced when the slot is reduced from 2 to 1 mm. Electric field action on the boiling process in short slot channels augments considerably the attainable thermal loads (by a factor of 2-3), while it hardly affects their limiting values in vaporization in relatively long channels. Motion picture filming made it possible to explain these trends. The heat transfer crisis in sufficiently long slot channels is local in character and is determined by the development of a stable dry spot at the heat-transfer surface. Since the field action hardly affects the critical thermal fluxes in boiling in channels with such a geometry, we shall not consider here the mechanism of crisis onset and development under these conditions. The considerable increase in the critical thermal fluxes during boiling in short slots is connected with a considerable reduction in the actual volumetric vapor content when a field is applied. The liquid thrown into the interelectrode space is in this case sufficient for wetting a considerable part of the heat exchange surface. The motion picture data indicate that the crisis onset mechanism in slot channels does not involve a certain saturation of the heating surface with vaporization nuclei. Therefore, experimental data processing from the point of view of the thermal crisis theory is impossible. In order to determine the form of the relationships generalizing the results obtained, we can use the well-known concept [10] of the heat exchange crisis in boiling as the stability loss in one mode of boundary layer existence and transition to another, more stable, mode. According to this approach, a two-phase boundary layer loses its stability wh en the kinetic energy E of the blown-in vapor flow is sufficient for the formation of a stable vapor film whose specific potential energy is Π. The condition of stability loss is given by

$$E^* \geqslant K_1^2 \Pi, \tag{12}$$

where K_1 is the stability criterion for a two-phase boundary layer.

Extending these concepts to boiling under constrained conditions, we assume that, in contrast to the free volume in narrow slot channels in the absence of a field, the specific potential energy of a stable vapor film will be reduced by an amount proportional to the work expended on overcoming the friction forces in filtering the vapor–liquid flow out of the slot. In this case, the modified equation of the hydrodynamic theory of crisis assumes the following form:

$$E^* \geqslant K_1^2 \Pi - K_2 A_f, \tag{13}$$

where A_f is the specific work in overcoming the friction forces, and K_2 is an empirical constant, determined experimentally.

If an electric field is applied under unconstrained boiling conditions, the density of the volumetric forces acting mainly in the liquid phase increases, which produces an increase in the potential energy of the stable vapor film, i.e.,

$$\Pi_E = [g(\rho' - \rho'') + f_E]\,\delta, \tag{14}$$

where f_E characterizes the density of ponderomotive field forces in the liquid phase and depends on the electrophysical characteristics of the liquid and the field configuration. Under unconstrained conditions with a field applied, the heat transfer crisis condition is given by

$$E^* \geqslant K_4^2 \Pi_E\,. \tag{15}$$

Assuming, as in [10], that $\delta \sim \sqrt{\sigma/(\rho' - \rho'')g}$, and that $f_E \approx \text{const}\, E^2 f(\varepsilon')\varepsilon_0$ in correspondence with [2, 11], and also defining E* and Π by using the well-known relationships [10], we rewrite (15) and (12) in the following form:

$$\left(\frac{q_{cE}}{r\rho''}\right)^2 \rho'' \geqslant K_1^2 \left[g(\rho' - \rho'') + \text{const}\, E^2 f(\varepsilon')\, \varepsilon_0 \sqrt{\frac{\sigma}{(\rho' - \rho'')\, g}}\right], \tag{16}$$

$$\left(\frac{q_c}{r\rho''}\right)^2 \rho'' \geqslant K_1^2 \, [g(\rho' - \rho'')] \sqrt{\sigma/(\rho' - \rho'')\, g}\, . \tag{17}$$

Using (16) and (17), we obtain

$$\frac{q_{cE}}{q_c} = \sqrt{1 + \text{const}\, \frac{E^2 f(\varepsilon')}{g(\rho' - \rho'')}\, \varepsilon_0}\ . \tag{18}$$

Similarly, in correspondence with [11], we obtain from (12) and (13) the following expression for boiling in slot channels in the absence of a field, interpreting A_f as $A_f \sim \Delta P_f$ where ΔP_f is the hydraulic drag in the filtering of the vapor–liquid mixture:

$$\frac{q_c}{q_{cS}} = \sqrt{1 + \left(\frac{\rho''}{\rho'}\right)^{0,25} \left[\text{const}\left(\frac{b}{S}\right)^3 + \text{const}\left(\frac{b}{S}\right)^2\right]}\ . \tag{19}$$

For slot clearances with an electric field applied, we obtain from (18) and (19)

$$\frac{q_{cSE}}{q_{cs}} = \sqrt{1 + C_1 \frac{E^2 \varepsilon_0}{g(\rho' - \rho'')} f(\varepsilon')}\ . \tag{20}$$

Figure 5 provides a generalization of the experimental data on the basis of expression (20). The scatter of experimental results does not exceed ±30%, which indicates the admissibility of these model concepts as a first approximation and suggests that the above relationship can be used for calculating critical thermal fluxes in boiling in short slot channels with thin-walled heaters under the action of a field for the constant C = 210. In Eq. (20), the function $f(\varepsilon')$ for the boiling of a nonpolar liquid in a uniform electric field has the following form:

$$f(\varepsilon') = (\varepsilon' - 1)(\varepsilon' + 2)\beta \Delta T_c\, ; \tag{21}$$

for a polar liquid,

$$f(\varepsilon') = \frac{\varepsilon'}{\varepsilon' - 1}\left(\frac{1}{T} + \frac{5}{3}\beta\right)\Delta T_c. \tag{22}$$

In (21) and (22), ΔT_c is the wall overheating at which the liquid phase cannot exist at the heating surface (the wall temperature corresponds to the explosive boiling temperature), while the values of ε', β, and T are averaged within the two-phase boundary layer; they pertain to the liquid phase.

In conclusion, we note that the maximum intensification of heat transfer due to electric field action in the boiling of liquid dielectrics within slot channels occurs for combinations of the operating parameters (P, q) which produce a vapor lock—emulsion structure of the two-phase flow.

The heat exchange intensification resulting from field action on the boiling process in slots is caused by a thinning of the liquid microlayer at the base of vapor bubbles due to the increasing displacement rate of interphase boundaries and, in particular, a higher growth rate of vapor bubbles. It is also connected with the suppression of dry spots due to the vapor phase breakup and the development of intensive electromechanical convection and stream transport of the coolant.

The increase in the heat exchange intensity and the decrease in the maximum transmitted thermal fluxes with a reduction in the slot clearance or the percentage of the dielectric coolant fill in the channel (to 40%) is related to the rise of the actual volumetric vapor content, an increase in the surface area of interphase boundaries, and the consequent intensification of the effect of their displacement velocity in an electric field on the liquid microlayer developing in the base of vapor bubbles.

The mechanism of heat exchange crisis in the boiling of Khladon like coolants in short channels on a thin heat-transfer element under the action of an electric field is determined by hydrodynamic phenomena and the vapor lock—emulsion mode of filtration of the vapor—liquid mixture.

The above experimental results and theoretical relationships can serve as a basis for developing and designing high-efficiency units, devices, and apparatus for readily controllable heat extraction, which, along with their miniaturization, would be very important in various branches of modern technology. Moreover, the realization of electrohydrodynamic vaporization—condensation systems, including those with forced coolant circulation, has great potential not only in cooling, but also thermostatic control, techniques and in providing stable operating conditions. It is, therefore, a problem of the highest importance in priority projects that would further the progress of science and technology.

NOTATION

q, thermal flux density; ΔT, temperature head; T, absolute temperature; E, electric field strength; E^*, kinetic energy of the vapor blown in during boiling; Π, potential energy of the vapor film; δ, thickness of the vapor film or microlayer; λ, c, ρ, r, σ, β, thermophysical characteristics; g, acceleration due to gravity; S, b, ℓ, d, height, width, length, and diameter of the slot channel, respectively; δ_h, heater thickness; φ, vapor content; φ_{ds}, percentage of the heating surface area occupied by dry spots; ξ, hydraulic drag coefficient; c_f, friction coefficient; τ, time; γ, channel slope relative to the horizontal; V_{mi}, two-phase flow velocity; V_v, displacement rate of the interphase boundary; ΔP_f, hydraulic friction resistance to the motion of the vapor—liquid mixture; A_f, work of friction; ε', relative permittivity of the liquid; ε_0, electric constant; f_E, density of ponderomotive forces of the field; q_c and q_{cS}, critical thermal flux during boiling in a free volume and in slot clearances, respectively; q_{cE} and q_{cSE}, same, in an electric field. Symbols and subscripts: ' and ", liquid phase and vapor phase, respectively; ds, dry spot; h, heater; mi, mixture; ℓ, liquid; v, vapor; r, relaxation.

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