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FEATURES OF THE DYNAMICS OF DEVELOPMENT AND THE THERMAL STABILITY OF DRY SPOTS IN FLOWING-DOWN LIQUID FILMS

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A numerical experiment for description of the critical phenomena in the case of intense heat exchange in flowing-down wave films of a cryogenic liquid on heat-releasing surfaces bounded in length has been carried out. Numerical modeling of the thermal stability of dry spots with heat-transfer conditions determined experimentally yields a satisfactory agreement with the values of the critical heat-flux density obtained in the experiments. This confirms the hypothesis that, in certain regimes of film flow, the development of a crisis is related to the upstream propagation of a temperature disturbance, when the threshold of thermal stability of the dry spots is attained. The value of the critical heat flux is much lower than that calculated from the existing hydrodynamic models.

Introduction. Crisis phenomena and local heat exchange in boiling and evaporation in flowing-down liquid films have recently become the subject of various experimental and theoretical investigations. Film flows of liquids (including cryogenic ones) are widely used in different technological processes for intensification of heat and mass transfer. The topicality of this subject matter is related, in particular, to the development of efficient and compact systems for cooling of the elements of electronics and computers and high-productivity graphical processors whose response and lifetime are substantially dependent on the efficiency of dissipated-power removal. In such systems, the limiting values of the heat fluxes are bounded by the occurrence of crisis phenomena, when dry spots occur on the surface wetted; the development of the dry spots leads, under certain conditions, to the total drainage of the surface and to uncontrolled heating and failure.

Flow of liquid films down heated surfaces brings about a number of problems related to the stability of their flow. In boiling and intense evaporation, the pattern of destruction of the film as a result of the formation of local dry spots and their merging becomes very complicated. The physics of crisis phenomena in boiling flowing-down films is not understood at present, which makes it difficult to construct theoretical models and computational procedures enabling one to predict the conditions of development of a drying crisis and finally to evaluate the reliability of the operation of equipment intended for various purposes. In this connection, the line of these investigations is topical from both the scientific and practical viewpoints.

High-speed visualization of the boiling process [1, 2] has shown that, in the lower part of the heater, nonstationary (and then stable) dry spots occur with increase in the heat flux in the first stage; these spots subsequently merge, and once the critical heat flux has been attained, a transient process with the displacement of the nucleate-boiling zone on the entire heat-transfer surface develops. Generalization of the experimental data obtained on high-thermal-conductivity thick-walled heaters has shown that, under the development of this type of heat-transfer crisis, the critical flux can be much lower than that calculated from the well-known hydrodynamic model [3]

$$\frac{q_{\text{cr}}}{\rho'' r U} = 0.121 \left(\frac{\rho'}{\rho''}\right)^{2/3} \left(\frac{\sigma}{\rho' U^2 L}\right)^{0.42} . \tag{1}$$

The development of drying crisis in this case is determined by the mechanism of parallel heat conduction and is realized by the propagation of a temperature disturbance occurring in the heater's lower part in the zone of large-

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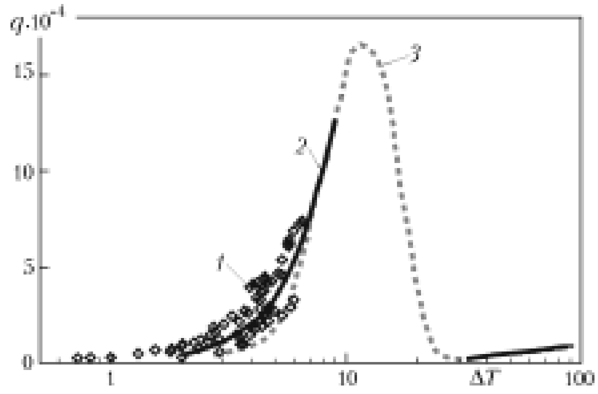


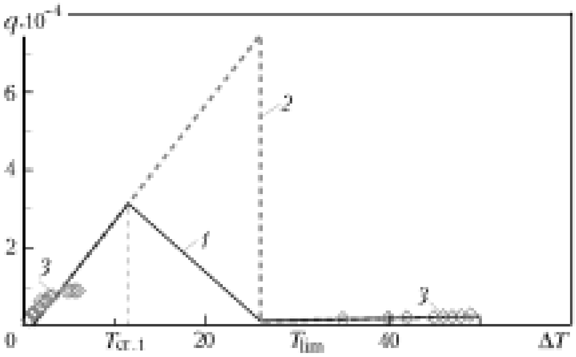


Fig. 1. Curve of heat transfer in film nitrogen flow on a bounded heat-transfer surface from Duralumin: 1) experimental data [1] for the heater of length 64 mm ($\text{Re}_{\text{in}} = 285$); 2) interpolation curve with the use of the data of [1]; 3) data of [5]. q, W/m^2; ΔT, K.

Fig. 2. Model curves of heat transfer under film flow of liquid nitrogen on a Constantan foil ($\text{Re}_{\text{in}} = 690$): 1) three-zone model, $\varepsilon \geq 1$; 2) two-zone model, $\varepsilon \ll 1$; 3) experimental data [2]. q, W/m^2; ΔT, K.

scale dry spots up the heater with the displacement of the high-intensity regime of nucleate boiling, which is also confirmed by direct temperature measurements [1, 2]. Numerical modeling of the development of a crisis of this type in film liquid flow carried out in the first approximation in parallel with experimental investigations seems of interest.

Investigation of heat exchange in boiling and evaporation of cryogenic liquids some properties of which are significantly different from the properties of high-temperature liquids is also important for refining the understanding of the processes under study and serves as a technique for checking the existing model descriptions of the heat exchange and development of transient and crisis phenomena.

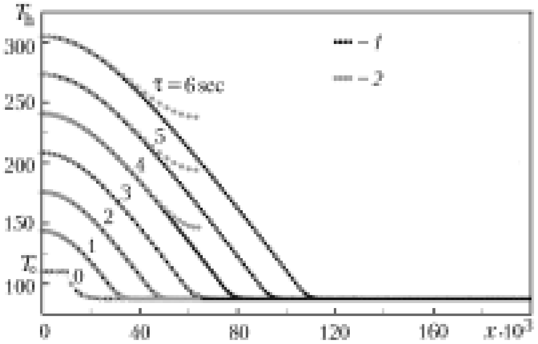
Experiments and Modeling. A mathematical model suggests the thermal nature of development of critical phenomena. The propagation of a temperature disturbance by the action of the mechanism of parallel heat conduction on a thin heater (Biot number $\text{Bi} = q\delta_{\text{h}}/[(\lambda_{\text{h}}(T_{\text{h}} - T_{\text{sat}})] < 1$) is described by the equation of nonstationary heat conduction with the corresponding initial and boundary conditions

$$\frac{\partial T_{\text{h}}}{\partial \tau} = LT_{\text{h}} + f(T_{\text{h}}) \,, \;\; f(T_{\text{h}}) = \frac{1}{\delta_{\text{h}} c_{\text{h}} \rho_{\text{h}}} [q_{+} - q_{-}(\Delta T_{\text{h}})] \,,$$

$L = \dfrac{\lambda_{\text{h}}}{c_{\text{h}}\rho_{\text{h}}} \dfrac{\partial^2}{\partial x^2}$ in the one-dimensional case and $L = \dfrac{\lambda_{\text{h}}}{c_{\text{h}}\rho_{\text{h}}} \left[\dfrac{\partial^2}{\partial R^2} + \dfrac{1}{R} \dfrac{\partial}{\partial R} \right]$ in the two-dimensional case. Here $q_{-} = q_{-}(\Delta T_{\text{h}})$ is the density of the heat flux removed to the liquid. The density of the heat release q_{+} along the heater is taken to be constant: $q_{+}(x) = q_{+} = \text{const}$. We model the initial temperature disturbance by the function in the form of a step smoothed exponentially in the region of high-intensity heat exchange. The maximum initial temperature in the zone of a dry spot in the first approximation is taken to be $T_0 = T_{\text{lim}}$.

The boundary conditions $\partial T_{\text{h}}/\partial x = 0$ for $x = 0$ and $x = L_{\text{h}}$ for a heater of finite length L_{h} correspond to the heater's heat-insulated ends. For an infinite heater, we have $\partial T_{\text{h}}/\partial x = 0$ for $x = 0$ (symmetry condition) and $T_{\text{h}} = T_{\infty} = \dfrac{q}{\tilde{\alpha}} + T_{\text{sat}}$ for $x = \pm\infty$.

The calculations have been performed for the development of dry spots (one-dimensional and quasi-two-dimensional ones) in flowing-down liquid-nitrogen films on heat-releasing surfaces bounded and unbounded in length at atmospheric pressure. In particular, to compare the results of numerical modeling and experiments we used, in the cal-



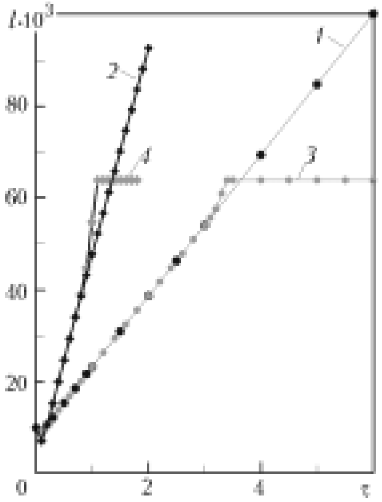


Fig. 3. Evolution of the temperature profiles for the heat-release density $q_+ = 15 \cdot 10^4$ W/m^2 (the heater material is Duralumin; $\delta_h = 4 \cdot 10^{-3}$ m and $Re_{in} = 285$): 1) semiinfinite heater; 2) heater of length $L_h = 64 \cdot 10^{-3}$ m. T_h, K; x, m.

Fig. 4. Dimension of a local dry spot vs. time: 1 and 2) semiinfinite heaters; 3 and 4) heater of finite length; 1 and 3) $\lambda = 50$ and 2 and 4) 420 W/(m·K). l, m; τ, sec.

culations, the boundary conditions determined experimentally for a thick-walled Duralumin heater ($\delta_h = 4 \cdot 10^{-3}$ m) and a thin-walled Constantan heater ($\delta_h = 25 \cdot 10^{-6}$ m).

For a physically substantiated selection of the boundary conditions in the front of change of boiling regimes, we use the parameter

$$\varepsilon = \frac{l_{char}}{\Lambda} = \left(\frac{\lambda_h \delta_h g \, (\rho' - \rho'')}{\tilde{\alpha} \sigma} \right)^{0.5} ,$$

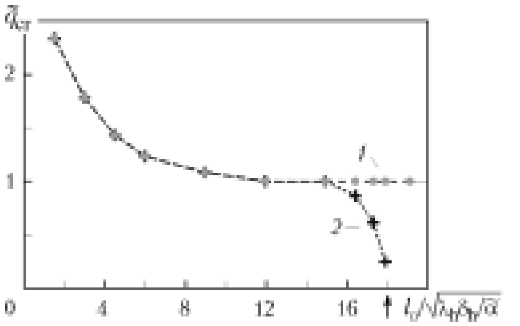
introduced in [4]; this parameter characterizes the ratio of the width of the temperature gradient along the heater in the front in the zone of high-intensity heat exchange to the characteristic scale of the action of capillary forces Λ.

The heat-transfer intensity is described by the heat-transfer curves presented in Fig. 1 and 2 in which the experimental data of [1, 2, 5] have been used.

In this work, we investigate the evolution of local dry spots in flowing-down liquid-nitrogen films of heat-releasing surfaces bounded streamwise in length and on unbounded surfaces and the influence of boundary conditions on the behavior of the originated spot for its different initial dimensions. A dry spot of dimension l_0 (one-dimensional case) is located, at the initial instant of time, at the left edge of the heater (Fig. 3). Certain results of the numerical modeling are presented in Figs. 3–7. The calculated dependences in Figs. 3 and 4 demonstrate the influence of boundary conditions on the time evolution of the temperature profile and the dimension of the dry spot.

As is clear from Fig. 3, the temperature in the right part of the heater of finite length begins to grow rapidly. The values of the velocity of motion of the boundary of the local dry spot over the surface of the infinite heater and the heater of finite length L_h coincide until the region of high-intensity heat transfer decreases to a dimension of the order $l_{char} = \sqrt{\lambda_h \delta_h / \tilde{\alpha}}$. Next, the boundary of the spot on the infinite heater continues to move with a constant velocity, whereas on the heater of finite length, we have a sharp nonlinear increase in the velocity, as the front approaches the heat-insulated edge (Fig. 4).

Figure 5 gives results of calculations of the critical heat-flux density for the semiinfinite Duralumin heater and for that bounded in length. In the calculations, we have taken the following thermophysical properties and geometric parameters of the heat-transfer surface: $\lambda_h = 50$ W/(m·K), $c_h = 300$ J/(kg·K), $\rho_h = 3000$ kg/m^3, and $\delta_h = 4 \cdot 10^{-3}$ m.



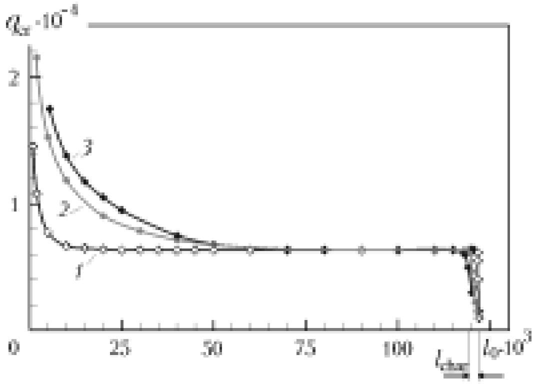


Fig. 5. Critical heat-flux density vs. initial dimension of the dry spot: 1) semi-infinite heater; 2) heater of finite length (the arrow on the abscissa axis points to the boundary of the heat-release zone).

Fig. 6. Critical heat-flux density vs. initial dimension of the dry spot for different thicknesses of the heater: 1) $\delta_h = 25\cdot10^{-6}$, 2) $1\cdot10^{-3}$, and 3) $2\cdot10^{-3}$ m. The region l_{char} corresponds to $\delta_h = 1\cdot10^{-3}$ m, (three-zone model of the heat-transfer curve). q_{cr}, W/m^2; l_0, m.

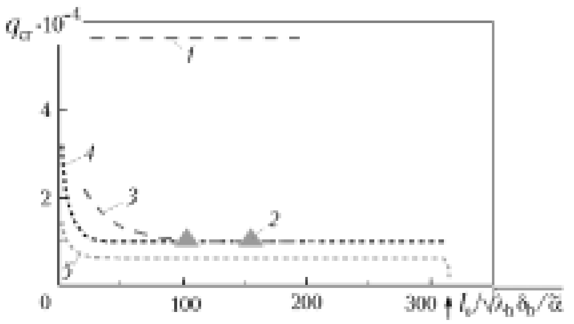


Fig. 7. Critical heat-flux density corresponding to the propagation of the drying front vs. initial dimension of the dry spot for film flow of liquid nitrogen on the foil: 1) calculation corresponding to the hydrodynamic model of the critical heat flux (1); 2) experimental data [2] for a Constantan foil ($\delta_h = 25\cdot10^{-6}$ m and $\mathrm{Re}_{in} = 690$); 3) three-zone model of the heat-transfer-curve, a quasi-two-dimensional problem, $\varepsilon << 1$; 4) two-zone model of the heat-exchange curve, $\varepsilon << 1$; 5) three-zone model of the heat-exchange-curve, a one-dimensional problem, $\varepsilon \geq 1$. q_{cr}, W/m^2.

Figures 6 and 7 give results of numerical modeling of the thermal stability of dry spots on the thin-walled constantan heater cooled by the flowing-down liquid-nitrogen film which is supplied on the saturation line at atmospheric pressure ($L_h = 122\cdot10^{-3}$ m, $\lambda_h = 18$ W/(m·K), $c_h = 245$ J/(kg·K), $\rho_h = 8850$ kg/m^3).

An analysis of the results obtained shows that a sharp reduction in the critical heat-flux density on the heat-releasing surface bounded in length is observed only upon the decrease in the initial dimension of local zones of high-intensity heat transfer to dimensions of the order of l_{char}. In the calculations, this characteristic dimension was $l_{char} \sim 3.5\cdot10^{-3}$ m for the Duralumin heater and $l_{char} \sim 0.4\cdot10^{-3}$ m for the Constantan foil.

As the heater thickness increases, the edge-effect zone in which we observe a "collapse" of the curve of critical heat-flux density increases to a dimension corresponding to l_{char} (Fig. 6). In the approximation of the two-zone model of the heat-transfer curve (curve 1 in Fig. 7), we do not observe this effect, as the front approaches the heater's edge, since a peak of high-intensity heat exchange is located at the boundary in this case.

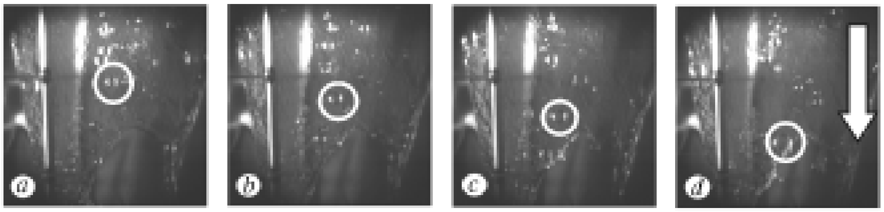


Fig. 8. Time evolution of an unstable local dry spot: a) $\tau = 0$, b) $8 \cdot 10^{-3}$, c) $16 \cdot 10^{-3}$, and d) $28 \cdot 10^{-3}$ sec ($Re_{in} = 690$ and $q_+ = 1.1 \cdot 10^4$ W/m^2); the direction of motion of the dry spot is shown by the arrow.

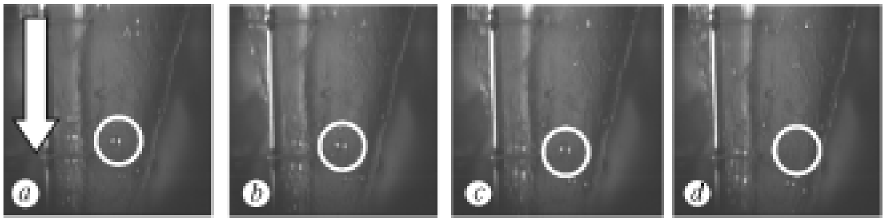


Fig. 9. Fragments of high-speed video filming ($Re_{in} = 690$ and $q_+ = 0.92 \cdot 10^4$ W/m^2) of film liquid-nitrogen flow in the presence of stable large-scale unwetted zones: a) $\tau = 0$; b) $2 \cdot 10^{-3}$, c) $4 \cdot 10^{-3}$, d) $6 \cdot 10^{-3}$ sec; the direction of flow is shown by the arrow.

Figure 7 compares the calculation results and experimental data [2] on the critical heat-flux density. It is clear from the figure that the curve of critical heat-flux density for circular dry spots in the region of small initial dimensions is located much higher than the curve corresponding to q_{cr} of one-dimensional sources with a plane boundary.

The value of the critical heat flux from the model dependence (1) is $\sim 5.6 \cdot 10^4$ W/m^2 for the prescribed parameters, which is much higher than the values obtained in the experiments. A fairly satisfactory coincidence of the results of numerical modeling with the experimental data confirms the hypothesis that the drying crisis is realized in this case by the upstream propagation of a temperature disturbance, when the threshold of thermal stability of dry spots is exceeded.

Figures 8 and 9 give fragments of digital high-speed video filming of flow of a cryogenic-liquid film on the constantan foil for different heat fluxes (according to the data of [2]).

As analysis shows, in the first stage of development of the crisis process, the local dry spots on a plane Constantan foil bounded in length appear in its lower part. It is seen in the photographs (see Fig. 8) that the region of a large-scale dry spot occurring in the wetted zone takes the shape of a "tongue" in the first step. As the heat flux increases, the upper boundary of unwetted zones begins to move upstream in the liquid film. In the lower part of the heating surface, the behavior of the wetting boundary is substantially nonstationary. As the Reynolds number increases, unstable circular dry spots which move downstream occur on single nucleation sites in the wetted zone for high heat fluxes. A tendency of these spots toward increasing monotonously with time from the instant of occurrence to their merging with the zone of a stable dry spot in the lower part of the heat-transfer surface is tracked (Fig. 8).

For lower threshold values of the heat fluxes, local dry spots of a small dimension that occur in the wetted zone can collapse with time (Fig. 9d), which is also confirmed by the results of numerical modeling (curve 3 in Fig. 7).

Conclusions. The thermal stability and evolution of dry slots have been investigated by numerical-modeling methods on heaters bounded and unbounded in length and with different thermophysical properties and geometric parameters. A numerical experiment has been carried out for describing of the critical phenomena in heat exchange in flowing-down wave films of a cryogenic liquid. The reliability of the results obtained has been confirmed by direct comparison with the existing analytical solutions in the limiting regions and to experimental data.

We have investigated the edge effects leading to the behavior of a dry spot localized at the heater's edge being different from the behavior of the spot on the heater unbounded in dimensions. It has been shown that a considerable reduction in the critical heat-flux density and a sharp nonlinear increase in the velocity of propagation of the front, as it approaches the heater's heat-insulated boundary to distances of the order of the dimension of the front, are observed on the bounded heat-releasing surface.

The practical significance of the work is determined by the importance of the results obtained for quantitative determination of the boundaries of optimum and emergency operating conditions for different types of heat exchanges with a high energy intensity. An important outcome of the numerical modeling carried out within the framework of the investigation of crisis phenomena in boiling in flowing-down liquid films is that we have found the dependence of the critical heat flux and the dynamic characteristics of the development of a crisis under given conditions on the thermophysical properties and the thickness of the heat-releasing wall.

Under the conditions of step and periodic pulse laws of heat release on low-inertia heat-releasing surfaces, the distribution of dry spots occurring in the first stage of crisis transition as far as their dimensions and location are concerned is substantially dependent on the wave characteristics of a flowing-down liquid film for the prescribed degree of wetting at entry and the heat-flux density. The dynamic characteristic of local dry spots will play an important role in describing the evolution of temperature profiles on the heat-releasing surface in nonstationary heat release, including those in rewetting regimes. Analogous calculations of the velocity of propagation of the moving boundaries of wetting and the thermal stability of local dry spots are necessary for predicting the character of the development of transient processes and crisis phenomena under the sharply changing thermal load in film liquid flow.

The results obtained are important for revealing the fundamental regularities of the development of transient processes and crises in boiling and evaporation, including those in flowing-down liquid films, and for development of new approaches to the description of crisis phenomena for different laws of heat release.

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NOTATION

c, specific heat at constant pressure, J/(kg·K); g, free-fall acceleration, m/sec^2; L, heater length, m; l_{char}, characteristic linear scale of the temperature gradient, m; l_0 and l, initial and running dimensions of the dry spot, m; q, heat-flux density, W/m^2; $\tilde{q}_{\text{cr}} = q_{\text{cr}}/q_{\text{cr}}^{l_0,R_0\to\infty}$, dimensionless critical heat-flux density; R_0 and R, initial and running radii of the two-dimensional dry spot, m; $\text{Re} = 4\Gamma/\nu$, film Reynolds number; r, latent heat of vaporization, J/kg; T, temperature, K; U, velocity, m/sec; x, coordinate along the heater with the point of reckoning at the center of the dry spot, m; $\tilde{\alpha}$, linearized coefficient of heat transfer in the region of high-intensity heat exchange, W/(m^2·K); Γ, degree of wetting, m^2/sec; $\Delta T = T - T_{\text{sat}}$, temperature head, K; δ, thickness, m; λ, thermal conductivity, W/(m·K); ν, kinematic viscosity, m^2/sec; ρ, density, kg/m^3; σ, surface-tension coefficient, N/m; τ, time, sec. Subscripts and superscripts: $'$, liquid; $''$, vapor; in, inlet conditions; cr, critical; h, heater; sat, saturation; lim, limiting superheating; char, characteristic; 0, initial; ∞, infinite.

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