We are IntechOpen, the world's leading publisher of Open Access books Built by scientists, for scientists

6,900
Open access books available

186,000
International authors and editors

200M
Downloads

154
Countries delivered to

Our authors are among the

TOP 1%
most cited scientists

12.2%
Contributors from top 500 universities

CLARIVATE ANALYTICS

BOOK CITATION INDEX

INDEXED

WEB OF SCIENCE™

Selection of our books indexed in the Book Citation Index in Web of Science™ Core Collection (BKCI)

Interested in publishing with us?
Contact book.department@intechopen.com

5

The Evolution of Temperature Disturbances During Boiling of Cryogenic Liquids on Heat-Releasing Surfaces

Irina Starodubtseva and Aleksandr Pavlenko
*Kutateladze Institute of Thermophysics Siberian Branch of Russian Academy of Sciences,
Russia*

1. Introduction

This publication is devoted to studying the regularities of the dynamics of temperature disturbances on the heat-releasing surfaces during boiling of cryogenic liquids under conditions of free convection and in the flowing-down wave liquid films.

Crisis phenomena and dynamics of transient processes at boiling are the subject of intense experimental and theoretical investigations. Nucleate boiling liquid is one of the most effective ways to remove heat from the heat-releasing surface. Temperature disturbances with different spatial-temporal scales occur on heat-releasing surface during boiling. Perturbations of the fluctuation character are the inner features of boiling. Crises of boiling liquids occur due to the change of boiling regimes with significantly different intensities of heat transfer. The transition from one regime to another occurs over a finite time, which is determined by the velocity of site propagation and the linear scale, which characterizes the average distance between the sites arising under the influence of different kinds of fluctuations. Knowledge of such characteristics as stability and speed of propagation of film boiling regime on heat-releasing surface is important in cryogenic fluids, for example, due to the necessity of cooling of superconducting devices. The emergence of film boiling and their expansion along the heat-transfer surface drastically affects the heat removal, leading to crash - overheating of the heater surface and to its destruction.

Dry spots formed in the pre-crisis mode in falling liquid films are the analogous sites of film boiling. Film flow of liquids (including cryogenic) are widely used in various technological processes for intensification of heat and mass transfer. Evaporation in the thin films of liquid provides high heat transfer rate at low cost and low temperature difference. The topicality of this subject matter is relates, 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. This raises the need for reliable prediction of the critical heat flux, whose excess leads to the complete draining of heat-releasing surface and uncontrolled heating. Study of heat transfer during boiling and evaporation of cryogenic fluids, a number of properties (purity, good wettability, near zero contact angles) differ essentially from properties of high-temperature liquids, is important to deepen understanding of the processes. This is a way to test the existing model descriptions of heat transfer and the development of transient processes and crisis phenomena.

The aim is to study the thermal stability and the evolution of temperature disturbances on the heat-releasing surface with different thermal properties and geometrical parameters at boiling under free convection and falling wave liquid films.

2. Numerical simulation of thermal stability and the evolution of local film boiling sites

A mathematical model suggests the thermal nature of development of critical phenomena. Unfortunately, to date, there is no closed mathematical description of the boiling process, the system of equations for dynamic systems «heat-releasing surface - boiling liquid», such a Navier - Stokes equations system. Therefore, we solve the nonstationary heat conduction equation in a heater and fluid assign the properties remove the heat from the surface according to the law, which can be described by the boiling curve. Boiling curve in this case is taken from the experiments, or we use the well-known theoretical relations for describing heat transfer in different zones of the front boiling regime change. This approach allows us to get quite interesting results satisfactorily describing the known experimental data. Moreover, the approach allows us to predict in some cases, the threshold heat flux above which the critical phenomena develop. Below are the results of studies on thermal stability and evolution of the local film boiling sites.

2.1 Problem statement and a numerical model

Evolution of the local site of film boiling on the heat releasing surface is considered in the first approximation as an extension of the temperature disturbance due to the action of the mechanism of the longitudinal thermal conductivity in a thin heater (Biot number $Bi = q\delta_h /[(\lambda_h(T_h - T_{sat})] < 1$). It is described by the nonstationary equation of heat conduction with the corresponding initial and boundary conditions

$$\frac{\partial T_h}{\partial \tau} = a \cdot L(T_h) + f(T_h), \quad \text{where} \quad f(T_h) = (\delta_h c_h \rho_h)^{-1}\left[q_+ - q_-(T_h)\right], \tag{1}$$

$L = \dfrac{\partial^2}{\partial x^2}$ is single-dimensional differential operator, or $L = \dfrac{\partial^2}{\partial x^2} + \dfrac{\partial^2}{\partial y^2}$ is two-dimensional,

or $L = \dfrac{\partial^2}{\partial r^2} + \dfrac{1}{r} \cdot \dfrac{\partial}{\partial r}$ is single-dimensional operator with axial symmetry.

Here T_h – heaters temperature, τ – time, $\Delta T_h = T_h - T_{sat}$ – temperature head, T_{sat} – saturation temperature, λ_h – coefficient of thermal conductivity, c_h – specific thermal capacity at constant pressure, ρ_h – density of the heater material, δ_h – thickness, $a = \lambda_h/(c_h\rho_h)$ – coefficient of thermal diffusivity, x,y,r – coordinate with the origin point in the center of a film boiling site. Density of the heat release q_+ along the heater is taken constant: $q_+(x) = q_+ = const$. Here $q_- = q_-(\Delta T_h)$ is the density of the heat flux removed to the liquid nitrogen, index h relates to the heater.

Boundary conditions determined by the symmetry in the center sites of film boiling and constant temperature heater at infinity:

$$\left.\frac{\partial T}{\partial x}\right|_{x=0,\infty} = 0, \quad \left.\frac{\partial T}{\partial r}\right|_{r=0,\infty} = 0 \tag{2}$$
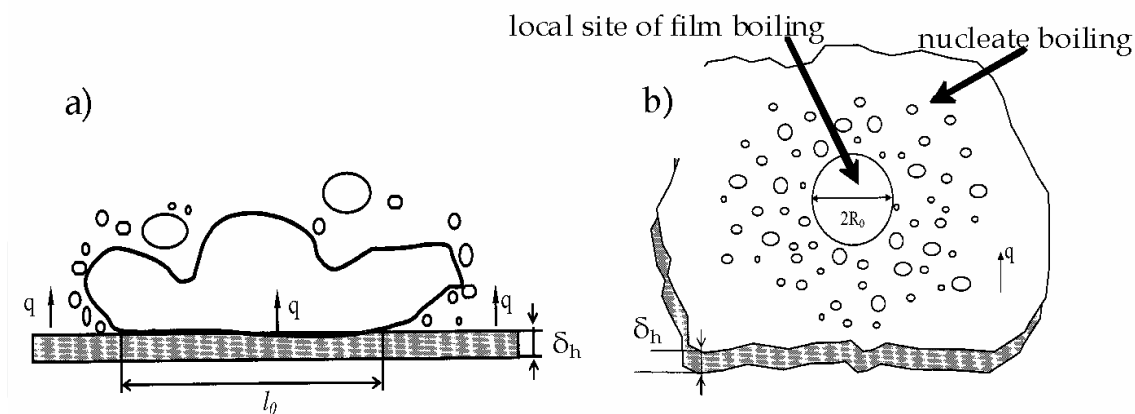
Fig. 1. a) – one-dimensional model, b) – round site on a flat surface

It should be noted that the equation in the case of axially symmetric differential operator has a singularity at r = 0, which should be considered when constructing the difference scheme. 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 $T_0 = T_{lim}$. The maximum temperature is reached in the center of the site.
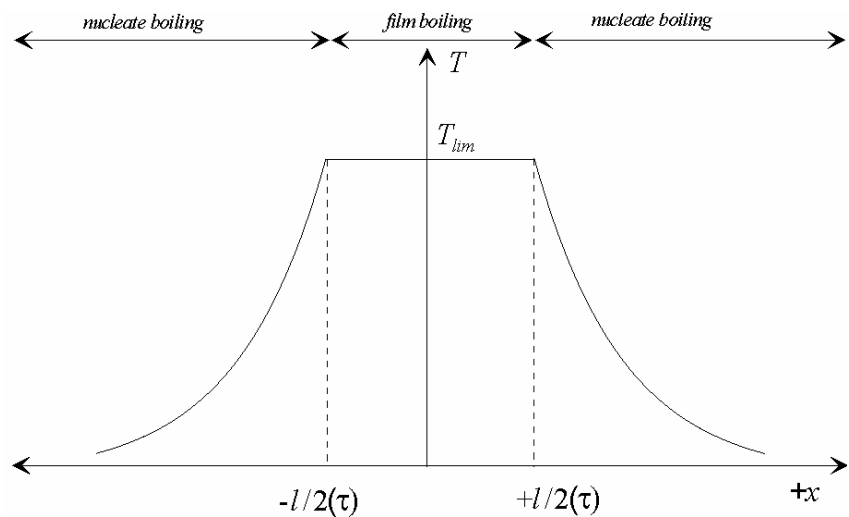

Fig. 2. The initial temperature distribution

For a physically grounded choice of heat transfer conditions at the front of boiling regime change we use the parameter ε, firstly introduced in (Pavlenko A.N. et al., 1998). The dimensionless parameter ε characterizes the ratio of the width of the temperature front along the heater in the zone of high-intensity heat transfer to the typical scale of capillary forces action Λ:

$$\varepsilon = \frac{l_{char.nuc.boil}}{\Lambda} = \sqrt{\frac{\lambda_h \delta_h g(\rho' - \rho'')}{\tilde{\alpha}_{nuc.boil}\sigma}}, \tag{3}$$

Here g is gravity acceleration, ρ' and ρ''- density of the liquid and vapor, σ - surface tension coefficient, Λ is the Laplace constant. According to the analysis, the ratio of the temperature front width in the zone of intensive heat transfer to the linear size of the liquid meniscus at

the boundary of film boiling regime may change in wide range depending on the thermophysical properties of the heater, its thickness and the relative pressure, wich is illustrated in fig. 3. For thin heaters and heaters of low heat conducting material, size of the width of the temperature front l_{char} may be much smaller than the characteristic internal scale of nucleate boiling regime Λ.
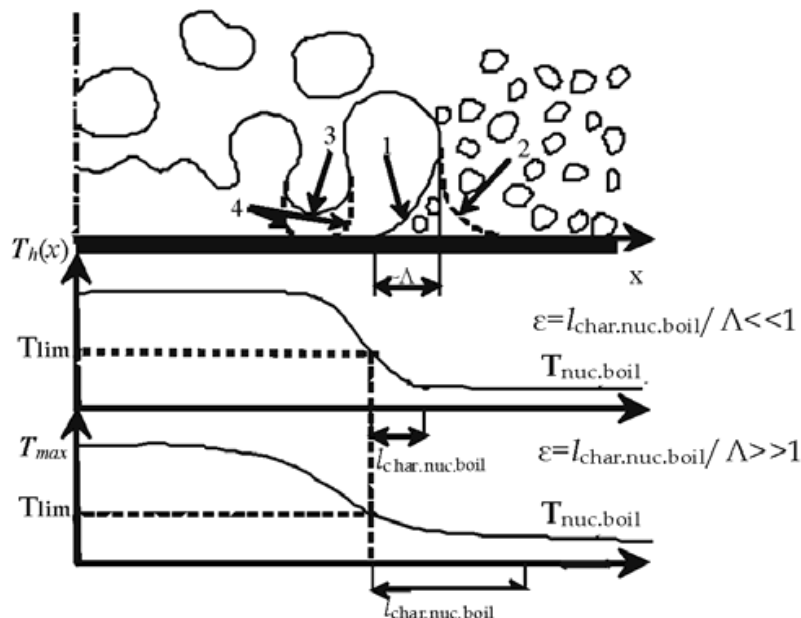

Fig. 3. The model front of boiling regime change. 1 ÷ 4 – typical positions of interphase boundaries in the front

In modeling the dynamic transition from one boiling regime to another, boiling curve obtained in experiments with quasi-steady heat release and averaged over time and heat-transfer surface is typically used. As it was shown in (Pavlenko A.N., 2001), in the case $\varepsilon \ll 1$ (low thermal conductive or thin-wall heaters), the use of quasi-stationary boiling curve with two characteristic points $q_{cr.1}$ and $q_{cr.2}$ for description of dynamic change in boiling regime is not appropriate. In this case, it should be assumed that the condition determining the transition of the film boiling boundary is attainable temperature of liquid overheating T_{lim}, corresponding to homogeneous nucleation, on the heat-releasing surface in the vicinity of the boundaries of film boiling. In the calculations, applicable in this case the two-zone shape of the boiling curve, resulting from the transformation form a quasi-stationary boiling curve by extrapolation of the line corresponding to the nucleate boiling until to a limiting temperature of overheating, fig. 4. Apparently, in the area of the capillary meniscus immediately before the boundary film-mode intense heat transfer occurs during boiling in a thin film of liquid. In this zone, heat-flux density can substantially exceed the critical heat flux $q_{cr.1}$. In general, the structure of two-phase layer in the front of boiling regime change, obviously, is not "frozen" and constant in time. Due to longitudinal and transverse oscillations of the wetting boundary, periodic complete evaporation or microlayer destruction (at drustic boiling up) in its vicinity, the dynamic contact angle is even for the high wetting liquids will change in time in a wide range, including the intermediate regimes with $\varphi \to 0$ and $\varphi > 90°$ (Fig. 3). If $\varepsilon \gg 1$ (high thermal conductive or thick-wall heaters) a quasi-stationary boiling curve with two characteristic points ($q_{cr.1}$, $q_{cr.2}$) is used. The zone of temperature front is localized at the linear distances, which significantly exceed the

characteristic "inner" scale of nucleate boiling of liquid. Under this condition spreading of film boiling is connected with a breaking of the wall thermal balance, when heat flux densities equal to the first critical density $q_{cr.1}$ are achieved in the front zone at certain linear scales due to additional inflow of heat to the wall heater. In this case (high heat-conductive or thick-wall heaters), the use of quasi-stationary boiling curve with two characteristic points ($q_{cr.1}$, $q_{cr.2}$) is more appropriate. In both cases ($\varepsilon \ll 1$, $\varepsilon \geq 1$) the question about influence of pulsating character of the local heat transfer coefficient stays open both in the zone of nucleate boiling in the front, and in the zone of transition boiling regime, as well as the influence of fluctuations of film boiling regime caused by Taylor instability at the interphase. Introduction of the parameter ε allows us to formulate reasonably the conditions on the boundary of boiling regime change at different combinations of geometric parameters and thermophysical properties of the heaters.

Let's consider the influence of the shape of the boiling curve on thermal stability and dynamics of the local one-and two-dimensional axially symmetric sites of film boiling. The intensity of heat transfer is described by boiling curves for liquid nitrogen $q(\Delta T)$, represented in figure 4 for different values of the parameter ε:
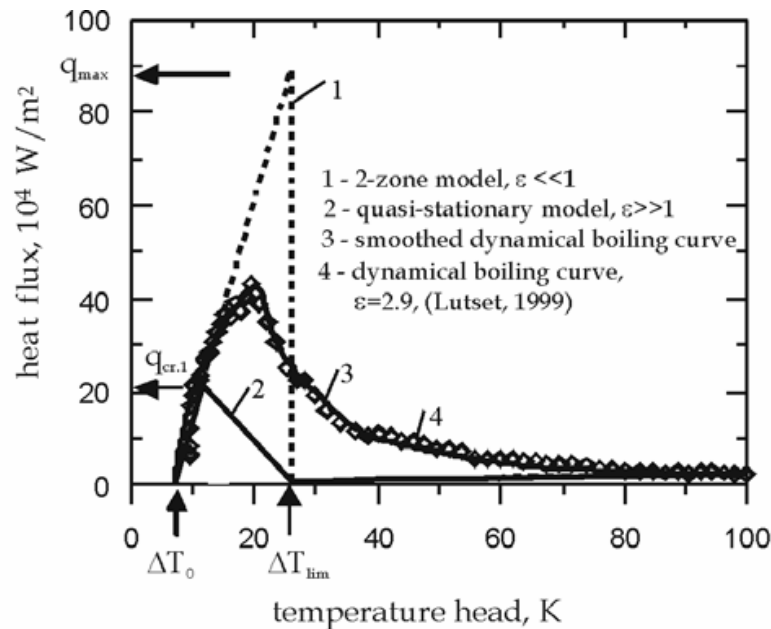

Fig. 4. Model curves for boiling of liquid nitrogen.

Heat transfer of the heater with a cryogenic liquid is calculated in accordance with the following conditions:

at case $\varepsilon \ll 1$ $\tilde{\alpha} = \tilde{\alpha}_{film}$ at $T_h \geq T_{lim}$, $\tilde{\alpha} = \tilde{\alpha}_{nuc.boil}$ at $T_h < T_{lim}$;

at $\varepsilon \gg 1$ $\tilde{\alpha} = \tilde{\alpha}_{film}$ at $T_h \geq T_{lim}$, $\tilde{\alpha} = \tilde{\alpha}_{trans}$ at $T_{cr.1} \leq T_h < T_{lim}$, $\tilde{\alpha} = \tilde{\alpha}_{nuc.boil}$ at $T_h < T_{cr.1}$.

The values of the linearized heat transfer coefficients and critical temperature differences correspond to conditions of liquid nitrogen boiling in a state of saturation and free convection: $\tilde{\alpha}_{film} = 247$, $\tilde{\alpha}_{nuc.boil} = 4.7 \times 10^4$ Wm^{-2}K^{-1}.

Dependence of heat flux q on the temperature difference is calculated as follows:

in the film boiling regime - $q = \tilde{\alpha}_{film}(T_h - T_{sat})$;

in nucleate boiling - $q = \tilde{\alpha}_{nuc.boil}(T_h - T_{sat} - \Delta T_0)$;

in the transitional region - $q = \tilde{\alpha}_{trans.boil}(T_{cr.2} - T_h) + q_{cr.2}$.

At the same time $q_{cr.1}$ = 21.15·10⁴ Wm⁻², ΔT_0 =7.0 K, $T_{cr.1} - T_{sat}$=11.5 K; T_{lim} -T_{sat}=26.0 K, $q_{cr.2}$ = 0.642·10⁴ Wm⁻², q_{lim} = 89.3·10⁴ Wm⁻².

Heat transfer coefficient changes abruptly by more than two orders at the boundary of boiling regime change in the case of two-zone model of the boiling curve. Since the problem is unsteady, nonlinear, with a moving boundary, and also with a discontinuous coefficient it is impossible to obtain a purely analytic solution under these conditions for the propagation velocity of the local site boundaries.

The problem was solved numerically using finite differences and also the method of spline collocation (Zav'yalov et al., 1980; Carl de Boor, 1985). The method of spline collocation is based on spline approximation. This approach allows us to construct algorithms, whose numerical implementation is not more complex then realization of difference schemes. The principal difference between the method of spline collocation and differences method is the fact that the approximate solution is found in the form of the spline S (x,τ), presented in the form of basis expansion of normalized cubic B-splines:

$$S(x,\tau)= \sum_{i=-1}^{N+1} b_i(\tau) \times B_i(x), \tag{4}$$

in the whole domain of problem-solving, while the difference solution is determined only on the grid. This yields much more complete information about the solution. The algorithm of mesh nodes concentration in the front was implemented in the numerical model. At the same time region of concentration "is glued" to the front and moves with it at transition process. In the case of discontinuous coefficients (two-zone model of boiling curve) break point was surrounded by closely spaced nodes.

According to test calculations, these results correspond to solutions obtained under asymptotic regimes. At this, divergence of numerical and analytical solutions did not exceed 0.5÷1%.

2.2 Evolution and thermal stability of 1- dimensional and 2- dimensional film boiling sites

The concept of equilibrium heat flux q_{equi}, applied to the surfaces of large extent was firstly introduced in (Petukhov, Kovalev, 1962) and possibility of simultaneous stable coexistence nucleate and film boiling on the surface of a heater was detected. The first experimental data in water on horizontal rods and tubes were also obtained there for equilibrium heat flux q_{equi}, where the above coexistence is possible. Authors proposed the expression for the value

$$q_{equi} = q_{cr.2} \sqrt{\alpha_{nuc.boil} / \alpha_{film}} ,$$

obtained by using the two-zone model of the boiling curve and allowing calculation of value q_{equi} for semi-infinite regions. Here $\alpha_{nuc.boil}$, α_{film} are heat transfer coefficients in nucleate and film boiling regimes, respectively. Stability analysis of dynamical systems is important from a practical point of view. Character reactions of a dynamic system to a small perturbation of its state can differ.

If arbitrarily small changes in the state of the system begin to grow with time - the system is unstable. If small perturbations decay with time, the system is stable. Changes can accumulate gradually and may occur abruptly in the form of catastrophes. Foundations of a rigorous mathematical theory of stability were laid in the proceedings of Russian

mathematician Lyapunov. Development of the bifurcation theory of dynamical systems is associated with the names Andronov, Arnold and their scholars. Bifurcation point is a state of a dynamical system, when a very small influence leads to global changes. Any dynamical system is associated in our view with evolution in time. The stationary state, when the rate of the process under study is zero, the equilibrium state, can also be viewed as a limiting case of the systems evolution in time.

There is an approach developed in the papers (Kovalev, Usatikov, 1988, 1991; Usatikov, Tivkov, 1997) to the problem of stability in terms of Lyapunov functional, which makes sense of thermal potential temperature fields. The equilibrium state of boiling regime was defined as a bifurcation point that separates the region of metastability and stability regimes. Under some approximations this approach allows us to obtain the expression for the critical size of the perturbation, depending on its amplitude.

In this study we dealt with thermal stability of local film boiling sites by numerical simulation. The solution of equation (1) is presented with the help of the following dimensionless parameters (time, temperature, spatial coordinates):

$$\tilde{\tau} = \frac{\tau}{\tau_{char.film}} = \frac{\tau \cdot \tilde{\alpha}_{film}}{c_h \rho_h \delta_h}, \quad \Theta = \frac{T_h - T_{lim}}{T_{film} - T_{lim}}, \quad \tilde{x} = \frac{x}{2 \cdot \sqrt{\lambda_h \delta_h / \tilde{\alpha}_{film}}}, \quad \tilde{\Delta} = \frac{\Delta}{\sqrt{\lambda_h \delta_h / \tilde{\alpha}_i}}. \quad (5)$$

Fig. 5a, 5b shows the simulation results that illustrate the evolution of temperature profiles in time. For small values of heat fluxes q < q_{equi}, a short-term increase in temperature occurs firstly in the film boiling site with a decreasing length, film boiling regime becomes unstable. Temperature disturbance quickly dissipated and the temperature drops to a temperature of nucleate boiling, (Fig. 5a). Film boiling site disappears.

In the region q > q_{equi} temperature of heat-transfer surface increases monotonically to a value determined by the stationary film boiling, (Fig. 5b). At large times the boundary of the site in the steady state moves with constant velocity.
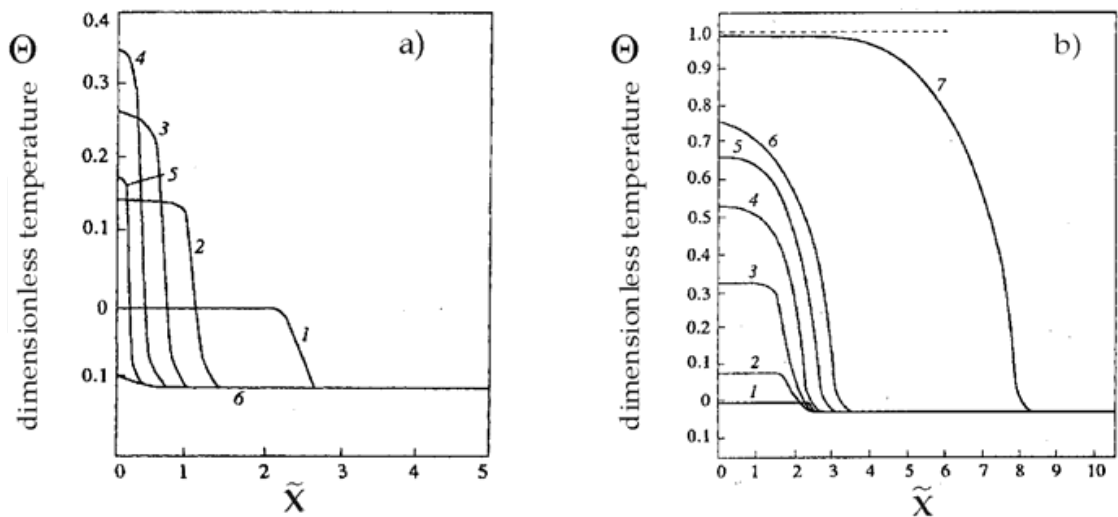

Fig. 5. Evolution of the temperature disturbance, corresponding to one-dimensional (1D) site of film boiling. l_0 /2 = 10 mm. a) the collapse of film boiling zone. q = 5·10⁴ W m⁻², 1 ÷ 6 - $\tilde{\tau}$ =0; 0.17; 0.33; 0.58; 0.83; 0.91. b) expanding the zone of film boiling, q = 15·10⁴ Wm⁻². 1 ÷7 - $\tilde{\tau}$ = 0, 0.08, 0.41, 0.83, 1.25, 1.66, 7.47. Stroke - the temperature of the isothermal surface at steady-state film boiling

Fig. 6 shows the evolution of temperature profiles for the local two-dimensional (2D) site of film boiling.
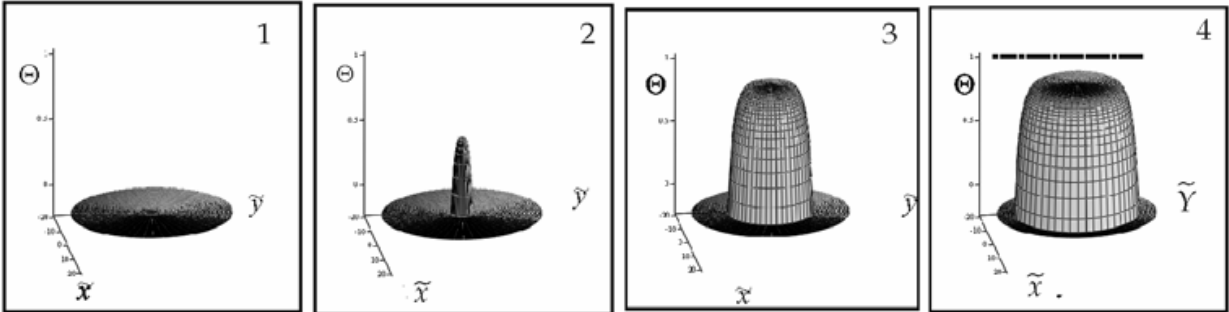

Fig. 6. Expansion of film boiling zone. $\tilde{\tau}$: 1 – 0; 2 - 0.83; 3 - 8.3; 4 - 12.4. q = 15 · 10^4 Wm^{-2}. Stroke - the temperature of the isothermal heat-releasing surface during steady-state film boiling.

Thermal stability of the local sites of film boiling was studied by the method of numerical simulation. Fig. 7 shows curves obtained numerically for the equilibrium heat flux in the case of 1 - dimensional (1D) and 2 - dimensional axially symmetric (2D) local sites of film boiling. Simulation was carried out in the approximation of 2-zone at $T_{bound}=T_{lim}$ ($\varepsilon < 1$) and 3-zone (quasi-stationary) forms of boiling curves. It is obvious that equilibrium curve 2 for 2D sites of film boiling is above coresponding curve 1 for 1D sites in the area of low values of their initial size $\tilde{l}_0/2, \tilde{R}_0 \le 4$. At high value of $\tilde{l}_0/2, \tilde{R}_0$ the equilibrium curves 1 and 2 coincide and correspond to analytical solution for semi-infinite zones.
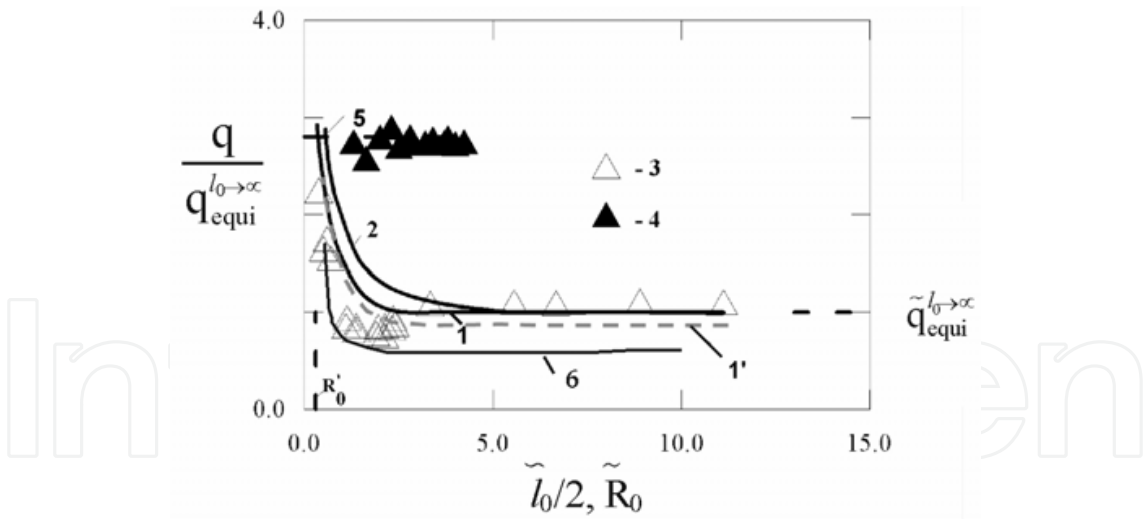

Fig. 7. Dependency of equilibrium heat flux density on the initial local site size (liquid nitrogen at the saturation line, p/p_{cr}=0.0297, $\delta_h=D_h/4$=0.125 mm, heater material – stainless steel, ε=0.153). 1, 2 – dimensionless equilibrium densities of the heat flux for a 1D and 2D local sites of film boiling; 1' – pulsation model (β=1; $\tilde{\omega}_{nuc.boil} = 0.63$); 3,4 – experimental data (Pavlenko & Starodubtseva, 1998) for q_{equi}, $q_{cr.1}$; 5 - experimental data for dimensionless critical density of the heat flux (Pavlenko, 1985); 6 - calculation with three-zone form of the boiling curve (2D geometry). Here $R_0'=\Lambda$ (Laplace constant).
$\tilde{q}_{equi}^{l_0 \to \infty}$ - calculation of the heat flux density for semi-infinite zone of film boiling at U=0.

Simulation results demonstrate a significant impact of the shape of the boiling curve on the value of equilibrium heat flux q_{equi}. The use of the quasi-stationary boiling curve in calculations decreases q_{equi} almost twice. Significant dependence of moving boundary velocity and lifetime of the sites on the shape of the boiling curve was determined. The velocity of motion boundary and site lifetime with heat transfer, described by two-zone shape of the boiling curve is considerably less than that in the case of quasi-stationary boiling curve. The same calculations show that when heat flux q, is close to equilibrium, evolution of the sites is fundamentally different for two shapes of the boiling curves (size increasing with time, or collapse). Thus, in calculation of parameters defining stability and dynamics of thermal perturbation, real ratio $\varepsilon = l_{char}/\Lambda$ should be taken into account.

According to test calculations, these results correspond to solutions obtained under asymptotic regimes. Thus, the simulated propagation velocity of the boundary between boiling regimes at critical heat flux perfectly coincides with the analyitical solution to the limit propagation velocity of the film boiling front shown in (Lutset, 1998),

$$U = 4\sqrt{\lambda_h \tilde{\alpha}_{film}/d}\sqrt{(T_2 - T_{cr.2})/(T_{cr.2} - T_{cr.1})}/(c_h \rho_h),$$

(6)

where $T_2 = T_{cr.2} + (q_{cr.1} - q_{cr.2})/\tilde{\alpha}_{film}$,

and asymptotic behavior of propagation velocity of the film site boundary during long time under the stabilized regime corresponds satisfactory to the analytical solution of (Zhukov S.A. et al., 1980) for semi-infinite zones:

$$U = \frac{\sqrt{2}}{\sqrt{\lambda_h \delta_h}} \frac{\lambda_h}{c_h \rho_h} \frac{\tilde{\alpha}_{film}(1 - \theta^2) - \tilde{\alpha}_{nuc.boil}\theta^2}{\sqrt{\tilde{\alpha}_{film}\theta(1 - \theta)^2 + \tilde{\alpha}_{nuc.boil}\theta^2(1 - \theta)}},$$

(7)

where $\theta = (T_{bound} - T_{nuc.boil})/(T_{film} - T_{nuc.boil})$ at $T_{bound} = T_{lim}$.

At that, divergence of numerical and analytical solutions did not exceed 0.5 - 1%.

2.3 The influence of unsteady pulsations of the local heat flux in the front on the dynamic characteristics

In the process of boiling on the heat surface temperature disturbances are associated with the periodic growth and detachment of vapor bubbles and their possible merger, the dynamics of evaporation of microlayer under steam conglomerates, etc. In the areas of film and transition boiling heat transfer due to transient nature of periodic oscillations of the interphase in the presence of her different types of waves of varying intensity.

The influence of non-stationary pulsations of the local heat flux near the boiling regime change on dynamic characteristics of the front development was investigated in the framework of the numerical model. The harmonic outflow of heat into the fluid, which acts in a small vicinity of the front was integrated into the model. Development of local film boiling sites is described by unsteady heat conduction equation (1) in the heater with the appropriate boundary and initial conditions. In first approximation we assume (without detail consideration of physical aspects of nonstationary character of heat transfer process) that the heat flux removed into liquid in some zone of nucleate or transitional boiling in the front is the periodic function of time only:

$$q = q^{ave}_{nuc,trans.boil}(1 + F(\Delta)\sin(2\pi\omega_i\tau)), \tag{8}$$

where $q^{ave}_{nuc,trans.boil}$ - the time averaged heat flux densities at given temperature difference in the zones of nucleate or transitional boiling. $F(\Delta)$ - characterizes the relative pulsation amplitude, it equals a constant β in a vicinity of the front with a length of Δ and equals zero beyond this vicinity.

The most interesting results of the numerical simulation of the temperature disturbances evolution and corresponding them film boiling sites demonstrate that at heat flux pulsations in the front, the zone spreading is non-monotonous with pulsation in time. At the stage of site expansion during certain time intervals, the current size becomes higher than the values corresponding to the stationary case. At that the higher the linear size of the zone with heat flux pulsation in the region of nucleate boiling, the higher the propagation velocity of front boundary.

Some simulation results, taking into account nonstationary character of heat flux in the front in area of transitional boiling are shown in Fig. 8. The behavior of the front boundary at different densities of heat flux at helium boiling is shown there.
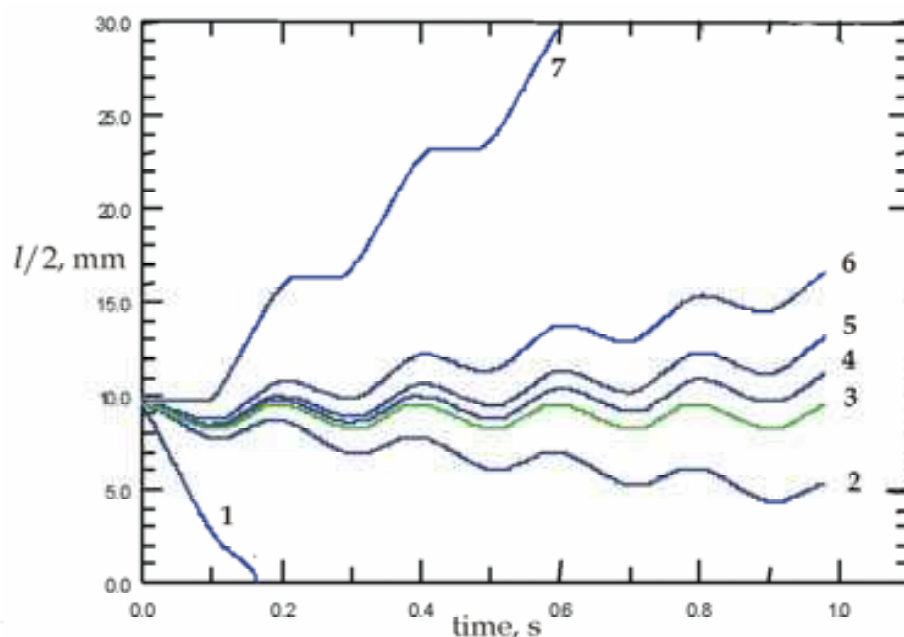

Fig. 8. Dynamics of behavior of the boundary of boiling regime change at different densities of the heat flux q. Helium at the line of saturation. The heater - stainless steel. The three-zone model of the boiling curve with extremes in points $T_{bound.1}=T_{lim}$ и $T_{bound.2}=T_{cr.2}$. $\delta_h=0.125$ mm ($\varepsilon=0.088$), $p/p_{cr}=0.23$, $\Delta=1$mm. 1÷7 - q=(0.55, 0.555, 0.556, 0.557, 0.56, 0.6)·10⁴ W/m², correspondingly

Heat flux pulsations in a small vicinity of the front in the zone of nucleate boiling into the numerical model was integrated ($\beta=1$, $\tilde{\omega}_{nuc.boil} = 0.068\cdot10^{-3}$). In the case of q=q$_{equi}$, the boundary between boiling regimes can oscillate near some fixed position on the heat-releasing surface. In this case, spatial amplitude of the front boundary increases with a decrease in pulsation frequency. Such regimes with significant oscillation amplitude near the equilibrium position were observed (Pavlenko, 1985) in experiments with boiling helium.

The degree of influence of pulsating heat transfer in different zones of the front on the boundary velocity depends significantly on the value of q/q_{equi}, characterizing heat flux deviation from the equilibrium position. At this pulsations of heat transfer coefficient in the zone of nucleate boiling in case of two-zone boiling curve ($T_{bound} = T_{lim}$ with $\varepsilon << 1$) for similar values of β have significantly stronger influence on dynamics of the process than pulsations in the transitional zone in case of quasi-stationary curve boiling because local pulsations of heat flux with very high amplitude (near $T \sim T_{lim}$) appear near the boundary of film boiling in comparison with the case of three-zone boiling curve.

A considerable increase in the average rate is also observed in the range of low pulsation frequencies, fig. 9. According to estimates made by calculation dependency from (Verkin et al., 1987), typical frequencies of heat flux pulsation in the zone of transitional boiling related to hydrodynamic instability of vapor film at $T < T_{cr.2}$ for liquid nitrogen at atmospheric pressure make up $\omega_{0, \text{trans.boil}} \sim 7s^{-1}, (\tilde{\omega}_{\text{trans.boil}} \sim 0.15)$. At the mentioned regime parameters, the effect of pulsation heat transfer in the transitional zone on the average rate of boundary propagation can reach 10 - 20% for the given heat-releasing sample.
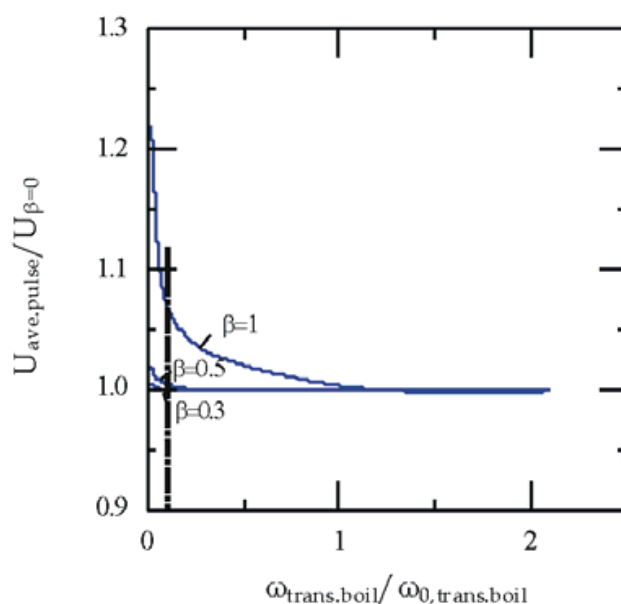

Fig. 9. Average propagation rate of the boundary between boiling regimes within the stabilized region ($\tilde{\tau} \gg 1$) depending on pulsation parameters (frequence and amplitude). The three-zone model of the boiling curve with extremes in points $T_{cr.1}$ and $T_{cr.2}$. δ_h=0.125·10⁻³ м. Dotted line - $\omega/\omega_{0, \text{trans.boil}} = 0.15$; $\omega_{0,\text{trans.boil}} = \tilde{\alpha}_{\text{trans.boil}}/(c_h\rho_h\delta_h)$=47.6 s⁻¹ . The heater - stainless steel.

According to the results of numerical simulation, the boundary of thermal stability of sites is also sensitive to oscillations of heat transfer intensity in different zones of the front. Consideration of pulsating heat transfer in the area of nucleate boiling in a vicinity of boiling regime change in the numerical model leads (curve 1 in Fig. 7) to an insignificant decrease in the threshold of thermal stability.

In Fig. 10a,b, experimental data from (Pavlenko et al., 1994) on the averaged rate of film boiling propagation under the stable regimes in nitrogen and helium are compared with calculation results obtained for conditions satisfying $\varepsilon << 1$. Calculated curves obtained with consideration of heat flux pulsation in the zone of front somewhat better describe

experimental data for cryogenic liquids on thin-wall heaters than pulsation-free boiling curve.

Reliability of theoretical modeling of thermal stability and development dynamics of the film boiling sites on thin-wall heaters under conditions formulated above is proved here by direct comparison with experimental results obtained under the identical conditions.

The question about boundary temperature T_{bound} corresponding to the value of maximal averaged density of heat flux removed to liquid at intermediate values of ε on the front of regime change remains unsolved.
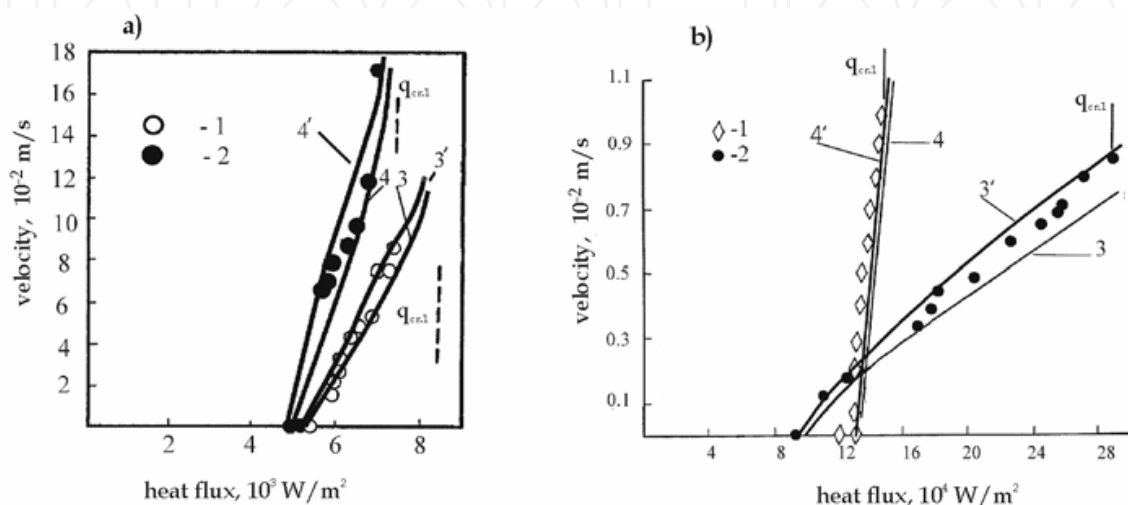

Fig. 10. Propagation velocity of the boundary between film and nucleate boiling under the asymptotic regime ($\tilde{\tau} \gg 1$) in comparison with calculations ($\varepsilon \ll 1$).

a) helium. $D_h=3 \cdot 10^{-4}$ m. Nichrome. 1,2 - p_{sat}=0.052, 0.101 MPa, correspondingly; 3,3',4,4' - calculation of U for the three-zone boiling curve with extremes in points T_{lim} and $T_{cr.2}$ for 1,2, correspondingly; 3,4 - pulsation-free model; 3',4' - pulsation in the zone of transitional boiling (β=1; $\tilde{\omega}_{nuc.boil} = 10^{-3}$); b) nitrogen. P_{sat}=0.101 MPa; wires: 1 - $D_h=5 \cdot 10^{-5}$ m, constantan; 2 - $3 \cdot 10^{-4}$ m, nichrome; 3,3',4,4' - calculation of velocity U for the two-zone boiling curve with $T_{bound}=T_{lim}=T_{cr.2}$ for 1,2, correspondingly; 3,4 - pulsation-free model; 3',4' - pulsation at the front (β=1; $\tilde{\omega}_{nuc.boil} = 0.05$)

3. Features of temperature disturbances evolution on the heat-releasing surface at the film flow of liquids

As well as at pool boiling, the crisis phenomena develop in the liquid film falling down over the heat-releasing surface, when the certain heat fluxes are achieved because of some reasons (breaking of the heated film under the action of capillary forces, local thinning and breaking of the liquid film at evaporation, liquid repulsion from irrigated heated surface by a vapor layer at boiling crisis in the film, etc.) (Gimbutis, 1988; Katto, 1994). Temperature field is deformed by disturbances, simultaneously or discontinuously corresponding to large-scale "dry" spots, existing and extending on the surface (which are the analogues of film boiling sites).

When the liquid films are flowing down over heat-releasing surfaces, a number of problems related to stability of the film flow arise. At boiling and intensive evaporation, the picture of film destruction due to the formation of local dry spots and their merging becomes

extremely complicated. Physics of crisis phenomena in boiling flowing-down films does not fully clear at present, and this makes it difficult to construct theoretical models and computational procedures enabling to predict the conditions of development of drying crisis and finally evaluate reliability of equipment operation intended for various purposes. Such detailed analysis is complicated by the limited amount of experimental data in a film flow of liquid on the heated surface in different hydrodynamic flows. The widespread use of cryogenic fluids in modern high performance systems and devices creates the need for reliable information on development of transition and crisis during boiling and evaporation of fuel in low-temperature liquids on different surfaces.

In this connection, the line of these investigations is topical both from the scientific and practical viewpoints.

3.1 Edge effects. Features of temperature disturbances evolution on the surfaces with limited extension

To describe the critical phenomena with intense heat transfer in falling wave films of cryogenic liquid on the limited-length heat-releasing surface, it is necessary to reveal the features of dynamics of temperature disturbances caused by the edge effects. Let's investigate the features of the disturbances behavior, when the front approaches the edge of the heater. The boundary conditions: $\partial T_h/\partial x = 0$ for x=0 and x=L_h for a heater of finite length L_h correspond to the heater's heat-insulated ends. For an infinite heater, we have $\partial T_h/\partial x = 0$ for $x = 0$ (symmetry condition) and $T_h = T_\infty = q/\tilde{\alpha} + T_{sat}$ for x=$\pm\infty$. Numerical simulation results showed that the behavior of dry spots (temperature disturbances), localized at the edge of the heater, differ from the behavior of spots on the heater of infinite extent. The boundary of the dry spots can be moved on the surface of the heater until dry spot finally fills the entire surface of the heater. With front approach to the edge its dynamic characteristics and thermal stability have a features compared with the behavior of the front moving over the unlimited surface. As it was shown by analysis of the numerical results, the geometric parameter that determines whether one disturbance interacts with another and whether the heater boundary effects the velocity of the front, is characteristic thermal size

$$l_{char} \simeq \sqrt{\lambda_h \delta_h / \tilde{\alpha}_{nuc.boil}} \quad .$$

The physical meaning of this characteristic scale is the width of the temperature disturbance front in zone with high intensity of heat transfer. If one spot is located at a distance greater than l_{char}, it evolves as a single one. If dry spot is farther from the edge of the heater than l_{char}, in this case its behavior is identical to the behavior on the the surface of an infinite extent. The behavior of disturbance, located from the other at a distance less than l_{char}, differs from the behavior of a single disturbance, and behavior of the front closer to the borderline heaters at a distance less l_{char}, differs from the behavior of the front moving over the heater of infinite extent.

The results of numerical simulation presented in Fig. 11a, 11b, demonstrate the influence of boundary conditions on the evolution of dry spots in time. The values of the velocity of the boundary of the local dry spot on 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}. The boundary of the spot on the infinite heater continues moving 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. 11a).

Figure 11b 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-releasing surface: λ_h = 50 Wm^{-1}K^{-1}, c_h = 300 J kg^{-1}K^{-1}, ρ_h = 3000 kg m^{-3}, and δ_h = 4·10^{-3} m.

Fig. 11. Edge effects. a) Dimension of a local dry spot vs. time: 1 and 2 - semiinfinite heaters; 3 and 4 - heater of finite length; 1 and 3 - λ = 50; 2 and 4 - λ= 420 Wm^{-1}K^{-1}. b) Critical heat-flux density vs. initial dimension of the dry spot: 1) semiinfinite heater; 2) heater of finite length (the arrow on the abscissa axis points to the edge of the finite length heater).

The size of the edge effects area, where critical heat flux density decreases drastically, depends on the thickness of the heater and is described by a relation:

$$l_{edg} \simeq l_{char} \simeq \sqrt{\lambda_h \delta_h / \tilde{\alpha}_{nuc.boil}} \,.$$

It is possible to make conclusions that the boundary effects lead to the fact that the behavior of dry spots, localized at the edge of the heater differ from the behavior of spots on an unlimited size heater. On a limited surface of the fuel there is a significant reduction in critical heat flux density and a sharp nonlinear increase in the velocity of the front when it approach to the boundary of the insulated heater at a distance of about ~ l_{char}.

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} ~ 3.5·10^{-3} m for the Duralumin heater and l_{char} ~ 0.4·10^{-3} m for the Constantan foil.

3.2 Drying crisis phenomena as upstream propagation of temperature disturbance

Upon onset of some certain conditions, crisis phenomena emerge on the irrigated heat-releasing surface. Dry spots (unirrigated areas) are formed on the heated surface, and lose stability at the critical heat flux (CHF) leading to total dry out, sudden temperature rise, device operation failure and even burning out.

High-speed visualization of the boiling process (Matsekh & Pavlenko, 2005; Pavlenko et al., 2006) has shown that, in the lower part of the heater, non-stationary (and then stable) dry spots occur with increase in the heat flux in the first stage; these spots subsequently merge, and once the CHF has been attained, a transient process with the displacement of the nucleate-boiling zone on the entire heat-transfer surface develops. High-speed (4800 PPS) visualization is accomplished using Phantom v7.0 camera. Detailed description of the experimental apparatus can be found in (Matsekh & Pavlenko, 2005).

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 heat flux can be much lower than that calculated from the well-known hydrodynamic model (Mudawar et al., 1987)

$$q_{cr}/\rho''rU = 0.121 \left(\rho'/\rho''\right)^{2/3}\left(\sigma/\rho'U^2L\right)^{0.42}. \tag{9}$$

Fig. 12 shows the results of generalization of the array of experimental data on critical heat flux density in dimensionless coordinates for Katto-Mudawar hydrodynamic model of heat-transfer crisis.
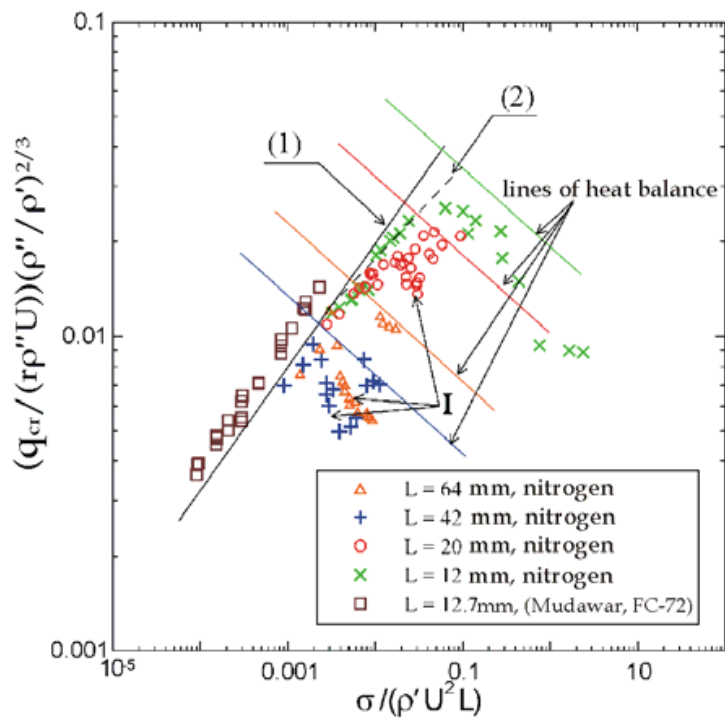

Fig. 12. 1 - calculation on hydrodynamic model, 2 - generalizing dependence for L = 12 mm; I - drying crisis on reaching the threshold of thermal stability of dry spots.

The graph shows experimental points for the heaters length of 12, 12.7, 20, 42 and 64 mm. The solid black line is calculation by Mudawar hydrodynamic model, dashed line is empirical relation that describes the data on heaters 12 mm long, obtained earlier in (Pavlenko & Lel, 1997). The graph shows that the deviation of experimental points from the calculated curves is the sooner, the longer the heater and a higher the liquid flow rate are. At the lowest values of estimated parameters We^{-1}, the experimental points for all heaters employed in the work are in good agreement with the calculation on model dependence.

With increasing this parameter, the deviation is observed for all lengths of the heaters used in this work (Pavlenko et al., 2006).

Thus, there is an area where surface drying is determined not by the hydrodynamic crisis. The basic idea of the hydrodynamic model is the fact that under the pre-crisis conditions the liquid-gas interface becomes unstable and the flow separates. The bulk of the liquid is separated from heating surface by generated vapor, and a crisis is reached when for remaining on the heating surface microlayer holds the heat balance (the total evaporation). Such model describes well the experimental data at low values of estimated parameters We^{-1} (high velocities of liquids). At higher values of We^{-1} experimental data have the value, which is 2 or more times lower than that predicted by the model formula (Mudawar et al., 1987), which obviously can not be used for the description of CHF in these ranges of determining parameter. The authors of (Pavlenko et al., 2006) proposed the hypothesis about new types of dry out crisis, whose nature is caused by the loss of thermal stability of dry spots in the lower part of the flow, and associated upstream propagation of critical temperature disturbance. It is reasonable to verify this experimental hypothesis by direct numerical simulation.

The intensity of heat transfer is described by the curves shown in Fig. 13a and 13b, which use the experimental data (Pavlenko et al., 2006, Grigor'ev et al., 1977) for thick-wall heater made of duralumin and the thin wall constantan heater.
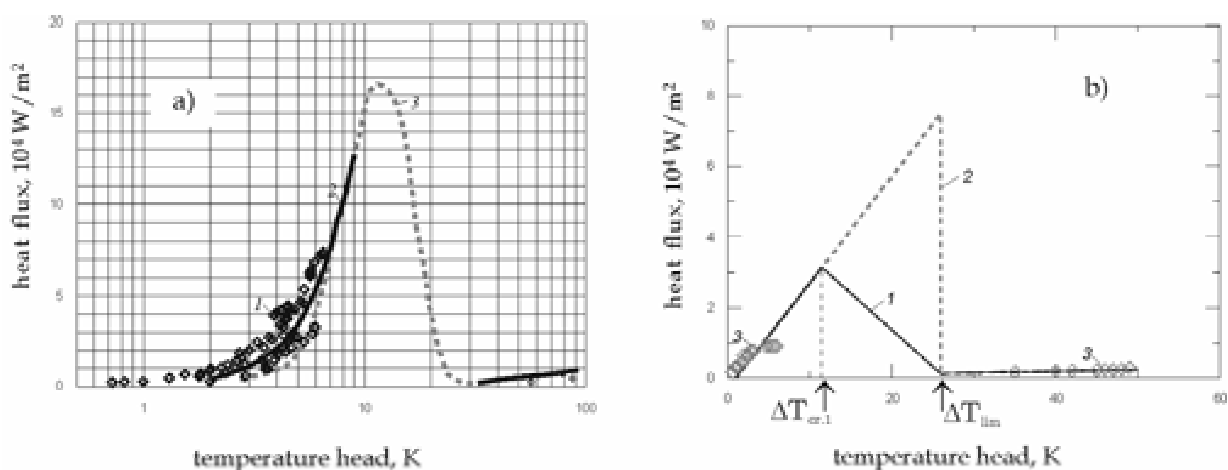

Fig. 13. a) Curve of heat transfer in film nitrogen flow on a bounded heat-transfer surface from duralumin: 1) experimental data (Matsekh & Pavlenko, 2005) for the heater of length 64 mm ($Re_{in} = 285$); 2) interpolation curve with the use of the data (Matsekh & Pavlenko, 2005); 3) data of (Grigor'ev et al., 1977). b) model curves of heat transfer under film flow of liquid nitrogen on a constantan foil ($Re_{in} = 690$) : 1) three-zone model, $\varepsilon \geq 1$; 2) two-zone model, $\varepsilon \ll 1$; 3) experimental data (Pavlenko et al., 2006).

As a results of a simulation of evolution of local temperature disturbances corresponding dry spot in falling films of liquid nitrogen, we obtain the CHF, whose excess leads to upstream propagation of disturbances and total drying of the surface.

Fig. 14 shows the comparison of calculation results with experimental data on critical heat flux density for the thin-wall heater. Value of the critical heat flux by model dependence (Mudawar et al., 1987) was for the given parameters is $\sim 5.6 \cdot 10^4$ Wm^{-2}, what is significantly higher than those obtained in the experiments.
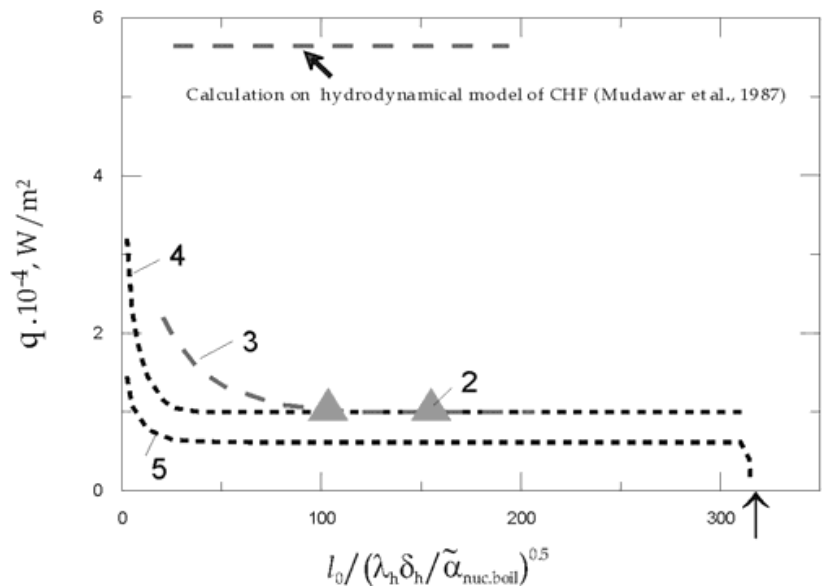
Fig. 14. Critical heat-flux density corresponding to the propagation of the drying front vs. initial dimension of the dry spot for film flow of liquid nitrogen on the foil: 2 - experimental data (Pavlenko et al., 2006) for a Constantan foil, ($\delta_h = 25 \cdot 10^{-6}$ m and $Re_{in} = 690$); 3 - three-zone model of the heat-transfer-curve, a quasi-two-dimensional problem, $\varepsilon \ll 1$; 4 - two-zone model of the heat-exchange curve, $\varepsilon \ll 1$; 5 - three-zone model of the heat-exchange curve, a one-dimensional problem, $\varepsilon \geq 1$.

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.

3.3 Features of rewetting dynamics of the overheated surface by the falling cryogenic liquid film

In (Surtaev & Pavlenko, 2009) it is shown in the result of the cycle of experimental studies of crisis phenomena in falling films (liquid nitrogen) that at periodically varying heat load parameters of occurring metastable regular structures, critical parameters of drying of heat-emitting surface, the reverse transition to a highly efficient regime of heat removal are determined by the dynamics of moving boundaries in the process of self-organizing system. After resetting of heat load the transition process, when the surface starts cooling again by a falling film of liquid nitrogen, is developing under the critical conditions. This phenomenon is usually called the rewetting process (repeated wetting). In the nuclear industry in the study of emergency modes in the active zones this phenomenon was termed re-Bay and studied for many years (Yamanouchi et al., 1968; Gabaraev et al., 2001). Similar problems (re-refrigeration) arise when developing the protection system of magnets in the transition from the superconducting to normal state (Unal & Nelson, 1992; Brahim Bourouga & Jerome Gilles, 2010). At operation of charged particle accelerators there are possible situations when certain superconducting magnets, or group of magnets pass to the normal state (quench process). The task of cryogenic system here is to ensure the absence of destruction of the magnet cryostat during quench, and the problems re-refrigeration arise.

Video fragment of the process of repeated wetting of the overheated surface (constantan foil, δ_h =25·10⁻⁶ m) after impulse heat release (pulse duration $\Delta\tau$ = 0.2 s, heat flux density q_+ = 21.23·10⁴ Wm⁻² are shown in Fig. 15. Visualization revealed the features of this process.
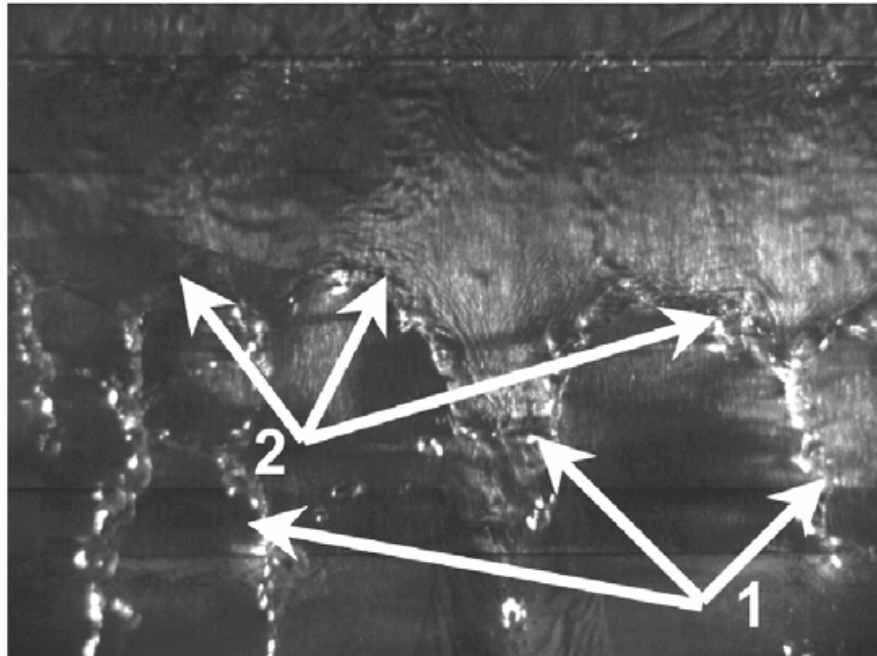

Fig. 15. The high-speed video fragment of overheated surface rewetting after the impulse heat release. q=21.23·10⁴ W/m², Re=1690, τ=2.5 s.

The complicated 2D character of the wetting boundary was discovered, it should be taken into account in the detailed simulation of front dynamics. It was found that the wetting front is not flat in transverse direction. Regular liquid jets with intense boiling in their lower part (areas 1, see Fig. 15) are being formed at the inlet of the heat-releasing surface. Liquid rolls are formed between the jets at the boundary of the dry surface (areas 2, see Fig. 15), where heat transfer is determined predominantly by evaporation.

According to the treatment of experimental data, at repeated wetting of the overheated surface by the falling liquid film, the local velocities of different zones of the 2D wetting front differ significantly. The local velocities of the wetting front in the jet area are significantly higher than those between the jets of falling liquid (Fig. 16). Therefore, a dynamical jet streams are formed during the transition process, and the total time of rewetting is determined by the velocity movement of film flow boundaries between the jets.

In the known works devoted to experimental and theoretical studies of repeated wetting of the overheated horizontal surface by a single jet (Hammad et al., 2003), flooding of the vertical channels from the bottom (Gabaraev et al., 2001), the heat transfer coefficient in the wetted zone at development of calculation models does not change and the wetting front is assumed to be flat with the same velocity of transverse motion.

The estimated ratio for velocity of wetting front displacement in one-dimensional formulation, obtained in (Yamanouchi, 1968), is known :

$$V^{-1} = \frac{\rho_h c_h}{2} \sqrt{\frac{\delta_h}{\tilde{\alpha}\lambda_h}} \left(\left[\frac{2(T_0 - \tilde{T})}{\tilde{T} - T_{sat}} + 1 \right]^2 - 1 \right)^{0.5}, \tag{10}$$

where: $\tilde{T}$ is temperature at the boundary of the wetting front; T_0 is initial temperature of the the overheated wall. In this model, the heat transfer coefficient in the wetted area is assumed to be some constant value, and in the drained field it equals zero.

We have implemented a numerical simulation of the observed transient phenomena that takes into account essential two-dimensional character of the front and spatial nonuniformity of heat transfer coefficients in a wetted area discovered in the experiments. The purpose of the simulation is the desire to explain and describe quantitatively the complicated two-dimensional shape of the rewetting front realized under the considered transient conditions.

Spatial and temporal changes in the temperature fields for the thin heater (Bi < 1) are described by the nonstationary equation of heat conduction with corresponding initial and boundary conditions:

$$\frac{\partial T_h}{\partial \tau} = \frac{\lambda_h}{c_h \rho_h}\left(\frac{\partial^2 T_h}{\partial x^2} + \frac{\partial^2 T_h}{\partial y^2}\right) + \frac{1}{\delta_h c_h \rho_h}(q_+ - q_-(T_h)) \,. \tag{11}$$

In this paper simulation was carried out in two-dimensional calculation domain. Here, x, y are transverse and longitudinal coordinates of the heater $(x,y) \in G$, where $G = \left\{0 \le x \le L_x, \ 0 \le y \le L_y\right\}$ is rectangle with sides L_x, L_y. Ordinate axis is directed along the vertical wall, where falling occurs, upstream of the film. $q_- = q_-(T_h)$ is density of heat-flux removed into the liquid. Density of heat release is taken constant $q_+ = q_+(x, y) = \text{const}$.

Equation (11) supplemented with initial and boundary conditions allows us to simulate evolution of temperature fields in time in the two-dimensional computational domain and receive as a result the dynamic pattern of the moving front.

The initial temperature of field $T_0(x, y)$, shown in Fig. 16, corresponds to experimental data obtained for the end of pulse of heat release from the data of (Surtaev & Pavlenko, 2009). Initial temperature drained by impulse of heat release surface at the time of development process of rewetting was $T_0 = 693$ K. At the top of the heater in a wetted area temperature is $T_0 = T_{sat}$, simultaneously in a calculations the temperature jump was smoothed exponentially.
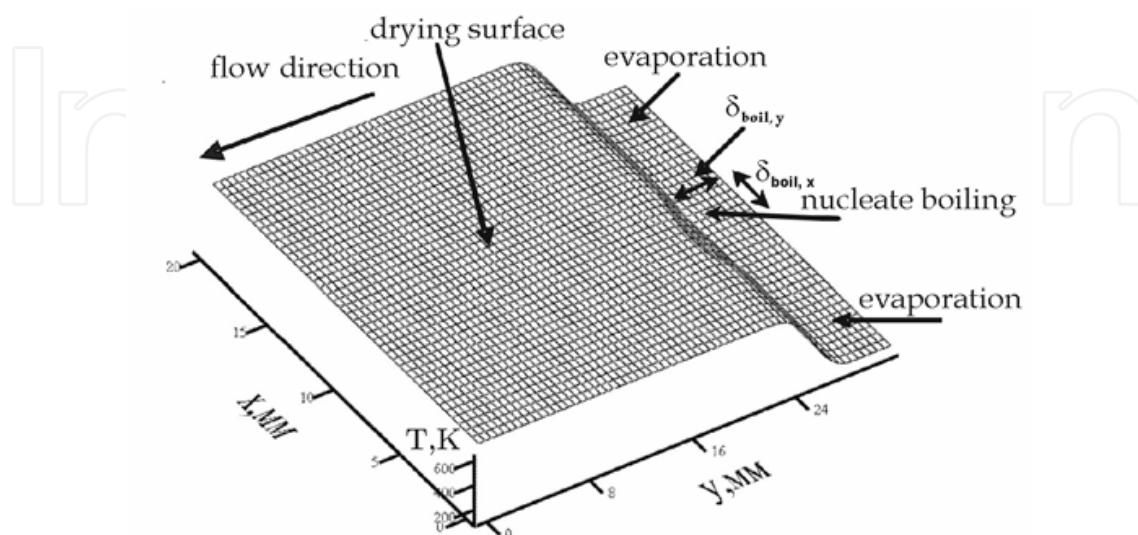

Fig. 16. The initial temperature distribution, $\tau = 0$.

Boundary conditions $\partial T_h/\partial y = 0$ for $y = 0$, $x = 0 \div Lx$, $\partial T_h/\partial x = 0$ for $x = 0$, $x = L_{x,}$ $y = 0 \div L_y$, were defined from symmetry considerations. For the upper edge of the heater $y = L_y$, $x = 0 \div L_x$ the boundary condition $T_h = T_{sat}$, was accepted.

The intensity of heat transfer q (ΔT_h) is simulated by curves of heat transfer, which used the experimental data (Matsekh & Pavlenko, 2005; Pavlenko et al., 2006). Linearized heat transfer coefficient changes abruptly at the boundary of the front in a different zones: in points $\Delta T_{lim} = \Delta T_{bound.1} = 26$ K at the lower boundary of the jet with the developed boiling, $\Delta T_{bound.2} = 11$ K at the boundary of the film flow with the regime of evaporation. Accordingly, at $T_h \le T_{bound\ 1}$ $\tilde{\alpha} = \tilde{\alpha}_{nuc.boil}$ (nucleate boiling), or, when $T_h \le T_{bound.\ 2}$, $\tilde{\alpha} = \tilde{\alpha}_{evap}$ (evaporation of the film), depending on the conditions in the local area of the film. If $T_h >$ T_{bound} $\tilde{\alpha} = \tilde{\alpha}_{d.s}$, that corresponds to heat transfer in the field of dry spots at a turbulent free convection in the vapor phase.

In the calculations we accepted thermophysical properties and geometric parameters of heat-transfer surface corresponding to constantan foil used in the experiments (Surtaev & Pavlenko, 2009): $\lambda_h = 18$ W·m^{-1}K^{-1}, $c_h = 245$ J·kg^{-1}K^{-1}, $\rho_h = 8850$ kg·m^{-3}, $\delta_h = 25 \cdot 10^{-6}$ m, $L_y = 32 \cdot 10^{-3}$ m, $L_x = 20 \cdot 10^{-3}$ m. Data on heat transfer is also taken from (Surtaev & Pavlenko, 2009) $\tilde{\alpha} = \tilde{\alpha}_{evap} = 6000$ W·m^{-2}K^{-1}, $\tilde{\alpha} = \tilde{\alpha}_{nuc.boil} = 4.7 \cdot 10^4$ W·m^{-2}K^{-1}, $\tilde{\alpha} = \tilde{\alpha}_{d.s} = 50$ W·m^{-2}K^{-1} at $T_{sat} = 77.4$ K.

Thus, considering the features of the process revealed in experiments, on the lateral surface of the jet and between the jets in wetted area heat transfer at evaporation is set with corresponding boundary conditions for the roll - like wetting front shape.

According to visualization of the process by the high-speed digital video camera, the emerging 3D waves effect mainly on dynamics of liquid jets formation and their transverse size in rewetting front. Video analysis of fragments shows that boiling is developed precisely in the zones of the thickened film. In a first approximation it is assumed that the transverse size of jets with boiling in the lower parts δ_{boil} is the characteristic transverse size of three-dimensional wave $\delta_{\perp,w}$, components for nitrogen films in the studied range Reynolds number this value is $\delta_{\perp,w} \sim 4$ mm.

The problem was solved numerically using the scheme of the method of alternating directions (Fletcher, 1991), combining the best qualities of the explicit and implicit schemes (economy and stability, respectively). In two-dimensional case, the scheme of the method of alternating directions has the form of:

$$\frac{T_{i,j}^{k+1/2} - T_{i,j}^{k}}{\tau/2} = \frac{a}{h_x^2}(T_{i+1,j}^{k+1/2} - 2T_{i,j}^{k+1/2} + T_{i-1,j}^{k+1/2}) + \frac{a}{h_y^2}(T_{i,j+1}^{k} - 2T_{i,j}^{k} + T_{i,j-1}^{k}) + f_{i,j}^{k+1/2} \qquad (12)$$

$$\frac{T_{i,j}^{k+1} - T_{i,j}^{k+1/2}}{\tau/2} = \frac{a}{h_x^2}(T_{i+1,j}^{k+1/2} - 2T_{i,j}^{k+1/2} + T_{i-1,j}^{k+1/2}) + \frac{a}{h_y^2}(T_{i,j+1}^{k+1} - 2T_{i,j}^{k+1} + T_{i,j-1}^{k+1}) + f_{i,j}^{k+1/2} \qquad (13)$$

Here $\qquad a = \lambda_h/(c_h\rho_h),\ f_{i,j}^{k} = 1/(\delta_h c_h \rho_h)(q_+ - q_-(T_{i,j}^{k}))$,

h_x, h_y are mesh steps in the direction of x and y, correspondingly. In addition to basic values T_{ij}^k and T_{ij}^{k+1} an intermediate value, which can be formally considered as a value at $\tau = \tau_{k+1/2} = \tau_k + 1/2$, is introduced. At each fractional time step one of the spatial differential operator is approximated by implicity (scalar factorizations are carried out in the respective coordinate direction) and the other are approximated explicitly.

In the next fractional step following differential operator is approximated by implicitly, and the rest - explicity and so clearly. Solution in this case is reduced to the solution of two three-diagonal matrix systems that allows us to use one-dimensional factorization for finding the solution.

Below in Fig. 17 shows the results of numerical simulations on the dynamics of movement of wetting fronts boundaries.

Fig. 17. Evolution of film flow boundary. δ_{boil} = 4 mm. $\Delta T_{bound.1}$=26 K in the bottom of the boiling jet. $\Delta T_{bound.2}$=11 K in the area with evaporating film. The time interval between curves $\Delta\tau$ = 0.5 s

Time-varying shape of the front is obtained as described above under the condition that at the initial time film in a local area of the upper part of the fuel surface, bounded by size $\delta_{boil,x}$, $\delta_{boil,y}$, is under the condition of boiling. In this case, the temperature on the boundary of evaporating film $T_{bound.2}$ = 88.4 K, on the boundary of boiling jet it is $T_{bound.1}$ = 103.4 K.

The results of numerical experiments shown that the instantaneous velocity of boundary motion varies not linearly - there is a sharp increase in the velocity when moving down the front on the heater. It is caused by the fact that in the dried zone, the temperature of heat-releasing surface in absence of heat generation is markedly reduced in the transition process due to heat transfer at free convection in a vapor phase.

Average velocity of moving boiling jets boundaries V_1 is significantly higher than average velocity of the evaporated film boundary V_2.

Comparison of simulation results with experimental data (Pavlenko et al., 2007) on the rates of rewetting front for boiling and evaporating film is presented in Figure 18.
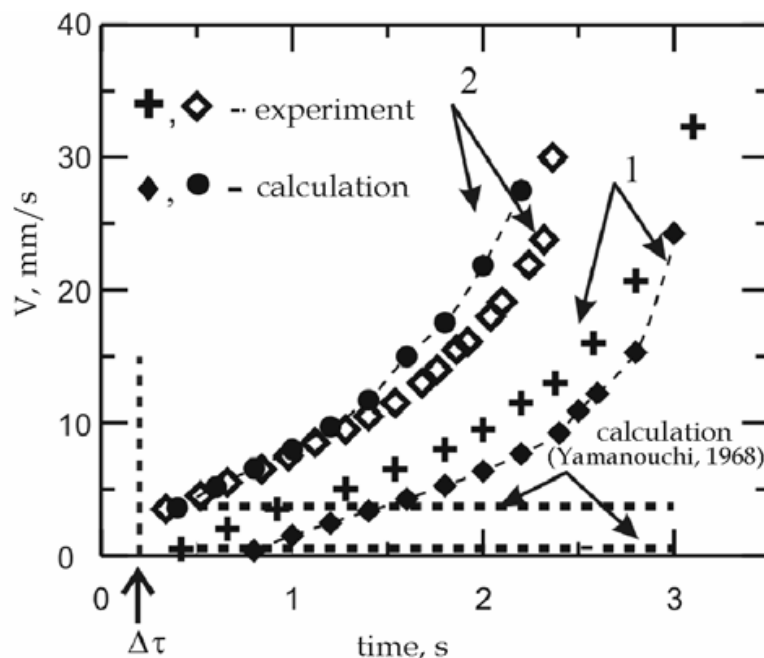

Fig. 18. Rewetting front velocity in time: 1 - in area with evaporating film, 2 - in boiling jets

Fig. 19 presents the results of numerical simulation of temperature fields evolution in the heat-transfer surface at motion of the film flow front. In high-speed video fragments (Figure 20) dotted lines are the boundaries of rewetting front, obtained in numerical experiment for the corresponding moments of time. It is obvious that the time of complete wetting of the entire heat-transfer surface is determined by the minimal velocity, i. e., by the velocity of evaporating film boundary in the interjet zones.

The numerical experiment was carried out to describe the process of repeated wetting of a thin-wall heater cooled by a falling wave film of cryogenic liquid. It was found that the average velocity of boiling jet boundary exceeds the average velocity of the evaporating film boundary. The instantaneous velocity of boundary motion changes nonlinearly. It is obvious that the time of complete collapse of dry spots is determined by the minimal velocity, i. e., by the velocity of evaporating film boundary in the interjet zones. Therefore, it is shown on the basis of modelling and proved experimentally that the total time of repeated wetting is determined by the minimal motion velocity of evaporating film boundaries in the zones of the front between the boiling jets. Reliability of results obtained by numerical methods is proved by the direct comparison with the experimental data. The developed numerical model has shown relatively good qualitative description of the total propagation of the repeated wetting front. It is obvious that in general the calculation simulates the physical processes typical to this experiment qualitatively correct.

Evolution of the front shape with complicated two-dimensional boundary of the film flow in the transition process, obtained by numerical simulations, agrees well with evolution observed in experiments.
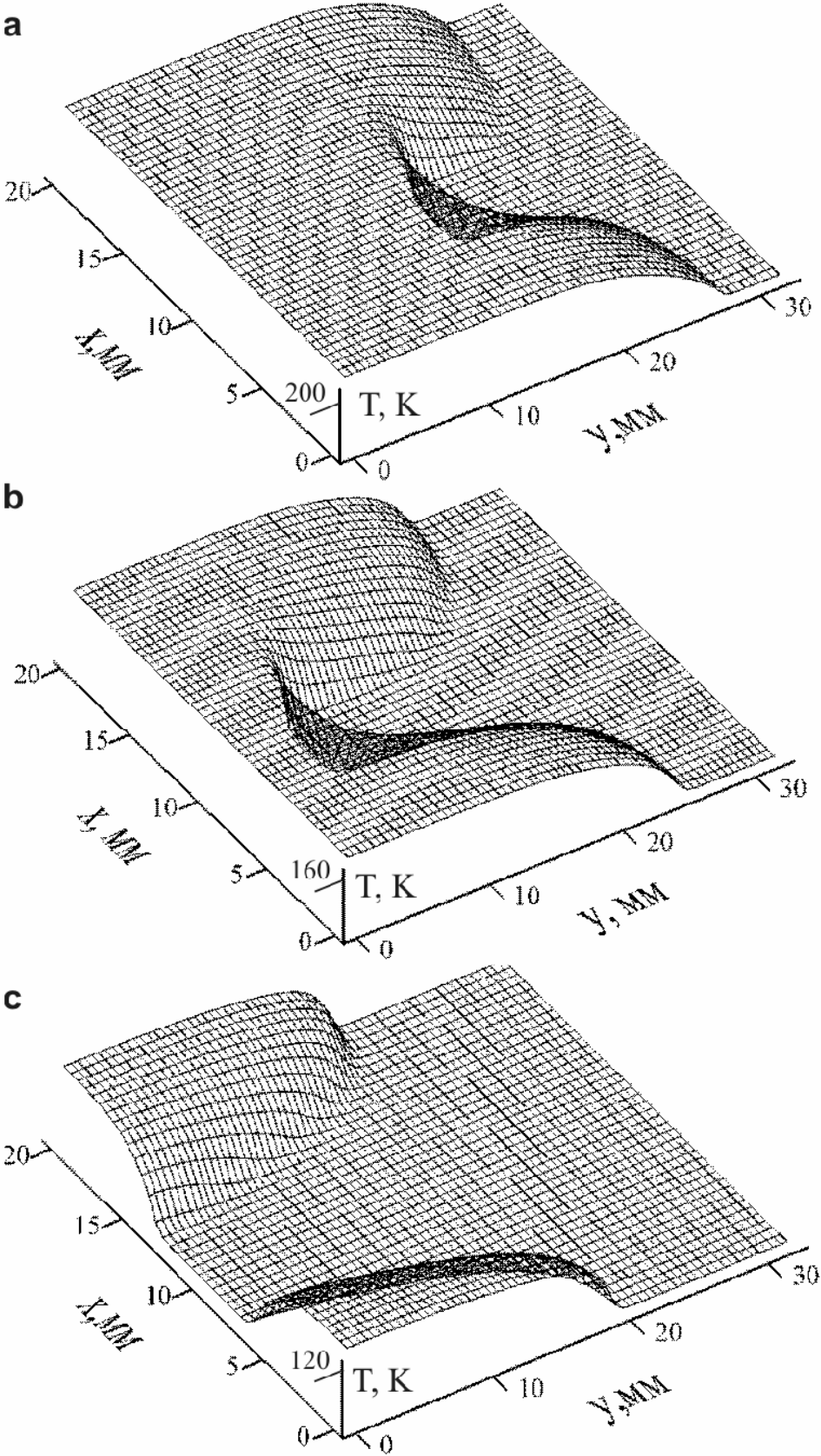
Fig. 19. Temperature field change in time. a ÷ c: τ = 1.5; 2.0; 2.5 s
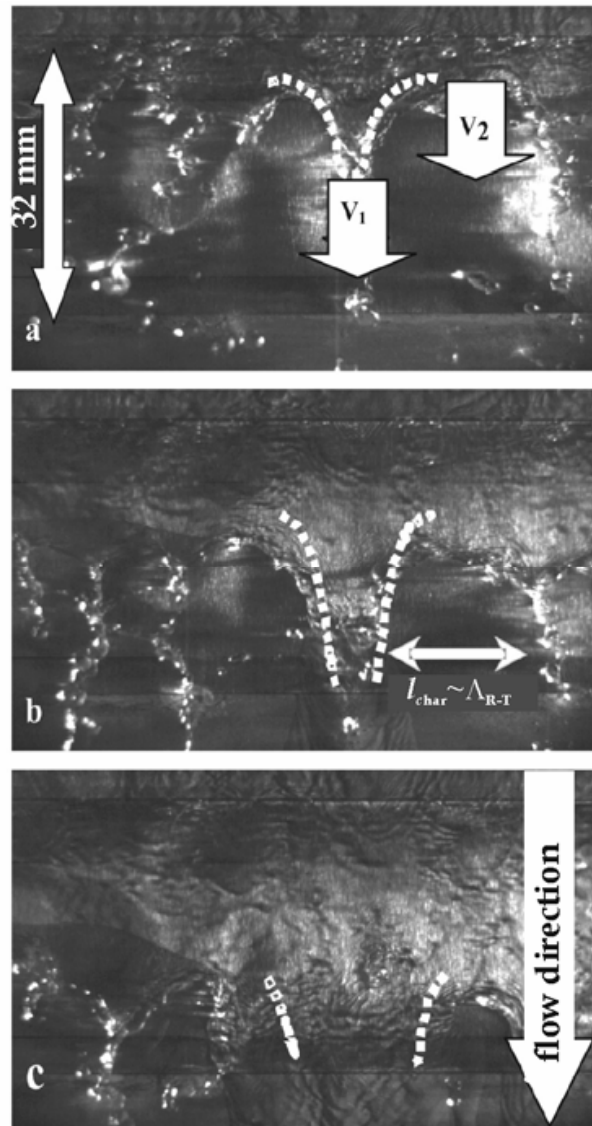
Fig. 20. Video fragments of the high-speed recording of transition after heat-releasing impulse with duration $\Delta\tau = 0.2$ s. Heat flux density $q_+ = 21.23 \cdot 10^4$ Wm^{-2}, Re = 1690, τ = 1.5; 2.5; 3.0 s

4. Conclusion

It was revealed in numerical experiments on regularities of temperature disturbance evolution that the threshold of thermal stability of nucleate boiling decreases significantly with a decrease in thickness and thermal conductivity of fuel element and with an increase in size of initial disturbance.

A significant influence of the boiling curve shape on parameters of thermal stability of temperature disturbance and development dynamics was determined.

The model of temperature disturbance evolution with consideration of unsteady heat transfer in the front of boiling regime change was implemented.

The edge effects were investigated. It is shown that the behavior of dry spots localized at the heater's edge differs from the behavior of spots on the infinite heater.

Numerical experiment confirms the hypothesis that under certain film flow conditions crisis development is determined by upstream propagation of temperature disturbance, when the threshold of thermal stability of dry spots is attained. This model allows us to predict the critical heat flux in the range of flow parameters, where the hydrodynamic model does not work.

Dynamic process of superheated surface rewetting was simulated. Evolution of the front shape is studied; it is shown that the local velocities in different areas of two-dimensional wetting fronts differ considerably. The front shape obtained in numerical experiment is in satisfactory agreement with the shape observed in experiments with self-organized regular structures. Complete time of transition process is determined by the minimum velocity of evaporating liquid boundaries in the zones of the front between boiling jets. The model allows us to quantify the wetting front velocity and temperature fields in the heater, variable in space and time.

The reliability of the results obtained has been confirmed by direct comparison with the existing analytical solutions in the limiting areas and to experimental data.

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.

5. Acknowledgements

6. Nomenclature

c specific thermal capacity at constant pressure, $J \, kg^{-1} \, K^{-1}$

g free-fall acceleration, m/s^2

L heater length, m

l_{char} characteristic linear scale of the temperature gradient, m

l_0, l initial and running dimensions of the dry spot, m

p pressure, MPa

q heat flux density, W/m^2

R_0, R initial and running radii of the two-dimensional dry spot, m

$Re = 4\Gamma/\nu$ film Reynolds number

r latent heat of vaporization, J/kg

T temperature, K

U, V velocity, m/s

$We^{-1} = \sigma/(\rho' U^2 L)$ reverse Weber number

x coordinate along the heater with the point of reckoning at the center of the dry spot, m

Greek Letters

$\alpha = q/\Delta T$ heat transfer coefficient, $Wm^{-2}K^{-1}$

$\tilde{\alpha}$ linearized heat transfer coefficient, $Wm^{-2}K^{-1}$

Γ degree of irrigation, m^2/s

$\Delta T = T - T_{sat}$ temperature head, K

Δ_i linear scale of pulsations of heat transfer coefficient

δ thickness, m

λ coefficient of thermal conductivity, $Wm^{-1}K^{-1}$

$\Lambda = \sqrt{\sigma / g(\rho' - \rho'')}$ Laplace constant, m

ν kinematic viscosity, m^2/sec

ρ density, kg/m^3

σ surface-tension coefficient, N/m

τ time, s

ω frequency, s^{-1}

$\omega_{0,i} = \tilde{\alpha}_i / (c_h \rho_h \delta_h)$ typical pulsation frequency for heat transfer coefficient

$\tilde{\omega} = \omega_i / \omega_{0,i}$ dimensionless pulsation frequency for heat transfer coefficient

Subscripts and superscripts:

'   liquid
"   vapor
bound   boundary
char   characteristic
cr   critical
equi   equilibrium of boiling regimes
film   film boiling
h   heater
in   inlet conditions
lim   limit overheating
nuc.boil nucleate boiling
sat   saturation line
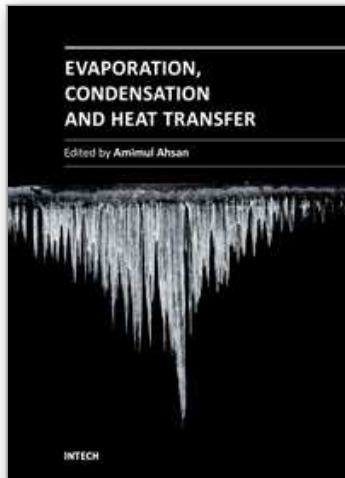trans.boil transitional boiling
0   initial
∞   infinite.

7. References

Brahim Bourouga & Jerome Gilles. (2010). Roles of heat transfer modes on transient cooling by quenching process, *International Journal of Material Forming*, Vol. 3, No. 2, pp. 77 – 88

Carl de Boor. (1985). *A Practical Guide to Splines*, Moscow, p. 304

Duffey, R.B. & Porthouse, D.T.C. (1973). The physics of rewetting in water reactor emergency core cooling, *Nuclear Engineering and Design*, Vol. 25. Issue 3, pp. 379-394

Fletcher, K (1991). *Numerical methods in fluid dynamics*, Vol.1, p.504

Gabaraev, B.A.; Kovalev, S.A.; Molochnikov, Yu.S. et al. (2001). Rewetting and autowave change of boiling modes, *High Temperature*, Vol. 39, No. 2, pp. 302 - 314

Gimbutis, G. (1988). *Heat transfer at gravitation flow of a liquid film* (in Russian), Vilnius, Mokslas, p. 232

Grigor'ev, V.A.; Pavlov, Yu.M. and Ametistov, E.V. (1977). *Boiling of Cryogenic Fluids* (in Russian), Energiya, Moscow

Hammad, J.; Mitsutake, Y.; Monde, M. (2003). Movement of maximum heat flux and wetting front during quenching of hot cylindrical block, *Int. Symposium on Transient Convective Heat and Mass Transfer in Single and Two Phase Flows*, Editors J. Padet, F. Arinc, Begell House, pp. 189 – 202

Katto, Y. (1994). Critical heat flux, *Int. J Multiphase Flow*, Vol. 20, pp. 53 – 90

Kovalev, S.A.; Usatikov, C.V. (1988). Calculation-theoretical study on stability of bubble-boiling and temperature pulsation of the wall heated by a hot liquid, *J Eng. Phys*, Vol. 55, No. 5, pp. 803-810

Kovalev, S.A.; Usatikov, C.V. (1991). Estimate of boiling regime stability by means of Lyapunov functional, *High Temperature*, Vol. 29, No. 4, pp. 730-737

Lutset, M.O. (1998). Limit rate of boiling regime change, *Techn. Phys. Lett.*, Vol. 24, No. 9, pp. 21 - 27

Matsekh, A.M. & Pavlenko, A.N. (2005). Heat-transfer and crisis phenomena features in falling films of cryogenic liquids, *Thermophysics and Aeromechanics*, Vol. 12, No. 1, pp. 105 - 119

Mudawar, I.A.; Incropera, T.A. and Incropera, U.P. (1987). Boiling heat transfer and critical heat flux in liquid film falling on vertically-mounted heat sources, *Int. J Heat Mass Transfer.* Vol. 30, pp. 2083 – 2095

Pavlenko, A.N. (1985). Experimental study of propagation of film boiling boundary in cryogenic liquid, *Actual Problems of Thermal Physics and Physical Hydrodynamics*, Novosibirsk, pp. 307 – 317 (Proc. Collection, publ. by Inst. of Thermophysics SB RAS)

Pavlenko, A.N.; Chechovich, V.Yu. & Starodubtseva, I.P. (1994) Study of propagation dynamics for the site of film regime boiling, *Russ. J Eng. Thermophys.*, Vol. 4, No. 4, pp. 323 - 347

Pavlenko, A.N. & Lel, V.V. (1997) Heat transfer and crisis phenomena in falling films of cryogenic liquid, Russ. J. of Eng. Thermophysics. Vol. 7, No. 3 – 4, pp. 177 – 210

Pavlenko, A.N.; Starodubtseva, I.P. (1998). The study of the development dynamics of semi-infinite and local sites of film boiling, *Thermophysics and Aeromechanics*, Vol. 5, No. 2, pp. 195 - 207

Pavlenko, A.N. (2001) Transitional Processes at Boiling and Evaporation: Thesis for a Doctor's degree, Novosibirsk

Pavlenko, A.N.; Matsekh, A.M.; Pecherkin, N.I.; Kneer, R.; Lel, V.V., and Surtaev, A.S. (2006) Heat transfer and crisis phenomena with intense boiling in the falling wave liquid films, *Thermophysics and Aeromechanics*, Vol. 13, No. 1, pp. 85 - 96

Pavlenko, A.N.; Starodubtseva I.P., and Surtaev, A.S. (2007). Features of dry spots evolution at the film flow of cryogenic liquids at nonstationary heat release, *Thermophysics and Aeromechanics*, 2007, Vol. 14, No. 4, pp. 505 - 513

Petukhov, B.S. & Kovalev, S.A. (1962). Measurement methods and some results fort the critical load at transition from the film to nucleate boiling, *Thermal. Eng.*, Vol. 9, No. 5, pp. 65 - 72

Surtaev, A.S. & Pavlenko A.N. (2009). Crisis phenomena in falling liquid films at periodic heat loads, *Thermophysics and Aeromechanics*, Vol. 16, No. 3, pp. 459-468

Unal, C. & Nelson, R. (1992). A Phenomenological model of the thermal-hydraulics of convective boiling during the quenching of hot rod bundles. Thermal hydraulic model, *Nuclear Engineering and Design* , Vol. 136, p. 277

Verkin, B.I.; Kirichenko, Yu.A. and Rusanov, K.B. (1987). *Heat Transfer at Boiling of Cryogenic Liquids*, Naukova Dumka, Kiev, p. 262

Yamanouchi, A. (1968). Effect of core spray cooling in transient state after loss-of-coolant accident, *Journal Nucl. Sci. Technol.*, Vol. 5, pp. 547 – 558

Zav'yalov, Yu.S.; Kvasov, B.I.; Miroshnichenko, V.P. (1980). Spline-Function Methods (in Russian), Moscow, Nauka, p. 352

Zhukov, S.A.; Barelko, V.V.; Merzhanov, A.G. (1980). Wave processes on heat generating surfaces on pool boiling, *Intern .J Heat Mass Transfer*, Vol. 24, No. 1, pp. 47 – 55

Evaporation, Condensation and Heat transfer

Edited by Dr. Amimul Ahsan

ISBN 978-953-307-583-9

Hard cover, 582 pages

Publisher InTech

Published online 12, September, 2011

Published in print edition September, 2011

The theoretical analysis and modeling of heat and mass transfer rates produced in evaporation and condensation processes are significant issues in a design of wide range of industrial processes and devices. This book includes 25 advanced and revised contributions, and it covers mainly (1) evaporation and boiling, (2) condensation and cooling, (3) heat transfer and exchanger, and (4) fluid and flow. The readers of this book will appreciate the current issues of modeling on evaporation, water vapor condensation, heat transfer and exchanger, and on fluid flow in different aspects. The approaches would be applicable in various industrial purposes as well. The advanced idea and information described here will be fruitful for the readers to find a sustainable solution in an industrialized society.

INTECH

open science | open minds