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Numerical simulation of heat transfer and determination of critical heat fluxes at nonsteady heat generation in falling wavy liquid films

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ABSTRACT

In the current work, we present the mathematical model, which allows the calculation of the wave surface profile, velocity and temperature fields as well as the study of their evolution at a drastic change in heat loads with time. This model allows calculations of the wave characteristics and parameters of liquid film decay at different regime parameters.

Using the presented model, we have simulated the wave formation process in falling film of liquid nitrogen and retrieved the resulting average wave characteristics for different inlet Reynolds numbers. We have also calculated the dependencies of boiling expectation time and total local evaporation time in falling wavy films of liquid nitrogen on heat flux density for different inlet Reynolds numbers.

It was found out that all calculated dependencies are approximately similar in the area of high heat flux rates for all examined inlet Reynolds numbers indicating the weak influence of irrigation rate on boiling expectation time in this range of heat loads. Discrepancy of calculated dependencies was found in the area of low heat flux rates, what could be explained by significant influence of evaporation on heat transfer under such conditions. The dependencies of characteristic heat flux density of boiling suppression and total local evaporation suppression on the inlet Reynolds number were also presented.

The regime map, which defines the different mechanisms of decay of falling wavy film of liquid nitrogen, was obtained by summing up the results of numerical simulation. The results of numerical simulations are in satisfactory agreement with experimental data.

1. Introduction

The liquid flow over a vertical surface is inevitably accompanied by development of wave perturbations on the free film surface, which bring considerable contribution to the heat transfer processes and development of crisis phenomena [1–9].

The area of highly efficient heat transfer at the film flow of liquid is limited by the heat flux and depends significantly on the heat release law.

When the system reaches the critical heat flux, this leads to decay of the film flow, formation of large-scale dry zones, reduction of heat transfer intensity, and, as a sequence, to a drastic increase in temperature of the heat-releasing surface. All these can cause destruction of the heat-releasing element.

The ability to calculate the critical heat fluxes and maximal times of their impact for a given system is required for the design of stably working heat exchangers.

Under the conditions of unsteady heat release, two scenarios of film flow decay are possible depending on heat load and intensity of irrigation: the first is liquid film explosive boiling-up with dispersion of drops and development of large-scaled unwetted areas, and the second is total local evaporation of the liquid film [3].

The time of crisis beginning and scenario of film flow decay are characterized by such parameters as time of boiling expectation ($\tau_{b.e}$) and time of total local evaporation (τ_{tle}) of the falling liquid film. These values determine maximal times of heat flux influence on the film with certain parameters. $\tau_{b.e} < \tau_{tle}$, $\tau_{b.e} < \infty$ is the criterion of explosive boiling-up during the nonsteady liquid heating with development of self-sustaining boiling-up fronts [2–4]. Motion of the self-sustaining boiling-up fronts is followed by liquid dispersion and leads to draining the heating surface in a short time period, which extremely decreases the heat transfer intensity. $\tau_{tle} < \tau_{b.e}$, $\tau_{tle} < \infty$ indicates that the heater draining would be provided by evaporation from the film free surface.

Therefore, the construction of the mathematical model, which allows calculation of boiling expectation time and time of total local evaporation for the heat-exchanging film systems, is an urgent problem applicable for the engineering practice.

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Nomenclature

h	local film thickness, m
h_0	film thickness at the inlet, m
$h_{max}(x) = \max h(x,t)$	local maximum of film thickness, m
$h_{min}(x) = \min h(x,t)$	local minimum of film thickness, m
h_{av}	average value of local film thickness, m
$h_{av.res}$	average thickness of residual film layer, m
Q	local liquid flow rate per unit of film thickness, m^2/s
Q_0	liquid flow rate per unit of film width at the inlet, m^2/s
ν	kinematic viscosity, m^2/s
$Re_{in} = 4Q_0/\nu$	Reynolds number at the inlet
σ	surface tension coefficient, N/m
ρ	liquid density, kg/m^3
R	dimensionless relative amplitude of perturbations
N	dimensionless normalization parameter
A	integration multiplier
$A_Q = (Q_0 R)/N$	amplitude parameter, m^2/s
ω	perturbation frequency, Hz
ω_0	limit of frequency integration, Hz
τ	total time of calculation, s
$\tau_{b.e}$	boiling expectation time, s
τ_{tle}	total local evaporation time, s
P	wave perturbations power spectrum, m^2/s
x	downstream coordinate, m
y	distance from the wall, m
u	downstream velocity, m/s
v	transversal velocity, m/s
η	dimensionless coordinate along ordinate axis after coordinate transformation
T	temperature, K
$\Delta T_{b.e}$	boiling expectation overheat, K
q	heat flux density, W/m^2
a	thermal diffusivity coefficient, m^2/s
$Fo = a\tau_{tle}/(h_{av.res})^2$	Fourier number
δ_h	heater thickness, m
C_h	specific heat capacity of heater, J/(kg·K)
ρ_h	density of heater material, kg/m^3

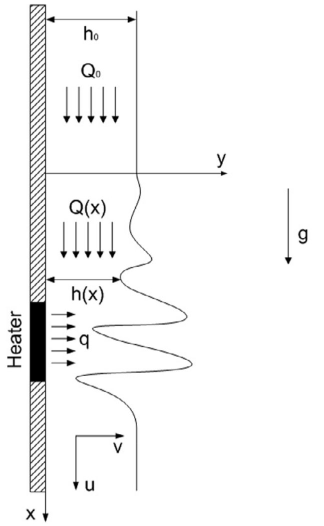

Fig. 1. The scheme of the calculation area.

Now there are many publications dealing with simulation of wave formation under the conditions of a liquid film flow and investigation of the wave motion influence on development of heat transfer processes and diffusion [10–16]. However, there were no studies related to simulation of heat transfer processes in the falling wavy films of liquid at unsteady heat release and making it possible to predict the prevailing mechanism of development of the crisis phenomena depending on the regime parameters.

In the current work, we present a mathematical model, which allows the calculation of the wave surface profile, fields of velocity and temperature as well as the study of their evolution at a drastic change in heat loads with time; this model allows calculations of the wave characteristics and parameters of liquid film decay at different regime parameters. We also compared the results of numerical simulation performed in the framework of the suggested model with experimental data obtained for liquid nitrogen in [3,5].

2. Mathematic model

Simulation has been carried out within a 2D calculation area (Fig. 1). The abscissa axis is directed along a vertical wall, downstream the liquid film flow. The ordinate axis is orthogonal to the abscissa axis and directed from the wall to the free film surface. The natural boundaries of the calculation area along the ordinate axis are the vertical plane, where the film flows, and free surface of the liquid film. The film region, where the first perturbation occurs (above this region, the film is considered waveless), and the film region, separated from the first boundary by the distance sufficient for completion of wave formation and formation of the flow with stable wave characteristics, are chosen as the boundaries of the calculation area.

To describe the processes of liquid flow and evolution of the wave surface profile, in the framework of the current study we used the 2D hydrodynamic model of Kapitza-Shkadov [15,16]:

$$\frac{\partial Q}{\partial t} + \frac{6}{5}\frac{\partial}{\partial x}\left(\frac{Q^2}{h}\right) = -\frac{3\nu Q}{h^2} + gh + \frac{\sigma}{\rho} h \frac{\partial^3 h}{\partial x^3}, \tag{1}$$

$$\frac{\partial h}{\partial t} + \frac{\partial Q}{\partial x} = 0, \tag{2}$$

$$u = \frac{3Q}{h}\left(\frac{y}{h} - \frac{1}{2}\left(\frac{y}{h}\right)^2\right), \tag{3}$$

$$v = -\int_0^y \frac{\partial u}{\partial x} dy. \tag{4}$$

The method of liquid flow description by means of flow rate characteristic Q allows us to exclude dependence on the ordinate and reduce the problem to the pseudo-single-dimensional one. Velocity components in the whole calculation area can be obtained from h and Q by means of expressions (3) and (4). The system of Eqs. (1)–(4) supplemented with the initial and boundary conditions allows calculation of flow dynamics and evolution of surface profile within the 2D calculation area.

We will set perturbations at the inlet of the calculation area through introduction of an addition to the flow rate of the undisturbed film under the condition of keeping the undisturbed thickness [13]:

$$h|_{x=0} = h_0 = \left(\frac{3}{4}\frac{\nu^2}{g}Re_{in}\right)^{1/3}, \tag{5}$$

$$Q|_{x=0} = Q_0 + A_Q \int_{-\omega_0}^{\omega_0} A \cdot \sin(\omega t) d\omega, \; A \in [0;1], \tag{6}$$