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The effect of natural convection in a liquid layer and the thermal inhomogeneity of vapor on the stability of a vapor film on a flat horizontal heater

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A B S T R A C T

The linear stability of a vapor film, formed on the surface of a flat horizontal heater in a subcooled film boiling regime under conditions of terrestrial gravity, is studied. The study is aimed to estimate the role of natural convection in a liquid cooled from above, which is influenced by an additional flow caused by the redistribution of matter in the phases, in the process of stabilization of a stationary base state with a balanced heat flux at the interface between the two media. A modification of the conventionally used model of convective heat transfer (Newton–Rikhman's law) is proposed. The calibration of the presented model, which is characterized by a dependence of the local coefficient of convective heat transfer on the rate of phase transition, is carried out on the basis of the experimental data available in the literature. The modified model allows to avoid the underestimation of the critical value of the heat flux in the subcooled liquid, at which a complete suppression of the Rayleigh–Taylor instability by a phase transition is achieved. In addition, it is demonstrated that the inhomogeneity of thermophysical properties of vapor and heat transfer by radiation at the boundaries of the vapor layer exert, respectively, stabilizing and destabilizing effects under the condition of a significant overheating of the heater surface.

1. Introduction

There are two main boiling regimes–nucleate boiling and film boiling (see, for example, [1]). The film boiling regime differs from the nucleate boiling regime in that the surface of a heater, immersed to a liquid, is covered by a rather stable vapor film. Heat insulating properties of such film essentially decreases the rate of heat transfer to the liquid, which can cause an unacceptable rise of the heater temperature.

Under normal conditions, a transition from the nucleate boiling to the film boiling regime (the first boiling crisis) and backward transition (the second boiling crisis) occur in a critical manner at certain values of the heat flux. The peculiarity of these transitions is that the heat flux of the first boiling crisis is considerably higher than that of the second boiling crisis. The hydrodynamic theory of boiling crises (see, for example, [2]) associates these phenomena with the two base types of instability encountered in multiphase systems.

The first one is the Kelvin–Helmholtz instability for the first boiling crisis, which arises at the liquid–vapor interface of the vapor jets penetrating the bulk of the liquid. Breaking of these jets requires a critical rate of vapor efflux. The second one is the Rayleigh–Taylor instability (see, for example, [3]) for the second boiling crisis, which is initiated under the action of gravity force at the surface of the vapor film due to a difference between the liquid and vapor densities. This leads to a continuous detachment of vapor bubbles from the film, in which the loss of vapor is compensated by its generation. It is assumed that, via the wavelength of the most rapidly growing disturbances, the Rayleigh–Taylor instability specifies the size of the vapor bubbles separated from the film and the diameter of the vapor jets.

The modulation of the gravity field, caused by vertical vibrations of the horizontal surface of the heater, is able to damp the Rayleigh–Taylor instability. Such modulation can also lead to the excitation of parametric instability at the liquid–vapor interface. In general, these effects of gravity modulation allow to control the second boiling crisis, increasing or decreasing the associated critical heat flux [4].

Under microgravity conditions, the film boiling regime occurs at significantly lower values of the heat flux in the system than under terrestrial gravity conditions [5,6]. This is due to the fact that buoyancy is the main mechanism that detaches the generated vapor bubbles from the surface of the heater and removes them away.

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Nomenclature

$\{O, x, z\}$	Cartesian coordinate system
t	time
$\vec{g} = \{0, -g\}$	gravity acceleration vector
h	vapor layer thickness in the non-boiling state
l	thickness of the liquid layer cooled from above in the non-boiling state
T_{h}	temperature at the heater surface
T_{c}	temperature of the liquid near the cooler
p_0	pressure at the stabilized, non-boiling interface
T_{s0}	saturation temperature corresponding to the pressure p_0
ΔT_{h}	overheating of the heater surface
Ra	Rayleigh number
Nu	Nusselt number
A	coefficient of convective heat transfer
q	heat flux of subcooling, removed by natural convection in the liquid
q_{cond}	heat flux from the heater, transferred by thermal conductivity in the vapor
α	radiation absorption coefficient
ε	emission coefficient
σ	Stefan–Boltzmann constant
q_{rad}	energy flux radiated by the heater and transmitted to the liquid
Pl	Planck number
β	thermal expansion coefficient
ρ	density
μ	coefficient of dynamic viscosity
υ	ratio of the bulk viscosity to the shear viscosity
c_{p}	specific heat capacity at constant pressure
κ	coefficient of thermal conductivity
χ	coefficient of thermal diffusivity
γ	surface tension coefficient
L	specific heat of evaporation

K	parameter of the non-equilibrium state of the interface
$\vec{n}$	unit vector of the outward normal to the interface
$\vec{\tau}$	unit vector of the tangent to the interface
U_{i}	flow velocity at the interface
p	pressure
$\vec{u}$	flow velocity vector
θ	temperature
G, f	interface position
ξ	phase transition rate
P	amplitude of pressure perturbations
U_x	amplitude of perturbations of the horizontal component of velocity
U_z	amplitude of perturbations of the vertical component of velocity
Θ	amplitude of temperature perturbations
F	amplitude of perturbations of the interface position
Ξ	amplitude of the phase transition rate
k_{c}	cut-off wavenumber
k_{l}	wavenumber of the longest-lived perturbations
$d_{\gamma g}$	gravity-capillary length
ω	growth rate of perturbations

Subscripts and superscripts

max	maximal value
cr	critical value
av	mean value
1	value in the liquid phase
2	value in the vapor phase
3	value for the heater surface material
$\bar{\ }$	value in the base state
$\hat{\ }$	perturbation of the base state
$^{(n)}$	number of a fundamental solution

Thus, the action of the Archimedean force prevents the early onset of the first crisis of boiling. Note that, in the case of subcooling, where the temperature in the liquid layer is kept lower than the saturation temperature, there is a flow caused by thermocapillary forces in the liquid phase and surrounding the vapor bubbles. This flow tends to press the bubbles to the surface of the heater, thus resisting the detachment forces [7].

The detachment of gas bubbles from a solid substrate in the absence of gravity can be affected by vertical vibrations [8].

The Rayleigh–Taylor instability can be completely suppressed by a phase transition at a certain critical heat flux of subcooling. This is shown in experimental studies [9,10], which consider thin films of vapor of thickness of about a hundred microns, formed on the surface of a flat horizontal heater. In this case, the interface between the two media tends to a stable state, in which the phase transition is absent and all amount of heat supplied to the interface is removed due to the process of thermal conductivity or natural convection in the liquid.

In [11], the following estimate, relating the critical heat flux of subcooling, q_{cr}, to the overheating of the horizontal wall of a flat heater, ΔT_{h}, is obtained within the lubrication approximation:

$$q_{\mathrm{cr}} = \left\{ \frac{L\rho_2 \rho_1^2 g^2 \kappa_2^4 \Delta T_{\mathrm{h}}^4}{48\gamma\mu_2} \right\}^{1/5}. \qquad (1)$$

Here, g is the gravity acceleration, γ is the coefficient of surface tension, L is the latent heat of the phase transition, ρ_1 and ρ_2 are the liquid and vapor densities, μ_2 and κ_2 are the coefficients of dynamic viscosity and thermal conductivity of vapor, respectively.

As noted in [11], expression (1) has the form of the equation from [12] for the minimum heat flux in the film boiling regime. In [11], a replacement of $\Delta T_{\mathrm{h}} \to \Delta T_{\mathrm{h}}/0.45$ in (1) made it possible to describe the experimental data of [13] for a thick cylindrical heater of diameter 15 cm. This allowed the author of [11] to interpret the obtained results in line with work [12] by correlating the effective averaged thickness of the vapor film at the point of the second boiling crisis with the thickness of the vapor layer stabilized by the phase transition. The case of a thin wire heater was studied in [14], using the approach developed in [11].

The evolution of the system to a stable configuration with a flat liquid–vapor interface was not the focus of study in work [11], which considers the linear stability of the already established base state. In [15], within the framework of the long-wave approach, a nonlinear amplitude equation was derived. It served as a basis for a weakly nonlinear analysis and numerical modeling of the interface dynamics in the subcooled or saturated film boiling regime. Stable nonlinear solutions are described for the case of subcooled boiling.

The situation where a developed natural convection in the liquid phase is absent for any reason was investigated in [16], based on the first principles, without using the lubrication approximation. Such a rigorous approach made it possible to reveal the existence of a threshold thickness for stable vapor films. At the values exceeding this threshold, a complete stabilization of the Rayleigh–