INTERFACIAL STABILITY AND HEAT TRANSFER DURING FILM BOILING ON A VERTICAL SURFACE

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From a consideration of a model for the development of perturbations at the interface during film boiling on a vertical surface in a large volume of saturated liquid, the conditions have been found for the loss of stability of the vapor–liquid interface, which characterizes the maximum attainable vapor film thickness. The motion of the vapor in the "thin" parts of the film not covered by bubbles is assumed to be laminar. The analytical expression which is obtained for heat transfer has the form $\mathrm{Nu} = 0.19\ \mathrm{Ar}^{1/3}$ and satisfactorily generalizes the experimental data.

In spite of numerous theoretical and experimental investigations of film boiling on vertical surfaces in large volumes of saturated liquids, up to now there is no generally accepted model for the process, and the hypotheses which are made differ considerably from one another.

The experimentally established differences in the nature of the motion of the vapor in the zone close to the wall near to the initial edge and far from it have provided the basis for assuming that a transition exists from laminar flow in the vapor film to turbulent flow. The independence of the heat transfer intensity, at some distance from the leading edge, of the height of the surface has also been treated from the point of view of this assumption, since this behavior is characteristic of the turbulent free convection of single-phase liquids. A number of models exist [1-9] whose authors, starting from the hypothesis that the vapor film is turbulent and using various assumptions, have obtained a variety of calculation formulas. At the same time in other papers models have been assumed which are based on the hypothesis of laminar motion of the vapor in the film [10-12]. In many of these papers there are discussions of the state of the interface, noting the formation of waves and vapor bubbles, but the results of the analysis are used as a rule only for selecting a closing relationship for the hydraulics at the vapor film interface.

Here, an attempt is made to relate the behavior of the heat transfer in the problem being considered to the conditions for the onset and development of interfacial instabilities. From the results of ciné- and still-photography [10, 12-15] it can be concluded that starting at some distance from the onset edge, bubbles appear on the surface of the vapor film, the thickness of which exceeds by an order of magnitude or more the thicknesses placed between them, and are covered by the fine waves of the "thin" vapor film. The bubbles move upwards along the interface without breaking away, increasing in size.

In accordance with the proposed model the development of the perturbations at the interface occurs as follows. For a short distance after the leading edge the surface of the film is smooth. With increasing height the flowrate of the vapor, and hence the liquid film thickness also, increases, and short wavelength sinusoidal perturbations arise at the vapor–liquid interface which have some definite wave number. Upon achieving some value of the film thickness as the longitudinal coordinate increases further the surface perturbations become unstable. This static instability of the Kelvin–Helmholtz type arises if the static pressure in the vapor film and the pressure from the reactive forces generated at the vapor interface (which depend on the movement of the wavy interface and which facilitate an increase in the vapor film thickness) together exceed the pressure from the capillary forces, which oppose this increase.

As regards the possibility of the development of dynamic instability, which is caused by differences in the phase velocities and which arises if the dynamic head in the wave

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"front" exceeds the viscous forces in the liquid, it is found that because of the small thickness of the vapor film (hundredths of a millimeter) and the small vapor velocities ($u_v < 10$ m/sec) the occurrence under the conditions being considered is not likely.

As a result of the static instabilities at the interface vapor bubbles appear, and in the sections of "thin" film which occur between them, the film thickness and vapor flowrate correspond to the stability limit. As the coordinate increases, the parameters of the "thin" film remain unchanged, and the vapor in the sections of "thin" film is removed in the bubbles, which behave like reservoirs whose dimensions increase as they float upwards.

Since the bubble thickness has a large value and causes a correspondingly large thermal resistance, heat transfer during film boiling on a vertical surface occurs practically only in the "thin" film zones. Hence, in order to determine heat transfer during film boiling on a vertical surface it is primarily necessary to determine the thickness of the "thin" films corresponding to the boundary of static instability of the Kelvin–Helmholtz type and the fraction of the total heat transfer surface which they occupy.

The subsequent discussion, as in [10, 12], will start from the assumption of the laminar nature of the motion of the vapor in the "thin" films, which appears to be most probable, since the flowrate of the vapor in the "thin" film remains limited at all times.

An arbitrary transverse cross section of the vapor film is taken and the balance of the forces is considered acting on the interface. On the vapor side the static pressure of the vapor and the reactive force of the flux of evaporating liquid act on the interface, while on the liquid side there are the hydrostatic pressure and the surface tension. The first two forces favor and the second two oppose a deviation of the mean film thickness in the direction of an increase. By applying the principle of least action, and ignoring the inertial components of the pressure, we find as the condition for the occurrence of static instability the combination of parameters for which the derivative of the resultant of the forces listed with respect to a small increase in the film thickness has a positive value

$$\frac{\partial P_\Sigma}{\partial \delta} > 0. \tag{1}$$

Correspondingly, the limit for static instability is determined from the condition

$$\frac{\partial P_\Sigma}{\partial \delta} = 0. \tag{2}$$

Expressions are now written for the constituent forces acting on the interface.

The static pressure of the vapor is

$$P_{st} = P_t - 0.5\rho_v u_v^2, \tag{3}$$

where P_t is the total pressure.

The pressure from the action of the reactive forces is

$$P_r = 0.5\rho_v'' v_v^2. \tag{4}$$

The pressure due to the surface tension is

$$P_\sigma = 2\sigma/R, \tag{5}$$

where R is the radius of curvature of the interface.

Since at a fixed distance from the leading edge the total pressure of the vapor and the hydrostatic pressure remain unchanged as δ changes, the condition determining the limit of static instability (2) can be written in the form

$$\frac{\partial}{\partial \delta}(-0.5\rho_v u_v^2 + 0.5\rho_v'' v_v^2 - P_\sigma) = 0. \tag{6}$$

The expressions for the mean longitudinal vapor velocity in the film and the transverse velocity of the vapor at the interface have the forms

$$u_V = \frac{G_V}{\rho_V \delta}, \tag{7}$$

$$v_V = \frac{q}{r' \rho_V''}, \tag{8}$$

where G_V is the vapor flowrate through unit width of the transverse cross section of the film.

Over a wide range of changes of the parameters the most applicable expression for r' is one obtained by an approximation calculation [16]:

$$r' = r(1 + 0.4c_{p,V}\Theta_{st}/r) = r(1 + 0.4K_V). \tag{9}$$

With these assumptions, the relationship for the heat flux density has the form:

$$q = c_1 \lambda_V \Theta_{st}/\delta, \tag{10}$$

where c_1 is a coefficient which takes into account the decrease in the thermal resistance of the vapor film as a result of the wave formation on its surface.

In [4] it is shown that $c_1 = (1 - \eta^2)^{-0.5}$, where η is the ratio of the amplitude of the sinusoidal waves to the mean film thickness. For the subsequent analysis the value $\eta = 0.5$ assumed in [12] is used, so that $c_1 = 1.15$.

In order to determine the pressure due to the surface tension, the radius of curvature of the interface is first found. In a two-dimensional approximation, suppose that the wave surface is described by the equation

$$y = a \sin kx, \tag{11}$$

where $k = 2\pi/\lambda_m$. The following expression is therefore obtained for the maximum curvature of the surface

$$\frac{1}{R} = \left| \frac{\partial^2 y}{\partial x^2} \right| = \frac{4\pi^2 a}{\lambda_m^2}, \tag{12}$$

where λ_m is the wavelength on the surface at neutral oscillation.

During film boiling under conditions of natural convection the vapor velocity is small, and hence, as shown in [17], capillary-gravitational waves arise on the surface which can be described by the following dispersion relationship

$$\omega = \left[\frac{gk(\rho_L - \rho_V) + \sigma k^3}{\rho_L + \rho_V} \right]^{0.5}. \tag{13}$$

It is found from Eq. (13) that for the most energetically favorable minimum velocity of the capillary-gravitational waves the wavelength is equal to

$$\lambda = 2\pi \sqrt{\frac{\sigma}{g(\rho_L - \rho_V)}}, \tag{14}$$

and the most probable wavelength is

$$\lambda_m = 2\pi \sqrt{\frac{3\sigma}{g(\rho_L - \rho_V)}}. \tag{15}$$

Note should be made of the agreement of Eq. (15) for the length of the capillary-gravitational waves at neutral perturbation in the Kelvin–Helmholtz theory with the expression for the most "dangerous" wavelength for Taylor instability.

It can be assumed that Eq. (15) remains valid for the conditions of film boiling being considered up to the onset of static instability. Then by making use of Eqs. (12), (15) in Eq. (5), an expression is obtained for the surface tension pressure:

$$P_\sigma = \frac{2}{3} g(\rho_L - \rho_V) a. \tag{16}$$

By substituting Eqs. (7), (8), (10), and (16) into (6) and differentiating, taking into account that $\partial/\partial a = \partial/\partial\delta$, the equation is found that

$$\frac{G_V^2}{\rho_V \delta^3} - \frac{\rho_V}{\delta^3}\left(\frac{c_1 \lambda_V \Theta_{st}}{r' \rho_V''}\right)^2 - \frac{2}{3} g(\rho_L - \rho_V) = 0. \tag{17}$$

An additional relationship between G_V and δ is established by the equation for the momentum of the vapor in the film, written to the one-dimensional approximation [18]:

$$g(\rho_L - \rho_V)\delta = \frac{\beta \mu_V G_V}{\rho_V \delta^2}, \tag{18}$$

where the coefficient β, which takes into account the effect of the longitudinal component of the velocity at the interface, has a value of $\beta \approx 9$ according to the data given in [19].

By expressing G_V by means of Eq. (18) and substituting it in (17), it is found that

$$\rho_V \delta^3 \left[\frac{g(\rho_L - \rho_V)}{\beta \mu_V}\right]^2 - \frac{\rho_V}{\delta^3}\left(\frac{c_1 \lambda_V \Theta_{st}}{r' \rho_V''}\right)^2 - \frac{2}{3} g(\rho_L - \rho_V) = 0. \tag{19}$$

By introducing the variable $z = \delta^3$ and the notation

$$A = \rho_V \left[\frac{g(\rho_L - \rho_V)}{\beta \mu_V}\right]^2; \quad B = \frac{2}{3} g(\rho_L - \rho_V); \quad C = \rho_V \left(\frac{c_1 \lambda_V \Theta_V}{r' \rho_V''}\right)^2,$$

a quadratic equation can be written

$$Az^2 - Bz - C = 0, \tag{20}$$

the solution of which has the form

$$z = \frac{B}{2A}\left[1 + \sqrt{1 + \frac{4AC}{B^2}}\right]. \tag{21}$$

After the corresponding back-substitutions it is found that

$$\delta = \left[\frac{\beta^2}{3} \frac{\mu_V^2}{g\rho_V(\rho_L - \rho_V)}\left(1 + \sqrt{1 + \left(\frac{3c_1 \rho_V K_V'}{\beta \rho_V'' \mathrm{Pr}_V}\right)^2}\right)\right]^{1/3}, \tag{22}$$

where $K_V' = c_{p,V}\Theta_{st}/r'$, and in accordance with (9), $K_V' = K_V/(1 + 0.4K_V)$.

Thus, starting with the height at which the mean thickness of the vapor film reaches the value defined by Eq. (22), vapor bubbles are formed on the surface, and beyond this neither the thickness δ of the film itself nor the mean flowrate of the vapor in the "thin" sections of the film varies.

On changing to the expression for the heat transfer coefficient, it is assumed that in accordance with the model presented above the surface area covered by bubbles is practically heat-insulating. Making use of Eq. (10), it can then be written that

$$\alpha = c_1 \frac{\lambda_V}{\delta} \bar{F}, \tag{23}$$

where $\bar{F} = 1 - F_V/F_\Sigma$ is the fraction of the heat transfer area occupied by the "thin" film. The results of measurements of the mean dimensions of the bubbles and the distances between them [12] make it possible to estimate this fraction of the surface area, which amounted to $\bar{F} \approx 0.7$.

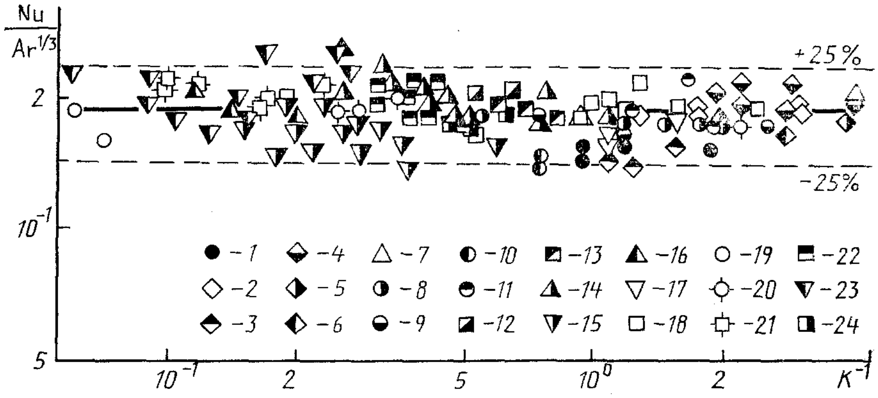

Fig. 1. Generalization of the experimental data: 1) nitrogen; 2) oxygen; 3) ethanol; 4) water; 5) F-12; 6) F-13 [24]; 7) nitrogen [25]; 8) nitrogen [26]; 9) nitrogen [27]; 10) nitrogen [28]; 11) nitrogen [29]; 12) nitrogen; 13) oxygen [30]; 14) ethanol; 15) benzene; 16) n-hexane [21]; 17) nitrogen [5]; 18) nitrogen; 19) helium [23]; 20) nitrogen; 21) hydrogen [31]; 22) ethanol [32]; 23) hydrogen [33]; 24) nitrogen [34].

By substituting Eq. (22) into Eq. (23) an expression is then obtained for the heat transfer coefficient

$$\alpha = c_1\left(\frac{3}{\beta}\right)^{1/3}\bar{F}\lambda_V\left[\frac{g\rho_V(\rho_L-\rho_V)}{\mu_V^2}\right]^{1/3}\left[1+\sqrt{1+\left(\frac{3c_1\rho_V K_V'}{\beta\rho_V''\mathrm{Pr}_V}\right)^2}\right]^{-1/3}. \quad (24)$$

For the real range of variation of the parameters appearing in (24), the groups vary over the following ranges: $\rho_V/\rho_V'' = 0.6\text{-}0.8$; $K_V' = 0.25\text{-}2.5$; $\mathrm{Pr}_V = 0.5\text{-}1.1$. In this case it is possible to assume with sufficient accuracy for engineering calculations that the latter factor in Eq. (24) is equal to 0.8.

Equation (24) can then be simplified to

$$\alpha = c_2\lambda_V\left[\frac{g\rho_V(\rho_L-\rho_V)}{\mu_V^2}\right]^{1/3} \quad (25)$$

or, in dimensionless form,

$$\mathrm{Nu} = c_2\,\mathrm{Ar}^{1/3}, \quad (26)$$

where the value of the numerical coefficient is $c_2 = 0.21$ for the values $c_1 = 1.15$, $\beta = 9$, and $\bar{F} = 0.7$ which have been assumed.

It should be noted that Eq. (26) is not original. Starting from an analogy with free convection, D. A. Labuntsov [20] proposed as early as 1963 a relationship of the form

$$\mathrm{Nu} = c\,\mathrm{Ar}^{1/3}\,\mathrm{Pr}_V^{1/3}. \quad (27)$$

The same relationship was also obtained in [6, 7] on the basis of analyses of specific physical models.

In the generalization of the experimental data in [21] Eq. (26) was used for a limited range of variation of the Archimedes number Ar, and a numerical coefficient of 0.33 was obtained. With the same objective Eq. (27) was used in [22, 23], with the result that in [22] the numerical coefficient was determined to be 0.18, while in [23], which was more recent and covered a larger number of experimental data, the value was found to be 0.2.

Equation (26) is compared in Fig. 1 with the data of [5, 21, 23-34] plotted in the same form as in [23] (which data had already been used in [23]), and it can be seen that the best agreement occurs with $c_2 = 0.19$.

Thus, in dimensionless form the relationship obtained finally has the form

$$\mathrm{Nu} = 0.19\,\mathrm{Ar}^{1/3}, \tag{28}$$

with which the accuracy of generalizing the experimental data is no worse than in [23].

It should be noted that the results which have been given are valid for vertical surfaces whose dimensions are at least commensurate with the value of λ_m.

The satisfactory results of generalizing the experimental data by the relationship which has been obtained and its simple and explicit structure confirm the effectiveness of the criterion which has been proposed for the stability of the vapor—liquid interface and its promise for solving related problems of film boiling on extended surfaces.

NOTATION

$\mathrm{Ar} = gL^3(\rho_L - \rho_v)/\nu_v{}^2\rho_v$, Archimedes number; a, amplitude of oscillation of interface; c_1, coefficient in Eq. (10); c_2, coefficient in Eq. (26); c_p, specific heat capacity; $\bar{F}$, fraction of surface area occupied by "thin" film; G, flow rate; g, acceleration of gravity; $K_v = c_{p.v}\Theta_{st}/r$; k, wave number; L, linear dimension; Nu, Nusselt number; P, pressure; Pr, Prandtl number; q, specific heat flux; r, heat of vaporization; r', heat of vaporization taking into account superheating of the vapor; u, mean longitudinal vapor velocity in film; v_v, transverse component of velocity of vapor being generated at interface; x, y, longitudinal and transverse coordinates; α, heat transfer coefficient; β, coefficient in Eq. (18); δ, vapor film thickness; Θ, temperature difference; λ, thermal conductivity or wavelength; λ_m, most probable wavelength; μ, dynamic viscosity; ν, kinematic viscosity; ρ, density; σ, surface tension coefficient; ω, angular frequency. Subscripts and superscripts: L, liquid; v, vapor; t, total; p, reaction; st, static, wall; Σ, overall; ", parameter for saturated vapor.

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INVESTIGATION OF THE INSTANTANEOUS TEMPERATURE FIELD IN A FLUID STREAM AROUND A HEATED CYLINDER

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Temperature fields in a fluid stream are investigated by a pulse holographic interferometry method at low Reynolds numbers.

In the majority of papers [1-3] devoted to investigation of the heat transfer of a cylinder, a method is used to determine the temperature profile in the fluid stream and to measure the heat elimination of the cylinder by using a different kind of sensor which possesses thermal inertia in addition to introducing a perturbation into the stream being studied, causing averaging of the quantities being measured over time. Consequently, it is interesting to investigate the instantaneous values of the temperature in the streaming fluid flow and, particularly, the temperature fluctuations in the thermal boundary layer.

At the present time, experimenters have a method permitting the investigation of the rapidly changing temperature field in a fluid flow. The method of two exposures described in literature devoted to holographic interferometry is used for the investigation. The research is performed by using the installation UIG-12.

A low-power ruby laser with a 1 mm diameter iris, a phototropic shutter that is a solution of vanadium phthalacionine in chlorobenzyl, and a positive long-focus sens installed within the resonator was the source of coherent radiation. The vanadium phthalacionine concentration was selected so that one short pulse would be obtained at the laser output.

Radiation of the master oscillator was incident in a ruby amplifier with a multiplication factor of 5-10.

Holograms of focused images were used for the research. This is associated with two reasons: firstly, application of focused image holograms reduces the requirement on coherence of the light source and permits utilization of light scattered by matte glass resulting in a reduction in the hologram and interferogram diffraction noise; secondly, a white light source can be utilized to restore such a hologram permitting rejection of the interferogram speckle structure. This would afford the possibility of investigating the thermal boundary

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