THE APPEARANCE OF THE VAPOR PHASE ON A HORIZONTAL HEATING SURFACE

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UDC 536.423.1

We investigate the conditions under which the vapor phase appears on a heating surface; this investigation is carried out from the standpoint of the theory of convection heat transfer.

Numerous references [1-5] are devoted to the study of the conditions under which the vapor phase appears at a heating surface.

References [2, 4] deal with the problem of the limit dimensions for active centers of vapor formation by analyzing the nonsteady heating of layers of liquid adjacent to the heat-transfer surface. However, the great indeterminacy in the selection of the thickness for the liquid layer that is being heated and the fact that the convection heat flow are neglected makes it impossible to regard the results derived in these references as definitive.

Reference [5] describes an investigation into the conditions prevailing in the onset of boiling in flows moving at rather high velocities, at which the variation in temperature near the wall, at height of the vapor nucleus, is assumed to be linear.

An attempt is made in this article to approach the analysis of this problem from the standpoint of the theory of convection heat transfer, for the case of free convection.

According to [6], the transfer of heat from a horizontal heat-exchanger surface to a liquid in the case of free convection is accomplished primarily by a system of paired vortices, which forms near the surface. Within the range of variation for the Rayleigh number from 1700 to 10^5 the flow in the horizontal layer exhibits a cellular structure. When $\mathrm{Ra} \gg 10^5$, as well as within a large space, the cellular structure is preserved only near the heat-transfer surface, in which case the Rayleigh number calculated from the thickness of the vortex layer near the wall, according to our experiment, is equal to ~3100.

We will assume that the heat-transfer intensity under these conditions depends primarily on the velocity of liquid circulation within the cellular layer which exists near the heat-transfer surface. In this case, the problem can be reduced to the calculation of the thermal boundary layer which forms at the surface of the body as a consequence of the interaction between the paired vortices forming the cellular structure of the liquid flow. We will also assume that the lift forces are primarily responsible for the liquid circulation velocity in the cells and exert no significant influence on the development of the thermal boundary layer. In first approximation, we will assume that the vortex flows exist in the form of cylindrical shafts.

Unlike [7], we assume that the flow of the liquid at large Ra numbers can be treated as a flow with constant vorticity within the core of the shaft where the viscosity forces are negligibly small [8]. The friction forces make their appearance only in the thin boundary layer about the perimeter of the shaft (Fig. 1a).

The solution for the equation

$$\frac{\partial^2\psi}{\partial x^2} + \frac{\partial^2\psi}{\partial y^2} = \omega$$

for the boundary conditions $\psi = 0$ at the edges of the shaft has the form

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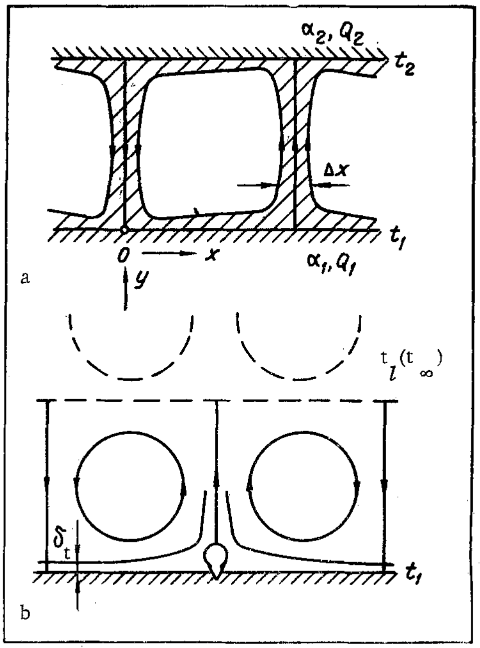

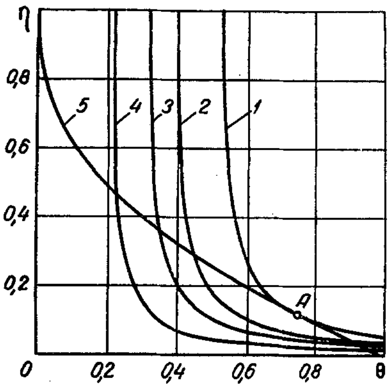

Fig. 1 Fig. 2

Fig. 1. Diagram of the liquid flow near the heating surface in a thin layer (a) and in a large space (b).

Fig. 2. Graphical solution of Eqs. (4) and (9) for water when P = 1 atm abs. and for $\Delta t_{sub} = 3°C$: 1-4) calculation results from (4) and (8); 5) after (9); for 1 we have $\Delta t = 6°C$; for 2 we have 8°C; for 3 we have 10°C; and for 4 we have 15°C.

$$\psi = \sum_{n=1}^{\infty} \frac{2\omega(1-\cos n\pi)}{l\lambda^3}\left[\left(\frac{1}{\operatorname{sh}\lambda l} - \operatorname{cth}\lambda l\right)\operatorname{sh}\lambda y + \operatorname{ch}\lambda y - 1\right]\sin\lambda x, \tag{1}$$

where $\lambda = n\pi/l$.

Limiting ourselves to the first term of the series, for y = 0 we have

$$u_0 = v_0 \sin\frac{\pi x}{l}. \tag{2}$$

Using the integral momentum and energy relationships and the laws governing friction and heat transfer for the boundary layer which appears at the surface of the body as a consequence of the vortex, it becomes possible to derive a closed system of equations and an analytical solution for the problem of heat transfer in the case of free liquid convection in horizontal layers and in a large space. The results of the solution are given in [6] and agree well with available experimental data on heat transfer.

We will assume that the proposed scheme for the liquid flow will remain intact until the instant that the vapor phase appears.

It is presently regarded as having been established that a vapor bubble is formed in a depression. The equilibrium condition for the vapor phase can be written in the following manner:

$$T_h - T_s = \frac{2A\sigma T_s}{r\gamma'' r_b}. \tag{3}$$

According to [2], we assume the following relationships between the height (h) of the bubble nucleus, its radius (r_b), and the radius of the depression (r_d):

$$h = c_1 r_d, \quad r_b = c_2 r_d, \quad h = c_3 r_b, \quad c_3 = \frac{c_1}{c_2},$$

where $c_1 = 2$, $c_2 = 1.25$, $c_3 = 1.6$.

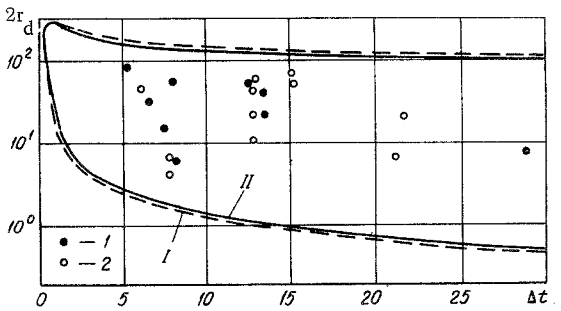

Fig. 3

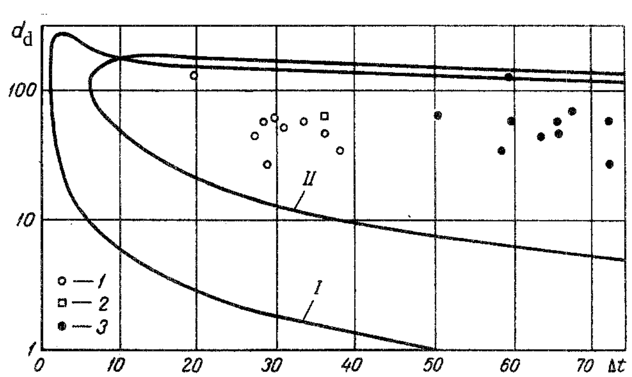

Fig. 4

Fig. 3. Region of existence for active centers of vapor formation: I) boiling of pentane when P = 1 atm abs. and at the saturation temperature, according to (4) and (9); II) boiling of diethyl ester when P = 1 atm abs. and at the saturation temperature, according to (4) and (9); 1, 2) after [11]; r_d, μm, and Δt, °C.

Fig. 4. Boiling of water at the saturation temperature: I) according to (4) and (9) for P = 1 atm abs.; II) according to (4) and (9) for P = 0.14 atm abs.; 1) after [12], P = 1 atm abs.; 2) after [3], P = 1 atm abs.; 3) after [12], P = 0.14 atm abs.; d_d, μm, and Δt, °C.

Let us introduce the dimensionless coordinate $\eta = y/\delta_t$ and the dimensionless temperature $\Theta = (T - T_0)/(T_W - T_0)$.

From (3) we will then have

$$\Theta_h = \Theta_{sub} + \frac{2A\sigma T_s}{r\gamma'' \frac{\delta_t}{c_3}(T_W - T_0)\eta_h}. \tag{4}$$

According to the diagram of the liquid flow near the heat-exchange surface that we have assumed here, the vapor nucleus must be situated in the boundary layer at a height Δ_t. In first approximation, considering the instability of position for the vortex cells at the surface, we define the thickness of the boundary layer as the average thickness along the length of the cell, which is close to the thickness of the boundary layer in the descending flow and according to [9] (see Fig. 1b) is equal to

$$\delta = 2.4\left(\frac{\nu l}{kv_0}\right)^{1/2}, \tag{5}$$

where k = π when x = 0. In the range of variation for the Prandtl number from 0.5 to 20 we can assume [10] that

$$\delta/\delta_t = \mathrm{Pr}^{0.4}.$$

From the solution of the system of equations describing the process of convection heat transfer at a horizontal surface we have [6]

$$\mathrm{Re}_l = 0.85\,\mathrm{Ra}^{1/2}\,\mathrm{Pr}^{-0.8}, \tag{6}$$

where

$$\mathrm{Re}_l = \frac{v_0 l}{\nu};\quad \mathrm{Ra} = \frac{\Delta t\beta g l^3}{a\nu} = 3100.$$

Consequently,

$$\delta_t/l = 0.195, \tag{7}$$

whence

$$\delta_t = 2.88\left(\frac{a\nu}{\Delta t\beta g}\right)^{1/3}. \tag{8}$$

The temperature distribution over the cross section of the boundary layer is approximated by a fourth-degree parabola

$$\Theta = 1 - 2\eta + 2\eta^3 - \eta^4. \tag{9}$$

We will assume in first approximation that the conditions for the growth of the bubble nucleus will be determined by the simultaneous solution of (4) and (9). The graphical solution of these equations for the case of the boiling of a subcooled liquid is shown in Fig. 2.

In Fig. 2 curves 1-4 have been derived from (4) and (8) for various values of the temperature difference between the temperature of the wall and that within the liquid volume, when the heated liquid volume exhibits a temperature which differs by 3°C from the saturation temperature at a pressure of 1 atm. abs. The point at which curve 1, calculated from (4) and (8), comes into contact with curve 5, which corresponds to the temperature profile (9) in the layer near the wall, corresponds to the conditions for the onset of liquid boiling at the heating surface.

Point A corresponds to the minimum temperature differences between the wall and the liquid volume at which it is possible to generate active centers of vapor formation. The points of intersection for curves 2-4 with curve 5 determine the minimum and maximum values for the radii of the depressions within which a vapor bubble may form.

Figures 3 and 4 compare the proposed solution with the experimental data of various authors. The experimentally established dimensions of the active depressions in the boiling of water, pentane, and diethyl ester are found to be in qualitative agreement with theory.

However, for definitive conclusions as to the validity of the adopted assumptions, we need more extensive experimental material on the effect of various factors on the process of vapor-phase formation.

NOTATION

v_0	is the maximum value of the velocity in the midsection;
ψ	is the stream function;
l	is the height of the cellular layer;
ω	is the vorticity of the shaft core;
δ_t	is the thickness of the thermal boundary layer;
ν	is the kinematic viscosity;
a	is the coefficient of thermal diffusivity;
γ	is the specific weight;
β	is the coefficient of volumetric expansion;
g	is the acceleration due to gravity;
σ	is the coefficient of surface tension;
r	is the heat of vapor formation;
T_0	is the temperature within the liquid volume;
T_s	is the saturation temperature, °K;
Θ_{sub}	is the dimensionless subcooling temperature;
A	is the thermal equivalent of mechanical work;
$\Delta t = T_w - T_0$;	
t_1 and t_2	are the temperatures of the bottom and top heat-exchange surfaces of the horizontal layer;
α_1 and α_2	are the heat-transfer coefficients at the bottom and top heat-transfer surfaces of the horizontal layer;
Q_1 and Q_2	are the heat flow through the bottom and top heat-transfer surfaces in the horizontal layer;
t_1	is the temperature of the liquid in a large volume.

Subscripts

cr	denotes critical;
w	denotes the wall;
'	denotes the liquid;
"	denotes the vapor.

LITERATURE CITED

1. I. T. Alad'ev (editor), Problems in the Physics of Boiling [in Russian], Mir (1964).
2. Hsiu, Journal of Heat Transfer, Transactions of the American Society of Mechanical Engineers, 84, Series C, No. 3 (1962).
3. P. Griffith and J. Wollis, Chem. Eng. Progr. Sump. Ser., 56 (90), 49 (1960).
4. C. E. Faneuff, E. A. McLean, and V. E. Scherrer, J. of Applied Physics, 29, 80 (1958).
5. A. E. Bergles and W. M. Rosenow, Transactions of the American Society of Mechanical Engineers, 89, Series C, No. 3 (1964).
6. A. I. Leontiev and A. G. Kirdyashkin, Third International Heat Transfer Conference, 1, 216; 6, 94 (1966).
7. A. I. Leont'ev and A. G. Kirdyashkin, Inzh. Fiz. Zh., 9, No. 1 (1965).
8. G. K. Batchelor, J. Fluid. Mech., 1, 177 (1956).
9. H. Schlichting, Boundary Layer Theory [Russian translation], IL (1956).
10. S. Goldstein, The State of the Art in the Hydrodynamics of Viscous Fluids [Russian translation], Vol. 2, IL (1948).
11. H. B. Clark, P. S. Strenge, and J. W. W. Westwater, Eng. Progr. Sump. Ser., 55 (29), 107 (1959).
12. A. P. Hatton and I. S. Hall, Third International Heat Transfer Conference, 4, 24 (1966).