BOUNDARY OF THE WAVE REGIME IN FILM CONDENSATION WITH CONSTANT HEAT FLUX ON A VERTICAL SURFACE

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UDC 536.423.4

An expression for the boundary of the origin of the laminar-wave section of condensation was obtained.

Film condensation with constant heat flux is effected in many heat-exchange devices where the principal thermal resistance is the heat transfer from the side of the cooling liquid. Calculation of heat exchangers with vertical pipes that are situated partly (up to 1 m) in the vapor space is possible when there are relations describing heat exchange on the laminar-wave section and expressions determining the range of their application. In the recommended calculation methods a fixed Reynolds number equal to five corresponds to the lower boundary of the wave regime [1, 2]. The authors of [3-6] obtained theoretically a change of the position of the boundary of wave flow of condensate as a function of the pressure, temperature gradient, and type of condensing substance. When these factors are taken into account, we are able to come closer to understanding the considerable scatter (up to ±200% [7]) of the experimental data.

Let us examine the stability of laminar flow of condensate when the heat flux is stable over the entire heat-exchange surface.

In a system of coordinates connected with the vertical condensation surface in such a way that the X axis is directed along the heat exchange surface downward and the Y axis along the normal to it, nonsteady flow of an incompressible film of condensate is described by the equations:

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}-\frac{\partial u}{\partial y}\int_0^y\frac{\partial u}{\partial x}dy=-\frac{1}{\rho_1}\frac{\partial P_1}{\partial x}+\nu_1\frac{\partial^2 u}{\partial y^2}+g, \tag{1}$$

$$\frac{\partial\delta}{\partial t}+\frac{\partial}{\partial x}U\delta=\frac{j}{\rho_1} \tag{2}$$

with the following boundary conditions:

$$y=0\quad u=0, \tag{3}$$

$$y=\delta\quad \frac{\partial u}{\partial y}=0, \tag{4}$$

$$P_1=P_2-\frac{j^2}{\rho_2}\left(1-\frac{\rho_2}{\rho_1}\right)-\sigma\frac{\partial^2\delta}{\partial x^2}. \tag{5}$$

For the analysis of the stability of flow of the condensate we use the Karman–Pohlhausen method which greatly simplifies the stated problem. In this case, to close the system of equations, we specify the instantaneous profile of the longitudinal velocity in the condensate film

$$u(x,\ y,\ t)=3U(x,\ t)(y/\delta(x,\ t)-0.5y^2/\delta^2(x,\ t)), \tag{6}$$

satisfying the boundary conditions (3), (4). The correctness of such a dependence is confirmed by experiments for wave film flows [8]. The existence of reliable experimental confirmation of expression (6) gives sufficient substantiation to the integral approach.

A. A. Zhdanov Polytechnic Institute, Gorkii. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 48, No. 6, pp. 958-962, June, 1985. Original article submitted May 14, 1984.

0022-0841/85/4806-0695$09.50

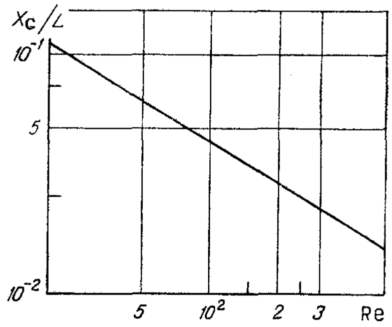

Fig. 1. Dependence of the coordinate of the onset of the wave regime on the Reynolds number.

Using the method of [5], we obtain a relation for the phase velocity of the originating waves and an equation of the neutral curve denoting the region of instability of condensate flow:

$$\frac{\omega}{\alpha} = (a_1 - a_2\alpha^2)\, a_3^{-1}, \tag{7}$$

$$a^6 + \beta_1\alpha^4 + \beta_2\alpha^2 + \beta_3 = 0, \tag{8}$$

where

$$a_1 = 3g + jg\delta_0/(3\rho_1\nu_1);\quad a_2 = \sigma j\nu_1/(\rho_1^2 g\delta_0^2);$$
$$a_3 = 37j/(30\rho_1\delta_0) + 3\nu_1\delta_0^{-2};\ a_4 = 1{,}2U_0^2;$$
$$a_5 = -j\,(7j/(30\rho_1\delta_0^2) + 3{,}5\nu_1\delta_0^{-3})\,\rho_1^{-1};$$
$$\beta_1 = a_2^{-1}\,(2{,}4U_0a_3 - 2a_1 - a_3^2\rho_1 g\delta_0^3\,(j\nu_1)^{-1});$$
$$\beta_2 = a_2^{-2}\,(a_4a_3^2 - 2{,}4U_0a_1a_3 + a_1^2);\ \beta_3 = a_5a_3^2\,a_2^{-2};$$
$$\delta_0 = (3\nu_1 jx/g\rho_1)^{1/3};\ U_0 = g\delta_0^2/3\nu_1.$$

The solution of Eq. (8) coincides qualitatively with the results presented in [5, 6] for the case when the transverse mass flow is directly proportional to the temperature gradient and inversely proportional to the thickness of the condensate film.

The critical parameters of the process of condensation up to which purely laminar flow may exist can be found from Eq. (8) as a result of its analysis as to the minimum Reynolds number

$$3\alpha^4 + 2\beta_1\alpha^2 + \beta_2 = 0. \tag{9}$$

Joint solution of Eqs. (8) and (9) yields the dependences of the coordinate X_c of the origin of instability of the phase boundary.

Writing Eq. (9) in dimensionless form enables us to find the criteria determining the conditions of the onset of instability of the phase boundary:

$$k^4 - 36\,\frac{U_0\mu_1}{\sigma}\,(0{,}2\mathrm{Re} + \mathrm{Pe}\,K/\mathrm{Nu})\,k^2 + 27\,(K\,\mathrm{Pe}/\mathrm{Nu})^2 \times$$
$$\times \left(\frac{U_0\mu_1}{\sigma}\right)^2 [9 - 0{,}96\mathrm{Nu}/(K\,\mathrm{Pe}) - 1{,}49\cdot 10^{-2}\,(\mathrm{Nu}/(K\,\mathrm{Pr}))^2] = 0. \tag{10}$$

In Eq. (10) the complexes characterize [1]: Nu/(KPe) the dimensionless velocity of phase transition; Nu/(KPr), the ratio of the inertial forces arising in phase transition to the forces of viscous friction; $U_0\mu_1/\sigma$, the ratio of the forces of friction and of surface tension.

According to the results of the calculations, the decisive criterion in (10) is the Reynolds number $\mathrm{Re} = jL/\mu_1$, where the characteristic length of the heat exchange surface is taken as L. The influence of the other criterial complexes contained in (10) is negligible. Figure 1 shows the dimensionless coordinate of the onset of the wave regime in condensation of saturated water vapor. In the calculation we adopted L = 1 m; this does not cause loss

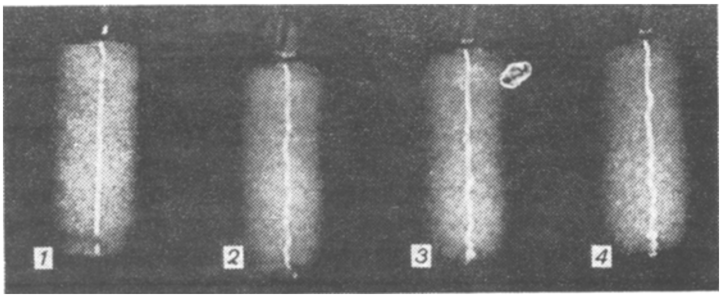

Fig. 2

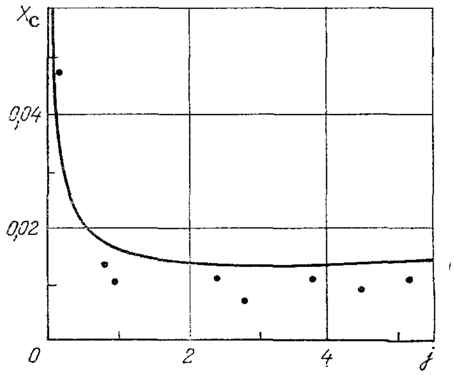

Fig. 3

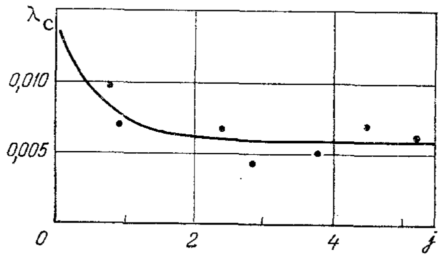

Fig. 4

Fig. 2. Wave generation at a water temperature of 7°C: 1) j = 0.128 kg/m²·sec; 2) 2.412; 3) 3.746; 4) 5.18.

Fig. 3. Coordinate of the onset of the wave regime (X_c, m; j, kg/m²·sec): curve) calculation [Eqs. (8) and (9)]; dot) experiment.

Fig. 4. Wavelengths of the oscillations of the liquid–gas interface (λ_c, m; j, kg/m²·sec). For notation, see Fig. 3.

of generality of the results because, in determining X_c, it is always possible to separate the initial section of the heat exchange surface 1 m long. These values in the range of Reynolds numbers from 0 to 800 are approximated by the following dependence:

$$X_c/L = 0.75\mathrm{Re}^{-0.611}. \tag{11}$$

The experimental confirmation of the obtained results entails considerable technical difficulties. We therefore use the method of analogy based on the similarity of the differential equations describing film flow of condensate and of a liquid film on a porous vertical surface ensuring constant mass supply.

First we check the suggested identity of the investigated differential equations. Equation (1) is identical for the film flows under examination because it expressed the general regularities of motion of an incompressible liquid.

The kinematic condition (2) was obtained for condensate film from the equations of continuity and of the phase boundary [y = δ(x, t)] with the following boundary conditions:

$$y = \delta \quad v = v_3 - j/\rho_1, \quad y = 0 \quad v = 0. \tag{12}$$

For the flow of a liquid on a porous surface we have

$$y = \delta \quad v = v_3, \quad y = 0 \quad v = j/\rho_1. \tag{13}$$

Using the continuity equation, relation (13), and the properties of the integrals depending on the parameter, we obtain a kinematic condition identical with (2).

The boundary conditions (3) and (4) are identical for the processes examined on the basis of analogy.

The difference in the expression for normal stresses (5) is connected with the reactive force of the phase transition. When the heat flux is constant, it does not depend on the coordinate x and does not affect the dynamics of the liquid flow.

Film flow of a liquid on a vertical porous surface was experimentally investigated on a pipe $8 \cdot 10^{-2}$ m long, with $3 \cdot 10^{-2}$ m diameter, with equivalent pore diameter $5 \cdot 10^{-6}$ m. During the experiments we ensured that the constraints on the blasting speed, on which the theory of boundary layers [9] is based, were fulfilled. To make the originating waves visible, we used the principle of modulating a plane light beam incident at an angle on the oscillating surface of the liquid. Figure 2 shows some photographs of the obtained images corresponding to different transverse mass flows. The coordinate of the onset of instability of the liquid—gas interface was determined from the point of deviation of the light beam from the straight line. The steady curving of the beam in the upper part of all photographs corresponds to the initial section of formation of the liquid film.

A comparison of the experimental values of the coordinate of the onset of instability and of the corresponding wavelength with Eqs. (8) and (9), obtained on the basis of an analysis, is presented in Figs. 3 and 4. The satisfactory agreement between the calculated and the experimental results makes it possible to recommend expression (11) for determining the lower boundary of the laminar-wave regime of the flow of water condensate.

NOTATION

t, time; u, longitudinal velocity; v, transverse velocity; P, pressure; ρ, density; ν, kinematic viscosity; $g = 9.81\ (1 - \rho_2/\rho_1)$, reduced acceleration of gravity; δ, thickness of the condensate film; U, mean velocity over the section of the condensate; $j = q/r$, density of the transverse mass flow of the condensing substance; q, heat flux density; r, latent heat of vaporization; σ, surface tension; α, wave number; ω, angular frequency; μ, dynamic viscosity; $k = \alpha\delta_0$, dimensionless wave number; Nu, K, Pe, Pr, Re, Nusselt, Kutateladze, Peclet, Prandtl, and Reynolds numbers, respectively. Subscripts: 1, liquid; 2, vapor; 3, phase boundary; 0, steady value; c, critical parameter.

LITERATURE CITED

1. S. S. Kutateladze, Fundamentals of the Theory of Heat Exchange [in Russian], Atomizdat, Moscow (1979).
2. V. P. Isachenko, Heat Exchange in Condensation [in Russian], Énergiya, Moscow (1977).
3. M. Unsal and W. C. Thomas, "Linearized stability analysis of film condensation," J. Heat Transfer, 100, 629-634 (1978).
4. B. Spindler, "Linear stability of liquid films with interfacial phase change," Int. J. Heat Mass Transfer, 25, No. 2, 161-172 (1982).
5. I. A. Shemagin, V. M. Budov, and V. A. Sokolov, "Waves of the phase boundary in vapor condensation," Izv. Akad. Nauk SSSR, Energet. Transport, No. 3, 160-162 (1983).
6. V. M. Budov, I. A. Shemagin, and V. A. Kir'yanov, "The boundary of the wave regime in condensation of motionless vapor on a vertical surface," Izv. Vyssh. Uchebn. Zaved., Energet., No. 11, 56-60 (1983).
7. I. I. Gogonin, A. R. Dorokhov, and V. I. Sosunov, Heat Exchange in Film Condensation of Motionless Vapor [in Russian], (Preprint 48-80/Institute of Thermophysics, Siberian Branch, Academy of Sciences of the USSR), Novosibirsk (1980).
8. V. E. Nakoryakov, B. G. Pokusaev, S. V. Alekseenko, and V. V. Orlov, "Instantaneous velocity profile in a liquid wave film," Inzh.-Fiz. Zh., 33, No. 3, 399-404 (1977).
9. G. Schlichting, The Boundary Layer Theory, McGraw-Hill (1972).