FORCED FLOW OF A VAPOR—LIQUID STREAM IN A HORIZONTAL PIPE
WITH FILM BOILING

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The stream structure and flow regime during film boiling of liquid nitrogen in a horizontal pipe are investigated. Data on heat transfer are obtained and a model is proposed for calculating the parameters of the two-phase stream along the channel length.

Film boiling during the forced flow of a liquid in a horizontal channel is of interest for a number of engineering fields, particularly in the creation of heat-exchange apparatus and the calculation of the cooling of cryogenic manifolds. In the limited number of papers [1-3] devoted to this question, however, the structure of the two-phase stream is inadequately studied and there are no experimentally founded data on the distribution of local heat transfer over the perimeter of the pipe.

Regimes of flow of a two-phase system and heat transfer during the film boiling of liquid nitrogen in horizontal pipes under the conditions of their steady and nonsteady cooling are investigated in the present paper.

The tests were carried out on experimental sections built of Kh18N10T stainless steel pipes with inside diameters of 19 and 35 mm and a wall thickness of 0.5 mm with their steady cooling and pipes with an inside diameter of 70 mm and a wall thickness of 3.35 mm with non-steady cooling in the ranges of operating parameters P = 0.12-0.5 MPa, ρu = 40-350 kg/(m²· sec), q_w = 10-82 kW/m², and T_h = 0-2.5°K. The liquid nitrogen flow rate and temperature, the wall temperature along the length and over a cross section of the pipe, the electric power supplied to the section, and the mass vapor content of the stream at the exit from the channel, by the "helium-indicator" method, were measured in the course of an experiment [4]. To study the structure of the stream, it was photographed in an electrically heated quartz section mounted at the exit from the channel, using a pulsed light source with a pulse length of 1 μsec [5].

This investigation of the stream structure enabled us to establish that five main flow regimes, represented in Fig. 1, occur in the film boiling of liquid nitrogen in horizontal pipes [4, 6]. Stratified regime (a): The liquid, separated from the walls by a thin vapor layer, lies in the lower part of the channel while the vapor lies in the upper part. Large-scale and capillary waves are observed at the liquid surface, as well as vapor cavities. Stratified regime with a disperse phase (b): Above the liquid core in the upper part of the channel there is a stable vapor—drop stream, originating from the separation of droplets from the wave crests by the vapor stream. A constant exchange of drops occurs between the liquid in the lower part of the pipe and the vapor—drop stream. Transitional regime (c, d): The liquid core breaks up into individual liquid formations of irregular shape. Disperse-annular regime (e): Drops of different sizes are concentrated mainly in the boundary zone of the pipe. Disperse regime (f): The liquid in the form of drops is uniformly distributed over the entire channel cross section.

The test data enabled us to establish the connection between the variation of the temperature of the channel wall at the upper and lower generatrices (as shown in Fig. 2) and the flow regimes. The stratified flow regime occurs in the entrance section of the pipe up to cross section A. A disperse stream lies above the liquid core in the vicinity of cross section A. The transitional flow regime exists in section A—B, while the disperse-annular and disperse regimes exist in the section beyond cross section B. The agreement of the data on heat transfer enables us to combine the stratified regime and the stratified regime with a disperse phase, as well as the disperse-annular and disperse regimes of flow, in the further
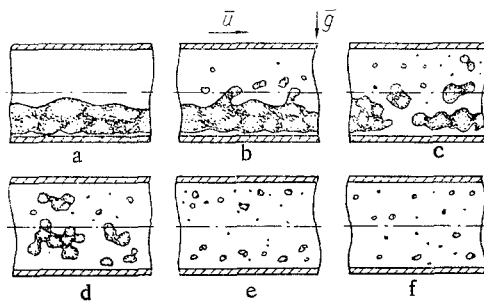
Fig. 1. Regimes of stream flow during film boiling in horizontal channels: a) stratified; b) stratified with a disperse phase; c, d) transitional; e) disperse-annular; f) disperse.
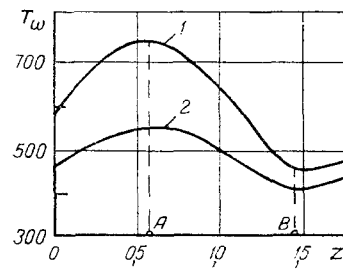
Fig. 2. Variation of wall temperature along the length of an electrically heated horizontal channel: 1) upper generatrix; 2) lower generatrix, T_W, °K; z, m.

analysis. Cross sections A and B were adopted as the characteristic cross sections in determining the boundaries of the respective flow regimes.

A comparison of the experimental data obtained on the limits of the flow regimes and the data of Baker's diagram [7] for gas—liquid streams showed their qualitative agreement. This permits us to conclude that the breakup of liquid formations takes place mainly under the action of the hydrodynamic head of the vapor, causing the appearance and development of waves at the liquid surface. The results of the tests on the boundaries of the regimes are generalized using a modified criterion of hydrodynamic stability [8]. The boundary between the stratified and transitional regimes corresponds to

$$K = (u_{\mathbf{v}} - u_l)\sqrt{\overline{\rho_{\mathbf{v}}}} / \sqrt[4]{g\sigma(\rho_l - \rho_{\mathbf{v}})} = 4, \tag{1}$$

while the boundary between the transitional and disperse regimes corresponds to

$$K' = u_{\mathbf{v}}\sqrt{\overline{\rho_{\mathbf{v}}}} / \sqrt[4]{g\sigma(\rho_l - \rho_l)} = 9. \tag{2}$$

The error of the proposed functions does not exceed ±15%.

An investigation of local heat transfer during film boiling of liquid nitrogen in horizontal channels was carried out in the stratified regime of flow and the stratified regime with a disperse phase. In these regimes, the stratification of the stream under the action of mass forces leads to considerable nonuniformity of heat transfer over the perimeter of the channel. The heat transfer in the upper part of the channel, bathed by superheated vapor or a vapor—drop stream, is determined by the velocity of the vapor, its thermophysical properties, and the hydraulic diameter of the channel not occupied by liquid.

The test results showed that in the upper part of the channel the heat transfer is described satisfactorily by a function valid for turbulent gas flow in pipes with allowance for the local values of the stream parameters:

$$\mathrm{Nu}_{\mathbf{v}} = 0.023\mathrm{Re}_{\mathbf{v}}^{0,8}\,\mathrm{Pr}_{\mathbf{v}}^{0,4}. \tag{3}$$

Here the hydraulic diameter is used as the determining size, while the physical properties of the vapor are determined from the temperature calculated with allowance for its superheating, $T_V = f(i_V, P)$, where

$$i_{\mathbf{v}} = i_{\mathbf{v}s} + (x_{\mathrm{p}}/x - 1)\,r. \tag{4}$$

The error in generalizing the experimental data by the function (3) does not exceed ±20%. The presence of drops in the vapor stream only affects the value of the vapor temperature calculated from the true value of the mass vapor content.

An analysis of the data presented in Fig. 3 on the distribution of local heat transfer over the perimeter in the lower part of the channel, bathed by liquid nitrogen, revealed that it increases along the perimeter of the channel with an increase in the angle Θ. The maximum
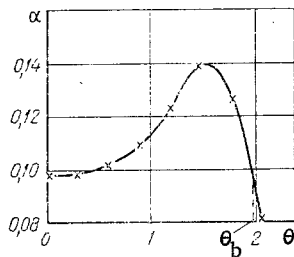
Fig. 3   Fig. 4

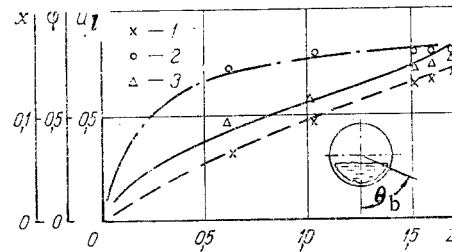Fig. 3. Distribution of the heat-transfer coefficient over the channel perimeter. α, kW/(m$^2 \cdot$K); Θ, rad.

Fig. 4. Results of a calculation from the model of the stream parameters along the length of a vapor-generating channel and their comparison with experimental data: 1) mass vapor content; 2) volumetric vapor content; 3) liquid velocity. u_l, m/sec; z, m.

of the heat transfer is reached at $\Theta = 90°$ and then $(\Theta > 90°)$ it decreases. The heat-transfer coefficient on the generatrix corresponding to the angle $\Theta = 90°$ grows by a factor of 1.4 over that at $\Theta = 0°$ for pipes 70 mm in diameter. The data obtained can be explained by the fact that turbulization of the vapor stream in the film and an increase in the oscillations of the phase interface prevail in the heat-transfer mechanism at $0 \leq \Theta \leq 90°$, while the increase in the thickness of the vapor film dominates at $90 < \Theta < 180°$.

The self-similarity of local heat transfer in the lower part of a horizontal pipe in the stratified regime of flow with respect to the liquid velocity in the investigated range of its variation, 0.5-2 m/sec, should be noted. Here the liquid velocity was calculated from the formula

$$u_l = 4G_l / \rho_l \, \pi D \, (1 - \varphi). \tag{5}$$

The volumetric vapor content is defined by the function [1]

$$\varphi = 1 - \frac{\Theta_b}{\pi} - \frac{\sin 2\Theta_b}{2\pi}. \tag{6}$$

For the stratified flow regime we obtained an empirical function for the heat transfer,

$$\mathrm{Nu}_{L,av} = 0.3 \, (\mathrm{Ra}_{L,av} / K_v^{*2})^{0,25} f, \tag{7}$$

where $f = 1 + 0.208[1 - \exp(-2K_v^{2 \cdot 5})][1 - \exp(-2.1 \cdot 10^{-4} \, \bar{D}^2)]\Theta^{1 \cdot 45}$ for $0 \leq \Theta \leq \pi/2$; $f = 1 + 0.4[1 - \exp(-2K_v^{2 \cdot 5})][1 - \exp(-2.1 \cdot 10^{-4} \bar{D}^2)](0.996 + 0.73\Theta - 0.46\Theta^2)$ for $\pi/2 < \Theta < \pi$. The scatter of the test data relative to the function (7) is ±10%.

A procedure for calculating the process of film boiling of a cryogenic liquid in horizontal channels in the stratified regime was developed on the basis of this experimental research. The following stream model was adopted: The liquid is concentrated in the lower part of the channel and separated from the walls by a thin vapor layer, while superheated vapor flows in the upper part of the channel. A one-dimensional, quasisteady model of the stream with a separate description of the phases was used for the mathematical description of the process under the following main assumptions: the temperature of the liquid equals the saturation temperature; the heat supplied to the vapor in the upper part of the channel goes into its superheating.

The system of equations for calculating the stream parameters under these assumptions has the following form:

continuity equations for the liquid and vapor,

$$\rho_l u_l \, (1 - \varphi)F = G(1 - x), \tag{8}$$

$$\rho_v u_v \varphi F = Gx; \tag{9}$$

momentum equations for the liquid and vapor,

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$$\rho_l u_l \frac{du_l}{dz} = -\frac{dP}{dz} + (\tau_{l-v}U_{l-v} - \tau_l U_l)/(1-\varphi)F +$$

$$+ \frac{G}{(1-\varphi)F}\frac{dx}{dz}(u_v - u_l),$$

(10)

$$\rho_v u_v \frac{du_v}{dz} = -\frac{dP}{dz} - (\tau_{l-v}U_{l-v} + \tau_{wv}U_{wv})/\varphi F - \frac{G}{\varphi F}\frac{dx}{dz}(u_v - u_l);$$

(11)

heat-balance equations,

(12)

$$Gx\frac{di_v}{dz} + G(i_v - i_v^*)\frac{dx}{dz} = \left| \left(\int_{\Theta_b}^{\pi} q_w d\Theta \right)/(\pi - \Theta_b) \right| U_{w,uv},$$

$$Gr(K_v^* + 1)\frac{dx}{dz} = D\int_0^{\Theta_b} q_w d\Theta;$$

(13)

equation of state of the vapor,

$$P/\rho_v = c_v i_v.$$

(14)

Uniqueness conditions are introduced for the solution of this system of equations (8)-(14): geometry of the interface, determined from the formulas

$$U_{wv} = D(\pi - \Theta_b), \quad U_l = D\Theta_b, \quad U_{l-v} = D\sin\Theta_b$$

(15)

and (6); temperature of the channel wall $T_w = T_w(z, \Theta)$; initial conditions at the entrance to the sections (P, φ, x, i_v); flow rate G. The system is closed by the functions for heat transfer to the vapor (3) and the liquid (7) and for friction at the wall and the phase interface:

$$\tau_{wv} = \frac{1}{2}\rho_v u_v^2 \xi_{wv}, \quad \tau_{l-v} = \frac{1}{2}\rho_v (u_v - u_l)^2 \xi_{l-v}, \quad \tau_l = \frac{1}{2}\rho_l u_l \xi_l.$$

(16)

The value of the hydraulic-resistance coefficient for the friction of the vapor at the wall is determined from functions for one-phase streams,

$$\xi_{wv} = \begin{cases} 64/\mathrm{Re}_v & \text{for} \quad \mathrm{Re}_v < 2000, \\ 0.3164/\mathrm{Re}_v^{0.25} & \text{for} \quad \mathrm{Re}_v \geqslant 2000. \end{cases}$$

The value of ξ_{l-v} at the phase interface is taken as 0.011 [8], which is valid for gas—liquid streams without mass exchange.

The value of the hydraulic-resistance coefficient ξ_l is obtained by generalizing experimental data on the pressure losses within the framework of this model and equals 0.03.

The results of a calculation of the stream parameters along the length of a vapor-generating channel, presented in Fig. 4, are in satisfactory agreement with test data on the volumetric and mass vapor content; the disagreement is no more than 15% in the investigated range of variation of the operating parameters.

Thus, the experimental results and the mathematical description of the process obtained in the work can be recommended for calculating the cooling of horizontal manifolds.

NOTATION

P, pressure; ρ, density; T, temperature; i, enthalpy; c_p, specific heat at constant pressure; μ, dynamic viscosity; λ, thermal conductivity; r, specific heat of vaporization; σ, surface-tension coefficient; q, heat-load density; u, velocity; G, flow rate; φ, volumetric

vapor content; x, mass vapor content; $K_V = c_{pv}(T_w - T_s)/r$, dimensionless temperature head; $K_V^* = K_V/(1 + 0.34K_V)^2$, modified dimensionless temperature head; $L = \sqrt{\sigma/g(\rho_\ell - \rho_v)}$, capillary constant; D, channel diameter; $D_h = D(\pi - \Theta_b + 0.5\sin 2\Theta_b)/(\pi - \Theta_b + \sin\Theta_b)$, hydraulic diameter; $\bar{D} = D/L$, relative diameter; F, cross-sectional area of the pipe; U, perimeter; $Pr = \mu c_p/\lambda$, Prandtl number; $Nu = qL/(T_w - T_s)\lambda_v$, Nusselt number; $Re = \rho u D_h/\mu$, Reynolds number; c_m, coefficient in the equation of state. Indices: ℓ, liquid; v, vapor; av, parameter determined at the average temperature $T_{av} = (T_w + T_s)/2$; w, at the heat-transfer wall; s, at the saturation line; e, parameter determined under equilibrium conditions.

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INFLUENCE OF ELECTRIC FIELDS ON THE KINETICS OF PHASE TRANSITIONS

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It is established that a nonuniform electric field with an average strength of 10^4-10^7 V/m has an insignificant effect on the evaporation of polar liquids, reducing its rate, while it does not affect the evaporation of nonpolar liquids.

The hypothesis that the state of the surface layer of a liquid, the degree of order of the molecules of this layer, has great influence on the kinetics of phase transitions was advanced in [1, 2]. The fact that high values of the evaporation coefficients, characterizing the kinetics of phase transitions, are obtained in evaporation from dynamic surfaces, e.g., in the discharge of liquids from orifices at a high velocity, testifies in favor of this hypothesis. The possibility of the influence of an electric field on the kinetics of phase transitions of polar substances, the molecules of which possess a constant electric moment in the direction of the axis of symmetry, due to a change in mutual orientation, disruption of surface dipoles, and the appearance of additional degrees of freedom, is discussed in [3].