HEAT TRANSFER TO TWO-PHASE FLOWS OF HELIUM AND NITROGEN IN VERTICAL CHANNELS

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Equations are presented for calculation of heat transfer in two-phase convection and well-developed bubble boiling of helium and nitrogen in vertical channels.

In studying two-phase flows of cryoagents it is possible to distinguish several regions of regime parameters in which heat liberation from the channel wall into the liquid is characterized by different laws. One of the most typical regions and one of great practical importance is that of developed bubble boiling. As is well known, the majority of cryogenic heat exchangers operate at parameter values within this region. The developed bubble boiling regime is observed at sufficiently high thermal loads, when continuous and stable vapor generation is acheived on the heating surface. The principles of heat exchange for forced motion in channels are determined for this case by the vapor formation process, with the heat liberation coefficient, as in the case of boiling in a large volume, being a function of thermal load and pressure. The intensity of heat exchange in developed bubble boiling is practically independent of the forced motion velocity and the vapor content of the flow over certain limits.

Of the various types of developed bubble boiling of cryogenic liquids in channels [1], that most studied is vapor formation center activation. In this regime increase in thermal load is accompanied by an increase in the number of centers active on the heating surface, which then leads to continuous increase in the heat liberation coefficient. This situation continues until the thermal flux reaches a critical value.* When cryogenic liquids move in channels, the relationship between the heat liberation coefficient and the thermal flux density in the vapor formation center activation regime corresponds to an expression well known for boiling in a large volume $\alpha \sim q^{0.6-0.7}$ [1-3]. The effect of pressure on heat liberation is less clear. It was concluded in [3] that the dependence of α on p for forced motion was weaker than under large volume conditions. At the same time the present authors have confirmed [1, 2] the possibility of using the Kutateladze and Borishanskii–Minchenko criterial systems for generalization of experimental data on helium and nitrogen boiling in channels and also have noted good agreement of the expression $Nu \sim K_p^{0.7}$ with the results of a majority of experimental studies.

Another no less important region of regime parameters for two-phase cryoagent flows is the low thermal flux range. Such regimes are especially characteristic of superconductive device cooling systems, where the values of specific thermal influxes and external heat liberations are as a rule insignificant. At low thermal loads liquid boiling on the heat liberating surface is either completely absent, or else undeveloped, so that convection plays the dominant role in heat exchange.

When the vapor content of the two-phase flow is close to zero, the heat liberation coefficient to the cryoliquid can be calculated [1, 2] from the equation for convective heat exchange with use of the circulation velocity

$$\alpha_0 = 0{,}023 \frac{\lambda}{d} \left(\frac{w_0 d}{\nu} \right)^{0{,}8} \Pr^{0{,}4}. \quad (1)$$

Increase in vapor content leads to a reduction in density of the medium, and for constant mass flow rate in the channel, to increase in the velocity of the two-phase mixture.

*The present study will consider only the subcritical heat-exchange region.

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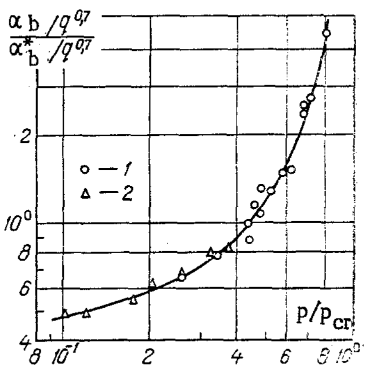

Fig. 1

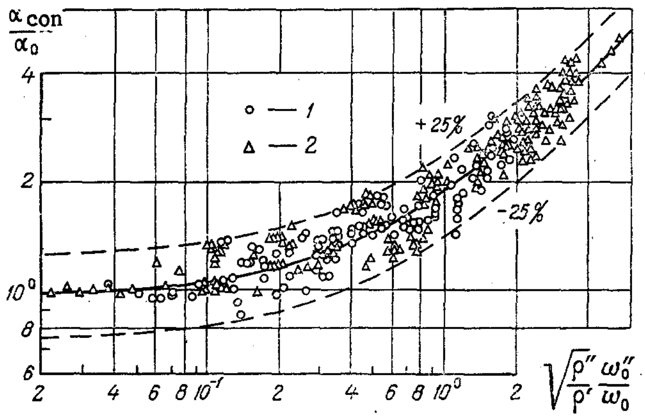

Fig. 2

Fig. 1. Effect of pressure on heat liberation coefficient for developed bubble boiling of helium and nitrogen in channels in the vapor formation center activation regime: 1) helium: $q = 40–1690\ W/m^2$; $w_0 = 0.3–2.3$ m/sec; $x = 0–0.4$; 2) nitrogen: $q = 9000–213{,}000\ W/m^2$; $w_0 = 0.2–2.7$ m/sec; $x = 0–0.6$; curve, calculation with Eq. (6).

Fig. 2. Heat liberation to two-phase flows of helium and nitrogen in the convective heat exchange regime: 1) helium: $p = 59–120$ kPa; $q = 20–1050\ W/m^2$; $w_0 = 0.3–2.6$ m/sec; $x = 0–0.7$; 2) nitrogen: $p = 500–900$ kPa; $q = 1000–9000\ W/m^2$; $w_0 = 0.3–0.9$ m/sec; $x = 0–0.9$.

Under such conditions the effect of forced flow on the heat liberation cannot be reduced to the circulation rate alone, but the vapor content of the flow will begin to play a significant role together with this parameter. The majority of experimental data involves horizontal channels [4-6], where gravitational effects can lead to a significantly nonuniform distribution of the liquid phase about the perimeter of the tube [7]. The available data for vertical channels [8, 9] are completely insufficient for production of generalized expressions for heat liberation.

In certain regime parameter ranges in two-phase flows conditions may exist under which factors defining one or the other heat exchange mechanism may prove to have an approximately identical effect on the heat liberation coefficient.

For example, it is known that in the zone of transition from single-phase convection to developed bubble boiling the heat liberation coefficient depends on both the circulation rate and the thermal flux density. The joint effect of these factors on the intensity of heat exchange can then be considered most simply by Kutateladze's interpolation expression [10]:

$$\frac{\alpha_{tp}}{\alpha_0} = \sqrt[n]{1 + \left(\frac{\alpha_b}{\alpha_0}\right)^n}. \qquad (2)$$

Equation (2) describes experimental data for water correctly at n = 2.

Another example of a two-phase flow regime parameter range in which the combined effect of vapor formation and forced convection appears is the region of high thermal loads and high vapor content. At such parameter values a dispersed-annular flow regime is formed, wherein in the central portion of the channel a vapor core moves at high velocity, with an annular liquid film flowing on the inner surface of the channel wall. With increase in vapor content the effect of thermal flux on the heat liberation coefficient gradually decreases, which explains the initial partial and final complete suppression of boiling on the wall [7]. Despite this fact, due to the low thermal resistance of the wall layer heat liberation in such regimes can be significantly higher than in developed bubble boiling.

At the present time there are no generally accepted methods for describing heat liberation to two-phase flows having high vapor content. One method which considers the combined influence of thermal load and velocity of the motion of the two-phased medium was proposed by Borishanskii [11]. The degree of influence of each of the factors is estimated from the value of the dimensionless complex $w_m\rho' r/q$, which characterizes the ratio of the quantity $w_m\rho'$, proportional to the mass velocity of the liquid in the film, to the mass velocity q/r of the vapor formed near the wall. According to experimental data for water vapor flows the limiting

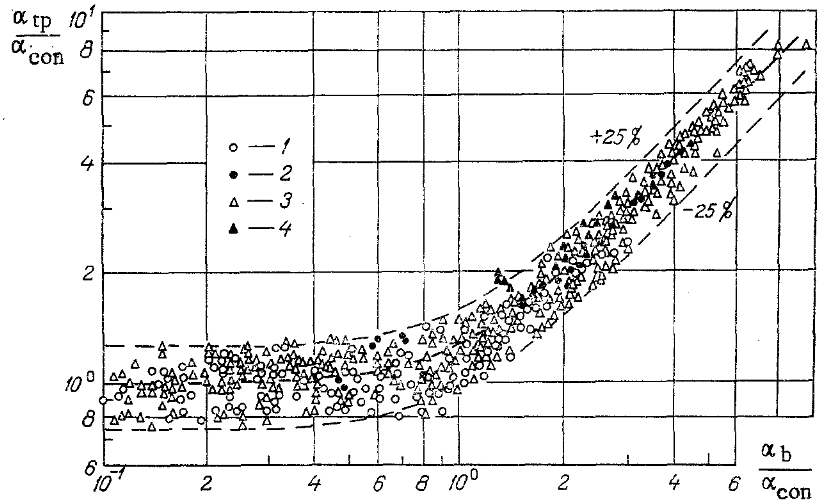

Fig. 3. Generalization of experimental data on heat liberation to two-phase flows of helium and nitrogen in vertical channels: helium: 1) present data, d = 1.63 mm, p = 59-182 kPa, q = 20-1690 W/m², w_0 = 0.3-2.6 m/sec, x = 0-0.7, 2) data of [8], d = 1.09 mm, p = 111 kPa, q = 157, 630, 1416 W/m², w_0 = 0.71 m/sec, x = 0.02-0.34; nitrogen: 3) present data, d = 2.6 mm, p = 340-1270 kPa, q = 1000-213,000 W/m², w_0 = 0.2-2.7 m/sec, x = 0-0.9; 4) data of [9], d = 10 mm, p = 180 kPa, q = 12,360, 18,630, 25,620, 34,370, 42,720 W/m², w_0 = 0.40-0.47 m/sec, x = 0-0.44; curve, calculation with Eq. (8).

value of the complex $w_m\rho'r/q$ corresponding to transition from the developed bubble boiling regime to convection is approximately $5 \cdot 10^4$. A similar approach to analysis of heat exchange in two-phase flow of cryogenic liquids in channels was used in [3]. Despite the completely obvious physical meaning of this approach, it should be noted that the dimensionless complex $w_m r\rho'/q$ is a far from complete reflection of the relationships between the various heat transfer mechanisms in the two-phase flow. The value of this complex is a proper indication only of the overall tendency of the behavior of the heat liberation coefficient with change in w_m and q for given concrete conditions. If these conditions are changed, then the limiting value of the complex $w_m\rho'r/q$ corresponding to change in the heat liberation regime can change as well. Thus, the calculation relationships obtained in [3, 11] as well as the limiting values of $w_m\rho'r/q$ obtained therein are not universal, and thus cannot serve as a basis for a broad generalization of experimental data on heat liberation to two-phase flows of cryogenic liquids in channels. In our opinion, a more promising approach to development of generalized expressions is Kutateladze's viewpoint, according to which the contributions of various heat exchange mechanisms in the two-phase flow should be evaluated by the ratio of the corresponding limiting values of the heat liberation coefficients. As has already been indicated above, use of this idea [see Eq. (2)] leads to good agreement of calculation results with experimental data for the zone of transition from single-phase convection to developed bubble boiling.

In order to obtain the general form of the computation relationship for the limiting case of convective heat exchange in a two-phase flow with high vapor content, we will consider the following approximate physical model. For the dispersed annular flow regime heat from the heating wall is transferred by thermal conductivity and convection through the liquid film moving along the inner surface of the channel to the interphase boundary, where it is expended in evaporation. In this case the intensity of heat exchange is determined essentially by the thermal resistance of the film and is practically independent of the thermal flux density. If the liquid flow regime within the film is turbulent, then the heat liberation equation can be written in the form

$$\frac{\alpha_f \delta}{\lambda} = C_\delta \left(\frac{w'\delta}{\nu}\right)^{0,8} \mathrm{Pr}^{0,4}, \tag{3}$$

where the characteristic values of length and velocity in the dimensionless quantities are the film thickness δ and the mean velocity of liquid motion in the film w'. However, both these quantities do not appear in the unambiguity condition for the process under consideration, so they must be eliminated from similarity Eq. (3). In a high speed two-phase flow

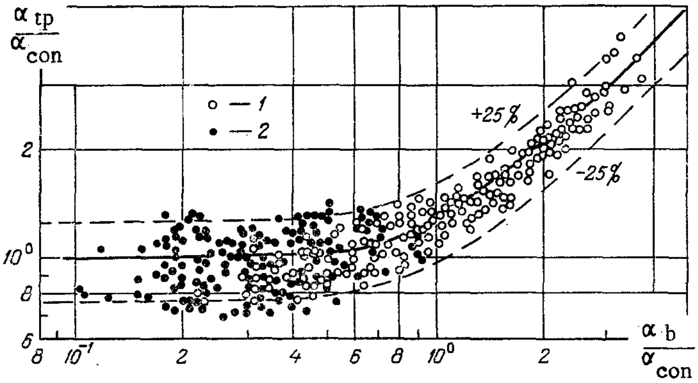

Fig. 4. Comparison of calculation with Eq. (8) with experimental data for water-vapor flow: 1) data of [11], d = 8, 12, 18 mm, p = 0.49, 1.08, 1.86, 2.55, 3.04 MPa, q = 0.24-1.55 MW/m^2, w_0 = 0.1-6.1 m/sec, x = 0.03-0.82; 2) data of [12], d = 4.6, 5.0, 6.9 mm, p = 0.18-0.80 MPa, q = 0.06-1.86 MW/m^2, w_0 = 0.45-1.35 m/sec, x = 0.3-0.9 curve; calculation with Eq. (8).

friction of the vapor flowing in the central portion of the channel on the film produces significant shear stresses on the interphase boundary, which are approximately proportional to the dynamic pressure head $\rho''(w'')^2/2$. Both the relative liquid film thickness δ/d and the speed of its motion w' depend mainly on the value of this shear stress. At high vapor content the true vapor velocity w'' can be replaced by a reduced vapor velocity w_0'' without significant error. With consideration of the remarks made above, in place of the velocity w' in Eq. (3) we may use the dynamic velocity $\sqrt{\frac{\rho''}{\rho'}}\, w_0''$. Choosing as the characteristic dimension the diameter of the tube, we obtain

$$\frac{\alpha_f d}{\lambda} = C_f \left(\sqrt{\frac{\rho''}{\rho'}}\,\frac{w_0'' d}{\nu}\right)^{0,8} \mathrm{Pr}^{0,4}. \tag{4}$$

To determine the convective heat liberation for intermediate vapor content, an interpolation expression of the form of Eq. (2) can be used, in which the limiting values of the heat liberation coefficients should be computed with Eqs. (1) and (4), in which case

$$\frac{\alpha_{con}}{\alpha_0} = \sqrt[n]{1 + C_{con}\left(\sqrt{\frac{\rho''}{\rho'}}\,\frac{w_0''}{w_0}\right)^{0,8n}}. \tag{5}$$

The magnitude of the constant C_{con} and the value of the exponent n in Eq. (5) must be determined from experimental data.

In order to answer the questions posed in the present study, experiments were performed on heat liberation in forced motion of two-phase flows of helium and nitrogen in stainless steel vertical tubes heated by an electrical current. The experiments were performed with test equipment described in detail previously [1, 2]. For helium a tube with inner diameter of 1.63 mm and heated length of 180 mm was used; the nitrogen tube was 2.6 mm in diameter and 212 mm long. The experimental data obtained encompass the following parameter ranges: $59 < p < 206$ kPa, $20 < q < 2000$ W/m^2, $0.3 < w_0 < 2.6$ m/sec, $0 < x < 0.7$ for helium; $340 < p < 1270$ kPa, $1000 < q < 213{,}000$ W/m^2, $0.2 < w_0 < 2.7$ m/sec, $0 < x < 0.9$ for nitrogen. Because a portion of the experimental data have already been published [1, 2] the present study will concern itself mainly with three questions: 1) study of the effect of pressure on heat liberation for developed bubble boiling in the vapor formation center activation regime; 2) study of the effect of velocity of motion and vapor content of the flow on two-phase convective heat exchange; 3) development of recommendations for engineering calculations of the heat liberation coefficient to a flow of cryogenic liquid over a wide range of regime parameters, including the regions of single- and two-phase convection, as well as developed bubble boiling.

In the experiments with helium the vapor formation center activation regime ($\alpha \sim q^{0.7}$) was observed in the range 59-182 kPa with thermal loads of 40-1690 W/m^2. At higher pressures, beginning at $q > 100$ W/m^2, we observed only the completely developed bubble boiling regime with its characteristic weak dependence of the heat liberation coefficient on thermal flux

($\alpha \sim q^{0.15}$) [1]. In the case of nitrogen, developed boiling with activation of centers occurred over the entire pressure range studied at $q > 9000$ W/m².

In order to determine the pressure dependence of the heat liberation coefficient in the vapor formation center activation regime, the experimental data obtained were processed in the form $\alpha/q^{0.7} = f(p/p_{cr})$. This processing established that in the range of dimensionless pressures 0.26-0.80 for helium and 0.10-0.37 for nitrogen, to an accuracy of ±25% the experimental data are described by the equation

$$\alpha_b = C_b \, q^{0,7}(1-p/p_{cr})^{-1,5}, \tag{6}$$

where C_b is equal to 12.8 for helium and 4.0 for nitrogen. The correspondence of Eq. (6) to the experimental data is shown in Fig. 1, where for convenience of presentation the experimental α values are reduced by a factor of α^*, where α^* is the value of the heat liberation coefficient calculated with Eq. (6) for a reference pressure of $p^* = 0.44\ p_{cr}$.

Analysis of the experimental data obtained revealed that in the low thermal load region the value of q has a weak effect on the intensity of heat exchange in the two-phase flow. Here the heat liberation coefficient increases with increase in circulation rate and vapor content of the flow, which indicates the convective character of heat exchange. In connection with this such experimental data are conveniently presented in the coordinates of Eq. (5). Results of processing the data are shown in Fig. 2. It is evident from the figure that the experimental points for helium and nitrogen are grouped about a curve corresponding to Eq. (5) with exponent n = 1.25. Thus, for calculation of the heat liberation coefficient to two-phase flows of helium and nitrogen in the convective heat exchange regime we can recommend the equation

$$\frac{\alpha_{con}}{\alpha_0} = \left(1 + 1,2\sqrt{\frac{\rho''}{\rho'}}\frac{w_0''}{w_0}\right)^{0,8}. \tag{7}$$

Further analysis of the experimental data consisted of a study of the transition from the convective heat exchange regime to developed bubble boiling. Results of the experiments confirm the conclusion reached previously that this transition occurs not at some constant, identical for all conditions, value of the dimensionless complex $w_m \rho' r/q$,† but when the heat liberation coefficients for convection and boiling become comparable in value. In connection with this it is desirable to represent the experimental data not as a function of the complex $w_m r \rho'/q$, but as a function of the ratio α_b/α_{con}. Results of processing the present data as well as data from [8, 9] in the form $\alpha_{tp}/\alpha_{con} = f(\alpha_b/\alpha_{con})$ are shown in Fig. 3. In all cases α_{con} was calculated with Eq. (7), the values of α_b were determined for the present experimental data with Eq. (6), and for the data of [8, 9] from corresponding expressions presented in [3, 8]. It is evident from Eq. (3) that in the proposed coordinates the values of α_{tp} for the two cryogenic liquids are generalized well. For engineering calculations the following interpolation expression can be recommended:

$$\frac{\alpha_{tp}}{\alpha_{con}} = \sqrt[3]{1 + \left(\frac{\alpha_b}{\alpha_{con}}\right)^3}. \tag{8}$$

It is obvious that at a vapor content close to zero Eq. (8) transforms to Eq. (2).

In conclusion it should be noted that the method of generalizing experimental results presented in the present study is applicable not just for two-phase flows of cryogenic liquids. As an example we can offer the experimental data of [11, 12] for a water-vapor flow, which generalize well in the coordinates of Eq. (8). Results of such processing are shown in Fig. 4.

NOTATION

C, constant; d, diameter, m; n, exponent; p, pressure, Pa; q, thermal flux density, W/m²; r, latent heat of vapor formation, J/kg; w, velocity, m/sec; w_0, circulation velocity, m/sec; w', mean liquid velocity in film, m/sec; w", mean vapor velocity, m/sec; w_0'', reduced vapor velocity, m/sec; x, vapor content; α, heat liberation coefficient, W/(m²·K); δ, film thickness, m; λ, thermal conductivity coefficient, W/(m·K); ν, kinematic viscosity coefficient, m²/sec; ρ' liquid density, kg/m³; ρ'', vapor density, kg/m³; K_p, pressure parameter; Nu, Pr, Nusselt and

†For helium, for example, the transition from convection to boiling at a pressure of 100 kPa occurred at $w_m \rho' r/q \sim 1 \cdot 10^4$, while for nitrogen the limiting value of this complex at p = 500 kPa comprised $\sim 2 \cdot 10^4$.

Prandtl numbers. Subscripts: tp, two-phase; b, boiling; con, convection; cr, critical; 0, single-phase; f, film; m, mixture; *, reference value.

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THERMAL ENTRY ZONE OF A FILM FLOW

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A simplified solution for the thermal entry zone in the stabilization of a film is confirmed by experiments at Re ≤ 450 for boundary conditions of the first type.

In the calculation, design and use of film heat exchange equipment in industrial plants and cooling systems in energy engineering, the description and evaluation of the processes of flow and heat transfer under the conditions of film stabilization are important, as is the estimation of the optimum conditions of generating the film in the thermal entry zone, where a considerable danger exists of disrupting the continuity of the flow and forming dry patches on the heat exchange surfaces [1-10]. This problem has been considered in a number of papers, a detailed analysis of which has been given earlier [3-8]. During flow under nonisothermal conditions in the entry zone a transformation of the temperature profile occurs as well as the stabilization of the velocity profile. The relationship between the lengths of the hydrodynamic entry zone, x_H, and the thermal entry zone, x_T, is determined by the value of the Prandtl number, Pr. Thus, when Pr = 1, $x_H \approx x_T$, but most often (when Pr > 1), $x_T > x_H$ [10].

A simplified analytical method has been proposed earlier [3] for calculating the velocity profiles and the lengths of the entry zones x_H for the laminar isothermal flow of wetting films on vertical surfaces, and this has been well confirmed experimentally in the zone Re ≤ 450.

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