EFFECT OF ORIENTATION OF AN ANNULAR CHANNEL ON HEAT EXCHANGE IN THE BOILING OF NITROGEN UNDER CONDITIONS OF FREE MOTION

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UDC 536.248.2.001.5

Heat transfer and the boiling crisis of nitrogen are studied in an annular channel given different orientations; the effect of the gap size on heat-transfer characteristics is explained.

The study [1] presented results of an investigation of heat transfer in the boiling of nitrogen in a vertical annular channel with different gap sizes δ. The present article is a continuation of [1] and examines the case of free motion of nitrogen in channels oriented in an arbitrary direction.

The tests were conducted at atmospheric pressure on the unit described in [1]. The 100-mm-long annular channel was a copper tube with a 7-mm-diam. heated inside surface and gauged cylindrical inserts: the gap ranged from 0.14 to 3.5 mm (without the insert). The position of the channel, defined by the angle Θ (Fig. 1), ranged from the vertical to the horizontal (Θ = 0, 45, 60, 80 and 90°); the error of Θ was no greater than ±2°. The slight difference from [1] in the method of determining the critical heat flux with a smooth transition to larger temperature heads in the case of small gaps consisted of the fact that, by analogy with [2], q_{cr} was nominally taken equal to the thermal load, corresponding to $\Delta T = 10°K$.

The effect of orientation on heat-transfer crises in boiling in plane channels and slits with free motion was investigated earlier [3-5] (for helium). Empirical formulas describing the decrease in q_{cr} as the channel deviates from the vertical were proposed for plane channels with one-sided heating. In [4] simple considerations regarding the dependence of the buoyancy acting on the vapor on Θ ($-90° < \Theta < 90°$) resulted in the expression

$$q_{cr} = [C_1 + C_2 (l/d_{eq}) (1 - C_3 \sin\Theta/\cos\Theta)]^{-1}, \tag{1}$$

where C_1 and C_2 are constants at the given pressure and the coefficient C_3 depends on the geometry of the channel. It is found by selection from the range ($0 < C_3 \leqslant 1$). In [6], generalization of test data on the boiling of helium led to

$$q_{cr} = C_4 L \sqrt{\rho_v}\, \sqrt[4]{\sigma g (\rho - \rho_v)}\, (190 - \Theta_1)^{0.65}\, \delta^{0.4}, \tag{2}$$

where Θ_1 was reckoned from the vertical to a normal to the heating surface and $C_4 = 0.065$. The range of applicability of Eq. (2) is Θ_1 = 30-150°, δ = 0.3-2 mm, $l/d_{eq} \leqslant 55$.

Equations (1) and (2) were obtained for relatively short channels (in our case, $l/d_{eq} \leqslant 178$) and cannot be used to calculate q_{cr} in horizontal channels. Also, the boiling process in annular channels is distinguished from boiling in slit-type channels particularly by the curvature of the gap. The greater this curvature, the greater the angle Θ; in connection with this, Eqs. (1) and (2) cannot be used to evaluate the relation $q_{cr}(\Theta)$ in annular channels. Evidently, no systematic experimental studies have yet been made of the effect of the orientation of channels of different geometries, including circular and annular channels, on the value of q_{cr}.

Figure 1 shows the data from out study on the relation $q_{cr}(\delta)$ in the boiling of nitrogen in an annular channel with different orientations. It is apparent that an increase in Θ from 0 to 90° leads to a decrease in q_{cr} by a factor of four to five, regardless of δ; the character of the relation $q_{cr}(\delta)$ remains the same at intermediate values of Θ.

Physicotechnical Institute of Low Temperatures, Academy of Sciences of the Ukrainian SSR, Kharkov. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 48, No. 2, pp. 181-186, February, 1985. Original article submitted October 31, 1983.

0022-0841/85/4802-0121$09.50

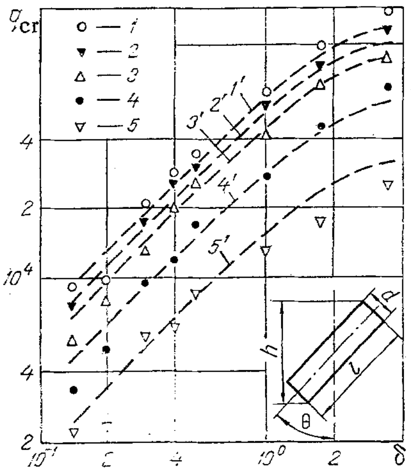

Fig. 1

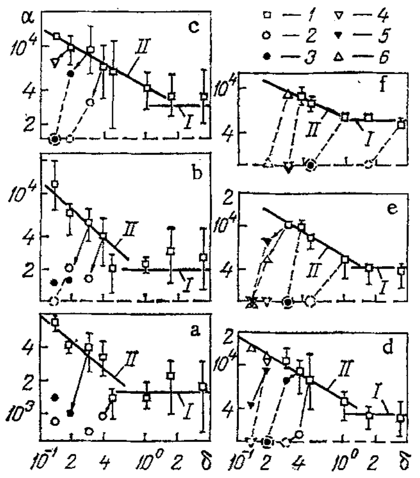

Fig. 2

Fig. 1. Relation $q_{cr}(\delta)$ with different channel orientations. Experimental data: 1-5) $\Theta = 0$; 45; 60; 80; 90°; 1'-5') calculation by (5) with $\bar{\varphi}_{cr} = 0.322$ for the same values of Θ. q_{cr}, W/m²; δ, mm.

Fig. 2. Dependence of the heat-transfer on the gap size: a-f) q = 0.5; 1; 3; 6; 10; 20 kW/m²; I) calculation by (7); II) calculation by (6) with A and n taken from Table 1. Experimental data: 1) mean values of α; 2-6) $\Theta = 90$; 80; 60; 45; 0°. α, W/m²·K; δ, mm.

Let us attempt to generalize the test data with a simple modification of the formula

$$q_{cr} = \frac{S}{F} L \sqrt{g\rho\rho_v h\varphi_{cr}}, \tag{3}$$

obtained in [2] for the case of free motion of a liquid in an annular vertical channel. Here, the channel height h determines the dynamic head, which in turns determines the possibility of evacuation of vapor from the channel. As the channel is inclined, the difference in height between upper and lower heated points of the channel decreases in accordance with the relation (see Fig. 1)

$$h = l\cos\Theta + d\sin\Theta. \tag{4}$$

Inserting (4) into (3) gives us the following for d = 7 mm and l = 100 mm

$$q_{cr} = \frac{S}{F} L \sqrt{g\rho\rho_v\varphi_{cr} l(\cos\Theta + 0.07\sin\Theta)}. \tag{5}$$

It is apparent from Fig. 1 that calculation by (5) with $\bar{\varphi}_{cr} = 0.322$ agrees satisfactorily with the experimental results; the standard deviation for φ_{cr} is ±0.083. The value of $\bar{\varphi}_{cr}$ is close to that obtained in [2, 7] in the boiling of different cryogenic fluids in vertical channels.

The effect of the angle of inclination of a slit channel on heat transfer during the boiling of water was studied in [8]; as the angle Θ increased from 0 to 90°, the heat-transfer coefficient increased by a factor of 2-2.5 in the region of moderate thermal loads. The literature does not contain any results of direct studies of this kind for annular channels. Nevertheless, it can be noted that the relations of $\alpha(\delta)$ obtained in the boiling of water in vertical [9, 10] and horizontal [11] annular channels are similar in character. At channel gaps exceeding the bubble separation diameter D_d, the heat-transfer coefficient is only slightly dependent on δ and can approximately be assumed constant and equal to α in the case of boiling in a large volume. A decrease in gap size with $\delta < D_d$ leads to a substantial increase in the heat-transfer coefficient:

$$\alpha = A\delta^{-n}, \tag{6}$$

where A is a coefficient; n = 0.57-0.67 [9-11]. The improvement in heat transfer in this case should be connected with intensive vaporization of the microscopic film of liquid under the deformed vapor bubble.

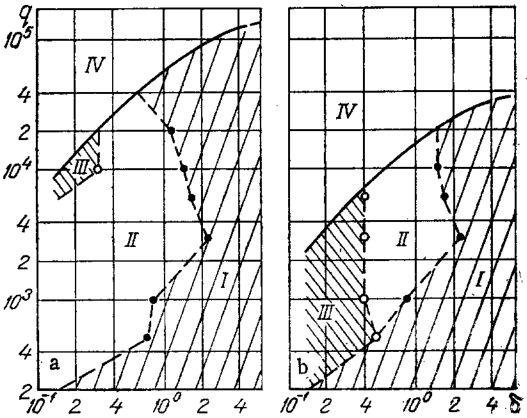

Fig. 3. Position of boundaries between heat-transfer regimes in boiling in a channel (a — $\Theta = 0°$, b — 90°; the solid lines denote q_{cr} obtained from (5) with $\bar{\varphi}_{cr} = 0.322$); I) regime of "normal" heat transfer; II) regime of "improved" heat transfer; III) regime of "deteriorated" heat transfer; IV) film boiling.

TABLE 1. Values of A and n in Eq. (6)

q, kW/m²	n	$A \cdot 10^{-3}$	δ_{br}, mm	$A\ (n = 2/3) \cdot 10^{-3}$	$K \cdot 10^2$
0,5	0,822	1,24	0,75	1,47	2,44
1,0	0,888	1,69	0,84	2,15	2,83
3,0	0,514	4,33	2,26	3,67	3,35
6,0	0,577	4,89	1,70	4,54	3,28
10,0	0,586	5,31	1,46	5,11	3,13
20,0	0,402	5,67	1,15	4,70	2,28
Average	0,631		1,36		2,88

A further decrease in δ with q = const leads at a certain moment either to the onset of the crisis (at large q) or to a transition to a region of "deteriorated" heat transfer (at moderate q), which is characterized by a rapid decrease in α with an increase in thermal load [9, 10]. This transition is probably connected with drying of the liquid film on the heat-emitting surface and the onset of a disperse regime of flow of a vapor—liquid mixture in a substantial portion of the channel.

We obtained curves of nitrogen boiling in an annular channel of the above dimensions with five different orientations and heat fluxes from 100 W/m² to those corresponding to $\Delta T \approx 30°K$ (with a further increase in ΔT, the power to the heating element was cut off due to the danger of burning of the element).

Analysis of the results established that the curves of q(ΔT) corresponding to different channel orientations are qualitatively similar to the data in [1], which was obtained only for a vertical orientation; in connection with this, the primary data is omitted here. It also turned out that the value of the angle Θ has almost no effect on the heat-transfer coefficient in the regimes of "normal" and "improved" heat transfer and determines only the conditions of the transition to "deteriorated" heat transfer or crisis onset.

Figure 2 shows test data on the relation α(δ) with six values of heat flux; the decrease in the heat-transfer coefficient with contraction of the gap and q, Θ = const is noted by arrows or dashed lines. In the last case, a dashed horizontal line and boxes conditionally (so as not to stretch the figure in the vertical direction) correspond to heat-transfer coefficients of 200-500 W/m²·K. Arithmetic mean values of α are shown for the "normal" and "improved" heat-transfer regimes for all channel orientations, along with maximum deviations from the mean values.

Despite the considerable (especially at moderate q) scatter of the data, it can be noted that at $\delta \geqslant 1$ mm there is similarity for the mean values of the heat-transfer coefficient relative to δ. Meanwhile, with a decrease in q, this region tends to expand in the direction of smaller gaps. The test data corresponding to the similarity regions (regime of "normal" heat transfer) was approximated by the expression

$$\alpha = 198q^{1/3}. \tag{7}$$

The results corresponding to regions with improved heat transfer were approximated by Eq. (6). The calculated values of A and n are shown in Table 1; it is apparent that n increases with a decrease in q, i.e., the relation $\alpha(\delta)$ becomes stronger.

The study [12] proposed a formula for the heat-transfer coefficient in boiling in a vertical slit channel:

$$\alpha = K\frac{\lambda}{\nu}\left(\frac{\sigma hq}{\rho\rho_V L\delta^2}\right)^{1/3}, \tag{8}$$

according to which $\alpha \sim \delta^{-2/3}$. The mean value of n from the table is 0.631, which corresponds roughly to the theoretical value from (8). The values of A (n = 2/3) in (6) determined from the test data are shown in Table 1. Also shown are values of δ_{br} obtained from the intersection of lines I and II in Fig. 2; the mean value δ_{br} = 1.36 mm. This is somewhat greater than the value of the Laplace constant at atmospheric pressure (1.06 mm) and is roughtly twice as great as the value of D_d in the boiling of nitrogen in a large volume [13].

Using the values A(n = 2/3) and the thermophysical properties of nitrogen and having equated (6) and (8), we can find the coefficient K for the region of "improved" heat transfer. Values of K are shown in Table 1. The mean $\bar{K}$ = 0.029, as in [1], which obtained data only for a vertical channel. Thus, Eq. (8), with K = 0.029, can be used here to evaluate α with any value of Θ.

The results obtained can be used to construct a diagram of the heat-transfer regimes; such a diagram is shown in Fig. 3 for vertical and horizontal channels. The position of the boundaries between the regimes was drawn approximately (and tentatively, in the regions bordered by film boiling and single-phase convection); all of the main tendencies can be seen fairly well. The diagram can be used for a prescribed set of regimes and geometric parameters to find which regime will occur, and the corresponding relation can be used to calculate α; by changing any of the parameters (such as the gap size), we can change over to the region II, which is more desirable in regard to intensifying heat transfer. It is apparent from Fig. 3 that this region is considerably smaller when the channel is horizontal, which makes it difficult to optimize the heat-transfer process.

NOTATION

A, C, coefficients; d, channel diameter; d_{eq} = 4S/P, equivalent diameter of channel; D_d, bubble separation diameter; F, area of heat-emitting surface; g, acceleration; h, channel height; K, coefficient; l, channel length; L, heat of vaporization; n, exponent; P, heated perimeter of channel cross section; q, heat flux; S, cross-sectional area of channel; ΔT, temperature head; $\alpha = q/\Delta T$, heat-transfer coefficient; δ, size of annular gap; λ, thermal conductivity of liquid; ν, kinematic viscosity of liquid; ρ, ρ_V, density of liquid and vapor; σ, surface tension; Θ, Θ_1, angles characterizing the channel orientation; φ_{cr}, calculated critical vapor content at channel outlet; δ_{br}, boundary value of gap size; q_{cr}, critical heat flux.

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BOILING OF SUPERHEATED n-PENTANE IN AN ELECTRIC FIELD

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UDC 536.423:537.212

Results are presented from an experimental study of the effect of a stationary electric field on the probability of boiling of superheated n-pentane.

The time that a system exists in the metastable state is determined by the probability of the nucleation of a new phase capable of subsequent growth in the system. The work expended in the formation of the new phase depends on the properties of the metastable system and external conditions [1]. In particular, according to theoretical estimates [2-4], the energy of formation of a critical vapor bubble in a superheated liquid increases, which leads to a decrease in the probability of boiling and an increase in the temperature of maximum superheating.

Relatively few studies [5-7] have experimentally investigated the effect of an electric field on a superheated liquid and each study has reported the effect opposite to that predicted by the theory, i.e., an electric field initiated the phase transition. The allowance made for compressibility of the liquid in later theoretical works [8, 9] showed that under certain conditions (restricted free movement of the liquid), an electric field can initiate boiling.

It should be noted that, according to the theoretical estimates, the effect of an electric field should appear at field-strengths close to the breakdown value — 10^8-10^9 W/m.

We studied the effect of a stationary electric field on the boiling of a superheated dielectric liquid. The mean strength of the field in the liquid was about 10^6 W/m. We used the method from [1] to measure the mean lifetime of the liquid in the prescribed metastable state. The method makes it possible to obtain comparable measurements with and without a field at relatively low field strengths (thus eliminating the possibility of breakdown of the liquid).

Department of Physicotechnical Problems of Power Engineering, Ural Science Center, Academy of Sciences of the USSR, Sverdlovsk. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 48, No. 2, pp. 186-189, February, 1985. Original article submitted November 23, 1983.

0022-0841/85/5802-0125$09.50