STUDY OF HEAT EXCHANGE DURING THE BOILING OF NITROGEN MOVING FREELY IN VERTICAL ANNULAR CHANNELS

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A study was made of heat transfer and the nucleate boiling crisis of nitrogen in annular vertical channels; it was established that the size of the gap affects heat-transfer characteristics.

The introduction of promising nitrogen-based technologies in several sectors of the national economy (storage of food products, etc.) requires knowledge of the heat-transfer laws in the boiling of liquid nitrogen under different conditions in order to develop economical and efficient cooling systems. There has been fairly detailed study of heat transfer during boiling in a large volume and with forced motion in channels; at the same time, only a few investigations [1, 2] have focused on the boiling of nitrogen during free motion in narrow annular channels. It is known nevertheless that heat transfer may be intensified considerably during boiling in narrow channels with certain gap sizes [3, 5]. Moreover, cooling systems with free motion in channels have the important property of being self-regulating: an increase in the heat input causes an increase in the rate of flow of the coolant through the channel.

The investigation [1] studied the heat-transfer crisis in the nucleate boiling of nitrogen and hydrogen in a flow-through vertical annular channel with a heated inner tube (diameter 12.7 mm); $h = 78\text{-}152$ mm, $\delta = 0.178\text{-}1.07$ mm. Pressure was $7.7 \cdot 10^4$ Pa. The data on the function $q_{cr}(\delta)$ is in satisfactory agreement with values calculated from the formula derived by the authors of [1]:

$$q_{cr} = \frac{S}{F} L (\rho \rho_v h g \varphi_{cr})^{1/2}, \tag{1}$$

$\varphi_{cr} = 0.42 - 0.54$.

The study [2] examined heat transfer in the boiling of nitrogen and neon at atmospheric pressure in a flow-through vertical annular channel with a heated inner tube 76 mm in diameter (steam heating); $h = 190$ mm, $\delta = 0.152\text{-}2.03$ mm. A criterional equation describing the test results was obtained.

Besides the practical value of studying the boiling of nitrogen under constrained conditions, the subject is also important for the development of the physics of boiling. It is well known that during the boiling of water and organic liquids there is a substantial increase in α with a decrease in the size of the gap in an annular or slitlike channel below a certain value [3, 5]; according to current representation, heat transfer is intensified as a result of an increase in the contribution of microlaminar boiling due to deformation of vapor bubbles in the narrow gaps. Thus, δ has a substantial effect on α when $\delta \leqslant AD_d$, where $A = 1\text{-}2$. These representations are supported by the available data: at atmospheric pressure $\delta_{bd} \simeq 3$ mm for water [3, 4] ($D_d \simeq 2.5$ mm according to [6]) and $\delta_{bd} \simeq 1.6$ mm [4] ($D_d \simeq 1.1$ mm according to [6]). The quantity δ was not seen to affect α in the boiling of helium in vertical channels, despite a decrease in gap size to $\delta = 0.254$ mm [7]. This is also consistent with the foregoing, since $D_d = 0.08\text{-}0.17$ mm for helium at atmospheric pressure [8, 9].

Nitrogen occupies an intermediate position between helium and water with respect to the bubble separation diameter ($D_d \simeq 0.44$ mm [10]); if the concept of microlaminar boiling is valid, then α should be quite dependent on δ at $\delta \leqslant 0.5\text{-}1$ mm. When $\delta < \delta_{bd}$

$$\alpha \sim \delta^n, \tag{2}$$

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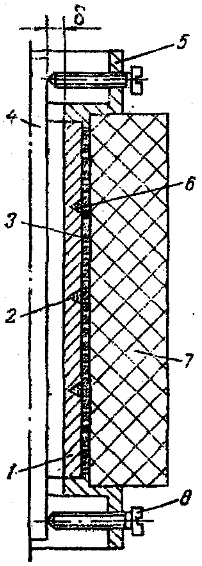

Fig. 1. Diagram of experimental channel: 1) copper tube; 2) working junction of thermocouple; 3) heating element; 4) rod-insert; 5) steel bushing; 6) removable copper ring; 7) heat-insulating material (textolite); 8) screw.

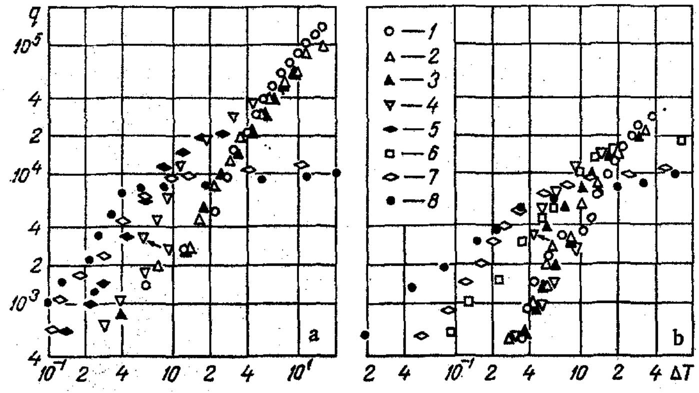

Fig. 2. Data on the boiling of nitrogen in flow-through (a) and blind (b) channels; 1-8) δ = 3.5; 1.75; 1.02; 0.49; 0.395; 0.295; 0.195; 0.14 mm. q, W/m²; ΔT, °K. The 10 of the ΔT axis should be 10°.

where n = −0.514 [3]; n = −0.667 [4, 11]. A similar relationship also follows from certain theoretical formulas [12]:

$$\alpha = B\frac{\lambda}{\nu}(\sigma h q/\rho\rho_v L\delta^2)^{1/3}. \qquad (3)$$

In analyzing the criterional equation which generalizes the data in [2], however, it turns out that the function α(δ) is absent in the above range of δ for the boiling of nitrogen and neon. This may be a consequence of the specifics of the method used to heat the heat-emitting surface in [2]; in any case, the question requires additional study.

The experiments conducted on water in [5] showed that boiling in blind channels is different from boiling in flow-through channels in regard to several characteristics. In connection with this, it is interesting to study the effect of the type of channel on α and q_{cr} during the boiling of a cryogenic liquid.

The present study of heat transfer during the boiling of nitrogen was conducted at atmospheric pressure in a vertical channel 100 mm long (Fig. 1). The heat-emitting surface

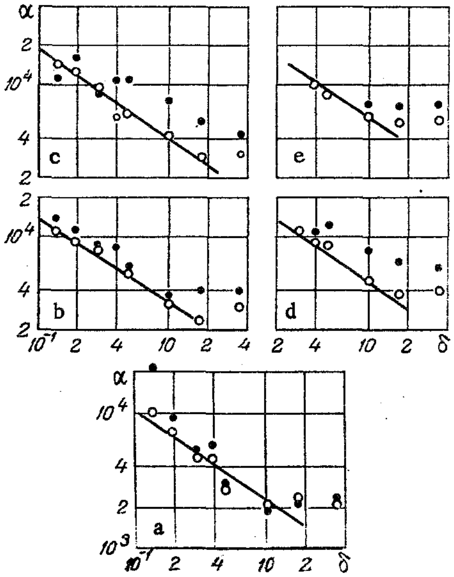

Fig. 3. Dependence of the heat-transfer coefficient on the gap size with different q = const: a-e) q = 1; 3; 6; 10; 20 kW/m². The clear points are for the through channels; the dark points are for blind channels. The solid lines are for results obtained from Eq. (3) with B = 0.029. α, W/m²•K; δ, mm. The number 10 on the δ axis in Fig. 3 and 4 should be replaced by 10°.

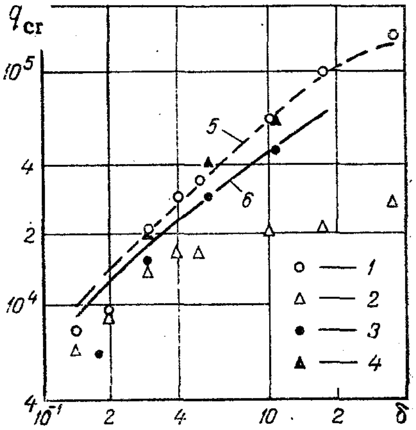

Fig. 4. Dependence of the critical heat flux on the gap size. Our data: 1) flow-through channel; 2) blind channel. Data from [1] (nitrogen): 3) h = 152 mm; 4) h = 78 mm; 5) data from Eq. (1) with $\varphi_{cr} = 0.365$; 6) data from Eq. (6) with $C_1 = 7.09 \cdot 10^{-6}$ m²/W, $C_2 = 5.77 \cdot 10^{-7}$ m²/W. q_{cr}, W/m².

was the inside part of a copper tube (7 mm in diameter, wall thickness of 1 mm) the outside surface of which was enveloped by the heating element. The channel was enclosed in a heat-insulating textolite shell. The temperature difference between the heat-emitting surface and the liquid was determined from the readings of three differential copper—constantin thermocouples, the working junctions of which were inserted into annular grooves under the heater 25, 50, and 75 mm from the bottom end of the channel. Copper rings were installed on top of the grooves. The common junction of the thermocouples was located in the liquid from outside the shell. The emf of the thermocouples was measured with an F-30 digital microvoltmeter. The heat flux was determined from the readings of an É59 kl. 0.5 voltmeter and an M104/1 kl. 0.2 ammeter; the power source was a VSA-5K rectifier.

Gaps of different sizes δ were created by placing gauged metal rod-inserts on the channel axis, centering them, and fastening them with screws. Gap size δ was changed from 3.5 mm (without an insert) to 0.14 mm; centering accuracy was about 0.05 mm. Tests were conducted with both a flow-through and a blind (closed at the bottom) channel. The textolite block was suspended together with the channel in a glass Dewar flask filled with liquid; there was less than 40-50 mm of liquid above the top end of the channel. The heat input during the tests was gradually increased either until the crisis was reached or until the temperature head went above 30°K. The tests with the inserts were repeated 2-4 times, with an interval of several days, and showed that the results were satisfactorily reproducible.

Figure 2 shows data on the boiling of nitrogen in the form $q(\Delta T)$, where ΔT is the arithmetic mean of the readings of three thermocouples. It is apparent that there is substantial layering of the data at $\delta \leqslant 1.02$ mm; the lower δ, the lower ΔT at the given heat input. Except for the precrisis region, the dependence of q on ΔT corresponds to $q \sim \Delta T^{3/2}$, as follows from Eq. (3). When $\delta \geqslant 0.49$ mm, there is a sudden transition to film boiling; the last two points in Fig. 2 correspond to the crisis. If $\delta \leqslant 0.39$ mm, there is a smooth transition with stable intermediate points, as in [1]. The curves for the boiling of nitrogen in the flow-through and blind channels are qualitatively of the same character (compare a and b in Fig. 2).

In tests with a gap size of 0.49 and 1.02 mm, there is a sharp decrease in ΔT with an increase in q to 2-4 kW/m^2; examples of such a decrease are shown by the arrows in Fig. 2. This phenomenon has at least two explanations. First, the decrease in ΔT may occur during intensive boiling of the liquid over the entire heat-emitting surface (as in [10]). We note, however, that the first vapor bubbles appear at the channel outlet as early as q = 1 kW/m^2. Another possible explanation is based on the fact the D_d increases with an increase in ΔT: if the separation regime is dynamic [13], then

$$D_d \sim \Delta T^{4/3}. \tag{4}$$

Moreover, after separation, the surfacing bubble continues to increase its velocity in proportion to ΔT [14]. It follows from this that if at small q the value of $D_d < \delta_{bd}$ (and α is independent of δ), then the relationship between D_d and δ will change with an increase in q. In fact, at q = 1 kW/m^2, ΔT = 0.3-0.5°K for δ = 0.49-1.02 mm and $D_d < \delta$. At q = 3 kW/m^2, ΔT = 0.8-1.4°K; and increase in ΔT by a factor of two or three, in accordance with Eq. (4), leads to an increase in D_d to 1.1-1.9 mm, i.e. to a situation where $D_d > \delta$.

Figure 3 shows the effect of gap size on the heat-transfer coefficient. The values of α were averaged over several tests, in contrast to the data in Fig. 2. The results, obtained in flow-through channels with $\delta \leqslant 1.02$ mm (and with δ = 1.75 mm in several cases), agree well with the values found from Eq. (3) at B = 0.029. Values of B = 0.0089 and 0.028 were obtained for ethanol and water, respectively, in [15]. Other conditions being equal, the heat-transfer coefficient is higher during boiling in the blind channel than in the through channel. Meanwhile, the difference increases with an increase in q and δ. This may be attributed to the different hydrodynamics of cocurrent flows and countercurrent flow.

An increase in α during the boiling of water in blind channels relative to the value obtained in through channels was also seen in [5].

It is interesting to note that the function $\alpha(\delta)$ obtained here agrees satisfactorily with the data in [16] on the boiling of oxygen in channels of larger diameter (d = 4-10 mm, which is much larger than the value of D_d). According to [16], an increase in α may occur at $h/d \geqslant 80$ and

$$\alpha \sim (h/d)^{0.65}. \tag{5}$$

In our case, the boundary value of h/δ = 60-100, while $\alpha \sim \delta^{-2/3}$

The transition to film boiling begins almost at the same time over the entire heating-emitting surface. Data on q_{cr} is shown in Fig. 4; in the case of small gaps, where the transition occurs without a jump in ΔT, for q_{cr} we took the thermal load at which there is a change in the slope of the boiling curve (see Fig. 2). It should be noted that in [1] in these cases the critical thermal load was established as corresponding to ΔT = 10°K; the results from [1] are also shown in Fig. 4 and agree well with our data here on the crises in through channels. It is therefore logical to use Eq. (1) to describe the data. The mean value $\varphi_{cr}=0.365$, calculated from the data in Fig. 4, lies between $\varphi_{cr}=0.3$ obtained in [7] for helium and the values of φ_{cr} found in [1] for nitrogen and hydrogen. The standard deviation our data here from the values calculated from (1) with $\varphi_{cr}=0.365$is ±16%. The relatively large deviations of the calculated values of q_{cr} from the experimental values at values of δ equal to 0.14 and 0.195 mm is probably due to the relative inaccuracy of centering of the inserts and some ambiguity in the determination of q_{cr}.

The fact that q_{cr} is directly proportional to S means that the corrected critical vapor velocity at the channel outlet is constant; it averages 7.8 m/sec in this case.

An alternative to (1) is an expression of the type [17]

$$1/q_{cr} = C_1 + C_2(h/d_{eqv}), \tag{6}$$

where C_1 is the inverse of the critical heat flux in a large volume of liquid. Determining the latter from Kutateladze's formula [18]

$$1/C_1 = KL\sqrt{\rho_v}\sqrt[4]{\sigma g(\rho-\rho_v)} \tag{7}$$

with allowance for Vishnev's correction [19] for the effect of orientation for a vertical surface

$$K = K_0\sqrt{(190-\Theta)/190}, \tag{8}$$

we obtain $C_1 = 7.09 \cdot 10^{-6}$ m²/W at $K_0 = 0.16$ and $\Theta = 90°$. We find $C_2 = 5.77 \cdot 10^{-7}$ m²/W from the test data using the least squares method. The standard deviation of the data form the values calculated from Eq. (6), with the values found for C_1 and C_2, is ±30%.

It can be seen from Fig. 4 that the transition to film boiling in blind channels occurs at lower q_{cr} than in flow-through channels with the same gap size δ. The form of the function $q_{cr}(\delta)$ for the two types of channels coincides at $\delta \leqslant 0.49$ mm ($q_{cr} \sim \delta$); if $\delta > 0.49$ mm, then $q_{cr} \sim \delta^{1/4}$ for blind channels. This does not agree with the data in [5, 20] (water), where such a substantial difference was not found; the question requires further study.

Thus, intensification of heat transfer during the boiling of nitrogen in annular channels occurs under conditions consistent with represenations on microlaminar evaporation and can be taken into account with known forumulas. The use of blind channels leads to an even greater increase in α but also leads to a decrease in the limiting thermal load.

NOTATION

A, B, C_1, C_2, constants; D_d, bubble separation diameter; d, channel diameter; $d_{eqv} = 4S/R$, equivalent diameter; F, area of heat-emitting surface; g, acceleration; h, length of vertical channel; K, stability criterion; L, latent heat of evaporation; R, heated perimeter of cross section of channel; q, heat flux; S, cross-sectional area of channel; ΔT, temperature head; $\alpha = q/\Delta T$, heat-transfer coefficient; δ, channel gap; λ, thermal conductivity of liquid; ν, kinematic viscosity of liquid; ρ, ρ_v, density of liquid and vapor, respectively; σ, surface tension; Θ, angle of inclination of heat-emitting surface; φ, vapor content at the channel outlet. Indices: bd, boundary value; cr, heat-transfer crisis.

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