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

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Heat transfer and the boiling crisis are studied in nitrogen in annular channels with various gap sizes at pressures from $1.25 \cdot 10^4$ to $9 \cdot 10^5$ Pa.

It is well known that in bubble boiling of liquids a decrease in the size of the gap (or diameter) δ to a certain point δ_{lim} has practically no effect on the heat-liberation coefficient; for $\delta < \delta_{lim}$

$$\alpha = A\delta^{-n}, \tag{1}$$

where n varies over the range $0 < n \lesssim 1$ depending on a combination of geometric and thermal parameters (most often n = 0.5-0.7). Data permitting approximate determination of δ_{lim} have been obtained for boiling of water [1-3], ethanol [3], some freons [4, 5], and nitrogen [6-8]. At the same time, in the case of helium boiling in channels [9, 10] it has been impossible to achieve the region of "improved" heat transfer even at $\delta = 0.2$ mm (i.e., $\delta_{lim} < 0.2$ mm). All of the studies noted with the exception of [1] offer values of δ_{lim} at atmospheric pressure; according to [1], δ_{lim} decreases with increase in pressure.

The intensification of heat exchange in narrow channels can be explained by deformation (oblation) of vapor bubbles as they grow and move along the channel [1-5]; in this case, the value of δ_{lim} should be related to the characteristic size of the vapor phase – the capillary constant b or the bubble breakaway dimension D_d. A choice of one of these parameters, both of which decrease with increasing pressure, can be made by studying their correlation to the quantity δ_{lim}. It is thus of interest to experimentally determine the conditions required for transition to "improved" heat exchange over a wide pressure range.

The present study is a continuation of investigations described in [6, 7], and was performed with the same devices and same 100-mm-long vertical channel with heat-liberating surface 7 mm in diameter. Annular channels with various gap sizes were constructed by placing calibrated cylindrical inserts into the heated copper tube: $\delta = 0.14$-3.5 mm (the last value corresponding to one half the channel diameter with no insert). Experiments were performed at $p = (0.125\text{-}9) \cdot 10^5$ Pa in a metallic cryostat, the construction of which was described in [11].

Figure 1 shows typical data on the function $\alpha(\delta)$ at various combinations of q and p. It is evident that in the region of "normal" heat exchange (practical independence of α from δ) increase in pressure leads to a significant increase in α; simultaneously, the boundary of this region shifts in the direction of smaller gaps. The experimental data corresponding to the "normal" regime were processed in the form

$$\alpha = Cq^m \tag{2}$$

for thermal loads from 500 W/m² to q_{cr}. Use of the method of least squares for pressures $p = (0.125, 0.2, 0.5, 1, 2, 4, 6, 9) \cdot 10^5$ Pa gives values of m = 0.66, 0.54, 0.48, 0.59, 0.49, 0.53, 0.49 and C = 5.42, 6.07, 21.9, 49.8, 18.4, 54.3, 41.1, 63.5.

In both their magnitude and the way they change with pressure the values of the exponents m are close to those which have been observed for nitrogen boiling in a large volume [12]. The effect of pressure on α is also similar; the expression proposed in [13] for boiling in a large volume:

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TABLE 1. Results of Processing Experimental Data in Form of Eq. (1) and Determination of δ_{lim}

q, W/m^2	$p \cdot 10^{-5}$, Pa							
	0,125	0,2	0,5	1,0	2,0	4,0	6,0	9,0
				$A \cdot 10^{-3}$				
$5 \cdot 10^2$	0,45	0,44	0,84	1,13	0,38	1,09	0,49	0,62
10^3	0,74	0,73	1,41	1,61	1,28	1,48	1,01	1,15
$3 \cdot 10^3$	1,71	2,60	2,75	3,30	2,48	1,14	2,04	1,57
$6 \cdot 10^3$	3,17	3,91	3,80	3,99	3,41	1,75	2,54	2,02
10^4	4,06	4,57	4,34	4,55	4,32	2,55	2,88	2,66
$2 \cdot 10^4$	—	5,26	5,73	4,36	4,95	3,51	3,93	4,16
				n				
$5 \cdot 10^2$	0,18	0,22	0,32	0,22	1,90	0,52	1,02	0,90
10^3	0,43	0,32	0,52	0,70	0,92	0,59	0,87	0,74
$3 \cdot 10^3$	0,78	0,54	0,61	0,56	0,75	1,36	0,89	1,13
$6 \cdot 10^3$	0,53	0,54	0,65	0,68	0,83	1,34	1,05	1,23
10^4	0,42	0,45	0,60	0,77	0,77	1,18	1,14	1,18
$2 \cdot 10^4$	—	0,25	0,30	0,81	0,60	1,05	1,03	1,02
				δ_{lim}, mm				
$5 \cdot 10^2$	5,08	4,05	2,32	2,13	0,73	0,96	0,46	0,43
10^3	2,17	1,90	2,04	1,31	1,28	0,92	0,59	0,53
$3 \cdot 10^3$	1,78	3,95	2,18	1,98	1,39	0,54	0,69	0,54
$6 \cdot 10^3$	3,15	3,57	1,92	1,42	1,22	0,57	0,64	0,52
10^4	3,41	3,12	1,60	1,19	1,15	0,59	0,58	0,52
$2 \cdot 10^4$	—	2,11	1,82	0,74	0,77	0,54	0,69	0,52
$\overline{\delta}_{lim}$, mm	3,12	2,77	1,98	1,46	1,09	0,68	0,61	0,51

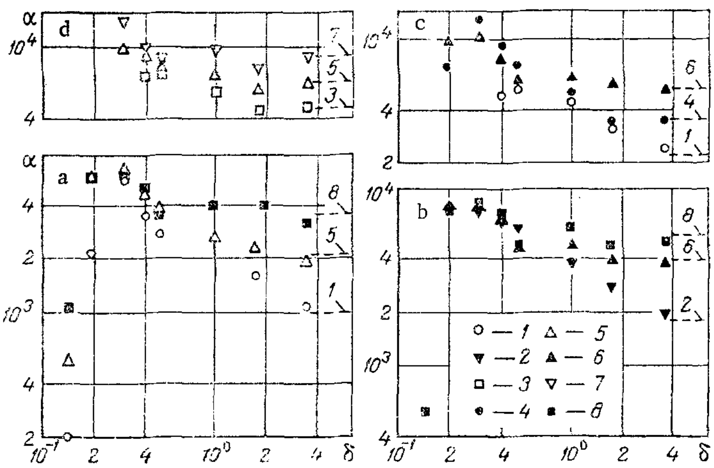

Fig. 1. Heat-transfer coefficient vs channel gap size: a-d correspond to q = 3, 6, 10, and $20 \cdot 10^3$ W/m^2; 1-8) p = (0.125, 0.2, 0.5, 1, 2, 4, 6, 9)$\cdot 10^5$ Pa; dashed lines are calculations with Eq. (3) for $B = 4.19 \cdot 10^{-4}$ α, W/m^2·K, δ, mm.

$$\alpha = B\,(qb/L\rho_v a)^{0.6}\,[p/\sqrt{\sigma g(\rho-\rho_v)}]^{0.7}\,(gb^3/\nu^2)^{0.125}\lambda/b \tag{3}$$

describes the data corresponding to "normal" heat exchange with a mean square deviation of 16% at $B = 4.19 \cdot 10^{-4}$. This value is quite close to that of $3.25 \cdot 10^{-4}$ recommended in [14] for cryogenic liquids.

In the "improved" heat-exchange regime, where the function $\alpha(\delta)$ follows Eq. (1), the pressure has practically no effect on the intensity of heat exchange; α increases only insignificantly over the p range studied, much less than in the "normal" regime, as in the case of freon-12 boiling in [4]. In [1], for boiling of water in the "improved" heat-exchange regime α decreased with increase in pressure. Apparently, increase in p, producing a

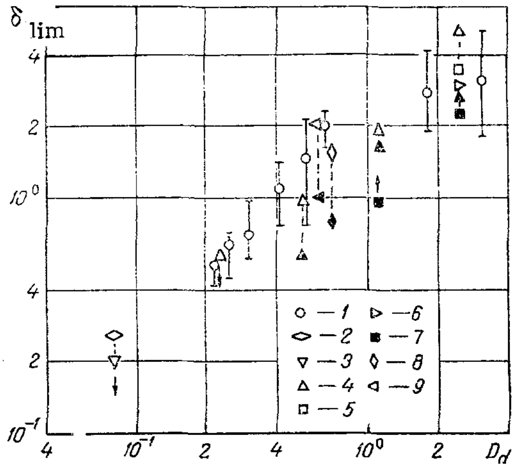

Fig. 2. Limiting gap size vs bubble breakaway diameter: 1) nitrogen, data from present study; 2) helium, data of [9]; 3) helium [10]; 4) water [1]; 5) water [2]; 6) water [3]; 7) ethanol [1]; 8) freon-12 [4]; 9) freon-113 [5]; δ_{lim}, D_d, mm.

decrease in D_d, leads to a decrease in bubble deformation, which is the cause of heat-transfer intensification.

Processing of the data on α corresponding to the "improved" regime in the form of Eq. (1) gave the results presented in Table 1. The value of n varies over a quite wide range ($0.2 \lessapprox n \lessapprox 1$), while maintaining a tendency to decrease with increase in q and reduction in p. The average value $\bar{n} = 0.75 \pm 0.36$.

Comparison of α values obtained experimentally with calculations by the expression

$$\alpha = B_1 \frac{\lambda}{\nu} \left(\frac{\sigma h q}{L \rho \rho_v \delta^2} \right)^{1/3} \tag{4}$$

proposed in [15], which satisfactorily describes data on nitrogen boiling in an annular channel at $p = 10^5$ Pa [7] with $B_1 = 0.029$, shows that the dependence of α on q in experiment and according to Eq. (4) are approximately identical. At the same time, the coefficient B_1 is a function of pressure: $B_1 = 0.13\,(\rho/\rho_v)^{0.34}$. Meanwhile, even a modified variant of Eq. (4)

$$\alpha = 0.13 \frac{\lambda}{\nu} \left(\frac{\sigma h q}{L \rho^2 \delta^2} \right)^{1/3} \tag{5}$$

gives a significant mean square deviation (37%) from the experimental data, basically because of the constancy of the exponent of δ.

For each combination of p and q the value of δ_{lim} was determined by simultaneous solution of Eqs. (1) and (2) with corresponding coefficients and exponents, and is presented in Table 1. It is evident that the limiting values δ decrease with increase in pressure, changing by almost an order of magnitude; the value of δ_{lim} obtained in the present study for $p = 10^5$ Pa agrees well with the $\delta_{lim} = 1.5b = 1.59$ mm indicated in [8].

Figure 2 shows values of δ_{lim} as functions of D_d, the bubble breakaway diameter determined in [12], for the range q = 500-20,000 W/m² (at $q \geq 40{,}000$ W/m² the "improved" regime is practically indetectable). In order to make the most general comparison possible, estimates of δ_{lim} for other liquids are also presented. Because of the definite subjectivity of such estimates, points are presented which approximately delimit the zone of transition from "normal" heat exchange (light symbols) to "improved" (dark symbols); the value of δ_{lim} lies between these points. The uncertainty of the transition is shown by arrows — δ_{lim} is below (above) the unpaired point, but its value is unknown. In constructing Fig. 2 values of D_d for water, ethanol, and freon-12 were taken from [16], for freon-113 from [17], and for helium, from [18].

Despite the approximateness of these estimates, it can be maintained that the value of δ_{lim} correlates quite closely with the bubble breakaway diameter for boiling in a large volume, with $\delta_{lim} \approx 2D_d$ at $D_d < 1$ mm (high dimensionless pressures) and $\delta_{lim} \to D_d$ at $D_d > 1$ mm (low reduced pressures). At the same time, no such correlation of δ_{lim} with the quantity b can be seen, since the significant change in δ_{lim} with change in pressure (nitrogen, water, Fig. 2) corresponds to a quite small change in b.

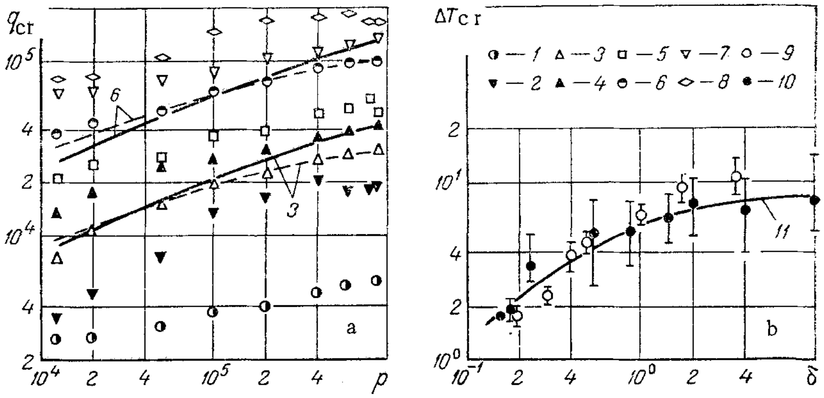

Fig. 3. Heat-transfer crisis characteristics vs pressure and gap size for nitrogen boiling: a) effect of p and δ on q_{cr}: 1-8) δ = 0.14, 0.195, 0.295, 0.395, 0.49, 1.02, 1.75, and 3.5 mm; solid line) calculation by Eq. (7) with K = 0.14, k = 1.40, C_1 = 0.0153; dashes) calculation by Eq. (6) with ϕ_{cr} = 0.370; b) effect of δ on ΔT_{cr}; 9) present study; 10) data of [21]; 11) calculation with Eq. (8) with ΔT_{cr_0} = 9°K, C_2 = 0.6 mm. q_{cr}, W/m²; ΔT_{cr}, °K; p, Pa.

In [6], which employed the same annular channel as the present study, it was shown that data on the dependence of $q_{cr}(\delta)$ in nitrogen boiling at p = 10^5 Pa is described satisfactorily by the expression [19]

$$q_{cr} = \frac{S}{F} L \sqrt{\rho \rho_v g h \varphi_{cr}} \tag{6}$$

with ϕ_{cr} = 0.365. Similar values of ϕ_{cr} were also obtained for the boiling of helium [9] and hydrogen [19]; we will note, however, that the applicability of Eq. (6) at various pressures has yet to be proved.

It was shown in [20] that for boiling of water and freon-12 in channels, the function q_{cr} agrees well with calculations by Kutateladze's expression, in which the stability criterion is determined by channel dimensions

$$\frac{q_{cr}}{L\sqrt{\rho_v}\sqrt[4]{\sigma g(\rho - \rho_v)}} = K_1 = \frac{K}{1 + C_1 (h/d_{eq})^k}, \tag{7}$$

where K is the stability criterion for boiling in a large volume; in [20] values K = 0.12, k = 1, C_1 = 0.047 were used. In [21] in a study of nitrogen boiling in channels of various lengths at p = 10^5 Pa the average values of k = 1.43, C_1 = 0.0166 were obtained.

The results of the present study for the function $q_{cr}(p)$ are shown in Fig. 3a (as in [7], at δ = 0.14 mm the critical thermal flux density was chosen as that corresponding to ΔT = 10°K). It is evident that the size of the gap does not introduce significant change into the character of $q_{cr}(p)$. Processing of the data by Eq. (7) gives K = 0.14, k = 1.40, C_1 = 0.0153. The mean square deviation of the data from the calculation is 19% (without consideration of the q_{cr} values at δ = 0.14 mm). A somewhat larger deviation (23%) is obtained by processing with Eq. (6) with ϕ_{cr} = 0.370.

Analysis of the ΔT_{cr} data of the present study reveals that the critical temperature head is practically independent of pressure (in contrast to nitrogen boiling in a large volume [12]) and is determined solely by the magnitude of δ: Figure 3b shows values of ΔT_{cr} with maximum deviations averaged over the entire p range studied. As is evident from comparison with the data of [21] (plane channel with h = 40 mm), these deviations are less than the deviations from the means in repetitive measurements of ΔT_{cr} at p = 10^5. The dependence $\Delta T_{cr}(\delta)$ from the results of [21] and the present study can be approximated with the expression

$$\Delta T_{cr} = \Delta T_{cr_0} (1 + C_2/\delta)^{-1} \tag{8}$$

with ΔT_{cr_0} = 9°K, C_2 = 0.6 mm.

As is evident from Fig. 1, in a number of cases decrease in gap size to 0.14-0.20 mm leads to a significant reduction in α, but not as great as in the heat-transfer crisis.

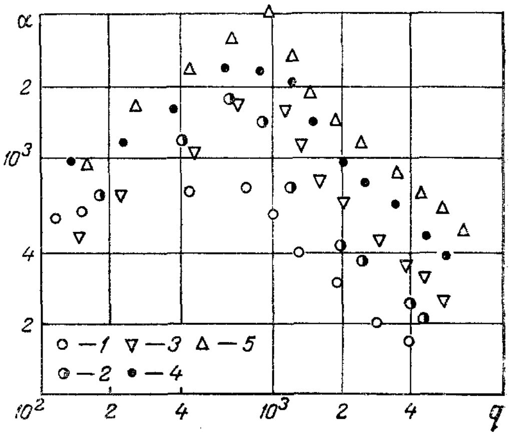

Fig. 4. Heat-transfer coefficient vs thermal load for nitrogen boiling in channel with gap δ = 0.14 mm: 1-5) p = (0.125, 0.5, 1, 4, and 9)$\cdot 10^5$ Pa. q, W/m^2.

It is known that this regime of "degraded" heat exchange ("liquid deficit") can be found in boiling of other liquids in narrow gaps [1, 3, 5, 10], and is characterized by reduction in the heat-transfer coefficient with increase in q (in Eq. (2), $m \approx -1$), and also by increase of α with increase in pressure [1](in contrast to the "improved" heat-exchange regime). Sometimes transition to "degraded" heat exchange is identified with the heat-transfer crisis; it is logical to refer to it in analogy to the case of constrained motion, as a crisis of the second sort [22]. We stress that onset of this regime occurs at very low thermal loads, approximately equal to those required for simmering of the liquid in a large volume or even less.

Typical data on heat transfer in the "degraded" regime (δ = 0.14 mm) are shown in Fig.4. It is evident that beginning at $q = 10^3$ W/m^2 the heat-transfer coefficient decreases with increase in thermal load ($\alpha \sim q^{-0.85}$) and increases with increase in pressure ($\alpha \sim p^{0.65}$), as in [1], more intensely than in the "normal" regime.

The principles of heat exchange in the "degraded" regime have not yet been studied thoroughly. Further studies are required, including investigation of the mechanism involved. It has been noted that in nitrogen boiling in a gap of δ = 0.14 mm a significant portion of the vapor exits from the channel in the input direction, i.e., downward.

NOTATION

A, B, B_1, C_1 C_2, constants. a, thermal diffusivity; $b = \sqrt{\sigma/g(\rho - \rho_V)}$, capillary constant; $d_{eq} = 4\,S/\Pi$; F, area of heat liberating surface; g, acceleration; h, channel length; L, heat of evaporation; n, m, k, exponents; p, pressure; Π, heated perimeter of channel cross section; ΔT, temperature head; α, heat-transfer coefficient; λ, thermal conductivity of liquid; ρ, ρ_V, density of liquid and vapor; σ, surface tension coefficient; ϕ, vapor content at channel output. Subscripts: lim, limiting value; cr, heat-transfer crisis; O, boiling in a large volume.

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INTERFEROMETER INVESTIGATION OF THE CONVECTIVE STABILITY OF A GAS IN HORIZONTAL CHANNELS HEATED FROM BELOW

S. P. Karlov and É. F. Shurgal'skii

UDC 532.529.2

The stability of the temperature field of a gas layer under natural and forced convection in horizontal channels heated from below is experimentally investigated by the method of holographic interferometry.

A horizontal layer heated from below in which thermal convection occurs is an example of instability and the transition to turbulence [1]. Interferometric methods of visualization [2] that permit investigation of a medium with different physical characteristics, from polymer solutions [3] to gases [4], are used to study the temperature fields in such layers.

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