CRITICAL HEAT FLUXES IN BOILING OF LIQUID NITROGEN UNDERHEATED TO SATURATION POINT IN FORCED-FLOW CONDITIONS

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Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, Vol. 10, No. 1, pp. 90–92, 1969

This paper gives the results of experimental determinations of the critical heat fluxes in the boiling of liquid nitrogen in forced-flow conditions in the mass velocity range $2 \cdot 10^3$–$40 \cdot 10^3$ kg/m^2 · sec, pressure range $29 \cdot 10^4$–$245 \cdot 10^4$ N/m^2, and at underheatings corresponding to the onset of normal boiling crises.

NOTATION

q_0—critical heat flux; r—heat of vaporization; i'—enthalpy of flow corresponding to saturation point; i—enthalpy of flow corresponding to liquid temperature; σ—surface tension; γ'—density of liquid; γ''—density of saturated vapor; C_f—friction factor; W_g—mass velocity; Fr_*—Froude number; g—acceleration due to gravity.

There are theoretical formulas for two limiting cases of boiling of a liquid heated to saturation point ([1], Chap. 8):

$$\frac{q_0}{r\sqrt{\gamma''}\,[g^2\sigma(\gamma'-\gamma'')]^{1/4}} = K \approx 0.14 \quad \text{for} \quad W_g \to 0$$

$$\frac{q_0}{rW_g\sqrt{\gamma''/\gamma'}} = K_1 \approx 0.34C_f \quad \text{for} \quad W_g \to \infty \tag{2}$$

In [2–4] experimental determinations of the critical heat fluxes in boiling of ethyl alcohol underheated to saturation point and moving at high velocity were represented by a linear interpolation formula of the form

$$q_0 = \left[1 + \frac{i'-i}{r}\left(\frac{\gamma'}{\gamma''}\right)^{1/2}\right]\left\{(0.34\,C_f r W_g\left(\frac{\gamma''}{\gamma'}\right)^{1/2} + 0.14r\sqrt{\gamma''}\,[g^2\sigma(\gamma'-\gamma'')]^{1/4}\right\} \tag{3}$$

in the range of reduced underheating

$$0 < \vartheta < 2, \qquad \vartheta = \frac{i'-i}{r}\left(\frac{\gamma'}{\gamma''}\right)^{1/2} \tag{4}$$

The hydraulic drag coefficient in formula (3) was calculated as for the case of isothermic single-phase flow in smooth tubes [4].

The aim of this work was to investigate experimentally the critical heat fluxes in relation to pressure, underheating of liquid to saturation point, mass velocity, and diameter of tube.

Technically pure nitrogen (99.9%) was used in the experiments.

We constructed an experimental apparatus specially designed for work with liquid nitrogen underheated to saturation point. A diagram of the apparatus is shown in Fig. 1.

The circulation system was made of thin-walled tubes of 1Cr18Ni10 stainless steel with vacuum-layer insulation. The liquid was driven by a NZhK-1M liquid-nitrogen pump with a working pressure of 220 atm abs.

Liquid nitrogen from tank 1 under a pressure of 1.5 atm abs was delivered to the circulating pump 2, from which it was pumped at high pressure through a regulating valve into the liquid cooler 3. It then passed through a tachometric flowmeter 4 and entered the auxiliary heater 5, where it was heated to the required temperature. The liquid then passed through the experimental section 7 and returned to the tank.

The experiments were carried out on experimental tubes with internal diameters 4.4, 2.68, and 1.13 mm and 60–100 mm long. The settling length was equal to the length of the heated region.

The power supplied to the experimental section was measured with a class 0.2 wattmeter. The wattmeter was connected to a current and voltage measuring transformer of the same accuracy class. The temperature of the liquid after the experimental section was measured with a copper-constantan thermocouple mounted in a mixer. The emf of the thermocouple was determined by an EPP-09 automatic potentiometer which had been calibrated against a standard R-306 potentiometer.

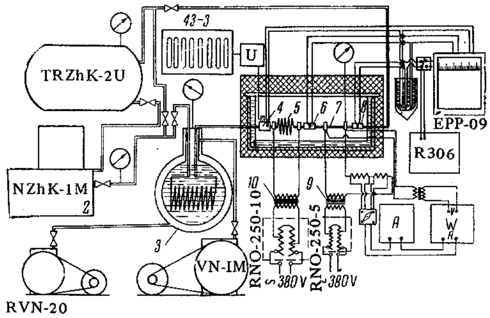

Fig. 1

The critical heat fluxes were attained by a gradual increase in the heat load on the experimental section. The crisis was determined from the sharp drop of current, measured by a class 0.2 ÉLA ammeter, in the electric circuit of the experimental section.

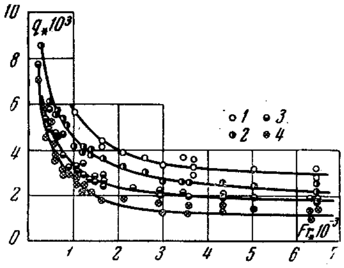

Fig. 2

The experiments were carried out in separate series at pressures $p = 29 \cdot 10^4 – 245 \cdot 10^4$ N/m^2, mass velocities $W_g = 2 \cdot 10^3 – 41 \cdot 10^3$ kg/m$^2 \cdot$ sec, and with variable underheatings corresponding to reduced underheatings of the liquid in the range (3); the tube diameter was 1– 4 mm.

According to [4], these underheatings correspond to the onset of normal boiling crises.

To determine the effect of velocity on the boiling crisis in the investigated velocity range we treated the experimental data in the form of the relationship

$$q_* = q_*(Fr_*), \quad q_* = \frac{q_0}{rWg}\left(\frac{\gamma''}{\gamma'}\right)^{1/2}, \quad Fr_* = \frac{W_g}{\sqrt{\gamma'}\,[g^2\sigma(\gamma' - \gamma'')]^{1/4}}$$

Figure 2 shows the reduced heat flux as a function of the Froude number; curves 1, 2, 3, and 4 correspond to reduced underheatings of 1.4, 1.0, 0.6, and 0.25.

An analysis of the obtained relationship indicates the existence of two regions which differ in the effect of underheating on the value of q_0.

The curve in the region of Froude numbers $Fr_* 10^{-2} > 200$ asymptotically approaches the horizontal straight line corresponding to values of q_0 calculated from formula (2). In this range of velocities ($W_g > 8 \cdot 10^3$ kg/m$^2 \cdot$ sec) there is a constant and strong dependence of q_0 on the underheating of the liquid. The lines of constant underheatings are equidistant from one another.

The region of low flow velocities ($67 < Fr_* 10^{-2} < 200$) is characterized by a variable dependence of q_0 on the underheating. This becomes much weaker with reduction of velocity, and at velocities $W_g < 2 \cdot 10^3$ kg/m$^2 \cdot$ sec

($Fr_*10^{-2} < 67$) the lines of constant underheatings, as the graph shows, merge into one straight line, which indicates that the underheating has no effect on q_0 in this region.

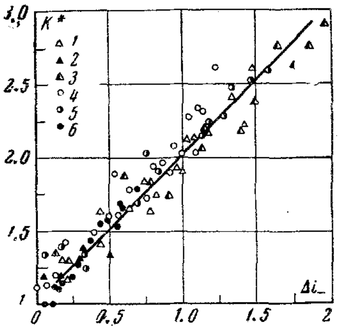

Fig. 3

The experimental data for the boiling crisis in the case of a flow of liquid nitrogen at high velocities were compared with the values calculated from formula (3). Figure 3 shows the data for the liquid nitrogen boiling crisis in the form of a relationship between the reduced heat flux

$$K_* - q_0 / 0.14r \sqrt{\gamma''}\,[g^2\sigma(\gamma' - \gamma'')]^{1/4} + 0.34C_f r W_g \sqrt{\frac{\gamma''}{\gamma'}}$$

and the underheating

$$\vartheta = \frac{\Delta i}{r}\left(\frac{\gamma'}{\gamma''}\right)$$

Experiments were carried out with a tube of diameter 2.68 mm and $W_g = 8 \cdot 10^3$ kg/m^2·sec. Points 1 correspond to $p = (118–147) \cdot 10^4$ N/m^2, points 2 to $p = 29 \cdot 10^4$, and points 3 to $p = (216–145)10^4$ N/m^2. Experiments with a tube of diameter 1.13 mm were carried out at velocities of $8 \cdot 10^3–22 \cdot 10^3$ kg/m^2·sec; and velocities of $8 \cdot 10^3–41 \cdot 10^3$ kg/m^2·sec. Points 4 are for $p = (118–145)10^4$ N/m^2, points 5 for $p = 216 \cdot 10^4$ N/m^2, and finally, points 6 for $p = 49 \cdot 10^4$ N/m^2.

An analysis of the obtained relationship indicates a satisfactory agreement between experiment and calculations from formula (3) in the range $0.25 < \vartheta < 2$. The great scatter of the experimental points for $0 < \vartheta < 0.25$ should be noted.

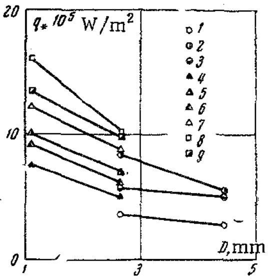

Fig. 4

Adamovskii and Shtokolov [4] clarified the role of the drag coefficient in the formula for the calculation of q_0. This coefficient was calculated from the formula for the case of an isothermal flow of liquid in smooth tubes. They considered this formula valid in the range $0.2 < \vartheta < 2$. Experiments indicate that in the range $0 < \vartheta < 0.25$ the drag coefficient varies inversely with the underheating. Figure 4 gives the results of a comparison of the values of q_0 obtained for tubes of different diameters with other conditions equal. The three numbers at each of the points 1, ..., 9 denote, respectively, the relative underheating $\Delta i/r$, the pressure p in 10^{-4} N/m^2, the velocity W_g in 10^{-3} kg/m^2·sec): 1 (0.15, 240, 4.0), 2 (0.85, 50, 4.0), 3 (0.12, 240, 4.0), 4 (0.023, 50, 8.0), 5 (0.083, 50, 8.0), 6 (0.125, 157, 9.5), 7 (0.12, 50, 8.0), 8 (0.22, 127, 8.0), 9 (0.175, 127, 8.0).

As the graph shows, the values of q_0 increase with reduction in the diameter, particularly between 2.68 and

1.13 mm.

However, as Fig. 3 shows, the values of q_0 obtained for tubes of different diameters are satisfactorily generalized by Eq. (3). This can presumably be attributed to the fact that the effect of diameter is taken into account in the calculation of the drag coefficient.

Thus, the obtained experimental data for the critical heat fluxes in the boiling of liquid nitrogen confirm that formula (3) can be used to calculate q_0 in the velocity range $41 \cdot 10^3 - 8 \cdot 10^3$ kg/m² · sec with reduced underheatings 0.25–2. In calculation of the value of q_0 at velocity $W_g < 8 \cdot 10^3$ kg/m² · sec the variable dependence of q_0 on the underheating can be taken into account by the introduction of an empirical coefficient for the ϑ term in formula (3) (according to the experimental data, this coefficient is 0.5 in the velocity range $2 \cdot 10^3 < \omega_g < 8 \cdot 10^3$ kg/m² · sec).

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12 March 1968

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