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INFLUENCE OF HEAT FLUX AND PRESSURE ON HEAT TRANSFER ASSOCIATED WITH FULLY DEVELOPED NUCLEATE POOL BOILING

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Heat transfer in the pool boiling of helium is investigated experimentally. The dependence of the heat-transfer coefficient on the heat flux and pressure is determined for the fully developed nucleate boiling regime.

The problems of heat transfer in liquid helium hold a special place in the thermal stability analysis of composite conductors used in the coils of superconducting magnets. Accordingly, we have conducted a systematic investigation of the inlfuence of various factors on the heat transfer and critical heat fluxes associated with helium pool boiling. The main factors investigated in our work include the heat-flux density, the prior "history" of the boiling process, the saturation pressure, the finish of the heating surface, the material of the heat-transfer surface, and the orientation of the surface in the field of gravity. The experiments were conducted with plane working test sections of various materials shaped into a disk with a diameter of 25 mm or a square plate with a cross section of 30 × 30 mm. The pressure was held constant in each experiment, while the heat input to the heating surface was gradually increased or decreased to produce the appropriate variation of the temperature differential. An analysis of the experimental data shows that the dependence of the temperature differential on the heat flux can be multi-valued in the nucleate boiling of helium, indicating the existence of different boiling regimes. For each surface it is possible to discern the most fully developed boiling regime, wherein the heat-transfer rate attains its maximum value for the given conditions. In that regime, the relationship between the heat flux q and the temperature differential ΔT is described by the power law

$$q = C\Delta T^n. \tag{1}$$

As in the case of other liquids, the proportionality factor C depends on the saturation pressure, and the value of the exponent n can be taken as roughly constant for different pressures. Also, C and n vary appreciably with the surface conditions.

In the present article we give the results of a study of fully developed nucleate boiling of helium in the pressure interval $(0.33 \text{ to } 2.13) \cdot 10^5$ N/m^2 on only two surfaces, one of copper and one of aluminum. The surface of the copper section (square plate) was polished to class 13 purity [according to All-Union State Standard (GOST) 2309-68], and the finish of the aluminum surface (disk) corresponded to class 10. For the copper heat-transfer surface, we obtained data both for horizontal (heating surface facing upward) and for vertical orientation, while for the aluminum surface we used only the horizontal orientation. In experiments on a rougher aluminum surface, the value of the exponent n in Eq. (1) is 1.5 for all investigated pressures, which is in good agreement with the data of other authors for copper [1, 2] and platinum [3] heating surfaces. The dependence of the heat flux on the temperature differential on the polished copper surface in our experiments is described by the power law (1) with exponent n = 3.33. The relationship between the heat-transfer coefficient $\alpha = q/\Delta T$ and the heat flux in this case is consistent with the well-known dependence for ordinary liquids: $\alpha \sim q^{0.7}$.

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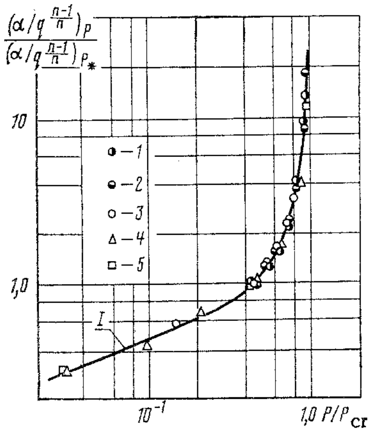

Fig. 1

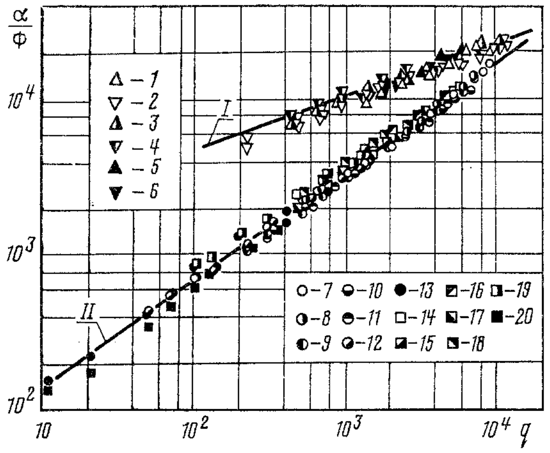

Fig. 2

Fig. 1. Influence of pressure on heat transfer in fully developed nucleate pool boiling of helium. 1) vertical surface; 2-5) horizontal surface; 1) copper; 2) copper; 3) aluminum (authors' data); 4) copper [2]; 5) platinum [3].

Fig. 2. Heat transfer α/Φ, $W/m^2 \cdot {}^\circ K$, versus heat flux q, W/m^2, for fully developed nucleate pool boiling of helium on a horizontal aluminum surface (1-6), on a horizontal copper surface (7-13), and on a vertical copper surface (14-20). 1) $P \cdot 10^{-5} = 0.33\ N/m^2$; 2) 1.00 to 1.03; 3) 1.20; 4) 1.39; 5) 1.60; 6) 1.79; 7) 1.01; 8) 1.22; 9) 1.42; 10) 1.62; 11) 1.82; 12) 2.03; 13) 2.13; 14) 1.01; 15) 1.22; 16) 1.42; 17) 1.62; 18) 1.82; 19) 2.03; 20) 2.13; I) according to Eq. (4); II) according to (5).

To exhibit the influence of pressure on the heat-transfer coefficient in helium boiling, we processed the experimental data in relative coordinates [4]

$$(\alpha/q^{\frac{n-1}{n}})_P/(\alpha/q^{\frac{n-1}{n}})_{P_*} = \Phi(P/P_{cr}), \tag{2}$$

where $(\alpha/q^{\frac{n-1}{n}})_P$ is the value of the characteristic at the investigated pressure P, $(\alpha/q^{\frac{n-1}{n}})_{P_*}$ is the same at the reference value P_*, which is taken to be equal to $10^5\ N/m^2$, and P_{cr} is the critical pressure.

The results of processing of the experimental data are given in Fig. 1, along with the published data of other authors [2, 3]. The experimental data are well generalized by a function of the type $\Phi(P/P_{cr})$ (curve 1 in Fig. 1), which can be represented analytically as

$$\Phi(P/P_{cr}) = \begin{cases} 1.2(P/P_{cr})^{0.4}, & 0.03 \leqslant P/P_{cr} \leqslant 0.25; \\ 0.47(1 - P/P_{cr})^{-1.3}, & 0.25 \leqslant P/P_{cr} \leqslant 0.95. \end{cases} \tag{3}$$

With appropriate scaling to the reference pressure $P_* = 0.03P_{cr}$, the function $\Phi(P/P_{cr})$ practically coincides with the graphically represented function $F_1(P/P_{cr})$ given by Borishanskii [4], which generalizes the results of experiments with water and various organic liquids. Thus, the nature of the influence of pressure on the heat-transfer associated with the boiling of helium and ordinary liquids is the same.

The variation of the quantity α/Φ with the heat flux q according to our experimental data is shown in Fig. 2. The results of experiments with a horizontal aluminum surface are generalized by the equation (curve I in Fig. 2)

$$\alpha/\Phi = 1020\,q^{1/3}. \tag{4}$$

The experimental data obtained for horizontal and vertical copper plates obey the general law (curve II in Fig. 2)

$$\alpha/\Phi = 28.5q^{0.7}. \tag{5}$$

The particularly strong discrepancy between the experimental results for the copper and aluminum surfaces in the interval of small heat fluxes, as reflected in the disparate heat-transfer laws (4) and (5), is attributable to the dissimilar stability of the vaporization centers on heating surfaces having different finishes.

NOTATION

q, heat flux, W/m^2; ΔT, temperature differential, °K; α, heat-transfer coefficient, W/m$^2\cdot$°K; P, pressure, N/m^2; P_{cr}, critical pressure, N/m^2; P_*, reference pressure, N/m^2; n, a power exponent; C, a proportionality factor; Φ, F_1, special functions.

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INVESTIGATION OF THE EVAPORATION PROCESS AND SONIC LIMITS IN SODIUM HEAT PIPES

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The maximum heat fluxes in the heating zone and the sonic limits of power transfer in sodium heat pipes and vapor chambers with composite (channel) wicks are investigated experimentally.

Heat pipes with composite wicks [1] are attractive for the rather unique possibilities that they afford for heat transfer and operation in various positions relative to the field of gravity. However, they have a substantial drawback: Their capillary hysteresis effect is such that even the slightest drying of the wick is enough to drastically reduce heat transfer. It is especially important, therefore, to know the limiting characteristics of such heat pipes and to ascertain all the processes that can lead to dryout of composite wicks.

Specific Heat Fluxes. We have conducted investigations of these effects in the heating zone in a sodium vapor chamber. The working surface to be heated by condensed sodium vapor had a diameter of 24 mm and a thickness of 0.3 mm; it was formed on a flat vertical heat-resistant steel wall. It was equipped with a composite wick, whose perforated screen was situated at a distance of 0.45 mm from the wall. A screen having a small surface porosity $\varepsilon = 0.08$ was used in order to attain high specific heat fluxes on the evaporation mirror. The holes in the screen had a diameter of 0.15 mm and were arrayed in a staggered pattern with a spacing of 0.5 mm. We measured the temperature of the heated wall, the vapor temperature in the vapor chamber, and the heating and flow of water transporting heat from the vapor chamber. Typical data from these experiments are summarized in Table 1.

At low vapor pressures the specific heat fluxes are limited by kinetic evaporation. The maximum heat flux for evaporation in vacuum can be represented by the expression

$$(q_0)_{\max} = f\,\frac{L_0 P_0}{\sqrt{2\pi R T_0/\mu}}\,. \tag{1}$$

If, on the other hand, the vapor has pressure P_V and the corresponding saturation temperature T_V, the following relation can be used for the heat flux in evaporation [2]:

$$q_0 = f\varkappa\left[\frac{L_0 P_0}{\sqrt{2\pi R T_0/\mu}} - \frac{L_V P_V}{\sqrt{2\pi R T_V/\mu}}\right], \tag{2}$$

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