EXPERIMENTAL STUDY OF HEAT TRANSFER IN
THE BOILING OF LIQUIDS AT LOW PressURES
UNDER CONDITIONS OF FREE MOTION

V. V. Yagov, A. K. Gorodov, and D. A. Labuntsov

The results of an experimental investigation into the boiling of water, ethyl alcohol (96% aqueous solution), and 13% NaCl solution under conditions of free motion at pressures of 0.036-1 bar are presented. The experimentally observed characteristics of the boiling mechanism at low pressures are discussed.

The experimental apparatus was housed in a thermal pressure chamber with a considerable inner volume, provided with a smoothly-regulated leak, enabling the pressure to be maintained to a high accuracy (±0.15 mbar). The pressure over the surface of the boiling liquid was measured with an MChR-3 mercury manometer having a scale division of 0.1 mm Hg.

As boiling surface we used the end of a round rod 56 mm in diameter. The rod was of the composite kind: the upper section, 30 mm long, was made of 99.72% pure nickel and the lower section of copper. The two sections were joined by diffusion welding. The total length of the rod was 96 mm. With this construction, boiling occurs on the nickel surface, which retains stable characteristics over a long period of time; in the lower (copper) section of the sample, slight axial temperature gradients occur.

The heat evolved by a low-resistance electric heater was received by the lower base of the rod and a heat concentrator; from this, in turn, it was transferred to the lateral surface of the rod.

The upper part of the rod was furnished with a circular edge 4 mm long and 0.4 mm thick set at a slight angle (about 15°) to the horizontal surface; this ensured sharp definition of the boundary to the heat-transfer surface and good sealing along the perimeter of the edge — it also eliminated the formation of edge vapor bubbles at the metal—substrate boundary. The liquid was poured into a stainless steel vessel with an internal diameter of 130 mm and a height of 200 mm. Directly under the vessel was a condenser, which ensured the complete return of the condensate obtained from the boiling liquid into the vessel. This enabled us to keep the height of the column of liquid over the heating surface and also the NaCl concentration constant (during the boiling of the solution). In order to keep the height of the column of liquid constant at the saturation temperature an auxiliary heater was employed.

The experimental vessel and the thermal pressure chamber were furnished with illuminating systems facilitating visual observation and high-speed motion-picture photography of the process in transmitted light.

In four horizontal cross sections of the rod situated at different depths in the nickel section, copper—constantan thermocouples were placed — three to each section. The good insulation of the lateral surface of the rod and the high heat release to the liquid from the upper end of the rod ensured the almost total absence of radial temperature gradients in the horizontal cross sections of the sample and a linear temperature variation along the axis of the rod; this enabled us to determine the thermal flux \( q \) carried away from the heating surface by reference to the axial temperature gradient and the known thermal conductivity of the sample, and also the temperature of the heating surface \( T_W \) by linearly extrapolating

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Fig. 1. Typical boiling curves of water, ethyl alcohol, and NaCl solution in vacuum \( (q, \text{W/m}^2; \Delta T, ^\circ\text{C}) \). a: 1) water, 200 mbar; 2) water, 36 mbar; b: 1) water, 60 mbar; 2) ethyl alcohol, 60 mbar; c: 1) 13% NaCl solution, 36 mbar; 2) ethyl alcohol, 36 mbar.

the relationship between the sample temperature and the coordinate of the cross section to the boiling surface.

The temperature head used in calculating the heat-transfer coefficient \( (\alpha) \) to the boiling liquid was defined as \( \Delta T = T_w - T_S \). The maximum error in determining \( \Delta T \) in our experiments was no greater than 7%, while the maximum error in determining the heat-transfer coefficient was 16%.

In order to confirm the reliability of the method chosen for measuring and analyzing the results, we studied the heat transfer associated with water boiling at atmospheric pressure. The resultant \( q = f(\Delta T) \) relationship agreed closely with published data on boiling at clean heating surfaces. (The surface finish in our experiments corresponded to class 9-10 of All-Union State Standard 2789-59; the surface was periodically carefully degreased with ethyl alcohol.) The picture of boiling at atmospheric pressure observed visually in our experiments also agreed closely with published data, comprising fixed centers of vapor formation from which the vapor bubbles rose in columns. Boiling at 0.036, 0.06, 0.1, and 0.2 bar differed sharply from boiling at 1 bar, even in external appearance. For low thermal fluxes (30-100 kW/m² for water), there were extremely long pauses in the process of vapor formation, after which a vapor bubble appeared in an explosive manner on the heating surface, attaining several tens of millimeters in size; then another pause in vaporization ensued. The break-off diameters exceeded those calculated by the well-known Fritz formula [7] by 1-2 orders of magnitude. The formation of these large bubbles was accompanied by severe perturbation of the liquid, which was partly ejected from the experimental vessel.

It should be noted that, up to the present time, monographs and review articles on the boiling of liquids [1-6] have never mentioned any qualitative difference between boiling in vacuum and boiling at higher pressures. This apparently arises from the small number of investigations devoted to boiling at pressures below atmospheric, and also the character of the initial investigations on this subject. For example, in [8], the article most frequently quoted in reviews and monographs, there were no visual observations of the process, and the order of magnitude of the heat-transfer coefficients at the lowest pressures (down to 0.037 bar) corresponded to free convection rather than developed boiling.

However, starting from [9], which was published in 1964, there followed a considerable number of investigations [10-16] from which it became clear that qualitative changes occurred in the boiling process at pressures of the order of 0.2-0.3 bar and under. The increase in the critical size of the vapor nucleus due to the reduction in the density of the vapor leads to considerable hindrances in the formation of the vapor phase; pauses accordingly occur in the process of vaporization [10, 12], and there are considerable fluctuations in the temperature of the heating surface. At the moderately low pressure of 0.184 bar, a complete "degeneration" of the bubble-type boiling process was observed in [9]; an attempt was made in the same paper at providing a theoretical explanation for this effect. A direct transition from the mode of free convection to film-type boiling was also observed in a number of other experiments [11, 14]. In another series of investigations [10, 12, 13], however, at no pressures (down to 10 mm Hg) was any complete "degeneration" of bubble-type boiling detected.