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
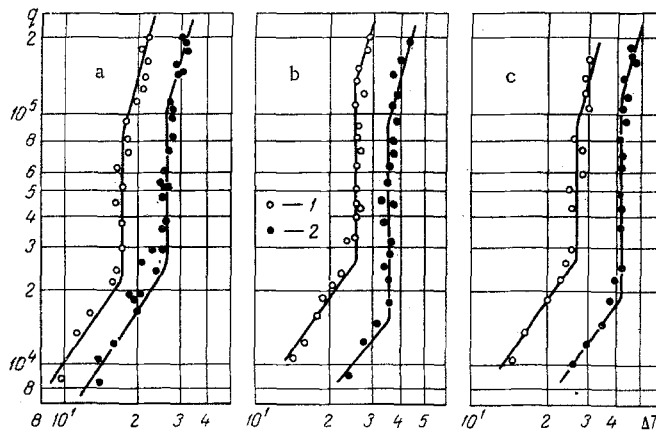
Fig. 1. Typical boiling curves of water, ethyl alcohol, and NaCl solution in vacuum (q, W/m²; ΔT, °C). a: 1) water, 200 mbar; 2) water, 36 mbar; b: 1) water, 60 mbar; 2) ethyl alcohol, 60 mbar; c: 1) 13% NaCl solution, 36 mbar; 2) ethyl alcohol, 36 mbar.

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 (α) to the boiling liquid was defined as $\Delta T = T_W - T_S$. The maximum error in determining ΔT 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(ΔT) 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.
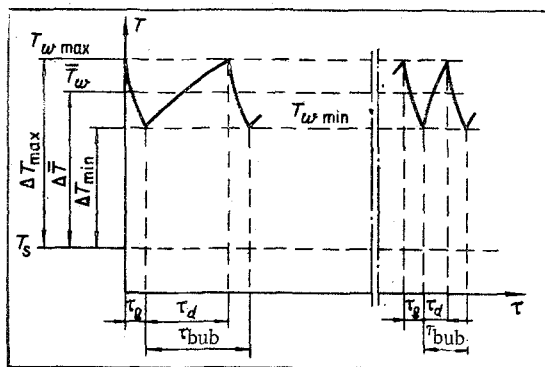
Fig. 2

Fig. 3

Fig. 2. Proposed nature of the changes in the temperature of the heating surface for the transitional mode of heat transfer.
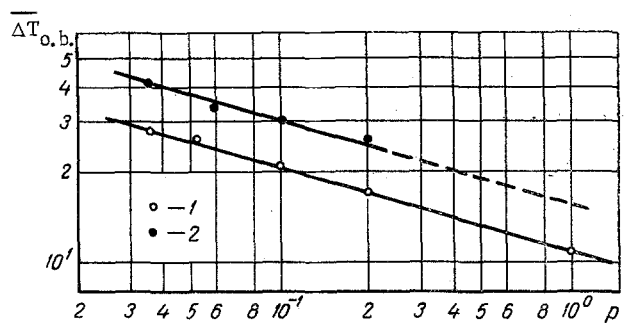
Fig. 3. Pressure (p, bar) dependence of the average temperature head corresponding to the onset of boiling $\Delta T_{o.b.}$: 1) water; 2) ethyl alcohol.

In our own opinion, this difference in the results may be explained by the fact that in [9, 11, 14] boiling took place on heating surfaces of extremely small sizes (the maximum diameter of the heaters was 5.0 mm in [11, 14] and 0.2 mm in [9]). Since the diameter of the vapor bubbles reaches several tens of millimeters at low pressures [10, 11, 14-16], for these heater diameters the first vapor bubble "covers" the whole surface and leads to the formation of a stable vapor film. On using the end of a round rod as boiling surface [10, 12, 13] no such effect could occur. (We note that in [17] there was a high proportion of the convective component of thermal flux, and hence a contraction of the zone of bubble-type vaporization, when boiling on thin wires at atmospheric pressure.)

In our own experiments we found no complete "degeneration" of the zone of bubble-type boiling at any of the four pressures indicated. For each of the pressures studied and each of the three liquids, three modes of heat transfer appeared: free convection, a transitional mode, and stable boiling. In Fig. 1 these modes correspond to different sections of the $q = f(\Delta T)$ curve.

The zone of free convection naturally offers nothing fundamentally new to our concept of convective heat transfer, unless we consider the fact that, as the pressure diminishes, this zone extends into the region of temperature heads which, under atmospheric conditions, would correspond not only to developed boiling but also to pore formation and critical conditions. Thus for water at 36 and 60 mbar the first, very rare vapor bubbles (1-2/min) only developed for an average temperature head $\overline{\Delta T}$ of over 20°C, while the boiling of alcohol (at 0.036 bar) only started at $\overline{\Delta T} = 38°C$. It is thus not surprising that the thermocouple recorded a very considerable superheating of the mass of liquid relative to the saturation temperature T_s (by 2-3°C). Even for boiling in the transitional mode the superheating of the mass of liquid is usually 0.1-1°C. There is no doubt that, for the thermal fluxes preceding the onset of boiling, the liquid evaporates intensively from the open surface. We may reasonably suppose that the possible superheating of the mass of liquid and the temperature head at the onset of boiling depend on the area of the evaporation surface.

Of greatest interest is the transitional mode of boiling. As noted earlier, for thermal fluxes of the order of 20-100 kW/m², boiling at the pressures here studied assumed an extremely unstable character. For pressures of 0.036 and 0.060 bar, the vaporization which occurs during the boiling of the water and salt solution (up to fluxes of the order of 80 kW/m²) was of such a nature that the frequency of vaporization could be determined by simple counting of the number of bubbles formed in a given period. (For the fluxes indicated this frequency was no greater than 1 sec⁻¹.) Then the frequency of vaporization increased and the pauses in the process shortened to fractions of a second, although we still failed to observe complete normalization of the water-boiling process up to thermal fluxes of 200 kW/m². The instability of the vaporization was naturally accompanied by sharp fluctuations in the temperature of the heating surface. The thermocouples placed in the section closest to the heat-transfer surface established temperature fluctuations with an amplitude of 5-12°C. These fluctuations were smoothed out as a certain stabilization of the process set in (with increasing thermal loading), and in the flux range $q = 150-200$ kW/m² the amplitude of the temperature fluctuations in the upper cross section of the sample was no greater than 2°C. (It should be noted that, in the other three sample cross sections further from the heating surface, the

423

temperature fluctuations were very slight, so that over the whole range of thermal loadings studied we were only able to determine the time-averaged values of q and T_w.)

The boiling of ethyl alcohol was, in general, the same as for the other two liquids. However, the difference in thermophysical properties (the thermal conductivity and heat of vaporization were lower for the alcohol) had the effect that, in the boiling of alcohol, the amplitude of the temperature fluctuations of the heating surface was considerably smaller than in the case of the boiling of water or salt solution, even in the region of least stable boiling, while for thermal fluxes of q = 100 kW/m² these fluctuations were hardly noticeable at all. For alcohol boiling at 0.1 and 0.2 bar, this value of the thermal flux charac- terized the transition to a fairly stable form of boiling, reminiscent of ordinary bubble-type boiling, al- though the number of vaporization centers recorded on the fairly large heating surface (some 25 cm²) was only 3-5. The comparatively frequent spontaneous "switching on" or "switching off" of a particular vapor- ization center led to a 3-5°C fall or rise in temperature respectively in all cross sections of the sample (and of course to an analogous change in ΔT). This is little doubt that such "switchings on" and "switchings off" of vaporization centers always occur when boiling at atmospheric or higher pressures also, but in these cases no effect is observed on the average characteristics of the process, since the total number of boiling centers is extremely large, and the heat-transfer process associated with boiling, although actually tran- sient in nature, may be regarded as quasistationary (almost steady-state). Under our own conditions the transience of this process appeared quite clearly. (It should be noted that fixed vaporization centers failed to appear at all on the heating surface up to fluxes of some 200 kW/m² in the boiling of water and salt solu- tions at pressures of 0.036 and 0.60 bar. Under these conditions the bubbles "jumped" around the heating surface.)

It is abundanently clear from Fig. 1a, b, c that, in the transitional mode of heat transfer, an in- crease in the thermal loading does not lead to any change in the average temperature head $\overline{\Delta T}$ (the q = = f(ΔT) curve is here vertical). The mode clearly corresponds to the earlier observed [9] S-shaped part of the q = f(ΔT) curve for the boiling of ethyl alcohol on a thin wire. An α = f(q) relationship corresponding to this region was presented in [12]; instead of values averaged for a specific thermal flux, two extreme values of α were given — the maximum for the instant at which T_w fell during vaporization, and the mini- mum for the pauses in this process. No such region on the q = f(ΔT) curves was established in [13]. In- stead zones of free convection and developed bubble-type boiling were presented, with a break in the region of unstable boiling. Our own method of determining the time-averaged values of q and T_w enabled us for the first time to establish the foregoing character of the q = f(ΔT) curve for the transitional mode of heat transfer.

This behavior of the relationship in question may be explained in the following manner. Starting from well established concepts as to the mechanism of boiling, the formation of the vapor phase requires the overcoming of an energy barrier, the magnitude of which may be characterized, under otherwise equal conditions, by a certain minimum superheating of the liquid in the boundary layer (relative to the satura- tion temperature) at which the first viable vapor space is able to develop. Let us suppose that, under our own conditions, a certain superheating of the wall ΔT_{max} (Fig. 2) corresponds to this superheating of the boundary layer of liquid. The formation of a vapor bubble, together with its subsequent explosive growth, reduces the wall temperature to a value of T_{wmin}; this reduction takes place very quickly, in fact during the period of growth of the vapor bubble, which under the present conditions is no greater than τ_g = 0.05- 0.08 sec. The subsequent "silent" or "idle" time of the bubble τ_d is very considerable for boiling in vacuum (as already indicated, for fluxes of q = 100 kW/m² the vaporization frequency in the boiling of water is of the order of 1 sec⁻¹, i.e., the bubble period τ_{bub} = 1 sec, while τ_d = 0.92-0.95 sec). During the "idle time" there is a rise in the temperature of the heating surface, which returns to its maximum value of T_{wmax}, and the process repeats itself.

We may suppose that under the conditions $\tau_d \gg \tau_g$ an increase in the thermal load only leads to an increase in the frequency of vaporization as a result of a reduction in the "idle time"; the values of T_{wmax} and T_{wmin} will on average remain unaltered, so that the temperature fluctuations of the heating surface will occur at an increasing frequency around the same average value of T_w (right-hand side of Fig. 2). Only when τ_d falls to values comparable with the bubble growth time τ_g will there be an increase in the average value of the temperature head $\overline{\Delta T}$ as the thermal loading increases; this in turn will lead to an increase in the number of vaporization centers, and the normal mechanism of bubble-type vaporization will accordingly ensue. (In all the curves of Fig. 1 we notice a tendency toward the slope usually en- countered in bubble-type boiling, corresponding to the relationship q ≈ ΔT³ for thermal fluxes of q > 100- 150 kW/m².)

It should be noted that, in practice, the surface sometimes develops not one but several bubbles (4-5, or occasionally up to 10); the deviations of the heating-surface temperature from the average value of $\overline{T}_w$ vary accordingly.

However, prolonged observation shows that both the frequency of vaporization and the amplitude of the temperature fluctuations on average remain unchanged for any particular thermal flux, so that the foregoing qualitative explanation of the heat-transfer mechanism in the transitional mode satisfactorily approximates the true picture, despite the idealization envisaged.

The existence of a transitional zone on all the $q = f(\Delta T)$ curves (Fig. 1) indicates that the value of $\overline{\Delta T}$ corresponding to this zone constitutes a particular "average" temperature head, starting from which boiling is able to take place freely under the conditions in question. To each pressure there corresponds a particular temperature head at which boiling takes place. Figure 3 gives the logarithmic form of the relationship $\overline{\Delta T}_{o.b.} = f(p)$ (pressure dependence of the mean temperature head at the onset of boiling). This relationship is identical for water and alcohol. The increase in $\overline{\Delta T}_{o.b.}$ with decreasing pressure is entirely natural and follows from the explanation given, for example, in [9].

NOTATION

q	is the specific thermal flux;
T_w	is the temperature of heating surface;
T_s	is the saturation temperature of the liquid determined from the pressure over its surface;
ΔT	is the temperature head;
α	is the heat-transfer coefficient;
τ_g	is the growth time of vapor bubbles;
τ_d	is the "idle" time;
τ_{bub}	is the period of bubbles;
p	is the pressure of the system;
$\Delta T_{o.b.}$	is the temperature head at the onset of boiling.

LITERATURE CITED

1. V. M. Borishanskii, in: Questions of Heat Transfer and the Hydrodynamics of Two-Phase Media [in Russian], GÉI (1961).
2. V. P. Isachenko et al., Heat Transfer [in Russian], Énergiya (1965).
3. S. S. Kutateladze, Fundamentals of the Theory of Heat Transfer [in Russian], Mashgiz (1962).
4. W. M. Rohsenow, in: Modern Problems of Heat Transfer [Russian translation], Énergiya (1966).
5. L. Leppert and K. Pitts, in: Problems of Heat Transfer [Russian translation], Atomizdat (1967).
6. E. I. Nesis, Uspekhi Fiz. Nauk, 87, No. 4 (1965).
7. W. Fritz and W. Ende, in: Questions on the Physics of Boiling [Russian translation], Mir (1964).
8. D. S. Cryder and A. C Finalborgo, Trans. Amer. Inst. Chem. Engrs., 33, 346-362 (1937).
9. C. J. Rallis and H. N. Jawurek, Inst. J. Heat and Mass Transfer, 7, No. 10, 1051-1068 (1964).
10. V. I. Deev et al., Teploénergetika, No. 8 (1965).
11. N. N. Mamontova, Zh. Prikl. Mekhan. i Tekh. Fiz., No. 3 (1966).
12. V. I. Petrovichev et al., in: Questions of the Heat Physics of Nuclear Reactors [in Russian], Atomizdat (1968).
13. J. Rabin, R. Beaubouef, and G. Commerford, Chem. Engng. Progr. Sympos. Series, No. 57, 61, 249-257 (1965).
14. S. S. Kuateladze and N. N. Mamontova, Inzh.-Fiz. Zh., 12, No. 2 (1967).
15. R. Cole and H. Shulman, Chem. Engng. Progr. Sympos. Series, No. 64, 62, 6-16 (1966).
16. R. A. G. Cole, ChEJ, 13, No. 4, 779-783 (1967).
17. S. S. Kutateladze et al., Inzh.-Fiz. Zh., 12, No. 5 (1967).