RATE OF HEAT TRANSFER TO BOILING LIQUIDS AT ATMOSPHERIC AND REDUCED PRESSURES DURING NATURAL CONVECTION

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An experimental study of the boiling of water and ethanol at atmospheric and reduced pressures in a large volume is described. The density of vapor-formation centers significantly affects the mechanism for heat transfer from the heating surface.

In addition to the experimental studies of heat transfer during boiling under vacuum in which the well-known correlation among the basic characteristics of the process – the heat flux, the temperature head, and the heat-transfer coefficient – is observed [1, 2], some studies have recently been published in which extremely peculiar heat transfer has been observed under these conditions. For example, the data of Mamontova [3] and Deev et al. [4] imply that bubble boiling occurs at reduced pressures only when there is a relatively large heat flux; in addition, it sometimes does not occur at all, even approaching the critical region.

This qualitative difference in experimental results calls for further study, both in an effort to construct a generalized dependence and to study the individual aspects of the boiling mechanism.

We report here an experimental study of heat transfer to boiling liquids, distilled water and ethyl alcohol (96 vol. %), under conditions of free convection. Three series of experiments were carried out. In all of them, the working region consisted of one set of horizontal brass tubes. The tube diameter was 8 mm, the wall thickness was 0.6 mm, and the length was about 250 mm. A polished tube of class 9 surface quality (according to All-Union State Standard 2789-59) was used in the first series of experiments; a tube covered by a thin nickel layer (11th class surface quality) was used in the second series of experiments: and a tube which had not been treated in any manner was used in the third series (class 7 surface quality). The pressure was varied from $0.98 \cdot 10^4$ to $1 \cdot 10^5$ N/m^2, and the heat flux was varied from $2 \cdot 10^3$ to $500 \cdot 10^3$ W/m^2. The maximum relative error in the determination of the heat-transfer coefficient did not exceed 6%.

Figure 1 shows dependence of the heat-transfer coefficient for boiling water on the specific heat flux at various pressures. Similar dependences were found in all series of experiments. As Fig. 1 shows, the experimental points obtained at pressures of $1 \cdot 10^5$ and $0.48 \cdot 10^5$ N/m^2 are in satisfactory agreement with straight lines having a slope of approximately 0.7. At lower pressures, however, there is a characteristic break in these lines. The mechanism for this phenomenon is discussed below.

It can now be considered established that the rate of heat transfer during the boiling of a liquid depends strongly on the density of vapor-formation centers acting at the heating surface, other factors being held constant. The number of active vapor-formation centers depends not only on the superheating of the liquid near the wall, but also on a whole series of properties of the media in contact. Accordingly, the functional relationship between the heat-transfer coefficient and the heat flux, expressed in the form $\alpha = Cq^m$, is not unambiguous: the exponent M as well as the factor C depends on the material from which the heat-transfer surface is made. Although a quantitative evaluation of the effect of the density of the vapor-formation centers on heat transfer during boiling is extremely difficult, it should be acknowledged that an evaluation of the vapor-producing ability of a surface depends on knowledge of the number of potential vapor-formation centers. When there is a relatively low density of centers, and the largest of them are active,

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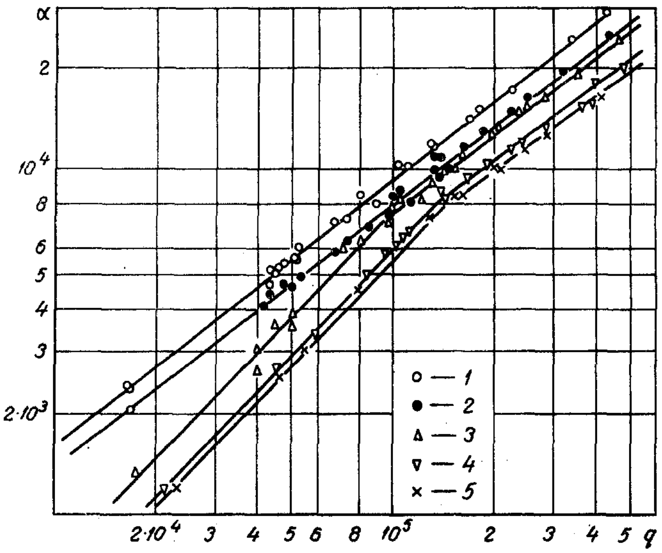

Fig. 1. Comparison of experimental data on heat exchange with boiling water at various pressures (first series of experiments). 1) $1\cdot10^5$; 2) $0.48\cdot10^5$; 3) $0.296\cdot10^5$; 4) $0.204\cdot10^5$; 5) $0.11\cdot10^5$ N/m^2.

their effect becomes especially noticeable. As the boiling rate increases (with, however, $q < q_{cr}$), the effect of the centers on the heat-transfer rate disappears at a heat flux characteristic of the given surface. This is the governing factor when the so-called surface conditions have a negligible effect, or no effect at all, on the heat-transfer rate during boiling.

Certain specific conditions for boiling, particularly reduced pressure, permit a significant change in the scale of the boiling curve and a qualitative but comprehensive evaluation of the effect of the number of vapor-formation centers on the heat-transfer rate. As the pressure in the boiling system decreases, the critical radius for the vapor-phase nuclei increases. As a result, the range of active-depression dimensions tends toward zero. Vapor formation is difficult on such surfaces and begins at relatively high heat loads. This is especially noticeable with thin tubes and wires, where the number of potential boiling centers of the necessary radius is limited.

Studies with motion-picture and high-speed motion-picture photography showed that, with a relatively low number of vapor-formation centers, the heat is carried away from the wall region primarily through free convection. Superimposed on this process, however, is the much more intense heat transfer in the form of the heat of vaporization. Agitation of the region near the wall by the vapor bubbles has a negligible effect. Under these conditions, each newly activated vapor-formation center makes a significant contribution to heat transfer. Therefore, even an extremely small increase in the superheating of the liquid near the wall (or an increase in the specific heat flux) causes a significant increase in the heat-transfer coefficient. In this case, according to our experimental data, we have

$$\alpha \sim q^{0.95}. \tag{1}$$

During the experiments under vacuum, there was an especially noticeable phenomenon called "heat-flux hysteresis." After the heating is stopped, and the heating surface is cooling, some of these vapor-formation centers fill with liquid and become inactive. When the boiling process is resumed on this surface, only individual depressions which have retained their vapor-formation capability begin to function. However, the vapor bubbles which grow at the depressions overlap neighboring inactive centers, filling them with vapor, and causing them to become active again. As a result, there is an explosive, discontinuous transition to boiling. One can visually follow the propagation of the vapor-formation front which starts at some part of the experimental tube.

For this reason, the boiling curves obtained with increasing and decreasing heat flux do not coincide. In the experimental results reported here, the points were found during the decrease of the heat flux. In this manner, very reproducible results are obtained, even at low pressure and with a low specific heat flux.

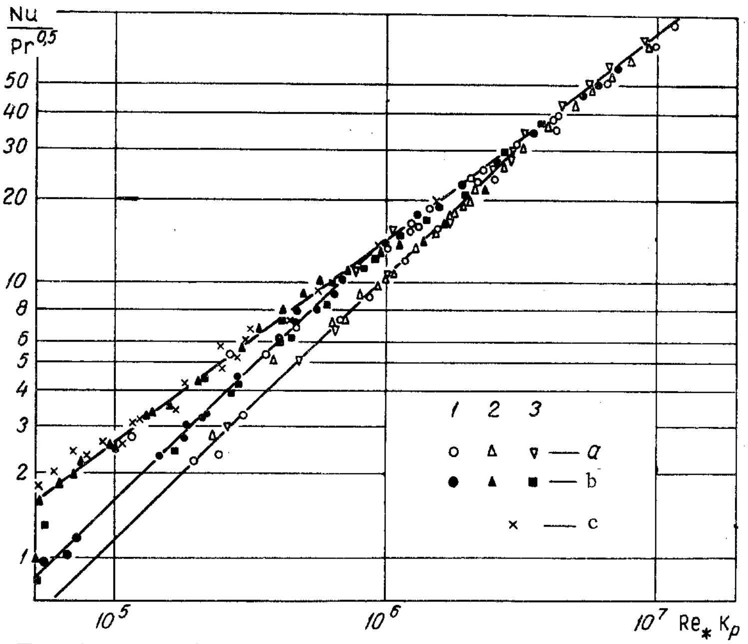

Fig. 2. Generalization of the experimental heat-transfer data. 1-3) Experimental series. a) Water; b) ethanol; c) water, data of [1].

All the experimental points were treated in the critical dependence

$$\mathrm{Nu} = f\,(\mathrm{Re}_* K_p)^m \,\mathrm{Pr}^n. \tag{2}$$

There exists a certain value of the product $\mathrm{Re}_* K_p$ (Fig. 2) above which the virtual changes in the number of vapor-formation centers no longer depend on the surface condition. For water, this occurs at $\mathrm{Re}_* K_p \geq 3 \cdot 10^6$; for ethanol it occurs at $\mathrm{Re}_* K_p \geq 8 \cdot 10^5$.

Specific confirmation of these results comes from the data of Averin [5], who asserted that the effect of surface conditions should appear only at low heat fluxes ($q \leq 1.16 \cdot 10^5$ W/m^2 for water at $P = 1 \cdot 10^5$ N/m^2); i.e., at $\mathrm{Re}_* K_p = 3.14 \cdot 10^6$. This is in complete agreement with our data.

When there are no factors which act to artificially limit the number of vapor-formation centers, the heat-transfer coefficient with boiling liquids at atmospheric and reduced pressure can be satisfactorily calculated from

$$\mathrm{Nu} = 5.6 \cdot 10^{-4}\,(\mathrm{Re}_* K_p)^{0.73}\,\mathrm{Pr}^{0.5}. \tag{3}$$

Figure 2 also shows the experimental data of Veneraki [1], who studied the boiling of water in a large volume in the same pressure range as used in this study. The working region in [1] was a brass tube 35 mm in diameter (technical grade surface, without any special treatment). Such a surface obviously had several active vapor-formation centers providing the superheating level necessary for the nucleation of vapor bubbles over the entire range of experimental parameters. The experimental data of [1] are in satisfactory agreement with dependence (3).

Visual observation and high-speed motion-picture photography showed that boiling of a liquid at a reduced pressure has several characteristic features. It is extremely difficult to determine the detachment diameters of the vapor bubbles, even at relatively low heat fluxes. At low heat fluxes, the stability of the boiling process is disrupted. Because of the simultaneous increase in the bubble dimensions and in the frequency at which they detach, the bubbles lose their spherical shape, vibrate, break up, and split into smaller bubbles. At large thermal fluxes, the boiling becomes more stable, but there is a transition from an isolated-bubble mode to one of vapor conglomerates, which form through coalescence of neighboring bubbles on the surface and of bubbles detached successively.

NOTATION

$\mathrm{Nu} = (\alpha/\lambda)\sqrt{\sigma/(\gamma' - \gamma'')}$ is the Nusselt number;
$\mathrm{Re}_* = (q/r\gamma''\nu)\sqrt{\sigma/(\gamma' - \gamma'')}$ is the Reynolds number;

$K_p = P/\sqrt{\sigma(\gamma' - \gamma'')}$	is the pressure number;
α	is the heat-transfer coefficient;
λ	is the thermal conductivity of the liquid at the saturation line;
q	is the specific heat flux;
P	is the pressure;
γ' and γ''	are the specific gravity of the liquid and vapor, respectively, at the saturation line;
r	is the heat of vaporization;
σ	is the surface tension of the liquid;
ν	is the kinematic viscosity.

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