EFFECT OF AN ELECTRIC FIELD ON HEAT TRANSFER OF A DROPLET IN THE SPHEROIDAL STATE

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Results of an experimental study of the effect of an inhomogeneous electric field on heat transfer of a droplet in the spheroidal state are offered. A comparison with theoretical data is made.

The decrease in heat transfer of a burning surface with a liquid freely flowing from it is related to formation of a vapor layer separating the spheroidal droplet from the cooling surface [1]. The heat-transfer coefficient is then inversely proportional to the thickness of this layer. In turn, the thickness of the vapor layer depends on the force acting on the liquid spheroid. The additional pressure below the droplet connected with this force may be approximated by the formula

$$\Delta P = -\frac{4}{\pi D^2}\mathbf{F}\cdot\mathbf{n}. \quad (1)$$

Using Eq. (1) to calculate the heat-transfer coefficient [1], we obtain

$$\alpha = A\sqrt[4]{|\mathbf{F}\cdot\mathbf{n}|}. \quad (2)$$

The coefficient A is determined by evaporation conditions and is independent of the forces acting on the droplet (this formula is valid for $\mathbf{F}\cdot\mathbf{n} < 0$).

The nature of **F** may vary: gravitational force, electric and magnetic forces, or a combination of these forces. In the experiments described herein, **F** was composed of the weight of the droplet and the force exerted on the droplet by an inhomogeneous electric field. From conditions of dimensionality it follows that

$$\mathbf{f} = \mathbf{b}U^2. \quad (3)$$

The vector **b** is dependent on the geometry of the electrodes creating the field, the form of the droplet, and the properties of the droplet material.

For the case described by Eq. (3), we obtain from Eq. (2)

$$\alpha = A\sqrt[4]{|\mathbf{G}\cdot\mathbf{n}|}\sqrt[4]{\left|1+\frac{\mathbf{b}\cdot\mathbf{n}}{\mathbf{G}\cdot\mathbf{n}}U^2\right|}. \quad (4)$$

Comparing the coefficients of heat transfer with and without the field, we arrive at the expression

$$\frac{\alpha}{\alpha_0} \equiv \varphi = \sqrt[4]{\left|1+\frac{\mathbf{b}\cdot\mathbf{n}}{\mathbf{G}\cdot\mathbf{n}}U^2\right|}. \quad (5)$$

From Eq. (5) it is evident that φ is independent of surface temperature.

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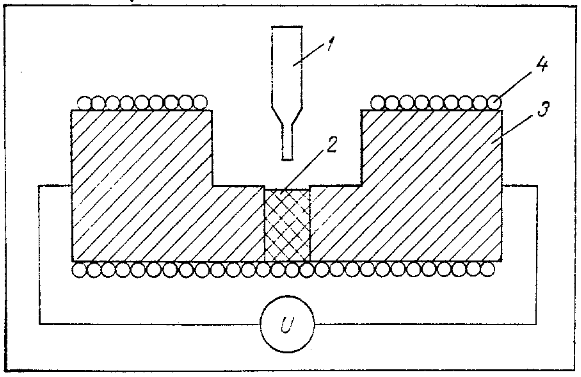

Fig. 1. Diagram of experimental apparatus.

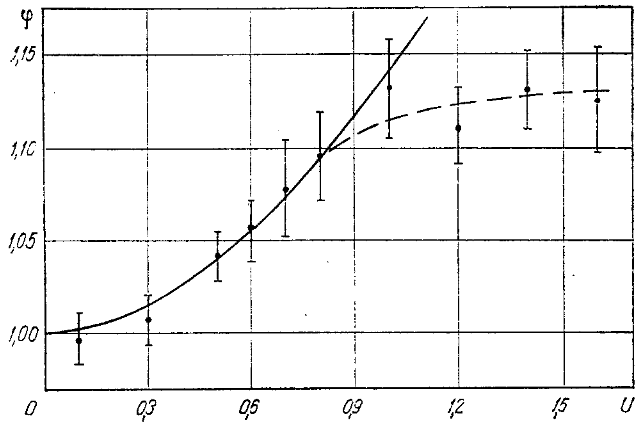

Fig. 2. Relative heat-transfer coefficient φ versus electrode voltage U (kV).

Equation (5) was verified with the apparatus depicted in Fig. 1. Calibrated droplets of distilled water were deposited by dropper 1 on the surface of an 8-mm-thick quartz plate 2. The inhomogeneous electric field was created by copper electrodes 3. The latter served simultaneously to heat the quartz plate. Heating was produced by filament 4. In all experiments electrode temperature was maintained constant and above the second critical point. Droplet charge on the electrodes was eliminated by the construction of the apparatus.

The quantity directly measured in the experiments was the time necessary for complete evaporation of a droplet of constant diameter (about 2.5 mm). Measurements were performed alternately at $U = 0$ and $U \neq 0$. For each value of electrode voltage, 10-15 measurements were taken. So that the electric field would not affect the volume of the spheroidal droplets, the voltage on electrodes 3 was switched on after detachment of the drop from the dropper 1.

Results of the measurements are presented in Fig. 2. The abscissa shows values of U, while the ordinate indicates the ratio of evaporation time without the field to evaporation with the field. As is well known [1], this ratio is equal to φ. Points on the curve indicate mean values, with vertical lines indicating mean square deviations. The solid line is the curve obtained from Eq. (5) for $|\mathbf{b}\cdot\mathbf{n}/\mathbf{G}\cdot\mathbf{n}| = 0.692\ (\text{kV})^{-2}$.

Figure 2 indicates that in the region up to 1 kV the agreement between experiment and theory is good. The reduction in growth of φ observed at higher voltages (U > 1 kV) can evidently be explained by deformation of the droplet by the field. This may be reflected theoretically by the dependence of **b** on the dimensionless complex $\varepsilon U^2/\sigma D$.

The direction of the electric field (the sign of U) had no effect on the results.

NOTATION

ΔP, excess pressure under the spheroid; **F**, force acting on the spheroid; **n**, unit vector externally normal to boiling surface; D, spheroid diameter; α, heat-transfer coefficient in external field; **f**, additional force acting on the spheroid; **b**, constant vector; U, electrode voltage, kV; G, weight of spheroid; α_0, heat-transfer coefficient in the absence of field; φ, ratio of times for complete evaporation without and with fields (or inverse ratio of corresponding heat-transfer coefficients); ε, liquid dielectric constant; σ, surface tension of liquid.

LITERATURE CITED

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REYNOLDS ANALOGY FOR BOILING

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A Reynolds analogy for boiling is proposed and a generalized heat-transfer equation for bubble boiling in tubes and in a large volume is presented.

Contemporary knowledge of heat transfer and hydrodynamics for bubble boiling of liquids is based mainly on theoretical and experimental investigations of the boiling process in a large volume. The general correlations developed by Soviet investigators (Kruzhilin, Kutateladze, Tolubinskii, Borishanskii, et al.), can be used to design complex vaporizing equipment for boiling a liquid in a large volume. In most contemporary heat exchangers, boiling does not occur in a large volume, but in tubes and channels. However, there are as yet no well-founded reliable general formulas to calculate the boiling process in tubes with natural and forced flow circulation. The available correlations for boiling in a large volume are not suitable for calculating boiling in tubes, since they do not contain the necessary parameters and conditions to account for the characteristic general and special processes. The analogy of the Reynolds number Re* does not take into account all the special hydrodynamic features of the process of boiling in tubes.

We recall that the parameter

$$\mathrm{Re} = \frac{wd_0}{\nu} \tag{1}$$

was proposed by Reynolds to describe the motion of a single-phase medium in tubes; here the velocity w is the ratio of the mass flow to the area of the flow or the tube, f: $w = V/f$ ($m^3/h/m^2 = m/h$).

To describe motion of a two-phase fluid with boiling, Kichigin has proposed [1] a Reynolds analogy

$$\mathrm{Re}^* = \frac{q/L\rho_V}{\nu}\left[\frac{\sigma}{g(\rho-\rho_V)}\right]^{0.5}. \tag{2}$$

In Eq. (2), which differs appreciably from Eq. (1), the velocity appears only as the mass flow rate $V = q/L\rho_V$ [$(\mathrm{kcal}/(m^2 \cdot h))(\mathrm{kg}/\mathrm{kcal})(m^3/\mathrm{kg}) = m/h$], usually called the vapor-formation rate, and there is no cross section f of the moving flow. Therefore, for the process in tubes, Re* accounts only for the effect of the vapor-formation rate and cannot account for the effect of velocity of motion of the vapor–liquid flow. Under operating conditions, with constant specific heat flux along a vertical tube with lateral circulation of a boiling flow, the vapor-formation rate and Re* will be constant at each tube section, while the rate of vapor motion will increase along the tube because of the increase of vapor-content at successive sections, and the absolute velocity of motion of the two-phase boiling flow will in-

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