NOTATION

p, pressure; T, t, temperature; q, heat flux; $\Delta t = t_w - t_q$, temperature difference; μ, ν, absolute and kinematic viscosities; ρ, density; u, velocity; ρu, mass velocity; x, distance from pipe inlet; d, pipe diameter; $\mathrm{Nu} = \alpha d/\lambda_q$; $\mathrm{Re} = \rho ud/\mu_q$; $\mathrm{Pr} = \mu_q c_{p_q}/\lambda_q$; $\mathrm{Pe} = \mathrm{Re}\,\mathrm{Pr}$; $\mathrm{Gr} = \frac{\beta_q g d^3}{\nu^2}\Delta t$ respectively, the Nusselt, Reynolds, Prandtl, Peclet, and Grashof numbers; X, corrected pipe length. Indices: w, wall; q, liquid; cr, critical; e, experimental.

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INFLUENCE OF A MAGNETIC FIELD ON THE CONTACT WETTING ANGLE IN BUBBLE BOILING

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It is experimentally shown that an external magnetic field applied to a bubble boiling region improves wetting of the surface heating the boiling liquid.

Investigations of recent years have shown that one possible way to improve heat transfer in bubble boiling is to apply an electric or a magnetic field to the boiling region. Here one finds appreciable changes in the heat-transfer coefficient and the critical heat flux [1-3], in the density of vapor forming centers, separation size of the bubbles, and their separation frequency [3-5]. All of this indicates that if one knows the mechanism of the action of the field on the boiling, one can use an electric field as a means of controlling heat and mass transfer. However, in spite of the practical value of these effects, the mechanism of the influence of the field on bubble boiling has not yet been elucidated conclusively. It is suggested that the external field alters the structure of the heated boundary layer or of the double electric field. In [1] the intensifying action of the electric field on the heat transfer is explained by the generation of electroconvective fluxes, and according to the research data of [6] the electric field alters the contact wetting angle. Further investigations are needed to pinpoint the mechanism of the field action.

It has been established earlier that the contact wetting angle strongly influences the heat-transfer coefficient [7], the critical heat flux [8], the density of vapor forming centers and their stability, the separation dimensions of vapor bubbles, and the mechanism and frequency of their separation [9, 10]. The present author attempts to explain the influence of a magnetic field on the contact wetting angle and to evaluate the relative changes in the microparameters D_0, Θ under the action of this field.

The experimental equipment has been described in [5]. The boiler chamber is equipped with windows for motion pictures and visual observation of the boiling process, as well as an external heater to maintain the saturation temperature. Inside the chamber are mounted a heat-transfer surface, a device to create and control the magnetic field, and a system of thermocouples to measure temperatures. The magnetic field intensity varied over a range in-

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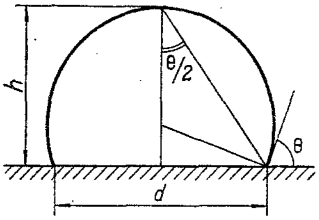

Fig. 1. Sketch of a vapor bubble for determining the contact angle Θ.

TABLE 1. Relative Diameter of the Separating Vapor Bubbles and the Relative Contact Wetting Angle as a Function of the Magnetic Field Intensity

Magnetic field intensity $\times 10^{-4}$ A/m	Mean contact angle, deg	Mean separation diam., mm	$\frac{\Theta_M}{\Theta_0}$	$\frac{D_M}{D_0}$
0	75	3,49	1	1
1,59	65	3,10	0,87	0,89
3,18	60	2,74	0,8	0,7
4,77	54	2,47	0,73	0,7
5,72	50	2,31	0,66	0,66

cluding the region of magnetic saturation of the material of the heat-transfer surface. The movies were taken at a rate on the order of 1000 frames/sec. From magnified frames of the exposed and developed movie film we measured the contact wetting angle and the diameters of bubbles at the moment of separation. The results were reduced by the methods of mathematic statistics of [5].

Measurement of the contact wetting angle, particularly during the boiling process, meets with great difficulties [7, 8, 10]. The following method was used here to measure Θ. At each vapor forming center we chose a frame with a picture of a bubble at the initial stage of its asymptotic growth, i.e., at the moment when the bubble shape has not yet been appreciably distorted under the influence of gravitational forces and is a part of a sphere. For such a bubble we measured the diameter of the wetted perimeter d from the thickening at the phase interface, and the height h of the bubble at the center (see Fig. 1), and then calculated the contact wetting angle from the formula

$$\Theta = 2 \operatorname{arctg} \frac{d}{2h}.$$

The values obtained were monitored by repeat measurements with the aid of a protractor using the method of [7]. The values coincided to within the measurement error limits of 2-4°.

In the experiments described we kept to a minimum factors distorting the bubble shape due to optical effects (throughout the whole volume the saturation temperature was maintained, there was no forced flow, the temperature head was small, and the path length of the light ray through the heated layer was $5 \cdot 10^{-3}$ m). The main error comes from the accuracy of measuring d and h and the statistical scatter in Θ at the different boiling centers.

The relative error of measurement of the contact angle at a given center $\varepsilon = [(\Delta d^2)/d^2 + (\Delta h^2)/(2h^2)]^{1/2}$ was 3-4%. Here $\Delta h = \Delta d = 0.5 \cdot 10^{-3}$ m is the maximum error of the measuring rule.

The statistical mean value of the contact angle $\overline{\Theta}$ and the confidence interval $\Delta\Theta$ for each picture were evaluated as follows: $\overline{\Theta} = \Sigma\Theta_i n_i/\Sigma n_i$; corrected dispersion is $S_{\overline{\Theta}} = [\Sigma(\overline{\Theta} - \Theta_i)^2 n_i/\Sigma n_i (\Sigma n_i - 1)]^{1/2}$. The Student factor t_γ was chosen from the tables according to the total number of values of contact angle on the film Σn_i and the degree of reliability $\gamma = 0.95$. The confidence interval $\Delta\Theta = S_{\overline{\Theta}} t_\gamma$ in the various tests was 4-6°.

The results of the tests and the calculations are shown in Table 1. The subscript 0 indicates values of the quantities with no field, and the subscript M indicates the same quantities with the field present.

It can be seen from Table 1 that: 1) under the influence of an external magnetic field there is a decrease of the contact wetting angle Θ and the mean diameter of separating bubbles D_0; 2) the greatest effect is observed in going from boiling without the field to boiling with the field. On further increase of the field intensity by a factor of 2 or 3 the effect of the field is diminished; and 3) the relative reduction of the separation diameter under the influence of the magnetic field is on the same order as the relative reduction of the contact angle.

From analysis of the experimental data we can make some observations regarding the mechanism of action of the magnetic field on the microparameters of boiling in the model comprising a bubble and a microlayer.

At moderate heat flux and normal atmospheric pressure the separation diameter of the vapor bubbles growing on a horizontal surface is described satisfactorily by the Fritz formula

$$D_0 = 0.02\Theta\left[\frac{\sigma}{g\Delta\rho}\right]^{1/2}.$$

Our tests have shown that under the influence of the magnetic field the separation diameter of vapor bubbles is reduced proportionally with the contact angle. This agrees with the Fritz formula if we take into account that the surface tension and the density of water and water vapor vary little under the influence of the field. The contact wetting angle Θ is the most important physicochemical characteristic of the molecular interaction at the phase boundaries:

$$\cos\Theta = \frac{\omega(l) - \omega_{12}}{\sigma}.$$

Under the influence of the magnetic field the quantity $\omega(l)$ can alter appreciably, since the external field has an orienting influence on the molecules of the microlayer, and this results in a change of the mean distances between the molecules and the forces between them. Here the equilibrium microlayer increases and the contact wetting angle decreases [11]. When the field is on the majority of the molecules are oriented, which markedly affects the microparameters. With increased field intensity one can additionally orient some of the remaining molecules. This explains the diminished influence of the field.

NOTATION

Θ, contact wetting angle; h, bubble height at its center; d, diameter of the wetting perimeter; $\omega(l)$, "effective surface tension" at the solid—vapor boundary, allowing for the liquid sublayer between them; ω_{12}, σ, specific free surface energies at the solid—liquid and liquid—vapor boundaries, respectively; l microlayer thickness; n_i, number of bubbles with contact angle Θ_i; t_γ, Student factor; $S_{\bar{\Theta}}$, adjusted dispersion.

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MECHANISM OF GROWTH AND SEPARATION OF AXISYMMETRIC DROPS AND BUBBLES

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A practical solution is obtained for the axisymmetric problem of quasistatic drop and bubble growth.

In practice, processes of mass transfer and heat exchange between drop-forming liquid and gaseous disperse media depend on the interaction of the two media. The bubbling of gases through liquids is a technique widely used in chemical engineering while air conditioning technology is based on producing a liquid spray in a vapor–air mixture [1-11]. The interaction of two media on the developed surface of packings finds application in various branches of industry. The interaction of the two media depends not only on the temperature difference, the partial pressure difference and the area of the contact surface but also on a number of other factors, such as capillary, surface and hydrodynamic effects. If the relative motion of the media in direct contact is due to the action of gravitational forces, then the influence of the velocity factor on the mass-transfer process is conditioned by the physical propties of the media and can be intensified by developing the contact surface. Accordingly, the question of the formation of the contact surface and the capillary effects on that surface are of considerable significance in connection with the solution of engineering problems.

Let us consider an axisymmetric drop of liquid suspended over a calibrated orifice of sufficiently small diameter in a plate of solid material. To this there corresponds a gas bubble formed over the orifice in a device made in the form of an individual nozzle, plate, or capillary. The diameter of the orifice is so selected that the velocity head of the liquid or gas is balanced by the resistance to the motion of the drop or bubble (Fig. 1). Then the total energy of the object at any moment of time $t \leqslant t_{sep}$ is composed of the surface energy and the energy of the force of gravity for drops or the energy of the buoyancy force for gas bubbles. Accordingly, the energy functional takes the form

$$W(t)=\int\limits_{D}\Big\{\sigma_{12}-\sigma_{10}+\sigma_{20}\Big(\sqrt{1+p^2+q^2}-\frac{z^2}{2a^2}\Big]\Big\}dxdy+\lambda\int zdxdy, \qquad (1)$$

where $z=z(x, y, t)$ is the equation of the surface and $p=\partial z/\partial x$; $q=\partial z/\partial y$; $a^2=\sigma_{20}/n\ (\rho_l-\rho_g)g$ is a certain parameter with the dimension of the square of length, since ρ_l and ρ_g are the densities of the liquid and the gas, respectively; σ is the surface tension at the interface of the corresponding phases; λ is the Lagrange multiplier taking into account the invariability of the volume at time t in seeking the extremal of functional (1).

The axisymmetry makes it possible to go over from the two-dimensional domain to the plane problem by making the substitution $r=\sqrt{x^2+y^2}$. Then (1) takes the form

$$W(t)=2\pi\int\limits_{0}^{r}\Big\{\sigma_{12}-\sigma_{10}+\sigma_{20}\Big(\sqrt{1+z_r'^2}+\lambda z\Big\}rdr. \qquad (2)$$

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