EXPERIMENTAL STUDY OF THE EFFECT OF A MAGNETIC FIELD ON MICROCHARACTERISTICS OF THE BOILING OF POLAR LIQUIDS

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It was established that the diameter at which vapor bubbles leave the heating surface in boiling polar liquids decreases with an increase in the strength of a magnetic field influencing the liquids.

The rate of heat transfer in boiling depends on many different factors, not all of which can be fully accounted for. In connection with this, no rigorous quantitative theory of boiling has yet been proposed. Studies of the boiling of liquids have been based on various physical models employing various assumptions and simplifications [1].

One possible explanation for the high heat-transfer rate in nucleate boiling which has recently come under investigation [1, 2] is the process known as "microlayer" evaporation. It is characterized by the transfer of heat from the heating surface to the bubble by evaporation of a thin layer of heated liquid underlying the bubble. The thickness of the microlayer, the subject of several studies, is important here. The microlayer thickness is directly connected with the microcharacteristics of nucleate boiling (bubble dimensions, temperature gradient in the vicinity of the bubble, the lifetime of the bubble on the heating surface, etc.).

Several basic researches [2-9] have shown that thin films and layers have their own specific properties and that these properties are dependent on the thickness h. External force fields also exert an effect on the structure of the films and their thermophysical characteristics. Given the above model of a microlayer, it is very important that the effect of electrical and magnetic fields on the microcharacteristics of the boiling process be studied if we are to gain a deeper understanding of the physical mechanism of heat transfer from the hot surface.

It should be noted that a few studies of the effect of electric and magnetic fields on the behavior of bubbles in a boiling liquid and the intensification of heat transfer were done many years ago. However, the effects observed were few, and these investigations were not carried further. Beginning with the 1960s, the question of the effect of electric and magnetic fields on the boiling process and on heat transfer, evaporation, condensation, crystallization, and other processes has attracted increasing attention.

More recent investigations have established that an electric field increases the heat transfer coefficient for weakly conducting liquids [10-12] and that a magnetic field decreases the rate of heat transfer to boiling alkali metals [13, 14]. It is interesting to note that both fields were observed in the above experiments to have decreased the diameter at which the bubbles left the heating surface (the separation diameter). A strong magnetic field significantly alters the shape and rate of growth of the bubbles in boiling metals, this effect depending on the bubble size [14].

The problem of the effect of electric and magnetic fields on boiling turns out to be a complicated one. The magnitude of the effect depends on the strength and frequency of the field, the supplied load, the nature of the boiling liquid, the material of the surface, etc.

Described below are the results of experimental studies of the effect of a magnetic field on the mean separation diameter of a vapor bubble $\langle D_0 \rangle$ in boiling liquids. A study was made of the saturation boiling of distilled water and an aqueous solution of isoamyl alcohol (1% by wt.) at atmospheric pressure on a horizontal heater. The experimental vessel was a cylinder 0.2 m high and 0.15 m in diameter equipped with two inspection holes to permit

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TABLE 1. Separation Diameters of Vapor Bubbles in the Presence and Absence of a Magnetic Field

Boiling liquid	Strength of magnetic field, $\cdot 10^{-4}$ A/m	Heat flux, $\cdot 10^4$ W/m^2	Mean separation diameter $<D_0>$, $\cdot 10^{-3}$ m
Distilled water	0	2	3,49
	1,59	1,54	3,1
	3,18	2,3	2,74
	4,77	1,8	2,47
	5,72	1,81	2,31
Isoamyl alcohol solution	0	4,0	2,85
	3,18	5,0	2,46

visual observation and filming of the process. The saturation temperature was maintained in the liquid volume by an external heater. The temperature of the heating surface and in the liquid volume was measured with copper–constantan thermocouples. The heating surface was a nickel plate $6.5 \times 0.5 \cdot 10^{-4}$ m and paramagnetic tubes 0.065 m long and 0.0022 m in diameter. These surfaces were heated by a direct electrical current. The heat flows were calculated from the supplied current and the area of the heater and ranged from $1.2 \cdot 10^4$ to $5 \cdot 10^4$ W/m^2. This ensured the existence of a region of individual bubbles and allowed us to obtain photographs (at a filming speed up to 1500 frames/sec) suitable for statistical analysis of the material. A magnetic field with a strength from $1.59 \cdot 10^4$ to $5.72 \cdot 10^4$ A/m was created with ferrite magnets. The magnitude of the field was sufficient to magnetize the nickel to saturation. To make sure the magnet and scale were within the field of view, we constructed a special holder which allowed us to easily change the magnitude and direction of the field. Before each series of experiments, the inside surface of the boiler and all elements of the structure which were immersed in the liquid were carefully cleaned, washed with distilled water, dried, coated with lacquer, and thermostated. The above procedures ensured fully reproducible measurements.

Since the separation diameter of vapor bubbles in a boiling liquid is essentially a statistical quantity, we used the methods of mathematical statistics to analyze the experimental data [15].

The exposed and developed film was viewed on a "Mikrofot" projector. The diameter of individual bubbles was determined as half the sum of their vertical and horizontal dimensions at the moment of separation. The mean separation diameter for each film was calculated from the formula $<D_0> = \frac{1}{n}\sum_{i=1}^{n} D_i$. The confidence interval ΔD_0, associated with a confidence level of 0.95, was within the range $(0.08\text{–}0.25) \cdot 10^{-3}$ m for the different experiments:

$$\Delta D_0 = t_\alpha(n)\, \Delta S_{\langle D_0 \rangle}; \quad \Delta S_{\langle D_0 \rangle} = \left[\sum_{i=1}^{n} (\Delta D_i)^2 / n(n-1)\right]^{1/2},$$

where $t_\alpha(n)$ is Student's coefficient; $\Delta S_{<D_0>}$ is the standard deviation. Table 1 shows the results of our statistical analysis of the films obtained in boiling the liquids on a paramagnetic tube.

The study results clearly show the effect of a magnetic field on the mean separation diameter of the vapor bubble. Figure 1a and b shows frames from filming of the boiling of the water and alcohol solution on a paramagnetic surface in the presence and absence of a magnetic field. The field strength H and direction are indicated below the pictures.

Visual observations show that the presence of the magnetic field changes the number of active centers and frequency of separation. This is particularly the case in the boiling of the alcohol solution.

Other conditions being equal, with a constant heat flow to the heating surface immersed in water, the magnetic field leads to a slight increase in the temperature head (tenths of a degree). A shift in the direction of the field has a slight effect on bubble diameter. The change in diameter was within the range of the experimental error, but the character of the change was always the same: bubble diameter was somewhat greater when the field was directed toward the heating surface.

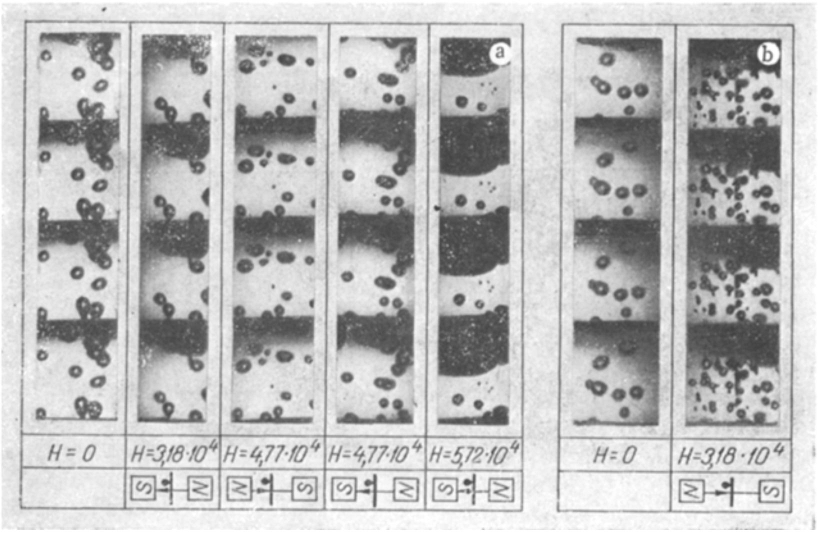

Fig. 1. Photographs of the boiling of water (a) and an aqueous solution of isoamyl alcohol (b) under the influence of a magnetic field and in the absence of the field. Indicated below is the direction of the field relative to the heating surface and the field's strength H, A/m.

Comparison of the measurements of separation diameter with values calculated from formulas allows us to make certain assumptions regarding the mechanism of the field's effect.

The separation diameter can be determined theoretically from the condition of the equilibrium of the forces acting on the bubble at the moment of separation. Here, it is necessary to take into account the surface tension, buoyancy, the inertia of the liquid, and the viscosity. A rigorous solution of this problem accounting for all of the forces acting on the bubble has yet to be realized [1].

The diameter value calculated with allowance for only the surface tension and buoyancy [1, 8, 9, 16-18] agrees satisfactorily with the experimental data for the boiling of liquids on a horizontal heater immersed in a large volume under atmospheric pressure, assuming the data are for the region of single bubbles. Let us examine the formula [17, 18]

$$\langle D_0 \rangle = 2a \sin \frac{\theta}{2}, \tag{1}$$

where θ is the contact angle; $a = [\sigma/g(\rho - \rho')]^{1/2}$ is the capillary constant. Equation (1) may be approximated when rewritten in the form [19]

$$\langle D_0 \rangle \approx \text{const}\, \sigma^{1/2} \sin \frac{1}{2} \left[\arccos \frac{\omega_{12} - \omega_{02}}{\sigma} \right]. \tag{2}$$

Here ω_{12}, ω_{02}, and σ are the surface tensions at the metal—vapor, metal—liquid, and liquid—vapor interfaces, respectively. It is apparent from Eq. (2) that one reason for the decrease in bubble separation diameter may be a change in the free surface energy. The microlayer under the bubble is a surface phase, with specific properties. The thickness of the microlayer decreases as the bubble grows. As is known [4, 6, 8, 9], the free surface energy $\sigma(h)$ and $\omega_{02}(h)$ is a function of the thickness of the film.

If we take steady-state boiling in the given system in the absence of a magnetic field as a standard, i.e., as a nominal "equilibrium" process, then the action of the external magnetic field on the system disturbs this "equilibrium" and will thus, in accordance with Le Chatelier's principle, stimulate processes that will tend to minimize the effect of the external force. One such process may be a change in the structure of the microlayer under the influence of the magnetic field, with the formation of phase boundaries at the solid—liquid interface. Such a development would lead to a reduction in the free surface energies ($\sigma(h)$, $\omega_{02}(h)$) and a corresponding decrease in the separation diameter.

NOTATION

H, magnetic field strength; D_i, diameter of vapor bubbles separating from the heating surface; $\langle D_0 \rangle$, mean diameter; g, acceleration due to gravity; ω_{12}, ω_{02}, σ, surface tensions at the metal—vapor, metal—solution, and solution—vapor interfaces, respectively; ρ and ρ', density of the liquid and vapor, respectively; h, film thickness.

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