INVESTIGATION OF THE STRUCTURE OF A BOILING FERROMAGNETIC LAYER BY MEASURING ITS MAGNETIC CHARACTERISTICS

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The possibility of determining the parameters of a boiling ferromagnetic layer by measuring characteristics is studied.

The papers [1-6, 8], exhibiting the ordering of the layer structure starting with some value of the magnetic field intensity, are devoted to an investigation of a boiling ferromagnetic layer in application to controlling its hydrodynamics by applying a magnetic field. The structure of the boiling ferromagnetic layer in all these papers was studied by neutral methods with respect to the magnetic field by using a turbulence meter [3] or capacitance-type sensors [8], for examples; at the same time, the influence of the layer structure on the magnetic field, for example, the deformation of the lines of force, has not been studied, although any change in the structure should cause a corresponding change in the magnetic permeability. Similarly to the method of magnetic defectoscopy in investigating the structure of a boiling layer of ferromagnetic particles, it is desirable to use not only the mixing in the layers, but also the ferromagnetic properties, which, meanwhile, permit modeling and studying the structure of a boiling layer of nonmagnetic particles. The present paper is an attempt to close this gap.

A column 1 with 92 mm inner diameter and ferromagnetic particles 2 surrounded by a four-section coil 3 with 180 mm inner diameter connected to the ac main through an autotransformer is shown in Fig. 1. The fluidizing agent (air) is delivered by means of the blast blower 4 through the supply pipe 5 and the perforated grating 6 in the layer.

The perforated grating consists of two 5-mm-thick disks with 37 uniformly distributed holes of d = 4 mm. A brass mesh with a cell size on the order of 0.05 mm was located between the disks. The thickness of the column wall was about 2 mm. The material of the column and disks is steel Kh18N10T. Measurements of the alternating magnetic field of a solenoid within the column and in the empty solenoid, performed with 0.5% accuracy by using a measuring winding and an F564 mean emf voltmeter, did not disclose any differences in the field intensity (H = 20 kA/m) for identical values of the current in the winding, i.e., there was practically no screening of the magnetic field by the current-conducting column. The gas velocity was determined by means of the discharge measured by an RS-40M counter 7. The exit of the pulse tube 8 by which the pressure pulsations were transmitted to the pressure sensor 9 (where they were converted sequentially into pulsations of a water column and into electrical signals recorded on film by using an MPO-2 oscillograph) was approximately at the center of the layer. The distinguishing peculiarity of this sensor was that the converted pulsations were discrete, since the sensor itself had 25 parallel electrical loops (see Fig. 1, where only seven loops are shown in order not to complicate the diagram), as many corresponding point contacts, and one contact, common to all the loops, with a significantly greater surface as compared to the point contacts. The point contacts had a 1-mm spacing. Each higher loop had less resistance than the preceding lower one, so that a sequential closure of the loops by water and a step diminution in the resistance of the whole sensor circuit occurred with the increase in height of the water column. A line of definite height, corresponding to the same depth of submersion of the sensor, was marked on the oscillograph film by successively submerging the sensor 1 spacing. The magnitude of the dc supplying the sensor was not more than 10 mA. The contacts were fabricated from d = 0.1-mm copper wire covered with water-impervious lacquer and were not wetted by water in practice.

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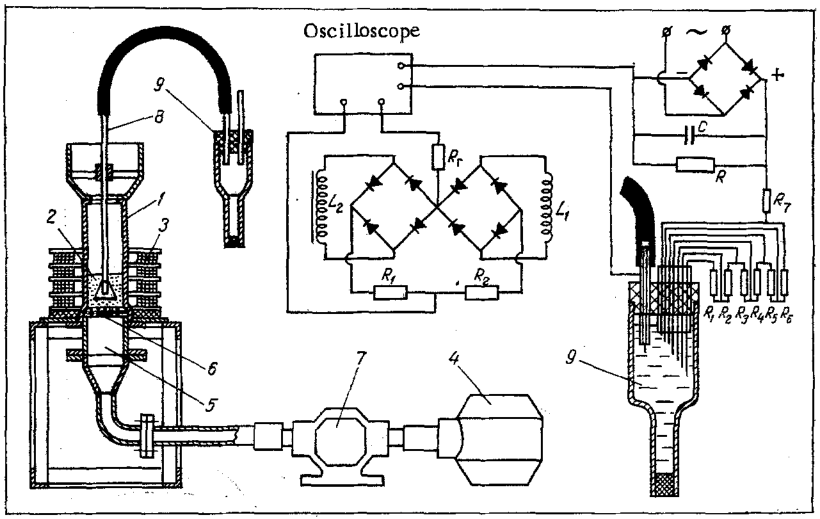

Fig. 1. Diagram of the test setup to investigate the structure of a ferromagnetic fluidized bed and the electrical circuits to record its magnetic and hydrodynamic characteristics: 1) column; 2) ferromagnetic disperse material; 3) solenoid; 4) blast blower; 5) supply pipe; 6) perforated grating; 7) RS-40M flowmeter; 8) pulse tube with measuring winding at its lower end; 9) pressure sensor.

A 3-mm-high measuring winding with D = 45 mm inner diameter and n = 150 turns was located at 5 mm from the entrance hole of the pulse tube and perpendicular to its axis. The measuring winding was from 0.05-mm-diameter wire. An ac magnetic field acted on the layer of ferromagnetic particles. The inductance of the solenoid, measured by using an ac bridge, was $L_s = 0.062$ H. The ratio of solenoid length l_s to the mean diameter D_m of its windings is $l_s/D_m = 120/200$.

The magnetic field intensity was measured by a second 10-mm-diameter and 2-mm-high measuring winding as the mean integrated intensity over the sensor cross section. The sensor was first placed in a calibrating solenoid with a homogeneous ac magnetic field of known intensity $H = K_1 I_0 = 6.554 I_0$ kA/m. Here I_0 is the current in the calibrating solenoid, and K_1 is the solenoid constant. By measuring the emf ε of the sensor for a known value of H, the constant of the measuring winding $K_2 = \varepsilon/H$ [7] was found from $\varepsilon = K_2 H$.

To take account of the influence of voltage fluctuations in the main ε was recorded on the film. However, no fluctuations in ε were detected.

Measurement and Recording of the Change in Magnetic Permeability of the Boiling Layer

A measuring winding placed within the layer or enclosing a whole column made from nonmagnetic material was the sensor for this purpose. The conductivity of the magnetic flux through the boiling layer of ferromagnetic dispersed material depends on the homogeneity and height of the layer. A change in the magnitude of the magnetic flux enclosed by the conducting loop of the sensor occurred during fluctuations in the height of the boiling layer with the passage of bubbles through a 10-50-mm-diameter and 0.5-1-mm-thick sensor; hence, the emf $\varepsilon = -d\psi/d\tau$ of the sensor was determined by the F564 voltmeter of mean parameters and was also recorded on the film of the MPO-2 oscillograph by means of the circuit shown in Fig. 1. Two measuring windings L_1 and L_2 with a mean diameter $D_m = 45$ mm for the turns were used in this circuit [9]. Each had n = 150 turns, and the wire diameter was d = 0.05 mm. The winding L_2 was placed directly in the boiling layer at a height of 20 mm above the gas-distributing grating, almost at a level with the exit of the pulse tube. The winding L_1 was outside the limits of the column, and by moving it in space the magnetic flux enclosed by its contour could be altered.

Composing the equation connecting the resistors R_1, R_2, $R_{b.d.}$ and the emf ε_1 and ε_2 with respect to the value of the current in the bridge diagonal on the basis of Kirchhoff's laws and solving, we find

$$I_{b.d.} = \frac{\varepsilon_2 R_1 - \varepsilon_1 R_2}{R_1 R_2 + R_1 R_2 + R_2 R_{b.d.}}.$$

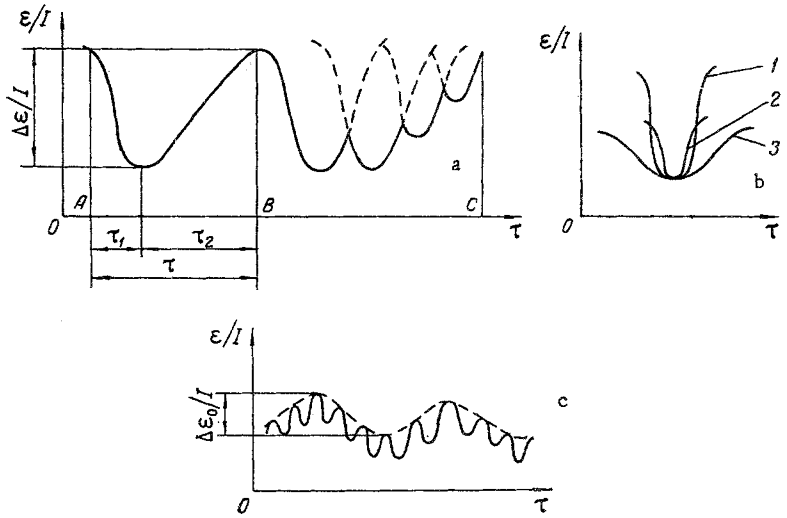

Fig. 2. Typical oscillograms of the emf pulsations in a plane measuring winding submerged in a ferromagnetic fluidized bed: a) $\Delta\varepsilon/I = f(\tau)$ corresponds to low values of the intensity H of the alternating magnetic field for which the layer structure remains disordered; b) the change in $\Delta\varepsilon/I$ with time [1) H = 2.5 kA/m; 2) 10; 3) 12.5]; c) oscillogram with abrupt pulsations in a background of smoother low-frequency pulsations shown by the dashes.

Here ε_1 is the emf of the measuring winding L_1 placed outside the limits of the boiling layer, and ε_2 is the emf of the measuring winding placed directly in the boiling layer.

By changing ε_1 by moving the sensor to some point of space enclosed by the magnetic field or by rotating the plane of the sensor through some angle φ to the direction of the magnetic lines of force, we obtain that $I_{d.c.} = 0$, i.e.,

$$\varepsilon_1 = \varepsilon_2 = -nS\mu_0 \frac{\partial H_1}{\partial \tau} = -nS\mu \frac{\partial H_2}{\partial \tau} \cdot \frac{\mu_0 \partial H_1}{\partial \tau} = \frac{\mu \partial H_2}{\partial \tau}.$$

In the general case, the magnetic permeability is practically independent of the field intensity for finely dispersed material to an H on the order of 50 kA/m, and is determined by the ratio between the layer length and diameter, the magnitude of the porosity, and the structure of the layer (the particle orientation and the porosity distribution). It is necessary to obtain the equality $\varepsilon_1 = \varepsilon_2 = \varepsilon$ in order to extract the component $\Delta\varepsilon$ due to the change in magnetic permeability more exactly, since $\Delta\varepsilon \ll \varepsilon$. Then disturbance of the equilibrium in the electrical circuit occurs with the change in the magnitude of ε, for example, because of the change in layer density and, therefore, in the inductance L_2 of the measuring winding, and a current $\Delta I_{b.d.}$ flows along the diagonal:

$$\Delta I_{d.c.} = \frac{(\varepsilon_1 - \Delta\varepsilon) R_1 - R_1\varepsilon_1}{R_{b.d.} R_1 + R_2 R_1 + R_{b.d.} R_2} = \frac{\Delta\varepsilon R + \varepsilon (R_1 - R_2)}{R_{b.d.} R_1 + R_2 R_1 + R_{b.d.} R_2}$$

For $R_1 = R_2$ we have $\Delta I_{d.c.} = \Delta\varepsilon/(2R_{b.d.} + R_1)$.

On the other hand,

$$\varepsilon = -\frac{d\Psi}{d\tau} = -\frac{nd\Phi}{d\tau} = -\frac{nSd(\mu H)}{d\tau} = -\left(nS \frac{\partial \mu}{\partial \tau} H + nS\mu \frac{\partial H}{\partial \tau}\right).$$

Here Ψ is the linkage; Φ is the magnetic flux penetrating the loop of the measuring winding.

Let a bubble pass through the measuring winding during the time τ, and let us correspondingly have $\Phi \to \Phi_{min}$ during the time τ_1; then $\Phi_{min} \to \Phi$ with the removal of the bubble from the loop of the measuring winding. Let us assume that during the change in magnetic flux from Φ to Φ_{min} the quantity is $\partial\mu/\partial\tau \approx \Delta\mu/\tau_1$. Let us take the average of the emf ε_2 during a half-period of the alternating current T/2 = 0.01 sec by assuming that the magnetic permeability is $\mu = \mu'$ at the time of reaching Φ_{min}. Then the mean emf ε' equals

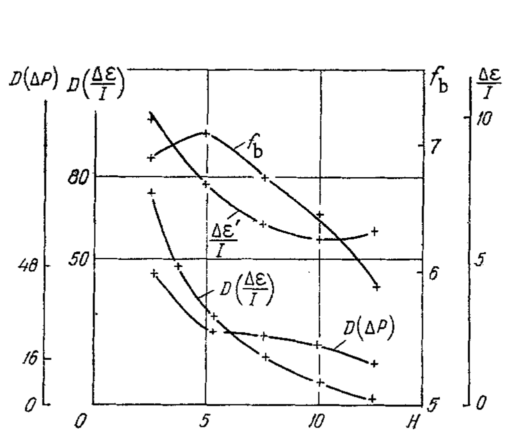

Fig. 3

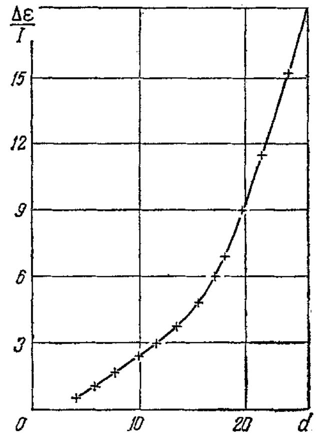

Fig. 4

Fig. 3. Dependence of the variances of the quantities ΔP and $\Delta\varepsilon/I$ on the alternating magnetic field intensity H and dependence of the amplitude of the low-frequency component of $\Delta\varepsilon/I$ and the frequency of bubble passage f_b on H. $D(\Delta P)$, mm^2 H_2O; $D(\Delta\varepsilon/I)$, mV^2/A^2; f_b, H; $\Delta\varepsilon/I$, mV/A.

Fig. 4. Dependence of the ratio $\Delta\varepsilon/I$ in a solenoid, measured by using a winding with D = 45 mm inner diameter placed in a d = 0.3 mm and h_0 = 40 mm layer of magnetite particles, on the diameter of balls simulating bubbles and arranged symmetrically relative to the measuring loop. $\Delta\varepsilon/I$, mV/A; d, mm.

$$\varepsilon' = -\left(2nS\,\frac{1}{T}\int_0^{T/2}\frac{\Delta\mu}{\tau_1}H\,d\tau + 2nS\mu'\,\frac{1}{T}\int_0^{T/2}\frac{\partial H}{\partial\tau}\,d\tau\right).$$

The magnetic permeability is $\mu = \mu''$ and $\Delta\mu/\tau_1 = 0$ before the beginning of the time counting $\tau = 0$ when the bubble approaches the loop of the measuring winding; the mean emf during the time T/2 = 0.01 sec is

$$\varepsilon'' = -\left(2nS\mu''\,\frac{1}{T}\int_0^{T/2}\frac{\partial H}{\partial\tau}\,d\tau\right).$$

Using the notation $\Delta\mu = \mu' - \mu''$, we have

$$\Delta\varepsilon = \varepsilon' - \varepsilon'' = -\left(nS\,\frac{\Delta\mu}{\tau_1}\,H_{av} + \nabla\mu\,\frac{4H_{max}nS}{T}\right);$$

since $H_{av} = H_{max}/1.54$, then

$$\Delta\varepsilon = -\left(nS\,\frac{\Delta\mu}{\tau_1}\cdot\frac{H_{max}}{1.54} + \Delta\mu\cdot\frac{4H_{max}nS}{T}\right).$$

According to our experimental results τ_1 = 0.0375-0.075 sec

$$\frac{\tau_1}{\frac{T}{2}} = 3.75\text{-}7.5 \text{ and } \frac{\Delta\mu\,\frac{4H_{max}nS}{T}}{nS\,\frac{\Delta\mu}{\tau_1}\cdot\frac{H_{max}}{1.54}} = 23\text{-}46.$$

Therefore, the influence of the first term in the expression for ε' is quite small compared to the second and $\Delta\varepsilon = -4fnS\Delta\mu H_{max}$, i.e., the quantity $\Delta\varepsilon$ for a boiling layer depends directly on the quantity $\Delta\mu$, but is practically independent of the time of its change (the velocity of bubble passage), since the linkage Ψ varies during the ac period and is simultaneously dissimilar during the time of bubble passage: The influence of a change in Ψ during a half-period is considerably greater than the influence of the change in linkage during the time τ_1 because of the rate of change in the quantity μ during bubble passage.

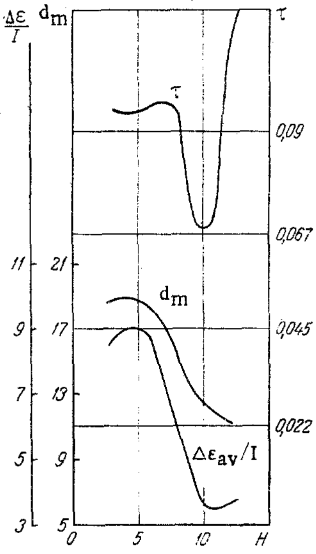

Fig. 5

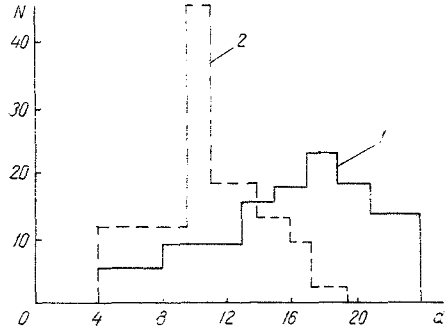

Fig. 6

Fig. 5. Dependence of the mean equivalent bubble diameter d_m, the mathematical expectation of the quantity $\Delta\varepsilon/I$ bubbling in the time $\Delta\varepsilon_{av}/I$, and the mathematical expectation of bubble passage through the plane of the measuring loop τ on the alternating magnetic field intensity H. τ, sec; H=kA/m.

Fig. 6. Histograms of the probability distribution of the passage of bubbles of any diameter through the measuring loop as a function of the alternating magnetic field intensity H: 1) H = 2.5 kA/m; 2) 10. N, %.

The quantity ΔI is recorded simultaneously with the magnitude of the pressure drop ΔP. Let $a = a'$ on the oscillogram be the coordinate of a current of magnitude $\Delta I'$. This current is produced by an ac source with the known voltage $-\ \varepsilon'$; then the voltage

$$\Delta\varepsilon = \varepsilon' \frac{a}{a'}$$

will correspond to any quantity a and current ΔI.

Processing the Test Results

An analysis of the oscillograms showed that the quantity $\Delta\varepsilon$, referred to the lines of force in the solenoid L, changes as follows during bubble passage through the loop of the measuring winding L_2: The dependence of the quantity $\Delta\varepsilon/I = f(\tau)$ corresponding to low H is shown in Fig. 2a (section AB); the curve describing this dependence is also nonsymmetric when a single nonsymmetric bubble with a shorter upper half-axis relative to the maximum horizontal section passes. The amplitude of the quantity $\Delta\varepsilon/I$ depends directly on the size of the bubble, and the quantity $d\Delta\varepsilon/Id\tau$ depends directly on the rate of its rise (taking account of symmetry separately). The same dependence is also shown in Fig. 2a (section BC) for the successive passage of four bubbles. Depending on the H changing the layer structure, appropriate changes were observed (see Fig. 2b) in $\Delta\varepsilon/I$ of the following form: curve 1 for H = 2.5 kA/m, curve 2 for H = 10 kA/m, and curve 3 for H = 12.5 kA/m.

A diminution in the quantity $\Delta\varepsilon/I$ with the growth in the magnetic field intensity H is characteristic of the graphs shown in the form of curves 1, 2, and 3; at the same time, curve 3 exhibits a simultaneous increase in the time τ of bubble passage, which indicates a diminution in the rate of climb and elongation of the bubble, their degeneration in the channel, and magnetic flux pulsations caused by pulsations in the channel diameters.

Processing the oscillograms was carried out as follows. The variance of the quantity $\Delta\varepsilon/I$ was determined at a given external magnetic field intensity for each separate case. To do this, the oscillograms were partitioned into 200 intervals of 0.075 sec duration each, the mathematical expectation of the quantity $\Delta\varepsilon/I$ — M and the mathematical expectation of the square of the deviation of the quantity $(\Delta\varepsilon/I)^2 - M^2$ were determined, and, finally the variance $D(\Delta\varepsilon/I)$ was determined:

$$D\left(\frac{\Delta\varepsilon}{I}\right) = \left[M\left(\frac{\Delta\varepsilon}{I}\right)\right]^2 - M^2\left(\frac{\Delta\varepsilon}{I}\right).$$

The variance of the pressure drop fluctuations was determined analogously:

$$D(\Delta P) = [M(\Delta P)]^2 - M^2(\Delta P).$$

The results of such processing are represented in Fig. 3, from which it is seen that the magnitude of the variance $D(\Delta\varepsilon/I)$ decreased significantly with the increase in the magnetic field intensity. As regards the quantity $D(\Delta P)$, it diminished significantly only up to an H = 5 kA/m field intensity and later continued to decrease, but considerably more slowly.

A graphical dependence of the mean-statistical frequency of gas bubble passage, determined by means of ΔP and Δε oscillograms, is given in Fig. 3. As is seen from the graph, a diminution in the frequency f_b of passage occurred starting with H = 5 kA/m and especially significantly with H = 10 kA/m. We have established that a reduction in the frequency of passage occurs simultaneously with the diminution in the pressure drop ΔP, which dropped by a 70% jump at H = 10 kA/m.

A sharp change in Δε occurs when the bubble passes through the measuring loop with a simultaneous, but slower, inertial process of oscillation in the height of the boiling layer. Namely, this process produces the common low-frequency background in which the local change in Δε/I occurs at the time of bubble passage.

An oscillogram with the characteristic sharp pulsations in the background of smoother low-frequency pulsations, given by dashed lines, is shown in Fig. 2c. The dependence of the amplitude Δε'/I of the low-frequency fluctuations in the quantity Δε/I on the magnetic field intensity is given in Fig. 3. It is seen from the graph that the amplitude Δε'/I of the low-frequency component of Δε/I diminishes with the increase in magnetic field intensity. As an analysis of the mean-statistical frequency of the low-frequency oscillations has shown, the frequency of oscillation grows from 1.5 H at H = 2.5 kA/m to 1.9 H at H = 10-12.5 kA/m.

A calibration measurement of the change in the mean emf ε and the quantity Δε/I as a function of the size and quantity of circular nonmagnetic balls placed within the loop of the measuring winding in a layer of 0.3-mm-diameter magnetite particles with a 40-mm-high charge in a column with a 92 mm inner diameter was made by an F564 voltmeter to estimate the bubble size. The graphical dependence shown in Fig. 4 was consequently obtained for single balls of diameter d.

The bubble shape in the real case is certainly different from the spherical. In particular, it is nonsymmetric (see Fig. 2a). Then, for example, the change in the quantity Δε/I when the bubble enters the measuring loop occurs more abruptly as compared with its change when this bubble emerges from this loop. Moreover, it is necessary to take into account the influence of the next bubble, which follows the preceding bubble leaving the measuring loop and is just entering the loop at this time, on the quantity Δε/I. However, such "overlaps" are determined quite well by using the oscillogram record of Δε/I (see section BC in Fig. 2a). An analysis of the oscillogram shows that the number of such bubbles mutually "overlapping" within the measuring loop reached 20% of the total number passing through the loop at a w = 0.5 m/sec filtration rate for H = 2.5 kA/m.

For an approximate estimation of the bubble size corresponding to any boiling layer structure, the equivalent bubble diameter can be defined by means of the quantity Δε/I (see Fig. 4) as the diameter of a ball whose diametral section is approximately equal to the maximum horizontal of a real bubble. Such computations were performed in each separate case, and the mean equivalent bubble diameter d_m was determined correspondingly for an intensity H. The graphical dependence $d_m = f(H)$ and also the quantity $\Delta\varepsilon_{av}/I$ as a function of H are given in Fig. 5. Moreover, here the dependence of the mean time τ of bubble passage through the measuring loop, defined as the mathematical expectation of the time of bubble passage through the plane of the measuring loop, is shown. As measurements of Δε/I as a function of the position of the balls relative to the lower or upper base of the measuring loop showed to 0.5% accuracy, the record of the quantity Δε/I starts at a distance on the order of b = 3-4 mm between the plane of the lower or upper base of the measuring winding and the surface of balls of diameter on the order of 10-24 mm. The height of the measuring winding is 3 mm. Therefore, if only the mean equivalent diameter d_m is taken in the computation, then the path which the globular bubble traverses, from the time of the beginning of the determination of the quantity Δε up to the time $\Delta\varepsilon_{max}$, will be $l = (d_m/2) + b + 1.5$. The whole path during the time in which the quantity was determined is $2l = d_m + 2b + 3$.

For instance, for H = 25 A/cm, $d_m = 18.3$ mm, and $\tau = 0.093$ sec, $2l = 18.3 + 8 + 3 = 29.3$ mm.

Bubble velocity $V_b = 2l/\tau = 29.3 \cdot 10^{-1}/0.093 = 31.5$ cm/sec.

For the value H = 100 A/cm, $d_m = 12.4$ mm, and $\tau = 0.067$ sec, $2l = 12.4 + 8 + 3 = 23.4$ mm and V_b = 34.9 cm/sec.

On the other hand, by knowing the bubble velocity the size of its vertical semiaxis can be determined.

Histograms of the probability distribution of the passage of any size bubbles through the measuring loop as a function of the magnetic field intensity imposed on the layer are shown in Fig. 6. The significant change in the nature of the spread in the probability of any size bubble origination is characteristic. The spread is large for a low intensity H = 2.5 kA/m (see histogram 1 in Fig. 6) and diminishes sharply with the rise in H exhibiting a simultaneous narrowing of the interval of most probable equivalent bubble diameters and their diminution as the magnetic field intensity grows (in particular, the histogram 2 in Fig. 6 corresponds to H = 10 kA/m). It should be noted that the equivalent diameters of 80% of the bubbles were in the 16-22-mm band for H = 2.5 kA/m, in the 10-19-mm band for H = 7.5 kA/m, and in the 9.2-14-mm band for H = 12.5 kA/m.

Therefore, the main deduction to be made from the investigations is that by using unusual magnetic defectoscopy the process of studying the structure of a boiling layer is facilitated, whereupon it will be possible to simulate processes proceeding in a nonmagnetic layer by using a ferromagnetic boiling layer if the external magnetic field is chosen so weak that it exerts no substantial effect on the behavior of the boiling layer particles. By using this method, the qualitative change in structure of the ferromagnetic layer as a function of the external magnetic field intensity can easily be tracked and a quantitative estimate can be given.

NOTATION

d_m, mean equivalent bubble diameter; D_m, mean solenoid diameter; f_b, mean statistical frequency of bubble passage; f, frequency of the alternating magnetic field; H_0, magnetic field intensity at the center of a solenoid with a homogeneous magnetic field; H, magnetic field intensity at the center of the layer; I, current in the solenoid; I_0, current in the calibrating solenoid; $I_{b.d.}$, current in the bridge diagonal; $\Delta I_{d.c.}$, disbalance current of a preliminarily balanced bridge; K_1, constant of the calibration solenoid; K_2, constant of the measuring winding; L_1, inductance of the measuring winding located within the layer; L_2, inductance of the measuring winding located in the ferromagnetic boiling layer; L_s, solenoid inductance; l_s, solenoid height; n, number of measuring winding turns; R_1, active resistance of measuring winding L_1; R_2, active resistance of measuring winding L_2; $R_{b.d.}$, resistance of bridge diagonal; ΔP, pressure drop in the layer; S, area of the measuring winding; T, period of the change in ac; w, filtration rate; ε_1, emf excited in the measuring winding L_1; ε_2, emf excited in the measuring winding L_2; ε', mean emf corresponding to bubble location at center of measuring winding L_2; ε'', mean emf corresponding to bubble location outside measuring winding limits L_2; $\Delta\varepsilon$, emf disbalance in diagonal of a prebalanced bridge because of the change in magnetic characteristics of the boiling layer; $\Delta\varepsilon'$, low-frequency component of fluctuations in the quantity $\Delta\varepsilon$; μ, magnetic permeability; $\Delta\mu$, change in magnetic permeability of the layer; μ_0, vacuum magnetic permeability; μ', magnetic permeability of the layer measured by the winding L_2 during bubble location at the center of a given winding; μ'', magnetic permeability of a layer measured by the winding L_2 during bubble location outside measuring winding limits; τ_1, time of the change in magnetic flux $\Phi \to \Phi_{min}$ during bubble entrance into the loop of the measuring winding L_2; τ_2, time of the change in magnetic flux $\Phi_{min} \to \Phi$ during bubble removal from the loop of the measuring winding L_2; τ, mean statistical time of bubble passage through the measuring loop.

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