MEASURING THE LOCAL GAS CONTENT IN A BUBBLING LAYER

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A method is proposed for the determination of the local gas content, involving the measurement of the electrical conductivity of a bubbling layer and these measurements are carried out in a column 300 mm in diameter, for a gas velocity ranging from 0.02 to 0.12 m/sec.

For a thorough understanding of the hydraulics involved in the bubbling of a gas through deep layers of liquid, we have to know not only the over-all gas content averaged through the height and cross section of the apparatus, but we must also know its local values at various points within the layer [1].

Theoretical examination of the bubbling mechanism [2] and measurements carried out by γ-ray treatment of the bubbling layer [3–6] have demonstrated that the gas content of the layer is greater at the center of the channel than it is at its periphery.

A method appeared some years ago for the measurement of the local gas content in a mercury-nitrogen system, involving the use of a needle probe [7]. This method was subsequently used for a water-air system [8, 9].

A method is proposed in this paper for the determination of the local gas content, and this method involves measurement of the electrical conductivity of the bubbling layer.

To determine the specific properties, which include the electrical conductivity or resistance of the heterogeneous system, a substantial number of formulas have been proposed [10]. The best and most general formula is that of Odelevskii [11]

$$\frac{\sigma}{\sigma_0} = 1 + \frac{\varphi}{f(\varphi) + \dfrac{\sigma_0}{\sigma_1 - \sigma_0}}. \qquad (1)$$

For cubic inclusions whose centers form a cubic lattice,

$$f(\varphi) = \frac{1-\varphi}{3}. \qquad (2)$$

Formula (1), with consideration of (2), was extended by Odelevskii to any configuration of the inclusions.

For the case of gas bubbling through an electrically conducting liquid we can assume that the electrical conductivity of the gas is equal to zero. Then, on transition from the conductivity to the specific resistance, Eq. (1) assumes the form

$$\frac{\rho}{\rho_0} = \frac{R_b}{R_{p.l}} = 1 + \frac{\varphi}{1 - [\varphi + f(\varphi)]}, \qquad (3)$$

while with consideration of (2)

$$\frac{R_b}{R_{p.l}} = 1 + \frac{\varphi}{1 - \dfrac{2\varphi + 1}{3}}. \qquad (3a)$$

The measuring cell was hooked into the bridge circuit (Fig. 1). The magnitude of the current in the indicator diagonal of the bridge is determined [12] from the following expression:

$$I = u_{in} \frac{\dfrac{R_1}{R_1 + R_3} - \dfrac{R_2}{R_2 + R_4}}{R_g + \left(\dfrac{R_1 R_3}{R_1 + R_3} + \dfrac{R_2 R_4}{R_2 + R_4}\right)}. \qquad (4)$$

The change of the resistance in the measuring cell can be represented as follows:

$$\frac{R_1 + \Delta R_1}{R_1} = \frac{R_b}{R_{p.l}}. \qquad (5)$$

Having denoted $R_3/R_1 = R_4/R_3 = \alpha$, from Eqs. (4) and (5) we obtain

$$I = u_{in} \times \frac{\alpha\left(1 - \dfrac{R_{p.l}}{R_b}\right)}{\left(R_g + \dfrac{R_3}{1 + \alpha\dfrac{R_{p.l}}{R_b}} + \dfrac{R_4}{1+\alpha}\right)\left(1 + \alpha\dfrac{R_{p.l}}{R_b}\right)(1+\alpha)}. \qquad (6)$$

Under our conditions $\alpha \sim 0.04$. The gas content varied from 0 to 0.3; this corresponds to a change in $R_{p.l}/R_b$ (from formula (3a)) from 1 to 0.06. Thus when $R_g \sim R_3 \sim R_4$, over the entire range of variation in gas content the denominator in Eq. (6) changes by less than 0.5%. Assuming the denominator in Eq. (6) to be constant, with consideration of (3a) we obtain

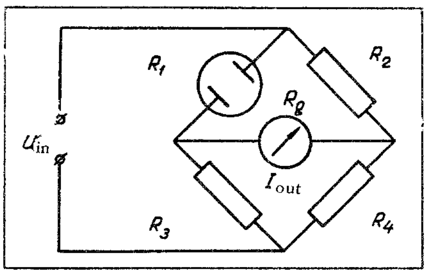

Fig. 1. Measuring cell connection circuit.

$$I = C_1 \frac{3\varphi}{2+\varphi}. \quad (7)$$

To verify the agreement between formula (7) and the experimental data, we set up a bridge circuit with a fixed bias. The measuring cell, made up of 2 silver electrodes 2.25 cm^2 in area and separated through a distance of 34 mm, was connected into one of the bridge arms. This measuring cell was placed into a column 38 mm in diameter, and it was possible to feed air into this column through a porous plate. The height of the pure-liquid layer in the column reached to 80 cm; the electrodes were positioned 60 cm above the gas-distributor plate. The gas content of the bubbling layer was measured as the gas was fed in by measuring the heights of the bubbling layer and of the pure-liquid layer, the magnitude of signal I being established on a potentiometer. Since the gas content in the bubbling layer is constant, with the exception of the small zones at the ends [13, 14], and in view of the fact that the electrodes encompass the entire thickness of the layer through the column diameter, we can assume that the magnitude of the signal applied to the potentiometer is a function of the averaged gas content in the column. Figure 2 shows the function $I = \psi(\varphi)$, calculated according to formula (7) (line 1), and the experimental data are plotted here. This theoretical relationship was obtained for $C_1 = 3.71$ (to bring the experimental point for $\varphi = 0.3$ into line with the calculated quantity). We see from the figure that the theoretical relationship differs somewhat from the experimental data and this, apparently, is associated with the extension of formula (3a) to any configuration of the heterogeneous inclusions. We will therefore find a function such as (3) for spherical inclusions of diameter d_n, uniformly distributed through the entire volume.

Two electrodes (the measuring cell), lowered into the layer and separated through a distance H from each other, exhibit an area S (each). The volume of the spherical bubble is $1/6\,\pi d_n^3$. The number of bubbles in the space between the electrodes is thus

$$n = \frac{6}{\pi}\frac{\varphi}{d_n^3} SH. \quad (8)$$

As an example of uniform bubble spacing in the layer, we can cite their distribution at the vertices of tetrahedra. In this case, the segment of the bubbling layer between the electrodes can be depicted as follows (Fig. 3). There are vertical planes parallel to the planes of the electrodes, and the bubbles in these planes are situated at the vertices of equilateral triangles of side l, which serve as the bases of the tetrahedra, and the distance between these planes is equal to the height h of the tetrahedron. In the volume Sh we will find the following number of bubbles:

$$k = \frac{2}{\sqrt{3}}\frac{S}{l^2}. \quad (9)$$

Since the tetrahedron height $h = (2/3)^{1/2} l$, the number of layers between the electrodes is

$$m = \frac{H}{l}\sqrt{\frac{3}{2}}, \quad (10)$$

and the number of bubbles in the volume between the electrodes is

$$n = km = \sqrt{2}\frac{SH}{l^2}. \quad (11)$$

Having equated Eq. (8) to (11), we find the relationship of the distance between the bubble centers to the gas content and to the bubble dimension:

$$l = d_n \sqrt[3]{\frac{\pi\sqrt{2}}{6\varphi}}. \quad (12)$$

The layer of thickness h can be presented as consisting of two parts: a segment of thickness d_n in which the bubbles are contained, and a segment of thickness $(h - d_n)$ in which there is only the liquid.

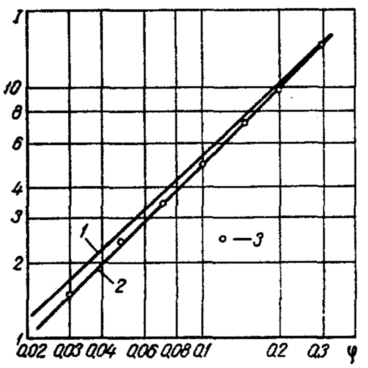

Fig. 2. Dependence of signal on gas content: 1) relationship according to Odelevskii formula [11]; 2) relationship according to formula (16); 3) experimental points; I, mA.

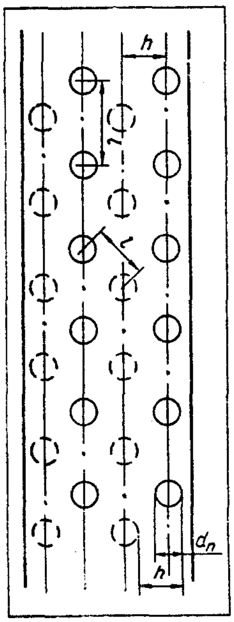

Fig. 3. Horizontal section of bubbling layer. Dot-dash lines show bubbles outside cross section.

Let us consider the magnitude of the resistance in a layer of thickness h and area S, since this quantity is directly proportional to the resistance of the volume between the electrodes.

When there is no bubbling, the resistance is

$$R_{p.l} = \rho_0 \frac{h}{S}. \tag{13}$$

For a bubbling layer of the same thickness h, the resistance is found from the equation

$$R_b = \rho_0 \frac{h-d_n}{S} + \rho_0 \frac{d_n}{S - \frac{2\pi k \int_0^{\frac{d_n}{2}} d(d_n - d)\,dd}{d_n}}. \tag{14}$$

Having taken the integral in Eq. (14), having divided it by (13), and having substituted (12), we obtain

$$\frac{R_b}{R_{p.l}} = 1 + \frac{\varphi}{1-\varphi^{\frac{2}{3}} \sqrt[3]{\frac{2\pi}{9\sqrt{3}}}}. \tag{15}$$

We see from a comparison of Eq. (15) with (3) that these are of identical form, but differ in the form of the function $f(\varphi)$.

The simultaneous solution of Eqs. (6) and (15) yields the following:

$$I = C_2 \frac{\varphi}{1+\varphi-\varphi^{\frac{2}{3}} \sqrt[3]{\frac{2\pi}{9\sqrt{3}}}}. \tag{16}$$

Figure 2 shows the function $I = \psi(\varphi)$, calculated according to Eq. (16) (line 2). If we substitute the quantity $C_2 = 4.62$ into Eq. (16), the experimental points will lie exactly on the curve of the theoretical relationship. Thus, our expression in (16) corresponds better to the experimental data than Eq. (3a). The tangent to the slope of this function in double logarithmic coordinates is equal to 0.985, i.e., in the interval being studied we have a virtually linear relationship between the magnitude of the signal and the gas content.

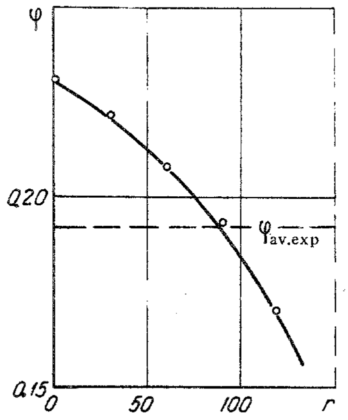

Fig. 4. Local gas content versus distance to column center at $W_r = 0.1$ m/sec, $\varphi_{av.exp} = 0.194$; r, mm.

In measuring the local gas content in a column 300 mm in diameter [15], we proceeded to calibrate the measuring cell in the following manner. We measured the relationship between the magnitude of the signal and the location of the measuring cell along the radius of the column for a certain gas velocity; graphical integration was employed to determine the magnitude of the signal averaged over the cross section and this was equated to the average gas content measured in the usual manner. A straight line with a slope tangent equal to 1.0 was drawn through the derived point in the double logarithmic coordinates. The derived calibration curve was used to determine the profile of the gas content in the range of gas velocities from 0.02 to 0.12 m/sec.

Figure 4 shows the gas-content profile for a gas velocity of 0.1 m/sec, while the table gives the cross-section averaged gas contents calculated from the local quantities along the radius and measured on the basis of the difference between the levels of the bubbling layer and the pure liquid.

We can see from the table that the divergence between these quantities does not exceed 7%.

Thus, the proposed method can be used to measure the local gas contents in the bubbling layer.

Table

Comparison of Theoretical and Experimental Average Gas Contents in the Column

Gas flow rate, m/sec	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09	0.10	0.11	0.12
Measured average gas content	0.077	0.11	0.147	0.156	0.158	0.171	0.18	0.189	0.194	0.212	0.218
Average gas content, calculated from local values	0.074	0.106	0.143	0.157	0.147	0.164	0.177	0.183	0.183	0.206	0.220
Percentage divergence between theoretical and experimental data	4.0	3.5	2.7	0.6	7.0	4.1	1.7	3.2	5.7	2.8	0.9

NOTATION

σ, σ_0, and σ_1 are the generalized thermal conductivities of the heterogeneous system, of the medium, and of the inclusions, respectively; φ is the volumetric content of the inclusions, of the gas content; R_b, $R_{p.l}$, R_1, and R_g are the resistance of the bubbling layer, of the pure liquid layer, of the measuring cell, and of the load, respectively; ρ_0 is the specific resistance of the pure liquid; C_1 and C_2 are the constants in Eqs. (7) and (16).

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