LOCAL MEASUREMENT OF GAS CONTENT

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The article examines problems related to the proper use and accuracy of methods of measuring local gas content in a gas—liquid stream.

One of the most important characteristics of the structure of two-phase gas—liquid flows is the pattern of distribution of gaseous (vapor) inclusions in the volume of the liquid or the profile of local gas content. In empirically studying local gas content, many investigators [1-6] use the point electrode method ("needle method"). The essence of the method is as follows. Two electrodes are placed in the gas—liquid stream. One, the point electrode (usually an insulated metal needle with a conducting tip), is placed in the region of the stream to be investigated. The point electrode has a slight perturbing effect on the stream. The second electrode is positioned at random (perhaps on the wall of the channel or a part of the unit) and is larger than the largest possible gas bubble. Voltage is supplied to the electrodes and a current flows between them when the point electrode is located in the liquid phase (the liquid should not be a dielectric); the current is interrupted when this electrode is surrounded by gas. The change in current over time is recorded. Thus, a determination is made of the time of location of each phase at a given point defined by radius vector **r**. Gas content at the point is determined from the following formula

$$\alpha(\mathbf{r}) = \frac{\sum_i \Delta t_i}{T}. \tag{1}$$

Summation is carried out for all circuit interruptions over time T.

Despite the wide use of this method, several methodological problems have yet to be solved before its correct use can be assured. Foremost among these problems is refining the concept of gas content as the average (1) and evaluating the accuracy of gas content values obtained by this averaging. Secondly, we need to examine the interaction of the point electrode with a gas bubble from the point of view of the effect of this interaction on the quantity being measured and the interpretation of the electrical signal that is obtained.

Gas content is usually taken to mean that portion of the total volume of the gas—liquid stream occupied by gaseous inclusions. Obviously, the average value for a point (1) is something quite different. To analyze it, we will make use of techniques of probability theory [7]. Let us introduce the function

$$S(\mathbf{r}, t) = \begin{cases} 1, & \text{if gas is at point r at moment t,} \\ 0, & \text{if liquid is at point r at moment t.} \end{cases} \tag{2}$$

Under quasi-stationary conditions (and we are examining only such conditions), for each point in the stream S(**r**, t) may be considered a stationary random function. We will determine the gas content at a point as the probability of finding gas at this point. The value of this probability is the expectation value M[S(**r**, t)].

Use of the ergodic hypothesis allows us to substitute for averaging of an ensemble of sample realizations of the stationary random functions S (i.e., the conventional determination of expectation value) the averaging of one of these realizations over time. A sufficient condition of ergodicity for the stationary process is

$$\lim_{t\to\infty} R(t) = 0. \tag{3}$$

If Eq. (3) is correct, we may use as an estimate of gas content the mean over time under the conditions of the given realization:

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$$\bar{S}(\mathbf{r}) = \frac{1}{T}\int_0^T S(\mathbf{r}, t)\,dt, \tag{4}$$

meanwhile

$$\bar{S}(\mathbf{r}) \to M[S(\mathbf{r}, t)] \quad \text{as} \quad T \to \infty, \tag{5}$$

if the dispersion of the expectation value

$$D\{M[S(\mathbf{r}, t)]\} \to 0 \quad \text{as} \quad T \to \infty. \tag{6}$$

It may be shown that conditions (3) and (6) are satisfied and $\bar{S}(\mathbf{r})$ is indeed a statistical estimate of gas content in our determination. It should be noted that procedure (4) is also realized in the point electrode method, being equivalent to the averaging (1).

Demonstration of the applicability of the ergodic hypothesis to determining local gas content also opens up ways of making the transition to the traditional concept of gas content, based on volume averaging. Integration of the local value measured by the method described here over a certain volume will give us an estimate of the expectation value of volume gas content in an isolated space.

In practice, averaging time T is limited. Let us determine the accuracy of the local gas content estimate obtained at fixed T. As a measure of accuracy, we will use the ratio of the standard deviation possible with measurement over an interval T to the mean itself

$$\frac{\delta}{M[S]} = \frac{\sqrt{D\{M[S]\}}}{M[S]}. \tag{7}$$

Taking into account Eqs. (4) and (5) and the properties of the dispersions of the random function and the integral of the stationary random function

$$D\{M[S]\} = \frac{2}{T^2}\int_0^T (T - t)\,R(t)\,dt. \tag{8}$$

For simplification, we will introduce the centered function

$$\mathring{s}(\mathbf{r}, t) = S(\mathbf{r}, t) - M[S(\mathbf{r}, t)] = S(\mathbf{r}, t) - \alpha, \tag{9}$$

here

$$\mathring{R}(t) = R(t) = M[\mathring{S}(\mathbf{r}, t)\cdot\mathring{S}(\mathbf{r}, t + \Delta t)]. \tag{10}$$

To compute the value of correlation function (10), we should multiply the values (three in all) possible for the product on the right side of function $\mathring{S}$ by the probability of the occurrence of these values and add the results of this multiplication. In determining the corresponding probabilities, it is assumed that the mean frequency of the shifts in the value of function S per unit of time (i.e., the doubled frequency of the passage of bubbles through the given point) λ and the distribution of the probabilities of the number of shifts in the values of function S are given by Poisson's formula

$$W[z] = \exp(-\lambda t)(\lambda t)^z/z! \tag{11}$$

The possibility of using Poisson's distribution in this case was confirmed by statistical analysis of oscillograms obtained during measurements in bubbling layers at different gas contents.

The calculations give the following

$$R(t) = \alpha(1 - \alpha)\exp[-2\lambda t]. \tag{12}$$

After substitution in (7) and (8) and the appropriate conversions, we obtain the following in the transition to the frequency of bubble passage ν:

$$\frac{\delta}{\alpha} = \sqrt{\frac{1 - \alpha}{2\nu\alpha T}}. \tag{13}$$

Equation (13) allows us to use the time of measurement, gas content, and frequency of bubble succession to determine the accuracy of the measurements and, conversely, use the required degree of accuracy to calculate the minimum required averaging time. The value of ν in the equation is easily determined either from an oscillogram of the signal obtained or by means of a special counter.

The gas-content transducer used here — the point electrode — was a manganese wire 0.1 mm in diameter covered with lacquer insulation. The sensitive element of the transducer was the uninsulated end of the wire. The transducer was made rigid by passing the wire through a medical needle 0.8 mm in diameter so that 15-20 mm of the tip of the wire, with the end uninsulated, projected through the needle. A simple dc battery amplifier on two transistors served as the voltage supply and primary signal converter. An MS-1 millisecond timing device was connected to the circuit to sum the time of location of the sensing element in the gas. The signal was simultaneously recorded on a loop oscillograph. The tests were conducted on a water—air system.

Special experiments in which we synchronously took high-speed photographs of the area around the transducer and recorded an electrical signal convinced us that the time the transducer was in the bubble coincided within 0.001 sec with the duration of the signal recorded in this instance. Thus, the various "limit" effects (drying of the liquid film on the transducer in the bubble, electrochemical phenomena, etc.) did not distort the measurements. Such distortions may occur, however, due to hydrodynamic perturbations introduced into the stream by the transducer, such as a change in bubble velocity in interaction with the transducer or the reflection of small bubbles which do not "break" on the needle. Theoretical examination of the interaction of the transducer with the bubbles is very complex, but some simple results can be obtained in analyzing the contact of a bubble with the transducer under the condition that the axis of the latter is directed along the velocity vector of the bubble and passes through its center. The bubble will not break on the transducer and will stop when the buoyancy acting on the bubble is equal to the force of interaction between the bubble and transducer

$$\frac{4}{3}\pi\rho g a^3 = \pi b\sigma. \tag{14}$$

The "critical" bubble radius determined from this for a water—air system at 20°C and transducer diameter of 0.1 mm is 0.82 mm. All bubbles of lesser diameter should be reflected off the transducer. Let us evaluate the change in bubble velocity in its interaction with the transducer. For this, we will write the balance of the forces acting on the bubble in its collision with the needle:

$$\frac{4}{3}\pi\rho g a^3 = F_{\text{cont}} + \pi b\sigma + \mu\frac{\partial u}{\partial t}. \tag{15}$$

In braking of the bubble by the needle $\partial u/\partial t \leqslant 0$. As is known, for bubbles of different diameters

$$F_{\text{cont}} = K_1 u \quad \text{or} \quad F_{\text{cont}} = K_2 u^2, \tag{16}$$

where K_1 and K_2 are constants. With uniform emersion

$$\frac{4}{3}\pi\rho g a^3 = F_{\text{cont}}, \tag{17}$$

where F_{cont} is computed from the velocity of uniform emersion u_0. Using Eqs. (15)-(17), it is not difficult to obtain the following estimate

$$\frac{u_0 - u}{u_0} \leqslant \frac{3b\sigma}{4a^3\rho g}. \tag{18}$$

For a bubble 5 mm in diameter in a water—air system at b = 0.1 mm, the velocity error is 4%. According to the analysis made here, a transducer 0.1 mm in diameter in a water—air system affects only very small bubbles, and such bubbles account for only a small portion of the total volume of gas.

It can be expected that the measurement error associated with perturbation of the stream by the transducer will depend most on the diameter of the transducer and its orientation relative to the velocity vector of the bubble. To investigate this further, we set up a series of experiments in a 200-mm-diam. bubble column with a gas content of about 10% and bubble sizes of 5-10 mm. We conducted measurements with different transducers to determine the effect of transducer diameter at the same point in the gas—liquid layer under the same conditions. Figure 1 shows the results. The strong dependence of measured gas content on transducer diameter can be explained by the fact that the number of bubbles reflected by the transducer increaseswith an increase in the diameter of the latter, as does deformation of

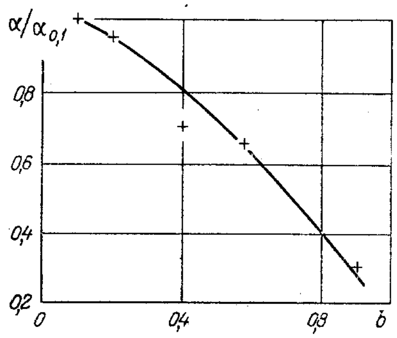

Fig. 1. Effect of transducer diameter on measured value of gas content: b) transducer diameter, mm; $\alpha_{0.1}$) readings of 0.1-mm-diam. transducer; α) readings of transducer of the given diameter.

the bubbles in their collisions with the transducer (deformation here meaning penetration of the bubble by the needle). The latter was observed visually in tests with single bubbles in water–glycerine mixtures (almost no bubble deformation occurred with a transducer 0.1 mm in diameter). Tests conducted under the same conditions with a 0.1-mm-diam. transducer oriented differently relative to the mean direction of bubble movement at the measurement point showed that there is no significant (within 10%) change in the results with a deviation of the transducer from this direction by as much as 20°. Similar data were obtained in [2].

The above results show that, without consideration of the questions examined here, use of the point electrode method may lead to substantial errors. This evidently also explains the wide (up to 35%) discrepancy in the results obtained from measurement of the gas content of the same objective using a point electrode and gamma-ray inspection [2].

It should be noted that methodological questions such as those discussed here were not at all considered in [8-10], in which local gas content was determined by measuring certain electrical characteristics (capacitance, components of vector impedance, etc.) of a dispersed medium in measurement cells with a large active surface and different shapes. Transducers of this type have a much greater (compared to the needle) perturbing effect on the stream. Individual calibration is required in this instance, and such calibration is necessarily of an indirect nature due to the impossibility of reproducing in the local volume of the transducer a two-phase layer with a prescribed gas content and structure. In connection with this, the advantages of the point electrode method are unquestioned.

The equipment and procedures developed for measuring gas content were checked through experiments in which a gas–liquid layer was probed simultaneously with a point electrode and gamma rays. The tests were conducted on a unit on which a bubbling layer was exposed to gamma radiation in a column 240 mm in diameter with countercurrent movement of the gas and liquid within a gas-content range of 45-60% [11]. The column was irradiated through its diameter with a radioactive source and measurements were made with a point electrode on the axis of the gamma-ray beam at 12 points. The resulting profile of gas content was integrated along the diameter and this result was compared with the gamma-ray inspection data. The discrepancy did not exceed 2% of the measured value.

NOTATION

α, gas content; r, radius vector; t, time; Δt_i, duration of circuit break by gas bubble; i, summation index; T, measurement time; S, function determined by condition (2); M, expectation; R(t), correlation function of stationary random function S; $\overline{S}$, mean value of function S with respect to time, determined by Eq. (4); D, dispersion; δ, standard deviation; $\mathring{S}$, centralized random function; $\mathring{R}(t)$, correlation function of centralized function $\mathring{S}$; λ, mean frequency of shifts in value of function S per unit of time; z, number of shifts in value of function S after time t; W, probability; ν, mean frequency of passage of bubbles by a given point; ρ, density of the liquid; g, acceleration due to gravity; a, radius of bubble; b, diameter of transducer; σ, surface tension; F_{res}, drag acting on a moving bubble on the side of the liquid; u, velocity of bubble; μ, apparent additional mass; u_0 rate of uniform rise of the bubbles.

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