FLOW OF A LIQUID OVER LARGE GAS BUBBLES

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An equation is given which allows calculation of the variation in size of a gas bubble as it moves through a liquid. It has been shown experimentally that the flow of a liquid over large deformed gas bubbles is not separated.

The flow of a liquid over gas bubbles has a considerable influence on absorption of gas during bubbling.

The initial volumes of the bubbles in mass transfer equipment are ordinarily 0.03 to 1.8 cm^3. With a degree of absorption of 87%, even if the gas being absorbed contains no inert impurities, the volume of the bubbles remains greater than 0.004 cm^3.

The absorption of gas from individual bubbles, the so-called elementary process in bubbling, was investigated in detail in [1] for bubbles of very small and moderate size ($v < 0.004$ cm^3). It was shown that by far the major part of the surface area of bubbles of moderate size had unseparated flow. For example, for Re = 625, the separation region extended only 2° on both sides of the wake center line.

The nature of the flow of a liquid over large deformed gas bubbles ($v > 0.004$ cm^3) is not known at present. It has been suggested by Levich that the flow will not be very different in nature from that of a liquid over gas bubbles of moderate size. The objective of the present paper is to elucidate the nature of the flow over large deformed bubbles.

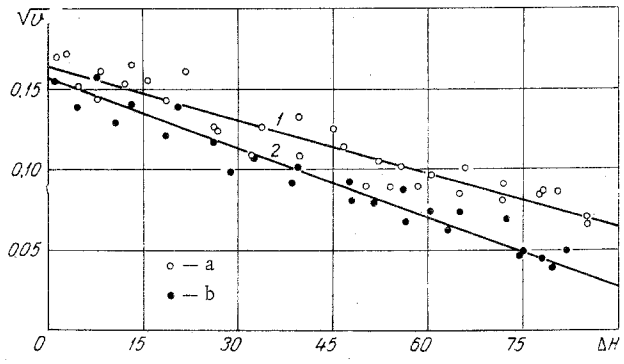
It is known that bubbles, when strained, take a form close to that of an oblate ellipsoid of revolution, the ratio (a/b) of the semi-axes of which does not exceed 2.5.

If the flow over large deformed bubbles does not differ from that over bubbles of moderate size, then experimental date on absorption of a gas must be described by the known equation for the total diffusion flux of gas through the surface of a bubble [2]

$$J = -\sqrt{4D/\pi\Delta t}\,(c'_s - c')F. \qquad (1)$$

The time of contact of an element of the liquid which slips along the surface of a deformed bubble is approximately 2 b/U. The surface area of a deformed bubble (with $a/b = 2.5$) is 10% larger than that of the sphere of equal size. The time of contact for maximum bubble deformation is 50% less than the corresponding value for a spherical bubble of equal size.

The use of (1) for reducing experimental data is difficult because it is not possible to measure the diffusion gas flow through the bubble surface. Simultaneous solution of the equation of gas mass balance in the bubble along with (1) allows us to establish a relation between the quantities obtained directly from experiment.



Dependence of bubble volume v, cm^3, on bubble path ΔH, cm, for the system N_2O—H_2O (1 and *a*), and CO_2—H_2O (2 and b).

It is evident that as the bubble moves through the liquid, its volume diminishes, the loss of mass of gas from the bubble in unit time being equal to the diffusion flux through its surface:

$$\frac{dm}{d\tau} = J. \qquad (2)$$

During absorption of a pure gas, its concentration in the bubble is constant with time, not allowing for variation in hydrostatic pressure of the liquid. Integration of (2) enables us to obtain a relation between bubble volume and the path traveled by the bubble. Solving (1) and (2) simultaneously, replacing F and Δt in the former by corresponding values for the equivalent sphere, and taking into account also that $m = cv$ and $c'_s/c = \Gamma$, we obtain the approximate relation

$$\Delta\sqrt{v} = \Gamma(1 - c'/c'_s)\sqrt{6DU}\,\Delta\tau, \qquad (3)$$

which differs from the exact solution by less than 30%.

It has been shown theoretically and experimentally in [1, 3–7] that the rising velocity of individual bubbles with $v > 0.004$ cm^3 as a result of their deformation is practically independent of bubble size and is approximately 28 cm/sec.

Taking into account that U = const, we have from (3)

$$\Delta\sqrt{v} = B\Delta H, \qquad (4)$$

where

$$B = \Gamma(1 - c'/c'_s)\sqrt{6D/U}.$$

We find that the expression obtained is most convenient for experimental checking.

Thus, if the flow of a liquid over large deformed bubbles is unseparated, the diffusion coefficient, determined from the dependence of bubble volume on the path traveled, should be of the same order as the molecular value.

We studied absorption of a gas when bubbled in N_2O—H_2O and CO_2—H_2O systems, which allowed the experimental method to be simplified because of the moderate solubility of these gases. The tests were conducted in a hollow glass column, with a bubbling bed 90 cm in height and 5.3 cm in internal diameter, located in a constant-temperature bath. To allow accurate determination of bubble size, the bath was equipped with flat parallel plexiglas walls. Gas under pressure, which was held constant with the aid of a regulator and measured on a mercury U-tube manometer, was introduced into the column through a capillary tube of diameter 0.9 mm. Determination of bubble size over the height of the bubbling bed was done photographically in transmitted light. Uniform illumination of the column was achieved by means of a vertically located DS-30 daylight lamp. There was a scale with millimeter divisions in the bath alongside the column, to determine the scale of the photographs. Volumes of bubbles, whose shape was assumed to be oblate ellipsoids of revolution, were calculated from the sizes of the two spheroid axes. Before each experiment, which lasted not more than 30 sec, the column was filled with fresh distilled water; the gas supply rate did not exceed 100 cm^3/min. For the tests we used medical nitrous oxide of purity not less than 99.0%, as determined by chromatography, and carbon dioxide of food industry quality containing not less than 98.5% of CO_2. The tests were conducted at temperatures of 25° C (N_2O absorption) and 24.5° C (CO_2 absorption).

For each system examined two parallel tests were performed, the results of which are given in the figure as a $\sqrt{v} - \Delta H$ plot. The points on the figure correspond to the mean results of measurements on 4–10 bubbles. The initial reading was taken as an arbitrary height not coinciding with the outlet aperture of the bubbler, because of unreliability of determining the volume at the moment of breakaway of a bubble.

It may be seen from the graphs that the experimental points fall satisfactorily on a straight line whose slope (calculated by the method of least squares) is $-1.1 \cdot 10^{-3}$ $cm^{2/3}$ and $-1.44 \cdot 10^{-3}$ $cm^{2/3}$ for N_2O and CO_2, respectively.

In the conditions of the experiment $\Gamma = 0.602$ cm^3/cm^3 for N_2O and $\Gamma = 0.826$ cm^3/cm^3 for CO_2 [8], the concentration of dissolved gas at the end of the experiment did not exceed 0.02 cm^3/cm^3.

The diffusion coefficients for the gases in water that we calculated from the experimental dependence v(H) were $1.61 \cdot 10^{-5}$ cm^2/sec for N_2O and $1.46 \cdot 10^{-5}$ cm^2/sec for CO_2. The molecular diffusion coefficients for the same gases in water, from the data of various authors, presented in [9], are $2.1 \cdot 10^{-5} \pm 10\%$ cm^2/sec for N_2O at 25° C, and $1.84 \cdot 10^{-5} \pm 10\%$ cm^2/sec for CO_2 at 24.5° C, i.e., 24–21% greater than our values.

The assumptions made in deriving (4) cannot change the order of magnitude of the diffusion coefficient. The agreement between our experimental diffusion coefficient values and those in the literature indicate an unseparated (laminar) regime of flow of the liquid over the deformed bubbles of volume 0.004–0.03 cm^3.

It should be noted that in this case transport of material along the normal to the surface is accomplished only by molecular diffusion.

NOTATION

a, b—semimajor and semiminor axes, respectively, of deformed bubble; v—bubble volume; m—bubble mass; F—bubble surface area; D—molecular diffusion coefficient; U—rate of rise of an individual bubble in liquid; Δt—phase contact period; Γ—Ostwald absorption coefficient; J—total diffusion flux through bubble surface; τ—time; c'_S—gas concentration in liquid at bubble surface; c'—mean concentration of gas dissolved in liquid; c—gas concentration in bubble; H—height of bubbler bed.

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