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Author	柘植, 秀樹(Tsuge, Hideki) Hibino, Shinichi
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BY

HIDEKI TSUGE and *SHIN-ICHI HIBINO*

FACULTY OF ENGINEERING
KEIO UNIVERSITY
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THE MOTION OF GAS BUBBLES GENERATING FROM A SINGLE ORIFICE SUBMERGED IN A LIQUID

HIDEKI TSUGE AND SHIN-ICHI HIBINO

Dept. of Applied Chemistry, Keio University, Yokohama 223, Japan

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ABSTRACT

The effects of gas flow rate, gas chamber volume, orifice diameter and liquid height on the gas volume of the air bubbles generating successively from a single orifice submerged in distilled water were studied and compared with the correlations published by other authors. The rising velocities of successive bubbles in distilled water were measured and the correlation between drag coefficient and Reynolds number was obtained. The period and the amplitude of the periodical variations of path and the ratio of minor to major axis of successive ellipsoidal bubbles rising in distilled water were measured. The results were compared with those of single air bubbles.

1. Introduction

The production of gas bubbles in liquids is very important in many chemical engineering processes. Bubble column, bubbling agitated gas-liquid contactor and perforated plate tower are typical bubble contactors. In analysing the performance of these apparatus, it is necessary to have the fundamental knowledge on the formation and the rising motion of bubbles.

Many workers have studied factors influencing the size of the successive gas bubbles generated from single orifices submerged in various liquids. Especially, theoretical and experimental researches have been done on the correlation between the gas bubble volume and the gas flow rate (van KREVELEN and HOFTIJZER 1950; TADAKI and MAEDA 1963; TAKAHASHI and SHIMIZU 1967; KUMAR and KULOOR 1970). These studies on bubble formation are considered to be grouped into three cases, that is (KUMAR and KULOOR 1970): (A) at constant gas flow rate, (B) in the presence of the pressure change of the upstream gas chamber* and (C) at constant gas pressure in the upstream gas chamber**. But, general conclusions have not been deduced from previous works especially in the case (B) (MAEDA 1967; KUMAR and KULOOR 1970).

Since the characteristics of the motion of gas bubbles rising in liquid is closely related to the mass transfer characteristics, the characteristics of the motion must be clarified in the study of mass transfer from gas bubbles in various liquids. For single gas bubbles, many works have been done on the velocity of rise, the shape of bubbles and so on (MAEDA 1967; HIBINO 1969), but in the case of successive bubbles from single orifices, quantitative studies on these items are rather meager (van KREVELEN and HOFTIJZER 1950).

It is well known that the medium sized bubbles rising in low viscosity liquid, which appear frequently in industrial applications, have approximately ellipsoidal shapes, and their rising paths are zig-zag in most cases, or spiral when the bubble size is smaller and also when the liquids used are carefully purified water or some organic liquids (MAEDA 1967; KUBOTA et al. 1967). The authors have studied the motion of single gas bubbles rising in various liquids to elucidate the nature of the variation of path and the related phenomena, and obtained the correlation between dimensionless groups which include the period or the amplitude of the variation of path, and other factors such as velocity of rise, bubble size and others (TSUGE and HIBINO 1971).

The objects of the present work are: (1) to clarify experimentally the factors influencing the sizes of successive bubbles generated from an orifice submerged in a liquid under the condition of case (B) aforementioned, (2) to study the behavior of successive bubbles rising in a liquid, and compare the results of the motion of successive bubbles generated at an orifice with those of the motion of single bubbles which were reported in the previous paper (TSUGE and HIBINO 1971).

2. Experimental

A schematic diagram of the experimental apparatus is shown in **Fig. 1.** Air was fed by the air compressor ①. The flow rate of air was regulated by the manostat ② and measured by the orifice flow meter ④. The bubbles were formed successively by blowing air into distilled water through an orifice ⑦.

The bubble column ⑧ of dimensions 120×120×1000 (height) mm was constructed of brass, and the glass windows in front and back sides of the column were used for counting bubble generation frequency and photographing. The orifices of 0.041, 0.071, 0.111 and 0.160 cm in diameter were made by drilling single holes at the center of the brass plate of 0.35 mm thick. The liquid depth above the orifice plate was varied from 30 cm to 70 cm. The upstream gas chamber volume was varied from 20 cm^3 to 205 cm^3 by changing the liquid level in the chamber.

The light beam was set to pass just above the orifice plate, and the bubble

* Bubble volume changes with the gas chamber volume.

** The pressure change of the gas chamber is negligibly small.

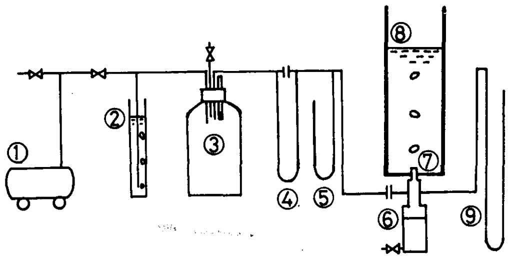

Fig. 1. Experimental apparatus
① Compressor ② Manostat ③ Gas tank ④ Flow meter
⑤ Manometer ⑥ Gas chamber ⑦ Nozzle ⑧ Test column
⑨ Water manometer

frequency was measured by detecting the change of intensity of light with phototransistor and counting the frequency of the change with the electronic digital counter. Bubble volume was calculated by dividing gas flow rate by bubble generation frequency assuming that equal volume bubbles were formed. Hence, the effects of gas flow rate, orifice diameter, gas chamber volume and liquid height on the bubble volume were investigated.

From these results, it was found that the size of bubbles and the bubble generation frequency could be changed widely by using the orifice whose diameter was 0.160 cm and changing the volume of the gas chamber. Therefore, in the study on the motion of bubbles, only this orifice was used, and the liquid height above the orifice plate was held constant at 50 cm. Equivalent spherical diameter of bubbles was changed from 0.5 to 0.9 cm, and bubble generation frequency, from 3 to 15 bubbles/sec.

The motion of bubbles was photographed with 16 mm movie camera (Bolex H16). The films were projected on the screen about 1.5 times as large as the actual bubble size, and the velocity of rise, the period and the amplitude of the variation of path, and the shape factor of bubbles were obtained in the following way.

The rising velocity was determined by counting the number of frames and then converting it to time interval* which was necessary for the bubble to travel a certain distance. When the generation frequency was smaller than 3 bubbles/sec**, the time interval was measured directly using two sets of light source and phototransistor, placed at 15.0 and 21.0 cm above the orifice plate, and an electronic digital counter.

To determine the period and the amplitude of the variation of bubble path, the projected images of bubble were traced frame to frame on a paper. **Fig. 2.** shows a typical example. The path can be approximated by a sine curve, and the

* The filming speed was calibrated by photographing uniformly rotating disk which was driven by the synchronous motor and analysing the relation between the revolution numbers of the disk and frame numbers.

** In this case, the orifice of 0.199 cm in diameter was used.

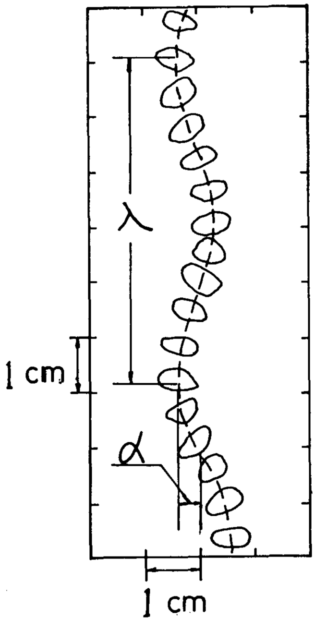

Fig. 2. The sketch of a rising bubble
d=0.50 cm, f=7.6 bubbles/sec.

amplitude α and the wave length λ of the variation of the path are shown in the same figure. The period T is the time for a bubble to pass one wave length. Average values of T and α were obtained for one bubble, then they were averaged over ten bubbles for each run.

Since the medium-sized bubbles used in the present work are usually assumed to be ellipsoidal in shape, their two dimensional projections can be approximated by ellipses. The ratio of apparent minor to major axis of the image of a bubble is adopted as a shape factor. Since the shape of a rising bubble changes periodically as it rises, a large number of measurements is necessary to obtain a characteristic value. In this experiment, the ratio of two axes was measured for about 100 bubble images in each run.

3. Experimental Results and Discussion

3.1. The Bubble Volume

Fig. 3-a, 3-b and **3-c** show the relations between gas bubble volume V_B and gas flow rate Q_g with the gas chamber volume V_c as a parameter, where the orifice diameters are 0.160, 0.111 and 0.071 cm, respectively. It is seen that gas bubble

volume increases with the increases of chamber volume and gas flow rate. This tendency becomes remarkable as the orifice diameter increases.

In the same figures, the calculated results of other researchers' correlations are shown (TADAKI and MAEDA 1963, TAKAHASHI and SHIMIZU 1967). The correlation by TAKAHASHI et al. (1967), shown in solid lines, is in agreement with our results except when the dimensionless group containing gas chamber volume and

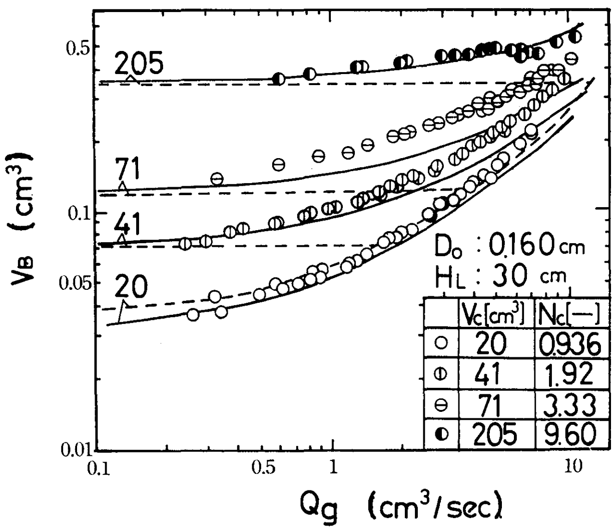

Fig. 3-a

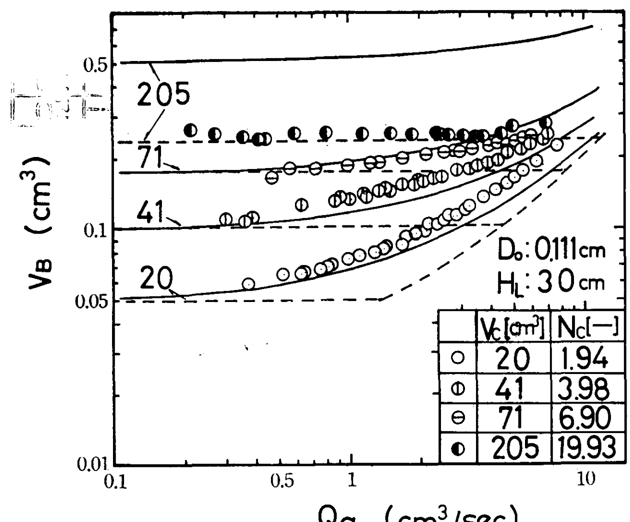

Fig. 3-b

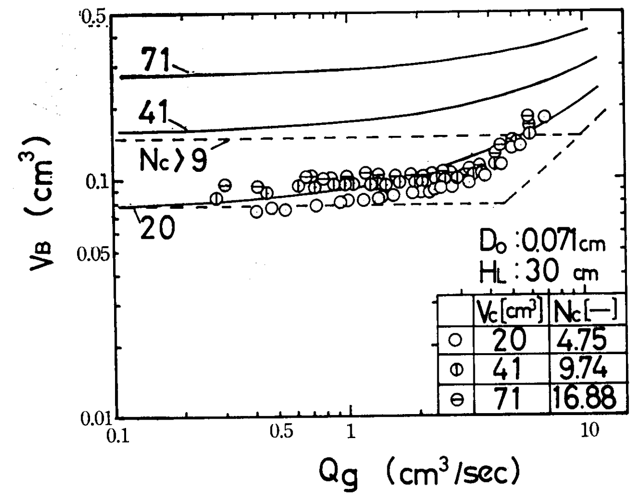

Fig. 3-c

Fig. 3-a, b, c.
Relations between V_B and Q_g. Solid lines show TAKAHASHI et al'.s correlation for each N_C number. Broken lines show TADAKI et al'.s correlation. Numerals in the figures show the chamber volume in cm³.

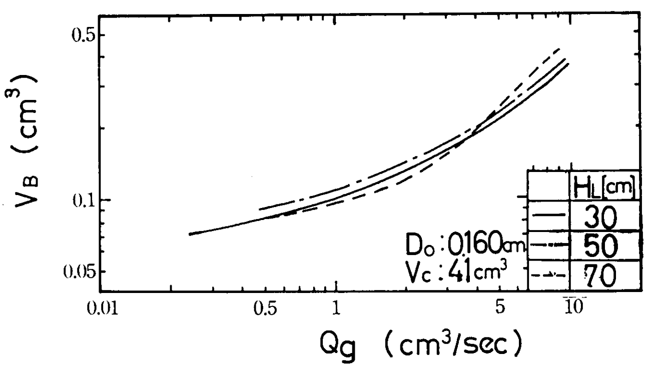

Fig. 4. Relation between V_B and Q_g for each liquid height.

orifice diameter $N_c(=4V_c/\pi D_0^2(P_0+P_{hs}))$ is larger than 9.

The correlation by TADAKI et al. (1963), shown in broken lines, does not agree with our results except those for $V_c=20\,\text{cm}^3$ in Fig. 3-a and $V_c=205\,\text{cm}^3$ in Fig. 3-b. Hence, the correlation by TAKAHASHI et al. (1967) would be more reliable for the range $N_c<9$.

Fig. 4 shows a typical relation between gas bubble volume and gas flow rate for different liquid heights. The effect of the liquid height is not obvious, and can be considered to be less important as compared with the effects of Q_g and V_c for the range of our experiment. There are some cases that the slope of the tangent to the curve is not monotonous, but oscillating when the liquid height is 70 cm and when the diameter of the orifice is small.

3.2. The Rising Velocity of Bubbles

As it is known by the analysis of the high speed photographs (HOTTA 1964) that the rising velocity of bubbles becomes nearly constant at 6–7 cm above the orifice, the average rising velocity U_b in the ranges of 15–30 cm (for generation frequency about 3 to 15 bubbles/sec) and 15–21 cm (for generation frequency about 1 to 3 bubbles/sec) above the orifice was measured for each run. **Fig. 5** shows the relation between the average rising velocity U_b and bubble generation frequency f

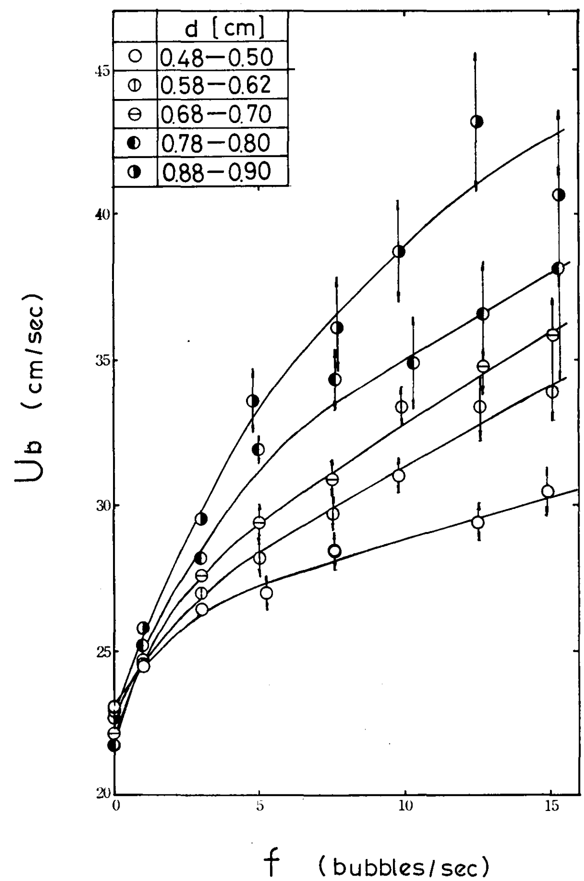

Fig. 5. Relation between U_b and f. The arrows show the 95% confidence intervals for U_b.

for various bubble diameters. The data of U_b are rather scattering, but U_b increases with increasing generation frequency for the equal bubble diameters. For the equal generation frequency, U_b increases with increasing bubble diameter. When this relationship between U_b and f is extrapolated to zero generation frequency, the curved line crosses the vertical axis at the value of U_b of single bubbles in doubly distilled water.

The arrows in Fig. 5 show the 95% confidence intervals for rising velocity U_b. The 95% confidence interval of bubbles, when generation frequencies are about 1 and 3 bubbles/sec, is not shown in Fig. 5 to avoid confusion since they overlap each other. The 95% confidence interval is about ± 0.3 cm/sec for generation frequency of 1 bubble/sec and about ± 0.4 cm/sec for generation frequency of 3 bubbles/sec, irrespective of the bubble diameter. When the bubble generation frequency is greater than 3 bubbles/sec, the 95% confidence interval is nearly constant for the equivalent spherical diameters of 0.5–0.7 cm, and is not influenced by the bubble generation frequency. Furthermore, the 95% confidence interval of U_b for the equivalent spherical diameters larger than 0.7 cm increases as the bubble diameter and bubble generation frequency increase.

Fig. 6 shows the relation between average bubble rising velocity U_b and linear velocity of gas through orifice U_0. U_b increses as U_0 increases. The broken line in Fig. 6 shows YOSHITOME's experimental results (1963) between the average rising velocity U_b of the bubble swarms formed at the perforated plate and U_0, which shows that the average rising velocity is independent of U_0. The discrepancy between our results and YOSHITOME's could be explained from the flow pat-

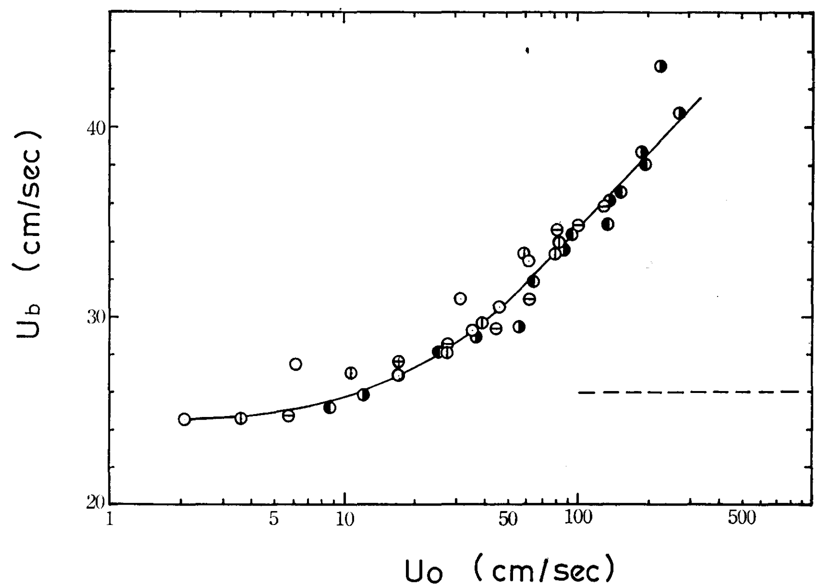

Fig. 6. Relation between U_b and U_0. The keys as in Fig. 5. The broken line shows YOSHITOME's experimental results.

tern in the apparatus. Bubbles formed from a single orifice in our experiments interfere with each other only in one dimension, whereas the bubbles formed at the perforated plate interfere with each other in three dimensions. It was observed in our laboratory (SATŌ 1969) that the circulating liquid flows are created in the bubble column when successive bubbles are formed from a single orifice. The liquid flows upwards in the center of the column where bubbles are rising, whereas the liquid flows downwards near the wall of the column. When bubbles are formed at perforated plates, the liquid circulations in the column are interfered by the motion of bubbles themselves. Therefore, it is considered that the rising velocities of bubbles formed at perforated plates are smaller than the rising velocities of bubbles formed from single orifices except when bubble generation frequency is low or $U_0<10$ cm/sec.

The relation between Reynolds number Re and the drag coefficient C_D obtained in our experiments is shown in **Fig. 7-a,** the generation frequency being larger for larger Re in each bubble diameter. In the same figure, the data for single bubbles obtained in our previous work (1971) are also shown. For the constant bubble diameter, the linear relation is obtained between log C_D and log Re including the data of single bubbles. The case of single bubbles is regarded as the limit of successive bubbles where the generation frequency becomes zero. The slope of these straight lines are equal for different bubble diameters.

VAN KREVELEN et al. (1950) reported that C_D did not depend on Re in the range $Re>10$ and was equal to 2.67 (as shown in **Fig. 7-b**), based on other researchers' results. But, their own experimental results using various single orifices in water in Fig. 7-b did not lie on the horizontal line $C_D=2.67$ which they proposed. Rather, they lie on the straight lines of our results for different bubble diameters. Though the data points of C_D and Re for successive bubbles should exist in the right-hand side of the curve for single bubbles in doubly distilled water (Fig. 7-b),

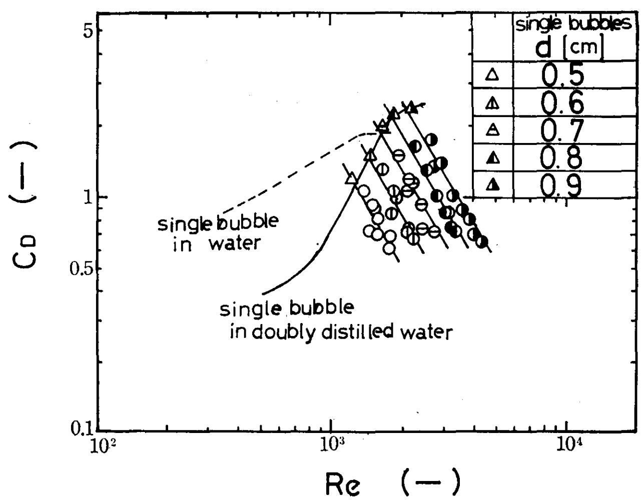

Fig. 7-a. Relation between C_D and Re. Keys as in Fig. 5.

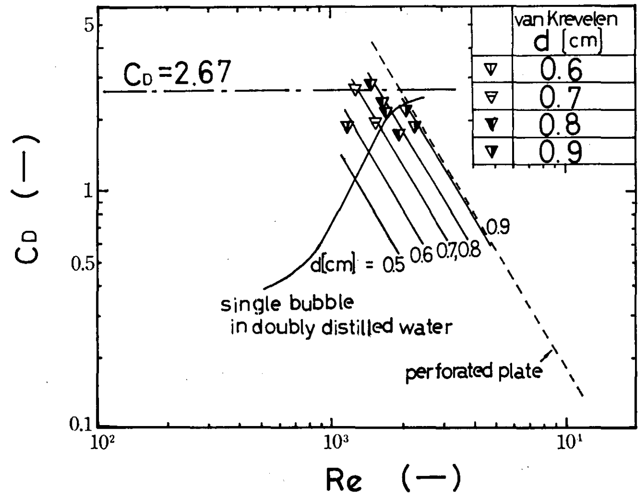

Fig. 7-b. Comparison of experimental results with the data of VAN KREVELEN et al. (Keys are shown in the figure) and TAKAHASHI (broken line). Numerals in the figure show the bubble diameters (in cm) for each straight line of our experiments, in cm.

many of their data points of C_D and Re exist in the left-hand side of the curve for single bubbles in doubly distilled water. One of the reasons of these results would be attributed to the difference of the diameter of the bubble column. Since they used the smaller bubble column whose diameter was 4.7 cm, the rising velocities of the bubbles were smaller by the wall effect than our experimental results. Thus their values of C_D are larger and their values of Re are smaller than those of our experimental results for the same experimental conditions.

The broken line in Fig. 7-b shows the experimental results of TAKAHASHI (1965) using the various perforated plates. The gradient of the broken line coincides with those of straight lines of our experimental results.

3.3. The Variation of the Rising Path of Bubbles

When the bubble generation frequency is low and the bubble diameter is small, the path of rising bubbles in water is zig-zag or spiral like single bubbles in water. But, as the bubble diameter and the generation frequency increase, the paths of rising bubbles become more irregular than those of single bubbles. **Fig. 8** shows the relation between the bubble diameter and the period of the variation of bubble rising path T with bubble generation frequency as a parameter. The effect of generation frequency on this relation is not clear-cut, but there is a tendency that T decreases with an increasing bubble diameter. The values of T are nearly equal to those of single gas bubbles in doubly distilled water.

Fig. 9 shows the relation between the bubble diameter and the amplitude of path

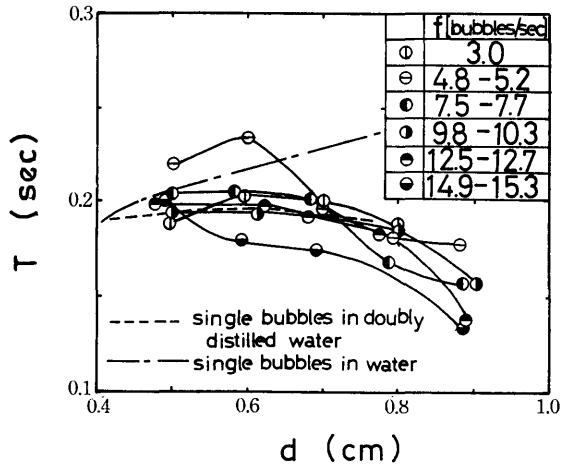

Fig. 8. Relation between T and d.

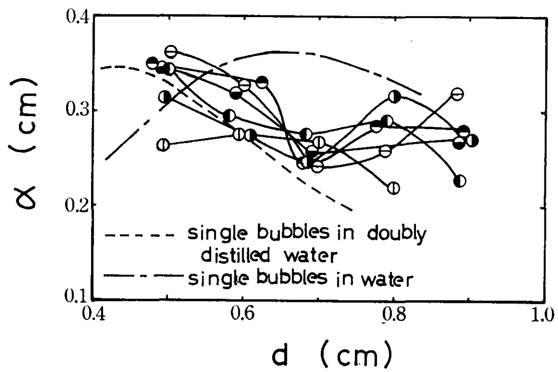

Fig. 9. Relation between α and d. Keys as in Fig. 8.

of a rising bubble α for each bubble generation frequency. Although the effect of the generation frequency on this relation is less striking, a similar tendency as single gas bubbles in doubly distilled water would be recognized.

In the case of single gas bubbles in low viscosity liquids, a dimensionless correlation between α/d and d/TU_b has been obtained (TSUGE and HIBINO 1971). The dimensionless groups α/d and d/TU_b in this experiment are plotted in **Fig. 10.** The relation shows a similar tendency to that of single air bubbles shown by a solid line in the figure.

3.4. The Shape of Bubbles

As the distribution of the ratio of minor to major axis of bubbles b/a nearly

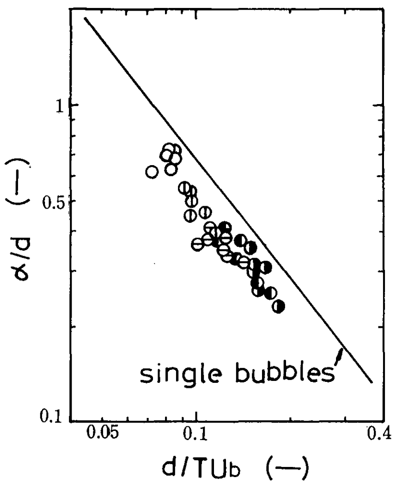

Fig. 10. Correlation between α/d and d/TU_b. Keys as in Fig. 5.

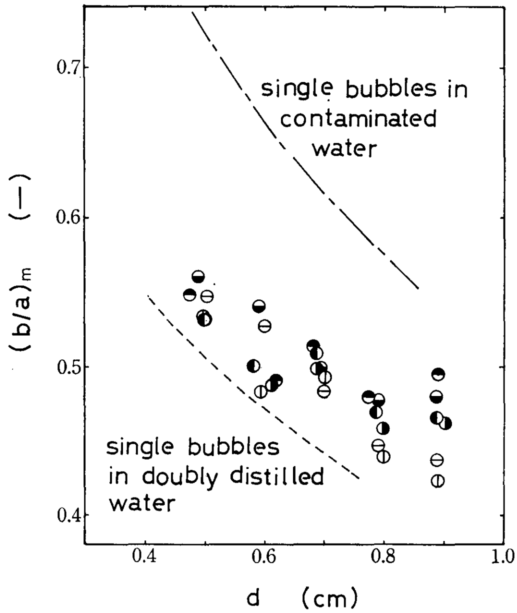

Fig. 11. Relation between $(b/a)_m$ and d. Keys as in Fig. 8.

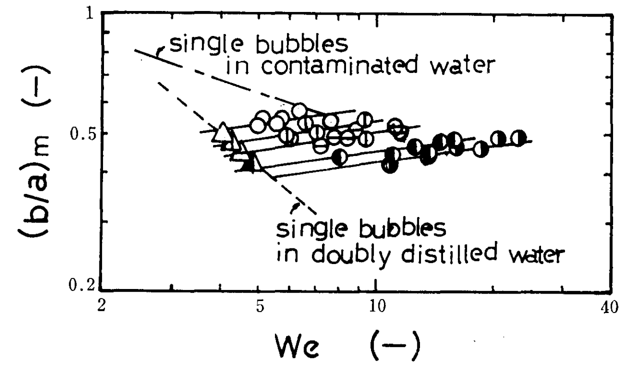

Fig. 12. Relation between $(b/a)_m$ and *We*. Keys as in Figs. 5 and 7-a.

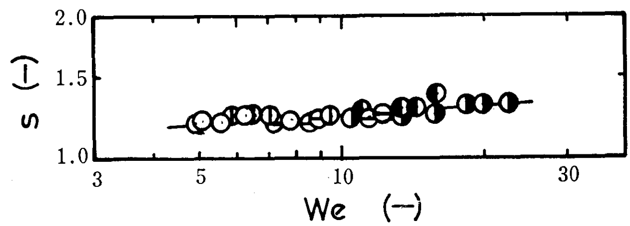

Fig. 13. Relation between *s* and *We*. Keys as in Fig. 5.

follows logarithmic probability distribution, the experimental results can be represented by using the geometric mean $(b/a)_m$, and logarithmic standard deviation *s*. **Fig. 11** shows the relation between $(b/a)_m$ and *d* with bubble generation frequency as a parameter. This relation is not so strongly affected by generation frequency, but as the bubble diameter increases, the ratio $(b/a)_m$ decreases.

The relation $(b/a)_m$ and Weber number *We* are plotted in **Fig. 12.** The results can be approximated by straight lines including the data for single bubbles for each bubble diameter. The relation between the logarithmic standard deviation *s* and *We* is shown in **Fig. 13**, where *s* increases slightly with increasing *We*.

As a factor which shows the degree of bubble deformation, the ratio of equivalent spherical diameter to major axis d/a is sometimes used instead of the ratio of minor to major axis of bubble b/a. The distribution of d/a also follows the logarithmic probability distribution. The relation between its geometric mean $(d/a)_m$ and the equivalent spherical bubble diameter *d* for each generation frequency is shown in **Fig. 14.** The effect of generation frequency on this relation is less striking, but the value of $(d/a)_m$ decreases as the bubble diameter increases. This relation is similar to that of single bubbles in doubly distilled water.

Fig. 15 shows the relation between $(d/a)_m$ and *We*. A nearly straight line is obtained irrespective of generation frequency, and the relation is similar to that of single air bubbles in doubly distilled water. The logarithmic standard deviation is nearly 1.15 irrespective of the value of *We*.

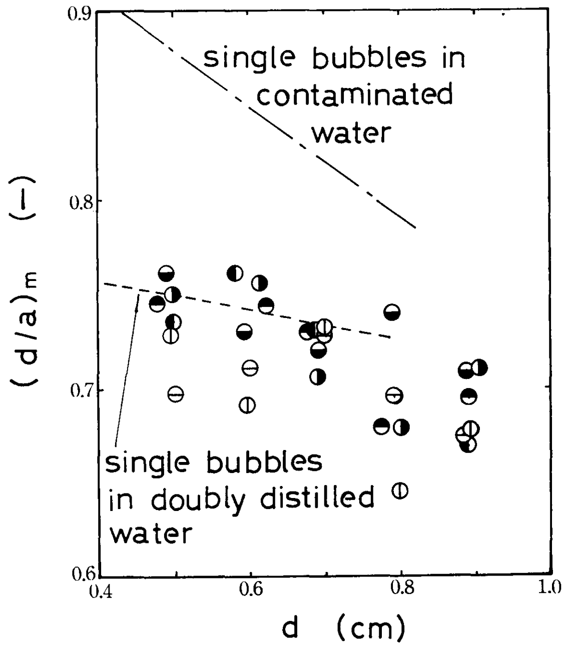

Fig. 14. Relation between $(d/a)_m$ and d. Keys as in Fig. 8.

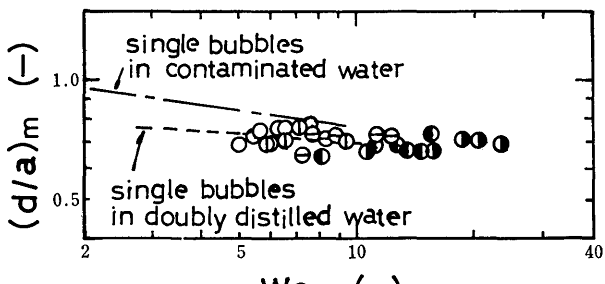

Fig. 15. Relation between $(d/a)_m$ and We. Keys as in Fig. 5.

4. Conclusion

(1) The effects of gas flow rate, gas chamber volume, orifice diameter and liquid height on the volume of bubbles generating successively from a single orifice submerged in distilled water were studied. The correlation by TAKAHASHI et al. is in general agreement with our results except when $N_c>9$. The liquid height is a less important factor as compared with gas flow rate, chamber volume and orifice diameter.

(2) The relation between the rising velocities of successive bubbles in distilled water and bubble diameter is shown in Fig. 5. For each bubble diameter, the linear relation was obtained between log C_D and log Re as shown in Fig. 7-a. It includes the case of single bubbles which is considered as the limit of successive bubbles when generation frequency becomes zero.

(3) The period and the amplitude of the variations of path of successive bubbles rising in distilled water were measured and the relation between dimensionless groups α/d and d/TU_b shows a tendency similar to that of single bubbles as shown in Fig. 10.

(4) The relation between $(b/a)_m$ and Weber number was approximated by straight lines for each bubble diameter, including the data for single bubbles.

Acknowledgement

The authors thank the Research Promotion Fund of Keio University for financial support and Mr. N. YOSHIKI for his assistance in the data analysis.

Nomenclature

a	=major axis of bubble	[cm]
b	=minor axis of bubble	[cm]
C_D	=drag coefficient of bubbles, $4dg/3U_b^2$	[−]
d	=equivalent spherical diameter of bubble	[cm]
D_0	=orifice diameter	[cm]
f	=bubble generation frequency	[bubbles/sec]
g	=gravitational acceleration	[cm/sec]
H_L	=liquid height	[cm]
N_C	=dimensionless parameter, $4V_c/\pi D_0^2(P_0+P_{hs})$	[−]
P_0	=atomospheric pressure	[dyne/cm²]
P_{hs}	=hydrostatic pressure at orifice plate	[dyne/cm²]
Q_g	=gas flow rate	[cm³/sec]
Re	=Reynolds number, $dU_b\rho/\mu$	[−]
s	=logarithmic standard deviation	[−]
T	=period of the zig-zag and spiral motion of bubble	[sec]
U_b	=average rising velocity of successive bubbles	[cm/sec]
U_0	=average gas velocity through orifice	[cm/sec]
V_B	=bubble volume	[cm³]
V_c	=gas chamber volume	[cm³]
We	=Weber number, $dU_b^2\rho/\sigma$	[−]
α	=amplitude of the zig-zag and spiral motion of bubble	[cm]
λ	=wave length of the periodical zig-zag and spiral motion of bubble	[cm]
μ	=liquid viscosity	[g/cm·sec]

ρ =liquid density [g/cm³]
σ =liquid surface tension [dyne/cm]
⟨Subscript⟩
m =median

REFERENCES

HIBINO, S. (1969): "Bubble and drop engineering—The behavior of single bubbles," Nikkankōgyo Shinbunsha Co., pp. 3-26.

HOTTA, M. (1964): "The motion of successive bubbles in liquids," The thesis of Keio Gijuku University.

KUBOTA, M., AKEHATA, M. and T. SHIRAI (1967): "The behavior of single air bubbles in liquids of small viscosity," *Kagaku Kōgaku*, **31**, 1074-80.

KUMAR, R. and N. R. KULOOR (1970): "Advances in chemical engineering Vol. 8. —The formation of bubbles and drops," Academic Press Inc., pp. 255-368.

MAEDA, S. (1967): "The formation and motion of bubbles," *Kagaku Kōgaku*, **31**, 438-443.

SATŌ, S. (1969): "The motion of successive bubbles," The thesis of Keio Gijuku University.

TADAKI, T. and S. MAEDA (1963): "The size of bubbles from single orifices" *Kagaku Kōgaku*, **27**, 147-155.

TAKAHASHI, T. (1965): "The characteristic of the behavior of bubble and foam layer on perforated plates," The Preprint of 4th General Symposium of Chem. Eng. Soc. Japan, Tokyo, pp. 19-24.

TAKAHASHI, T. and K. SHIMIZU (1967): "The bubble size formed from a single orifice," The Preprint of the 1st Fall Meeting of Chem. Eng. Soc. Japan, Osaka, pp. 401-2.

TSUGE, H. and S. HIBINO (1971): "The motion of single gas bubbles rising in various liquids," *Kagaku Kōgaku*, **35**, 65-71.

VAN KREVELEN, D.W. and P. J. HOFTIJZER (1950): "Studies of gas-bubble formation—Calculation of interfacial area in bubble contactors," *Chem. Eng. Prog.*, **46**, 29-35.

YOSHITOME, H. (1963): "Average ascending velocity of air bubbles in water from perforated plates," *Kagaku Kōgaku*, **27**, 27-31.