BUBBLES GENERATED FROM POROUS PLATE†

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Preface

The porous plate is frequently used as a gas distributor for the purpose of dispersing small gas bubbles into the liquid phase in chemical apparatuses. There has been little known about the bubble size generated from the porous plate. Vershoor⁶⁾ recognized that small bubbles generated from a porous plate into water and organic solvent coalesced on the plate, but an addition of acetic acid in water obstructed this coalescence. In the authors' previous paper⁵⁾ empirical equation correlating the bubble size in a bubble column equipped with a porous plate as a gas distributor was given. It was pointed out that this correlation held for only a few kinds of liquids, e. g. pure water and glacial acetic acid, and did not hold for solutions which included salts and organic substances. In additional information on the nature of bubbles generated this paper from porous plate distributors is presented.

Experimental

A gas bubbling cell was submerged in liquid which was contained in a rectangular glass vessel (10cm × 15cm × 25cm high). Dehumidified gas at constant flow rate was introduced into the cell and bubbled out through the porous plate distributor (about 2.5cm in diameter) which was placed on the top of the cell. Details of the porous plates used are summarized in **Table 1**. Before each experimental run, the distributor was well washed in soap solution, soaked in dilute hydrochloric acid solution for a few minutes and then washed with ion-exchanged water.

The liquids used and their physical properties are shown in **Table 2**. Chemical reagents used were of special

grade obtained commercially and were used without purification.

The temperature of liquid in the glass vessel was kept constant at 20°C. Photographs of the bubbles were taken at a position a slightly removed from the distributor, where the bubbles are almost freely rising and an appreciable coalescence of bubbles was not observed. Air was used as the gas to the cell in most runs, however hydrogen and carbon dioxide were also used. The nature of the gas used did not give any remarkable effect on the behavior of bubbles.

Influence of Porous Plate Material

Except in the case when the teflon porous plate was used as a distributor, the material used for construction of the porous plate did not have an appreciable effect on the bubble formation behavior. Gas bubbles from a teflon plate in ion-exchanged water, as shown in **Fig.1**, spread

Name of porous plate	Material	Composed particle size*	Thickness [cm]	Area [cm ²]	Porosity [—]
B1	bronze	10 μ	0.278	4.90	0.326
B2		40 μ	0.278	4.90	0.329
B3		70 μ	0.300	4.90	0.414
S1	stainless steel	10 μ	0.290	4.90	0.381
S2		10 μ	0.300	4.90	0.500
S3		40 μ	0.320	4.90	0.420
S4		70 μ	0.300	4.90	0.407
G1	glass	120~250 mesh	0.300	3.63	0.326
T1		10 μ	0.500	4.90	0.474

* Porous plates used are made by sintering of particles.

Group	Sort of liquid	Concentration	Density [g/cm ³]	Surface tension [dyne/cm]
group A	Ion-exchanged water	100%*	1.00	72.6
	Glacial acetic acid	100%	1.05	29.3
	Cyclohexane	100%	0.779	25.3
	Cumene	100%	0.865	29.3
	Toluene	100%	0.868	28.7
	Mixture of toluene and cyclohexane	10% cyclohexane	0.859	28.5
	Mixture of toluene, cyclohexane and acetic acid	10% cyclohexane, 10% acetic acid	0.867	27.9
Group B	Aqueous solutions of polyethyleneglycol	0.5%	1.00	67.0
	isoamylalcohol	1.0%	1.00	39.6
	Tween 20**	0.3%	1.00	46.5
	Toluene solution of isoamylalcohol	10%	0.866	29.7
	siliconeoil	0.1%	0.868	28.7
Group C	Aqueous solution of acetic acid	10%	1.02	55.8
	"	50%	1.06	40.7
	potassium chloride	0.01M***	1.00	73.8
	"	0.1 M	1.00	74.0
	"	1.0 M	1.04	73.9
	sodium sulphate	0.01M	1.00	73.0
	"	0.1 M	1.00	73.0
	"	1.0 M	1.06	74.4
	glycerin	60%	1.26	61.4

* weight percentage

** Tween 20 (polyoxyethylene sorbitan monolaurate, commercial name: Nissan nonion LT-221)

*** M shows g-mole/lit

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over a wide area of distributor at the moment of formation and gave large bubbles having a semi-spherical cap shape. It seems that this is due to the unwettability of teflon with water. The other materials used, i. e. stainless-steel, glass and bronze are wetted well with any liquid in their clean state. Of course, if plates were not sufficiently clean, the same kind of phenomenon as observed in the case of teflon appears. Therefore, a careful decontamination of the distributor is necessary to disperse fine bubbles.

Average Bubble Size and Size Distribution

Bubbles generated from porous plates change their size with gas flow rate through the distributor. There are two typical cases for this change as shown in Fig. 2, i. e. the case where the gas flow rate has only small effect on

Fig. 1 Photographic view of bubbles generated from a porous teflon plate

(liquid: ion-exchanged water, distributor: Ti, $u_g = 3.15$ [cm/sec])

the bubble size, and that where the effect is rather appreciable. It is clear that these phenomena depend mainly upon the kind of liquid. Therefore the liquids tested here are classified in three groups as shown in Table 2.

Group A : For this group of liquids, the size of bubbles generated from the distributor changes with increasing gas flow rate as shown in Fig. 2. Also the bubble size distribution tends to broaden.

Pure water and pure organic solvents belong to group A. Mixtures of organic solvents should also be in this group, unless one of the solvents works as a surfactant, as mentioned below.

Group B : The liquids which belong to this group are solutions of surfactants. Tween 20 and isoamylalcohol are well known as surfactants. Polyethylene-glycol which is not usually known as a surfactant behaves also like a surfactant in water. For organic solvents a small amount of isoamylalcohol and silicon oil may have the same effect. Therefore, the change of bubble size with gas flow rate in these systems behaves as group B as shown in Fig. 2 (c). For this group, the change of bubble size with gas flow rate is small, and the size distribution is sharp. It is clear that the stable films covering the bubbles obstruct the coalescence of bubbles after their generation from the distributor. In this case only a small amount of the surfactants is enough to make the film stable, if it covers the bubble surfaces as monomolecular layer, and the excess amount of the surfactants does not give any more effect on the behavior of bubbles.

Group C : Aqueous solutions of inorganic salts, acetic acid and glycerine belong to this group. By increasing the concentration of inorganic salts in the solutions, the bubble size tends to become smaller and the behavior of the solution shifts from that of group A to that of group B. This change with the salt concentration is illustrated in Fig. 2(d). At concentration of the salt below 0.3

Fig. 2 Volume equivalent bubble diameter vs. gas flow rate

Fig.3 Photographic view of bubbles on distributor
(liquid: toluene, distributor: G1, $u_g=1.68$ [cm/sec])

Fig.4 Photographic view of bubbles on distributor
(liquid: toluene solution of isoamylalcohol, distributor: G1, $u_g=1.68$ [cm/sec])

mol/lit, bubbles generated change gradually in their size and their distribution. At the higher concentration, the behavior is almost close to group B. Glacial acetic acid (guaranteed more than 99.0% pure) behaves as group A as mentioned above, and by decreasing the concentration of acetic acid, bubble size becomes smaller and the behavior of 10% acetic acid solution approaches almost to that of group B. A similar result was reported by Vershoor⁶⁾, who recognized that in water the coalescence of bubbles is obstructed by an addition of some acetic acid. In this group, it seems, although the second substance added in water do not work as surfactants, there exists some obstruction of the coalescence of bubbles at their concentrated solutions.

Coalescence of Bubbles

Fig.3 shows the photograph of bubbles generated from a porous glass distributor into toluene which belongs to group A. This is seen as follows. The bubbles just above the distributor are very small and are of essentially the same size. The coalescence of these small bubbles occurs at a location slightly removed from the distributor, where the bubbles have a velocity less than the steady state rising velocity and the gas hold up is large. At this place the chance of contact between bubbles is so frequent that, if the interface between gas and liquid is not strong enough (it seems that this is the case for group A), the coalescence of bubbles may occur easily. Therefore, the large bubbles and their broad size distribution are obtained. With increase of gas flow rate the number of bubbles generated from the distributor per unit time increased, so that the gas holdup above the distributor becomes large, the chance of coalescence increases, and then the large and broad size-distributed bubbles appear. On the other hand, for the system of group B, the coalescence of bubbles may be neglected as shown in Fig.4. This is the photograph of bubbles in the toluene with a small amount of isoamylalcohol. Here the latter acts as a surfactant, makes the interface rather stable and obstructs the coalescence of bubbles. In this case, therefore, the size distribution of bubbles is kept narrow and almost the same as that just generated. Fig.5 shows bubble size distributions for the two typical cases. It is well known that a trace of surfactants in water makes stabilized surfaces of bubbles and obstructs their coalescences^{1,2)}.

(a) for glacial acetic acid (distributor B2)

(b) for aqueous solution of Tween 20
(distributor B2)

Fig.5 Bubble size distribution

It should be noted here that in inorganic salt solutions a large amount of salt makes the interface stable and gives small bubbles. It is sometimes observed that in concentrated solutions a portion of the bubbles becomes quite small, i.e. about 0.3mm in diameter. The reason for

this is not clear.

If the interface of bubbles is stabilized, these bubbles can build up a foaming bed easily. In the liquids which belong to group A the foaming bed is not obtained, while in the liquids which belong to group B very stable foaming beds are formed. In the liquids belonging to group C which behave as those between group A and group B a limited height of foaming bed is obtained. Accordingly, it is felt that the factors which affect the coalescence of bubbles in the liquid are the same as the factors which affect the stabilization of the foaming bed.

Correlation for Average Bubble Diameter

The property of the porous plate is characterized only with the average pore diameter, because the plate material does not affect the bubble formation if the plates are wetted with liquid as mentioned above. The pore diameter δ was determined by the method proposed by Houghton et al.⁽⁴⁾, i. e. the following equation was used:

$$\delta = \frac{4\sigma}{\Delta P_0} \quad (1)$$

where ΔP_0 is the excess pressure required to generate the bubbles on the distributor. This is obtained from the extrapolation of ΔP to zero gas flow rate, where ΔP is the pressure drop on and through the distributor at any gas flow rate. For the case when no coalescence of the bubbles is observed, i. e. for the liquids of group B, it is expected that a rather clear correlation between the average bubble diameter and the conditions of the bubble generation will be obtained. **Fig. 6** shows the correlation of the average bubble diameter with the condition of bubble generation expressed in the non-dimensional factors proposed by the authors⁽⁵⁾. From Fig. 9 the following correlation is obtained.

$$\bar{d} \left(\frac{g\rho}{\delta\sigma} \right)^{1/3} = 0.64 \left(\frac{Fr}{We^{0.5}} \right)^{0.100} \quad (2)$$

On the other hand, for the case when the coalescence of bubble exists, the clear correlation may not be expected. However, in the case when the coalescence of the bubbles occurs at the maximum rate, which corresponds to the case for the liquids of group A, a correlation of the same type as Eq. (2) is obtained as shown in **Fig. 7**. Therefore,

$$\bar{d} \left(\frac{g\rho}{\delta\sigma} \right)^{1/3} = 1.65 \left(\frac{Fr}{We^{0.5}} \right)^{0.160} \quad (3)$$

Fig. 6
 $\bar{d} \left(\frac{g\rho}{\delta\sigma} \right)^{1/3}$ vs. $Fr/We^{0.5}$,
Correlation of average bubble size for liquids of group B

Fig. 7
 $\bar{d} \left(\frac{g\rho}{\delta\sigma} \right)^{1/3}$ vs. $Fr/We^{0.5}$,
Correlation of average bubble size for liquids of group A

Fig. 8

$\bar{d} \left(\frac{g\rho}{\sigma} \right)^{1/3}$ vs. $Fr/We^{0.5}$,
Correlation of average
bubble size for liquids of
group C

Fig. 9

Comparison of Eq. (2) and
Eq. (3) with Houghton et
al.'s results

For the liquids of group C, the experimental data scatter between both the cases of the extreme conditions as shown in Fig. 8.

In order to correlate the data for this group C, a parameter to express the bubble film strength will be required. A quantitative theory for bubble film strength has been presented by Gleim and coworkers^{2,3}. According to their theory for pure liquid the energy of the bubble film rupture is proportional to the surface tension and the film thickness. The adsorption of the surface active substances on the interface strengthens the bubble films. This overcomes the tendency to weaken the films by lowering of surface tension of liquid and then stabilizes the bubbles. In electrolyte solutions only the increase of surface tension, which is very small, acts to increase the film strength. They also have presented a method of calculating the minimum energy required for a film rupture. Although their theory interprets our data qualitatively well, the

quantitative measure, which corresponds to the parameter correlating our data, is not given. More extensive work is required.

In comparison with our results, the data obtained by Houghton et. al.⁴ are shown in Fig. 9. As the porosity of the porous plates used, ϵ , is not given in their case, ϵ is assumed 0.5 to correlate their data. Therefore, the exact comparison of their results with our results is not possible. However, the data obtained for liquids, water, glacial acetic acid and ethylacetate are correlated as group A of our results. The values of $\bar{d} \left(\frac{g\rho}{\sigma} \right)^{1/3}$ are a little larger than those of Eq. (3). This discrepancy might arise from the difference of the apparatus in their case and that in the present study. Houghton et al. used a bubble column having inner diameter of 7.98 cm which is nearly equal to the diameter of the distributor. Then the gas holdup over the distributor interrupts the free rising of the bubbles,

enhances the probability of the bubble coalescence and makes bubble larger. On the other hand, in the present study the dimension of the apparatus is far larger than that of the distributor and the depth of the liquids is shallow. Therefore, the probability of the bubble coalescence over the distributor is less than that of the Houghton et al.'s case, because the circulation of the liquid in the apparatus makes bubbles easy to apart each other. This fact is recognized when the porous plate distributor is used for liquid of group A and C in the bubble column with continuous liquid flow.

Summary

Bubbles which have been just generated from the porous plate are small and have an equal size, but sometime coalescence of these small bubbles occurs at a location slightly removed from the distributor, where the gas hold-up is very large. Therefore, large and wide size distribution of bubbles are observed. This occurs easily in pure water and pure solvents. The surface active substances in water and solvents obstruct this coalescence of bubbles. In concentrated inorganic salt solutions, this obstruction is also recognized. For the extreme cases when no coalescence is observed and the coalescence occurs at the maximum rate, the correlations of the average bubble diameter and the conditions of bubble generation

are obtained.

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Nomenclature

d	= volume equivalent bubble diameter	[cm]
$\bar{d}$	= average bubble diameter	[cm]
g	= gravitational acceleration	[cm/sec ²]
ΔP_0	= excess pressure required to generate bubble	[g/cm·sec ²]
u_g	= gas flow rate per unit area of porous plate	[cm/sec]
$Fr = u_g^2/\varepsilon^2 g \bar{d}$	= Froude number	[—]
$We = u_g^2 \bar{d} \rho / \varepsilon^2 \sigma$	= Weber number	[—]
ρ	= density of liquid	[g/cm ³]
$\bar{d}$	= average pore diameter defined by Eq.(1)	[cm]
ε	= porosity of porous plate	[—]
σ	= surface tension of liquid	[dyne/cm]

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MASS TRANSFER COEFFICIENTS BETWEEN GAS AND LIQUID PHASES IN PACKED COLUMNS*

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Introduction

Mass transfer coefficients for gas absorption, desorption and vaporization in packed columns have been studied by many investigators^{3,5,11,22,26,30,31}. Assuming that the wetted surface on packing pieces is identical with the gas-liquid interface, Onda et al. presented the empirical equations of the gas and liquid-side mass transfer coefficients, k_G and k_L , for the gas absorption and desorption¹²⁻¹⁸.

Recently, a new equation for the wetted surface area, a_w , taking into account the liquid surface tension and the surface energy of packing materials was derived as follows¹⁸:

$$\begin{aligned} a_w/a_t &= 1 - \exp\{-1.45(\sigma_c/\sigma)^{0.75} (L/a_t \mu_L)^{0.1} \\ &\quad \times (L^2 a_t / \rho_L^2 g)^{-0.05} (L^2 / \rho_L \sigma a_t)^{0.2} \\ &= 1 - \exp\{-1.45(\sigma_c/\sigma)^{0.75} (Re)^{0.1} \end{aligned}$$

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$$\times (Fr)^{-0.05} (We)^{0.2} \} \quad (1)$$

It has been shown that Eq. (1) can be applicable within $\pm 20\%$ error to the column packed with Raschig rings, Berl saddles, Spheres and rods made of ceramic, glass, and polyvinylchloride, and also coated with paraffine film.

This paper presents the correlations on the mass transfer coefficients for gas absorption and desorption based on Eq. (1) of a_w and confirms the applicability of those to the vaporization of water and the gas absorption into organic solvents. Furthermore, its applicability to the distillation in packed columns is also discussed.

1. Liquid-side Mass Transfer Coefficient: k_L

1.1 Gas absorption and desorption with water

The $k_L a$ data for gas absorption into water and desorption from water reported in the literature^{3,6,12,16,18,20,24,27,28} are divided by a_w of Eq. (1). The k_L thus obtained are correlated as well as that in our previous paper^{12,18} by