SIZE OF BUBBLES GENERATED FROM PERFORATED PLATES IN NON-NEWTONIAN LIQUIDS

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Bubble columns are frequently used in the chemical industry as absorbers, fermenters and reactors. Recently bubble columns have been used as bio-reactors for non-Newtonian liquids. Thus, experiments were performed to investigate the size of bubbles generated from a perforated plate in a non-Newtonian liquid. The bubble size distribution may follow a logarithmic normal probability distribution despite the plate geometry and physical properties of the liquids. The characteristic correlation for the size of bubbles generated from the perforated plates in non-Newtonian liquids was derived.

Introduction

Bubble columns are frequently used in the chemical industry as absorbers, fermenters and reactors. The principal advantages of bubble columns compared to other multiphase contactors are: low maintenance due to the absence of moving parts; high effective interfacial areas which translate into high mass and heat transfer; low cost; and high residence time of liquid. Specifically, bubble columns have been used recently as bio-reactors for non-Newtonian liquids.

The gas-liquid interfacial area is an important parameter necessary for practical design of bubble columns in characterizing the mass transfer. Therefore, in the literature many articles can be found on theoretical and experimental studies on the size of bubbles generated from perforated plates, involving determination of the gas-liquid interfacial area. Previous studies, however, are mainly based on the bubble formation from a single hole in Newtonian and non-Newtonian liquids (Tadaki and Maeda, 1963; Tsuge, 1986; Miyahara *et al.*, 1988) and the size of bubbles generated from perforated plates and porous plates in Newtonian liquids (Akita and Yoshida, 1974; Koide *et al.*, 1966; Miyahara *et al.*, 1983). As for the size of bubbles generated from perforated plates and/or porous plates in non-Newtonian liquids, which are frequently used in bio-reactors, reports are not yet available due to the complexity, thereof. Only Buchholz *et al.* (1978) studied qualitatively the size distribution of bubbles generated from porous plates using 1% CMC solution.

Therefore the aim of this paper is to experimentally determine the size of bubbles from perforated plates using CMC aqueous solutions, which are non-Newtonian liquids represented by the power law and have never been reported. In addition, the results will be compared with those for water, which is a Newtonian liquid.

1. Experimental

A schematic diagram of the experimental apparatus is shown in **Fig.1**. The Plexiglas column has a 0.1 m i.d. and the test section is 1.5 m high. The test section was surrounded by a viewing vessel, which was also constructed of Plexiglas to eliminate optical distortion and was used as a circulating jacket to maintain a constant operating temperature. Bubbles were generated from a perforated plate. The three types of perforated plates were made of brass, with the holes arranged in the form of equilateral triangles. Details of the geometry are given in **Table 1**.

Air was first blown through the system, and a predetermined amount of liquid was introduced into the top of the column in such a way that there was no weeping. Air from the compressor passed through a filter to remove any oil and dust, then through the pressure regulator, the buffer tank, the orifice flow meter and into the air chamber. It then passed through the perforated plate, becoming dispersed in the liquid in the form of bubbles, after which it left the system.

The data were recorded by a video recorder at 5 cm intervals along the column axis and at the column center. The data were then analyzed on the video monitor, and the major and minor axes of each bubble, which was assumed to be an ellipsoid, were measured. The volumetric mean bubble diameter was then calculated from the expression

$$d_{30} = \left(\frac{\Sigma 6 V_b / \pi}{n} \right)^{1/3} \qquad (1)$$

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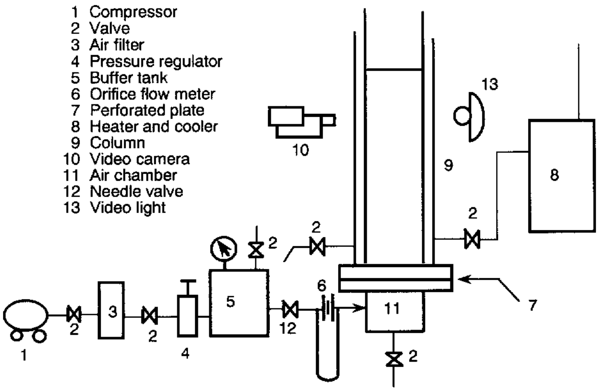


Fig. 1 Schematic diagram of experimental apparatus

Table 1 Geometry of perforated plate

Plate	Hole diameter δ [m]	Free area F [-]	Ratio of pitch to hole diameter P/δ [-]
P-1	0.0015	0.01925	6.7
P-2	0.0010	0.00850	10.0
P-3	0.0007	0.00417	14.3

number of holes = 85
P = 0.01 m

The number of bubbles needed to be measured in order to establish their diameter for any given condition was 100, which was confirmed by preliminary experiments and the same level as that which is presumed to be reliable for statistical purpose (Miyahara *et al.*, 1983). Under these experimental conditions, there was an appreciable amount of variation in the size of the bubble in the longitudinal direction along the column due to bubble-bubble coalescence. **Figure 2** shows the results. The data were rec orded at a distance of 40-45 cm from the bottom because this height provided a constant volumetric mean diameter of bubbles.

Two types of liquids, listed in **Table 2**, were employed. Aqueous CMC solutions are non-Newtonian liquids represented by the power law of a two-parameter rheological model of the form

$$\tau = -m\left(\frac{du}{dy}\right)^n \tag{2}$$

For n=1, it reduces to the Newtonian law of viscosity with $m = \mu$. The deviation of n from unity indicates the degree of deviation from Newtonian behavior. The determination of two parameters, n and m, were measured by a coaxial-cylinder viscometer at shear rates of 2 - 40 s^{-1}. For comparison, we also used water, which is a low-viscosity Newtonian liquid.

2. Results and Discussion

Figure 3 shows some photographs of a bubble swarm. For water, which is a Newtonian liquid, the bubbles ascend individually without bubble-bubble coalescence. On the other hand, remarkable coalescence and/or bubble breakage can be observed for aqueous CMC solutions which are non-Newtonian liquids. As the m value shown in Table 2 becomes larger, in other words, the Morton number increases, the frequency of coalescence appears to be larger.

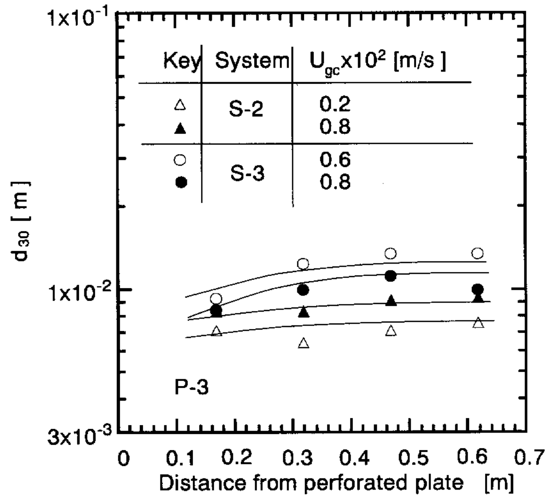


Fig. 2 Vertical profile of volumetric mean diameter of bubbles

Coincidentally, it is assumed that the size distribution of bubbles generated from perforated plates may follow a logarithmic normal probability distribution (Miyahara *et al.*, 1983; Tadaki and Maeda, 1963). **Figures 4, 5** and **6** show the size distribution of bubbles for water (Fig.4) and aqueous CMC solutions (Figs.5 and 6). In each case, the size distribution data fit roughly to a logarithmic normal probability distribution regardless of the gas velocities and can be represented by the expression

$$\frac{d(1-R)}{d(\ln d/d_g)} = \frac{1}{\sqrt{2\pi}\ln s}\exp\left[-\frac{\{\ln(d/d_g)\}^2}{2(\ln s)^2}\right] \tag{3}$$

where d_g is the geometric mean diameter:

$$d_g = (d_1 \cdot d_2 \cdot d_3 \cdots d_n)^{1/n} \tag{4}$$

and s is the geometric standard deviation

$$s = \exp\left[\Sigma\{\ln(d/d_g)\}^2/n\right]^{1/2} \tag{5}$$

The relationship between d_{ji} and d_g of a logarithmic normal probability distribution is (Mugele, 1951)

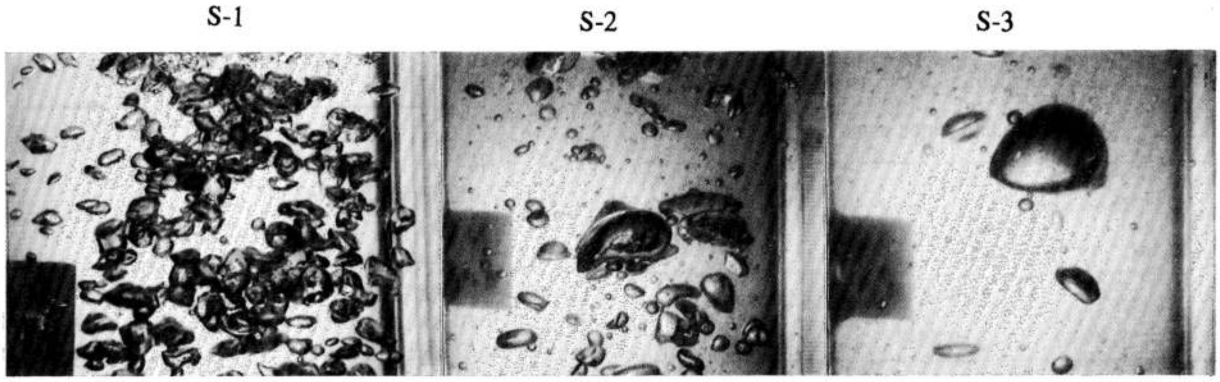
$$d_{ji} = d_g \exp\{(i+j)(\ln s)^2/2\} \tag{6}$$

As can be seen from these figures, as the Morton number increases, the size distribution shifts in favor of larger bubbles, and the slope becomes small, which indicates a large distribution width.

The size distribution of the bubbles generated from the perforated plates follows a logarithmic normal probability distribution given by Eq.(3); therefore, it is necessary to know the geometric standard deviation s. **Figure 7** shows

Table 2 Physical properties of liquids employed

Liquid	Density ρ [kg / m^3]	μ [Pa·s]	n [-]	m [kg / m·s^{2-n}]	Surface tension σ [N / m]	Morton number M $\{g^{3n-2}m^4/(\rho^{2-n}\sigma^{n+2})\}$ [-]	System
Water	996	0.008			0.073	1.06×10^{-11}	S-1
CMCaq.	1002		0.9465	0.031	0.063	1.48×10^{-5}	S-2
	1004		0.9302	0.093	0.067	7.15×10^{-4}	S-3



Bubbles generated from perforated plate P-1, $U_{gc} = 0.8\times10^{-2}$ m/s

Fig. 3 Photographs of bubble swarm generated from perforated plates

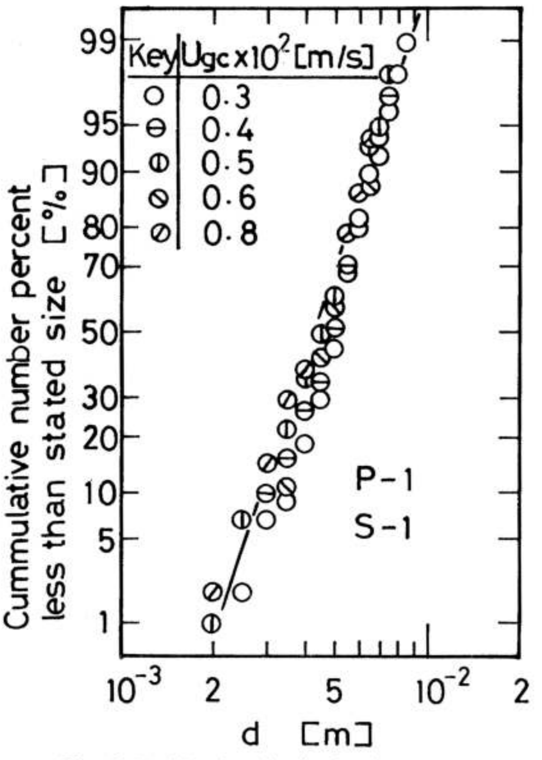


Fig. 4 Bubble size distribution for water

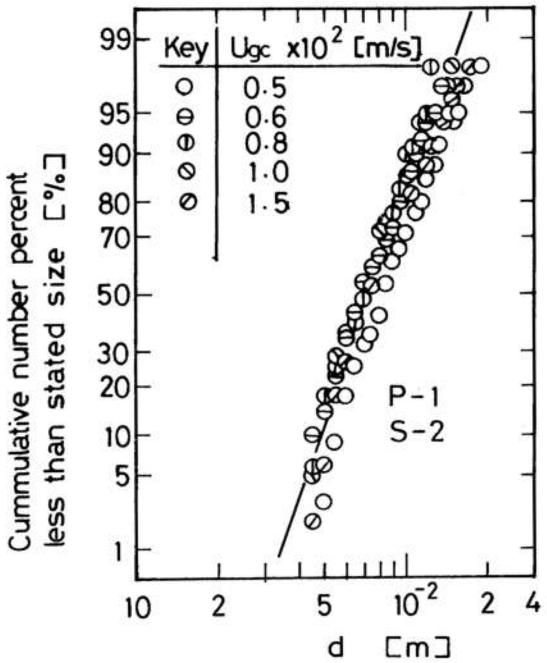


Fig. 5 Bubble size distribution for aqueous CMC solution (S-2)

the relationship between s and N_w for water. From this figure, it is apparent that s is reasonably constant and is about 1.2 (close to unity), thus indicating that the bubbles are fairly uniform in size for water. However, s is higher in the case of non-Newtonian liquids and also has a roughly constant value of about 1.5 as shown in **Fig.8**, which is only to be expected in view of the coalescence corresponding to the photographs of bubbles shown in Fig.3. These two figures correspond to Figs. 4, 5 and 6.

When it is assumed that the size distribution of bubbles obeys a logarithmic normal probability distribution, we can understand the whole image of distribution by

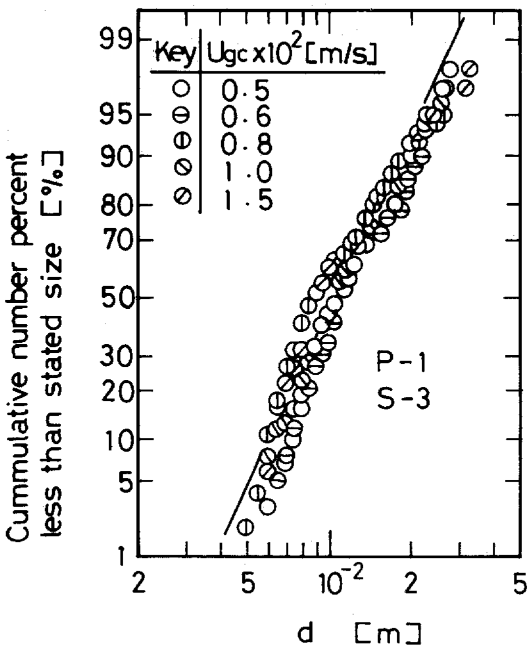


Fig. 6 Bubble size distribution for aqueous CMC solution (S-3)

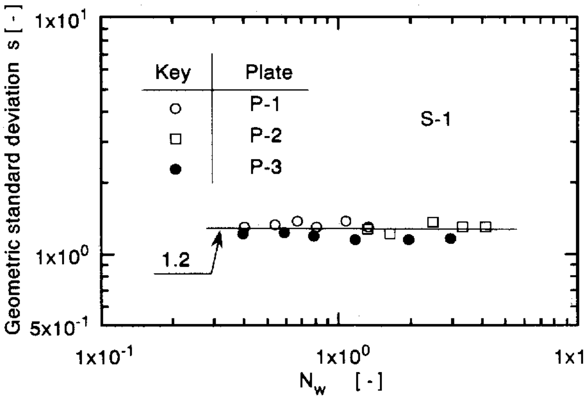


Fig. 7 Geometric standard deviation for water

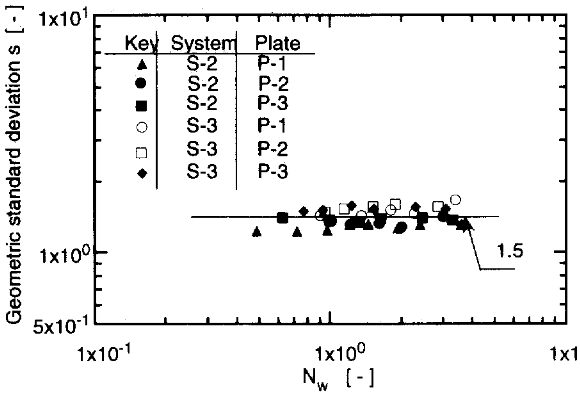


Fig. 8 Geometric standard deviation for aqueous CMC solutions

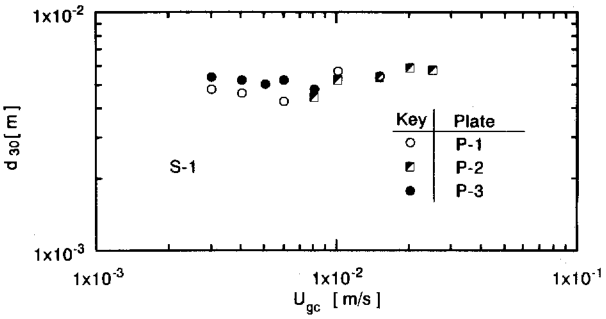


Fig. 9 Volumetric mean diameter of bubbles generated from perforated plates for water

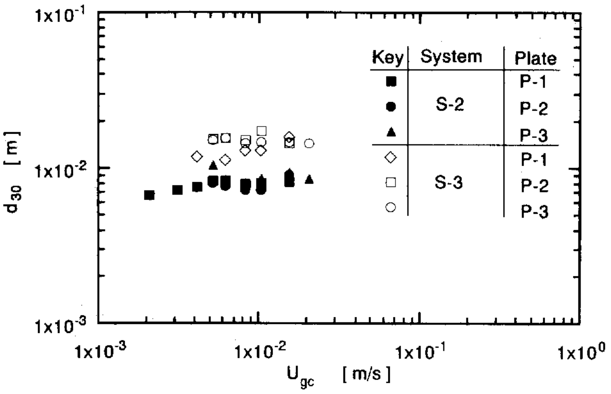


Fig. 10 Volumetric mean diameter of bubbles generated from perforated plates for aqueous CMC solutions

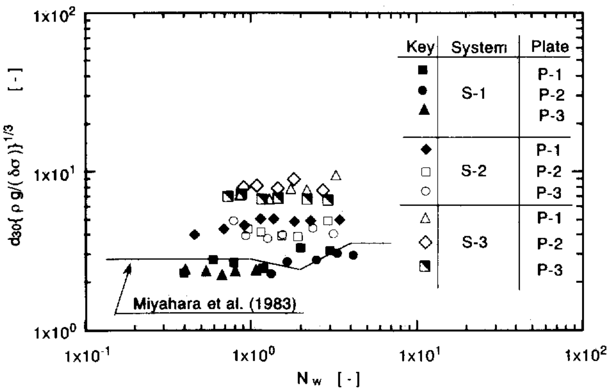


Fig. 11 Correlation of volumetric mean diameter of bubbles

knowing the arbitrary mean diameter. Thus we tried to correlate the volumetric mean diameter d_{30} of bubbles. **Figure 9** shows the volumetric mean diameter of the bubbles for water. The volumetric mean diameter first decreases as the gas velocity increases, then passes through a minimum, increases, and finally converges at a more or less constant value. The trend agrees well with the results reported by the authors previously (Miyahara *et al.*, 1983). However, for aqueous CMC solutions as shown in **Fig.10**, the same trend as that for water was not observed, and the volumetric mean diameter was roughly constant depending on the liquid system, regardless of the plate geometry.

Figure 11 shows the correlation of the dimensionless bubble diameter with the dimensionless parameter N_w. In the same graph, the solid line is the results for Newtonian liquids obtained by the authors (Miyahara *et al.*, 1983). The results for aqueous CMC solutions become high compared

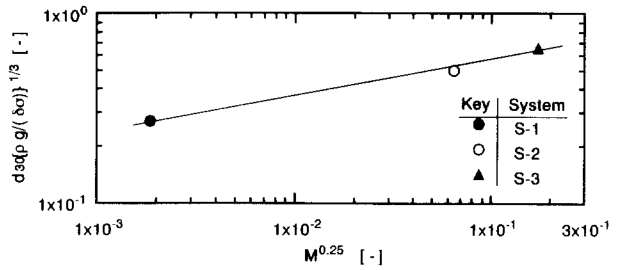


Fig. 12 Effect of the Morton number on volumetric mean diameter of bubbles

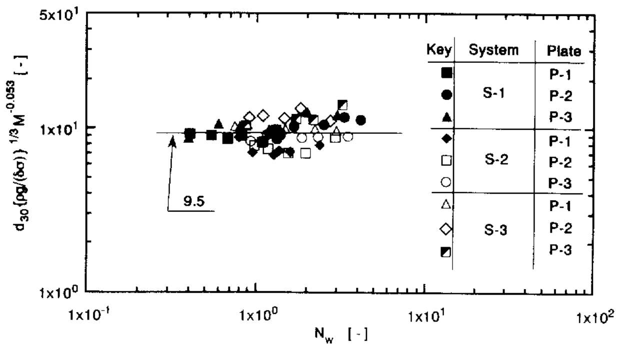


Fig. 13 Correlation of volumetric mean diameter of bubbles

to those for water; however, the effect of plate geometry on the dimensionless bubble diameter was not observed. **Figure 12** shows the effect of the Morton number on the dimensionless bubble diameter as mean values for each liquid. From this figure

$$d_{30}\{\rho g/(\delta\sigma)\}^{1/3} \propto M^{0.053} \tag{7}$$

From this consideration, **Fig.13** was obtained. In this graph, all the data are represented by the solid line

$$d_{30}\{\rho g/(\delta\sigma)\}^{1/3} = 9.5M^{0.053} \tag{8}$$

regardless of the dimensionless parameter N_w, which was about 9.5.

Concluding Remarks

The size of bubbles generated from perforated plates was measured for water (Newtonian liquid) and aqueous CMC solutions (non-Newtonian liquids). The following conclusions were drawn:

1) The bubble size distribution for non-Newtonian liquids roughly follows a logarithmic normal probability distribution, as reported for Newtonian liquids (Miyahara *et al.*, 1983)

2) The geometric standard deviation for non-Newtonian liquids used in this study is about 1.5, which leads to bubble coalescence.

3) The volumetric mean diameter of bubbles in non-Newtonian liquids is large because adjacent bubbles tend to coalesce.

4) The dimensionless bubble diameter for non-Newtonian liquids becomes high compared to that for Newtonian liquids, thus indicating bubble coalescence.

5) An empirical correlation for the volumetric mean diameter of bubbles for non-Newtonian liquids was obtained based on the effect of the Morton number of each liquid.

Nomenclature

d = bubble diameter [m]
d_g = geometric mean diameter [m]
d_{ji} = mean diameter [m]
d_{30} = volumetric mean diameter of bubbles [m]
F = free area [-]
Fr = Froude number $(=U_{gh}^2/(g\ \delta))$ [-]
g = gravitational acceleration, [m/s^2]
M = Morton number $(=g^{3n-2}m^4/(\rho^{2-n}\ \sigma^{n+2}))$ [-]
m = coefficient in power law liquid [Pa.s^n]
N_w = $We/Fr^{1/2}$ [-]
n = number of bubbles, power law liquid exponent [-]
P = pitch [m]
R = cumulative number fraction greater than stated size [-], [%]
s = geometric standard deviation [-]
U_{gc} = superficial gas velocity [m/s]
U_{gh} = gas velocity through hole [m/s]
V_b = bubble volume [m^3]
We = Weber number $(=\delta U_{gh}^2\rho/\sigma)$ [-]

δ = hole diameter [m]
μ = liquid viscosity [Pa.s]
ρ = liquid density [kg/m^3]
σ = surface tension [N/m]

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