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THE STUDY ON LIFETIME OF MICRO-BUBBLE

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ABSTRACT
Micro-bubbles are peculiar bubbles and shrink in liquid gradually. This study aimed to make clear the process of its shrinkage and the factors controlling its shrink speed. The temperature and interfacial tension of the liquid were changed to controll the diffusion coefficient and the pressure difference between a micro-bubble and surrounding liquid. The pressure difference relates on the solubility of gas in a bubble at its surface. More than 50 bubbles were observed under each c ondition. As the result, the shrink speed increases with the decrease of diameter of micro-bubble and with the increase of interfacial tension. In case that temperature changes, the most suitable temperature where the shrink speed shows the highest exists because the solubility decreases and the diffusion coefficient increases with the increase of temperature.

KEYWORDS：Micro-bubble, Shrink speed, Bubble diameter, Interfacial tension

1. INTRODUCTION

Micro-bubbles mean small bubbles which diameter is from 10 micro-meter to 100 micro-meter. Micro-bubbles began to be used in the field such as the sterilizing and revitalization of organisms, the pureification of liquid, the decrease of friction, etc..

However, most of all are applocation in a pooled water. If the micro-bubble can be confined in small droplets by atomization, disinfection by water spray may possible. Moreover, there is a report[1)] that combustion changes by containinng micro-bubbles in liquid fuel.

The micro-bubble in liquid shrinks gradually until about 30μm in diameter, after that it shrinks rapidly. It is necessary to know the disappearance time of the micro-bubble accurately to use the micro-bubble effectively. In this research, it aimed to clarify the factor given at the reduction speed and the disappearance time of the micro-bubble and the level of the influence experimentally.

The solubility and diffusivility of gas to liquid are focused as factors that influence the shrink speed of the micro-bubble in this study. The solubility at surface of bubble depends on interfacial tension and babble diameter and diffusivility on liquid temperature. Therefore, the interfacial tension and liquid temperature are controlled in this study.

2. EXPEWIMENT AND ANALYSIS

2.1 Experimental setup

The behaivior of bubble in liquid was recorded under various conditions and the cange of bubble diameter with time was caluculated from each image.

The outline of the experimental apparatus is shown in Fig.1. Apparatus consists from the bubble generating unit and recording unit. Micro－bubbles was generated by stirring the water in the glass container. The interfacial tension and temperature of liquid was adjusted as shown in Table 1. After generating the micro-bubble, liquid including micro-bubbles was moved to a small reservoir by an injection syringe. Test liquid was covered by a thin glass to prevent from blowing up or diffusing into atmosphere directly because micro-babble rises gradually to the surface of liquid. The behaviour of micro-babbles was recorded by CCD camera through a micro-scope. The enlargement ratio was 1000 times and recording speed 7.5 fps. As a result, an area of 120×90μm was recorded.

Distilled water was used as the basic liquid and add a surfactant for controoling interfacial tension. The surfactant was Toriton X that was non-ion neutral. The interfacial tension and temperature of test liquid are shown in Table 1.

A small conteiner was set on a heat controoling unit to prevent a test liquid from temperatur change during recording.

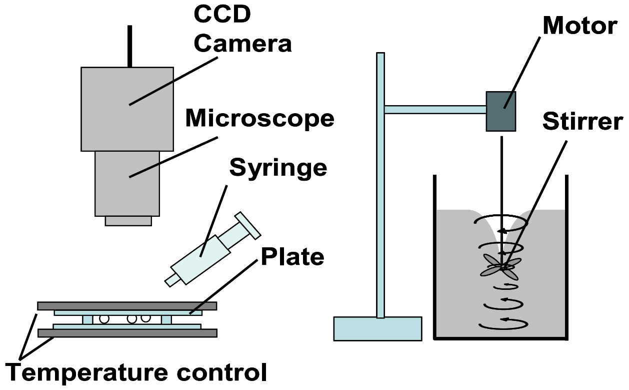


Fig.1 Experimental apparatus

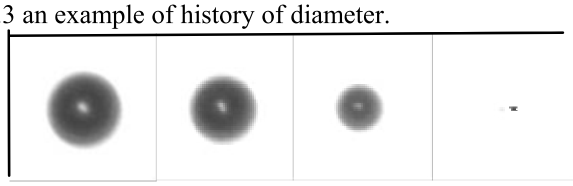
Table 1 Experimental condition

Interfacial tension [mN/m]	30,45,60	45
Temperature [℃]	25	5, 25, 45
Pressure [MPa]	0.1	
Liquid	Distilled water	
Gas phase	Air	
Surfactant	Toriton X	
Trial times	More than 50	

2.2 Measurement and Analysis

2.2.1 Shrink speed of micro-bubble

The shrink process of micro-bubble was recorded and the history of bubble diameter obtained from the images. The bubble with less than 60μm in diameter shrinks gradually, but one with more than 70μm hardly shrinks. Figure 2 shows an example of images that its diameter gradually decreases and Fig.3 an example of history of diameter.



D=41 t =0 D=36 t =15 D=22 t =30 D=3 t =45

Interfacial tension = 45 [mN/m]

Fig.2 Example of micro-babble Images

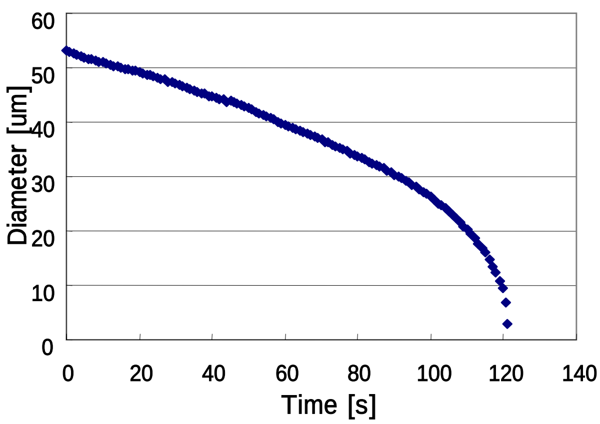
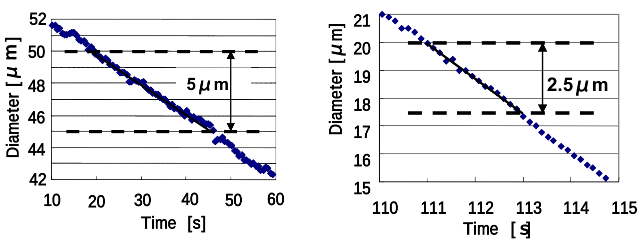


Fig.3 Example of diameter history

The bubble diameter decreases with time, and the shrink speed increases rapidly beyond aproximetry 20μm.

The instantanious shrink speed that was the change of diameter in time(dD/dt) was calculated from the history of diameter. The data within each 5 μm at more than 20μm in diameter and within each 2.5 at less than 20μm are approximated as the linear at certain time as shown in Fig.4 and the instantanious shrink speed was obtained from its gradiant.



(a) more than 20μm (b) less than 20μm

Fig.4 Approximation method

2.2.2 Pressure in bubble

Pressure P in a micro-bubble can be caluculated by Laplace's formula as follows:

$$P = P_0 + \frac{4\gamma}{D} \tag{2.1}$$

Here, P_0 : surrounding pressure,

γ : interfacial tention,

D : bubble diameter

Differential pressure between pressure in micro-bubble and one of surrounding liquid is decided depending on a bubble diameter and an interfacial tension. Figure 5 shows the relation between babble diameter and pressure in bubble caluculatede by Eq.(2.1). Pressure in babble increases gradualy with the decrease of babble diameter and greatly at less than approximarely 20μm. The critical solubility at bubble surface increases greatly, and the diffusion is accelerated. As a result, the shrink speed increases with the decrease of bubblle diameter as it depends strongly on differential pressure.

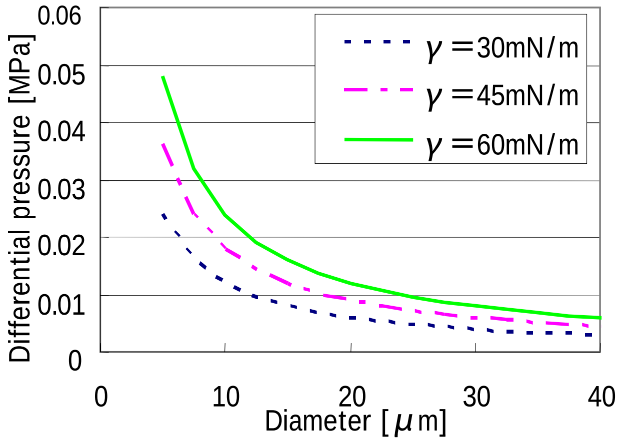


Fig.5 Relation between diameter and pressure in bubble

2.2.3 Amount of diffusion gas from bubble

Amount of gas(air) in a babble that disolves into surrounding liquid(water) is caluculated ing from Because the gas in the bubble dissolved from the change of bubble diameter and shrink speed.

Mass flux of disolving gas is drived as follows:

$$n = \frac{PV}{RT} \tag{2.2}$$

$$\frac{dn}{dt} = \frac{1}{RT}\left(\frac{dP}{dt}V + P\frac{dV}{dt}\right) \tag{2.3}$$

$$\frac{dP}{dt} = -\frac{4\gamma}{D^2}\frac{dD}{dt} \tag{2.4}$$

$$\frac{dV}{dt} = \frac{1}{2}\pi D^2 \frac{dD}{dt} \tag{2.5}$$

$$\frac{dn}{dt} = \frac{1}{RT}\left\{\frac{1}{6}\pi D^3\left(-\frac{4\gamma}{D^2}\frac{dD}{dt}\right) + \left(P_0 + \frac{4\gamma}{D}\right)\left(\frac{1}{2}\pi D^2\frac{dD}{dt}\right)\right\} \tag{2.6}$$

$$\frac{dn}{dt}\Big/\pi D^2 = \frac{1}{RT}\left(\frac{1}{2} + \frac{4\gamma}{3D}\right)\frac{dD}{dt} \tag{2.7}$$

Here, n : amount of gas (mol),

R : Gas constant (Pa・m^3/mol・ K),

T : Tempreture (K),

V : Volume of bubble (m^3)

2.2.4 Concentration of air at the surface of bubble and in surounding liquid

The difusion of air is expressed Fick's Low shown in Eq.(2.8). Gas concentration at the surface of bubble and one in liquid are expressed Eqs.(2.9) and (2.10) respectively. Therefore, the difference of air concentration relates greatly to the diameter of the bubble. When temperature increases, solubility decreases according to temperature. As a result, the difference of concentration of gas at bubble surface and one in liquid decreases.

$$J = \Phi \frac{dC}{dx} \tag{2.8}$$

$$C_{L=\infty} = K_T P_0 \tag{2.9}$$

$$C_{L=D/2} = K_T (P + \frac{4\gamma}{D}) \tag{2.10}$$

$$C_{L=D/2} - C_{L=\infty} \approx K_T \frac{4\gamma}{D} \tag{2.11}$$

Here, J : mol flux (mol/m^2 s)

Φ : diffusibity of gas in liquid (m^2/s)

C : concentration of gas (mol/m^3)

K_T : solubility at temperature T (mol/m^{3}P$_a$)

D : babble diameter (m)

L : distance from center of bubble (m)

3. RESULTS AND DISCUSSION

3.1 History of bubble diameter

Figure 6 shows the relation between bubble diameter and elapse time as an example. In this case, the initial bubble diameter was 60μm. Reduction rate of bubble diameter increases with the decrease of interfacial tension because of the increase of differential pressure, i.e. the deference of critical solubility at the surface of bubble. Further, the reduction rate increases gradually at beginning and rapidly beyond around 20μm in all cases.

The case that the initial diameter of babble is different is shown in Fig.7. The ordinate is the dimensionless bubble diameter (D/D_0) and the abscissa the dimensionless time (t/T_0). Here, D_0 is initial bubble diameter and T_0 lifetime. The lines

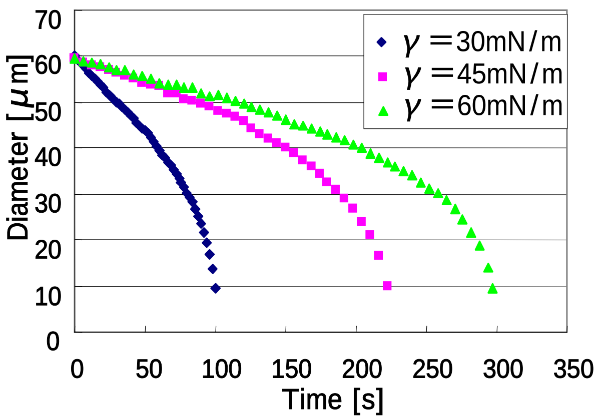


Fig.6 The relation between diameter and time

indicate the mean dimensionless diameter of bubbles with different initial diameter at each dimensionless time.

When the relation between bubble diameter and time is expressed by dimensionless values, all results are illustrated on the same curve even if the initial diameter and interfacial tension are deferent. This fact signifies that the shrink of bubble is the same from macroscopic point of view.

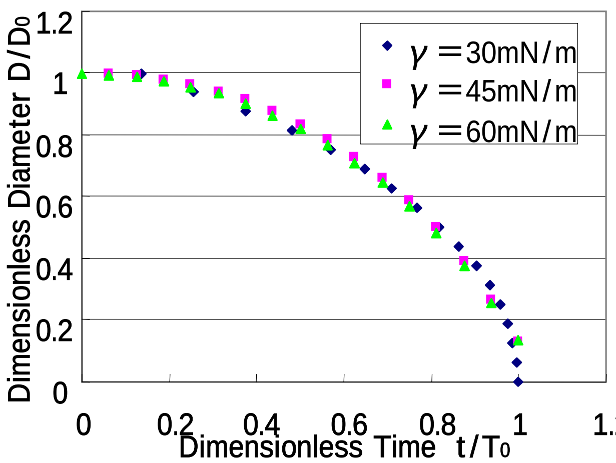


Fig.7 The relation between dimensionless diameter and dimensionless time

3.2 Lifetime of bubble

Figure 8 shows relation between the lifetime of bubble that is the time until bubble disappears and the initial bubble diameter. It is understood that lifetime is shorter with the increase of interfacial tension. This originates in the difference of pressure in a bubble.

It means that the lifetime of bubble can be controlled by interfacial tension of liquid.

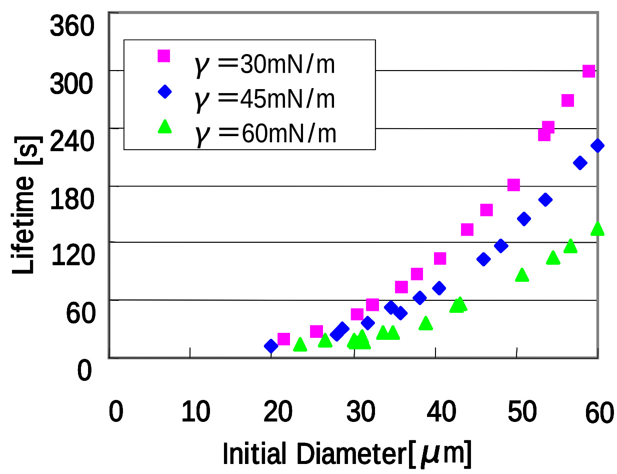


Fig.8 Life time of micro-bubbles

3.3 Shrink speed of bubble

The bubble diameter decreases rapidly at less than apploximatery 20μm as shown in Fig.6. From this results, the shrinkage speed was obtained as shown in clause 2.2.1.

The relation between the bubble diameter and the shrink speed is shown in Fig.9. Each key is the mean value shrink speed of bubbles with different initial diameter.

The shrink speed increases gradually with the decrease of bubble diameter, and rapidly at less than apploximatery 20μm in diameter. This tendency is greatly similler to the relation between babble diameter and pressure in bubble as shown in Fig.5.

It is because that pressure in the bubble increases rapidly with the decrease of bubble diameter and the difference of concentration of air at surface of bubble and in liquid increases. As a result, amount of dissolved gas increases. The shrink speed is also affected by the interfacial tension and it increases with the increase of interfacial tension even if the bubble diameter is the same.

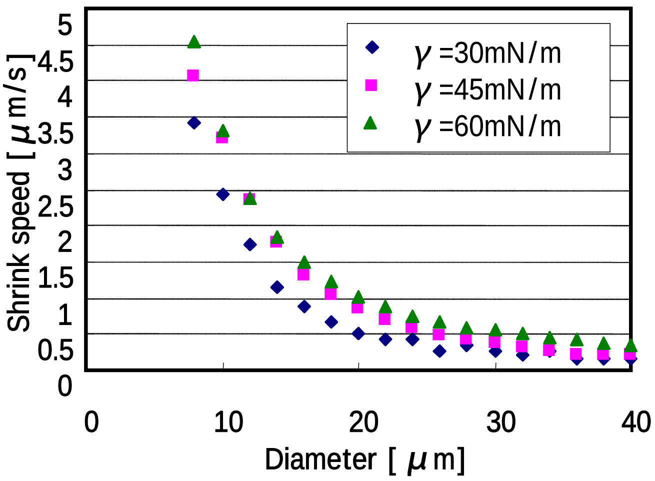


Fig.9 The average speed of shrinkage

3.4 Effect of differential pressure on shrink speed

The differential pressure that affects on the reduction speed of bubble is decided by the interfacial tension and bubble diameter as mensioned above. Figure 10 shows the relation between the differential pressure and the shrink speed.

It indicates that the shrink speed increases in propotional to the differential pressure within the region of rerative low differential pressure. However, the differential pressure acrosses certain value, the shrink speed increase rapidly. The babble diameter is smaller at the same differential pressur when the interfacial tension is smaller. The certain value corresponds to approximatery 20μm in all cases with different interfacial tension. It sugests that the distribution of concentration of air becomes unstable because the change rate of diameter becomes rapidly at less than 20μm.

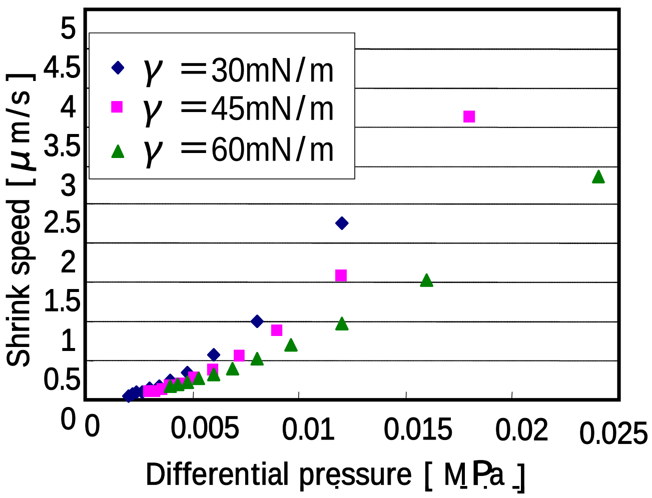


Fig.10 Relation between differential pressure and shrink speed

3.5 Effect of differential pressure on the amount of dissolved gas

The amount of dissolved gas was calculated from shrinkage speed of bubble as shown Eq.(2.7) and Fig.9. The amount of dissolved gas is evaluated by the mol flux, i.e. mol of dissolved gas per unit time and unit area, as the gas in the bubble dissolves from the bubble surface and shown in Fig.11.

The mol flux of gas also increases rapidly with the increase of the differential pressure. However, the mol flux of gas shows larger incase that the interfacial tension is lower even if the differential pressure is same. It also sugest that the concentration distribution of air is unstable inthe range of bubble diameter being small as same reason with Fig.10.

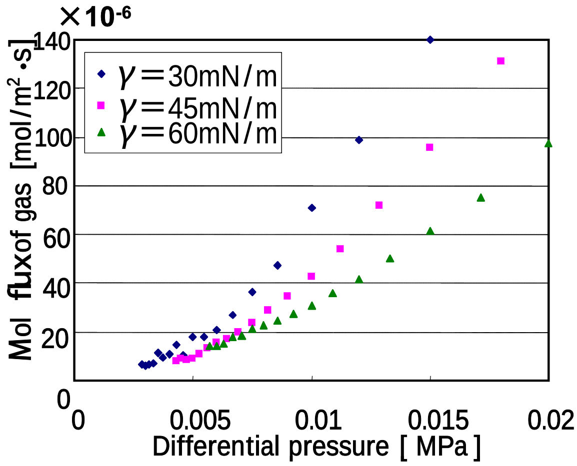


Fig.11 Relation between differential pressure and amount of dissolution of gas

3.6 Effect of temperature

3.6.1 Shrink speed of bubble

To analyze the effect of liquid temperature on shrink speed of bubble, the behavior of bubble in liquid with different temperature was examined. The solubility decreases and diffusibility increase with the increase of temperature.

Figure 12 shows the reration between bubble diameter and shrink speed in liquid with constant interfacial tension and different temperature.

The shrink speed at 25℃ is the largest and it decreases at 5℃ and 45℃. The shrink speed decreases in case that the the critical solubility is high or diffusibility high. When the temperature is lower, the former infreases but the latter decreases. When the tenperature is higher, the behaivior is contrary it. As a result, the optimal temperature exists.

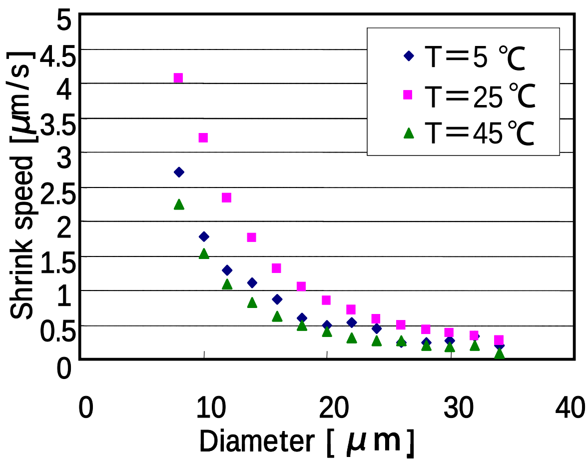


Fig.12 The average speed of shrinkag

3.6.2 Effect of temperature the amount of dissolved of gas

The differential air concentration at bubble surface and one in surounding liquid was calculated from pressure in the bubble and solubility at each temperature and mol flux of gas from the shrink speed and bubble size. To evaluate the effect of diffusivity on the amount of desolved gas excluding the effect of solubility, the relation between differential air concentration is illustrated in Fig.13.

As a result, the difference of solubility is excluded, and the influence of the diffusion coefficient is appreciable.

Within the differential air concentration being small, mol flux of 25℃ and 45℃ is almost same and increases with the increase of the differential air concentration. However, mol flux increases gradualy with the increase of the differential air concentration and difference of mol flux of them increases.

On the other hand, in case of temperature being 5℃, mol flux is smaller because of low diffusivity. The ratio of mol flux aproaches the ratio of diffusivity in range where the diffrential air concentration is large.

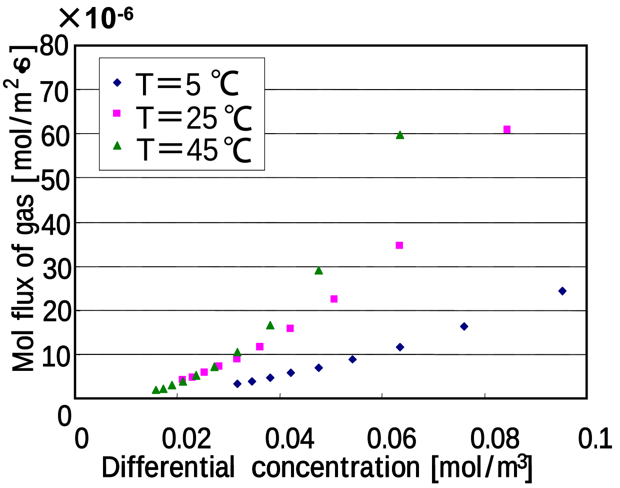


Fig.13 Relation between differential density and mas flux of gas

4. CONCLUSION

To clarify the shrinking process of micro-bubble and the factor given to the shrink, the history of micro-bubble was recorded and analyzed. The results are summarized as follows:

(1) The shrink speed of bubble increases rapidly with the increase of bubble diameter.

(2) The shrink speed of bubble increases with the increase of interfacial tension when bubble diameter is the same.

(3) Lifetime of bubble decreases with the increase of interfacial tension. Therefore, lifetime of bubble can be controlled by interfacial tension of liquid.

(4) The optimal temperature that the shrink speed indicates maximum exists.

(5) Though the shrink speed of bubble is greatly influenced from the differential pressure between an inside of bubble and a surrounding liquid, the shrinkage speed goes up by the bubble diameter small in the range where the bubble diameter is very small when the differential pressure is the same.

(6) It is suggested that the concentration distribution becomes unstable because the mol flux increases extremly when the bubble diameter becomes small enough.

5. REFERENCES

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