Effect of electrical potential of microbubbles on ozone dissolution

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Abstract. Microbubbles make ozone water generation effective due to the high dissolution rate of gas in contrast to a conventional generating method. Therefore, it is presumable that ozone water generation using microbubbles can be achieved by the low concentration ozone gas. In our previous study, a compact and low power microbubble generator was developed. The microbubbles are generated by the local shear stress in the flow through a pipe with slits. In the present study, in order to investigate the relationship between the electrical potential of the gas-water interface and the cleaning of cloth using ozone microbubbles, two models with different slit angles (θ=30 and 60 deg) were installed. High concentration ozone water is produced for θ = 60 deg in contrast to the θ=30 deg case. When a cloth is washed in the θ=60 deg case, the soiled cloth can be cleaned easily in comparison with the θ=30 deg case, because the zeta potential of microbubbles for θ=60 deg is larger than that for θ=30 deg.

1. INTRODUCTION

Microbubbles are very small air bubbles with an average diameter of about 50µm. Microbubbles have various unique chemical and physical characteristics in contrast to bubbles on the order of several tens of microns. For example, water quality can be improved by increasing the air supply with microbubble dissolutions. Furthermore, the electrical properties of the gas-water interface promote interaction with other materials, such as solid particles and oil droplets, to provide a basis for technical application in many fields, such as foam fractionation, food processing, and purification processes.

Ozone is a powerful oxidizing agent and is also unstable at high concentrations. Ozone is capable of bleaching substances and can be used for sterilization in place of the more common chlorine. Moreover, ozone is widely used to improve the taste and color of drinking water as well as to remove organics and inorganic compounds in drinking water and wastewater. Up until now, many factors have hindered the use of ozone, including its relatively low solubility and stability in water and the high cost of production. Ozone dissolution efficiency is improved by the use of microbubbles to generate ozone water, a method that is easy in comparison with other conventional methods. Furthermore, it was reported that microbubble technology was applied to increase the mass transfer rate of ozone as well as to enhance the ozone oxidation of synthetic wastewater containing azo dye (Li-Bing Chu,
2007). In our previous study, high ozone concentrations were achieved using our proposed microbubble generator and cold water temperatures. However, the effective microbubble characteristics that enhance ozonation efficiency have yet to be completely clarified. In the present study, the relationship between the electrical properties of microbubbles and the effect of ozonated water generated by ozone microbubbles on the cleaning of cloth is investigated.

2. EXPERIMENTAL APPARATUS AND METHOD

2.1 Microbubble generator

Our proposed microbubble generating system has advantages such as simplicity, ruggedness and low cost. Figure 1 shows the schematic diagram of the proposed microbubble generator developed in our previous study (Hasegawa, 2007). The microbubbles are generated by the local shear stress in the flow through a pipe with slits. The slit angle $\theta$ is defined as the angle of the slit against the main-flow direction in the pipe, and the same slit angle is set in the slit array. There are ten slits in the microbubble generating device, each of width 0.6 mm. The pipe water flow is discharged solely from the slits into the water tank. This changes the flow direction and produces a shearing force at the corner of the slits. That is, the flow separates at the corners of the slits and a shearing force at the gas-water interface is produced by the Kelvin-Helmholtz instability in the separated shear layer. Furthermore, the flow velocity is increased in the slit section due to the small cross-sectional area.

![Fig.1 Microbubble generating device.](image)

![Fig.2 Bubble size distribution.](image)
thereof. The shearing force is also produced by discharging water into the tank from the slit section with a large velocity gradient between the flow of water through the slits and the stationary surrounding water in the tank. This occurs because the accelerated flow of water through the slits quickly decreases when the water is discharged in the tank. In the present study, two models with different slit angles ($\theta = 30$ and 60 deg) were installed.

Figure 2 shows the bubble size distribution. The bubble size distribution was measured by a light transmission method (Tabei, 2004). The principle method was based on changes in light transmission due to bubbles rising to the water surface. Small bubbles with a diameter of 50$\mu$m were generated for $\theta = 60$ deg. On the other hand, the peak value in the distribution of the bubble diameter was 60$\mu$m for $\theta = 30$ deg. In the $\theta=60$ deg case, a large number of smaller bubbles can be produced in comparison with the $\theta=30$ deg case.

2.2 Measuring system of zeta potential of microbubbles

Figure 3 shows the experimental apparatus used to measure the zeta potential of microbubbles with an enlarged view of the zeta potential measuring cell shown in Fig.4. In the present study, the surface charge of microbubbles was measured by an electrophoresis method. The zeta potential measurements
were carried out by using a water reservoir with the microbubble generator, an electrophoresis cell consisting of two electrodes and a constant voltage power source (200 V), a pump, a camera system and a personal computer. The electrophoresis cell was composed of acrylic. In this measuring system, the direction of the flow of electrons in the measuring cell can be reversed per a constant time interval to clearly interpret the bubble movement in the horizontal direction. Microbubbles in the water tank were introduced to the electrophoresis cell and the movement of the bubbles in the horizontal direction was observed using a high speed camera. Light was scattered using a thin white sheet behind the cell for clear observation of the spherical bubbles in the cell. The horizontal movement of the microbubbles was analyzed under an electric field for the calculation of zeta potential using a graphical data processing method. The zeta potential was calculated from electrophoretic mobility in the horizontal direction using the Smoluchowski equation. (Takahashi, 2005)

3. RESULTS AND DISCUSSION

3.1 Microbubble Zeta potential

Figure 5 shows the zeta potential of microbubbles versus bubble diameter. The zeta potential of...
microbubbles for θ=60 deg is larger than that for θ=30 deg. The microbubbles are negatively charged with an average zeta potential of approximately -38mV and -43mV in purified water (pH=7) for θ=30 and 60 deg, respectively. There was no relationship between the zeta potential of microbubbles and the bubble diameter, and the results suggest that the amount of electricity per unit surface area at the interface is independent of the bubble size. Figure 6 shows the zeta potential of microbubbles versus pH. The value of the pH was adjusted by the addition of HCl and NaOH to tap water. The zeta potential was negatively charged over a wide range of pH conditions and the negative potential decreased with decreasing pH. The changing mechanism has been explained as the adsorption of OH⁻ onto the interface by the difference in hydration energy between H⁺ and OH⁻. The hydrogen atoms point towards the water phase and oxygen atoms towards the gas phase, thereby attracting anions to the interface. The adsorbed of H⁺ and OH⁻ are crucial factors influencing the interface charge, and the electrolyte ions are attracted to the interface of the microbubbles. However, the zeta potential of the microbubbles is positively charged at pH=2, and it is difficult to explain the mechanism of a positively charged gas-water interface by the experimental result. To confirm these phenomena, more detailed information regarding the gas-water interface charge is required.

In order to investigate the relationship between the zeta potential and adsorption of bubble onto the surface of a fiber, the behavior of microbubbles was observed using a high speed camera under different pH conditions. In this experiment, a fiber was centered vertically in the measurement cell and...
the microbubbles were discharged from the bottom of the cell. Bubble adsorption to the fiber is encouraged in the pH=10 case in contrast to the pH=4 case. The zeta potentials at pH=10 and 4 were measured to be approximately -50 mV and -10 mV, respectively (see Fig.6). The number of bubbles absorbed onto the surface of a fiber increased as the zeta potential of the microbubbles increased. That is, a huge amount of bubble adsorption was accomplished at large zeta potentials.

3.2 Ozone water generation using microbubbles

Figure 8 shows the variation in ozone water concentration after ozone microbubble generation. In the present study, measurements of ozone water concentration were performed by the colorimetric assay method. The ozone gas concentration of 80-100 ppm was used to generate ozone microbubbles. The ozone water concentration for $\theta = 60$ deg becomes larger with elapsing time than that for $\theta = 30$ deg. A high concentration of ozone water is achieved for the $\theta=60$ deg case in contrast to the $\theta=30$ deg case because the microbubbles with small size and large zeta potential are produced for $\theta=60$ deg (see Figs.2 and 5). In other words, the result suggests that the ozone water generation is affected by the bubble size distribution and the electrical properties of microbubbles. In order to better understand ozone water generation, the relationship between the electrical potential of microbubbles and ozonation efficiency will be discussed later.

![Fig.8 Ozone water concentration.](image1)

![Fig.9 Ozone water concentration.](image2)
3.3 Soiled cloth cleaning using ozone microbubbles

In order to investigate the effect of the ozonated water generated by our proposed microbubble generator on cleaning power, experiments involving the cleaning of cloth were performed for the cases of $\theta = 30$ and 60 deg. The cloths are artificially soiled by water including coffee powder and sauce. The soil was removed in the $\theta = 30$ deg case after 40 minutes of generator operation. On the other hand, the same soil was removed in only 30 minutes in $\theta = 60$ deg case. Furthermore, the laundered cloth in the $\theta = 60$ deg case was cleaner than that for $\theta = 30$ deg. In order to verify the effect of ozone water concentration from two generators on cleaning cloth, the same concentrations of ozone water were created by adjusting the ozone gas flow rate $Q_g$. Figure 9 shows the ozone water concentration for two

![Image of cleaning cloths](image)

(a) $\theta = 30$ deg

(b) $\theta = 60$ deg

Fig.10 Cleaning soiled cloths with coffee powder using ozone microbubbles. (a) Before washing; (b) 10 minutes washing; (c) 20 minutes washing; (d) 30 minutes washing; (e) 40
generators in the case where the ozone gas flow rate was adjusted. Ozone water concentrations for θ = 30 and 60 deg show the same tendency. Figures 10 and 11 show the photographs of the soiled cloth during 40 minutes of the washing using ozone microbubbles under the same ozone water concentration., and Figs. 10 and 11 indicate the cases for soiled cloths with coffee powder and with sauce, respectively. Ozone microbubbles make soiled cloths clean effective for θ = 60 and 30 deg in both cases. In particular, the soiled cloth can be cleaned easily for the θ=60 deg case. That is, the θ=60 deg case shows superior performance in contrast to the θ=30 deg case for the washing using ozone microbubbles. The result suggests that washing using ozone microbubbles is affected by the electrical potential of microbubbles.

A bubble diameter of less than approximately 40 µm increases the zeta potential in the bubble shrinking process (Tokushige, 2008). It is presumable that a large number of small bubbles (less than 40 µm) exist in the bubble shrinking process for θ=60 deg because small bubble generation is achieved and the zeta potential becomes larger in contrast to the θ=30 deg case. Therefore, ozone microbubbles are easily absorbed onto the surface of the cloth for θ=60 deg, and the soil can be effectively removed from the cloth in comparison with the θ=30 deg case.

4. CONCLUSIONS

In the present study, the relationship between the electrical properties of microbubbles and the effect of ozonated water generated by ozone microbubbles on cleaning cloth was investigated. The findings of the present study are summarized as follows:

(1) In the proposed microbubble generator, the θ=60 deg slit angle exhibited superior performance due to its bubble size and electrical properties. That is, the microbubbles with small diameters and large electrical potentials are generated for θ=60 deg in comparison with the θ=30 deg case.
(2) The ozone water concentration with elapsing time for θ = 60 deg becomes larger than that for θ=30 deg.
(3) When a cloth is washed using the proposed microbubble generator with the $\theta=60$ deg slit, the soiled cloth can be cleaned easily in comparison with the $\theta=30$ deg case. That is, the $\theta=60$ deg case shows superior performance in contrast to the $\theta=30$ deg case for washing using ozone microbubbles.

(4) The zeta potential of microbubbles for $\theta=60$ deg is larger than that for $\theta=30$ deg. In cleaning cloth, the elapsed time during washing is improved by the microbubbles with large zeta potential, because the bubble adsorption onto the surface of a cloth is promoted due to the large electrical potential.

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