# Water Purification Using the Adsorption Characteristics of Microbubbles 

Akira Yoshida, Osamu Takahashi, Yorishige Ishif, Yoshihiro Sekimoto, and Yukio Kurata<br>Precision Technology Development Center, SHARP Corporation, 2613-1 Ichinomoto-cho, Tenri, Nara 632-8567, Japan

(Received December 4, 2007; accepted April 9, 2008; published online August 8, 2008)
Recently, technology using microbubbles has been studied for water purification. However, the mechanism and physical parameters of the purification process have not yet been sufficiently clarified. The purpose of this study is to clarify the physical parameters of microbubbles that influence water purification. Firstly, we measured and analyzed the purifying performance using various millimeter-sized bubbles, and we obtained the equilibrium constant of the pollutant adsorbed on the bubble surface from the experimental results. Secondly, we experimented with purifying the polluted water using microbubbles and clarified that the purification performance of microbubbles agreed with that theoretically expected using the equilibrium constant obtained in the preparatory experiment. We assume that an important parameter affecting adsorption on the surface of microbubbles is the equilibrium constant in the chemical potential. Because the equilibrium constant is derived from the surface chemical potential, it is equal to the bulk chemical potential of the liquid. In the microbubbles diameter $(70 \mu \mathrm{~m})$ range in this study, we have found that the most significant factor determining the adsorption is the surface area. The surface tension of microbubbles is not significant factor. [DOI: 10.1143/JJAP.47.6574]
KEYWORDS: microbubbles, purification, adsorption coefficient, oleic acid, chemical potential

## 1. Introduction

There are various ways of purifying polluted water such as using microorganisms and supplying heat and so on, in the way. However, these methods do not have high efficiency or a stable performance.

On the other hand, the technology of microbubbles has been developed and purification systems using microbubbles have been studied in recent years. ${ }^{1,2)}$ However these studies were only on the performance of systems, and studies on the adsorption of microbubbles have not been carried out.

The adsorption on the boundary layer of a bubble between air and water has been clarified in terms of the chemical potential and chemical equilibrium theory. As a result, the main parameter that influences adsorption on the boundary layer has been clarified. In this paper we predicted the purification time of an adsorption system by using the equilibrium constant of the adsorption.

## 2. Characteristics of Microbubbles

Microbubbles have the characteristic that the surface area per unit volume increases with decreasing diameter. This relation is expressed by eqs. (1)-(3).

In eq. (1), the air bubble radius is $r$ and the surface area is $S$.

$$
\begin{equation*}
S=4 \pi r^{2} \tag{1}
\end{equation*}
$$

In eq. (2), the volume of the air bubble is $V$.

$$
\begin{equation*}
V=\frac{4}{3} \pi r^{3} \tag{2}
\end{equation*}
$$

The surface area per unit volume of a bubble is $S / V$. Thus,

$$
\begin{equation*}
\frac{S}{V}=\frac{3}{r} \tag{3}
\end{equation*}
$$

Decreasing the air bubble radius $r$ causes an increase the in surface area per unit volume of a bubble $S / V$, because $S / V$ is inversely proportional to the air bubble radius $r$, as expressed by eq. (3).
There are various types of microbubbles generators, for example, a swirl-flow-type, and a pressurization-type. In this


Fig. 1. (Color online) Photograph of the venturi-type microbubble generator.
study, microbubbles were generated by a venturi-type bubble generator. The venturi-type generator is compact, and operates with a low pump power, and generates highdensity microbubbles, whose mean diameter is under $100 \mu \mathrm{~m}$.

The features of the venturi-type microbubbles generator are shown in Fig. 1. The generator is composed of an inflow, a tubule part, and a tapered outflow. The pressurized fluid flows into the tubule part from the inflow. The static pressure in this tubule part is decreased, because the velocity in the tubule part is increased. Cavitation occurs because of the decreasing static pressure in the tubule part under saturated vapor pressure. The tubule part has a hole for the introduction of gas from outside.

The multiphase-flow of the gas and liquid is enabled by the cavitation or the introduced gas. The multiphase-flow is compressible and the speed of sound of this fluid decreases by 2 orders of magnitude. Therefore, the flow is accelerated at the tapered outflow, similar to in a Laval nozzle. When the fluid exceeds the speed of sound, a pressure wall with a shock wave occurs in the tapered outflow. The microbubbles are generated by the gas colliding with the pressure wall.


Fig. 2. (Color online) Schematic of the laboratory equipment.


Fig. 3. (Color online) Photographs of the experiment: (a) initial appearance and (b) after 40 min .

## 3. Laboratory Equipment and Experimental Method

Bubbles were generated by introducing a constant air flow of $1.0 \mathrm{~L} / \mathrm{min}$ into a porous material placed up in a water tank. A diagram of the equipment is shown in Fig. 2. The purification characteristic was compared using two sizes of air bubbles ( 1.5 and $1.0 \mathrm{~mm} \phi$ ). The change of the air bubble diameter was carried out by exchanging the porous material. The polluted water was made by mixing water and oleic acid. The initial pollutant concentration was $0.002 \mathrm{wt} \%$. and the quantity of water was 15 L .

The photographs of the experiment are shown in Fig. 3. The left photograph shows the initial appearance and the right photograph shows the appearance after 40 min .
In each photograph, the water in the left tank was purified using air bubbles of $1.0 \mathrm{~mm} \phi$ and the water in the right tank was purified using the air bubbles of $1.5 \mathrm{~mm} \phi$.

The photograph after 40 min shows that the water in the tank was purified. The purity of the water was measured by the variation of the power of a laser as it passed through the water, as shown in Fig. 2.

The purity $C$ is expressed as


Fig. 4. (Color online) Experimental results.

Table I. Number of generated bubbles.

|  | Diameter of bubble (mm) |  |
| :---: | :---: | :---: |
|  | 1.5 | 1.0 |
| Number of bubbles | $1.0 \times 10^{6}$ | $3.4 \times 10^{6}$ |

$$
\begin{equation*}
C=\frac{I(t)-I(0)}{I(n)-I(0)} \tag{4}
\end{equation*}
$$

where $I(0)$ is the initial laser power at the initial condition, $I(n)$ is the laser power under the nonpolluted condition, and $I(t)$ is the laser power at after time $t$.

## 4. Experimental Results

The experimental results are shown in Fig. 4.
In Fig. 4, the vertical axis shows the concentration of oleic acid, the horizontal axis shows the elapsed time, and the parameter is the air bubble diameter.

Table I shows the calculated number of air bubbles generated in 1 min . The number of air bubbles increases as the air bubble diameter decreases, as shown in the Table I.

Figure 4 shows that the number of air bubbles or the air bubble diameter is an important parameter in the purification. A high purification performance is obtained when the air bubble diameter is small and the number of air bubbles is large. The mechanism of the purification is as follows.

1) A pollutant is adsorbed at the boundary between the gas and liquid.
2) The bubbles rise because of the specific gravity difference between the liquid and gas.
3) The pollutant in the water becomes concentrated at the surface of the water.
The adsorption occurs at the boundary between the gas and liquid. The surface tension affects the rate of adsorption, and the chemical potential is an important parameter determining the adsorption. The relationship between the chemical potential and the surface tension is described in the next section.

## 5. Theoretical Results

The adsorption at the boundary between the gas and liquid can be described by chemical equilibrium theory. Surface tension is generated at the boundary between a gas and liquid and a solute concentration gradient is generated in the boundary layer. The contaminant adheres to the boundarylayer between the gas and liquid because of the surface


Fig. 5. (Color online) Relation between the solute concentration of bulk water and the solute concentration on an air bubble surface.
tension and concentration gradient. These phenomena are based on chemical equilibrium theory and are described by the following equation. ${ }^{3)}$ The solute concentration on the air bubble surface $x_{\mathrm{s}}$ is expressed as

$$
\begin{equation*}
\frac{x_{\mathrm{s}}}{1-x_{\mathrm{s}}}=\frac{K \times x_{\mathrm{b}}}{1-x_{\mathrm{b}}} \tag{5}
\end{equation*}
$$

where $x_{\mathrm{b}}$ is the solute concentration of bulk water, and $K$ is the equilibrium constant of the pollutant adsorbed on the bubble surface, expressed as

$$
\begin{equation*}
K=\exp \left[\frac{\left(\sigma_{1}-\sigma_{2}\right) \times \omega}{R \times T}\right] \tag{6}
\end{equation*}
$$

where $\omega$ is the surface area of the air bubble, $\sigma_{1}$ is the surface tension of the solvent, $\sigma_{2}$ is the solute surface tension, $R$ is the gas constant, and $T$ is the absolute temperature of the solvent. When $x_{\mathrm{s}}$ and $x_{\mathrm{b}}$ are less than 1 , eq. (5) can be rewritten

$$
\begin{equation*}
x_{\mathrm{s}}=K \times x_{\mathrm{b}}, \tag{7}
\end{equation*}
$$

i.e., $x_{\mathrm{s}}$ is proportional to $x_{\mathrm{b}}$.

The equilibrium constant $K$ shows that the adsorbed quantity is related to the surface tension difference between the solvent and the solute.
The adsorbed quantity decreases, increasing the absolute temperature of the solvent. From eq. (7), the quantity adsorbed by one bubble is proportional to the concentration of solvent. If $K$ is given, the quantity of pollutant adsorbed on the bubble surface can be calculated using eq. (7).

Figure 5 shows the relation between the quantity adsorbed on one bubble and the solvent concentration, using the number of air bubbles given in Table I. The vertical axis of Fig. 5 is the concentration of pollutant on the air bubble surface and the horizontal axis is the solvent concentration of the bulk water. The relationship between these quantities is proportional. The data surrounded by the dotted circles show the adsorption limit. The rhombuses show the results for bubbles of $1.5 \mathrm{~mm} \phi$ and the squares show those for bubbles of $1.0 \mathrm{~mm} \phi$. We ignore the data surrounded by the dotted areas and we obtain the relationship.

$$
\begin{equation*}
y=3.1 \times 10^{-7} \times x_{\mathrm{b}} \tag{8}
\end{equation*}
$$

## 6. Comparison of Experimental Results with Calculated Results

We calculated the change in the concentration over 20 min


Fig. 6. (Color online) Comparison of experimental data with calculated data.


Fig. 7. (Color online) Photograph of the microbubbles used by the evaluation equipment.


Diameter of the micro-bubble ( $\mu \mathrm{m}$ )
Fig. 8. Diameters of microbubbles mesured using the evaluation equipment.
for each bubble diameter using eq. (8), as shown in Fig. 6. The data obtained by purification by microbubbles are compared with the data for 1.0 and $1.5 \mathrm{~mm} \phi$ bubbles.

Experimental data are also compared with calculated data in Fig. 6. Each mark is an experimental data point and each line is calculated from eq. (8). The vertical axis is the concentration of pollutant in the water and the horizontal axis is the elapsed time.

In this experiment, the microbubbles were generated by the venturi-type and the air flow rate was $0.15 \mathrm{~L} / \mathrm{min}$. The quantity and size of microbubbles were estimated using the VisiSizer system from Oxford Lasers. This system recognizes air bubble passing through the test section from images from which counts the number of air bubbles per unit time and measures their size. A typical image is shown in Fig. 7. The spheres in the photograph are air bubbles.

Figure 8 shows the diameters of microbubbles measured using the VisiSizer system. The vertical axis is the concentration of microbubbles and the horizontal axis is the diameter. The diameters are mainly between 70 and $100 \mu \mathrm{~m}$ when the air flow rate is $0.15 \mathrm{~L} / \mathrm{min}$. The total
numbers of microbubbles is estimated to be $1.5 \times 10^{9}$ and the average diameter of a microbubble is $70 \mu \mathrm{~m}$.
Figure 6 shows that the calculated results are in agreement with the experimental data. This shows that the eq. (8) is valid for estimating the purify of water.
Therefore, the polluted water is purified by the adsorption of the pollutant on the surface of the bubbles, and the change in concentration of the oleic acid can be predicted using eq. (8).

## 7. Conclusions

We summarize our results as follows.
(1) The adsorption of the bubbles is determined by the chemical potential and equilibrium constant of the
pollutant.
(2) The rate of purification can be calculated using the equilibrium constant.
(3) The most significant factor determining the adsorption is the surface area.
(4) The surface tension of microbubbles is not a significant factor in this study.

1) Y. Goto, A. Serizawa, T. Yahiro, H. Tanaka, and M. Itsumi: Abstr. Annu. Gen. Meet. Japanese Society for Multiphase Flow, Okayama, 2004, p. 35 [in Japanese].
2) K. Terasaka and Y. Shinpo: Nihon Konsoryu Gakkaishi 21 (2007) 77 [in Japanese].
3) H. Kimizuka: Kagaku Potensharu (Chemical Potential) (Kyoritsu, Tokyo, 1984) p. 88 [in Japanese].
