Enhancement of microbubble generation in a pressurized dissolution process by packing the nozzle with porous ceramics

Hiroshi Yamashita, Hideki Aoyagi and Hisato Minagawa

ABSTRACT

The pressurized dissolution method is often used for microbubble generation. However, the main disadvantage of this method is that a large amount of energy (more than 0.3 MPa) is required to generate many microbubbles, each of which have a diameter of several dozen μm. To overcome this problem, we investigated the effectiveness of porous ceramic when used as the packing material in the pressurized dissolution method. The results showed that when compared with the control (no porous ceramics), use of porous ceramics resulted in a 39% increase in the number of microbubbles. Furthermore, when this system was used for the flotation separation of artificial suspended solids and activated sludge, the level of separation achieved with porous ceramics at 0.15 MPa was the same as that achieved using no porous ceramics at 0.25 MPa. It was estimated that the use of porous ceramics led to a 40% reduction in the energy required for the dissolved air flotation, with subsequent decreases in the operating cost.

Key words | dissolved air flotation, microbubble, porous ceramics

NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>suspended solid concentration (mg/L)</td>
</tr>
<tr>
<td>C₀</td>
<td>initial suspended solid concentration (mg/L)</td>
</tr>
<tr>
<td>C'</td>
<td>dimensionless suspended solid concentration (−)</td>
</tr>
<tr>
<td>k</td>
<td>the suspended solid separation coefficient (min⁻¹)</td>
</tr>
</tbody>
</table>

INTRODUCTION

Microbubbles are bubbles with diameters ranging from a few μm to a few hundred μm. They are applied in various fields such as oyster farming (Ohnari et al. 2002), cleaning of electronic parts (Miyamoto 2009), waste water treatment (Sumikura et al. 2007), soil purification (Goto et al. 2006) and as contrast agents for ultrasonic image diagnosis (Matsumura & Sugihara 2007).

Methods used for microbubble generation include the shearing (Li & Tsuge 2006), pressurized dissolution (Yamada et al. 2007), membrane permeation (Kukizaki 2006), ultrasonic (Sung-Ho et al. 2005) and electrolysis (Tsuge et al. 2008). Of these methods, the pressurized dissolution has an advantage of producing large amounts of small microbubbles and it is widely used in the dissolved air flotation (DAF) during wastewater treatment (Mooyoung et al. 2007).

The DAF is a separation process by which sludge, oil and other solid particles present in wastewater are attached to microbubbles, carried to the surface and are then separated from the wastewater. By comparing with the conventional gravitational sedimentation method that is used for solid–liquid separation, the DAF can be used for the efficient and rapid separation of non-residual solid particles in wastewater. However, the generation of stable microbubbles requires high pressure (usually higher than 0.3 MPa). The DAF is energy intensive, resulting in high operating costs (Feris et al. 2001).

To solve this problem, Feris et al. (2001) recommended the addition of surfactants. Although the addition of surfactants reduces the energy requirement for microbubble generation, there is an additional cost for the surfactants and the need to separate the surfactants after treatment. There is therefore a need to develop an efficient microbubble generation method that does not require the addition of surfactants at low pressures.
It has been reported that microbubble generation using pressurized dissolution methods occurs in two stages: the generation of bubble nucleation and bubble growth (Xavier et al. 2007). Furthermore, it is known that the generation of bubble nucleation is more effective on solid surfaces (especially on porous surfaces) than on liquids (Li & Yortsos 1993). However, there have been no reports regarding the incorporation of porous materials in the pressurized dissolution method to enhance microbubble generation.

This study was therefore aimed at enhancing microbubble generation at low pressures using porous ceramics. A special type of microbubble generation nozzle was constructed and porous ceramics were packed in its outer tube. We compared the efficiency of microbubble generation and the characteristics of the bubbles both with and without porous ceramics. Furthermore, the microbubbles generated in this study were subsequently used for flotation separation experiments, and the effectiveness of porous ceramics in reducing the required pressure and the overall operating costs of the DAF were evaluated.

MATERIALS AND METHODS

Characteristic of the porous ceramics

The porous ceramics used in this study were produced by Clay-burn Technology Research Corporation (Tochigi, Japan). This foam ceramic was made from slag, bentonites and other plastic clay by-products by the ductile cast iron production process. The chemical composition of the cast iron slag is as follows: SiO₂, 38%; Al₂O₃, 13%; CaO, 43%; MgO, 2%; K₂O + Na₂O, 1.8%; MnS, 1.8% and FeS, 0.4%. The slag surface was coated with bentonite and heated at 900–1100 °C. During heating, SO₂ is released from MnS and FeS, leading to the formation of porous ceramics. An efficient method of recycling large amounts of ductile cast iron slag (up to 30% of the product) is the production of porous ceramics and other products using it, which in turn reduces environmental pollution and production costs.

Various packing materials such as porous ceramics, granulated active carbon with a high specific surface area and grain diameter of 3.35–4.75 mm (01084-12; Kanto Chemical Co., Inc., Tokyo, Japan) and glass balls with smooth surfaces were used. The generation of microbubbles and their characteristics were then compared. The characteristics of these packing materials are shown in Table 1.

Experimental apparatus

A schematic diagram of the microbubble generation equipment is shown in Figure 1. It comprises of an air separator equipped with a cylindrical water tank (diameter = 150 mm, liquid height = 600 mm), a pump (KED 15; Nikuni Co., Ltd, Kanagawa, Japan), an air vent valve (AF-6N; Venn Co., Ltd, Tokyo, Japan) and a microbubble generation nozzle. The suction pump is equipped with a check valve at the air inlet for pumping air into the apparatus. The air flow rate is measured using a gas flow metre and is regulated using a flow regulating valve.

The microbubble generation nozzle was developed in this study. It comprises of an inner and outer tube. On the wall of the inner tube, there are three evenly-spaced holes of equal diameter. To maintain the same liquid flow rate under varying pressure conditions, the diameters of the holes were maintained between 1.7 and 2.2 mm and a section of the outer tube was expanded at an angle of about 30°.

Liquid is pumped through the holes of the microbubble generation nozzle into the walls of the outer tube at a flow rate of 13–16 m/s. Pressure is then applied and most of the bubble nucleation takes place between the exit of the nozzle and the expanded section of the tube, after which microbubbles form inside the outer tube and are released from the exit of the tube. In this study, we investigated the effects of the packing materials, such as porous ceramics, inside the expanded section of the outer tube on the quantity and efficiency of the microbubbles that were generated.

Microbubble generation and measurement

The liquid flow rate for microbubble generation was 8 L/min, while the pressure was set at 0.15, 0.20 or 0.25 MPa. We also investigated the effects of using four different packing volumes of the porous ceramics (0, 50, 100 and 200 mL) on microbubble generation.

Table 1 | Characteristics of porous ceramic and filler

<table>
<thead>
<tr>
<th>Filler</th>
<th>Shape</th>
<th>Particle diameter (mm)</th>
<th>Pore diameter (μm)</th>
<th>Specific surface area (m²/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Porous ceramic</td>
<td>Granular</td>
<td>8</td>
<td>0.26</td>
<td>3.24</td>
</tr>
<tr>
<td>Activated charcoal</td>
<td>Granular</td>
<td>4</td>
<td>2.15 ×10⁻³</td>
<td>1,100</td>
</tr>
<tr>
<td>Glass ball</td>
<td>Spherical</td>
<td>8</td>
<td>–</td>
<td>0.03</td>
</tr>
</tbody>
</table>
We applied the electrical sensing method using a particle analyzer (Multisizer 4; Beckman Coulter Inc., California, USA) to measure the bubble size distribution and the quantity of bubbles per unit volume.

Flotation separation using microbubbles

Fine, inorganic particles have been used as artificial suspended solids in flotation separation experiments (Terasaka & Shinpo 2007) and surfactants are added in order to facilitate the adsorption of inorganic particles to microbubbles. However, as surfactants affect the generation of microbubbles, fine, inorganic particles are not suitable for use in this study.

In this study, we therefore used cellulose powder with a particle size of 50 μm (KC floc W-50S; Nippon Paper Chemicals Co., Ltd, Tokyo, Japan) as an artificial suspended solid. The cellulose powder (600 mg/L) was added to tap water, and after mixing, flocculation was induced by the addition of 0.5 mg/L of amphoteric polymer coagulant (Diaflo KA3329; Dia-Nitrix Co., Ltd, Tokyo, Japan). Furthermore, in order to evaluate the practicality of the system, the activated sludge (MLSS 2,000 mg/L) of aerobic tank of domestic wastewater treatment plant was also used as suspended solid.

RESULTS AND DISCUSSION

Effects of porous ceramics on microbubble generation

For the cases having: (i) no packing material (control), (ii) porous ceramics (Ce), (iii) granulated active carbon (Ac), and (iv) a glass ball, the number of microbubbles and the average size of the bubbles per millilitre are also shown in Table 2.

It is observed that the packing material had no significant impact on the size distribution of the bubbles. In both the cases, i.e. with and without the packing material, the bubble size ranged from 30 to 35 μm, which is consistent with a previous report that determined that the average
size of bubbles for the pressurized dissolution method ranges from 30 to 60 μm (Sumikura et al. 2007).

However, the number of microbubbles generated per millilitre of water was higher with packing materials (each material tested) than that generated without any packing material (control). This situation is because the addition of packing materials leads to an increase in the surface area of the solids, which serves as the generation site for bubble nucleation. In particular, when porous ceramics were used as the packing material, the number of microbubbles increased to about 56,000/mL, which is approximately 39% greater than the number of 40,000/mL obtained in the control. In previous reports (Li & Yortsos 1995), increasing the pressure resulted in an increased number of microbubbles in the pressurized dissolution method. In this study, however, we have successfully increased the number of microbubbles without increasing the pressure.

It is also interesting to note that the number of microbubbles generated using porous ceramics is higher than that obtained using granulated activated carbon, which has a much higher surface area. This finding shows that bubble nucleation does not depend only on the surface area but also on other factors such as the nature of the surface and the pore diameter, both of which affect the flow characteristics within the vicinity of the solid surface. The pore size distribution for the porous ceramics used in this study is very wide (10 nm–200 μm with an average of 0.25 μm). These types of surface characteristics increase the solid surface area which serves as a site for bubble nucleation and also affect the flow characteristics on the surface, thereby increasing bubble nucleation and thus microbubble generation.

**Effect of pressure**

Using different packing materials, the effects of pressure on the quantity and average size of the bubbles are shown in Figure 2.

The type of packing material did not significantly affect the average diameter of the microbubbles, but for each packing material, the diameter of the bubble decreased as pressure increased. This result is consistent with the results obtained in previous studies (Mooyoung et al. 2007).

On the other hand, the number of microbubbles increased as the pressure increased. According to Henry’s law, an increase in pressure results in an increase in the amount of gas that dissolves in the liquid before it is ejected from the generation nozzle. This situation will then lead to an increase in bubble nucleation and a subsequent increase in the number of microbubbles.

Furthermore, it is important to note that when porous ceramics were used as the packing material at a low pressure, the number of microbubbles was also high. For example, at a relatively low pressure of 0.15 MPa, the number of microbubbles generated was 50,000/mL when porous ceramics were used, which is almost the same as the number generated at 0.25 MPa in the control. These results have demonstrated that at low pressures, porous ceramics can be used to increase microbubble generation.

**Effect of packing volume on microbubble generation**

Figure 3 show the effects of the volume of the porous ceramic packing on the bubble diameter and the number of bubbles.

Figure 3 shows that the bubble diameter was not affected by the porous ceramics packing volume. However,
the number of microbubbles increased as the volume of the porous ceramic packing increased, because increasing the porous ceramic packing volume results in an increase in the surface area of the solid, which serves as the bubble nucleation site. Increasing the porous ceramics packing volume above 100 mL did not result in further increase in the number of microbubbles. With the pressurized dissolution method, the maximum number of microbubbles is determined by the pressure and liquid flow rate. It is apparent that 100 mL of porous ceramics is sufficient to achieve the maximum number of microbubbles under the present conditions of pressure and flow rate. It can therefore be concluded that under the present experimental conditions, the optimum volume of porous ceramics that will result in increased microbubble generation is 100 mL, which corresponds to a space velocity of about 1.3 s⁻¹ in the porous ceramic column.

In Figure 4, we compare the flotation separation of suspended solids both with and without porous ceramics using artificial suspended solid (a) and activated sludge (b). The Y-axis is the dimensionless value of the suspended solid concentration which is obtained by dividing each suspended solid concentration by the initial suspended solid concentration. For the porous ceramics, the efficiencies of the suspended solid separation were much higher than those obtained in the control experiment under all the pressures tested and each suspended solid. In previous reports (Feris et al. 2001), effective flotation separation was achieved by adding surfactant or by increasing the pressure. It is important to note that the results of this study have demonstrated that by using porous ceramics, we can achieve the efficient separation of suspended solids without the need of adding surfactants, even under low pressures.

To explain the effectiveness of using porous ceramics for efficient separation of suspended solids, the results shown in Figure 4 were represented by a first order reaction (Equation (1)) and the suspended solid separation coefficient was calculated:

\[ C = C_0 \times e^{-kt} \]  

where \( k \) is the suspended solid separation coefficient (min⁻¹) and \( t \) is the time (min).

The relationship between the number of microbubbles and the suspended solid separation coefficient is shown in Figure 5. There is a good correlation between the number
of microbubbles and the suspended solid separation coefficient. This result implies that using porous ceramics as the packing material resulted in improved suspended solid separation by increasing the number of microbubbles.

Table 3 shows the effectiveness of porous ceramics in the reduction of the energy requirement for the separation of suspended solids. As the efficiency of the separation process obtained using porous ceramics at 0.15 MPa was almost the same as that obtained without porous ceramic at 0.25 MPa, the energy requirements for operating at 0.15 and 0.25 MPa could then be compared. Table 3 has demonstrated that the energy consumption for suspended solid separation can be reduced by 40% using packing porous ceramics. If this process is used in a wastewater treatment plant that has a capacity of 10 m³/day, it is estimated that the operating cost can be reduced by 70,000 yen per annum.

In this study, the effectiveness of porous ceramics was only evaluated in laboratory scale. So, we need further investigation in pilot scale in future. Ahn et al. (1998) reported that the fouling occurred on the surface of ceramics in wastewater treatment. So, if the fouling occurred on the surface of the porous ceramics, the method for cleaning the porous ceramics to restore integrity is very important.

CONCLUSIONS

The results of this study on the use of porous ceramics for microbubble generation using the pressurized dissolution method are summarized as follows:

1. The number of microbubbles generated by packing porous ceramics was 39% higher than the value obtained without using the porous ceramics.
2. Under the present experimental conditions, the optimum packing volume of porous ceramic is equivalent to a space velocity of 1.3 s⁻¹ in the packing site.
3. For the artificial suspended solids and activated sludge used in this study, There is good correlation between the suspended solid separation coefficient and the number of microbubbles.
4. The required energy consumption for separating suspended solids was reduced by 40% by using packing porous ceramics, demonstrating that porous ceramics can be used for effective reduction of energy consumption.

ACKNOWLEDGEMENTS

We wish to thank Mr. Yutaka Ikami and Mr. Hideo Ikami of Clay-burn Technology Research Corporation for supplying us with the porous ceramics and Mr. Takahiro Hishida of Toyota Technical Development Corp. for the technical assistance provided.

REFERENCES


Miyamoto, M. 2009 Chemicals-free technology by microbubble. Industrial Cleaning of Japan 4, 4–8.

First received 28 April 2011; accepted in revised form 25 August 2011