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Effects of bubble size on air-scoured backwashing efficiency in a biofilter

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ABSTRACT

The effect of bubble size on air-scoured backwashing efficiency in a biofilter was investigated using experiments and simple mathematical models based on collapse-pulsing theory. Four types of backwashing experiments were conducted: water alone, water and large bubbles (diameter = about 1 cm), water and small bubbles (diameter = about 0.2 cm), and water containing dissolved air. The third type, water and small bubbles, was found to be the most efficient. Modeling results confirmed the experimental results, indicating that even when the same volume of air was used, smaller bubbles generate higher shear stress on the surface of the medium, resulting in more efficient removal of biomass. In the case of dissolved air, however, micro-bubbles (diameter = 10–100 μm) are too small and rise too slowly to produce a strong-enough collapse-pulsing effect. This produces less shear stress and ultimately results in poor backwashing efficiency.

Keywords: Backwashing; Air-scoured; Biofilter; Biomass; Bubble size

1. Introduction

Biofiltration technology is an environmentally friendly and cost-effective method for the treatment of volatile organic compound emissions, compared with other technologies such as incineration, activated carbon adsorption, and chemical washing in packed columns. Recently, biological trickling filters (BTFs) have been used to remove substances such as BTEX (benzene, toluene, ethylbenzene, xylene), MEK (methyl ethyl ketone), MIBK (methyl iso-butyl ketone), and chlorinated hydrocarbons from waste gas streams [1].

In spite of its cost advantages, BTF has the considerable drawback of decreased removal efficiency due to the accumulation of excess biomass [2,3]. For a stable, long-term operation of highly loaded BTFs to occur, plugging by excessive biomass accumulation must be prevented [3]. Biomass may clog the filter bed packing material, which can then produce large pressure drops and form air channels. Attempts to unclog the filter by increasing backpressure on the blower equipment only make the system inefficient and raise electrical demand. Air channeling also worsens the performance of the biofilter [1].

There have been some previous studies on excess biomass control. Holubar and his colleagues suggested

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limiting nitrogen and potassium in a BTF and removing a mixture of hydrocarbons [4]. Weber and Hartman investigated nitrogen limitation, as well as increasing NaCl in a BTF treating toluene vapor. Although both methods controlled excessive biomass, they produced removal efficiencies below 50% [5]. Smith et al. [3] reported that periodical backwashing is very effective in the removal of excessive biomass. Using water only, however, results in a large amount of wastewater, which then must be treated. This suggests that while maintaining effective removal of excessive biomass in a short amount of time is important, it is also necessary to minimize the volume of wastewater generated. Other research also confirms that backwashing with water alone is relatively ineffective in separating biomass from the medium surface and fluidizing the overall medium. These studies suggest that backwashing efficiency is improved by the simultaneous use of an air scour with a subfluidization water wash [6,7].

Most studies on backwashing focus mainly on water treatment facilities using sand or anthracite as the medium [8–12]. There have only been a few studies on the use of a backwashing mechanism for biofilters [1]. In this study, the state-of-the-art collapse-pulsing theory, developed by Amirtharajah in 1984, and the equation below relating air-to-water ratio with efficiency are applied to biofilter backwashing processes.

$$aQ_a + \left(\frac{V}{V_{mf}}\right) \times 100 = b \quad (1)$$

where V—backwashing velocity (m/min); V_{mf}—minimum fluidization velocity (m/min); Q_a—backwashing air flow rate (m/min); a, b—medium characteristics constants.

Eq. (1) has been applied to filter backwashing in water treatment plants, using backwashing velocity and air flow rate as variables. If backwashing velocity and airflow rate are identical for the same medium, the equation states that the backwashing efficiency is identical. However, some chemical engineers revealed that when in liquid, the behavior of bubbles and turbulence patterns are dependent on surface tension, Reynolds number, and bubble size [13]. Thus, a representation of the behavior of bubbles in the medium using only backwashing velocity and airflow may not be accurate. That is, even in the same quantity, bubbles of different sizes produce different turbulence patterns by collapse pulsing, and this would affect the shear velocity field around the medium.

The purpose of this study was to examine the effect of bubble size on backwashing efficiency. Then, using hydrodynamic concepts, a simple mathematical model was developed to supplement Eq. (1). The three-phase behavioral characteristics of bubbles, water, and medium were modeled by simulating the shear velocity field produced by bubbles and water around the medium surface.

2. Experimental methods

2.1. Media

Porous ceramic medium was fabricated from powdered blast furnace slag, fly ash, and gypsum. The specific gravity of the medium was 0.35–0.45, the water adsorption capacity was 1.5 by weight, and the pH was 8–9. Medium characteristics are presented in Table 1 and Fig. 1 shows images of the medium.

Table 1 and Fig. 1(a) demonstrate that large pores (0.3–2 mm) are evenly distributed, and Fig. 1(b) and (c), which is a magnified view of the ceramic surface, shows that small pores (0.01–6 μm) are also uniformly distributed. This pored structure is very effective for microbial retention [10,11]. Also, the large specific surface area (50 m^2/g) helps maintain a large biofilm mass on the surface. These characteristics prevent excessive loss of biofilm due to high shear velocity during the backwashing process.

2.2. Biofilm formation

Recycled activated sludge from a wastewater treatment plant was used as the seed micro-organism after 10 h of gravity settling. MLVSS of the condensed sludge was 11,000 mg/L and the mass of sludge attached to the medium was 0.0837 g MLVSS/g dry packing material. For biofilm growth on the medium, the nutrient solution was supplied at 4.5–5 L/d for 22 d. Toluene gas was used as carbon source at 300–320 mg/L (v/v) every day. Table 2 shows the composition of the nutrient solution supplied.

Table 1
Characteristics of the porous ceramic medium used in this study

Pore classification	Pore size	%
Interparticle pore	0.01–0.8 μm	4–8
Intercluster pore	0.1–6 μm	12–20
Macro-pore	0.3–2 mm	50–60
Specific surface area	50 m^2/g	

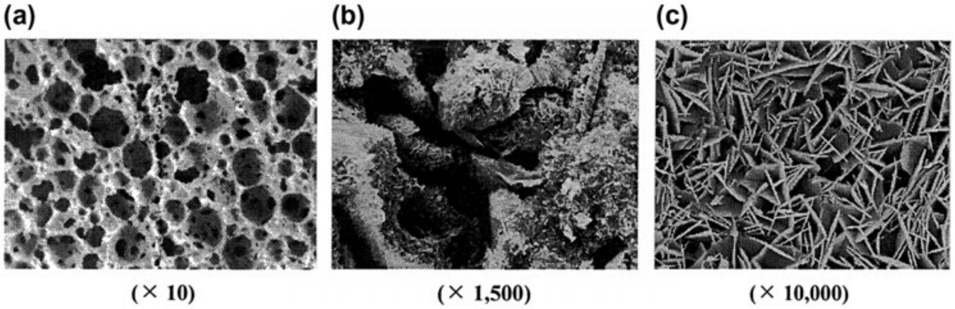

Fig. 1. SEM images of porous ceramic medium used in this study.

Table 2
Composition of nutrient solution supplied for biofilm growth

Solution components	Concentration (mg/L)
K_2HPO_4	3,000
KH_2PO_4	700
KNO_3	600
$MgSO_4 \cdot 7H_2O$	80
$CaCl_2 \cdot 2H_2O$	3
Tracer metal ($FeSO_4$)	0.6

2.3. *Set-up of backwashing experiment*

Fig. 2 shows the experimental set-up for biofilter backwashing. The set-up consists of four identical columns, each with an inner diameter of 5 cm and a height of 50 cm. A nozzle 5 mm in diameter was placed at the bottom of each column to let backwash water in and a flow meter was installed to keep the flow rate constant.

Column I was backwashed with water alone, column II with water and air bubbles with a 1 cm average diameter, column III with water and air bubbles with a 0.2 cm average diameter, and column IV with water containing dissolved air. For convenience, the bubbles used for columns II and III are referred to as 1.0 cm and 0.2 cm bubbles, respectively. A nozzle 1 mm in diameter was set at the bottom of the second column to produce 1 cm air bubbles and an air diffuser was set at the bottom of the third column to produce the 0.2 cm bubbles. Column I also had an air diffuser set at the bottom. To estimate the diameter of the bubbles in columns II and III, their behaviors were recorded using a video camera with a deep blue background. The diameters of the dissolved air in column IV were estimated to range from 10 to 120 μm, which was experimentally investigated by several researchers [14]. The height of the porous medium bed in each

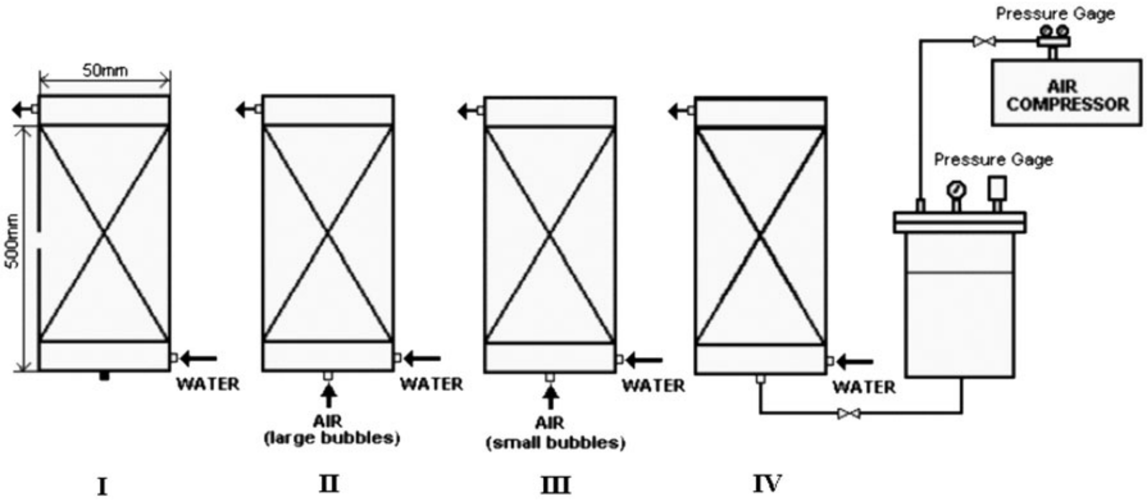

Fig. 2. Schematic diagram of the packed bed backwashing system.

column was 50 cm. A perforated acryl plate was set at the top and bottom of all columns to prevent excessive expansion during backwashing.

2.4. Backwashing methods

In the case of water-alone backwashing (column I), the flow rate was set at 0.6 L/min, based on previous investigations [3]. Since biomass adhesion to the porous medium was weak, the backwash flow rate of 0.6 L/min was considered sufficient to obtain shear stress. Backwashing continued for 3 min. The backwash effluent was sampled every 10 s after the first effluent flowed out of the top outlet. The turbidity and VSS of each sample were measured.

Column II was backwashed with water and 1.0 cm air bubbles. The flow rates of water and air were set at 0.6 and 0.4 L/min, respectively. The ratio between the two elements was selected because, although no previous recommendations for water/air exist, the same ratio of 40% air was used for backwashing an anthracite filter in water treatment [15]. The interval and methods of sampling and measurement were identical to those used for column I.

Column III was backwashed with water and 0.2 cm bubbles. All other conditions for this column were identical to those of column II. Lastly, column IV was backwashed with water containing dissolved air, which had been compressed into the water at 5 atm (507 kPa). The flow rates of water and air-dissolved water were 0.6 and 0.4 L/min, respectively.

The VSS of each collected sample was measured using a Whatman 934-AH 47 mm∅ filter (pore size = 1.2 μm) as suggested in Standard Methods [16]. A total of 15 samples were taken for each test. Turbidity was measured in NTU using a spectrometer (Model YPM269).

3. Results and discussion

Fig. 3 shows the results of turbidity measurements for all four cases. The most efficient method was that used in column III (water and 0.2 cm bubbles), followed by column II (water and 1 cm bubbles), then column I (water alone), and, lastly, column IV (water with dissolved air). Turbidities in samples from each column were reduced to lower than 500 NTU after 60 s. Biomass formed on the medium surface is easily separated by the moderate shear stress used in these experiments, while biomass in the pores is not separated even by high shear stress. Therefore, after backwashing, the remaining biomass in the pores provided an initial treatment and acted as a seed micro-organism for cell re growth.

The turbidity profiles in Fig. 3 show that bubble size affects the shear stress produced on the medium surface, and ultimately the backwashing efficiency, with small bubbles being more effective than large bubbles. That is, even with the same quantity of air volume, different-sized bubbles produce quite different turbulence patterns by collapse pulsing, and this affects the shear velocity field formed around the medium. In the case of dissolved air (column IV), the micro bubbles (10–100 μm diameter) are small and rise slowly; therefore, the collapse-pulsing effect is relatively small, less shear stress is produced, and backwash performance is poor. In the case of water-alone backwashing (column I), the shear stress around the medium is weak, and the turbidity is stabilized after 40 s with no further biomass separation.

As shown in Fig. 4, VSS measurements showed the same trend as turbidity, indicating that the concentration of VSS is proportional to the degree of washing. Backwashing using water with the 0.2 cm bubbles (column I) was most effective.

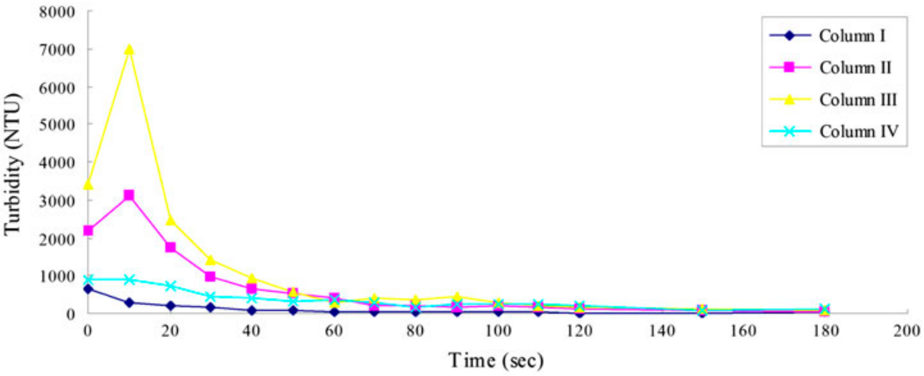

Fig. 3. Results of turbidity measurements.

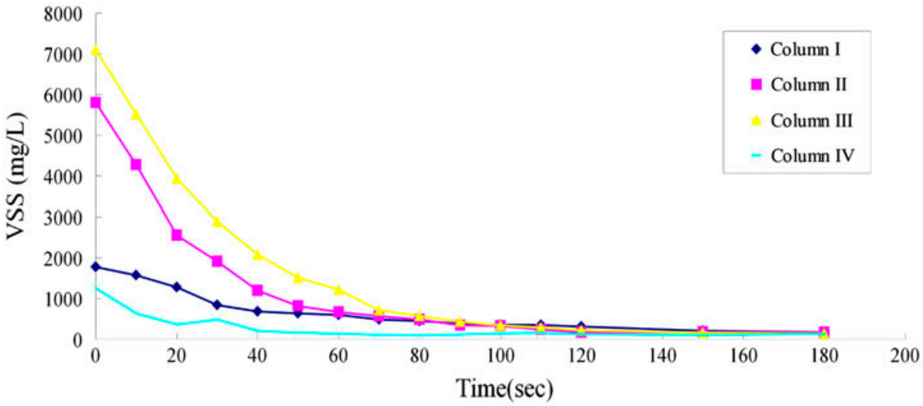

Fig. 4. Results of VSS measurement.

Accordingly, from Figs. 3 and 4, it can be concluded that air bubble size affects backwashing efficiency. This is due to the turbulence patterns associated with different bubble sizes, and their impact on the medium surface. This makes sense, since it is understood that the shear stress that removes the biofilm from the medium surface is caused by turbulence.

To conceptually investigate collapse-pulsing mechanisms with simple mathematical models, two bubble sizes are used: one with a radius of r and the other with that of $\frac{r}{\sqrt{[3]2}}$. The volume of the former, $\frac{4}{3}\pi r^3$, is twice that of the latter, $\frac{2}{3}\pi r^3$. As shown in Fig. 5, one of the former and two of the latter are considered here, such that their total volumes are identical.

Fig. 6(a) describes a simplified diagram of the collision and scatter of air bubbles with a radius of r with the medium. The shapes of both the medium and the air bubbles are assumed to be spherical, and the biofilm and mass are assumed to be uniformly formed on the medium surface. As shown, when the bubble is collapsed or slides by the medium, fluid parcels move to the center of the bubble to replace its volume. This creates a velocity field in a tangential direction to the medium surface and in the central direction of the sphere occupied by the air bubble. This velocity field is superimposed on to the uniform vertical velocity field of the backwashing water. These phenomena can be expressed mathematically as follows. The volume of the air bubble with radius r is $\frac{4}{3}\pi r^3(V_b)$.

When this bubble collapses and scatters on the surface of the medium, the flow rate of the fluid parcel, which moves to the center of the bubble, can be calculated using the continuity equation.

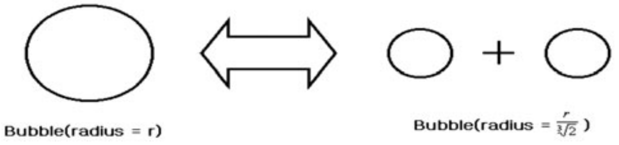

Fig. 5. Example bubbles for analysis.

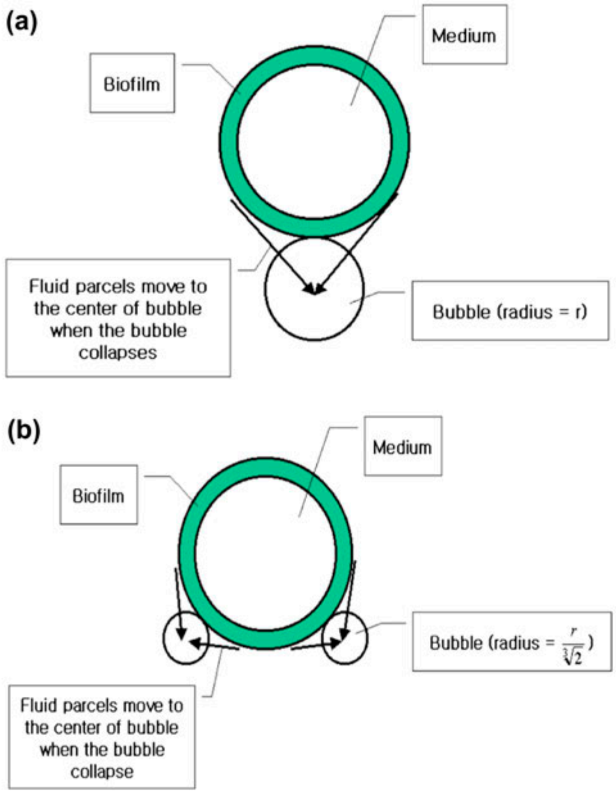

Fig. 6. Schematic diagrams of bubble collapse (a) radius = r and (b) radius = $\frac{r}{\sqrt{[3]2}}$.

$$v = \frac{Q}{A} \tag{2}$$

$$Q = \frac{V_b}{t_c} \tag{3}$$

where Q—the flow rate of the fluid parcel moving to the center of the bubble; t_c—the time required for air collapsing and scattering; A—the surface area of the air bubble ($4\pi r^2$).

Incorporating Eq. (2) into Eq. (3) yields Eq. (4), which represents the velocity of the fluid parcel on the medium surface.

$$v = \frac{\frac{4\pi r^3}{3t_c}}{4\pi r^2} = \frac{r}{3t_c} \tag{4}$$

Fig. 6(b) shows a simplified diagram of small bubbles. Two bubbles of radius $\frac{r}{\sqrt{[3]2}}$ are used so that the total volume equals to that of one large bubble (refer to Fig. 5). In this case, the volume of an air bubble is $\frac{2}{3}\pi r^3(V_b)$.

When this bubble collapses and scatters on the medium surface, the flow rate can be expressed as follows.

$$Q = \frac{\frac{2}{3}\pi r^3}{t_c} = \frac{2\pi r^3}{3t_c} \tag{5}$$

Incorporating Eq. (5) into Eq. (2) results in Eq. (6), which represents the velocity fields on the medium surface.

$$v = \frac{\frac{2\pi r^3}{3t_c}}{\frac{4\pi r^2}{(\sqrt{[3]2})^2}} = \frac{(\sqrt{[3]2})^2 r}{6t_c} \tag{6}$$

Since there are two bubbles (Fig. 5), the equivalent velocity fields equal $2v$. Therefore, the final velocity is

$$v_f = 2v = \frac{2(\sqrt{[3]2})^2 r}{6t_c} = \frac{(\sqrt{[3]2})^2 r}{6t_c} = \frac{1.59r}{6t_c} \tag{7}$$

Comparing Eqs. (4) and (7), it can be concluded that the fluid's velocity in the case of two small bubbles (radius = $\frac{r}{\sqrt{[3]2}}$) is larger than that in the case of one large bubble (radius = r).

$$\frac{r}{3t_c} \langle \frac{1.59r}{3t_c} \tag{8}$$

The models developed above have been applied to the cases of columns II (bubble diameter = 1.0 cm) and III (bubble diameter = 0.2 cm) and their results are shown in Table 3.

As shown in Table 3, with the same volume of air, a 1.0 cm bubble (column II) produces an equivalent velocity of $\frac{0.167}{t_c}$ on the medium surface (Table 3). On the other hand, 131 0.2 cm bubbles (column III) have an equivalent velocity of $\frac{4.323}{t_c}$. That is, even though a 0.2 cm bubble produces a smaller rising velocity ($\frac{0.033}{t_c}$) than a 1.0 cm bubble does, it may produce a larger equivalent velocity and more turbulent flow around the medium. This explains why backwashing with water and 0.2 cm bubbles was more effective than backwashing with 1 cm bubbles. Accordingly, since the fluid velocity on a stationary medium surface in moving fluid is zero, we can conclude that the shear stresses around the medium depend on the fluid velocity caused by the collapse pulsing of the injected air bubbles [Eqs. (8) and (9)].

$$\tau = \frac{\Delta v}{\Delta r} \tag{9}$$

Table 3
Computational results of column II (diameter = 1.0 cm) and column III (diameter = 0.2 cm)

Division	Column II (diameter = 1.0 cm, radius = 0.5 cm)	Column III (diameter = 0.2 cm, radius = 0.1 cm)
Volume of an air bubble (V_b), cm^3	0.524	0.004
Number of bubbles for the volume of 0.524 cm^3	1	131
Surface area of an air bubble ($4\pi r^3$), cm^2	3.142	0.126
Fluid velocity caused by an air bubble [Eq. (2)]	$\frac{0.167}{t_c}$	$\frac{0.033}{t_c}$
Equivalent velocity [Eq. (7)]	$\frac{0.167}{t_c}$	$\frac{4.323}{t_c}$

4. Conclusions

In this study, we examined the effects of bubble size on backwashing efficiency by conducting experiments and developing a simplified mathematical model to work with collapse-pulsing theory developed by Amirtharajah. The conclusions are summarized as follows:

Backwashing a biofilter using water and air bubbles was more effective than using water alone. Using water containing dissolved air (minute bubbles with an average diameter of 40 μm) was less effective than using water and air bubbles. In fact, dissolved air is even less effective than using water alone. With the same volume of air, smaller air bubbles (diameter = 0.2 cm) improved the backwashing efficiency over that of larger air bubbles (diameter = 1.0 cm).

We hypothesize that the difference in backwashing efficiency is due to the fact that different-sized bubbles produce different shear velocity fields on the medium surface by collapse-pulsing. When air bubbles rise up uniformly through the biofilter bed during backwashing, the relatively small bubbles produce a more turbulent flow and shear stress around the medium than do the larger bubbles. This shear stress is the most important factor for removing the biomass from the medium surface.

Even though the smaller bubbles improved the backwashing efficiency, with dissolved air the microbubbles are too small and rise up too slowly to produce a sufficient collapse-pulsing effect. These results suggest that there may be a critical bubble size most effective for backwashing, between 0.2 cm and 40 μm. This study, however, could not identify a specific bubble size that produces the most appropriate turbulent flow around the medium because the methods used to generate air bubbles were not delicate enough. Therefore, experiments with bubbles of various sizes and advanced measurement devices are needed.

The mathematical model developed in this study can simply examine the effects of bubble size and supplement Eq. (1), in that it provides more detailed information on hydrodynamic conditions in collapse-pulsing effects. Additional studies are required to modify Eq. (1) or to develop alternative equations for designing and operating the biofilter process. For example, terms related to bubble size may be added to Eq. (1), or the constants "a or b" in the equation for each different-sized bubble may be redetermined.

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