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Modeling and experiment for removal of algae and nutrient using a DAF system installed on a ferryboat

Seok Dockko[a], Jeonghan Kim[b], Haegyun Lee[a,*]

[a]*Department of Civil and Environmental Engineering, Dankook University, 119, Dandae-ro, Dongnam-gu, Cheonan-si, Chungnam, 330-714, Korea, Tel. +82 (41) 550 3516; Fax: +82 (41) 550 3520; email: haegyun@dankook.ac.kr (H.Lee)*
[b]*GeoMarine #608, Anyang Megavalley #799, Gwangyang-dong, Dongan-gu, Anyang-si, Gyeonggi-do 431-767, Korea, Tel. +82 (31) 423 0700; Fax: +82 (31) 423 0006; email: gm@geomarine.kr*

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ABSTRACT

Many lakes or irrigative reservoirs in Korea are rapidly polluted with algae because of the increasing amounts of pollutants discharged from nonpoint sources. Though dissolved air flotation (DAF) is one of the most efficient processes for removing algae, there are limitations associated with conveying polluted water to a plant located on the lakeside. In this study, a reaction tube was optimized to enhance collision between microbubbles and pollutants. The length, diameter, and space of the reaction tube were modified and tested in the laboratory. A numerical model using three-dimensional Navier–Stokes equations was set up for the analysis of flow around the reaction tube. The laboratory tests showed that the efficiency of phosphorus removal is improved as the reaction tube length is reduced. Phosphorus removal efficiency was improved, as the tube diameter was larger and the reaction space was reduced. A pilot test was performed to verify these results and modeling results. A ferryboat installed with an air saturator of DAF on the main deck and an underwater screen curtain was introduced to remove suspended solids (SS), chlorophyll-a (Chl-a), and phosphorus in the middle of the lake. The results showed that removal of SS, Chl-a, and phosphorus were efficient as the reaction space was reduced in length.

Keywords: Dissolved air flotation (DAF); Microbubble; Algae; Chlorophyll-a

1. Introduction

Eutrophication of water sources and damage by algal contamination can cause problems such as death of aquatic animals and deterioration of the landscape [1,2]. Recently, temperature increases due to climate change have caused algal blooms even in winter [3,4]. In Korea, the emergence of *Anabaena spiroides* has been associated with bad smells in drinking water systems since December 2011.

Conditions required to increase algal growth include providing sufficient sunlight, temperature, and CO_2 in the environment. Phosphorus has a greater effect on algal growth compared with nitrogen. Both biological and physical/chemical approaches have been used for the study of phosphorus removal underwater [5]. Cheong [6] has reported that during the coagulation and sedimentation, both alum and polyaluminum chloride (PAC) are efficient treatments for chlorophyll-a (Chl-a) removal. However, there are negative aspects regarding use of these chemicals,

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*Corresponding author.

such as the expense of chemical purchase and problems with sludge disposal [7,8].

The dissolved air flotation (DAF) process is effective for algae removal and has other advantages in natural systems. Because the density of flocs formed by flocculation is low, sedimentation is poor. The DAF process has positive effects on filtration, which can cause shortening of the operation. Han et al. [9] reported that it was more reasonable to remove algae in natural systems by flotation than by sedimentation processes. Also, removal of algae in natural systems is different from that in previous times as there are now demands for larger treatment capacities and limitations of chemical use [10]. Bubble size depends on the amount of pressure provided, which means that the bubble size could decrease if high pressure is applied [11,12]. The actual bubble sizes in DAF systems are affected by injection device, especially the type of nozzle is an important factor affecting bubble size [13].

Teixeira and Rosa [14,15] compared the effect of removing blue-green algae (cyanobacteria) using DAF and sedimentation processes. DAF showed 90–99% removal compared with 70–94% removal by the sedimentation process. Researchers have reported that the effect of removing algae by sedimentation was 60–90% [16]. Henderson et al. [17] reported that up to 96–99.6% of algae could be removed if pretreatment and DAF are optimized.

The purpose of this study is to optimize the type of reaction tube in the process of bubble-pollutant reaction in DAF systems. Laboratory tests, mathematical analyses and pilot tests in a lake were performed.

2. Materials and methods

2.1. Synthetic water and DAF system

Synthetic water was made to 2 mg P/L, which was blended with Na_2HPO_4 (Samchun Chemicals, Korea) in the tap water. PAC (10%) was used as coagulant. The coagulant of 5 mg/L was injected into the reactor at 15 mL/min for 5 min. The reactor volume is 90 L, which was connected to the DAF system as in Fig. 1. The reactor was filled with 81 L of water, then 9 L as 10% of recycling ratio of reactor volume was injected with microbubble. Samples were taken at 20, 40, and 60 cm from the bottom every 1 min after bubble injection. The influent mixed with pressurized water from the DAF tank was injected into the reactor at the rate of 30 L/min. DAF system conditions of operation are shown in Table 1. The pH was maintained at 7 ± 0.5 using HCl (0.1 N) and NaOH (0.1 N).

2.2. Effectiveness of reaction tube and contact time for phosphorus removal

The reaction tube is shown in Fig. 1. The reaction tube length (150, 300, 450 mm) and diameter (20, 40, 60 mm) were altered to determine the optimum dimensions. The space between the reaction tube and the pressurized water outlet was either 60 or 120 mm. The experiments were performed using three experimental cases as shown in Table 2. Samples were taken every minute for 5 min at 200, 400, and 600 mm from the bottom of the reaction tube, to determine the microbubble diffusion at each reactor depth or depending on retention time.

Phosphorus was analyzed by Humas Method No. 3000 (0.01–3 mg/L) using the DR 5000 (HACH Company, USA). Mathematical modeling was applied to evaluate diffusion effects in the reaction tube and to compare with experimental data.

2.3. Numerical model

A numerical model was applied to analyze flow around the reaction tubing. The governing equations are three-dimensional Navier–Stokes equations shown by Eq. (1):

$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial p}{\partial x_i} + g_i + v\frac{\partial^2 u_i}{\partial x_j \partial x_j} \tag{1}$$

and the continuity equation for incompressible flow using Eq. (2):

$$\frac{\partial u_i}{\partial x_i} = 0 \tag{2}$$

where μ_i ($i = 1,2,3$) are the velocity components in x (x_1)-, $y(x_2)$-, and $z(x_3)$-directions, respectively. ρ is the density, v is the kinematic viscosity of water, and p is the pressure.

The passive scalar transport model was employed for simulation of the advection and diffusion of air bubbles as shown by Eq. (3):

$$\frac{\partial B}{\partial t} + u_j \frac{\partial B}{\partial x_j} = D\frac{\partial^2 B}{\partial x_j \partial x_j} \tag{3}$$

where B is the bubble volume concentration and D is the diffusion coefficient. For the spatial discretization of the domain, the characteristic Galerkin finite element method was used, and the fractional four-step algorithm was employed for time integration of

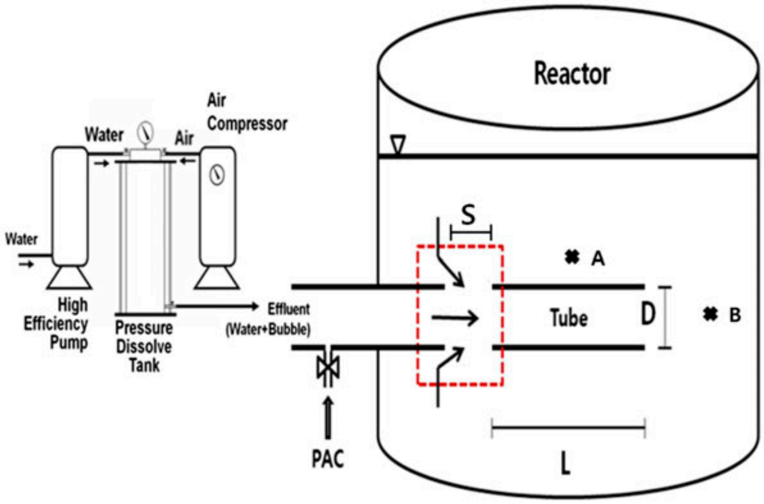

Fig. 1. Schematic of DAF saturator, reactor, and reaction tube.

Table 1
DAF system conditions

Material	Stainless steel
DAF saturator flow rate	30 L/min
Recycle ratio	10%
Pressure	4 atm
Retention time	5 min
Temperature	20°C

incompressible flow. For the effect of turbulence, the subgrid large-eddy simulation model was used. Details on the numerical model employed can be found in Lin et al. [18].

2.4. Ferryboat experiment

In order to evaluate operating data in the lake, the DAF saturator and reaction tube were set up on a ferryboat in Giheung Lake. The screen curtain was drawn down under the water so as not to disperse the algae and nutrients after coagulant injection. Microbubbles were injected from the DAF saturator through the reaction tube at 2.5 m below the water surface on the ferryboat. Recycling ratio was 10% and retention time was changed to 30–100 min in the screen curtain. Controlling the space between the outlet of the DAF saturator and the reaction tube made it possible to change the frequency of collisions between bubbles and phosphorus in the reaction tube. After a while, algae and nutrients mixed with bubbles floated to the surface and were collected with a scraper to the edge of the ferryboat. TP, Chl-a, and suspended solids (SS) removal were monitored and evaluated depending on the reaction tube space in the ferryboat.

3. Results and discussion

3.1. Effect of reaction tube length (L)

Two types of reaction tubes that have the same diameter of 40 mm and different lengths of L150 and L450 mm were used in Exp. 1 to test phosphorus removal in the reactor. Approximately 98% of phosphorus was removed with the L450 mm reaction tube at 60 cm from the bottom, while 68% of phosphorus was removed at 20 cm from the bottom (Fig. 2). However, about 90% of phosphorus was removed with the L150 mm reaction tube at the point of 60 cm right after

Table 2
Experimental cases (in mm) of the reaction tube in the reactor

	Length	Diameter	Space	Sampling point from bottom
Exp. 1	150/450	40	120	200, 600
Exp. 2	300	20/60	120	200, 400
Exp. 3	300	40	60/120	200, 600

injection, while 90% was removed after 5 min at 20 cm. The efficiency of phosphorus removal increases as the reaction tube length is reduced from 450 to 150 mm.

3.2. *Effect of reaction tube diameter (D)*

The reaction tube diameter was changed from 20 to 40 mm while the length was fixed at 300 mm in Exp. 2. Other conditions were the same as in Exp. 1. Fig. 3 shows that 100% of phosphorus in the reactor was removed with *D* 40 mm at 60 cm, while 93% was removed 5 min postinjection at 20 cm. If the reaction occurs rapidly through the reaction tube, the amount of coagulant to be injected can be reduced. It is shown that the amount of coagulant and the reaction time decreased as the diameter of the reaction tube increased.

3.3. *Effect of space between reaction tube and outlet of DAF saturator (S)*

In Exp. 3, the space between the reaction tube and the DAF saturator outlet was tested at 60, 120, and 180 mm. Fig. 4 shows that 99% of phosphorus was removed with $S = 120$ mm at 60 cm, while 83% of phosphorus was removed at 20 cm. The results show that phosphorus removal was more efficient in shallower water. As algae are light and are generally found near the surface, removal of phosphorus associated with algae is easier than removal of water-soluble phosphorus. Phosphorus removal was more efficient as the space between the reaction tube and the DAF saturator outlet was reduced.

3.4. *Numerical model*

Numerical simulations were carried out with the reaction tube set at 300 mm. The distance between the bubble tube and the reaction tube was tested at 60, 120, and 180 mm. Fig. 5 is a snapshot of the flow pattern at $t = 1.0$ min after the start of the bubble shoot. Figs. 6 and 7 are plots of the time history of air bubble concentrations at points *A* and *B* (in Fig. 5), respectively. The unit of air bubble concentration is dimensionless; the air volume of air bubble generated from nozzle (m^3) over the air volume used for producing bubble (m^3).

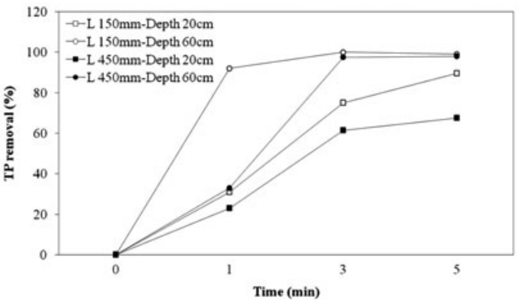

Fig. 2. Phosphorus removal according to reaction tube length.

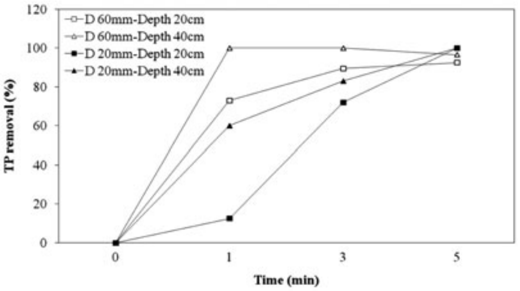

Fig. 3. TP removal according to reactor tube diameter.

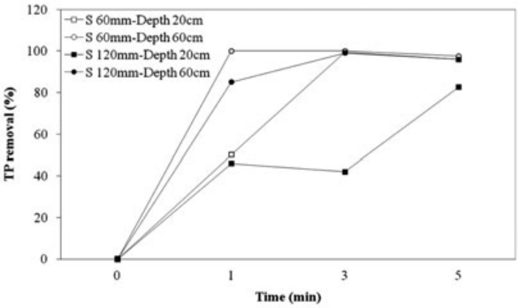

Fig. 4. TP removal according to length between DAF saturator outlet and reaction tube.

While the air bubble concentration at point *B* is slightly lower when $S = 180$ mm, the concentration at point *A* is highest for this distance. It seems that the presence of the reaction tube hinders the mixing of bubbles at point *B* in the case of $S = 180$ mm. However, we expect that this difference will be minimized if further time is allowed for mixing.

3.5. *Reaction tube monitoring on the ferryboat in the lake*

To evaluate the effects of reaction tube space, monitoring was performed in Giheung Lake. Conditions for this experiment are shown in Table 3. As the reaction tube space increased, influent velocity and flow also increased.

Figs. 8 and 9 show that phosphorus removal increased as the reaction tube space length was

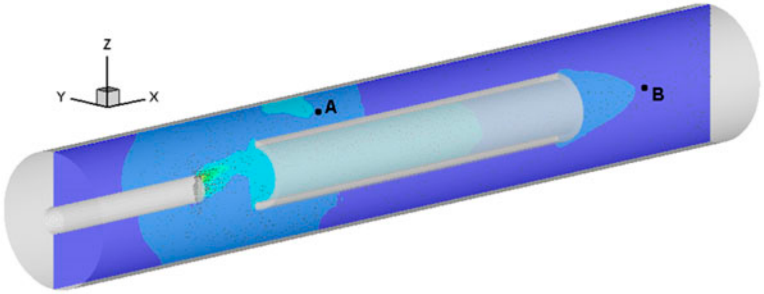

Fig. 5. Advection–diffusion of air bubble concentration at $t = 1.0$ min.

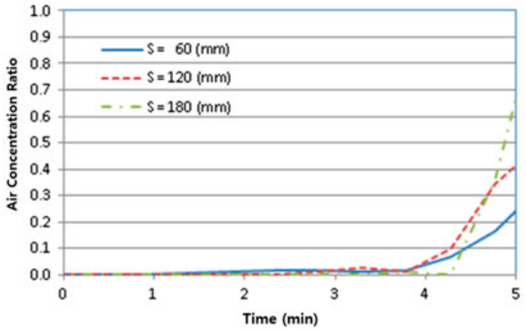

Fig. 6. Air bubble concentrations at point A over time.

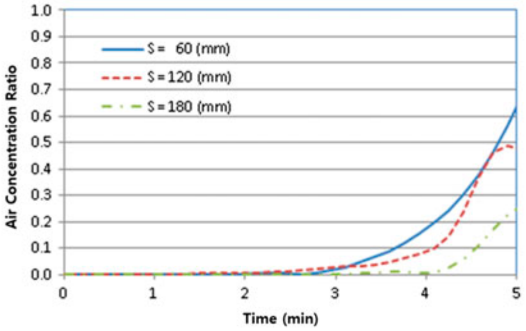

Fig. 7. Air bubble concentrations at point B over time.

reduced. Phosphorus concentrations were reduced from 0.056 to 0.023 mg/L at S-0 cm (Fig. 8). When the

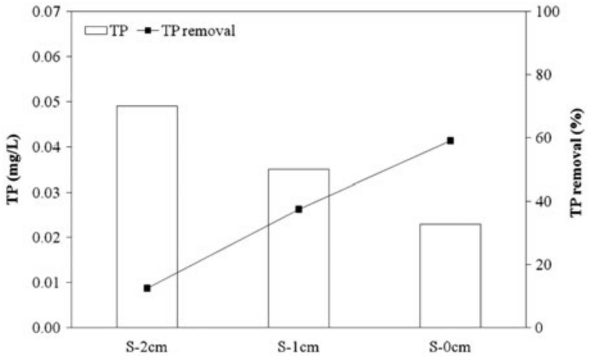

Fig. 8. TP removal in Giheung Lake as affected by tube space and length.

reaction tube length was reduced, microbubbles were able to react well with pollutants such as phosphorus. Phosphorus removal efficiency was improved with increased tube diameter and reduced tube length.

Fig. 9 shows the removal of SS and Chl-a. Similar to the results obtained for phosphorus removal, SS and Chl-a removal was more efficient as the space between the reaction tube and the DAF saturator outlet was reduced. Removal of Chl-a was more efficient compared with SS removal. Low SS removal showed that flocculation in pipe was not completed as we expected. Changing the tube space was more sensitive to SS removal than Chl-a removal.

Table 3
Influent, retention time and flow in reaction tube depending on space

Pressure (kg/cm^2)	Space (cm)	Influent velocity (cm/s)	Retention time (min)	Influent flow (m^3/d)
3.0	0	0.4	100	2,592
	1	0.75	44	4,860
	2	1.1	30	7,128

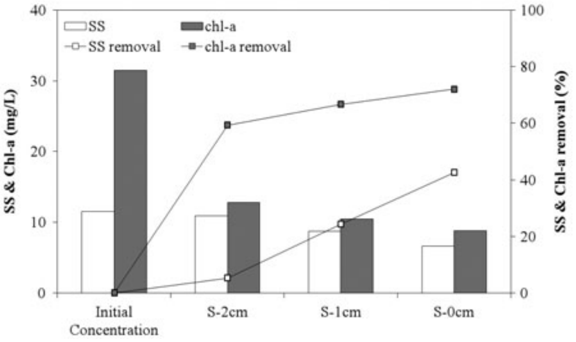

Fig. 9. SS and Chl-a removal in Giheung Lake as affected by tube space and length.

4. Conclusions

To enhance the efficiency of DAF system interactions between microbubbles and pollutants, the length (*L*), diameter (*D*), and space (*S*) of the reaction tube were changed in the laboratory. A numerical model using three-dimensional Navier–Stokes equations was set up for the analysis of flow around the reaction tubing. The laboratory test showed that the efficiency of phosphorus removal was increased as the reaction tube was reduced in length. Phosphorus removal efficiency was also increased as the tube diameter was increased and tube space length was reduced. During pilot-scale testing to monitor the reactor performance in Giheung Lake, SS, Chl-a, and phosphorus removal was more efficient as the space between the reaction tube and the DAF saturator outlet was reduced.

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