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Physical characteristics of bubbles in dissolved air flotation processes in seawater reverse osmosis desalination plants

Tschungil Kim[a], Tatek Temesgen[b], Hyunju Park[a,*], Mooyoung Han[b]

[a]*Institute of Construction and Environmental Engineering, Seoul National University, 599 Gwanak-ro, Gwanak-gu, Seoul 151-744, Korea, emails: narjjis@hanmail.net (H. Park), amor77@gmail.com (T. Kim)*
[b]*Department of Civil and Environmental Engineering, Seoul National University, 599 Gwanak-ro, Gwanak-gu, Seoul 151-744, Korea, emails: tate95et@gmail.com (T. Temesgen), myhan@snu.ac.kr (M. Han)*

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ABSTRACT

In this study, we analyzed the impacts of salinity on the physical characteristics of bubbles in the pretreatment process of seawater desalination facilities to optimize the dissolved air flotation (DAF) process. Bubble size became smaller with increased salinity. Particularly, the difference was marked for relatively large bubbles formed under low pressure and high-molecular weight gases, such as CO_2. We suggest that coalescence decreased at the nozzle because the Laplace pressure decreased with an increase in the repulsive force due to salinity. Bubble bed depth also increased with a reduction in bubble rising velocity because of increased drag force in the water due to salinity. However, there was not a large difference in particle removal efficiency of the lower density bubble bed. Therefore, salinity affects the physical characteristics of bubbles, but does not have a substantial impact on performance, except for DAF processes with high loading rates in which the bubble bed is lower density.

Keywords: Bubble bed; Bubble size; Bubble rising velocity; Coalescence; Pretreatment; Salinity

1. Introduction

Dissolved air flotation (DAF) is a water treatment process that clarifies particles using attached bubbles and is widely used to remove low-density algae in water purification plants. In 2005, Singapore's Tuas seawater reverse osmosis (SWRO) desalination plant pioneered use of the DAF process as a pretreatment process. Particularly in the Middle East, DAF has become an essential pretreatment process for SWRO desalination plants because of frequent red tides and oil and grease.

The design and operating conditions of DAF processes of water treatment plants and SWRO desalination plants are basically the same, except for corrosion of equipment and materials. In the Middle East, a variety of challenges may occur in practice, such as loss of efficiency due to use of $FeCl_3$ coagulants at high temperatures. In a recent literature review, DAF received a favorable evaluation as a high-efficiency pretreatment process that can reduce carbon emissions, but cautions that polymers cannot be used because of their effects on the reverse osmosis membrane [1]. Basic research is still needed before research on optimization of the DAF process in SWRO desalination plants can proceed.

Salinity is the basic difference between seawater and freshwater. The presence or absence of salinity affects corrosivity as well as viscosity and density. These factors have a distinct effect on the physical characteristics of bubbles (size, bubble volume, bubble bed depth) and chemical properties (zeta potential of bubbles).

Therefore, the purpose of this study was to analyze the impacts of salinity on bubble size, bubble bed depth due to bubble size, and the efficiency of particle removal. Ongoing basic research such as this study will allow more accurate design and operation of the DAF process in SWRO desalination plants.

* Corresponding author.

2. Methods

To analyze bubble size, bubble bed depth, and particle removal efficiency, tap water was used as raw water and recycle water. The pH and alkalinity were adjusted to 7.55–7.65 and 50 ppm (as $CaCO_3$), respectively. Salinity was adjusted to 35 ppt using NaCl to imitate standard seawater [2] at the water temperature of 22°C–24°C.

Bubbles were generated using air or CO_2 which has higher molecular weight, to determine the physical characteristics of the bubbles under a variety of conditions. For generating bubbles, the pressure was set to 2, 3, 4, and 5 atm and air or CO_2 was continuously injected at 20 mL·min^{-1} under high pressure.

2.1. Measurement of bubble size with a particle counter

Bubble size distribution and average bubble size were measured with an online particle counter (Laser-Trac PC3400D; Chemtrac Systems Inc., USA) [3]. A single particle counter was used measuring seven channels (15–25, 25–35, 35–45, 45–55, 55–65, 65–75, and 75–85 μm) with a flow rate of 100 mL·min^{-1}.

Experiments were carried out in a recycle reactor manufactured from transparent acrylic (Fig. 1). Bubbles were measured 30 cm below the surface in the center of the bubble bed. The experimental method applied by Han et al. [4] was followed to achieve a similar statistical reliability.

2.2. Measurement of bubble bed depth with a particle counter

The bubble bed depth experiment was carried out in the recycle reactor illustrated in Fig. 1, which continuously generated bubbles forming a bubble bed. Bubbles were generated for 30 min to stabilize the bubble bed and the bubble bed depth was then measured with the online particle counter (Laser-Trac PC3400D). Changes in the number of bubbles were analyzed at 5 mm intervals [5].

2.3. Measurement of particle removal efficiency in a pilot plant

To evaluate particle removal efficiency, an experiment was carried out in a pilot plant (Fig. 2). The pilot plant was composed of three parts, a flocculation process, a contact zone, and a separation zone. The design and operating conditions of the flocculation process are shown in Table 1. The DAF process area was 55 cm long, 50 cm high, and 10 cm wide, the loading rate was 15 m^3·h^{-1}·m^{-2}, and the recycle ratio was 10%. Turbid water was adjusted to 20–22 NTU using kaolin powder (Duksan Pure Chemicals Co., Ltd., Korea) and 15 ppm Al_2SO_4 (DaeSung Co., Korea) was injected as a coagulant. Turbidity of the water before and after bubbling was measured using a turbidity meter (Hach 2100Q) to determine the particle removal efficiency percentage in the pilot plant.

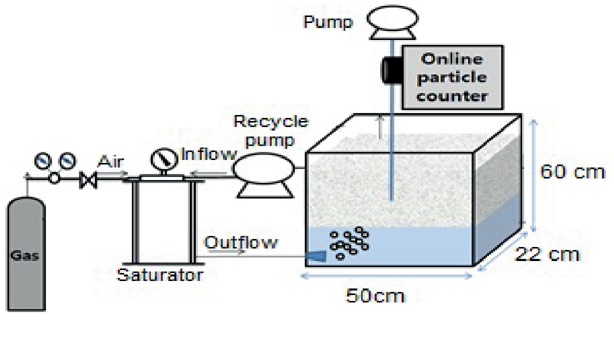

Fig. 1. Schematic diagram of the bubble size measurement apparatus.

3. Results

3.1. Change in bubble size with salinity

To measure changes in air and CO_2 bubble sizes due to salinity, the pressure was adjusted to 2, 3, 4, and 5 atm. Fig. 3 shows the bubble size distributions under air at 2 and 5 atm. In saline water at 2 atm, the average size was smaller with many fine bubbles. There was not a substantial difference in bubble size distribution and average bubble size at 3, 4, and 5 atm between tap water and saline water (Fig. 3(b)).

Fig. 4 shows bubble size distributions under CO_2 at 2 and 5 atm. Similar to bubbles in air, in saline water at 2 atm, the average size was smaller with many fine bubbles. Unlike the air bubbles, at 3 and 4 atm this trend was also observed. There was not a substantial difference in average size with salinity at 5 atm (Fig. 4(b)).

Table 2 shows the average bubble size under various gas and pressure conditions. For tap water, the bubble size was >45 μm, which is relatively large (Table 2, Bold values: air, 2 atm; CO_2, 2, 3, and 4 atm). In saline water, there was a trend toward smaller bubbles of 40–43 μm. For these operating conditions the bubble size shows a decreasing trend for both air and CO_2 gases as the salinity increased. Ruengam et al. [6] reported that electrolytes such as salt increase the repulsive hydration force by enhancing water structure due to hydrogen bonds at the interface, leading to a more stable bubble than in freshwater systems. This facilitates the formation of smaller bubbles more easily in saline water as

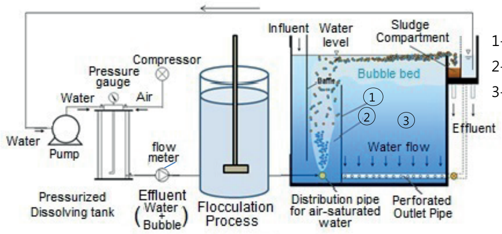

Fig. 2. Schematic diagram of the pilot plant.

Table 1
Design and operating conditions for the flocculation process

Process		*G* value	*T* (min)	*G–T* value
Flash mixing		177.7	0.5	5.3×10^{-3}
Flocculation	Stage 1	82.5	5	3.7×10^{-4}
Flocculation	Stage 2	55.0	5	2.4×10^{-4}

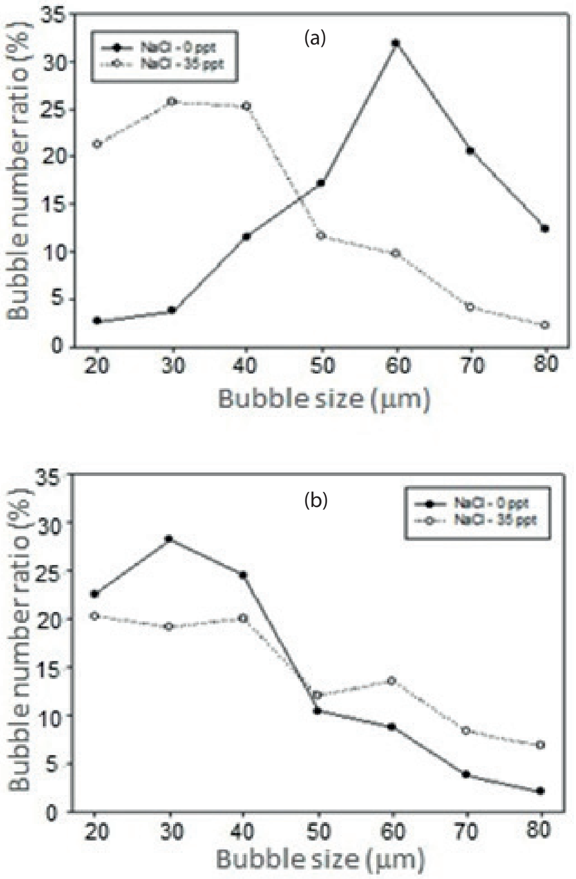

Fig. 3. Bubble size distribution under air at: (a) 2 atm and (b) 5 atm.

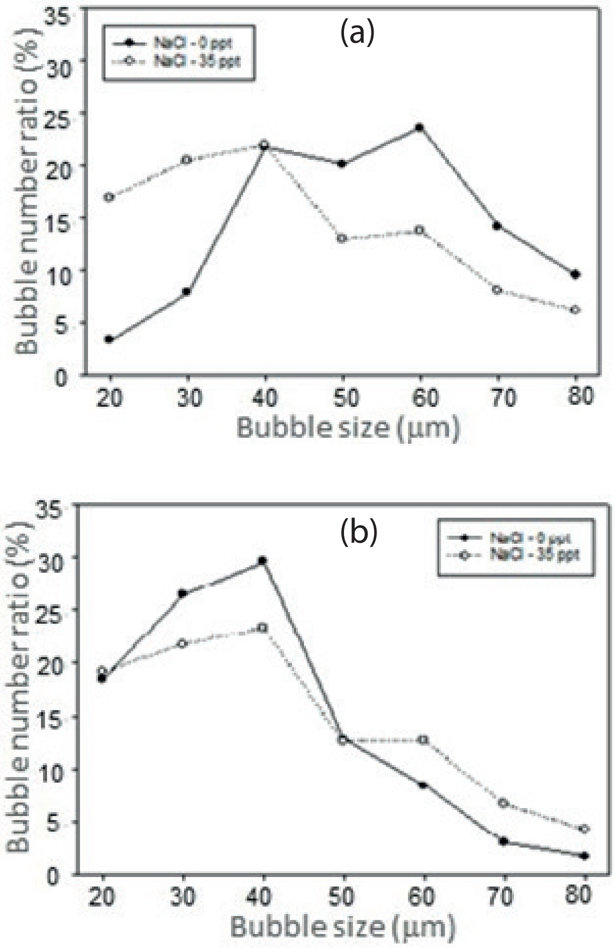

Fig. 4. Bubble size distribution under CO_2 at: (a) 2 atm and (b) 5 atm.

depicted by Lessard and Zieminski [7], because of less possibility of big bubble formation by coalescence. Bubble coalescence is reduced in saline water due to formation of stable bubble surfaces resulted from high density of surface charges as well as the possibility of an increase in water viscosity by the presence of the salt electrolyte. Which is consistent with the observed results (Table 2). Based on the experimental results, salinity influences CO_2 bubble size more than that of air bubbles. This is supported by the effect of an increase in gas density due to an increase in gas molecular weight. The increase in gas density increases the bubble break up reducing the number and size of big bubbles [8,9].

Table 2
Average bubble size under various gas and pressure conditions

Gas	Salinity	2 atm	3 atm	4 atm	5 atm
Air	NaCl 0 ppt	**58 μm**	42 μm	40 μm	38 μm
Air	NaCl 35 ppt	**43 μm**	42 μm	41 μm	38 μm
CO_2	NaCl 0 ppt	**53 μm**	**47 μm**	**45 μm**	39 μm
CO_2	NaCl 35 ppt	**43 μm**	**42 μm**	**41 μm**	40 μm

3.2. Change in bubble bed depth with salinity

The change in bubble bed depth with a constant average bubble size was measured under air at 3, 4, and 5 atm and under CO_2 at 5 atm to investigate the effects of salinity. Fig. 5 shows bubble bed depth with salinity at 5 atm. The bubble bed depth was 47 cm for tap water and 50 cm for saline water, a difference of 3 cm. There was a difference of 2 cm at 3 and 4 atm, and a difference of 5 cm under CO_2 at 5 atm (Table 3). Considering that the full depth of bubble bed is about 50 cm, a 2–5 cm difference in depth is relatively small but consistent; the same results were obtained in this experiment repeated five times.

Bubble bed depth is influence by bubble volume and bubble rising velocity [5,10]. In this experiment, the bubble volume can be neglected when evaluating the effects of salinity, because the same amount of gas is injected at the same gas pressure. Also, the bubble rising velocity does not need to be considered because the average size of the bubbles is constant. Therefore, in this study, the change in bubble bed depth resulted from the salinity, indicating solution effects. Kulkarni and Joshi [11] reported that the rising velocity of bubbles was affected by an electrolyte solution (NaCl), similar to the influence of a surfactant on bubble rising velocity. Frumkin and Levich [12] proposed that drag force increases

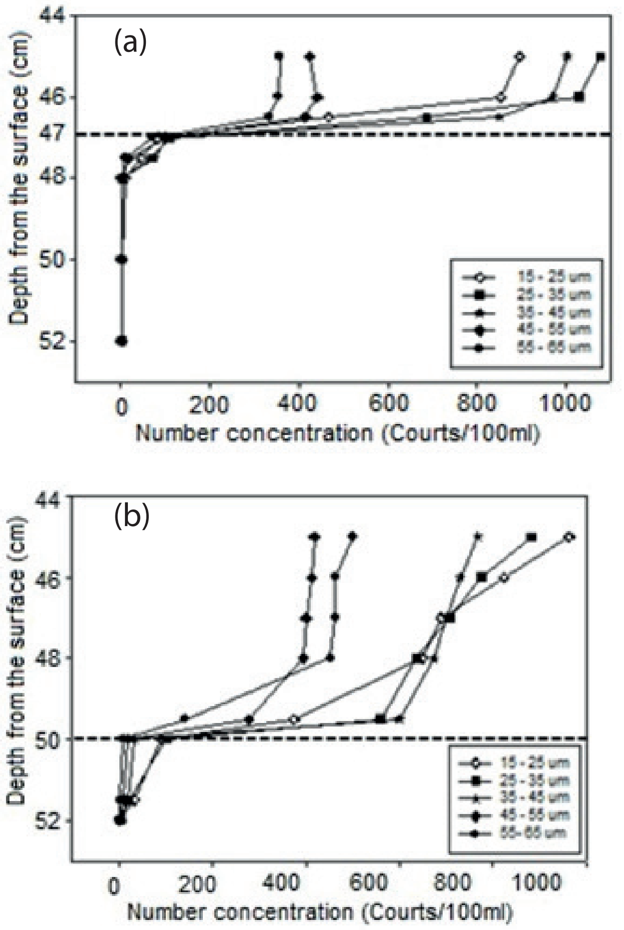

Fig. 5. Bubble bed depth under air at 5 atm with: (a) NaCl 0 ppt and (b) NaCl 35 ppt.

Table 3
Average bubble bed depth under various gas and pressure conditions

Gas	Salinity	2 atm	3 atm	4 atm	5 atm
Air	NaCl 0 ppt	–	40 cm	44 cm	47 cm
Air	NaCl 35 ppt	–	42 cm	46 cm	50 cm
CO_2	NaCl 0 ppt	–	–	–	40 cm
CO_2	NaCl 35 ppt	–	–	–	45 cm

in a solution through the Marangoni effect, which is the equilibrium between surface tension and increased shear stress with increasing salinity. In other words, in saline water, the bubble rising velocity is decreased by increasing drag force, which in turn increases the bubble bed depth due to salinity.

3.3. Particle removal efficiency with salinity

To compare particle removal efficiencies between saline water and non-saline water, air bubbles were generated at 2, 3, 4, and 5 atm. Table 4 shows the particle removal efficiencies with salinity under these various pressures. At 35 ppt NaCl and 3, 4, and 5 atm, the bubbles were similar in average size and the bubble bed depth was somewhat deeper due to the salinity. Therefore, contrary to expectations that the process would be higher efficiency in saline water, there were no substantial differences at these pressures.

Table 4
Particle removal under various gas and pressure conditions

Gas	Salinity	2 atm	3 atm	4 atm	5 atm
Air	NaCl 0 ppt	64.7%	92.3%	89.7%	92.3%
Air	NaCl 35 ppt	69.3%	91.0%	91.5%	90.0%

In saline water, the bubble bed is deeper because of rising velocity reduction; on the other hand, the bubble bed is lower density. Accordingly, there is not a large difference in particle removal efficiency. At 2 atm and NaCl 35 ppt, efficiency was slightly higher in the saline water; the collision efficiency may have been increased by smaller bubbles [3,13].

4. Conclusions

When generating bubbles under air, the influence of salinity on the physical characteristics of the bubbles (bubble size and bubble bed depth) is not large enough to cause significant differences. Efficiency has a greater dependence on operation and design conditions; in particular, similarly high efficiencies were observed at a certain pressure (3 atm in this study). Therefore, we suggest that the impact of salinity need not be given special consideration. However, salinity should be given some consideration for higher loading rate DAF processes with a high downward velocity, because the bubble bed is deeper and lower density due to salinity.

The DAF process has been applied in SWRO desalination plants at dozens of million imperial Gallons per day since 2009. Because such a short period of time has elapsed since its initiation, basic research remains to be carried out to determine optimum design and operating conditions.

Acknowledgement

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