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Feasibility of carbon dioxide bubbles as a collector in flotation process for water treatment

Dong-Heui Kwak and Mi-Sug Kim

ABSTRACT

A series of laboratory experiments were carried out to investigate particle separation efficiency and flotation characteristics using CO_2 bubbles. The primary objective of this study was to discover the feasibility of CO_2 bubbles as an applicable unit of flotation process in water and wastewater treatment plants. Fundamental measurements were conducted to characterize the CO_2 bubble from the physical viewpoint in water, including bubble size distribution and zeta potential under various operational conditions. In addition, the removal efficiency of solids was experimented using laboratory scale plant applied CO_2 bubbles, namely the dissolved carbon dioxide flotation (DCF) process. CO_2 bubble diameter was a little larger than air bubble diameter and macro-bubble numbers increased considerably above 202.65 kPa saturator pressures. The CO_2 bubble demonstrated a little higher electrical charge in a typical pH range. This study confirmed the feasibility of CO_2 bubbles in the flotation process for water treatment, as a part of reducing greenhouse gas emission. Further study is positively necessary to reduce the CO_2 bubble size (larger than the air bubble size) and to prevent the formation of macro bubbles causing the reduction of water treatment efficiency, especially.

Key words | bubble, carbon dioxide, dissolved air flotation, flotation, particle, water treatment

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INTRODUCTION

Flotation is classified by existence of froth as well as by objects to be applied (Hyde *et al.* 1977). According to bubble generation skills, it can be classified into dissolved air flotation (DAF), dispersion air flotation (DF), vacuum flotation (VF), electrolysis flotation (EF), microbiological flotation (MAF), etc. Among the processes mentioned above, DAF is known to be a process of the simplest and the safest efficiency and the dissolved air in water produces bubbles as decreasing pressure in a stream of water with saturated air. Three kinds of flotation are mainly in use: VF, micro flotation, and pressurized flotation. Pressurized flotation is also called DAF, which is commonly widely used. The DAF process, however, requires high energy consumption and high operating pressure of about 405.3–607.95 kPa. It has a tendency to decrease the soluble oxygen percentage in the pressurized saturator of the DAF process. As a part of resolving this problem and reducing carbon emission, a technical development for water treatment has been tried using a high soluble gas such as carbon dioxide (CO_2) in recent years, but it is not entirely satisfactory yet.

There are many cases of froth flotation or electroflotation using various gases (i.e., hydrogen gas) instead of air in the field of industry but few in the field of water treatment. The AGF (anoxic gas flotation) process is an improved anaerobic digestion process that uses anoxic gas (without oxygen) to float, concentrate, and return bacteria, organic acids, protein, enzymes, and undigested substrate to the anaerobic digester for the rapid and complete conversion of waste slurries to gas and soluble constituents (Burke 1997). Carbon dioxide or a 1:3 mixture of carbon dioxide and nitrogen has been applied to treat abattoir wastewater in laboratory scale tests (Travers & Lovett 1985). Meanwhile, most industrial facilities using fossil fuel emit carbon dioxide (CO_2), and the emitted CO_2 is recognized to be a typical greenhouse

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gas causing global warming problems. Recently, CO_2 reduction and its reuse have been actively studied in several fields. Carbon capture and storage (CCS) plays a role as part of the technology industry for greenhouse gas reduction but there are still some significant problems to resolve. Capturing CO_2 is associated with high upfront investment costs, highly variable operating costs and, in most cases, leads to a significant energy penalty. Carbon capture and utilization (CCU) has been suggested as a partial alternative to divert some carbon dioxide from the transport and storage route (Styring *et al.* 2011). Representative plans for CO_2 utilization consider chemical conversion to chemical feedstock and fuel, accelerated mineralization through carbonization of rocks, biorenewable fuels and materials from algae, and so on.

The digestion processes of anaerobic water treatment, bio-gas plant, landfill, industries, and so on, emit large amounts of CO_2. Thus, the application of CO_2 bubbles in water treatment plants with the CO_2 gas emission source may be a very useful tool as an alternative to CCU for wastewater treatment as well as the reduction of CO_2 gas emission. Based on the CO_2 gas emission reduction, the primary objective of this study is to discover the feasibility of CO_2 bubbles as a particle collector of the flotation process in water or wastewater treatment plants. The applicable unit of the flotation process considered is the dissolved carbon dioxide flotation (DCF) process, which uses CO_2 gas instead of air as an alternative to DAF. DCF also has the advantage of CO_2 reduction and its reuse as a solution to the global warming problem.

In confirming the feasibility of CO_2 in water treatment, it is necessary to evaluate the actual efficiency of water treatment by the flotation process. Many previous studies (Edzwald 1995; Fukushi *et al.* 1995; Han 2002; Kwak *et al.* 2009) have reported that the most important parameters in the DAF system are the surface characteristics (zeta potential) and the size distribution of both bubble and particle. Particle size as an important parameter in flotation has been the focus of flotation research for decades (Shahbazi *et al.* 2010). According to critical review of the various models existing in the literature for the calculation of collision efficiency between particle and single rising gas bubble (Dai *et al.* 2000; Edzwald 2010), the differences in collision efficiencies obtained between the various models are mainly explained in terms of the degree of mobility of the bubble surface and a consideration of the inertial forces acting on the particle. As pointed out above, however, the mobility degree of the bubble surface and the inertial force are essentially decided by the zeta potential and the sizes of bubble and particle.

This study estimated the fundamental feasibility of the DAF system using CO_2 as an alternative to reduce CO_2 gas emission and to resolve the disadvantage of the existing DAF process's high energy consumption. To discover the possibility of CO_2 application in the field of water treatment, this study focused on estimating the removal efficiency depending upon the most important parameters, such as bubble size distribution and the zeta potential. The fundamental measurements were conducted to characterize the CO_2 bubble from the physical viewpoint in water including bubble size distribution and rising velocity under various operational conditions.

METHODS AND MATERIALS

Experimental equipment

A series of laboratory experiments were carried out to investigate particle removal efficiency and flotation characteristics using CO_2 bubbles and air bubbles. In addition, the removal efficiency of solid was examined using laboratory scale plant applied CO_2 bubbles, namely the DCF process. Results of treatment efficiency and the flotation separation characteristics in the DCF process were compared with those of the DAF process. Kaolin as particle was spiked into the pure water to make the samples that were tested.

In the laboratory scale plant dimensions for the DCF or the DAF shown in Table 1, CO_2 bubbles or air bubbles were applied for attachment on the surface of flocs formed by coagulants. The saturator pressure was from 101.325 to 303.975 kPa for the DCF and it was from 405.3 to 607.95 kPa in the DAF for comparison. A pressure gauge was installed at the top of the saturator to ensure the correct pressure. Experiments in this study were replaced by a CO_2 bombe and air bombe if necessary, rather than using an air compressor or CO_2 compressor. A bombe is defined as a steel container of compressed gas for storage, transportation, and utilization. A schematic diagram of the DCF

Table 1 | Dimension of laboratory scale pilot plant and equipment

Compressor	**Mass flow controller**
Inflow air, 111 L/min	Maximum pressure, 9.9 kg_f/cm^2
Outflow air, 60 L/min	Control range, 0–10 kg_f/cm^2
Operation range, 8 atm (maximum)	Air flow rate, 0–10 L/min
Saturator	Flotation column
Diameter, 148 mm	Diameter, 100 mm
Height, 430 mm	Height, 1,000 mm
Total volume, 7.40 L	Total volume, 7.85 L (effective volume 6.28 L)

laboratory scale plant used in this study is described in Figure 1. Two factors, saturator pressure and injection nozzle, may have a slight influence on the bubble diameter. Thus, this study used a typical valve instead of an injection nozzle for both air and CO_2 to determine the diameter difference due to gas properties.

The recycle ratio is one of the main operational parameters when operating the flotation tank consecutively. In this batch test, the recycle ratio in the saturator (R_s) was defined as percent (%) of saturated water volume (V_s) inflowing into flotation column to sample volume (V_t) treated at the flotation column.

Bubble diameter and zeta potential measurement

Prior to flotation, artificial raw water containing clay was coagulated using poly-aluminum chloride (PACl). The pH was adjusted for measuring zeta potential by adding HCl or NaOH. The zeta potential was measured to examine the underlying surface charge to obtain further insight into the mechanism of removal by an electrophoretic light scattering (PhotalOtsuka ELS-8000, Japan) apparatus. Micro-bubble size distribution was investigated using the laser beam particle resolver of 'Eye Tech' by ANKERSMID (The Netherlands). The Eye Tech generates voltage (charge) as reducing light requirement of an auto-diode detector if the laser beam with high speed revolution is blocked by the particle while scanning each particle. It can directly measure a particle size by the blocked time because the scanning speed of the laser beam is constant. It measures the particle size in ranges of $0.1 \sim 3,600\ \mu m$ and produces a highly accurate analysis due to eliminating data which are off-center of the particle by pulse wave-type analysis and pass through the outside of the laser beam. The measurement was performed for 2 seconds in constantly generating bubbles. In measuring bubble size diameter, the quickest measurement was performed because it was difficult to measure accurately size since large-sized

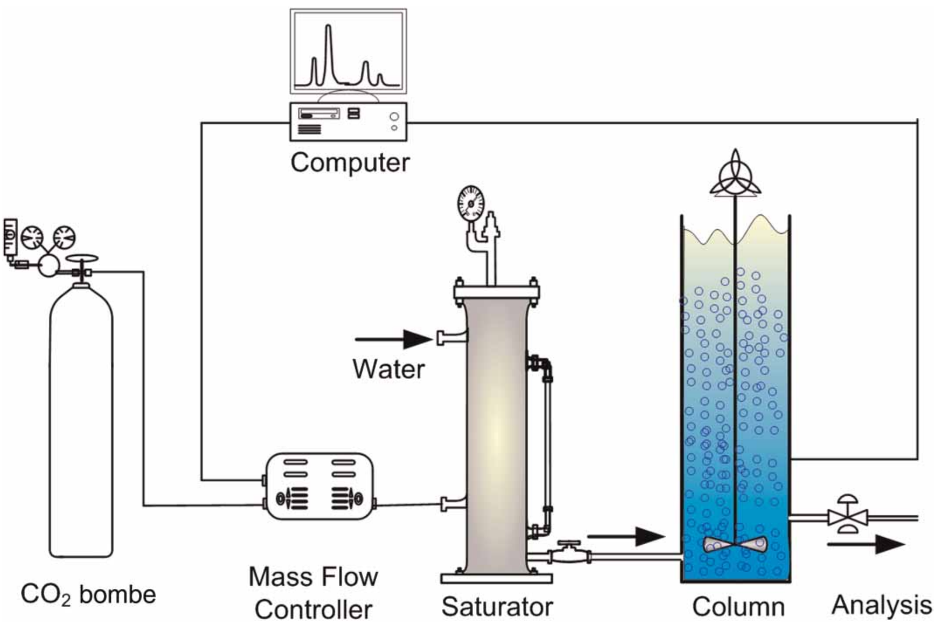

Figure 1 | Schematic diagram of laboratory scale pilot plant used in this study.

bubbles floated and disappeared quickly and only small-sized bubbles eventually remained.

Set-up for coagulation and bubble volume measurement

The samples used in this experiment were artificial standard solution (turbidity 10–200 NTU) mixed with pure tap water and the kaolin. The coagulation condition, after adding a coagulant PACl (poly-aluminum) 20 ppm and an alkaline (NaOH), was to mix rapidly at high speed 200 rpm for 5 min and slowly at low speed 50 rpm for 15 min. In the DCF tank, residence time was a total of 10 min, this being considered the necessary time to float sufficiently. After completing the flotation, samples were collected for analysis. The flotation column was made from a transparent acrylic tube which included an inlet from the saturator 4 cm from the bottom of the flotation column and an outlet 5 cm from the bottom of the flotation column, and then connected to a controlled volume pump. Saturated water (or milky water) from the saturator flowed into the flotation tank continuously. The volume of the micro-bubble layer formed in the flotation column was measured. The micro-bubble layer was called 'milky water or bubble cloud' because it looked like a cloud. When the saturated water instantly flowed into the flotation column filled with pure distilled water, the micro CO_2 bubbles formed a group and, at the same time, floated up spreading out slowly. Also, the rising velocity of CO_2 bubbles formed in the DCF was determined as measuring the time required for floating and passing through the constant height of the flotation column.

RESULTS AND DISCUSSION

Suspended solids (SS) removal efficiency

SS removal efficiency was compared between a DCF pilot plant and a DAF pilot plant. The DCF used CO_2 bubbles as a particle collector during water treatment, while the DAF applied an air bombe instead of a CO_2 bombe. As shown in Figure 2, the results showed opposing patterns. Below 202.65 kPa of saturator pressure, the SS removal

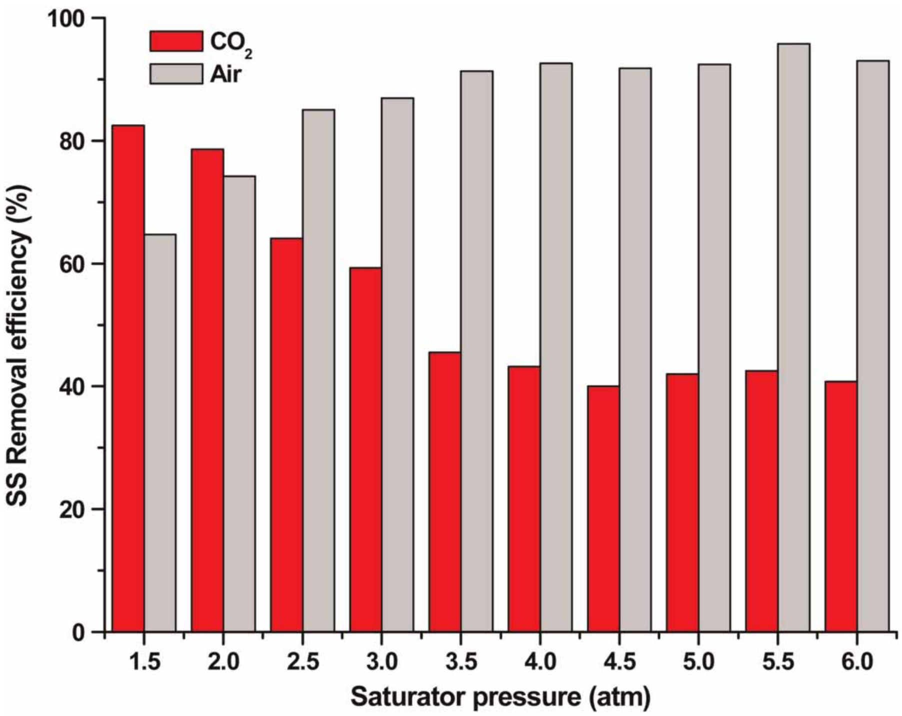

Figure 2 | Comparison of SS removal efficiency between CO_2 bubbles and air bubbles.

efficiency by the CO_2 bubbles was higher than that by the air bubbles. In a higher pressure range, however, the DAF using the air bubbles achieved better results. The SS removal efficiency by DCF in particular tended to decrease sharply in excess of 202.65 kPa. The falling tendency was considered an impact of the macro bubbles as they are known to decrease the efficiency of water treatment and many macro bubbles in the flotation column were observed with the naked eye. In this respect, further study is required to investigate the cause of the macro-bubble formation at over 202.65 kPa of saturator pressure in the DCF pilot plant.

Diameter of CO_2 bubble

Measurement of micro-bubble diameter formed in the DAF was not easy because bubbles formed not individually but in a group like a cloud and their sizes were also very fine in a range of bubble diameters (d_b) 20–100 μm. Recently, image analysis methods, such as particle image velocimetry (PIV) and X-ray filming technique, have been used to measure micro bubbles but as yet have not been applied to measure micro bubbles in the bubble cloud formed in the DAF. The bubble diameter distribution in the flotation column is shown in Figure 3. Figure 3(a) shows the CO_2 bubble diameter measured by Eye Tech. When the CO_2 bubble diameter, generated in the CO_2 gas solution tank with a pressure condition under 1.5 kg_f/cm^2, was analyzed, bubbles less than 30 μm in diameter comprised 10% (D_{10}) of the total generation of bubbles, 50% (D_{50}) about 65 μm, about 3% for more than 100 μm in diameter, and 72.9 μm was the average CO_2 bubble size.

Figure 3(b) shows the air bubble diameter produced in the air solution tank under the pressure condition 4.0 kg_f/cm^2. It indicates 10% (D_{10}) of the total generation was less than 10 μm of the air bubble diameter, 50% (D_{50}) was about 40 μm, about 0.5% was more than 100 μm, and the average air bubble diameter was 46.5 μm. The results of bubble size measurement revealed that the CO_2 bubble diameter, formed from the DCF pilot plant in this study, was greater than the diameter of a typical DAF process in the range of bubble diameters (d_b) 20–100 μm.

The next measurement was to inspect the size distribution of the CO_2 bubble with variations of pressure. Table 2 included the measuring results of the CO_2 bubble diameter with various pressure conditions. The average CO_2 bubble diameter in the DCF increased depending on the saturator pressure, as shown in Table 2. D_{50} denoted 50% of the total bubbles; the bubble diameter did not increase greatly with increasing pressure, but the bubble diameters for D_{80} and D_{90} increased very much with increasing pressure.

According to Leppinen & Dalziel (2004), bubbles greater than 100 μm reduce the water treatment efficiency because it is difficult to separate particles from water due to their large hydraulic shear force as well as for the low efficiency of collision and adhesion between floc particles and macro bubbles. Also, the number of macro bubbles was increased greatly over 202.65 kPa, as shown in Figure 4.

The saturator pressure in the DAF was controlled at 405.3–607.95 kPa and it became saturated air in the pressurized water of the saturator. The bubble sizes over 354.64 kPa did not decrease any further and the bubble diameter 30 μm was obtained at 405.3 kPa (Han *et al*. 2002). However, the results of the DCF process were comparatively different from those of the DAF. The average CO_2 bubble diameter increased with increasing pressure and rose towards the higher figures of the macro bubble over 100 μm in diameter. Therefore, it is desirable to maintain the operating pressure of the saturator within 202.65 kPa.

pH and zeta potential

Carbon dioxide is soluble in water and it reversibly converts to H_2CO_3 (carbonic acid). The relative concentrations of CO_2, H_2CO_3, and the deprotonated forms HCO_3^- (bicarbonate) and CO_2^- (carbonate) depend on the pH. If CO_2 is soluble in water, H^+ (hydrogen ion) in water increases, pH decreases, and it can cause difficulty in treating water. Thus, the pH of water was measured to examine the CO_2 solubility change with change of the saturator pressure.

Figure 5 exhibits the various pH values of the saturated water (recycle water) with the saturator pressure. The results show the pH value was maintained over 4 with the increasing pressure and remained above 4.5 irrelevant of the amount of CO_2 bubbles dissolved at saturator pressure 1.5 atm. Figure 6 shows the change in pH value by carbon dioxide bubbles of saturated water in the flotation column. The saturated water with low pH flowed into the flotation

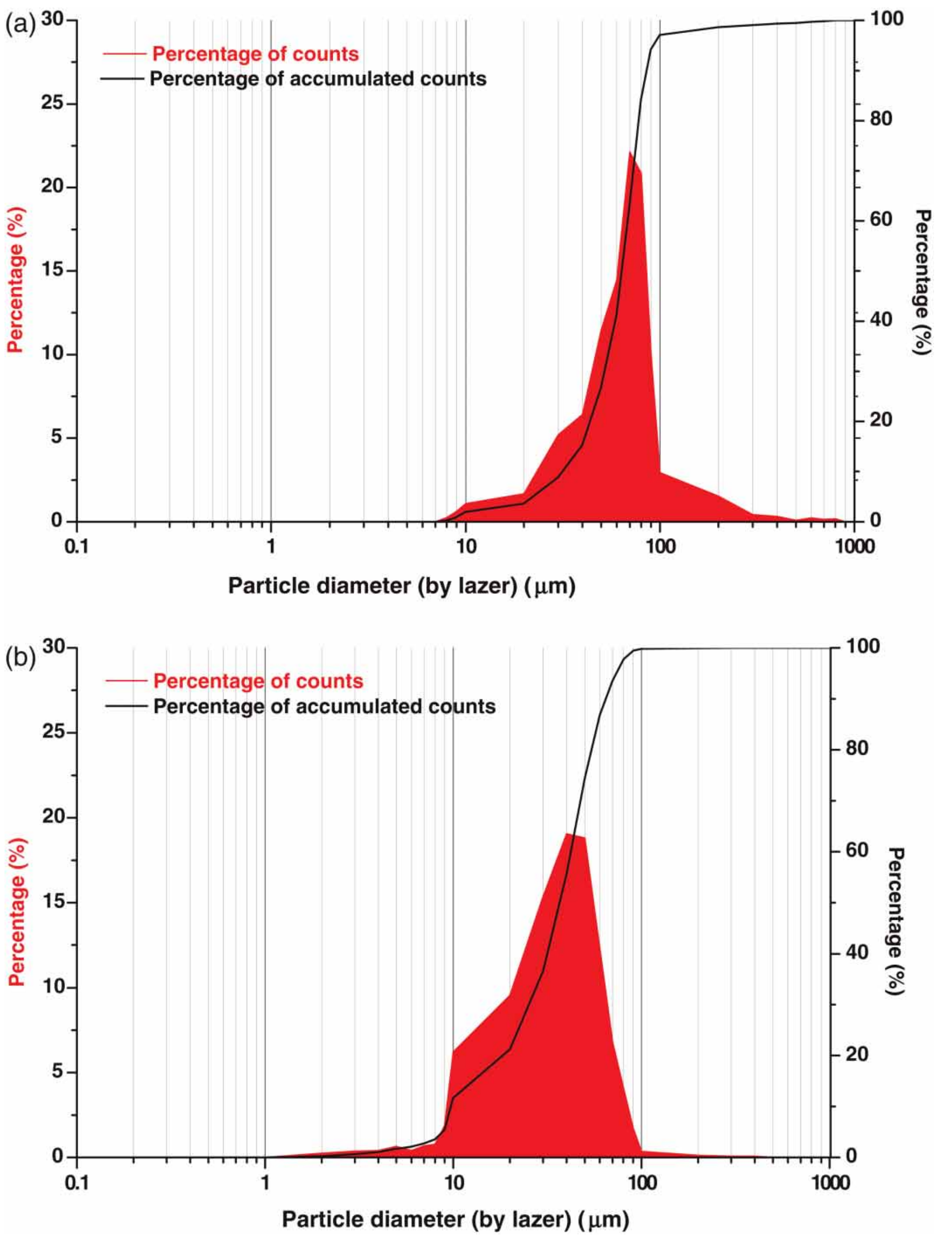

Figure 3 | Bubble diameter distribution in flotation column. (a) CO_2 bubbles, (b) air bubbles.

column and the pH was measured for saturated water, influent of the flotation column, and effluent of the flotation column. After the influent (pH 6.34 ~ 6.92) mixed with the saturated water (pH 4.67 ~ 5.34), the pH of the effluent was in the range of 5.78–6.27. As mentioned above, the pH, in general, decreased in the DCF pilot plant using CO_2 bubbles as a particle collector but it did not create any serious problems when applying the DCF for the water treatment. In this study, coagulation in raw water was conducted for the floc formation. After the coagulation process, effluent and milky water collided and attached in the flotation column. The pH of milky water became low for CO_2 saturation and this low pH of milky water did not influence the coagulation of the raw water.

Zeta potential is a term commonly used and a scientific term for electrokinetic potential in colloidal systems. When

Table 2 | Summary of bubble diameter measurements (μm)

Description	Pressure of saturator P_s 1.25	P_s 1.50	P_s 1.75	P_s 2.00	P_s 2.50	P_s 3.00
D_{10}	27.3	31.8	32.0	40.5	44.2	48.8
D_{50}	59.8	64.0	65.7	71.2	76.5	82.6
D_{80}	78.8	78.0	83.1	90.8	114.8	279.4
D_{90}	89.0	85.8	96.2	154.4	334.1	552.2
Average	76.9	72.9	87.4	102.6	145.9	204.3

tiny mineral or organic particles are suspended in fluid, zeta potential maintains the dispersion or discreteness of the particles in suspension. Commonly, zeta potential is high as pH is low. In this respect, advantageous conditions for water treatment may be achieved in floating the particles using the bubbles of the negatively charged electrons in water as the low pH causes the zeta potential of particles to increase. This study (Figure 7) examined the change of the zeta potential of the particles and the bubbles, which appeared with decreasing pH by the amount of dissolved CO_2 and characteristics of CO_2 bubble.

The result of zeta potential measurement indicated the negative value for both the air bubble and the CO_2 bubble in the common range of pH. The average pH was reduced by about 0.64 from 6.69 to 6.05 due to CO_2 dissolution in the laboratory test. Some growth of the zeta potential was increased in water but there was no significant difference. The pH had a very slight effect on the zeta potential and the CO_2 bubble also produced slightly higher electrical charges. The ranges of pH, measured in each step of the water treatment, are classified as shown in Table 3 for stability of the solution-zeta potential. Both air bubbles and CO_2 bubbles were moderately stable in the influent near pH 6.5. Also, they were included in the threshold domain of light dispersion. In the range of pH $4.5 \sim 5.5$, on the other hand, the zeta potential of the CO_2 bubble indicated more than -10 mV in the agglomeration range (the threshold of agglomeration is -10 mV). In the flotation column, there was a collision–attachment reaction between the bubble and the particle, pH value was 6 ± 2, and the zeta potential of the CO_2 bubble was about 13 mV, which was in the threshold range of agglomeration.

Bubble volume concentration (BVC) and effective bubble yield

When CO_2 concentration of the air is 0.0335%, water vapor pressure is 3.1715 kPa, and Henry constant of CO_2 is 3.3358×10^{-4} mol/L kPa at 25 °C of air temperature, the partial pressure of CO_2 in the air, P_{CO2}, is 3.435×10^{-2} kPa and the concentration of CO_2, [CO_2], is 1.028×10^{-5} mol/L. This study observed BVC depending on the rising velocity of the CO_2 bubble cloud formed when the saturated water flowed into the flotation column. The BVC decided air to solid ratio as the most fundamental operating parameter and the particle concentration for treating water by the flotation.

This study was conducted at 18 ± 2 (T) average water temperature. Saturator pressure was 121.59 kPa initially and increased up to 202.65 kPa with 20.265 kPa pressure increments. CO_2 gas was input until the CO_2 gas could be seen by eye in the unfilled space with the pressurized water because the CO_2 gas was supersaturated in the pressurized water. Inflow was 10% of the flotation tank volume 1 L. Figure 8 shows variation of bubble volume fraction (concentration) depending on the rising velocity of CO_2 bubble cloud (saturator pressure). The CO_2 bubble cloud was measured for rising velocity, 1.88 m/min, related to 240 μm that was twice 120 μm known as the typical upper limit of the bubble diameter. The bubbles (greater than this rising velocity) belonged to macro bubbles, which remained out of the actual water treatment. As shown in Figure 8, there was not much difference depending on saturator pressures below 120 μm but a significant difference at various saturator pressures in the range between 120 and 240 μm. Therefore, it can be supposed that macro bubbles over 120 μm influence the removal efficiency of particles (SS).

Figure 9 presents the removal efficiency of SS depending on the saturator pressure. The SS removal efficiency was over 80% at 151.99 and 177.32 kPa. Above 202.65 kPa, the removal efficiency had a low average and wide deviation. When the saturator pressure increased, the low SS removal efficiency was caused by the macro-bubble numbers. As shown in Figure 8, the higher pressure occurred when the macro-bubble numbers increased. In fact, when the operating saturator pressure was over 202.65 kPa, the macro bubbles were definitely observed with the naked eye because

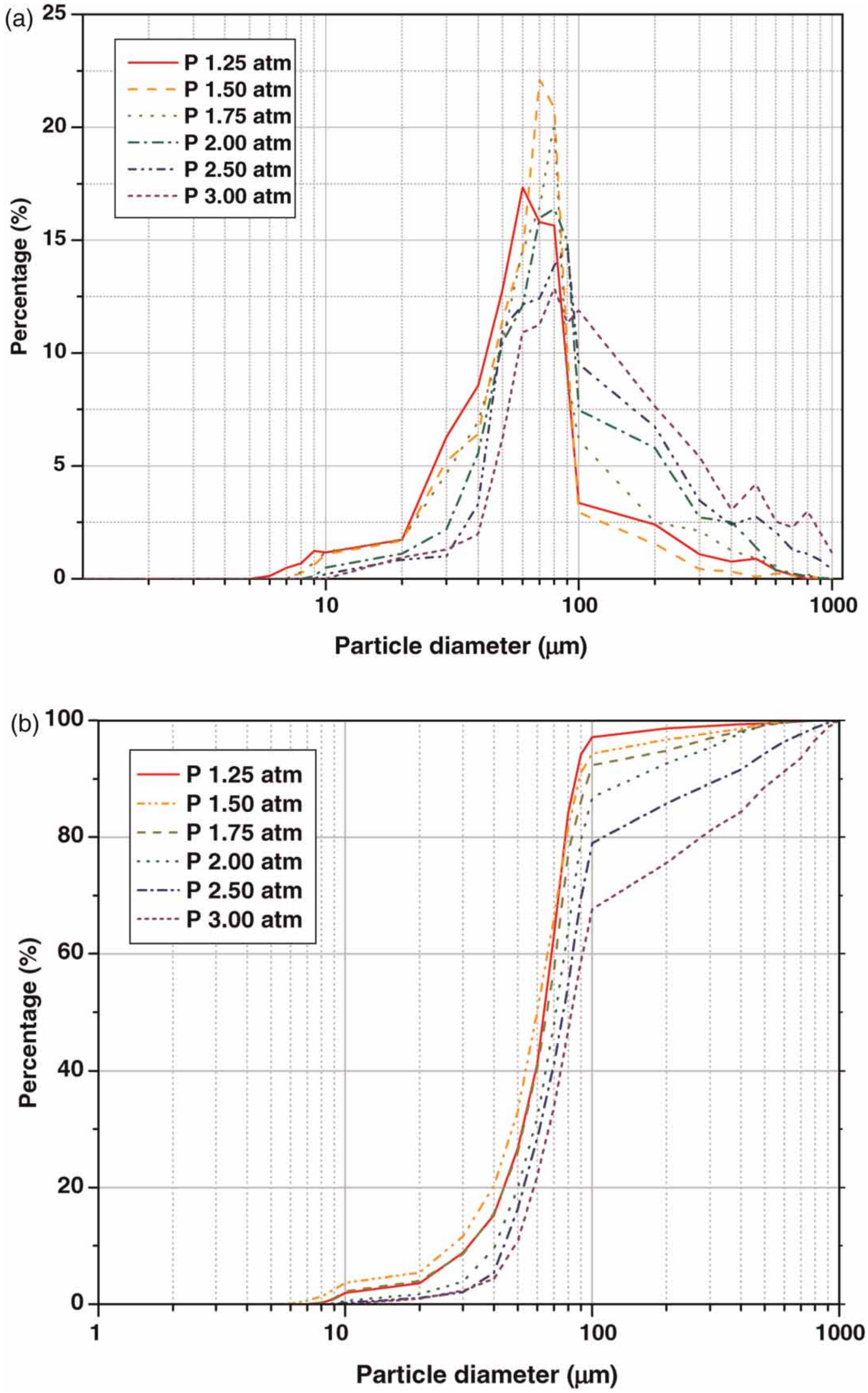

Figure 4 | CO_2 bubble diameter distribution in terms of saturator pressure. (a) Percentage of bubble counts; (b) accumulated percentage of bubble counts.

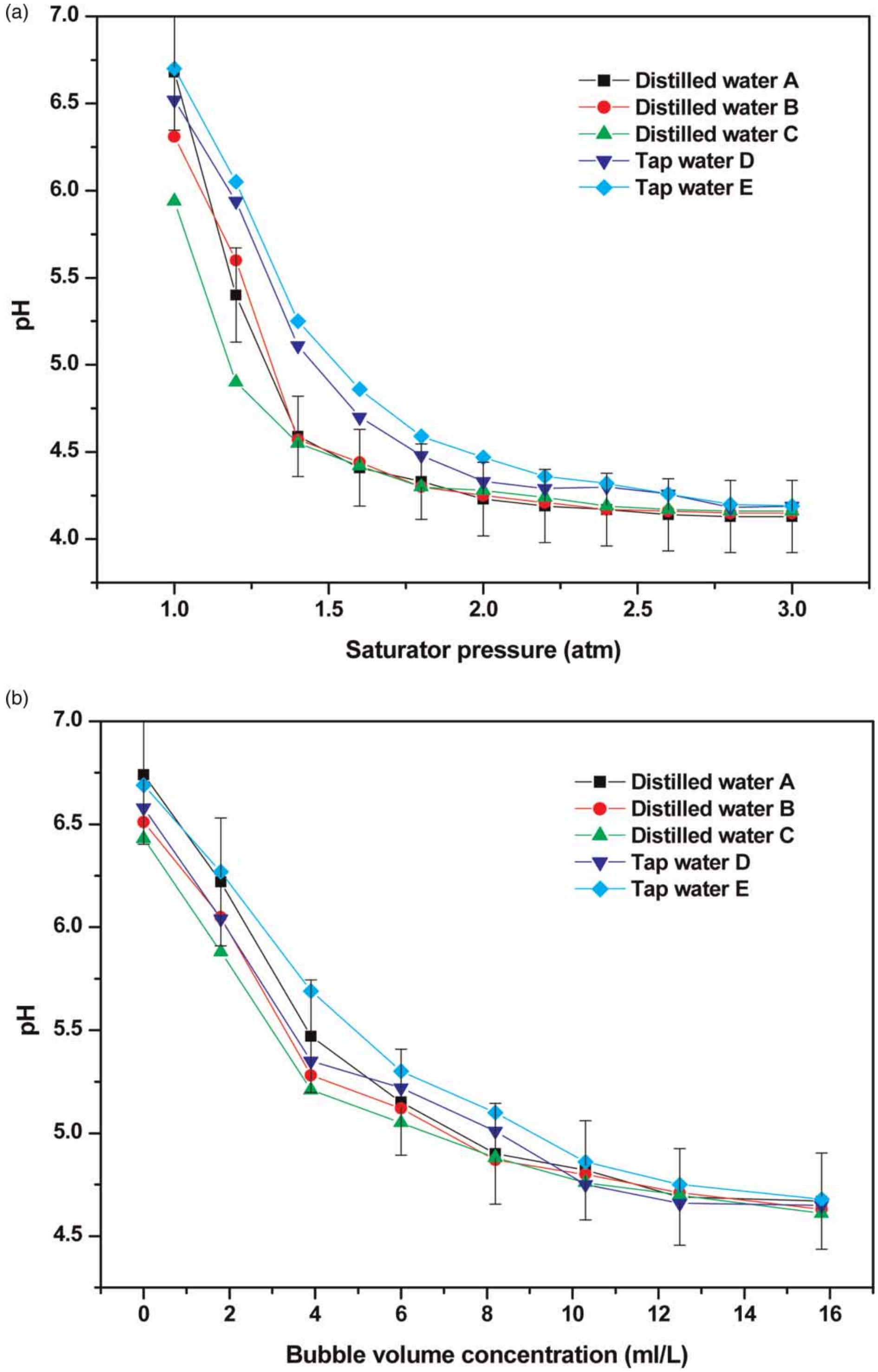

Figure 5 | Change of pH by carbon dioxide bubbles in saturation tank. (a) Saturator pressure (BVC 4.5 ml/L); (b) bubble volume concentration (P_s 151.99 kPa).

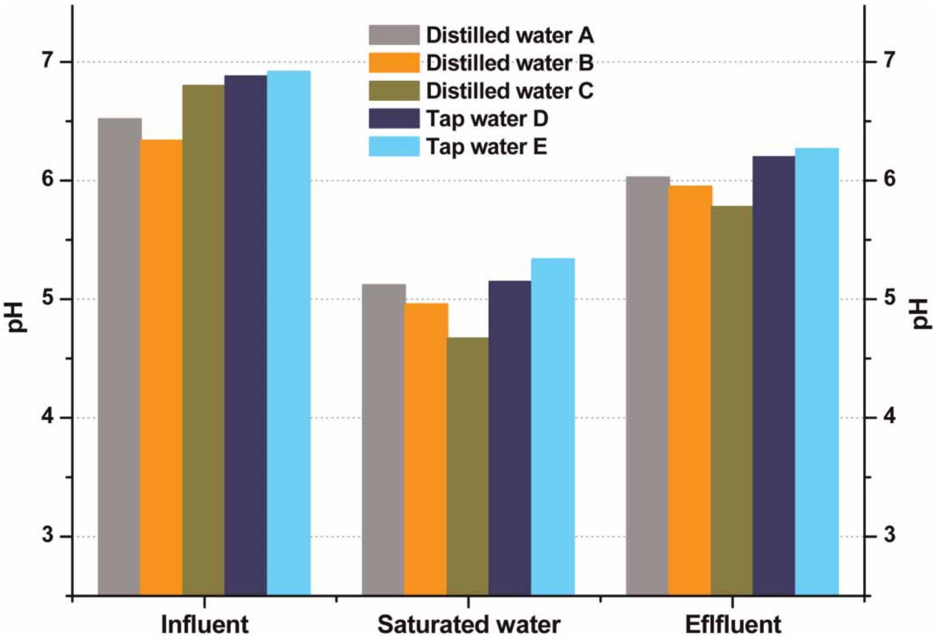

Figure 6 | Change of pH by carbon dioxide bubbles of saturated water in flotation column. (Operation condition: recycle ratio 10% (V/V), P_S 151.99 kPa.)

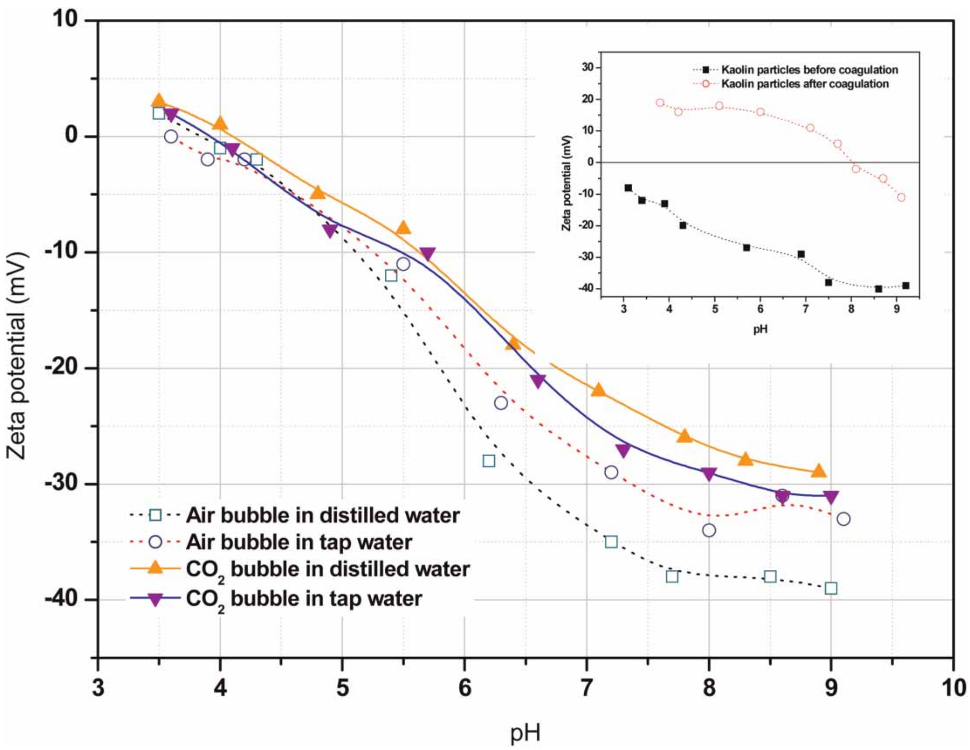

Figure 7 | Zeta potential for before and after coagulation in terms of pH.

Table 3 | Stability of solution-zeta potential (Riddick 1968)

Stability	Average zeta potential (millivolts)
Extreme to very good stability	−100 to −60 mV
Reasonable stability	−60 to −40 mV
Moderate stability	−40 to −30 mV
Threshold of light dispersion	−30 to −15 mV
Threshold of agglomeration	−15 to −10 mV
Strong agglomeration and precipitation	−5 to +5 mV

they grew exponentially up to several mm in diameter and the water stream in the flotation column was disturbed by the macro bubbles.

Gas to solid (G/S) ratio

Air to solid (A/S) ratio is a principal design parameter for a dissolved flotation system. It is theoretically measured as the available gas volume quantity per the removable solid quantity. Typical values of DAF range between 0.005 and 0.06 mL/mg. In this study, G/S ratio was employed instead of A/S. For the gas dissolving saturator vessel, the relation between G/S ratio, gas solubility, operating pressure, solid concentration, flow rate, and recycle rate, is given by the following equation:

$$\frac{G}{S}\,\text{ratio} = \frac{c \cdot \text{Sg} \cdot (f \cdot P - 1) \cdot R}{\text{SS} \cdot Q}$$

where G/S is gas to solid ratio (mL-gas/mg-solid), c is weight constant of gas (mg/mL), Sg is solubility of gas in water (mL/L), f is fraction of saturation (usually 0.5), P is gas dissolving system pressure (atm), SS is influent suspended solids (mg/L), R is pressurized recycle flow rate (m^3/day), and Q is flow rate (m^3/day).

Figure 10 shows the removal efficiency of turbidity in terms of saturator pressure depending on the G/S ratio of air bubble and CO_2 bubble. In the typical design range of G/S ratio in DAF, 0.005 ~ 0.06, the removal efficiency by DCF using the CO_2 bubbles was a little lower than that by DAF using the air bubbles as the particle collector. The low particle separation efficiency in the flotation process

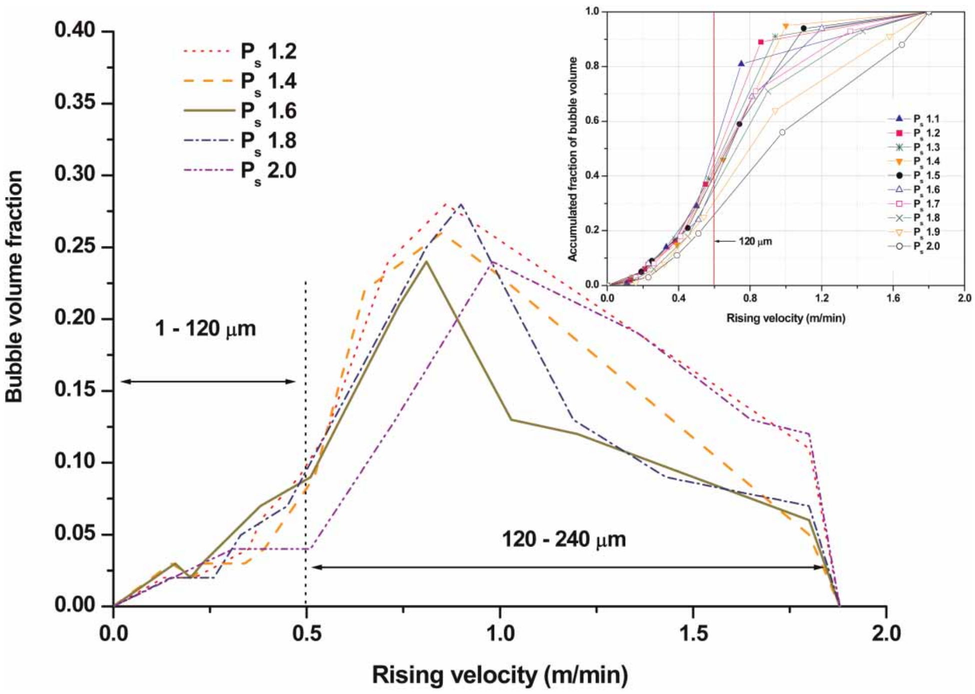

Figure 8 | Variation of bubble volume fraction depending on saturator pressure.

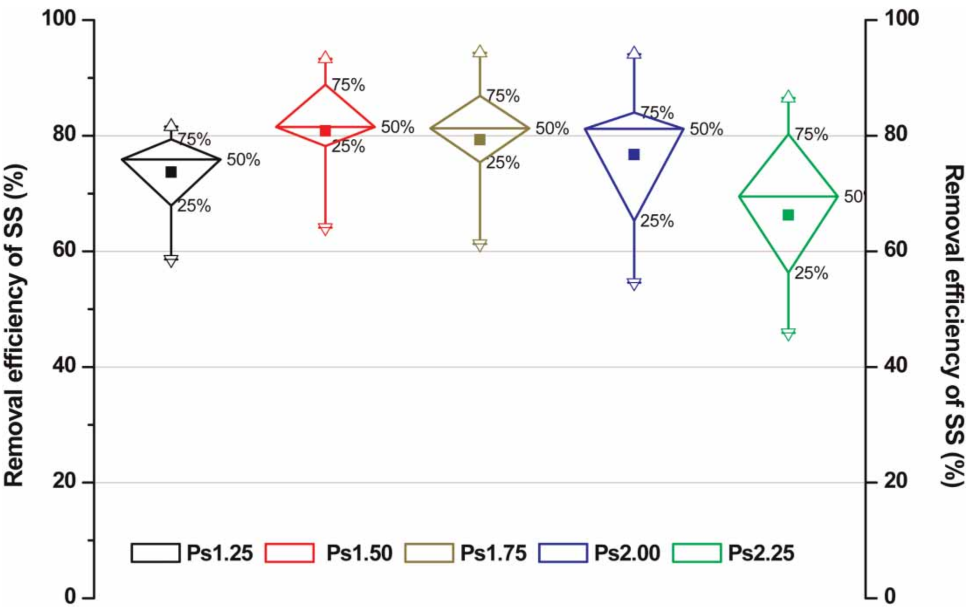

Figure 9 | Removal efficiency of SS depending on saturator pressure. (Operation condition: influent SS 84.2 mg/L, recycle ratio 10%.)

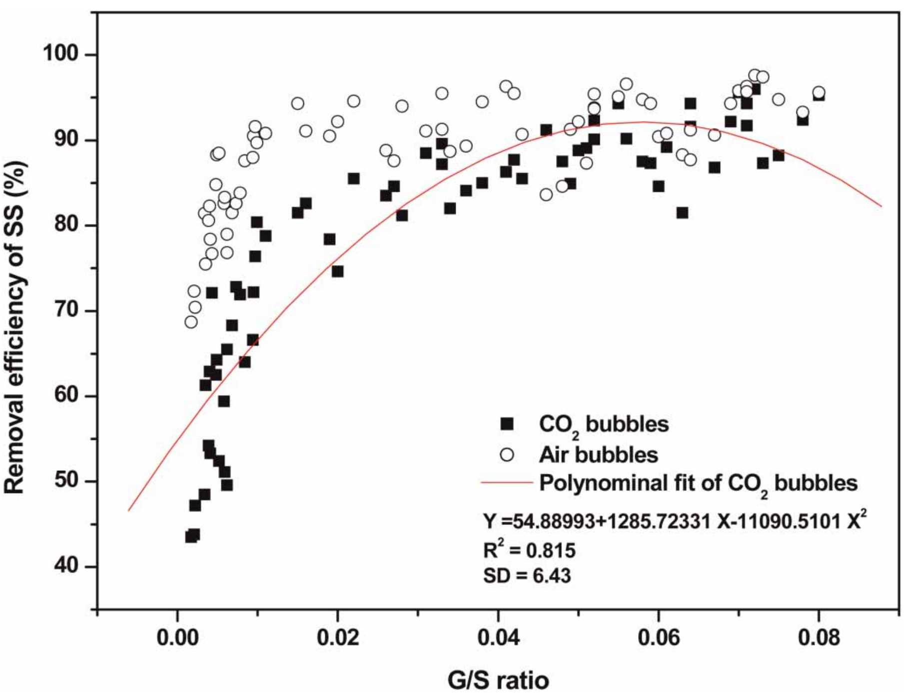

Figure 10 | Removal efficiency of turbidity in terms of saturator pressure.

may be improved by an alternative operation with high G/S ratio. In the case of high G/S ratio being applied to approaching this aim in the DCF process, it is desirable to operate not with high saturator pressure but with high recycle ratio, and to prevent macro-bubble generation. However, the operation with the high recycle ratio causes an increase in power consumption. Thus, in order to minimize power consumption the optimal recycle G/S ratio is required.

Ultimately, the affordable efficiency for the water treatment might be obtained by applying the CO_2 bubble as a particle collector under operating conditions of high recycle ratio and low saturator pressure. The fundamental experimental results of this study proved the possibility of energy consumption reduction for low operating pressure in the DCF, and the useful condition of particle separation. However, there was no significant effect of increasing the zeta potential, indicated by the decreasing pH in the water.

SUMMARY AND CONCLUSION

This study conducted a series of experiments to examine the fundamental feasibility, focused on bubble size distribution and zeta potential of CO_2 bubbles, as an alternative to reduce CO_2 emission into the air as well as solving the disadvantage of high power consumption in the conventional DAF process.

According to bubble diameter distribution, the CO_2 bubble diameter was distributed a little more than air bubble diameter and the macro-bubble numbers increased considerably above 202.65 kPa of saturator pressure. It could be seen that the SS removal efficiency decreased rapidly above 202.65 kPa when testing water treatment using DCF. Zeta potential had negative values for both CO_2 bubbles and air bubbles in the typical pH range but the CO_2 bubble demonstrated a little higher electrical charge.

In the typical G/S ratio range, the SS removal efficiency by the CO_2 bubbles was a little lower than the efficiency by air bubbles because the macro CO_2 bubbles caused the SS removal efficiency to decrease. The more the G/S ratio, the less difference in the efficiency was confirmed. Therefore, it is desirable to operate at a high recycle ratio (not at a high saturator pressure) for the maintenance of the high G/S ratio as well as for reduction of the macro-bubble formation.

This study confirmed the feasibility of CO_2 bubbles in the flotation process for water treatment as a part of reducing greenhouse gas emission, recycling the gas CO_2, and reducing energy consumption with low pressure operation. Further study is positively necessary to reduce the CO_2 bubble size (larger than the air bubble size) and to prevent formation of the macro bubble which especially causes a reduction in the water treatment efficiency.

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