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Continuous clarification and thickening of activated sludge by electrolytic bubbles under control of scale deposition

Kang Woo Cho [a], Chong Min Chung [a], Yun Jung Kim [b], Tai Hak Chung [b,*]

[a] Water Environment Center, Korea Institute of Science and Technology, P.O. Box 131, Cheongryang, Seoul 130-650, Republic of Korea
[b] Department of Civil and Environmental Engineering, Seoul National University, Gwanak 599 Gwanak-ro, Gwanak-gu, Seoul 151-742, Republic of Korea

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ABSTRACT

Electroflotation (EF) was investigated as a final clarification of an activated sludge process, to intensify its novel clarification and thickening efficiency. During operation of a biological reactor combined with an EF clarifier, deterioration of clarification efficiency was observed. Scale deposition on electrodes caused a coarse electrode surface, significantly increasing the size of the electrolytic bubbles. The average bubble size was initially 34 μm and increased to 80 μm after bulk cell electrolysis for 150 h. X-ray diffractometry and scanning electron microscopy further characterized the scale deposition as a cluster of calcite ($CaCO_3$) and brucite ($Mg(OH)_2$). Switching the polarity of electrical current clearly alleviated the increase of bubble size, when applied before scale growth. Under the control of scale deposition, excellent clarification was observed, with the effluent turbidity consistently lower than 2 NTU. An efficient thickening, with the concentration of return activated sludge higher than 15 g L^{-1}, was additional advantage of the EF clarifier.

1. Introduction

Efficient separation of biological solids from mixed liquor is an essential aspect governing the performance of an activated sludge process (Cho et al., 2007; Gnirss et al., 1996). Application of tertiary treatment for further solids reduction has became popular for more strict effluent criteria or for water reuse (USEPA, 2004). On the other hand, proper thickening of the return and waste activated sludge is an important consideration since it determines the cost of sludge processing such as stabilization, dewatering and disposal (Campos et al., 2009; Choi et al., 2005; Li et al., 2008). Settling tank has been employed as a final clarifier and a thickening tank for clear effluent and thickened biological solids (Choi et al., 2009). The sedimentation, however, can not be operated by an occurrence of sludge bulking, since it strongly depends on the sludge settleability (Gnirss and Peter-Frölich, 1996; Vocks et al., 2005). A large detention time, directly linked to land use and capital cost, for thickening of waste activated sludge is another limitation (Cho et al., 2009).

Flotation has often been applied to water and wastewater treatment for the separation of low-density particles (Burns et al., 1997; Edzwald, 1995; Meyssami and Kasaeian, 2005; Rijk et al., 1994). Excellent clarification has been reported, while relatively shorter detention time was required than settling. However, the application of flotation to an activated sludge process has been limited to thickening of waste activated sludge (Bratby and Ambrose, 1995; Chung and Kim, 1997; Haarhoff and Bezuidenhout, 1999), using DAF. A few studies could be found employing the DAF as a secondary clarification (Gnirss et al., 1996; Gnirss and Peter-Frölich, 1996; Métivier et al., 2002). However, the reported clarification efficiencies were somewhat ineffective, due to fine flocs escaping from the collision with bubbles.

In this study, based on the knowledge that EF produces very fine bubbles (Burns et al., 1997; Chen, 2004; Cho et al., 2009), it was postulated that the EF as a final clarification would be suitable to separate tiny flocs in the mixed liquor. The EF has been extensively used to separate colloidal pollutants for industrial wastewater treatment (Chen et al., 2002). Several studies (Cho et al., 2007, 2009; Choi et al., 2005, 2009) recently demonstrated the applicability of EF to the clarification and thickening of the activated sludge. It was simple to adjust G/S ratio depending on sludge characteristics and solids loading rates (Cho et al., 2007, 2009). The EF would be relatively independent upon sludge settleability and require a smaller detention time than settling (Choi et al., 2005, 2009). In addition, the separated sludge bed generally showed high solids concentrations more or less than 30,000 mg L^{-1} (Cho et al., 2007; Choi et al., 2009). Thus, a flexible control of the sludge retention time in the biological reactor was also expected by proper thickening for the RAS. Chen (2004) pointed out another strength of EF that the specific electricity consumption (W/m^3) of EF was 16–40% lower than DAF and 40–70% lower than settling in treating oily effluents.

* Corresponding author. Tel.: +82 2 880 7369; fax: +82 2 889 0032.
E-mail address: thchung@snu.ac.kr (T.H. Chung).

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Nomenclature

AA tank	alternately aeration tank
COD	chemical oxygen demand
DAF	dissolved air flotation
DSA	dimensionally stable anode
EDS	energy dispersive X-ray spectrometer
EF	electroflotation
EPS	extracellular polymeric substance
ESEM	environmental scanning electron microscopy
G/S ratio	gas to solids ratio
ICP-AES	inductively coupled plasma atomic emission spectroscopy
MLSS	mixed liquor suspended solids
MLVSS	mixed liquor volatile suspended solids
ORP	oxidation–reduction potential
RAS	return activated sludge
SS	suspended solids
SVI_{30}	sludge volume index for 30 min
SRF	specific resistance to filtration
XRD	X-ray diffraction

On the other hand, it has been reported that scale deposition on electrodes was the major problem in the application of electrolytic techniques (Ge et al., 2004; Mollah et al., 2004). The scale deposition on cathode is known to be a dynamic process of nucleation and growth of precipitates (Devos et al., 2003) for Ca^{2+} and Mg^{2+} through following reactions (Deslouis et al., 2000; Hasson et al., 2008):

$$2H_2O + 2e^- \rightarrow H_2 + 2OH^- \quad (1)$$

$$OH^- + HCO_3^- \rightarrow H_2O + CO_3^{2-} \quad (2)$$

$$Ca^{2+} + CO_3^{2-} \rightarrow CaCO_3 \downarrow \quad (3)$$

$$Mg^{2+} + 2OH^- \rightarrow Mg(OH)_2 \downarrow \quad (4)$$

The characteristics of scale has been studied as a desalination technique to decrease hardness (Hasson et al., 2008), or as a cathode polarization (Cachet et al., 2001; Deslouis et al., 2000). However, little attention has been given to the effects of scale deposition on the bubble generation characteristics.

In this study, continuous separation and thickening of activated sludge by EF was performed to extend our previous works (Cho et al., 2007, 2009; Choi et al., 2005, 2009), presenting batch or semi-continuous experiments. The effects of the scale deposition and relevant control strategy were suggested, based on bulk cell electrolysis and operation of a biological reactor combined with the EF clarifier.

2. Methods

2.1. Bulk cell electrolysis experiments

The effects of scale deposition on the bubble generation characteristics were investigated in terms of bubble size and bubble generation efficiency. One anode and two cathodes were arranged to construct a monopolar electrode module with an effective area of 30 cm^2. The spacing between each electrode was fixed at 0.5 cm. The electrodes were commercial IrO_2–TiO_2–Ti DSA (DIOES, Korea) whose IrO_2 contents were 50% in molar fraction (Cho et al., 2009). The DSAs have been commonly used in EF because of their anodically insoluble property and electrocatalytic activity for oxygen generation (Chen et al., 2002; Lei and Maekawa, 2007).

Bulk cell electrolysis was performed in the 1 L acrylic cylinder with 6 cm diameter, filled with artificial wastewater with the constituents summarized in Table 1. The pH of the electrolyte was adjusted to be neutral, while the electrical conductivity was measured to be 835 μS s^{-1}. The size distributions of bubbles from the electrode were measured every 10 h of bubble generation under the current density of 50 A m^{-2}. The bubble size distribution was determined by an online particle counter (LaserTrac PC 2400D, Hemtrac, USA) for its simplicity in experimental setting and measurement. Han et al. (2002) demonstrated the reliability of the method compared with an image analysis method. The device employed a light blockage volumetric method by infrared laser and the dynamic range of measurement was 2–400 μm. The electrolyte with the generated bubbles was pumped into the sensor at a fixed flow rate of 100 mL min^{-1} through a straight tube located 5 cm above the electrodes. The bubble generation efficiency, defined as the ratio of the actual gas generation rate to the theoretical one calculated by Faraday's law, was measured as referred to Cho et al. (2009). The variation of major cationic constituents (Ca, Mg, Na, K) during bubble generation was analyzed by ICP-AES (OPTIMA 4300DV, Perkin–Elmer, USA). After the end of bulk cell electrolysis, the XRD patterns of the deposited scale were recorded from 10° to 80° (2θ) in step size of 0.02° by a powder XRD (D5005, Bruker, Germany) with Cu Kα radiation (40 kV, 40 mA). A characterization of the deposited scale was performed using an ESEM (FEI, Phillips, Netherlands) equipped with an EDS.

2.2. Design of a biological reactor combined with EF clarifier

A lab scale biological wastewater treatment process was prepared combining a 12 L biological reactor with an EF clarifier of 8 cm in diameter, as shown in Fig. 1. The biological reactor, with the hydraulic retention time to be 6 h, consisted of a 2 L anaerobic tank and two subsequent 5 L AA tanks (Hong et al., 2005). The biological process was a modified one of the typical intermittent aeration system (Sasaki et al., 1996) for structural simplicity. Neglect of internal recycle made it suitable for retrofit of conventional activated sludge process (Hong et al., 2005; Osada et al., 1991).

Mixed liquor in the biological reactor was poured onto the EF by hydraulic head difference, passing through the upper sludge blanket. After a given duration, about 0.3 L of the effluent was returned to the EF unit to push out the upper sludge bed into the sludge retention tank connected to the anaerobic tank. The drainage valve was closed during this period, with the skimmer working at 3 rpm.

Table 1
Composition of the synthetic wastewater used in biological reactor operation.

	Constituent	Concentration
Carbon	Glucose	300 mg L^{-1} as COD
	Yeast extract	50 mg L^{-1}
Buffering capacity	$NaHCO_3$	150 mg L^{-1} as $CaCO_3$
Nitrogen	NH_4Cl	30 mgN L^{-1}
Phosphorus	KH_2PO_4	5 mgP L^{-1}
Minerals	$CaCl_2{\cdot}2H_2O$	25 mgCa L^{-1}
	$MgSO_4{\cdot}7H_2O$	5 mgMg L^{-1}
	$MnSO_4{\cdot}H_2O$	0.07 mgMn L^{-1}
	$ZnSO_4{\cdot}7H_2O$	0.07 mgZn L^{-1}
	$FeCl_2{\cdot}4H_2O$	0.17 mgFe L^{-1}