Effective sludge solubilization treatment by simultaneous use of ultrasonic and electrochemical processes

T. Watanabe*, D.-Y. Zeng*, K.-J. Cho* and M. Kuroda*

*Department of Civil Engineering, Gunma University, 1-5-1 Tenjin-cho, Kiryu-shi, Gunma 376-8515, Japan
(E-mail: *watanabe@ce.gunma-u.ac.jp*; *kjcho@ce.gunma-u.ac.jp*; *mkuroda@ce.gunma-u.ac.jp*)

Water Science & Technology **Vol 53 No 6 pp 37–42** © IWA Publishing 2006

Abstract Sludge disintegration treatment by using simultaneously ultrasonic irradiation and electrolysis was investigated experimentally. A lab-scale diaphragm cell irradiated with ultrasound at a constant oscillating frequency of 20 kHz was used as a reactor. The batch experiments were carried out under different conditions of electric outputs of the ultrasonic generator, electric current for the electrolysis and different initial SS concentrations. A simultaneous treatment in the cathodic compartment without any chemical doses considerably facilitated the sludge solubilization, compared to the sonication alone. An increase in the electric current up to 400 mA under a constant ultrasonic density decreased the specific energy by 55% within the experimental range. The specific energy consumption was also reduced when the initial SS concentration increased. In addition, before carrying out the simultaneous treatment, a brief electrolysis was effective for further reduction of the specific energy and the acceleration of soluble COD generation.

Keywords Alkaline condition; electrolysis; sludge disintegration; solubilization; sonication; ultrasound

Introduction

The activated sludge process has been extensively utilized for wastewater treatment, resulting in the considerable generation of waste sludge. Recently, from the resource sustainability point of view, significant interest in an effective recovery of methane through anaerobic digestion, and recovery of available organic matter as well as the reduction in mass and volume of the wasted sludge disposed, has increased.

In order to develop such treatment systems suitable for these purposes, many researchers have focused their attention on the sludge disintegration as a pretreatment process. For example, there are many reports about the enhancement of biogas yield and about the considerable reduction of hydraulic retention time in the anaerobic sludge digestion because of the release of the intracellular constituents in the microbial cells. The mechanical, chemical, hydrothermal, enzymatic and biological methods for the sludge disintegration have been extensively investigated so far (Kopp *et al.*, 1997; Aravinthan *et al.*, 1998; Weemaes *et al.*, 2000; Tiehm *et al.*, 2001; Goel *et al.*, 2003). The desirable process requires a high disintegration rate with energy consumption as low as possible and operational simplicity. Among them, the sonication has been an attractive technique with no chemical additions and no moving mechanical parts in contact with the sludge, whereas there is much room for the improvement of the specific energy consumption. Chiu *et al.* (1997) reported that the combined disintegration process of alkali addition and sonication enhanced the generation of soluble COD. Recently, Watanabe *et al.* (2004) demonstrated considerable improvement in the sludge solubilization by the simultaneous use of ultrasonic and electrochemical processes in an electrolytic cell in comparison to the sonication alone and the electrolysis alone. In this method, the electrolysis acted as a generator of alkaline and acidic conditions with no chemical doses. It might be a potential alternative

doi: 10.2166/wst.2006.168

for the effective sludge disintegration with low specific energy consumption. The previous investigation suggested the necessity of keeping alkaline and acidic conditions for a long time in the reactor. Therefore, in this investigation, the feasibility of a lab-scale diaphragm cell was explored. The performance of the sludge disintegration by the simultaneous use of ultrasonic and electrochemical processes was investigated experimentally and the dependency of the specific energy on the operational conditions was discussed. In addition, the combination of the operation procedure for more effective disintegration of sludge was examined.

Materials and methods

Apparatus

The schematic diagram of the experimental apparatus is shown in Figure 1. A vessel made of a polyvinyl chloride resin, 9 cm in width, 9 cm in depth and 12 cm in height, was used as a reactor. The reactor was equipped with a porous diaphragm to divide it into the anodic and cathodic compartments. The working volume of each compartment was 300 mL. A pair of electrodes was installed in the reactor and connected to the D.C. power supply. Pt-coated titanium of expanded metal, 8.9 cm in width was used as the electrodes. A horn-type ultrasonic homogenizer was utilized for the ultrasonic irradiation. The oscillating frequency was 20 kHz and the maximum electric output was 200 W.

Activated sludge

The activated sludge used for this investigation was cultivated in a 50-L culture vessel that was inoculated with a return sludge taken from an actual municipal wastewater treatment plant. The culture vessel was aerobically operated in fed-batch manner at room temperature by adding synthetic sewage at 0.2 kg-COD/kg-SS/d. The average mass ratio of volatile solid to total solid in the activated sludge was approximately 0.9.

Experimental procedure

The activated sludge withdrawn from the culture vessel was adjusted to the predetermined SS concentration ranged from 10 to 40 g/L. The prepared activated sludge sample was poured into both anodic and cathodic compartments of the reactor. The batch-wise experiments were carried out under different conditions. The electric power output of the ultrasonic generator and the electric current applied to the electrodes ranged from 0 to 180 W and from 0 to 1,000 mA, respectively. The activated sludge in the reactor was stirred with a magnetic stirrer to avoid the sludge settling during each experiment.

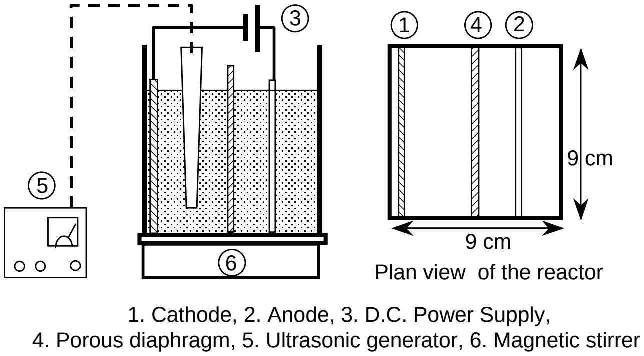

Figure 1 Schematic of the reactor

Analytical methods

The collected samples were filtered through the filter paper with 0.45 μm nominal pore size. The filtrates were utilized for measuring the soluble COD, soluble proteins and soluble carbohydrate. The proteins and carbohydrate were analyzed by the simplified Lowry-protein method and phenol-sulfuric acid method, respectively (Dubois *et al.*, 1956; Peterson, 1977). The COD, pH, SS and VSS were determined according to *Standard Methods* (1998).

Results and discussion

Difference in sludge disintegration in anodic and cathodic compartments

Typical examples of changes in the degree of disintegration and pH value in anodic and cathodic compartments are shown in Figure 2(a) and (b). The degree of disintegration, η, was defined as the following equation:

$$\eta = \frac{\mathrm{SCOD_t} - \mathrm{SCOD_0}}{\mathrm{TCOD_0} - \mathrm{SCOD_0}} \tag{1}$$

where $\mathrm{TCOD_0}$ and $\mathrm{SCOD_0}$ are initial values of total and soluble CODs, respectively, and SCODt is soluble COD at time t. As can be seen in Figure 2(a), even at relatively low electric current supply, strong acidic and alkaline conditions readily appeared and were kept in the anodic and cathodic compartments, respectively, indicating that the diaphragm cell served our purpose. Compared to the control experiment, the sludge disintegration increased considerably in the cathodic compartment with ultrasound irradiation, especially, within the first ten minutes. On the other hand, the sludge disintegration was very low in the anodic compartment, indicating no acceleration effect. Aravinthan *et al.* (1998) reported that alkaline solubilization of sludge was more efficient than acid solubilization because the capability for protein solubilization was different in each medium. Similar to their findings, alkaline conditions were desirable to facilitate the sludge solubilization when ultrasonic irradiation and electrolysis were simultaneously utilized. Indeed, generation of soluble proteins was 5.4 times larger in the cathodic compartment than in the anodic compartment, whereas generation of soluble carbohydrate was only 1.8 times larger in the cathodic compartment (data not shown). According to the results shown in Figure 2, ultrasound was only supplied to the cathodic compartment in the following experiments.

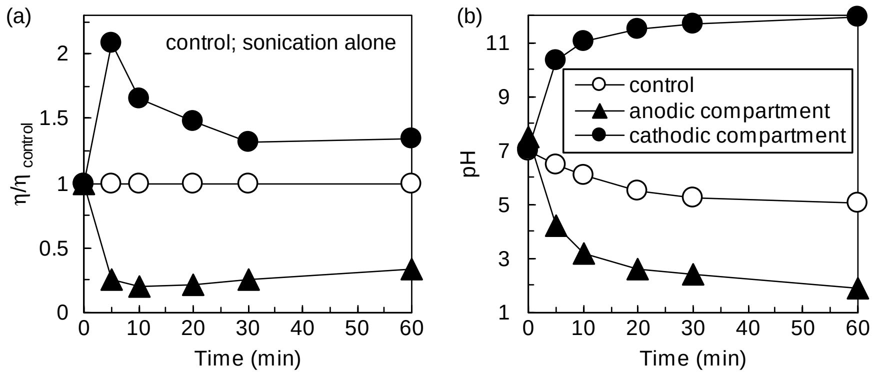

Figure 2 Difference in the sludge disintegration in the anodic and cathodic compartments at 0.6 W/mL of ultrasonic density and 400 mA of electric current; (a) changes in the degree of disintegration and (b) pH value with time

Specific energy consumption in the simultaneous processes

The effect of electric current supplied for electrolysis on specific energy consumption under a constant ultrasonic density is shown in Figure 3. The pH value in the cathodic compartment is also shown. The specific energy, SE, was defined as integral power consumption for the electrolysis and the ultrasonic generator divided by the mass of soluble COD generation during a predetermined operation period. The specific energy shown in Figure 3 was calculated for the first 10 minutes of each experiment. The specific energy decreased with increasing electric current up to 400 mA. However, further increase in the electric current did not lead to the reduction of specific energy. When the electric current increased up to 400 mA, it was observed that the pH increased and approached a constant value, proper for an alkaline condition, indicating some kind of limitation. Therefore, lower electric current was desirable as long as the strong alkaline condition appeared in the cathodic compartment. Within the experimental range, the specific energy consumption decreased by 55%, compared to that of the sonication alone.

Figure 4 shows the effect of initial solid concentration on the specific energy during the first 15 minutes of operation and the degree of disintegration for 1 h operation under constant conditions of ultrasonic density and electric current. The specific energy tended to decrease with an increase in the initial solid concentration; for instance, it decreased by 40%, when the solid concentration changed from 10 g/L to 35 g/L. When the sonication is operated at higher solid concentration, potential cavitation nuclei and the statistical probability of the sludge exposed to the mechanical shear stress can increase due to

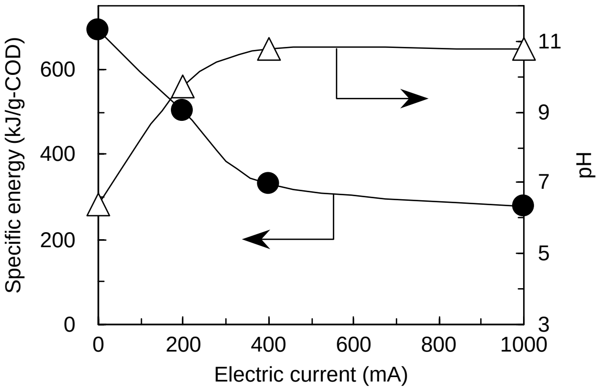

Figure 3 Effect of electric current on the specific energy under a constant ultrasonic density

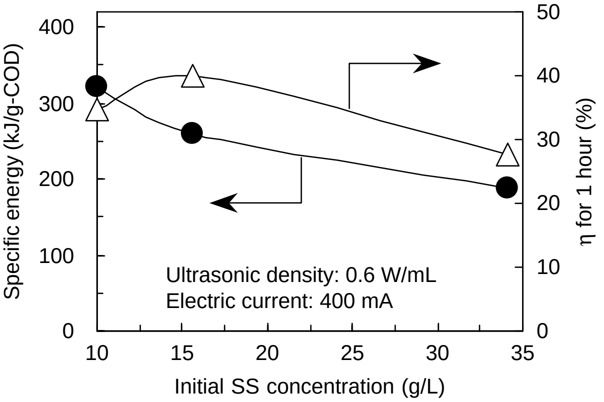

Figure 4 An example of the effect of initial solid concentration on the specific energy

the increase in the inhomogeneities of the suspension (Neis *et al.*, 2001). Moreover, alkaline conditions developed by the electrolysis may help cell disruption. Therefore, the operation under higher solid concentration gave larger generation of soluble constituents. However, the degree of disintegration after 1 hour tended to slightly decrease with an increase in the initial solid concentration.

Trials of operational procedure for more efficient disintegration

As mentioned above, the specific energy could be significantly reduced by the simultaneous use of ultrasonic and electrolytic processes in the diaphragm cell. In order to attain more effective disintegration, any combination of sonication, electrolysis and simultaneous use of both was further investigated. Table 1 lists the tested operational procedures.

Figure 5(a) shows the average generation rate of soluble COD during the first 15 minutes after pre-treatment and the degree of disintegration for 1 hour operation at different experimental runs. When run-C was compared to run-D, it was found that a brief sonication before the electrolysis treatment increased the disintegration rate by 50%. In addition, it doubled the degree of disintegration for long time operation (1 hour). In case of run-C, the floc size reduction by a sonication pretreatment seems to facilitate the exposure of the microbial cells to alkaline solution generated by the electrolysis and therefore the cell wall disruption occured easily. However, the observed disintegration rate was much lower than that in run-A and run-B, indicating that the simultaneous use of ultrasound and electrolysis was preferable. The soluble COD generation rate in run-B was increased by 20%, compared to the experimental run-A. No large difference in the degree of disintegration after a long operation time between them was significantly observed.

Table 1 The tested operational methods

Run No.	Pre-treatment	Main treatment
A	–	Simultaneous use of ultrasound (0.6 W/mL) and electrolysis (400 mA)
B	Electrolysis (400 mA) for 15 minutes	Simultaneous use of ultrasound (0.6 W/mL) and electrolysis (400 mA)
C	Ultrasound (0.6 W/mL) for 5 minutes	Electrolysis (400 mA)
D	–	Electrolysis (400 mA)

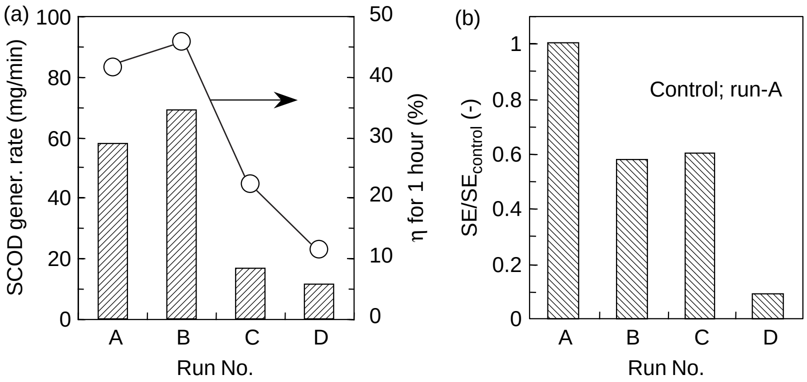

Figure 5 Comparison of the sludge disintegrations at four experimental runs tested; (a) soluble COD generation rate and the degree of disintegration and (b) ratio of the specific energy to that of control experiment

Figure 5(b) shows the ratio of the specific energy, SE, to the specific energy of the control experiment (run-A) in the first 15 minutes after pre-treatment. The energy consumption during pre-treatment was considered for the calculation of the specific energy shown in this figure. The specific energy in run-B was approximately 60% of that in run-A. In run-B, a strong alkaline condition (pH of 11) had already appeared due to electrolysis before the simultaneous treatment. In addition, electric power for the electrolysis at 400 mA was about two orders of magnitude less than that for the ultrasonic generator. These two factors contributed to the reduction of specific energy in run-B, that is, soluble COD generation increased with negligible small addition of energy consumption during the pretreatment. By the way, the specific energy consumption in run-D was smallest among the tested runs. However, as shown in Figure 5(a), the disintegration rate was also the lowest, indicating an obvious deficiency. Therefore, the disintegration treatment by the electrolysis alone seems not to be practically useful.

Conclusions

The simultaneous use of ultrasonic and electrochemical processes in the cathodic compartment of the diaphragm cell could considerably accelerate the activated sludge disintegration, compared to the sonication alone. The specific energy decreased with an increase in the electric current up to 400 mA under a constant condition of ultrasonic density and could be reduced by 55% within the experimental range. The specific energy consumption was also reduced by 40%, when initial solid concentration changed from 10 g/L to 35 g/L. Prior to the simultaneous use of the ultrasound irradiation and the electrolysis, a brief electrolysis as a pretreatment was effective for the further reduction of the specific energy and acceleration of soluble COD generation. This was caused by the appearance of strong alkaline conditions with negligible addition of electric power through the electrolysis.

References

Aravinthan, V., Mino, H., Satoh, S., Takizawa, S. and Matsuo, T. (1998). Alkaline, acid and thermal solubilization for minimization of waste sludge. *Environ. Eng. Res.*, **35**, 189–198.

Chiu, Y., Chang, C., Lin, J. and Huang, S. (1997). Alkaline and ultrasonic pretreatment of sludge before anaerobic digestion. *Wat. Sci. Tech.*, **36**(11), 155–162.

Dubois, M., Gilles, K.A., Hamilton, J.K., Rebers, P.A. and Smith, F. (1956). Colorimetric method for determination of sugars and related substances. *Anal. Chem.*, **28**(3), 350–356.

Goel, R., Tokutomi, T. and Yasui, H. (2003). Anaerobic digestion of excess activated sludge with ozone pretreatment. *Wat. Sci. Tech.*, **47**(12), 207–214.

Kopp, J., Muller, J., Dichtl, N. and Schwedes, J. (1997). Anaerobic digestion and dewatering characteristics of mechanically disintegrated excess sludge. *Wat. Sci. Tech.*, **36**(11), 129–136.

Neis, U., Nickel, K. and Tiehm, A. (2001). Ultrasonic disintegration of sewage sludge for enhanced anaerobic biodegradation. In *Advances in Sonochemistry*, Vol. 6, Mason, T.J. and Tiehm, A. (eds), Elsevier Science, Amsterdam, pp. 59–90.

Peterson, G.L. (1977). A simplification of the protein assay method of Lowry *et al.* which is more generally applicable. *Analytical Biochem.*, **83**, 346–356.

Standard Methods for the Examination of Water and Wastewater (1998). 20th edn, American Public Health Association/American Water Works Association/Water Environmental Federation, Washington DC, USA.

Tiehm, A., Nickel, K., Zellhon, M. and Neis, U. (2001). Ultrasonic waste activated sludge disintegration for improving anaerobic stabilization. *Wat. Res.*, **35**(8), 2003–2009.

Watanabe, T., Zeng, D., Cho, K. and Kuroda, M. (2004). Sludge disintegration treatment by the simultaneous use of ultrasonic and electrochemical processes. *Environ. Eng. Res.*, **41**, 521–530.

Weemaes, M., Grootaerd, H., Simoens, F. and Verstaete, W. (2000). Anaerobic digestion of ozonized biosolids. *Wat. Res.*, **34**(8), 2330–2336.