

Evaluation of non-thermal effects by microwave irradiation in hydrolysis of waste-activated sludge

I. G. Byun, J. H. Lee, J. M. Lee, J. S. Lim and T. J. Park

ABSTRACT

The activation energy (E_a) for waste-activated sludge (WAS) hydrolysis was compared between microwave irradiation (MW) and conventional heating (CH) methods to evaluate the non-thermal effect of MW. The microwave-assisted hydrolysis of WAS was assumed to follow the first-order kinetics on the basis of volatile suspended solids (VSS) conversion to soluble chemical oxygen demand (SCOD) for different initial VSS concentrations. By comparing the VSS decrement and the SCOD increment between MW and CH at different absolute temperatures of 323, 348 and 373 K, the average ratio of VSS conversion to SCOD was determined to range from 1.42 to 1.64 g SCOD/g VSS. These results corresponded to the theoretical value of 1.69 g SCOD/g VSS based on the assumption that the molecular formula of sludge was $C_{10}H_{19}O_3N$. Consequently, the E_a of the MW-assisted WAS hydrolysis was much lower than that of CH for the same temperature conditions. The non-thermal effect of MW in the hydrolysis of WAS could be identified with the lower E_a than that of CH.

Key words | activation energy, conventional heating, hydrolysis, microwave irradiation, non-thermal effect, waste-activated sludge

I. G. Byun

Institute for Environmental Technology and Industry,
Pusan National University,
63beon-gil, Geumjeong-gu,
Busan,
Korea

J. H. Lee

J. M. Lee

J. S. Lim

T. J. Park (corresponding author)
Department of Environmental Engineering,
Pusan National University,
63beon-gil, Geumjeong-gu,
Busan,
Korea
E-mail: tajoo@pusan.ac.kr

INTRODUCTION

The generation of waste-activated sludge (WAS) in Korea has increased rapidly in the last 20 years with the construction of many wastewater treatment plants (WWTPs). The cost-effective and environmentally friendly treatment and disposal of WAS are a major problem of environmental management for all countries because ocean dumping was prohibited by the London Dumping Convention and its high cost represents over 50–60% of the total operating cost of WWTPs (Neyens & Baeyens 2003; Appels *et al.* 2008).

Anaerobic digestion, consisting of hydrolysis, acid fermentation and methane fermentation, has been widely adopted to stabilise WAS. The hydrolysis is well known as the rate-limiting step of anaerobic digestion due to very low rate of solid dissolution. For the hydrolysis of WAS, anaerobic bacteria should release extracellular enzymes to breakdown the rigid cell wall of microorganisms in WAS (O'Flaherty *et al.* 2006). Therefore, many pretreatment methods to enhance the hydrolysis rate of WAS have been developed to disintegrate the cell wall, such as acid/alkali (Lin *et al.* 2007), pulse power (Choi *et al.* 2006) and ultrasound (Pham *et al.* 2009). Cell wall destruction by these

pretreatments improves the dissolution of solid components (Choi *et al.* 2006; Lin *et al.* 2007; Xie *et al.* 2009).

In the past decade, microwave irradiation (MW; mainly 2,455 MHz) has been applied to the hydrolysis of WAS and cellulosic biomass (Ha *et al.* 2011). In contrast to conventional heating (CH), which is slow and transferred into the inside from the surface, MW has a very short reaction time and high efficiency for heating the whole material. Therefore, MW has been effectively used for the extraction of valuable material such as homoharringtonine from *Cephalotaxus koreana* (Kim *et al.* 2010). As MW can induce dielectric heating, it exerts two different effects on the hydrolysis of WAS. One is the thermal effect by temperature rise that can burst the cell wall by increasing the internal pressure of the cell wall caused by the evaporation of internal water (Golmakani & Rezaei 2008; Uquiche *et al.* 2008). The other is the non-thermal effect caused by the electric field alternation of microwaves, which is not observed in CH.

This non-thermal effect is expected to weaken or break the hydrogen bonds of the polymer forming the cell wall of WAS through the alternation of the electric field of

polar substance like water at a frequency of 2,455 MHz (Hong *et al.* 2004; Katalin *et al.* 2011). This non-thermal effect can be used efficiently to enhance the hydrolysis rate compared to CH. However, few studies have examined the non-thermal effect of MW by the evaluation of energy absorbance and enhancement of biogas production using secondary wastewater sludge (Katalin *et al.* 2011).

Thus, this study was performed to evaluate the non-thermal effect of MW by comparing the hydrolysis kinetics of WAS with that of CH, which could only provide a thermal effect. This comparison was performed through the development of reaction order, rate constant and activation energy (E_a) on the basis of the volatile suspended solids (VSS) dissolution rate and soluble chemical oxygen demand (SCOD) increment for each heating method.

METHODS

Waste-activated sludge samples

WAS samples were provided from the return line of the secondary settling tank and thickener of Suyoung municipal sewage treatment plant (MSTP) in Busan, Korea. This plant treats a typical domestic wastewater (450,000 m³/d) and operates three major treatment processes: conventional activated sludge process, modified Ludzack–Ettinger process and membrane bio-reactor process. The sludge used in the study was from a conventional activated sludge process operated at an average hydraulic retention time of 6 h and a sludge retention time of 13 d. The higher solid concentrations of WAS were prepared by further centrifugation of WAS collected from a centrifugal thickener in Suyoung MSTP. Collected WAS samples were immediately sieved with mesh no. 24 (0.800 mm) and used for every experiment within 5 h at the state of room temperature.

WAS hydrolysis by MW and CH

MW experiments were performed in an experimental microwave oven (Synthos 3000: 2,455 MHz, output power range 0–1.2 kW, maximum temp. 350 °C and maximum pressure 6.0 bar) equipped with a thermocouple sensor to control the temperature of sample. Eight quartz sample vessels were a closed system and were placed in the microwave oven. Each vessel (effective volume 80 mL) was filled with 50 mL sludge sample for all experiments. In the experiments of kinetic analysis (Table 2), CH experiments were conducted in a capped water bath (CW-10G, Jeiotech, Korea)

under the same target temperature as those of the MW experiments. For both experiments of MW and CH, exposure time at target temperature was the same but ramp times to target temperature of MW were shorter than those of CH due to the difference of heating mechanisms of MW (dielectric heating) and CH (conductive heating) (Adnadjevic & Jovanovic 2012). In the experiments of CH, 50 mL falcon tube vessels with screw cap were used to prevent the loss of organics and water. Temperatures of samples during CH were measured by a thermocouple sensor of the water bath. Each experiment was performed in triplicate.

Hydrolysis rate at different initial VSS concentrations by MW

The WAS samples with different initial solid contents (SCs) of 8.22, 31.51 and 52.88 g VSS/L were irradiated by MW for 3, 6 and 10 min at 600 W output power with 2,455 MHz. The hydrolysis temperature of the WAS samples was fixed at 100 °C (373 K). The experimental conditions are summarised in Table 1. Sets 1, 2 and 3 correspond to the SC of the secondary settling tanks, centrifugal thickener and further centrifugation sludge, respectively. The reaction rates of WAS hydrolysis were obtained from the conversion of VSS to SCOD according to the MW irradiation times and initial SCs. The experimental solubilisation of VSS to SCOD was verified by comparing with the theoretical conversion of 1.69 g SCOD per gram VSS under an assumed molecular formula for WAS of C₁₀H₁₉O₃N.

Experiments of hydrolysis kinetics for WAS by MW and CH

MW and CH were applied to WAS hydrolysis to evaluate the non-thermal effects of MW when applied to WAS

Table 1 | MW conditions for different initial VSS concentrations to evaluate the hydrolysis rate of WAS (600 W with 2,455 MHz)

Experimental condition	Set 1	Set 2	Set 3
Initial TSS (g/L)	9.55 ± 0.46	39.60 ± 0.85	65.00 ± 0.82
Initial VSS (g/L)	8.22 ± 0.38	31.51 ± 0.64	52.88 ± 0.78
Initial SCOD (g/L)	0.030 ± 0.003	0.056 ± 0.005	0.086 ± 0.006
MW irradiation time (min)	6, 10	6, 10	6, 10
Hydrolysis temperature (°C)	100	100	100

Table 2 | Experimental conditions of MW and CH to analyse the kinetics of WAS hydrolysis

Parameter	MW			CH		
	Initial TSS (g/L)	6.21 ± 0.11	15.64 ± 0.43	6.21 ± 0.11	15.64 ± 0.43	6.21 ± 0.11
Initial VSS (g/L)	5.06 ± 0.10	12.39 ± 0.22	5.06 ± 0.10	12.39 ± 0.22	5.06 ± 0.10	12.39 ± 0.22
Initial SCOD (g/L)	0.056 ± 0.004	0.211 ± 0.011	0.056 ± 0.004	0.211 ± 0.011	0.056 ± 0.004	0.211 ± 0.011
Target temp. (°C)	50	75	100	50	75	100
Ramp time to target temp. (min)	1.05	1.95	4.20	20	35	50
Exposure time on target temp. (min)	10			10		
Total exposure time (min)	11.05	11.95	14.20	30	40	60

hydrolysis by comparing the kinetics for each heating method. As shown in Table 2, two WAS samples with different SCs of 5.06 and 12.39 g VSS/L were heated for 10 min at 50, 75 and 100 °C by MW and CH to evaluate the effect of temperature on the kinetics of WAS hydrolysis. Ramp times to target temperatures are also presented in Table 2. Total exposure times and target temperatures were moderate compared with other reported experimental conditions for the hydrolysis of WAS by MW (Ahn *et al.* 2009; Katalin *et al.* 2011; Kuglarz *et al.* 2013). The initial temperature of the raw WAS samples was 18 °C. MW irradiation was performed at 900 W output power and 2,455 MHz. Table 2 presents the experimental condition of hydrolysis kinetics for WAS by MW and CH.

Kinetics of WAS hydrolysis

Reaction temperature and pressure, and reactant concentration are well known as the major parameters of reaction rates ($-r_h$). However, reaction temperature and reactant concentration can be the main parameters of reaction rates in liquid phase reactions such as hydrolysis (Fogler 2010). Therefore, the reaction rates of WAS hydrolysis by MW and CH could be expressed as:

$$-r_h = k_h C_S^a \quad (1)$$

where $-r_h$ is the reaction rate of WAS hydrolysis, k_h is the reaction rate constant of WAS hydrolysis, C_S is the concentration of WAS expressed as VSS and a is the reaction order of WAS hydrolysis. The order of reaction for WAS hydrolysis was obtained by evaluating the conversion rate of VSS to SCOD at different initial SCs.

The activation energy (E_a) of WAS hydrolysis by MW and CH could be calculated using the Arrhenius equation

expressed as follows:

$$k_h(T) = A e^{-E_a/RT} \quad (2)$$

$$\ln k_h(T) = \ln A - E_a/RT \quad (3)$$

where k_h is the reaction rate constant of WAS hydrolysis, A is a frequency factor (y -intercept of Equation (3)), E_a is the activation energy of WAS hydrolysis, R is the gas constant and T is the absolute temperature of the reaction. The E_a could be obtained from the reaction rate constants at different temperature conditions of WAS hydrolysis by MW and CH.

RESULTS AND DISCUSSION

The reaction progression of WAS hydrolysis by MW

To evaluate the reaction progression of WAS hydrolysis by MW, the variation of VSS and SCOD concentration was analysed with different initial VSS concentrations of WAS according to MW time at an output power of 600 W. The solubilisation ratio of VSS was evaluated with C/C_0 , where C is the VSS concentration at microwave irradiation time (t) and C_0 is the initial VSS concentration of WAS.

The VSS and SCOD profiles of WAS hydrolysis for different initial SCs at an output power of 600 W are presented in Figure 1. The VSS decrements for WAS of the secondary settling tank, centrifugal thickener and further centrifugation were 0.397, 1.393 and 2.533 g/L · min at 6 min MW, and 0.294, 1.182 and 2.031 g/L · min at 10 min irradiation, respectively, indicating that the dissolution rate of VSS increased with increasing WAS concentration. In the MW system, the high VSS concentration means that more microbial cells were able to contact with MW, which

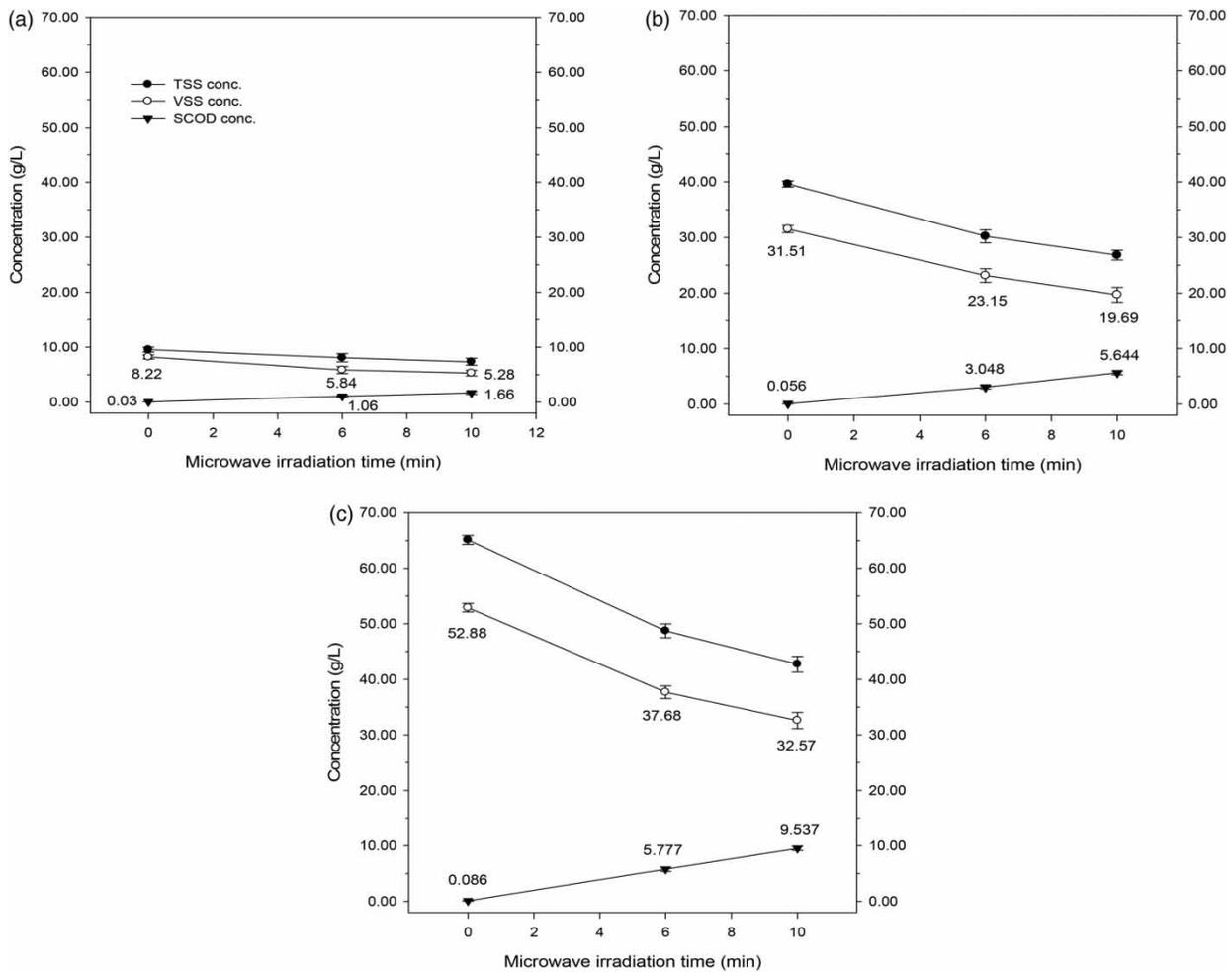


Figure 1 | VSS decrement and SCOD increment for different initial SCs in the hydrolysis of WAS by MW with 600 W output power and 2,455 MHz. (a) Second settling tank WAS, (b) centrifugal thickener WAS, (c) further centrifuged WAS.

thus increased the dissolution rate of VSS with increasing concentration. The hydrolysis rates of WAS in the MW system can also vary widely for the same output power and irradiation time because the microwave absorption of samples varies according to the type of cavity, waveguide and the presence of isolator (Collin 1992). In addition, as the hydrolysis rates are affected by the characteristics of WAS, the effect of the hydrolysis rate on microwave-assisted WAS hydrolysis varies (Hong *et al.* 2004; Ahn *et al.* 2009; Katalin *et al.* 2011; Kuglarz *et al.* 2013).

From the result of Figure 1, VSS solubilisation to SCOD could be expressed by C/C_0 . Figure 2 shows the values of C/C_0 for different initial SCs according to MW time. As presented in Figure 2, the C/C_0 ratio was virtually unchanged with the equivalent irradiation time for all initial SCs. Therefore, WAS hydrolysis by MW could be assumed to follow the

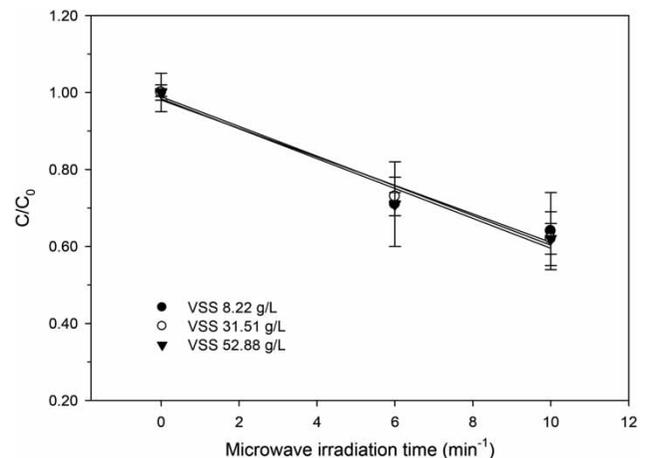


Figure 2 | Reaction order of WAS hydrolysis by MW with 600 W output power and 2,455 MHz.

first-order reaction. WAS hydrolysis by pH control was reported to follow the first-order kinetics for 8-day fermentation (Feng *et al.* 2009). Sucrose hydrolysis by MW and CH was also revealed as the first-order chemical reaction (Adnadjevic & Jovanovic 2012). In a kinetic study of thermo-hydrolysis for excess activated sludge according to temperature conditions (423–523 K), thermal dissolution of raw activated sludge particles was shown to follow first-order reaction (Imbierowicz & Chacuk 2012). As WAS hydrolysis by MW occurred fundamentally by thermal effect, it is reasonable to follow the first-order kinetics for WAS hydrolysis by MW. And the reaction rate of WAS hydrolysis by MW is expected to decrease as the exposure time increases due to the first-order reaction of MW-assisted WAS hydrolysis. Therefore, it will be necessary to extend the exposure time of WAS hydrolysis to determine the ultimate solubilisation potential of WAS. However, the exposure time and output power of MW should be optimised to enhance the economics and feasibility of sludge pretreatment (Sándor *et al.* 2011).

Kinetics and activation energy (E_a) of WAS hydrolysis by MW and CH

The kinetics and E_a of WAS hydrolysis by MW and CH were studied at different reaction temperatures of 50, 75 and 100 °C using different initial SCs. In the WAS hydrolysis, the VSS and SCOD profiles were monitored for 15 min MW time at 900 W output power. The solubilisation ratio of VSS was also evaluated with C/C_0 . The conversion of VSS to SCOD by the solubilisation of VSS was verified by

evaluating the SCOD increment per VSS decrement. The molecular formula of VSS was assumed to be $C_{10}H_{19}O_3N$ (McCarty 1974).

The VSS dissolution rates varied according to the temperature conditions, as presented in Figure 3. For WAS of the secondary settling tank, the VSS dissolution rates at 50, 75 and 100 °C were 23.03, 65.53 and 93.03 mg VSS/L-min by MW, and 9.70, 33.67 and 37.73 mg VSS/L-min by CH, respectively. For the thickened sludge, the rates at the same temperatures were 87.50, 125.00 and 155.83 mg VSS/L-min by MW, and 17.30, 78.33 and 85.23 mg VSS/L-min by CH, respectively. The VSS dissolution rates by MW were much higher for both initial SCs than those by CH. Considering the temperature effect, the VSS dissolution rate at 50 °C by CH was much lower than that at the other temperature conditions, whereas that by MW was proportionally increased with increasing temperature. Thus, we concluded that the temperature of 50 °C does not have a significant effect on the VSS dissolution rate in the thermal-only applied system. At 75 and 100 °C, the ratios of the VSS dissolution rate between MW and CH (MW/CH) were 1.95 and 2.47 for WAS of the secondary settling tank and 1.60 and 1.83 for the thickened sludge, respectively. These results indicated that the non-thermal effect of MW is more efficient at low concentration than at high concentration. More sludge floc agglomeration is thought to have occurred in the high concentration condition, which decreased the MW transfer efficiency from the surface to the inside of WAS.

After the microwave pretreatment of WAS, the SCOD concentration increment may have been caused by the aggravating deagglomeration and the transfer from non-soluble

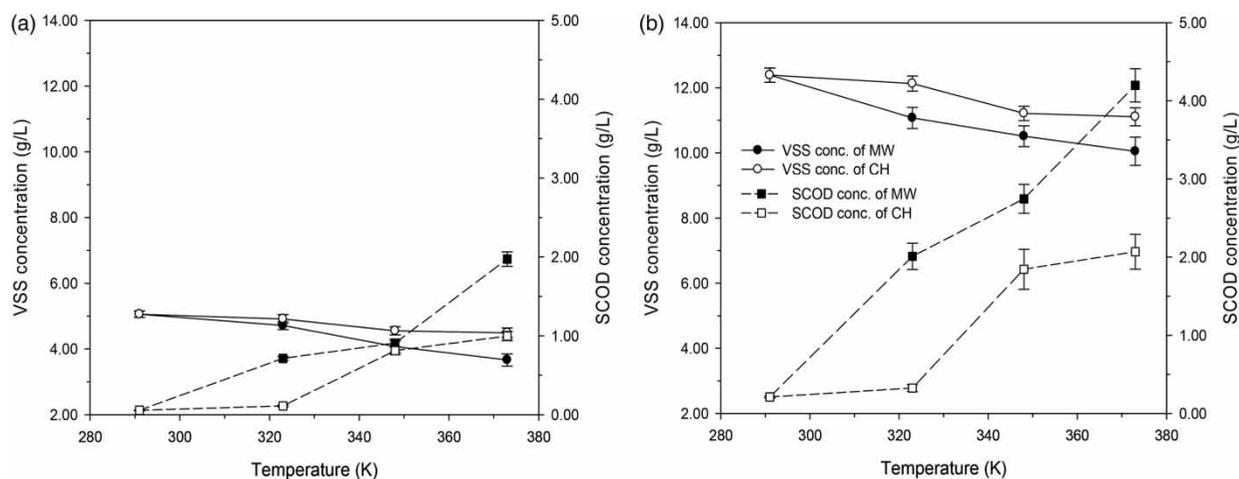


Figure 3 | VSS and SCOD concentrations in the hydrolysis of (a) second settling tank WAS and (b) thickener WAS at different temperature conditions by MW (900 W output power, 2,455 MHz) and CH.

organic material into soluble organic material (Rani *et al.* 2013). Intracellular organic materials were also released into the medium due to the cell wall disintegration, indicating that MW could breakdown the sludge floc (Park *et al.* 2004; Eskicioglu *et al.* 2006). In these experiments of both hydrolysis methods, the VSS conversion to SCOD ranged from 1.42 to 1.64 g SCOD/g VSS and these results corresponded to the value of 1.69 g SCOD/g VSS under an assumed molecular formula for the sludge of $C_{10}H_{19}O_3N$.

The evaluation of the VSS profiles with C/C_0 , presented in Figure 4(a), revealed that the kinetics of WAS hydrolysis followed the first-order reaction. Therefore, the variation of VSS concentration of WAS hydrolysis could be expressed by the following equation:

$$-r_h = dC/dt = k_h C \quad (4)$$

$$\ln C = b - k_h t \quad (5)$$

where b is the constant of integration. From Equation (5), the reaction constant (k_h) and the constant of integration are the slope and y -intercept of the linear equation. The value of k_h (min^{-1}) for MW-assisted WAS hydrolysis was increased linearly with increasing temperature. R^2 was 0.984 and 0.997 for each initial SC, which strongly suggested that WAS hydrolysis by MW follows the first-order reaction. In the case of WAS hydrolysis by CH, k_h was increased with increasing temperature, but R^2 of k_h was 0.856 and 0.826. With the increase of temperature, the value of k_h for the MW-assisted WAS hydrolysis was increased more than that of CH. In particular, the value of k_h in WAS hydrolysis

by CH at 100 °C was not significantly increased compared to that at 75 °C, but in the MW-assisted WAS hydrolysis, k_h value was sharply increased. The comparison of k_h by MW and CH also revealed that degradation of extracellular polymeric substances in VSS compounds required non-thermal effects or chemical addition to enhance the dissolution rates apart from thermal effects (Feng *et al.* 2009; Chi *et al.* 2011; Adnadjevic & Jovanovic 2012).

The relationships between reaction temperatures and reaction rate constants (k_h) are presented in Figure 5 with the terms of $1/T$ and $\ln k_h$. For both heating methods of MW and CH, the relationships between $1/T$ and $\ln k_h$ obviously follow the first-order hydrolysis reactions. And E_a does not change according to concentration of reactant; we could find E_a from an Arrhenius plot (plot of $\ln k_h$ as a function of $1/T$; Figure 5) for WAS hydrolysis (Fogler 2010). For WAS, the Arrhenius plots for MW and CH are $\ln k_h = -0.6004 - 1401.2438/T$ ($R^2 = 0.9978$) by MW and $\ln k_h = 5.7414 - 3911.7453/T$ ($R^2 = 0.9524$) by CH, respectively. As a steep slope means high E_a in the Arrhenius plot, E_a of WAS hydrolysis by MW is lower compared to that by CH.

Table 3 presents the E_a of WAS hydrolysis by MW and CH. The non-thermal effect on dielectric materials by MW is a significant increase in rotation of the polarised dipoles in the molecules. This increases the probability of collision between molecules and thereby generates heat. Thus, the non-thermal effect enhances the reaction rate and reduces the E_a (Shibata *et al.* 1996; Adnadjevic & Jovanovic 2012). In this experiment, the E_a values of WAS hydrolysis by MW were much lower than that of CH with 22.6–31.0% of CH. Therefore, it could be suggested that the non-thermal effect of MW for WAS

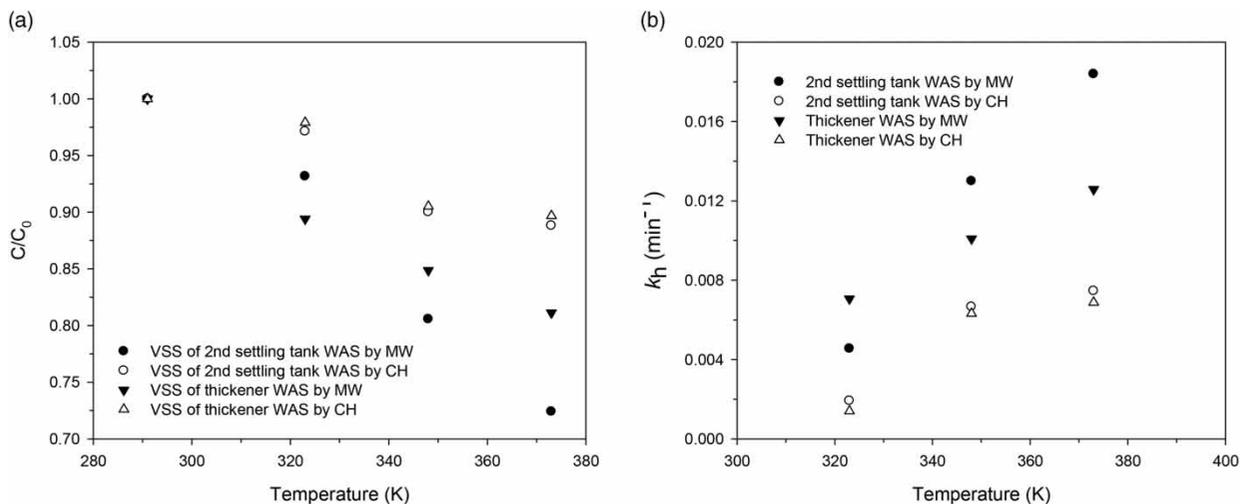


Figure 4 | VSS conversion efficiencies (a) and first-order rate constants (b) for the hydrolysis of WAS at different temperature conditions by MW (900 W output power, 2,455 MHz) and CH.

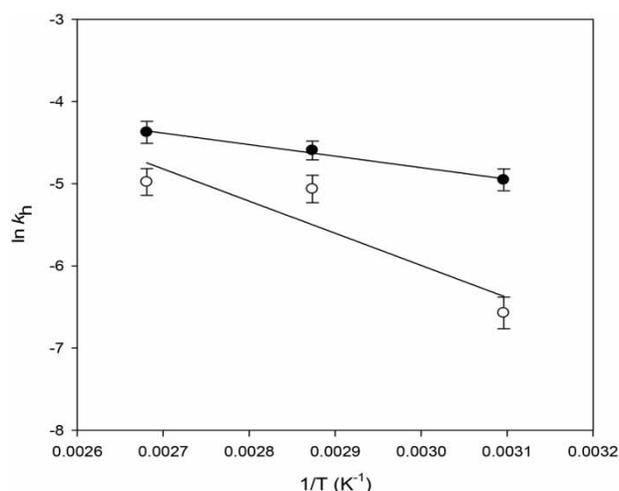


Figure 5 | Relationship between $\ln k_h$ and $1/T$ of WAS hydrolysis by MW (●) and CH (○).

Table 3 | Activation energy (E_a) of WAS hydrolysis by MW (900 W, with 2,455 MHz) and CH

Method	E_a (kJ/mol)	E_a (kJ/kg VSS)
MW	11.50 ± 1.88	57.27 ± 9.36
CH	43.18 ± 11.28	214.83 ± 56.12

hydrolysis worked because MW heating increased the reaction rate constants and decreased the E_a of WAS hydrolysis for the same temperature condition compared with CH.

Few studies have examined the kinetics of WAS hydrolysis by MW. Nevertheless, it has been suggested that, compared to CH, MW could better enhance the solubilisation and hydrolysis of solid organics (Eskicioglu *et al.* 2007; Ballardin *et al.* 2011; Adnadjevic & Jovanovic 2012). This enhancement was attributed to the non-thermal or athermal effect of MW caused by dielectric heating. In this study, the non-thermal effect of MW was confirmed through the increase of $-r_h$ for the same temperature and the decrease of E_a . However, any quantitative comparison with other results is difficult because the results of MW-assisted WAS hydrolysis vary greatly according to the type of cavity, waveguide, presence of isolator and sludge characteristics (Collin 1992).

CONCLUSIONS

WAS hydrolysis by MW almost followed the first-order reaction irrespective of the initial SC. CH was also assumed to obey the first-order reaction with R^2 value of 0.826–0.856 between the VSS concentration and exposure time at

target temperature. In the comparison of the reaction constants ($-r_h$, min^{-1}) of WAS hydrolysis by heating method, the values of MW were much higher than those of CH at the same temperature. Consequently, the E_a of MW-assisted WAS hydrolysis was much lower than that of CH. Therefore, the increase of reaction rates and the reduction of E_a by MW suggested the action of a non-thermal effect due to the dielectric heating of MW.

ACKNOWLEDGEMENT

This research was supported by the Basic Science Research Program through the National Research Foundation of Education, Science and Technology (2012R1A1A1043827).

REFERENCES

- Adnadjevic, B. K. & Jovanovic, J. D. 2012 A comparative kinetics study on the isothermal heterogeneous acid-catalyzed hydrolysis of sucrose under conventional and microwave heating. *J. Mol. Catal. A Chem.* **356**, 70–77.
- Ahn, H. J., Shin, S. G. & Hwang, S. 2009 Effect of microwave irradiation on the disintegration and acidogenesis of municipal secondary sludge. *Chem. Eng. J.* **153**, 145–150.
- Appels, L., Baeyens, J., Degreve, J. & Dewil, R. 2008 Principles and potential of the anaerobic digestion of waste-activated sludge. *Prog. Energy Combust.* **34**, 755–781.
- Ballardin, M., Tusa, I., Fontana, N., Monorchio, A., Pelletti, C., Rogovich, A., Barale, R. & Scarpato, R. 2011 Non-thermal effects of 2.45 GHz microwaves on spindle assembly, mitotic cells and viability of Chinese hamster V-79 cells. *Mutation Res.* **716**, 1–9.
- Chi, Y., Li, Y., Fei, X., Wang, S. & Yuan, H. 2011 Enhancement of thermophilic anaerobic digestion of thickened waste activated sludge by combined microwave and alkaline pretreatment. *J. Environ. Sci.* **23**, 1257–1265.
- Choi, H. N., Jeong, S. W. & Chung, Y. J. 2006 Enhanced anaerobic gas production of waste activated sludge pretreated by pulse power technique. *Bioresour. Technol.* **92**, 198–203.
- Collin, R. E. 1992 *Foundation for Microwave Engineering*, 2nd edn. IEEE, New York, USA, pp. 33–38.
- Eskicioglu, C., Kennedy, K. J. & Droste, R. L. 2006 Characterization of soluble organic matter of waste activated sludge before and after thermal pretreatment. *Water Res.* **40**, 3725–3736.
- Eskicioglu, C., Terzian, N., Kennedy, K. J., Droste, R. L. & Hamoda, M. 2007 Athermal microwave effects for enhancing digestibility of waste activated sludge. *Water Res.* **41**, 2457–2466.
- Feng, L., Yan, Y. & Chen, Y. 2009 Kinetic analysis of waste activated sludge hydrolysis and short-chain fatty acids production at pH 10. *J. Environ. Sci.* **21**, 589–594.

- Fogler, H. S. 2010 *Essentials of Chemical Reaction Engineering*. Pearson Education, Boston, USA, pp. 74–90.
- Golmakani, M. T. & Rezaei, K. 2008 Comparison of microwave-assisted hydrodistillation with the traditional hydrodistillation method in the extraction of essential oils from *Thymus vulgaris* L. *Food Chem.* **109**, 925–930.
- Ha, S. H., Mai, N. L., An, G. & Koo, Y. M. 2011 Microwave-assisted pretreatment of cellulose in ionic liquid for accelerated enzymatic hydrolysis. *Bioresour. Technol.* **102**, 1214–1219.
- Hong, S. M., Park, J. K. & Lee, Y. O. 2004 Mechanisms of microwave irradiation involved in the destruction of fecal coliforms from biosolids. *Water Res.* **38**, 1615–1625.
- Imbierowicz, M. & Chacuk, A. 2012 Kinetic model of excess activated sludge thermohydrolysis. *Water Res.* **46**, 5747–5755.
- Katalin, S., Rafael, B. M., Sara, I. P. E. & María, J. C. 2011 The influence of the energy absorbed from microwave pretreatment on biogas production from secondary wastewater sludge. *Bioresour. Technol.* **102**, 10849–10854.
- Kim, W. K., Chae, H. J. & Kim, J. H. 2010 Microwave-assisted extraction of homoharringtonine from *Cephalotaxus koreana*. *Biotechnol. Bioprocess Eng.* **15**, 481–487.
- Kuglarz, M., Karakashev, D. & Angelidaki, I. 2013 Microwave and thermal pretreatment as methods for increasing the biogas potential of secondary sludge from municipal wastewater treatment plants. *Bioresour. Technol.* **134**, 290–297.
- Lin, J. G., Chang, C. N. & Chang, S. C. 2007 Enhancement of anaerobic digestion of waste activated sludge by alkaline solubilization. *Bioresour. Technol.* **62**, 85–90.
- McCarty, P. L. 1974 *Anaerobic Process*, Presented at the Birmingham Short Course on Design Aspects of Biological Treatment, International Association of Water Pollution Research, Birmingham, UK.
- Neyens, E. & Baeyens, J. 2003 A review of thermal sludge pretreatment processes to improve dewaterability. *J. Hazard. Mater.* **98**, 51–67.
- O’Flaherty, V., Collins, G. & Mahony, T. 2006 The microbiology and biochemistry of anaerobic bioreactors with relevance to domestic sewage treatment. *Rev. Environ. Sci. Biotechnol.* **5**, 39–55.
- Park, B., Ahn, J. H., Kim, J. & Hwang, S. 2004 Use of microwave pretreatment for enhanced anaerobiosis of secondary sludge. *Water Sci. Technol.* **50** (9), 17–23.
- Pham, T. T. H., Brar, K., Tyagi, R. D. & Surampalli, R. Y. 2009 Ultrasonication of wastewater sludge consequences on biodegradability and flowability. *J. Hazard. Mater.* **163**, 891–898.
- Rani, R. U., Kumar, S. A., Kaliappan, S., Yeom, I. T. & Banu, J. R. 2013 Impacts of microwave pretreatments on the semi-continuous anaerobic digestion of dairy waste activated sludge. *Waste Manage.* **33**, 1119–1127.
- Sándor, B., Zsuzsanna, L., Zsuzsanna, H. H., Gábor, S. & Cecilia, H. 2011 Comparison of the effects of microwave irradiation with different intensities on the biodegradability of sludge from the dairy- and meat-industry. *Bioresour. Technol.* **102**, 814–821.
- Shibata, C., Kashima, T. & Ohuchi, K. 1996 Nonthermal influence of microwave power on chemical reactions. *Jpn. J. Appl. Phys.* **35**, 316–319.
- Uquiche, E., Jeréza, M. & Ortíz, J. 2008 Effect of pretreatment with microwaves on mechanical extraction yield and quality of vegetable oil from Chilean hazelnuts (*Gevuina avellana* Mol). *IFSET* **9**, 495–500.
- Xie, B., Liu, H. & Yan, Y. 2009 Improvement of the activity of anaerobic sludge by low-intensity ultrasound. *J. Environ. Manage.* **90**, 260–264.

First received 7 November 2013; accepted in revised form 17 June 2014. Available online 27 June 2014