High-Rate Moving-Bed Biofilm Anaerobic Digestion for Waste Activated Sludge Treatment

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ABSTRACT

In a mesophilic anaerobic digestion process, decayed waste activated sludge biomass fed to a digester formed soluble COD substrates, which were eventually converted to methane by anaerobic microorganisms. To improve the decomposition of the soluble materials, performance of a high-rate anaerobic digester was experimentally evaluated. A lab-scale moving-bed biofilm digester having 83.33 m²-carrier surface/m³-reactor was operated for 200 days with decreasing HRT from 20 days to 1 day, while comparing its response to a conventional chemostat digester. Although both reactors gave a comparable methane production until a 15-day HRT, the soluble TOC in the chemostat digester elevated to 3,000 mg/L at 4-day HRT suggesting washout of the anaerobic microorganisms. On the other hand, the moving-bed biofilm digester kept a reasonable methane production rate without accumulation of the soluble materials until 3-day HRT. When the HRT was reduced to 2 days, the soluble fraction decreased due to limited production of the decayed materials. To simulate the responses, an extended IWA-Activated Sludge Model was applied and individual kinetics were estimated. The simulation demonstrated that the relevant active anaerobic biomass (acidogens and methanogens) accumulated in the moving-bed biofilm digester showing high TVS digestion efficiency (25%) at even very short HRT.

Keywords: environmental modeling, wastewater treatment, water purification, water quality

INTRODUCTION

Anaerobic digestion of waste activated sludge (WAS) is a system wherein microorganisms in the WAS are anaerobically decomposed into inert particulates and biodegradable material giving methane and carbon dioxide as end-products. Although this system has been widely applied to the reduction of WAS in municipal wastewater treatment plants (WWTPs), its long reaction time of 15 – 25 days has also pointed out to be an essential research topic for the improvement of system performance (Appels *et al.*, 2008). Apart from slow-growing methanogens Yasui *et al.* (2006) demonstrated that the anaerobic decay of heterotrophic organisms (X_{OHO}) in WAS governed the entire digestion rate in the digester as long as the acidogenic and methanogenic biomass were reasonably kept. Therefore, to realize high-rate digestion system, application of a moving-bed process to the anaerobic digestion process would be an interesting option since relevant slow-growing microorganisms may grow and retain in the biofilm at the moving-bed carrier media. Based on this expectation, a study was formulated to develop a mathematical model depicting the biological reactions occurring in the systems that could simulate the dynamic responses.

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The model developed was a modification of the Anaerobic Digestion Model No.1 (ADM1) (Batstone *et al.*, 2002) and the Activated Sludge Model 1 (ASM1) (Henze *et al.*, 2000) which were presented by task groups at International Water Association (IWA) and some of the most implemented mathematical models in many sectors. The degradation of organic compounds is assumed to be divided into the following steps in ADM1: (1) disintegration of homogenous particles to carbohydrates, proteins and lipids, (2) hydrolysis of the complex organic molecules to monomers as sugars, amino acids and long-chain fatty acids, (3) acidogenesis, (4) acetogenesis and (5) methanogenesis. Acidogenesis and acetogenesis include the dynamics of the volatile fatty acids (VFAs) acetate, propionate, butyrate and valerate. Ultimately, acetate and hydrogen compounds are utilized by the methanogens and converted into methane. On the other hand ASM1 describes an activated sludge system with organic oxidation, nitrification and denitrification. The organic material in ASM1 is divided into biodegradable COD and non-biodegradable COD (inert material (X_U)) which are partly produced from the biomass decay with fixed stoichiometry. The biodegradable COD is further divided into active biomass, readily soluble biodegradable substrate (S_B) and slowly hydrolysable materials (XC_B) that eventually becomes S_B (Corominas *et al.*, 2010). To reduce the complexity on ADM1 structure it was decided to use ASM1 as a platform of the development with adding essential reactions in ADM1, since the structure of ASM1 was thought to be the main contributor to the production of new biomass and removal of COD. This model would allow to simulate the variation of total volatile solid (TVS) digestion efficiency (ratio of decomposed material to the amount fed), methane production rate (MPR) and soluble total organic concentration (S-TOC) in the digesters.

MATERIALS AND METHODS

Estimation of organic particulate constituents and specific decay rate of the heterotrophic biomass in the activated sludge

The fresh WAS was collected for 100 days at a regular interval of 2 weeks from Kogasaki WWTP, Kitakyushu, Japan, operated at about 5-day sludge retention time (SRT). The samples were then transferred to an incubation vessel of 500 mL working volume with the addition of 20 mg/L of allylthiourea (Tokyo Chemical Industry, Japan) to suppress oxygen uptake by nitrifiers for the aerobic batch tests. The percentages of individual ASM-based WAS constituents (ordinary heterotrophs (X_{OHO}), slowly hydrolysable materials (XC_B) and non-biodegradable particulate (X_U)) were estimated focusing on the chronological response of oxygen uptake rate (OUR) that was mostly attributed to the decay of X_{OHO} . The OUR was logged every 10 minutes for 5 – 7 days using a respirometer with an automatic oxygen gas supply system provided by Challenging Systems Inc, USA (AER-8). For the anaerobic tests, anaerobically digested sludge for seed was simultaneously taken from a mesophilic digester at Hiagari WWTP, Kitakyushu, Japan, receiving 30.8 kg/m³ of primary sludge and 43.9 kg/m³ of WAS at 36 – 41-day HRT, and its 450 mL was mixed with 50 mL of the WAS. Nitrogen gas was purged before sealing the incubation vessels and MPR was logged every 30 minutes using a respirometer without supplying oxygen. Based on the MPR response, the specific decay rate of X_{OHO} in the anaerobic condition was estimated. The average specific decay rates (0.15 d⁻¹) was used for the dynamic simulation in the continuous experiments.

Continuous anaerobic digestion test

A lab-scale continuous moving-bed biofilm digester (MD) (filled with short plastic tube corresponding to $83.33 \text{ m}^2\text{-carrier surface/m}^3\text{-reactor}$) was operated at $35 \pm 2^\circ\text{C}$ with a working volume of 8 liters and stirring speed of 70 rpm while a control digester (CD) with a working volume of 1 liter was also simultaneously operated under chemostat mode with an identical condition except the addition of the carrier media (Fig. 1). Anaerobic inoculum was collected from the mesophilic digester at Hiagari WWTP, Kitakyushu, Japan. The fresh WAS was collected at about 1 – 7-day intervals from Kogasaki WWTP, Kitakyushu, Japan, and stored at 4°C . The sludge was fed daily to the two digesters while decreasing the HRT from 20 days to 1 day in a step-wise manner. The methane gas production from the digesters was continuously logged using a gas counter after passing it through caustic pellets to remove CO_2 in the biogas (MGC-1, Litre Meter Limited, UK).

Analytical procedures

Total solid (TS), total volatile solid (TVS), chemical oxygen demand (COD) and soluble organic carbon (S-TOC) concentrations were measured according to Standard Methods, 21st edition (APHA, 2005). The soluble COD concentration was approximated from the measured S-TOC with a stoichiometric factor of 2.67 ($= 32/12$), which was deduced from typical WAS elemental constituents ($\text{C}_5\text{H}_7\text{O}_2\text{N}$).

Dynamic simulation

The dynamic simulations of the two continuous experiments were performed focusing on responses of the methane production, soluble and particulate concentrations obtained from the COD in the digesters. The system responses were simulated using GPS-X ver. 6.2 (Hydromantis Environmental Software Solutions Inc., Canada). The simulation layout for the two digesters are shown in Fig. 2. To express the concentrated biomass in the moving bed digester, a solid-liquid separator was customized to entrap the relevant state variables in the system (*e.g.* acidogens and methanogens in the system). Although diffusion resistance of soluble substrates in the biofilm was not incorporated in the model, it was thought that the impact would be limited in the anaerobic digester because the entire reaction was mostly governed by the decomposition of particulates. For simulating the responses of the individual state variables and digestion performances, an extended Activated Sludge Model 1 (ASM1) was applied as shown in Table 1 and Table 2 (Yasui *et al.*, 2006).

Fig. 1 - Continuous anaerobic digesters (a): control digester (CD); (b): moving-bed biofilm digester (MD).

Fig. 2 - Simulation layout of the digesters.

Table 1 - Gujer matrix of the extended ASM1.

Process	Description	X_U	X_{OHO}	X_{ACO}	X_{MEO}	X_{CB}	$S_{B,MEO}$	S_{CH4}
r1	Decay of methanogens	f_U			-1	$1-f_U$		
r2	Growth of methanogens				+1		$-1/Y_{MEO}$	$(1/Y_{MEO})-1$
r3	Decay of acidogens	f_U		-1		$1-f_U$		
r4	Growth of acidogens			+1		$-1/Y_{ACO}$	$1/Y_{ACO}-1$	
r5	Decay of heterotrophs	f_U	-1			$1-f_U$		

X_U : non-biodegradable particulate (g-COD/m³), X_{OHO} : ordinary heterotrophs in WAS (g-COD/m³), X_{ACO} : acidogens (g-COD/m³), X_{MEO} : methanogens (g-COD/m³), X_{CB} : slowly hydrolysable materials for acidogens (g-COD/m³), $S_{B,MEO}$: substrate for methanogens (g-COD/m³), S_{CH4} : methane (mole-CH₄/L), f_U : Production of inert materials (-), Y_{ACO} : Yield of X_{ACO} (-); Y_{MEO} : Yield of X_{MEO} (-)

Table 2 - Process rate equations of the extended ASM1.

Process	Description	Process rate equations
r1	Decay of methanogens	$b_{MEO} \cdot X_{MEO}$
r2	Growth of methanogens	$\mu_{max_MEO} \left(\frac{S_{B,MEO}}{K_{S,MEO} + S_{B,MEO}} \right) \cdot X_{MEO}$
r3	Decay of acidogens	$b_{ACO} \cdot X_{ACO}$
r4	Growth of acidogens	$\mu_{max_ACO} \left(\frac{X_{CB}}{K_{S,ACO} + X_{CB}} \right) \cdot X_{ACO}$
r5	Decay of heterotrophs	$b_{OHO} \cdot X_{OHO}$

b_{MEO} : Specific decay rate of methanogens (d⁻¹), b_{ACO} : Specific decay rate of acidogens (d⁻¹), b_{OHO} : Specific decay rate of heterotrophs (d⁻¹), μ_{max_MEO} : Maximum specific growth rate of methanogens (d⁻¹), μ_{max_ACO} : Maximum specific growth rate of acidogens (d⁻¹), $K_{S,MEO}$: half-saturation substrate coefficient on growth of methanogens (g-COD/m³), $K_{S,ACO}$: half-saturation substrate coefficient on growth of acidogens (g-COD/m³)

RESULTS AND DISCUSSION

Compositions of the waste activated sludge

The fed WAS constituents and the volumetric loading rates (VLRs) in the continuous experiment over 200 days were summarized in Fig. 3. Since the WAS was collected on different days, the concentration of WAS thickened at the laboratory slightly varied and VLR was changed accordingly. Corresponding to the decrease of hydraulic retention time (HRT), the VLRs elevated from 1 to 10.4 kg-COD/m³/d except that there was no feeding of WAS on day 179. According to the batch tests under aerobic and anaerobic conditions, X_{OHO} fraction in WAS during the experimental period was estimated to be 33 – 52% while 4 – 17% of X_{CB} (intermediate from the partially decayed biomass $\approx S_{\text{S,ACO}}$) were detected in the WAS.

TVS digestion efficiency and decomposition of particulate COD

The trend of TVS digestion efficiency and particulate COD concentration (P-COD) in the digesters were plotted as shown in Fig. 4. The two digesters showed comparable responses for both P-COD concentration and TVS digestion efficiency until day 150 (HRT = 20, 15, 10-day) whereas a maximum of 40% of digestion efficiency was observed at 20-day HRT. When the HRT was reduced to 5 days, a divergence in the TVS digestion efficiency of the two digesters was recognized. The divergence became larger when the HRT was reduced to 1 day. In the operating condition, TVS digestion efficiency in the CD declined sharply from 30 to 10% whereas TVS digestion efficiency in the MD decreased only until 25%. The deterioration of TVS digestion efficiency for the CD was thought to be due to a washout of active anaerobic biomass. Since the digestion efficiency at the MD did not change significantly in the operating conditions, it seemed that the presence of carrier media could give a positive effect on the anaerobic digestion. The responses of the P-COD concentration in the two digesters, which corresponded to their TVS digestion efficiency, had fluctuation over the experimental period due to fluctuation of fed WAS concentration. Nevertheless, the change in P-COD concentration could be well reproduced using the simplified mathematical model.

Fig. 3 - Constituents of the fed WAS and volumetric loading rate to the digesters.

Fig. 4 - Digestion performances in the digesters (a): TVS digestion efficiency; (b): particulate COD concentration in the digesters (triangles: MD, circles: CD, dotted line: HRT, thin line: simulation of P-COD concentration)

Soluble TOC and methane production rate

As shown in Fig. 5, even at 5-day HRT the S-TOC in the MD was detected to be only around 300 mg/L. On the other hand, in the CD the S-TOC concentration elevated to 3,000 mg/L suggesting a washout of the anaerobic microorganisms took place. When the HRT was further reduced to 2 days, the soluble fraction started decreasing. Perhaps this was due to the limited decay rate of microorganisms of WAS in the system producing small amount of soluble substrate in such short HRT (r5 at Table 2 and Table 3). The response of S-TOC concentration was also reasonably simulated. During this operation the MD could keep a reasonably low S-TOC. Based on the distinct responses, the specific decay rate of X_{OHO} and the specific growth rate of X_{ACO} were calibrated. The MPRs of the two digesters provided almost identical response until day 150 (until reduction of HRT to 5 days). Corresponding to the deterioration of digestion efficiency at the CD, the MPR decreased remarkably. On the other hand, the MPR at the MD showed very high MPR until 4-day HRT because the VLR was doubled comparing to that at 8-day HRT due to more feeding of the WAS. The MPR declined afterward when the HRT was changed to less than 3 days. The kinetic of the methanogen on the growth was estimated from the elevation/decrease of MPR and the change of S-TOC.

Concentration of microorganisms in the digesters

The calculated concentration of the microorganisms is summarized as shown in Fig. 6 ((a): heterotrophic biomass (X_{OHO}), (b): acidogens (X_{ACO}) and (c): methanogens (X_{MEO})) in the digesters. Higher X_{ACO} and X_{MEO} concentrations in the MD were obtained comparing to those of the CD while comparable concentration of X_{OHO} in the digesters was recognized. This meant that the difference of the process performance for the two digesters could be attributed to the difference of active anaerobic biomass for the two digesters. According to the kinetic simulation, the concentration of X_{ACO} decreased when the HRT was set at less than 8 days. Although most sludge in the CD was lost at day 92 because a mechanical problem of the experimental apparatus occurred and re-startup of CD was obliged, the unexpected event could be also reasonably simulated as the reduction of MPR in Fig. 5b, which was the consequence of

anaerobic biomass concentrations in the digesters. At the very short HRT conditions (< 4-day HRT) X_{MEO} was not supposed to grow in the CD resulting in the discontinuation of methane fermentation. In contrast, methanogenic activity was still observed and simulated for the MD at such very short HRT.

Fig. 5 - Production of soluble organics and methane gas in the digesters (a): S-TOC concentration; (b): Methane gas production rate (triangles: MD, circles: CD, dotted line: HRT, thin lines: simulation of S-TOC concentration and MPR).

Fig. 6 - Calculated concentration of microorganisms in the digesters (triangles: MD, circles: CD, dotted line: HRT).

Table 3 - List of kinetics and stoichiometry of the anaerobic digestion process.

Kinetics	This study	References	Unit
Maximum specific growth rate of acidogens	0.4	0.41-21 ¹⁾	d ⁻¹
Half-saturation coefficient on growth of acidogens	20	50-200 ¹⁾	gCOD/m ³
Maximum specific growth rate of methanogens	0.17	0.02-8 ¹⁾	d ⁻¹
Half-saturation coefficient on growth of methanogens	30	30-900 ¹⁾ (acetate utilizer)	gCOD/m ³
Specific decay rate of methanogens	0.01	0.01-0.1 ^{1), 3)}	d ⁻¹
Specific anaerobic decay rate of heterotrophs	0.15	0.21 ⁴⁾	d ⁻¹
Stoichiometry	This study	References	Unit
Production of acidogens	0.08	0.08 ⁵⁾	-
Production of methanogens	0.04	0.04 ⁵⁾	-
Production of inert materials	0.08	0.08 ²⁾	-

¹⁾ Batstone *et al.* (2002), ²⁾ Henze *et al.* (2000), ³⁾ Siegrist *et al.* (2002), ⁴⁾ Yasui *et al.* (2006), ⁵⁾ Yasui *et al.* (2008)

Model calibration

The COD concentration in the two digesters was used as composite variables to estimate the kinetics of individual microorganisms. The entrapped proportions of X_{ACO} and X_{MEO} that retained in the MD were calibrated to be 80% and 60% respectively. This suggested that the use of carrier media on the anaerobic digestion process would help the improvement of digestion performance by keeping the relevant active biomass for the decomposition of slowly degradable materials. The kinetic parameters obtained from the experiments are listed in Table 3, and the calibrated values were also compared with the default ones in ADM1 (Batstone *et al.*, 2002), ASM1 (Henze *et al.*, 2000), the anaerobic digestion of sewage sludge (Siegrist *et al.*, 2002) and anaerobic decay of WAS (Yasui *et al.*, 2006; Yasui *et al.*, 2008). Although it appeared that slightly lower kinetics for μ_{max_ACO} , μ_{max_MEO} , b_{MEO} and b_{OHO} were obtained, in general, most of the kinetics were in the reasonable range even applying the simplified extended activated sludge model.

CONCLUSION

A simplified mathematical model was developed to simulate the moving-bed biofilm digester process in the dynamic condition. The calibrated coefficients used in the model allowed to reasonably simulate the experimental results. The results suggested that the biological activity of the microorganisms in the moving-bed biofilm digester could be sustained even in very short hydraulic retention time of below 4 – 5 days. A clear improvement in TVS digestion efficiency and methane gas production rate were obtained when short plastic tubes were filled in the digester for the carrier material of biomass. Even though the conventional digester (without filling media) showed TVS digestion efficiency at only 10% during such critical HRT, 25% of TVS digestion

efficiency was achieved because the soluble organic intermediates from the decayed biomass was successfully decomposed by the anaerobic microorganisms entrapped in the moving-bed biofilm digester. This organic material was further degraded to methane gas.

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