ENVIRONMENTAL SCIENCES Vol. 1, No. 2, 125~136
Bulletin of the Korean Environmental Sciences Society

Feasibility Studies on Anaerobic Sequencing Batch Reactor for Sludge Treatment

Duk Chang, Joon-Moo Hur, Bu-Soon Son*, Jong-An Park* and Bong-Ki Jang*

Department of Environmental Engineering, Konkuk University, Kwangjin-gu Mojin-dong, Seoul 143-701, Korea
**Department of Environmental Health Science, Soonchunhyang University, Asan Shinchang-Myon, Choongnam 336-745, Korea*

(Manuscript received on 30 October, 1997)

Digestion of a municipal wastewater sludge by the anaerobic sequencing batch reactor (ASBR) was investigated to evaluate the performance of the ASBR process at a critical condition of high-solids-content feed. The reactors were operated at an HRT of 10 days with an equivalent loading rate of 0.8-1.5 gVS/L/d at 35℃. The main conclusions drawn from this study were as follows:

1. Digestion of a municipal wastewater sludge was possible using the ASBR in spite of high concentration of settleable solids in the sludge. The ASBRs with 3- and 4-day cycle period showed almost identical high digestion performances.
2. No adverse effect on digestion stability was observed in the ASBRs in spite of withdrawal and replenishment of 30% or 40% of liquid contents. A conventional anaerobic digester could be easily converted to the ASBR without any stability problem.
3. Flotation thickening occurred in thicken step of the ASBRs throughout steady state, and floating bed volume at the end of thicken period occupied about 70% of the working volume of the reactor. Efficiency of flotation thickening in the ASBRs could be comparable to that of additional gravity thickening of a completely mixed digester.
4. Solids were accumulated rapidly in the ASBR during start-up period. Solids concentrations in the ASBRs were 2.6 times higher than that in the completely mixed control reactor at steady state. Dehydrogenase activity had a strong correlation with the solids concentration. Dehydrogenase activity of the digested sludge in the ASBR was 2.9 times higher than that of the sludge in the control reactor, and about 25 times higher than that of the subnatant in the ASBR.
5. Remarkable increase in equivalent gas production of 52% was observed at the ASBRs compared with the control reactor in spite of similar quality of clarified effluent from the ASBRs and control reactor. The increase in gas production from the ASBRs was believed to be combined results of accumulation of microorganisms, higher driving force applied, and additional long-term degradation of organics continuously accumulated.

Key words : Municipal wastewater sludge, Anaerobic sequencing batch reactor

1. Introduction

Anaerobic process has been widely used as an ideal process for the treatment of high strength organic wastes, since the process can be operated with low maintenance cost and produce valuable bio-gas. However, difficulties associated with the process stability have been experienced in the conventional anaerobic processes because anaerobic microorganisms are very susceptible to environmental conditions. Considerable works on the high-rate anaerobic processes, which involve the anaerobic contact, the two-phase digestion, the upflow anaerobic sludge blanket, the anaerobic filter, and the anaerobic fluidized bed, have been done focusing mainly on decreasing hydraulic retention time and increasing bio-solids. Nevertheless, more attention needs to be directed to the development of high-rate anaerobic processes dedicated to the treatment of various types of wastes with simple and stable operation regardless of influent solids concentration.

The anaerobic sequencing batch reactor (ASBR) process, which repeats a cycle including feeding, reaction, solid-liquid separation, and withdrawal steps in a single reactor, is believed to be a promising process, because the process could maintain a high concentration of slow-growing methanogenic bacteria in the system without additional facility and serious operational difficulties.

It is therefore expected that a remarkable improvement of anaerobic treatment stability and efficiency could be achieved with the ASBR process. Studies on the ASBR process have been carried out in recent years by several investigators. Kennedy et al. (1991) conducted a study on the anaerobic sludge blanket sequencing batch reactor treating a soluble synthetic wastewater to investigate the effect of fill period to react period ratio on the reactor performance. The authors indicated that the fill: react ratio was a critical design parameter for the reactor. Suthaker et al. (1991) also reported that the fill period and the fill: react ratio affected the performance of the ASBR treating a synthetic wastewater. Sung and Dague (1992) studied the effects of reactor configuration and mixing type on the performance of the ASBR using a synthetic milk substrate. They pointed out that reactor configuration appeared to be significant in the performance of the ASBR, particularly with regard to the development of granular sludge, and that intermittent mixing resulted in a superior performance than continuous mixing. Effect of vacuum application to the ASBR prior to settle step was investigated by Herum and Dague (1993). Vacuum application resulted in an improved sludge settleability and consequent enhanced reactor performance.

Difficulties associated with solid-liquid separation are often encountered in anaerobic processes. Good solid-liquid separation is especially essential to the design and operation of the ASBR process, since sludge should be separated before draw step for biomass accumulation and good effluent quality. The most serious solid-liquid separation problem would occur in the ASBR process treating a high-solids-content waste such as a municipal wastewater sludge. Application of the ASBR to the sludge digestion is therefore worth challenging to evaluate the performance of the ASBR at a critical condition. Higher microbial activity of settled sludge than that of supernatant after solid-liquid separation should be also clearly demonstrated prior to an application of the ASBR process. Previous study revealed that the thickened digested sludge from a municipal sludge digester had a seven times higher microbial activity than the supernatant, while both supernatant and thickened digested sludge from a digester treating a distillery waste had a nearly same microbial activity (Cho, 1992). The ASBR process was therefore believed to be applicable to the digestion of a municipal sludge.

The objective of this research was to investigate the performance of the anaerobic sequencing batch reactor for the digestion of a municipal wastewater sludge in order to develop an improved anaerobic process for high-solids-content waste.

2. Materials and Methods

2.1. Description of digestion system

Two laboratory-scale anaerobic digestion systems were used for the experimental study. Each digestion system consisted of a conventional high-rate type anaerobic reactor installed in an environmental chamber temperature of which was maintained at 35±1℃, and a floating type gas collector equipped with a counterpart. Two reactors, one for ASBR and the other for control were identical except eleven sampling ports on side wall of the ASBR. Each reactor made of Plexiglas were 32 cm in height with an inner diameter of 14 cm, and had a working liquid volume of 4 liters. Mixing was carried out using a paddle type mechanical mixer equipped with a skimmer. Shaft of the mixer was covered with a tube from the top of the reactor to the two third of the liquid depth to keep the reactor in anaerobic condition.

2.2. Characteristics of feed sludge

The feed sludge was obtained from a gravity thickener for the mixed sludge of primary and activated sludge in a municipal wastewater treatment plant located in Kwacheon, Korea. The feed sludge was collected about bimonthly, and stored in a refrigerator maintained at the temperature below 4℃ after screening with standard sieve #8. Temperature of the feed was raised in an environmental chamber just before feeding to avoid a temperature shock. Feed composition had a remarkable variation with collection time. The feed sludge showed typical characteristics of the mixed sludges produced from the municipal wastewater treatment plants in Korea. Table 1 shows the characteristics of the feed sludge. Average volatile fraction of total solids was 54.4%.

Table 1. Characteristics of feed sludge.

Parameters	Range	Mean±SD
pH	5.87~6.96	6.38±0.3
ORP(mV)	-107~-250	-183±31.8
TS(mg/L)	11,990~27,950	20,120±3,148
VS(mg/L)	7,200~15,440	10,950±1,994
VS/TS(%)	45.6~68.4	54.4±4.8
COD(mg/L)	11,110~27,950	21,120±3,148
Thickened volume(%)*	24~92	58±18.3
Centrifuged volume(%)**	16~30	21.5±3.9
Volatile acid(mgHAc/L)	147~697	490±113.4
Alkalinity(mg $CaCO_3$/L)	277~1,187	620±205.7

*Sludge volume after 1 day thickening in a 100mL graduated cylinder

**Sludge volume after centrifugation at 2,500rpm for 5 minutes

2.3. Operation methods

Each cycle of the ASBR process was comprised of fill, react, thicken, and draw steps. Mechanical mixing was provided during fill and react periods. The ASBR was operated with two cycle periods of 3 and 4 days consisting of respective ratio of react period to thicken period (react: thicken ratio) of 2:1 and 3:1 with the same thicken period of 1 day to meet the operational constraint obtained from a preliminary solid-liquid separation test. Fill and draw steps were performed manually for about 30 minutes. Simultaneous control run is essential to evaluate the performance of the ASBR because the nature of the municipal sludge varied widely with time. A completely mixed daily-fed reactor without solid-liquid separation step was therefore operated as a control run to be able to compare its baseline performance with that of the ASBR. All ASBRs and control reactor were operated at an equivalent hydraulic retention time (HRT) of 10 days with an average equivalent loading rate of 1.1 gVS/L/d and 1.6 gCOD/L/d at the temperature of 35℃. the HRT of 10 days was chosen as the HRT was found to exhibit stable digestion generally accepted in the literature. The operating conditions of the ASBRs and control reactor are given in Table 2. The main operation parameter of the ASBR was a react: thicken ratio.

The seed sludge was obtained from a laboratory-scale mesophilic digester operated at a HRT of 20 days with the same municipal sludge used in this study. Two reactors for the control and ASBR runs were inoculated with the seed sludge, and operated as completely mixed daily-fed reactors at the same operating conditions for three months to confirm identical performances of both reactors prior to start-up of the sequencing batch operation with thicken step for the ASBR run.

Table 2. Operating conditions.

Parameters	ASBR		Control
	10-day HRT		10-day HRT
	3-day cycle	4-day cycle	
Temperature(℃)	35	35	35
Operation periods(days)*	50	140	190
Working volume(L)	4	4	4
Organic loading rate			
(gVS/L/day)	0.80~1.54	0.75~1.45	0.75~1.54
(gCOD/L/day)	1.11~2.20	1.05~2.15	1.11~2.20
Cycle time			
Fill period (hrs)	0.5	0.5	0.5
React period (days)	2	3	1
Thicken period (days)	1	1	-
Draw period (hrs)	0.5	0.5	0.5
Withdrawal volume	1.2L/cycle	1.6L/cycle	0.4L/day

*After start-up of ASBR

2.4. Analysis methods

Analyses were performed for the digested sludge and clarified effluent after thickening on pH, ORP, alkalinity, volatile acids (VA) concentrations, total solids (TS), volatile solids (VS), and COD. All analyses were conducted as per procedures in the APHA Standard Methods (1992). Gas production was monitored, and expressed as a calibrated value at the standard condition. Composition of the digester gas sample from reactor headspace was determined by gas chromatography using a thermal conductivity detector and Porapak Q as a packing material. Dehydrogenase activity (DHA) was also determined as an absorbance by a modified procedure of TTC method (Ghosh, 1969). Interface height of the sludge during 1 day thickening was recorded as a measure of solid-liquid separation characteristics. Interface height of the digested sludge in the ASBR was measured directly from the reactor during thicken period, while those of the sludge in the control reactor and feed sludge were measured in a 100 ml and 1 liter graduated cylinder, respectively. Centrifuged volume of the sludge was also measured by centrifugation at 2,500 rpm for 5 minutes.

3. Results and Discussion

3.1. Relationship between equivalent HRT and withdrawal volume ratio

The minimum equivalent HRT of the ASBR treating a high-solids-content sludge depends upon a permissible effluent withdrawal volume in draw step under a fixed cycle period, since the digested sludge has a large thickened volume. A permissible withdrawal volume in draw step could be estimated by a preliminary solid-liquid separation test using a similar digested sludge. The required cycle period can be determined under a designed equivalent HRT and a withdrawal volume not exceeding the permissible volume. A simple equation can be derived to demonstrate a relationship between equivalent HRT, cycle period, and withdrawal volume for the ASBR process, as follows:

Equivalent HRT
= Cycle period / Withdrawal volume ratio

Withdrawal volume ratio is a ratio of the withdrawal volume in draw step to the working volume of the ASBR. Figure 1 shows the relationship between equivalent HRT and withdrawal volume ratio at various cycle periods. The cycle period should satisfy the react period required for stabilization of organics, and also include the thicken period required to obtain predetermined withdrawal volume.

3.2. Preliminary solid-liquid separation test

Solid-liquid separation characteristics of the sludge should be the most important design and operational parameter of the ASBR process treating high concentration of settleable solids, because a permissible effluent withdrawal volume is restricted by the thickened volume of the digested sludge in thicken step to keep the solids in the reactor and obtain a good effluent quality. Preliminary solid-liquid separation test was therefore carried out to evaluate the feasibility of application of the ASBR process to the sludge digestion. Poor solid-liquid separation was expected undoubtedly for the digested sludge in the ASBR, since the feed sludge collected at the beginning of this study had thickened volume ranging from 40% to 80% after 1 day thickening. The digested sludge from a completely mixed digester operated at a HRT of 20 days at 35℃ with a municipal sludge as a feed had thickened volume of 50-70% after 1 day thickening. Time required to obtain a thickened volume of 70% was 12 to 18 hours. The thickened volume of the sludge in the ASBR was expected to be larger than that of the completely mixed digester because solids would be continuously accumu-

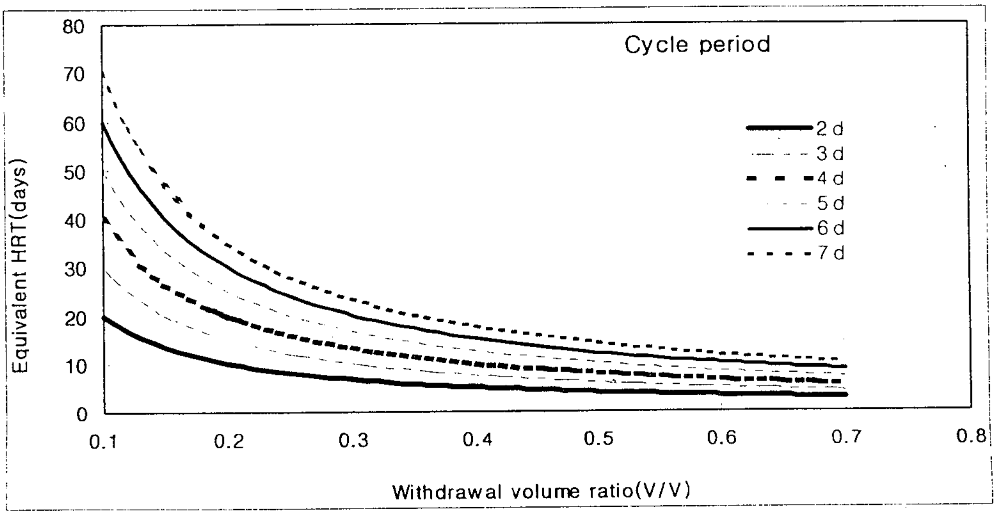

Fig. 1. Relationship between equivalent HRT and withdrawal volume ratio of the ASBR.

lated in the ASBR. This preliminary test clearly demonstrated that the permissible clarified effluent volume in draw step of the ASBR would be 30-50% of a working volume of the ASBR, and also suggested that at least 12 hours was required for thicken period to achieve favorable operation of the ASBR without loss of thickened sludge. Consequently, the operation of the ASBR was initiated with a cycle period of 3 days consisting of a react period of 2 days and a thicken period of 1 day to keep the designed equivalent HRT of 10 days.

3.3. Start-up behavior of the ASBR

The reactor for the ASBR run had been operated with a completely mixed mode at the operating conditions of the control run for three months until it showed the same performance as that of the control run. Two reactors for the ASBR and control run showed almost same steady state performances in terms of pH, ORP, VA, and alkalinity of the digested sludge, except 12% lower average gas production from the reactor for the ASBR run. Conversion of the reactor for the ASBR run to the ASBR was initiated with 3-day cycle period at the equivalent loading rate to that of the control run.

Figure 2 shows the cumulative gas production during each batch period and pH of the digested sludge at the initial start-up of the ASBR with 3-day cycle period. The pH was lowered slightly by 0.15 unit only at the initial stage of react period in the first cycle of the ASBR operation, and no significant change of pH was observed as the cycle repeated. Significant accumulation of volatile acid did not occur even in the first cycle. Solids concentrations were not changed noticeably during any react period. However, gas production during on cycle of the ASBR became higher than the equivalent 3 days gas production of the control run even at the beginning of the ASBR operation. Solids were accumulated rapidly in the ASBR during start-up period. The digested sludge in thicken step settled, did not float, during the initial operation of 5 cycles, and its thickened volume after 1 day thickening increased up to 90%, while that of control reactor remained around 50%. The thickened sludge was therefore included in the effluent from the ASBR

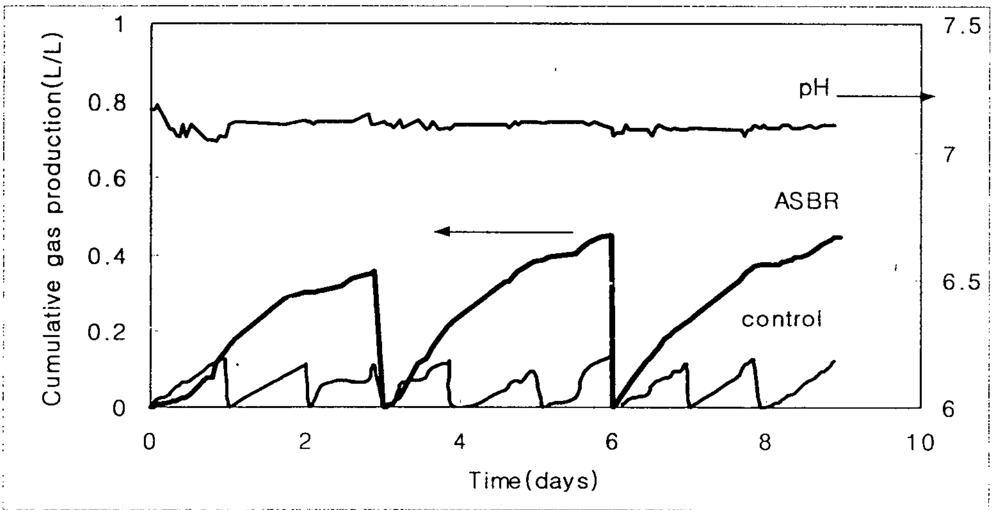

Fig. 2. Cumulative gas production and pH at the initial start-up of the ASBR with 3-day cycle period.

during the initial operation of 5 cycles.

After 50 days operation of the ASBR with 3-day cycle period, the ASBR was converted to the mode of 4-day cycle period. No adverse effect of shock loading on digestion stability was observed during start-up of both ASBRs with 3- and 4-day cycle periods in spite of withdrawal and replenishment of 30%, 40% of liquid contents, whereas stable digestion could not be expected in the completely mixed control run under such abrupt draw and fill conditions. This start-up behavior of the ASBR indicates that a conventional digester could be easily converted to the ASBR without any stability problem. It is also believed that a conventional digester could be started with such a sequencing batch operation with thicken step to minimize start-up period.

3.4. Characteristics of solid-liquid separation

Characteristics of the solid-liquid separation of the digested sludge in the ASBR was quite different from that of the control run. The digested sludge in the ASBRs always floated during thicken period throughout the experimental period except a half month start-up operation of the ASBR with 3-day cycle, while that of the control run settled well in a cylinder. This flotation thickening occurred after 5 to 13 hours thickening in thicken step as a result of formation of gas bubbles entrapped in the digested sludge. The effluent of the ASBR was therefore withdrawn from the lower part of the reactor.

Floating sludge bed volume at the end of thicken period of the ASBRs occupied 50-80% of the reactor working volume. Average bed volume was 70% for the 3-day cycle mode, and 69% for the 4-day cycle mode, respectively. Interface thickening curves of the digested sludge at steady state and that of the feed sludge are plotted in Figure 3. Solids concentrations in the ASBR were 2.6 times higher than that of the control sludge. Thus, the solids accumulated more than twice in the ASBR compared to the control run.

Settling was considered to be better than flotation for simple operation of effluent withdrawal, although the flotation thickening did not

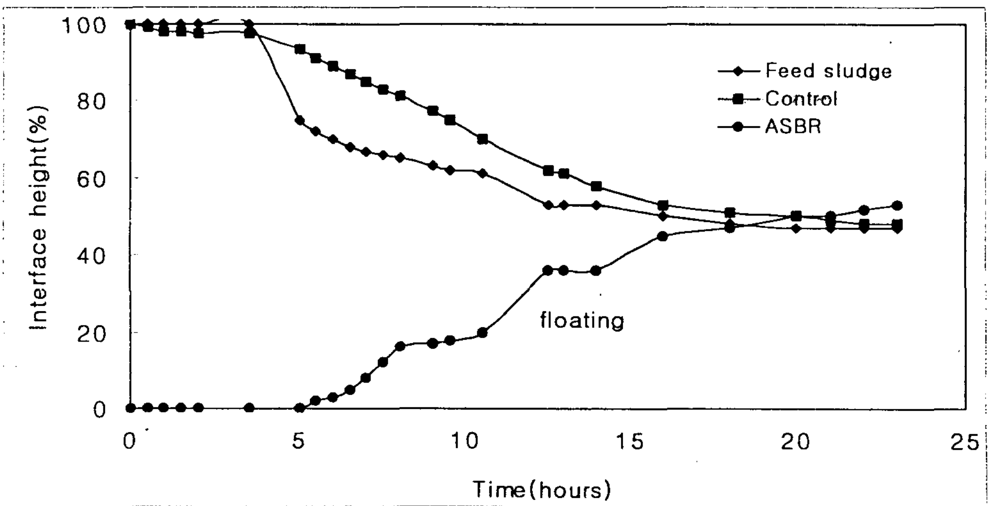

Fig. 3. Interface thickening curves of the digested sludge and feed sludge.

cause any serious operational problem during the operation of the ASBR with 3-day cycle. The operation mode of the ASBR was therefore changed to the cycle period of 4 days to examine whether an increase in react period could reduce gas bubble formation in thicken step, and check whether the ASBR system could be operated without any adverse effect even at the condition of 40% withdrawal and replenishment of liquid contents. However, identical flotation also continued during the 4-day cycle operation. On the other hand, settling was achieved with a gentle mixing of the reactor contents of the ASBR with 4-day cycle in a 1liter cylinder at 35℃, since the entrapped gas bubbles were removed by vertical pickets. A settled volume of 87% was observed after 1 day gentle mixing of 4 rpm. Gentle mixing by vertical pickets during thicken period was therefore applied directly to the ASBR for 3 cycles so as to settle the sludge. However, solid-liquid separation never occurred with such a gentle mixing in the reactor. On the contrary, effluent contained the sludge, and solids loss from the reactor resulted in decrease in gas production during gentle mixing. Flotation also occurred with a 15 minutes rapid mixing to remove the gas bubbles prior to thickening.

3.5. Steady state performances

Steady-state performances of the ASBRs and their corresponding control runs are summarized in Table 3. The performance of the ASBR could be regarded as a pseudo-steady state since intentional control of solids retention time (SRT) was not employed. The SRT of the ASBR was controlled only by solids loss in draw step. The average SRT estimated based on the TS was 205 days in the ASBR with 3-day cycle, and 161 days in the ASBR with 4-day cycle, whereas the SRT of the control reactor was kept at constant 10 days. There was no noticeable dynamic

Table 3. Steady state performances(Average±Standard deviation).

Parameters	HRT(10days)-3day cycle		HRT(10days)-4day cycle	
	ASBR	Control	ASBR	Control
pH	7.09±0.08	6.97±0.09	6.90±0.10	6.85±0.10
ORP(mV)	-261±60	-290±42	-206±57	-199±38
Volatile acid (mgHAc/L)	214±19	225±30	192±48	182±63
Alkalinity (mg $CaCO_3$/L)	1,710±85	1,710±83	1,550±213	1,290±193
TS removal (%)				
Digested sludge basis	-	8.3±4.8	-	16.1±7.7
Clarified effluent basis	91.7±1.2	90.2±0.5	93.0±1.9	93.5±2.3
VS removal (%)				
Digested sludge basis	-	21.0±11	-	20.4±10
Clarified effluent basis	92.4±3.5	91.1±2.8	93.4±3.7	93.5±2.3
COD (%)				
Digested sludge basis	-	18.2±5.2	-	21.9±7.4
Clarified effluent basis	95.2±2.0	92.0±7.5	95.4±2.3	92.2±7.1
Gas production				
Gas production rate (L/L/d)	0.15±0.03	0.10±0.01	0.15±0.03	0.1±0.03
Gas yield (L/gVS added)	0.14±0.02	0.09±0.02	0.14±0.04	0.09±0.04
Methane content (%)	73.2±0.2	73.0±0.1	73.0±0.1	72.6±0.3
Thickened volume (V/V%)	70±15	49±1.2	69±6.1	61±12
Centrifuged volume (V/V%)	-	-	38±4.1	20±2.7

change of the chemical composition and organics concentrations during the completely mixed batch period of all reactors due to a low organic loading rate of 0.75 to 1.54 gVS/L/d.

3.5.1. Chemical characteristics of the digested sludge

The pH, ORP, VA, and alkalinity of the digested sludges in the ASBRs and their control runs were almost identical in the ranges indicating favorable anaerobic digestion of the municipal wastewater sludge. No difference in alkalinity was observed between the subnatant and thickened sludge in the ASBRs.

3.5.2. Organics removals

The VS and COD removals based on the clarified effluent after 1 day thickening were also almost identical regardless of the operational mode of reactor, though the subnatant of the ASBR had a slightly lower COD than supernatant of the control run. The VS removals based on the clarified effluent were 83-99% in the ASBRs, and 81-97% in the control run, respectively. The COD removals of the ASBRs were consistently above 90%, while that of the control reactor ranged from 71 to 97%. Removals based on the digested sludge were not available for the ASBR because representative reactor contents could not be sampled at the end of the cycle period. These high organics removals based on the subnatant of the ASBRs indicate that efficiency of flotation thickening in the ASBRs could be comparable to that of gravity thickening of the control run. It should be noted that additional thickening facility is required at a conventional completely mixed digester to obtain such a high organics removal based on the supernatant, while the ASBR can achieve high organics removal without additional thickener. About 20% organics removal based on the digested sludge of the control run was quite lower than those reported in the literature due to low biodegradable organics content of the mixed sludge from the municipal wastewater treatment plants in Korea (Choi and Chang, 1988).

3.5.3. Gas production

Figure 4 shows variation of equivalent daily organic loading rate (OLR) and cumulative gas

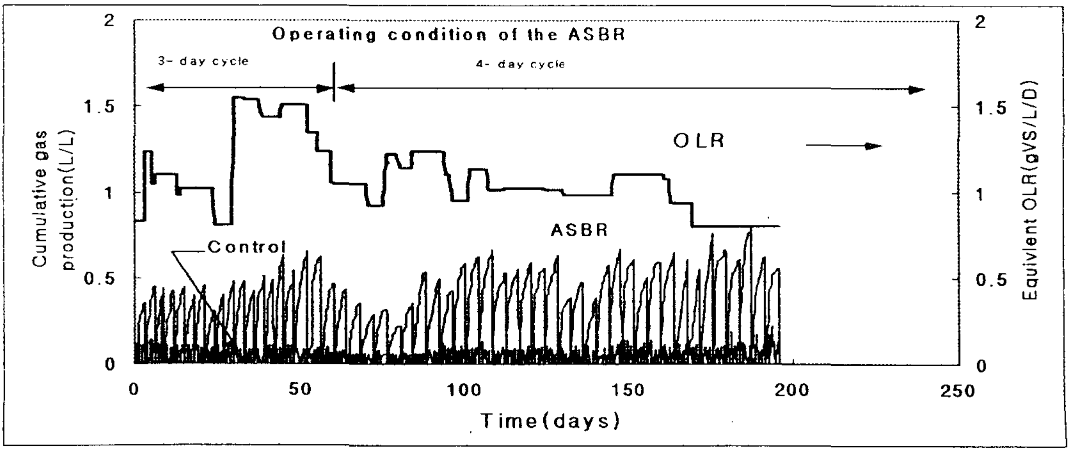

Fig. 4. Cumulative gas production during sequences of batch period and organic loading rate after start-up of the ASBR.

production per reactor working volume from the ASBRs and their corresponding control run during sequences of batch period after start-up of the ASBR. Gas production from the ASBR lowered during the operation period of 70 to 80 days after start-up due to lowered loading rate and losses of solids by gentle mixing in thicken step. Identical gas production rates from both ASBRs, as listed in Table 3, indicate almost same digestion efficiencies.

Remarkable increase in gas production was observed at the ASBRs compared with the control run, as shown in Table 3 and Figure 4, in spite of similar quality of clarified effluent from the control and ASBRs. Average increase in equivalent daily gas production from the ASBRs was 52% compared with that from the control run. It was believed that the increase in gas production from the ASBRs was combined results of accumulation of microorganisms, higher driving force applied, and additional long-term degradation of organics continuously accumulated. Approximate 50% of total gas production during one cycle of the ASBRs was produced for initial one day reaction, and 5% to 13% of total gas production during thicken period. Maximum gas yields based on VS added were 0.25 and 0.18 L/g VS from the ASBR with 4-day cycle and the control run, respectively. Observed gas yields presented in Table 3 were lower than those in the literature because of low biodegradable content of the feed sludge.

Figure 5 shows change of the gas production ratio expressed as gas production from the ASBR per equivalent gas production from the control run. It should be noted that the gas production ratio increased dramatically just after start-up of the ASBR, even though the reactor for the ASBR run showed slightly lower gas production than the control run during the period of completely mixed operation. Average gas production ratio was 1.5 during the operation of both ASBRs. Gas composition was almost identical in all reactors, and average methane content of 73% was maintained throughout the experimental period. Gas composition was not changed noticeably during react period of the ASBRs.

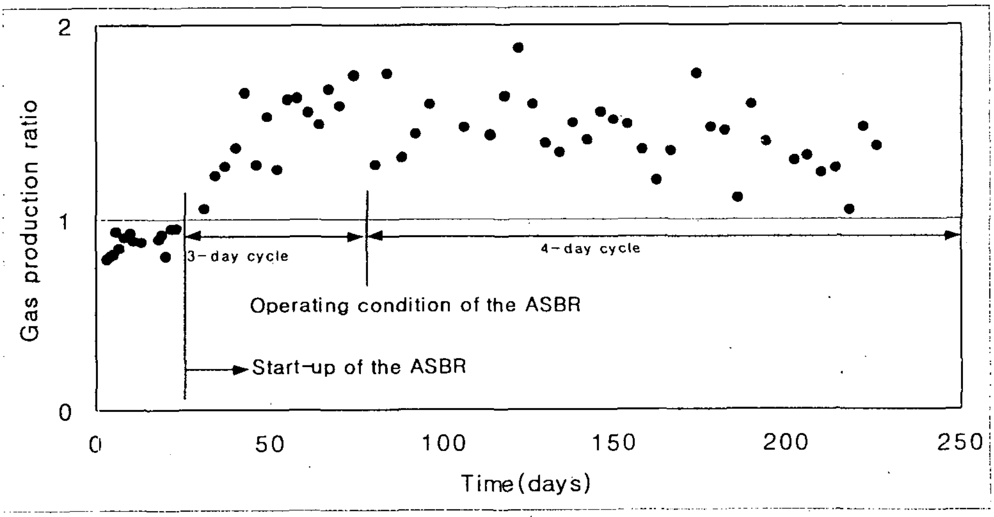

Fig. 5. Gas production ratio of the ASBR to the control run.

3.5.4. Solids profiles in the ASBR

Solids concentration profiles in the thickened sludge bed were examined at the end of thicken period of the ASBRs, as shown in Figure 6 and 7. The profiles clearly demonstrate the flotation thickening of the digested sludge occurred in the ASBRs. Slight increase in solids concentrations was observed with increasing bed height. The volatile fraction of the total solids was almost uniform between 40% and 45% throughout the bed height.

3.5.5. Dehydrogenase activities

The digested sludge in the ASBR operated over

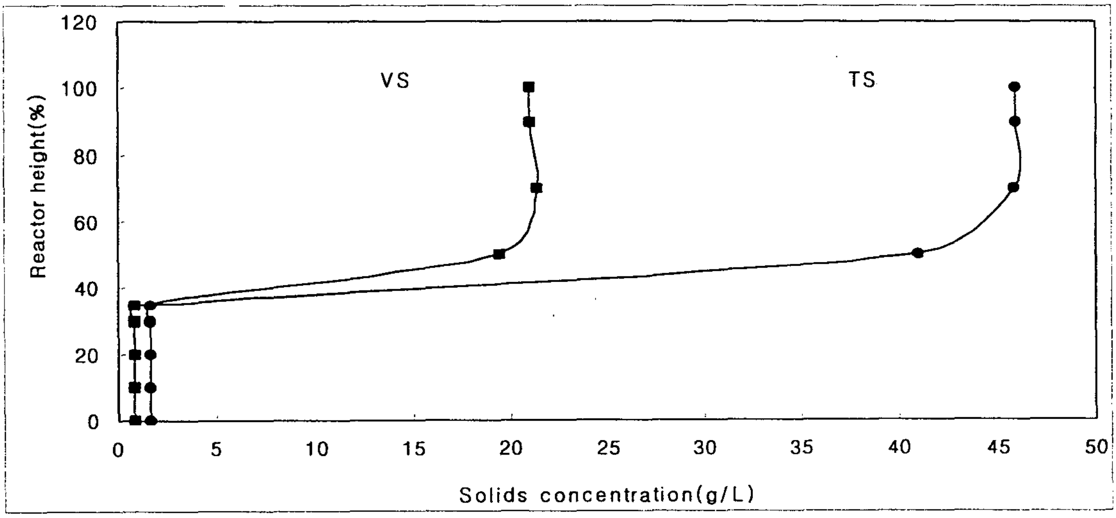

Fig. 6. Solids profiles at thicken step of the ASBR with 3-day cycle period.

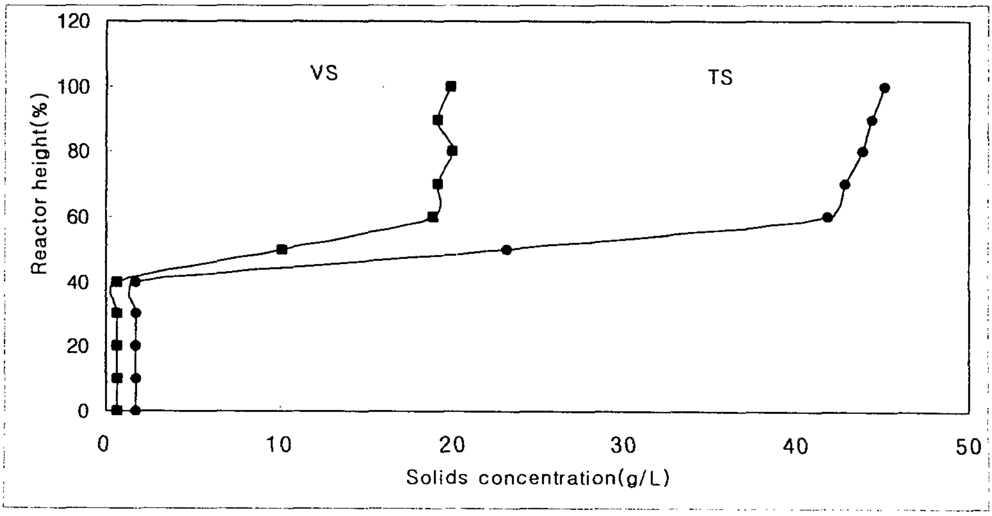

Fig. 7. Solids profiles at thicken step of the ASBR with 4-day cycle period.

six months had a 2.9 times higher dehydrogenase activity (DHA) than that in the control run, while the DHA of the sludge in the ASBR during start-up period was only 20% higher than that of the sludge in the control run. The DHA of the subnatant showed only 2-6% of that of the digested sludge in the ASBR. The DHA had a strong correlation with the solids concentration, since average solids concentration of the sludge in the ASBR was 2.6 times higher than that of the sludge in the control run, and 30 times higher than that of the subnatant in the ASBR.

Reference

APHA-AWWA-WPCF(American Public Health Association, American Water Works Association, Water Pollution Control Federation), 1992, Standard methods for the examination of water and wastewater, 18th ed., APHA.

Cho, N. Y., 1992, Distribution of microbial activity in anaerobically digested sludge. M. S. Thesis, Kon-Kuk Univ., Korea.

Choi, E. S. and K. Chang, 1988, Evaluation of design data for anaerobic sludge digestion in Korea, J. Korean Soc. Water and Wastewater. 1(1). 1-8.

Ghosh, S. 1969, Kinetics of aerobic utilization of mixed sugars by heterogeneous microbial population, Ph.D. Thesis, Georgia Institute of Technology, U.S.A.

Herum, B. A. H. and R. R. Dague, 1993, The effects of applied vacuum on the performance of the anaerobic sequencing batch reactor. Paper Presented at The 48th Industrial Waste Conference, Purdue University, West Lafayette, Indiana. May 11-13.

Kennedy, K. J., W. A. Sanchez, M. F. Hamoda and R.L. Droste, 1991, Performance of anaerobic sludge blanket sequencing batch reactor, Journal of Water Pollution Control Federation, 63(1), 75-83.

Sung, S. and R. R. Dague, 1992, Laboratory studies and modeling of the anaerobic sequencing batch reactor, Proceedings of Water Environment Federation 65th Annual Conference and Exposition, New Orleans, Louisiana, September 20-24, pp. 171-182.

Suthaker, S., C. Polprasert and R. L. Droste, 1991, Sequencing batch anaerobic reactors for treatment of a high-strength organic wastewater, Water Science Technology, 23, 1249-1257.