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Performances of Anaerobic Sequencing Batch Reactor for Digestion of Municipal Sludge at the Conditions of Critical Solid-liquid Separation

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혐기성 연속 회분식 공정에 의한 도시하수슬러지 소화시 고액분리 특성에 따른 처리효율평가

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ABSTRACT

The objective of this study was to evaluate the performances of the ASBR under critical conditions of solid-liquid separation, caused by extremely high solids concentration, for wider application of the ASBR to various wastes. The ASBRs and completely-mixed daily-fed control runs were operated using a municipal mixed sludge at 35°C and 55°C. Conversion of completely-mixed daily-fed reactor to sequencing batch mode and changes in HRT of all ASBRs were easily achieved without adverse effect, regardless of digestion temperature. Solids accumulation was remarkable in the ASBRs, and directly affected by settleable solids concentration of the feed sludge. Noticeable difference in solids-liquid separation was that flotation thickening occurred in the mesophilic ASBRs, while gravity thickening was a predominant solid-liquid separation process in the thermophilic ASBRs. Solids profiles at the end of thickening step dramatically changed at solid-liquid interface, and slight difference in solids concentrations was observed within thickened sludge bed. Organics removals based on subnatant or supernatant after thickening always exceeded 80% in all reactors. Thickened sludge volume and gas production of the ASBRs affected mutually. Gas production increased as thickened sludge accumulated, and continuous gas evolution during thickening could cause thickened sludge to expand or resuspend. Thickened sludge volume exceeding a predetermined withdrawal level resulted in loss of organic solids as well as biomass during withdrawal step, leading to decrease in gas production and SRT. Such an adverse mutual effect was significant in gravity thickening, while it was not sensitive in flotation thickening. Changes in organic loading had no significant effect on organic removals and gas production after build-up of solids in the ASBRs.

Keywords : Anaerobic sequencing batch reactor, Digestion, Sludge, Thickening

요 약

중온과 고온의 혐기성 연속회분식 공정(anaerobic sequencing batch reactor ; ASBR)에서 소화슬러지의 고액분리특성이 처리효율에 미치는 영향을 규명하고자 하였다. 연구결과 침전가능 고형물농도가 높은 도시하수슬러지 처리시 고액분리특성 및 고액분리형태가 전체처리의 안정성 및 처리효율에 상당한 영향을 미쳤다. 중온ASBR에서는 부상농축현상이 일어났으나, 고온ASBR에서는 중력농축에 의한 고액분리가 일어났으며, 상대적으로 고온ASBR의 처리효율이 우수하였다. 그리고 수리학적 체류시간, cycle period 및 고액분리형태는 소화슬러지의 농축특성과 임계 고형물농축을 지배하는 중요한 인자였다. 중온ASBR에서 고액분리 후 농축슬러지베드용적(thickened sludge bed volume)은 매우 중요한 운전 요소이며, 소화슬러지의 중력농축특성은 배출시 농축고형물의 유실현상과 침전시 계속적으로 발생하는 소화가스에 의한 슬러지계면의 파괴현상 및 슬러지베드의 불안정성을 야기시켜 처리효율을 감소시켰다. 중력농축의 경우 소화가스와 슬러지농축용적간의 상호작용(cyclic mutual effect)이 주기적으로 일어났으나, 부상농축에서는 이러한 현상이 일어나지 않았다.

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I. Introduction

Application of aerobic sequencing batch reactor technology to anaerobic treatment is a new concept to improve performance and stability of conventional anaerobic processes. The anaerobic sequencing batch reactor(ASBR) process, which repeats a cycle including four typical discrete sequences ; fill, react, settle, and draw step, can retain high concentration of slow-growing anaerobic bacteria in the reactor. Researches on the ASBR have been carried out by several investigators. Satisfactory phenol degradation and suspended solids removal using the ASBR were reported by Earley and Ketchum.[1] Dague and Pidaparti reported the ASBR for a swine waste was capable of biomass retention without any serious operational problem.[2] Chang and Chung indicated continuous accumulation of volatile solids and biomass in the ASBR improved the treatability of a starch wastewater.[3] Kennedy *et al.*[4] and Sung and Dague proposed that use of granular sludge was good for easier operation of the ASBR.[5] It should be noted that most of investigators used soluble feeds, and did not experience any difficulty associated with critical solid-liquid separation which would be a key operational parameter of the ASBR treating high-solids-content waste.

Anaerobic process has been often reported to give adverse effect on solid-liquid separation because of poor settleability of anaerobically digested sludge. Previous study also showed settleability of digested municipal sludge was more deteriorated through thermophilic digestion than was the case of mesophilic digestion.[6] The most serious problem in solid-liquid separation would therefore occur in the ASBR treating a high-solids-content waste such as municipal sludge.

The objective of this study was to evaluate the performances of the ASBR under critical conditions of solid-liquid separation, caused by extremely high settleable solids in the feed and digestion temperature, for broader application of the ASBR process to various high-solids-content wastes.

II. Materials and Methods

1. Reactor Setup and Feed Sludge

Laboratory-scale ASBRs as illustrated in Fig. 1 and their corresponding completely-mixed daily-fed control reactors were operated in an environmental chamber maintained at 35°C and 55°C. Simultaneous operation of control runs without solid-liquid separation was essential to evaluate the performances of the ASBR because the nature of the feed varied widely with time. The ASBRs and the control reactors were identical except sampling ports on side wall of the ASBRs. Each reactor made of

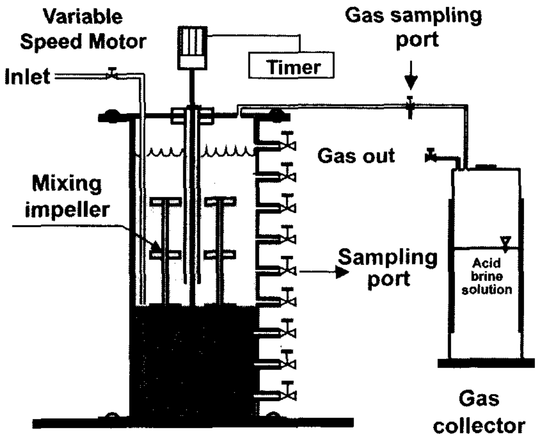

Fig. 1. Schematic diagram of ASBR system.

Table 1. Characteristics of feed sludges for different operating conditions

Parameters	Mesophilic runs		Thermophilic runs		
	HRT 5 days	HRT 10 days	HRT 3.3 days	HRT 5 days	HRT 10 days
pH	5.1~6.6	5.9~7	5.9~6.6	6.2~6.8	6.2~7.1
VS(g/L)	9.1~17.8	7.2~15.4	6.3~18.7	8.8~13.6	6.3~18.7
COD(g/L)	13.1~32.8	11.1~28.0	10.5~26.5	12.4~22.3	10.5~26.5
Volatile acids(mgHAc/L)	970~3,630	150~700	160~280	180~300	30~310
Alkalinity(mgCaCO$_3$/L)	480~1,290	280~1,190	540~1,850	560~1,130	560~1,610
Thickened volume(%)[a]	30~99	24~92	50~94	60~82	41~82

[a]Thickened sludge volume after one-day thickening in a 1 liter graduated cylinder.

Plexiglas had a working volume of 4 liters with a liquid depth of 26 cm. Reactor mixing was accomplished by impeller type mechanical mixer for highly viscous sludge.

The feed was taken from a gravity thickener for the mixed sludge of primary and activated sludge in a municipal wastewater treatment plant. Feed sludge was collected bimonthly, and stored in a refrigerator maintained at 4°C after screening with standard sieve #8. Feed composition varied remarkably with collection time, and its volatile fraction ranged from 35.4% to 81.7%. Characteristics of the feed sludges for different operating conditions are given in Table 1. Each reactor was inoculated with a digested municipal sludge from a laboratory-scale mesophilic digester fed with the same feed sludge.

2. Start-up and Operation Methods

The reactors for ASBR run had been operated with completely-mixed daily-fed mode at the same operating conditions of their corresponding control reactors until they showed the same performances as those of the control runs. The ASBR had a cycle time consisting of a 30-minute fill and draw period, one- to three-day react period, and one-day thicken period. One-day thickening was adopted to minimize loss of thickened sludge during draw step based on a preliminary thickening test with a digested municipal sludge. Mesophilic reactors were converted to thermophilic runs by a method of direct temperature raising with subsequent digester resting.[7] The operating conditions of the ABSRs and control reactors are given in Table 2. The pH, ORP, COD, solids, alkalinity and volatile acids(VA) of digested sludge and clarified effluent were routinely monitored according to the APHA Standard Methods.[8] Dehydrogenase activity(DHA) was examined as an absorbance by a modified procedure of triphenyl tetrazolium chloride method using ultrasonic homogenizer(Cole Parmer model No. CPX 601) for cell wall disruption.

3. Relationship between Equivalent Hydraulic Retention Time(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. The cycle period should satisfy the react

Table 2. Operating conditions

Parameters	Mesophilic runs(35°C)				Thermophilic runs(55°C)			
	Control	ASBR			Control	ASBR		
HRT(days)[a]	5,10	5	10	10	3.3, 5, 10	3.3	5	10
Cycle period(days)	-	2	3	4	-	2	2	3
Fill and draw period(hours)	-	0.5	0.5	0.5	-	0.5	0.5	0.5
React period(days)	-	1	2	3	-	1	1	2
Thicken period(day)	-	1	1	1	-	1	1	1
Withdrawal volume(%)[b]	20, 10	40	30	40	30, 20, 10	60	40	30
OLR[c] gCOD/L/d	1.1~6.6	2.6~6.6	1.1~2.2	1.1~2.2	1.6~8.0	3.2~8.0	2.7~3.6	1.6~2.2
gVS/L/d	0.8~3.6	1.8~3.6	0.8~1.5	0.8~1.5	1.1~5.6	1.9~5.6	1.8~2.7	1.1~1.4

[a]Equivalent HRT for the ASBR.
[b]Effluent withdrawal volume percent to working volume of the reactor.
[c]Equivalent daily organics loading rate for the ASBR.

period required for stabilization of organics, and also include the thicken period required to obtain predetermined withdrawal volume.

III. Results and Discussion

1. 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 an 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 accumulated 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.

2. 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.

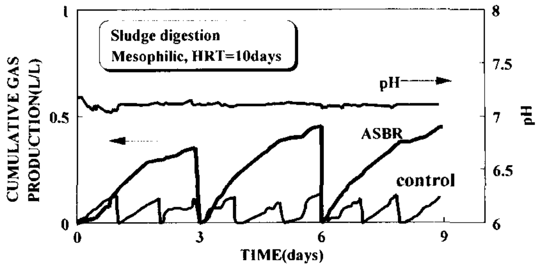

Fig. 2. Cumulative gas production and pH at the initial start-up of the mesophilic ASBR at an HRT of 10 days with cycle time of 3 days.

Fig. 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 reacting period in the first cycle of the ASBR operation, and no significant change of pH was observed as the cycle repeated. Significant accumulation of VA 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 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. Overall Process Performances

Conversion of completely-mixed daily-fed reactor to sequencing batch reactor was easily achieved without any adverse effect. Noticeable effect of shock loading during the start-up period on process stability was not observed in the ASBRs with 5 to 10-day HRT in spite of draw and fill of 30% to 40% of the liquid contents, whereas stable reaction could not be expected in the completely-mixed reactor under such an abrupt draw and fill. Start-up behaviors of the ASBRs indicate conventional digester could be easily converted to the ASBR without stability problem. Adverse effect during and after temperature shift was not observed in all reactors.

The performance of the ASBR could be regarded

Table 3. Pseudo-steady state performances(average values)

Parameters	Mesophilic runs						Thermophilic runs					
	HRT 5 days		HRT 10 days				HRT 3.3 days		HRT 5 days		HRT 10 days	
	ASBR 2-day cycle	Control reactor	ASBR 3-day cycle	Control reactor	ASBR 4-day cycle	Control reactor	ASBR 2-day cycle	Control reactor	ASBR 2-day cycle	Control reactor	ASBR 3-day cycle	Control reactor
Sludge properties[a]												
pH	6.9	6.9	7.09	6.97	6.9	6.85	7.17	7.22	7.2	7.2	7.26	7.21
ORP(-mV)	251	251	261	290	206	199	242	248	204	209	212	223
VA(mgHAc/L)	212	270	214	225	192	182	1,110	369	222	164	132	99
Alkalinity($mgCaCO_3/L$)	2,190	2,120	1,170	1,710	1,550	1,290	2,360	2,230	2,540	2,460	2,160	2,400
Organics removals												
VS removal(%)												
digested sludge		23.2		21.0		20.4		22.6		18.5		12
clarified effluent[b]	91.8	90.7	92.4	91.1	93.4	93.5	65	83	78	81	88	90
COD removal(%)												
digested sludge		28		18		22		31		20		22
clarified effluent[b]	93.7	92.8	95.2	92.0	95.4	92.2	65	83.7	81	85	87	90
Gas production												
GPR(L/L/d)[c]	67[f]	5[f]	15	1	15	1	81	92	56	35	0.27	0.17
Gas yield(L/gVS_{added})	0.28	0.23	0.14	0.09	0.14	0.09	0.23	0.25	0.26	0.17	0.17	0.11
CH_4 content(%)	69.5	69.0	73.2	73	73	72.6	65.2	65.4	67	68	69	68
S/L separation												
Thickened volume(V/V%)[d]	71	59	70	49	69	61	70	79	53	86	65	89
Centrifuged volume(V/V%)[e]	56	23.7	-	-	38	20	34.8	21.9	36.8	20.4	38.9	20

[a]Digested sludge of the ASBR was withdrawn at the end of reacting step.
[b]Based on the supernatant in a 100 ml graduated cylinder for the control.
Based on the clarified effluent for the ASBR ; subnatant for mesophilic run, supernatant for thermophilic run.
[c]Equivalent daily gas production rate for the ASBR.
[d]Thickened sludge volume after one-day thickening in the ASBR, and in a 100 ml graduated cylinder for the control.
[e]Centrifuged volume of mixed digested sludge after centrifugation at 2,500 rpm for 5 minutes.
[f]Due to increase in organics loading rate on account of night soil included in feed sludge.

as a stabilized pseudo-steady state since no intentional attempt was provided to control of solids retention time(SRT). Pseudo-steady state performances of the ASBRs and their corresponding control runs are summarized in Table 3. Chemical characteristics of the mixed digested sludge in all reactors were almost similar in the ranges indicating ordinary digestion of the municipal sludge, except volatile acids accumulation in the thermophilic ABSR with a 3.3-day HRT. Organics removals of the ASBRs increased at longer HRT, and lower efficiencies of the thermophilic reactors were attributed to poor solid-liquid separation of the sludge. Change in cycle period of the mesophilic ASBR did not significantly affect the performances. The mesophilc ASBRs always had higher organics removals than those of their corresponding controls, whereas the thermophilic ASBRs had lower removals than those of control runs due to poor settleability resulting in solids loss during draw step, which was reflected in smaller thickened volumes of digested sludge in the thermophilic ASBRs than those in controls as listed in Table 3. Average thickened volumes of the mesophilic ASBRs were larger than those of the thermophilic ASBRs, and the thermophilic control reactors had larger thickened volume than those of the mesophilic control runs because of poor solid-liquid separation in the thermophilic controls. Analysis of standard deviations indicated that performance stability of the mesophilic ASBR was better than that of the thermophilic run.

Variations in the gas production presented as equivalent gas production from the ASBR per gas production from the control run are shown in Fig. 3 and Fig. 4. Remarkable increase in gas production was observed in the ASBRs after changing in operation mode from completely-mixed daily-fed to SBR operation, even though the reactors for the

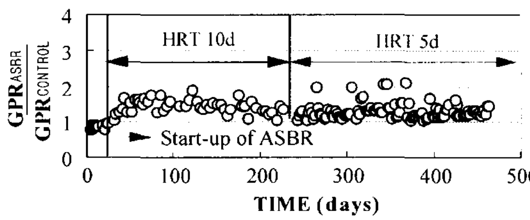

Fig. 3. Changes in gas production ratio of the mesophilic ASBR to the control run.

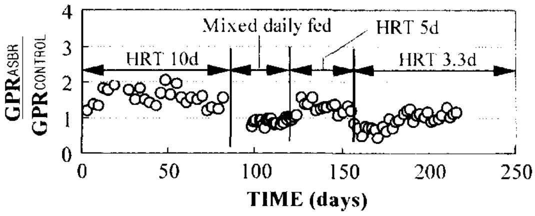

Fig. 4. Changes in gas production ratio of the thermophilic ASBR to the control run.

ASBR run showed slightly lower gas production than the control runs during the period of completely-mixed operation. Reduction in gas production just after start-up of the thermophilic ASBR with a 3.3-day HRT was attributed to high solids loss as a consequence of increase in withdrawal volume. Increase in average gas production rate from the ASBR compared with the control run at the HRT of 5 days and 10 days was 25~50% and 55%, respectively, regardless of digestion temperature. Approximate 40~62% and 5~20% of total gas production in a cycle were produced during one day of react period and one-day thicken period, respectively.

2. Evaluation of Solid-liquid Separation

(1) Thickening Behaviors

Good solid-liquid separation of digested sludge is essential to retain biomass and meet the pre-determined withdrawal volume without significant loss of solids. Flotation thickening always occurred in the mesophilic ASBRs whereas gravity thickening was a predominant solid-liquid separation process in the thermophilic ASBRs, although reactor performances were not relatively quite different.

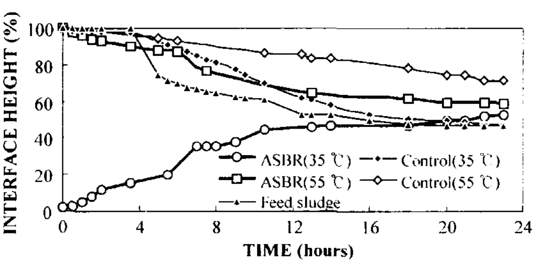

Fig. 5. Interface thickening curves of the digested sludge and feed sludge.

The digested sludge of the control runs always followed gravity thickening regardless of temperature. Typical interface thickening curves of the sludges for one-day thicken period after the operation of 10 to 20 cycles at a 10-day HRT are plotted in Fig. 5. Flotation thickening was attributed to entrapment of gas bubbles to the digested sludge resulting in lower specific gravity of the sludge enough to float the sludge bed. Specific gravity of the settled thermophilic sludge was consistently maintained above 1.015 at any operating HRT. Floating velocities of the sludges in the mesophilic ASBRs were faster than settling velocities of the sludges in the thermophilc ASBRs. Adverse effect of thermophilic digestion on sludge settleability was also observed in study[6)]. Average initial settling velocities of the sludges in the mesophilic control runs were 1.3 times faster than those in the thermophilic controls.

(2) Solids Accumulation and their Vertical Profiles

Solids accumulation was remarkable in all ASBRs during the start-up period, and directly affected by settleable solids of the feed sludge. Approximate solids accumulation rates based on solids mass balance during start-up period at the HRT of 10, 5, and 3.3 days were 3.0~3.3, 4.5~5.1, and 6.8~7.1 gVS per cycle, respectively. Observed maximum net increase in thickened sludge volume was 10 to 20% of the reactor volume during a cycle at any operating condition. Settleabilty of digested sludge in the thermophilic ASBRs was deteriorated as solids accumulated. Solids accumulation in the ASBR was governed by effluent withdrawal volume prescribed by a designed HRT and cycle period rather than influent solids concentration after sufficient build-up of sludge bed, because solids accumulated above a predetermined level for effluent withdrawal should be carried away during draw step. Average SRTs based on the effluent total solids of the ASBRs at various operating conditions were 7 to 25 times longer than those of the control runs. Solids accumulation was accompanied by biomass accumulation, which was observed with an increase in the DHA. The DHAs of mixed sludges in all ASBRs were strongly correlated with solids concentrations and centrifuged sludge volumes. Increase in gas production from the ASBRs, as shown in Fig. 2 and Fig. 3, can be explained by a combined synergistic effect of simultaneous accumulation of biomass and remaining biodegradable solids, and continuous degradation of accumulated organics. Solids concentrations and DHAs of mixed sludge in the ASBRs at various operating conditions were 1.9~2.6 times and 1.6~3 times higher than those of the control runs, respectively. The centrifuged volumes of mixed sludge in the ASBRs were also maintained 1.6~2.3 times larger than those of the sludge in the control runs.

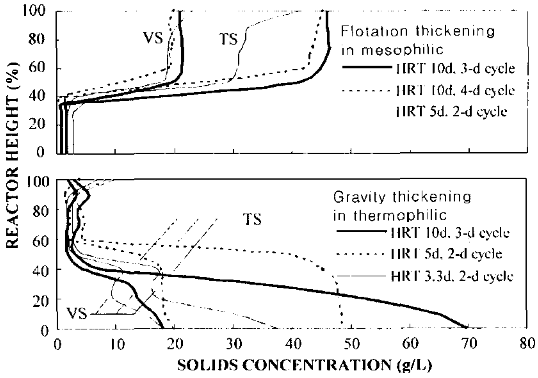

Fig. 6. Typical solids profiles at thicken step of the ASBRs.

Vertical distribution of solids concentration in thickened sludge bed and clarified effluent in the ASBR dramatically changed at solid-liquid interface, as shown in Fig. 6. Solids concentration profiles in the mesophilic ASBRs clearly demonstrate the flotation thickening of digested sludge. Noticeable difference in solids concentration was not observed within the floated sludge bed, while there was a distinct difference in vertical solids distribution in settled sludge bed. The HRT and cycle period affected the solids profile, especially in gravity thickening, as a result of decrease in total solids mass in sludge bed due to higher solids loss at shorter HRT and longer cycle period. The thermophilic ASBR with a 10-day HRT had a unique profile of a stratified solids distribution vertically different in physicochemical characteristics such as specific gravity and organic content. The volatile solids fraction at the bottom of its sludge bed was quite lower than those in the others, because of fixed solids accumulation probably due to a higher digestion efficiency at longer HRT and increased

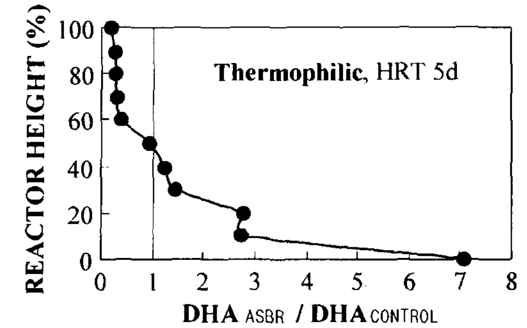

Fig. 7. Typical DHA profile in the thermophilic ASBR.

temperature. A typical distribution of microbial activity at the end of thicken step is shown in Fig. 7, expressed as a ratio of DHA in the ASBR to the activity of mixed sludge in the control reactor. Thickened sludge had a dramatically higher microbial activity than clarified effluent in the ASBRs. The DHAs of clarified effluent at any ASBR was below 6% of that of mixed sludge at the end of the react step. The DHAs and their profiles clearly showed the ability of the ASBR process to retain higher concentration of active biomass.

3. Impact of Critical Solids Build-up on Process Performances

Solid-liquid separation, particularly critical accumulation of solids at the end of thicken step of the ASBR, had a profound effect on the process performance. Performance responses of the mesophilic and thermophilic ASBRs to changes in thickened sludge volume are illustrated in Fig. 8 and Fig. 9, respectively. Thickened sludge bed volume increased as cycle progressed, and consequently

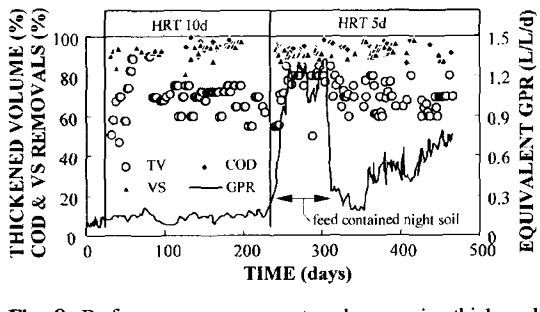

Fig. 8. Performance response to changes in thickened volume at the mesophilic ASBRs.

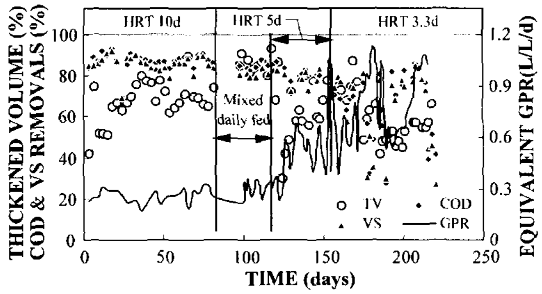

Fig. 9. Performance response to changes in thickened volume at the thermophilic ASBRs.

reached a critical level, which is above predetermined level for effluent withdrawal. Organics removals based on subnatant of the mesophilic ASBRs were maintained relatively stable regardless of HRT and thickened sludge volume, as shown in Fig. 8. However, the removals based on supernatant of the thermophilic ASBRs decreased with shorter HRT, and significantly fluctuated with variation of thickened sludge volume particularly at an HRT of 3.3 days, as shown in Fig. 9. Unstable and lower removals of the thermophilic ASBRs were caused by loss of thickened sludge bed volume exceeding a predetermined level for effluent withdrawal, and intermittent disruption of settled sludge interface and rising of settled solids by internal gas evolution irrespective of thickened volume, or unstable sludge bed and its expansion by continuous gas evolution during thicken step. These behaviors resulted in loss of organic solids and biomass during draw step, leading to subsequent decrease in gas production and SRT. Lower organics removals and smaller thickened volume in the thermophilic ASBRs than those in the control runs, as listed in Table 3, clearly demonstrate a significant effect of such an unstable sludge bed. Whereas, flotation thickening was insensitive to interface disruption of thickened sludge bed since sludge once floated was only compressed by continuous gas evolution. Analysis on ratios of DHA and VS in the ASBR to those in the control run showed a balance between biomass and organics worsened with gravity thickening at shorter HRT, whereas enough biomass balanced on accumulated organics to be removed could be retained through flotation thickening.

The SRTs of the mesophilic ASBRs were

always above 1.4 times longer than those of the thermophilic runs due to a difference in capacity of solids and biomass capture. The SRT and HRT were strongly correlated at all ASBRs, and cycle period also affected the SRT. Increased withdrawal volume at shorter HRT and longer cycle period resulted in higher loss of solids and consequent shorter SRT. As a result, process performance of the ASBR for municipal sludge digestion primarily depended on the critical condition of solids accumulation. Thickened sludge volume at gravity thickening was more critical operating variable than was the case of flotation thickening.

IV. Conclusions

Performances of the ASBR for municipal sludge digestion clearly showed that stability of the ASBR process treating a high-solids-content waste could be greatly affected by critical conditions of solid-liquid separation. Sludge thickenability and solids accumulation as well as process performance were significantly governed by HRT, cycle period, and type of thickening.

Flotation thickening in a mesophilic ASBR showed better sludge thickenability and consequent superior performance than gravity thickening in a thermophilic ASBR. Poor performances with gravity thickening were caused by loss of thickened solids above a critical level for effluent withdrawal and intermittent disruption of settled sludge interface by internal gas evolution, or unstable sludge bed and its expansion by continuous gas evolution. Thickened sludge volume at gravity thickening was a critical operating variable, although it was not in the case of flotation thickening. Dynamic mutual effect between critical solids accumulation and gas production resulting in loss of solids was a peculiar feature of gravity thickening, while it was insignificant in flotation thickening. Sludge thickenability was improved with longer HRT and shorter cycle period regardless of effluent quality, and this was especially remarkable in flotation thickening.

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