대한위생학회지. 제15권 제2호(2000)
Korean J. Sanitation. Vol. 15, No. 2, pp75~84(2000)

혐기성 연속 회분식 반응조에 의한 분뇨처리

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Night Soil Treatment by Anaerobic Sequencing Batch Reactor

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요 약

운전 온도 35℃, 평균 유기물부하 3.1 kgCOD/m^3/day 및 수리학적체류시간 10일에서 혐기성 연속회분식공정에 의한 분뇨처리를 수행하였다. 공정의 평가는 대조 소화조로 완전혼합형의 소화조와 병행하여 수행되었다. 본 실험에서 분뇨는 고농도의 암모니아성 질소와 침전성 고형물을 함유하고 있음에도 불구하고 희석 없이 소화가 가능하였다. 혐기성 연속회분식공정에서 고형물은 급속하게 증가하여 완전혼합형의 대조 소화조에 비하여 소화조내 고형물(biomass)의 농도가 2.4배로 증가하였고, 가스발생량에 있어서도 대조 소화조에 비해 현격한 증가를 보였으며 그 증가율은 205~220%에 달했다. 부가적인 침전 시설이 없이도 혐기성 연속회분식공정의 유출수질이 대조 소화조 보다 높게 나타났는데 상징액 기준으로 휘발성고형물 제거율은 혐기성 연속회분식공정이 대조 소화조 보다 12~14% 높았다. 한편, 혐기성 연속회분식공정의 운전인자로 반응/침강비(R/T ratio)를 조사한 결과 R/T비가 1인 경우가 3의 경우보다 가스발생량, 메탄함량 및 유기물 제거율이 약간 높았으나 큰 차이는 없었다. 위의 실험결과들로 부터 혐기성 연속회분식공정은 고농도의 암모니아성 질소와 침전성 유기물을 함유하고 있는 분뇨의 처리에 효과적이고 안정적인 공정으로 판단된다.

Key words : Anaerobic sequencing batch reactor ; night soil ; digestion ; solid-liquid separation ; ammonia toxicity.

I. Introduction

Night soil, which is a residual product of human life, includes not only high strength organic matter and ammonia nitrogen but also pathogenic bacteria. Problems of public health and water pollution caused by uncontrolled disposal of night soil have been a pending issue throughout the Asia. Various night soil treatment processes including conventional anaerobic digestion have been applied for rural and un-sewered areas in Korea. The anaerobic process has been widely used as an ideal process for the treatment of high strength organic wastes, since it can be operated with low maintenance cost, and produce valuable biogas. Accordingly, the development of new energy source has been a prominent figure throughout the world, highrate anaerobic processes enhancing valuable biogas production from wastes attract environmental scientists and engineers attention.

Considerable work on highrate anaerobic processes, which have the ability to hold biomass within the reactor, have been focusing mainly on decreasing hydraulic retention time (HRT) and increasing biomass. The initial work on a highrate anaerobic process called anaerobic contact process had been developed in the 1950s by Fullen[1]. Most other highrate anaerobic processes, which include the anaerobic filter, the two phase digestion, and the upflow anaerobic sludge blanket process, have been also designed mainly in order to decrease HRT and increase solids retention time(SRT). The anaerobic sequencing batch reactor(ASBR) process, which repeats a cycle including feeding, reaction, thickening, and withdrawal steps in a single reactor, is one of the novel and promising highrate anaerobic processes. While most of the highrate anaerobic processes require an external clarifier or solids recycle facility, the ASBR process can maintain a high concentration of methanogenic bacteria in the system without additional facility or serious operational difficulties. Recently, several investigators have carried out studies on the ASBR process. Kennedy *et al.* [2] and Suthaker *et al.* [3] indicated that feeding/reaction period ratio was a critical design parameter on the ASBR process. Sung and Dague [4] studied the effect of reactor shape and mixing type on the performance of the ASBR process. Herum and Dague [5] investigated the effect of vacuum application to the ASBR prior to the thickening step, and pointed out vacuum application resulted in improved sludge thickenability. Chang *et al.* [6] investigated the performance of the ASBR for the digestion of municipal wastewater sludge in order to develop an improved anaerobic process for high-solid-content waste.

The objectives of this research were to investigate the performance of the anaerobic sequencing batch reactor for digestion of a night soil under inhibitory condition caused by high ammonia nitrogen in the feed night soil, and to assess the effect of reaction/thickening period ratio on the digestion efficiency.

II. Materials and Methods

1. Experimental system

Three laboratory scale anaerobic digestion systems were used for the experimental study. Figure 1 shows the schematic diagram of the ASBR system used in this study. Each digestion system consisted of a conventional highrate type anaerobic reactor and a floating type gas collector equipped with a counterweight, and was maintained at the temperature of 35±1℃. Each reactor made of Plexiglas was 40 cm high, and had a working volume of 5 liters. Three

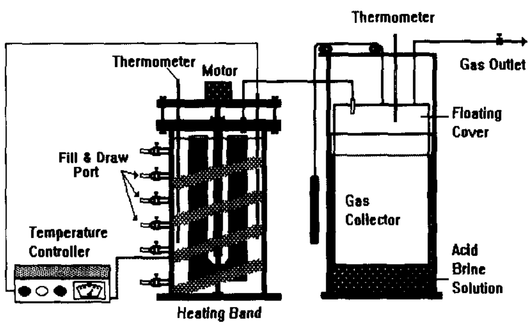

Fig. Schematic diagram of the ASBR system.

reactors, two for ASBR run and the other for control run, were identical except for mode of operation. Two reactors for ASBR run were operated with different reaction period/thickening period ratios (R/T ratios). All reactors had six fill and draw ports, which were placed at 5cm interval from the top of the reactor.

2. Characteristics of night soil

Feed night soil was collected periodically from a flow equalization chamber in a night soil treatment plant located in Andong, Korea. Collected night soil was screened with a standard sieve #20(850m), and kept at a temperature below 4℃. The feed night soil was

Table 1. Characteristics of the feed night soil.

Parameters	Range	Average	Standard deviation
pH	6.9~8.4	7.6	0.36
Alkalinity(mg$CaCO_3$/ℓ)	10,270~20,830	14,390	2,470
Volatile acids(mgHAc/ℓ)	1,840~14,820	9,340	4,900
COD(mg/ℓ)	22,330~38,750	32,140	3,870
Total solids(mg/ℓ)	26,810~46,800	36,690	3,520
Volatile solids(mg/ℓ)	15,060~36,400	25,350	3,270
Suspended solids(mg/ℓ)	24,700~30,800	27,300	2,750
Volatile suspended solids(mg/ℓ)	10,600~25,300	22,600	2,410
Total kjeldahl nitrogen(mg/ℓ)	7,120~8,850	7,760	710
Ammonia nitrogen(mg/ℓ)	2,240~7,500	4,650	1,190
Un-ionized ammonia nitrogen(mg/ℓ) [a]	16~570	103	
Thikened volume(V/V%) [b]	22~89	42	15
Centrifuged volume(V/V%) [c]	13~22	17	3

[a] Calculated values at given pH
[b] Sludge volume after 1day thickening in a 1 liter graduated cylinder.
[c] Sludge volume after centrifugation at 3,000rpm for 5 minutes.

Table 2. Operating conditions.

Parameters	Control reactor	ASBR(R/T ratio 1)	ASBR(R/T ratio 3)
Temperature(℃)	35	35	35
Equivalent HRT(days)	10	10	10
Working volume(ℓ)	5	5	5
Withdrwal volume(ℓ/cycle)	0.5	1.0	2.0
Organic loading rate			
One cycle basis(KgVS/m^3/d)	2.6	2.6	2.6
(kgCOD/m^3/d)	3.1	3.1	3.1
Feeding period basis(KgVS/m^3/d)	2.6	5.1	10.3
(kgCOD/m^3/d)	3.1	6.1	12.3
Operation period(days) [a]	290	290	290
Cycle time(days)	1	2	4
Reaction period/thickening period ratio		1	3
Feeding and withdrawal period(hours)	0.5	0.5	0.5
Reaction period(days)	1	1	3
Thickening period(days)		1	1

[a] Operating period after change in 10day HRT.

heated to approximately 35℃ just before feeding to avoid a temperature shock. The feed night soil had high ammonia nitrogen content, and the average volatile fraction of total solids was 69%. Average C/N (COD/ammonia nitrogen) ratio of the feed was 6.9. Table 1 shows the characteristics of the feed.

3. Operational methods

The operating conditions of the ASBRs and completely mixed control reactor are summarized in Table 2. A cycle of the ASBR including feeding, reaction, thickening, and withdrawal step was sequenced continuously. Feed night soil was supplied and discharged manually for about 30 minutes.

Mechanical mixing was provided during feeding and reaction period. During the 1day thickening period, digested sludge in the ASBR was thickened under hydraulically ideal quiescent conditions. Since efficiency and stability of the ASBR system relies on internal solid-liquid separation, the thickening period determination of high-solids-content night soil was important. A thickening period of one day was determined through preliminary thickening test of feed night soil. ASBR systems were operated with two R/T ratios of 1 and 3 under the same thickening period of 1day. A completely mixed daily-fed reactor (CSTR) without thickening step was simultaneously operated as a control run to compare its baseline performance with that of the ASBR.

4. Analytical methods

Analyses were performed for the feed night soil and clarified effluent after thickening of pH, alkalinity, volatile acids (VA), total solids (TS), volatile solids (VS), and COD. All analyses were conducted as described in the APHA Standard Methods[7]. Gas production and pH were recorded daily and other analysis items were tested twice a week for alkalinity, VA, TS, VS, and COD. Dynamic changes in organics concentration and gas production in the system during 1-cycle were also determined hourly to identify digestion dynamics in the ASBR system. Composition of digester gas was determined by gas chromatography using a thermal conductivity detector and Porapak Q as a packing material. Interface height of the digested sludge in the ASBR was measured directly in the reactor during the thickening period, while those of the sludge in the control reactor and feed night soil were measured in a 1-ℓ graduated cylinder.

Ⅲ. Results and Discussion

1. Performance behaviors during acclimation period

All reactors were operated as a CSTR mode at 30day HRT during the initial period for acclimation to night soil. The HRT of 30 days, which was chosen as the HRT during acclimation period, was found to exhibit stable digestion of night soil generally accepted in the literature. As showed in Table 1, feed night soil has high ammonia concentration of 4,650 mg/ℓ. Average un-ionized ammonia nitrogen concentration, which was calculated from measured ammonia nitrogen concentration and pH, was 103 mg/ℓ. Previous research by McCarty [8] reported that ammonia nitrogen was essential nutrient for anaerobic bacteria, and those concentrations between 50 and 200 mg/ℓ were beneficial, while those in excess of 3,000mg/ℓ were toxic to methanogens regardless of pH. On the other hand, other investigators, Parkin and Miller,[9] reported that under optimal conditions, methanogens were able to acclimate to the near 10,000 mg/ℓ of ammonia nitrogen without any decrease in process performance. Bhattacharya and Parkin[10] indicated that with continuous addition of ammonia nitrogen, high SRT systems can tolerate higher concentrations than low SRT systems, and the toxic level of un-ionized ammonia nitrogen is strong function of SRT. During the initial acclimation period of this study, some problems were occurred in all reactors by ammonia toxicity. Behaviors of digestion during the acclimation period under high ammonia concentration are given in Fig. 2. It takes about five months to reach a steady-state in all reactors.

2. Startup behaviors 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 six months until it showed the same performance in terms of pH, VA, and gas production as that of the control run. Two reactors for ASBR run were converted to sequencing batch mode, while the other reactor for control run was operated at CSTR mode. After startup at 30day HRT, change in HRT was carried out gradually for minimizing shock loading.

The mixed liquor total solids accumulation profiles during the HRT conversion are shown in Fig 3. At the beginning of the HRT conversion period, solids were accumulated rapidly in the ASBRs. Fig. 3 showed a fairly linear increase in solids concentrations in the ASBRs from 30days of HRT to the middle phase of 20days of HRT regardless of the R/T ratios. During the latter half of 20days of HRT, solids concentrations in the ASBRs had a little margin according to R/T ratio, because the ASBR with R/T ratio of 1 had relatively poor thickenability caused by shorter reaction period than that with

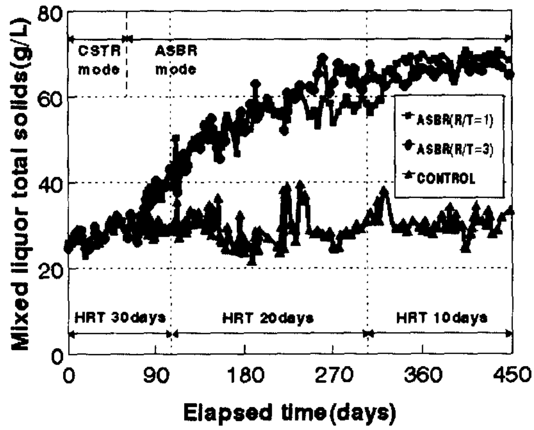

Fig. 3. Solids accumulation profiles during the period of HRT change

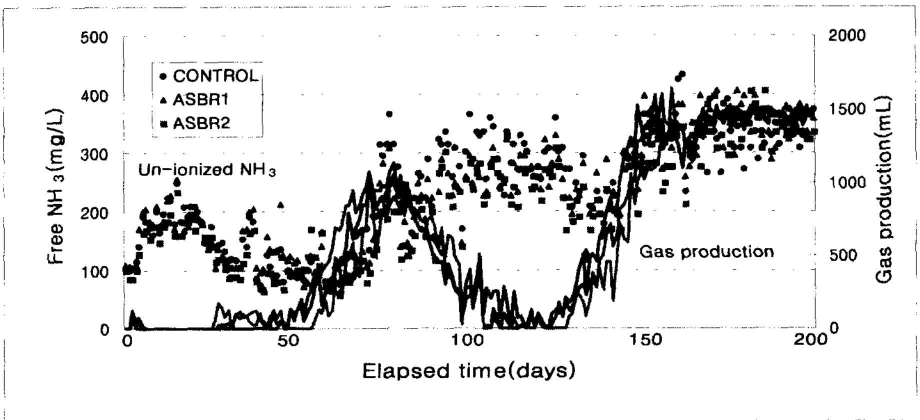

Fig. 2. Acclimation behaviors during initial period under high un-ionized ammonia concentration with CSTR mode operation at 30-day HRT

R/T ratio of 3. The solids concentrations in the ASBRs were 2.4 times higher than that in the control reactor at 10days of HRT.

3. Characteristics of solid-liquid separation

Difficulties associated with solid-liquid separation are often encountered in anaerobic processes. Good solid-liquid separation is especially important to the design and operation of the ASBR process. Characteristics of the solid-liquid separation of the digested sludge in the ASBRs were different from that of the control run, as shown in Fig. 4. Poor solid- liquid separation was expected undoubtedly for the digested sludge in the ASBR, since thickened volume of the feed having an average of 42% ranged from 22% to 89% after 1day thickening period. The thickened volume in the ASBRs ranged from 36% to 37%, while the digested sludge from a control reactor had thickened volume of 17% after 1day thickening period. Thickening velocities of the sludge in the ASBRs were lower than that in the control run. Sludge thickenability is closely related to the solids concentration and internal gas evolution. Because the ASBR with low R/T ratio had shorter reaction period than that with high R/T ratio, the amount of night soil solids left when thickening begins in the ASBR with low R/T ratio were larger than that in the ASBR with high R/T ratio. It should be noted that the ASBR with high R/T ratio had faster thickening velocity than that with low R/T ratio. Identification of solid-liquid interface was impossible for initial 5 hours in the ASBR with R/T ratio of 1 during thickening period. This was caused by active interface gassing between solids and liquid. Time required to obtain a thickened volume of 50% was 12 hours in the ASBR with R/T ratio of 3, while that in the ASBR with R/T ratio of 1 was 16 hours. Solids concen- tration profiles in the thickened sludge bed were also examined at the end of the thickening period of the ASBRs, as shown in Fig. 5. The profiles clearly demonstrate remarkable accumulation of solids in the ASBRs.

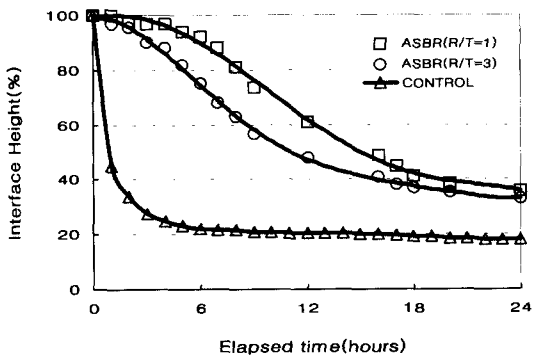

Fig. 4. Characteristics of the solid-liquid separation.

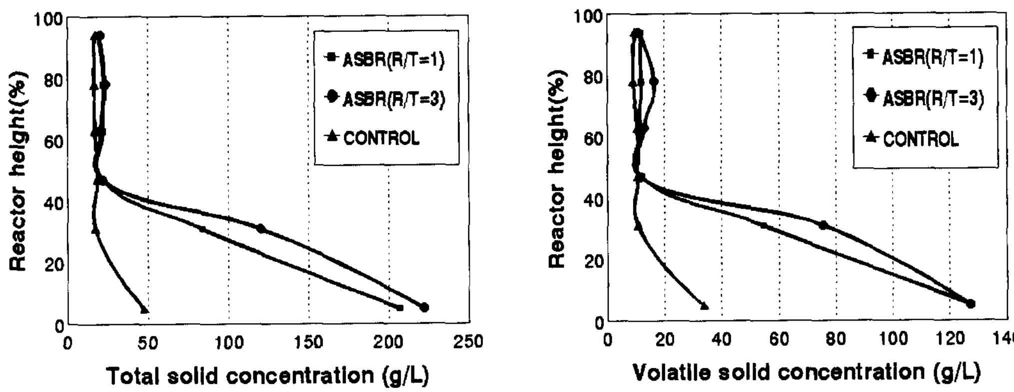

Fig. 5. Solids profiles at thickening step.

4. Steady-state performances

Steady-state performances of the ASBRs could be regarded as a pseudo-steady state, since artificial control of SRT was not employed. The SRT of the ASBR was controlled only by the loss of solids in the withdrawal step. Steady-state performances of the ASBRs with an equivalent HRT of 10 days and their corresponding control run are summarized in Table 3.

4.1 Organics removals and gas productions

The COD removal efficiencies based on clarified effluent after 1day thickening were 67% in the ASBR, while it was 56% in the control reactor. The VS removal efficiencies of the ASBRs were 59%, while that of the control reactor was kept at 45%. On the other hand, organics removals based on digested sludge were remarkably different between ASBR and control. The VS removals based on digested sludge in the ASBRs were 46%, whereas that of the control reactor was as low as 28%. The COD removal based on the clarified effluent of the control run was a little lower than that reported in the literature, which was obtained using a conventional completely mixed digester at an HRT of 16 days[11], while those of the ASBRs were higher than that reported in the literature.

Table 3. Steady-state performances(Average±standard deviation)

Parameter	Control reactor	ASBR(R/T ratio 1)	ASBR(R/T ratio 3)
Digested sludge [a]			
pH	8.04±0.11	8.14±0.11	8.13±0.11
Volatile acids(mgHAc/ℓ)	5,660±1,460	2,230±800	2,056±690
Alkalinity(mg$CaCO_3$/ℓ)	15,370±1,880	14,990±1,870	15,800±1,700
Organics removal			
TS removal(%)			
Digested sludge basis	28.2±6.2	38.6±4.4	39.8±6.1
Clarified effluent basis[b]	41.3±5.8	49.5±6.2	49.1±5.8
VS removal(%)			
Digested sludge basis	28.3±3.8	45.5±3.7	45.4±5.7
Clarified effluent basis[b]	44.6±5.8	59.3±7.9	57.2±8.4
COD removal(%)			
Digested sludge basis	26.0±4.9	49.2±4.3	48.4±7.8
Clarified effluent basis[b]	56.3±7.5	67.4±3.9	65.5±5.3
Gas production rate(GPR)			
Equivalent GPR(mℓ/day)	1,440±120	3,200±250	2,950±260
Specific GPR(ℓ/ℓ/day)[c]	0.29±0.02	0.64±0.03	0.59±0.03
Gas yield(m^3/kgVSfed)	0.11±0.02	0.25±0.02	0.23±0.02
(m^3/kgCODfed)	0.09±0.02	0.21±0.02	0.19±0.02
Methane content(%)	69.7±0.2	72.4±0.1	72.1±0.1
Solid-liquid separation			
Centrifuged volume(V/V%)	10.8±1.5	6.3±0.5	8.6±0.5
Thickened volume(V/V%)	16.9±5.7	37±11	35.8±10.5

[a] Digested sludge of the ASBR was withdrawn at the end of reaction period.
[b] Supernatant after 1 day thickening in a 100 mL graduated cylinder at 35℃
[c] Equivalent gas production per unit reactor volume.

It should be noted that an additional thickening facility is required at a conventional completely mixed digester to obtain such organic removal, whereas the ASBR can achieve same organic removal at shorter HRT without any additional thickener.

Fig. 6 shows variation of pH and cumulative gas production per one cycle from the ASBRs and their corresponding control run during sequences of batch period after startup of the ASBR. As shown in Figure 6, the pH increased to near 8.5 by deamination after 30 days elapsed. Significant change in gas production was observed with pH change. The gas production decreased in all reactors according to the increment of un-ionized ammonia caused by pH increase. Since the urea in night soil, was hydrolyzed to ammonium carbonate by the enzyme urease, the pH of anaerobic reactor increased and affected the anaerobic micro-organisms. From the first affected period by pH to the middle of sequenced batch period, gas production changed susceptibly with pH variation. During the latter half of sequenced batch period, gas production was stabilized according as the pH of anaerobic reactor was maintained 8.2. In all cases, remarkable increase in gas production was observed at the ASBRs compared with the control run, as shown in Table 3 and Fig. 6. Average increase in equivalent daily gas production from the ASBRs were 205~220% compared with that from the control run. Maximum gas yields based on VS added were ranged from 0.23 to 0.25 m^3/kgVS from the ASBRs, while that from the control run was 0.11 m^3/kgVS. It was believed that the increase in gas production from the ASBRs was the combined results of accumulation of micro-organisms and additional long term degradation of organics. The Fig. 7 shows variation of equivalent daily organic loading rate and cumulative gas production from the ASBRs and their corresponding control run during sequences of batch periods after start-up of the ASBR. Gas production decreased in direct proportion to organic loading rate.

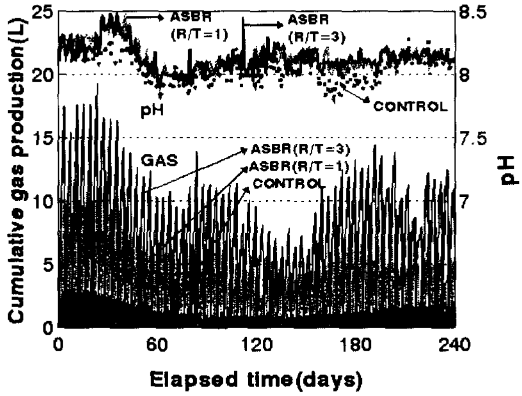

Fig. 6. Cumulatice gas production according to the pH variation during sequences of batch period after startup of the ASBR.

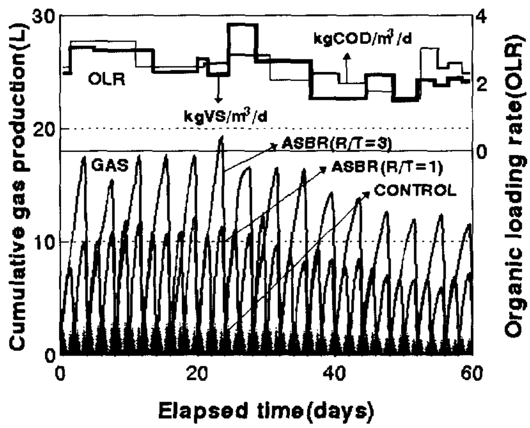

Fig. 7. Equivalent organic loading rate and cumulative gas production during sequences of batch period.

4.2 Dynamic changes in organics and gas production during one cycle.

The Fig. 8 shows the dynamic changes in organic matter and gas production behaviors during one cycle in the system at an equivalent HRT of 10 days. Approximately 72% of total gas production during one cycle of the ASBR with a R/T ratio of 1 was generated for 1day reaction, and 28% of total gas production was generated during the 1day thickening period, while in case of R/T ratio of 3, 88% of total gas was produced for 3day reaction, and rest of total gas was produced during the 1-day thickening period. It was noted that 50% of gas production during 1day thickening period in the ASBR with R/T ratio of 1 was generated within the initial 10 hours, and internal gassing during the initial thickening period caused sludge solids to resuspend. The COD removal was higher than VS removal during 1-day thickening period in all cases.

Ⅳ. Conclusions

Digestion of night soil by the anaerobic sequencing batch reactor (ASBR) was investigated to evaluate the performances. The reactor performances were assessed at an equivalent HRT of 10 days with an average equivalent loading rate of 2.6kgVS/m^3/d at 35℃. The main conclusion drawn from this study was as follows :

1. Digestion of a night soil was possible using the ASBR at an HRT of 10 days in spite of high concentration of ammonia nitrogen and settleable solids in the night soil. The ASBRs showed high digestion performances than CSTR.
2. The reaction period/thickening period ratio (R/T ratio) of the ASBR could be considered as a meaningful operational parameter.
3. The ASBR with R/T ratio of 1 showed higher gas production and organic removal efficiency than that with R/T ratio of 3, while the ASBR with R/T ratio of 3 had faster thickening velocity than that with R/T ratio of 1.
4. Increases in equivalent daily gas production from the ASBRs were 205~220% compared with that from control reactor. The remarkable increase in gas production from the ASBRs was believed to be the combined results of accumulation of microorganisms and additional long-term degradation of organics.
5. Solids were accumulated rapidly in the ASBRs, and their concentrations were 2.4

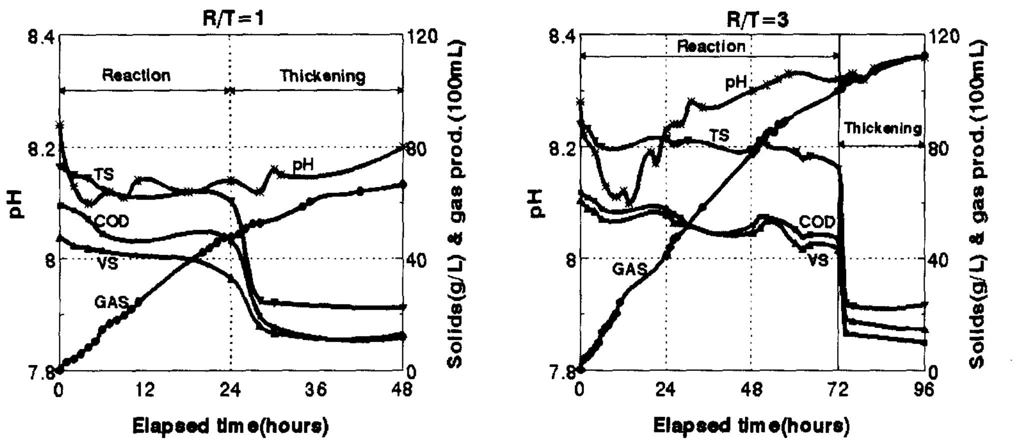

Fig. 8. Dynamic changes in organic matter and gas production in the ASBRs during one cycle.

times higher than that in the control reactor. No adverse effect on solid-liquid separation was observed in the ASBRs in spite of solids accumulation.

6. The VS removals based on the digested sludge of the ASBRs were 46%, whereas that of the control reactor was as low as 28%. It should be noted that completely mixed digester requires an additional thickening facility to obtain similar organics removal to ASBR.

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