J. Microbiol. Biotechnol. (1999), 9(6), 737–743

JOURNAL OF
MICROBIOLOGY
AND
BIOTECHNOLOGY

Treatment of Distillery Wastewater Using a Thermophilic High-Rate Hybrid Anaerobic Reactor in Industrial Scale

NAM, KI-DU*, IN CHUNG[1], JAMES C. YOUNG[2], AND WAN PARK[3]

Department of R & D, Il San Trading Co., Ltd, Pusan 608-044, Korea
[1]*Jindo Co., LTD., R & D Center, Seoul 153-023, Korea*
[2]*Department of Environmental Engineering, University of Arkansas, Fayetteville, AR 72701, USA*
[3]*Department of Microbiology, College of Natural Sciences, Kyungpook National University, Taegu 702-701, Korea*

Received: June 21, 1999

Abstract A conventional thermophilic anaerobic digester was converted into a thermophilic high-rate hybrid anaerobic reactor (THAR) for treating distillery wastewater. The THAR has been operating successfully since May 1995 at a loading rate of 5.45 to 11.52 kg/m^3/d (maximum of 15.02). The THAR has demonstrated a soluble Chemical Oxygen Demand (sCOD) removal efficiency of 85 to 91% and a total COD (tCOD) removal efficiency of as much as 72 to 84%. Product gas had a methane content of 59 to 68%. The tCOD removal rates were 4.31 to 5.43, 6.26 to 6.89, and 9.03 to 9.78 kg tCOD/m^3/d for tapioca, corn, and naked-barley wastewater, respectively. The sCOD removal rates ranged from 3.75 to 4.79, 3.28 to 4.89, and 5.57 to 6.21 kg sCOD/m^3/d for tapioca, corn, and naked-barley wastewater, respectively. There were unknown substances in a naked-barley distillery wastewater that were identified as being toxic for microorganisms. However, the THAR treated naked-barley wastewater continuously for 26 days, operating at an average tCOD loading of 11.08 kg/m^3/d without any signs of deterioration in either COD removal efficiency or gas production rate. During this period, the average removal efficiencies of tCOD and sCOD were 84% and 91%, respectively, and the gas production rate averaged 6.61 to 7.57 m^3/m^3 reactor/d which produced 0.57 to 0.69 m^3 biogas/kg tCOD$_{rem}$. From tapioca and corn wastewater, the reactor showed an average gas production rate of 3.18 to 3.46 and 4.91 to 5.22 m^3/m^3 reactor/d which produced 0.53 to 0.69 and 0.62 to 0.71 m^3/kg tCOD$_{rem.}$, respectively.

Key words: Anaerobic treatment, distillery wastewater, hybrid reactor, thermophilic, naked-barley

There are 12 distilleries in Korea and eleven of them have fermentation processes to produce potable alcohol. These 11 distilleries use naked-barley, barley, rice, tapioca, sweet potato, potato, and corn as raw materials for alcohol fermentation. All of the 11 distilleries at one time operated thermophilic anaerobic digesters [1, 8, 11, 13, 15, 16], having hydraulic retention times (HRT) of 15 to 45 days followed by aerobic treatment [18] of the anaerobic effluent. All 11 distilleries experienced numerous reactor failures when naked-barley wastewater was treated anaerobically. In one case, a digester operating at a 36-days HRT failed after receiving naked-barley wastewater for 15 days continuously. Korean distilleries have not reported any specific difficulties in anaerobic treatment of wastewater from fermentation of other raw materials except for naked-barley. When various options for treating distillery wastewater were compared, it was concluded that evaporation for cattle feed production was the most attractive option for the grain distillery wastewater [9]. The capital costs estimated by Maiorella *et al.* [9] were 3 million US dollars for evaporation and 3.5 million US dollars for anaerobic treatment. However, in Korea, the capital cost associated with evaporation of 300 m^3/d distillery wastewater is around 3.9 million US dollars, while the capital cost for anaerobic reactor installation is about 1.2 million US dollars. These estimates do not include the cost for aerobic treatment that should follow both evaporation and anaerobic treatments. However, Korean distilleries with fermentation processes are required to use some amount of naked-barley as a raw material. Unfortunately, due to some anaerobic reactor failures that occurred during the continued use of naked-barley for fermentation, the work was very tiresome. Therefore, six out of 11 distilleries are currently either operating or constructing evaporators, giving up a more economical option of the anaerobic treatment. The characteristics of distillery wastewater produced in Korea have a wide variation of raw materials which were used for fermentation [2, 5, 12], yield of fermentation, and efficiency of alcohol recovery [6]. Total suspended solid (TSS)

---

*Corresponding author
Phone: 82-51-646-2643; Fax: 82-51-637-9696;
E-mail: lab7394@ppp.kornet.net

concentrations in the raw wastewater typically average 25,000 to 100,000 mg/l. Usually, decanters (centrifuges) are used to remove as much of SS from the raw wastewater as possible and the decanter effluent is treated anaerobically. The characteristics of decanted distillery wastewater typically are as follows: pH, 3.5 to 4.5; temperature, 70 to -80°C; sCOD, 25,000 to 60,000 mg/l; tCOD, 40,000 to 100,000 mg/l; and TSS, 4,000 to 20,000 mg/l.

Prior to May 1995, 50 kl/d of 95% ethanol was produced and the flow rate of decanted wastewater was 400 m^3/d. Two thermophilic anaerobic digesters having a total effective volume of 6,000 m^3 (digester #1 with 4,000 m^3 and digester #2 with 2,000 m^3) were employed for anaerobic treatment of decanted wastewater. Since the sCOD removal efficiency of anaerobic treatment was not high enough, 1:1 dilution with tap water was required for a successful aerobic treatment. Ono [10] reported that, in Japan, treatment of distillery wastewater in thermophilic anaerobic digesters at 4 to 7 days HRT resulted in a BOD removal of as much as 80 to 90%. However, the COD removal efficiency of our digesters (and other distillery digesters in Korea) was about 50 to 70%. As a result, we attempted to increase the efficiency of anaerobic treatment and hoped to operate anaerobic reactor(s) without any influence of toxicity [7] when naked-barley wastewater was treated. In addition, the use of dilution for the aerobic treatment should be discontinued. In order to solve the above problems, the digester #2 was converted into a THAR, that is, similar in configuration to those used successfully for treating other industrial wastewaters in addition to using procedures and criteria established by Young and Yang [19, 20].

MATERIALS AND METHODS

Reactor Description

The THAR design is slightly different from conventional hybrid reactors in such that it has two zones of media rather than one zone (Fig. 1). Both the upper and lower zones contained modular blocks of cross-flow media that had a surface area of 102 m^2/m^3 (Model #2, DaeBongKyunYoung Co., Ltd., Seoul, Korea) and was specially formulated for the thermophilic operation. Two media zones were used to minimize the possibility of short-circuiting and to maximize biomass accumulation in the reactor. Like conventional hybrid anaerobic filters, the THAR had a sludge bed zone below the media zone. The THAR is 15.5 m in diameter and 12.2 m in height. Effluent lines are located at 11 m from the bottom of the reactor while the collecting lines for recycle are located at 10.8 m. The total reactor volume is greater than 2,300 m^3 and the effective volume is 2,076 m^3. The support for the lower media zone is located at 3 m from the floor, thereby providing a sludge bed volume of 566 m^3. For an even distribution, 13 distribution lines were installed 0.5 m above the floor and each distribution line is 1 m apart. Anaerobic biomass withdrawal lines were located 0.25 m above the floor of the reactor. A heat exchanger is used to cool the wastewater to the desired operating temperature. Two pH sensors and two temperature sensors are installed at 1.7 m and are connected to a computer in a laboratory. Flow meters for influent and recycle are also connected to the computer so that close monitoring of pH, temperature, influent flow rate, and recycle rate is possible. The THAR is insulated and designed to treat 400 m^3/d with a maximum recycle rate of 3,200 m^3/d.

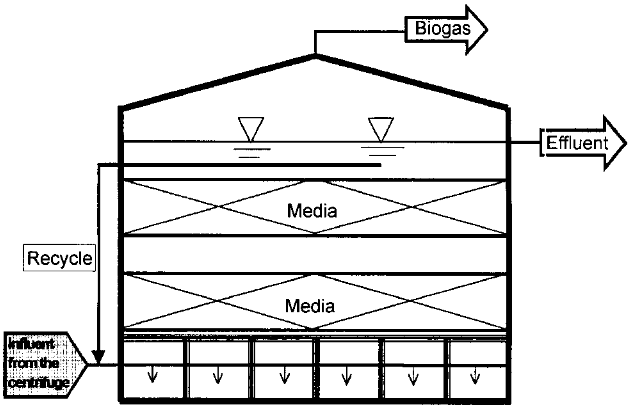

Fig. 1. Schematic diagram of the thermophilic hybrid anaerobic reactor.

THAR Operation

The THAR was seeded by pumping the settled sludge from the bottom of the anaerobic settling tank for 3 days. As soon as seeding was complete, raw wastewater flow rate was applied to the THAR in increasing steps of 50, 100, 200, 300, and 400 m^3/d. The flow rate increased when the sCOD removal efficiency was above 85% for 2 days or more. The recycle ratio was maintained at 8:1 throughout the operation. Start-up took only 1.5 months, thanks to good quality microorganisms which were available. The pH of the reactor was maintained between 6.8 to 7.5 without any chemical addition. The temperature of the decanted wastewater was 70 to 80°C and thus a heat exchanger was used to cool the wastewater to maintain the temperature of the reactor between 53 to 57°C. Trace minerals were supplied to the reactor from time to time by adding them to the decanter effluent channel.

Sampling and Analysis

The influent to the reactor was sampled from a decanter effluent channel, and effluent samples were obtained from the effluent sampling port. Influent and effluent were sampled twice a day and analyzed accordingly as soon as possible. SS, tCOD, sCOD, volatile SS (VSS), and alkalinity were measured according to the Standard

Method [17]. COD was measured using a Closed Reflux Titrimetric Method. Methane gas content was checked by using both gas chromatography (HP 5890series II, Hewlett Packard, U.S.A.) and Orsat methods. The volatile acid content was not measured for either the influent and effluent because characteristics of the distillery wastewater varies radically in terms of what type of raw materials were used for fermentation, and the volatile acid content was thought to be hardly relevant to the reactor condition. Every 1 to 4 days, two samples were obtained from a sampling port that was located at 1.6 m from the bottom of the reactor to measure VSS, SS, and pH of the sludge bed. These samples were taken carefully after wasting enough sludge so that samples could represent the sludge bed.

RESULTS AND DISCUSSION

Operating Results in General

The THAR maintained a pH of 6.8 to 7.5, temperature of 53 to 57°C, and an effluent alkalinity of 2,960 to 5,240 mg/l as CaCO$_3$. Thus NaOH addition was not necessary. Even though, unexpectedly, a high SS input occurred due to decanter failures, the THAR reached its steady state of the SS concentrations in the sludge bed of 3,520 to 10,250 mg/l. Recommended SS concentrations of sludge beds in mesophilic hybrid anaerobic reactors range from 30,000 to 50,000 mg/l [20]. In addition, Fischer and Greene [3], and Garber [4] reported that thermophilic digesters have a higher solid concentration than mesophilic digesters. Therefore, in an attempt to obtain a more concentrated sludge bed in the THAR, more seeding was done during a break that lasted for 7 days while there was no raw wastewater input. However, this action produced no long-term effect on the reactor performance or the SS concentration in the sludge bed. From time to time, one or more of the decanters was mechanically out of order or needed some maintenance. During maintenance of decanters, the reactor had to treat SS concentrations up to 67,500 mg/l for 1.5 days. Effluent quality deteriorated just slightly during this period (Figs. 2 and 3). As indicated, the influent tCOD concentration usually reflected the influent SS concentration. For example, from the elapsed periods of 60 to 73 and 84 to 88 days, influent SS concentrations of greater than 20,000 mg/l caused increased tCOD concentrations in both influent and effluent, but the effluent sCOD remained relatively constant (Figs. 2 and 3). On the other hand, when the THAR was restarted after the break period from days 92 to 99, both the effluent tCOD and sCOD deteriorated for 2 to 3 days but stabilized thereafter (Figs. 2 and 3). When the SS concentration of the sludge bed was maintained at 3,520 to 10,250 mg/l regardless of a high SS input during the 10 months operation period, the THAR could have been converting a lot of SS into biogas. Figure 4 shows the sCOD and tCOD removal efficiencies along with an influent SS concentration. As indicated, the effect of an increased SS loading on the sCOD removal efficiency was not as serious as the effect on the tCOD removal efficiency (Fig. 4). These results suggested that the THAR having HRT of 5 to 7 days could digest almost all of the biodegradable sCOD, even in an increased SS influent.

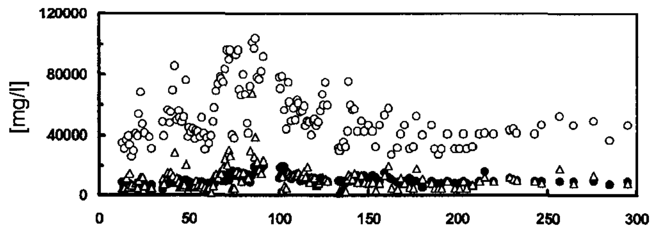

Fig. 2. Total COD concentration of influent (○, tCOD$_{in}$) and effluent (●, tCOD$_{out}$) of the THAR along with an influent SS (△, SS$_{in}$) concentration.

The THAR was operated at pH 6.8-7.5, 53-57°C, and 5 or 7 days HRT during the 10-months period. According to the fermentation condition of a plant at that time, the THAR treated the distillery wastewater of tapioca (for 81 days), corn (for 36 days), naked barley (for 38 days), or a mixture of above raw materials (for remaining days).

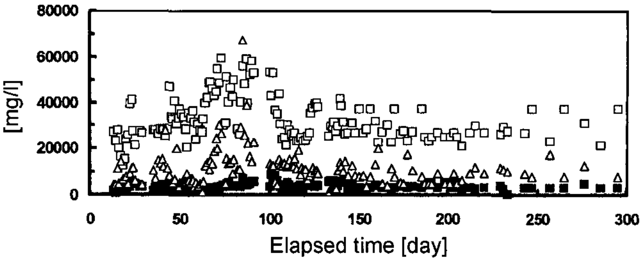

Fig. 3. Soluble COD concentration of influent (□, sCOD$_{in}$) and effluent (■, sCOD$_{out}$) of the THAR along with an influent SS (△, SS$_{in}$) concentration.

The running condition of the THAR was the same as in Fig. 2.

SS Removal

Comparing influent SS concentrations, it is evident that decanter failures took place while treating 300 m^3/d of the

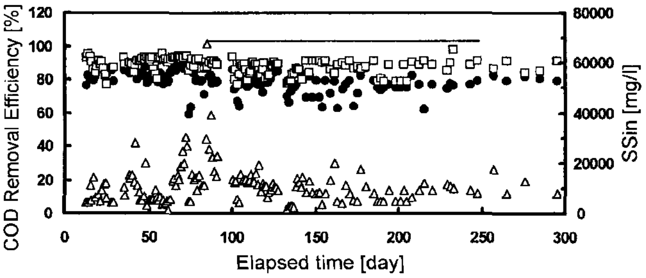

Fig. 4. Total (●) and soluble COD (□) removal efficiencies of the THAR along with an influent SS (△, SS$_{in}$) concentration.

The running condition of the THAR was the same as in Fig. 2.

Table 1. THAR performance summary on SS removal[a].

Raw material	Tapioca		Corn		Naked-barley	
Flow rate (m³/h)	300	408	300	408	300	408
SS_{in} (mg/l)	4,334 (1,333~9,000)	7,731 (4,000~19,950)	12,161 (6,500~19,250)	10,780 (4,867~14,500)	18,857 (9,334~67,500)	11,750 (10,167~14,000)
SS_{out} (mg/l)	3,945 (1,917~6,000)	6,491 (3,533~8,000)	6,208 (4,750~9,000)	6,977 (3,125~10,900)	7,500 (4,375~11,000)	3,406 (2,875~4,000)
Rem. Eff. (%)	~9	~16	~49	~35	~60	~71

[a] Values were obtained from the running condition as shown in Fig. 2.

decanted naked-barley wastewater (Table 1). When treating 408 m³/d of tapioca wastewater, decanters experienced minor failures and this effect is also shown in Table 1. Decanted tapioca wastewater had less SS than either corn or naked-barley wastewater, but the SS of the decanted tapioca wastewater was degraded to a lesser degree than others (Table 1). Decanted naked-barley wastewater and decanted corn wastewater had almost the same SS concentration level [19], but SS of decanted naked-barley wastewater seemed to be more biodegradable than those in a decanted corn wastewater (60 to 71% vs. 35 to 49%).

Generally, anaerobic filter and a related upflow anaerobic sludge blanket and fluidized bed reactors are considered to operate in its high efficiency when treating wastewater with SS concentrations amounting to less than 10% of the influent COD [19, 20]. Anaerobic filters containing randomly oriented media such as Pall Rings are known to have clogging problems, especially when treating wastewater with a high SS concentration level. Such reactors usually require a periodic cleaning of the media and some designers recommended changing it every 3 to 6 years. However, well-designed anaerobic filters using a structured cross-flow media are relatively free of these clogging problems. Our experience demonstrates that the ability for a cross-flow media to handle SS concentration is up to 67,500 mg/l. Much of the credit for a successful operation of the THAR can be attributed to a high conversion of SS in the thermophilic environment.

Total COD Removal

Minor decanter failures during treatment of 408 m³/d did not affect the tCOD of decanted tapioca wastewater, while major decanter failures did affect the tCOD of the decanted naked-barley wastewater (Table 2). This difference is attributable to the intensity and duration period of these failures. That is, the decanter failures when treating the naked-barley wastewater were longer than when treating other wastewater.

Decanted corn wastewater had an average tCOD concentration of about 49,000 mg/l, which was about 12,000 mg/l more than that of the decanted tapioca wastewater and about 9,000 mg/l less than that of decanted naked-barley wastewater (Table 2). In addition, the tCOD removal efficiency was the highest when treating naked-barley wastewater, while corn and tapioca showed almost the same efficiency. In one case of treating naked-barley wastewater, the reactor once received an influent that had 103,910 mg tCOD/l and 67,500 mg SS/l for 1.5 days. However, even the worst effluent contained 19.600 mg tCOD/l and 11,000 mg SS/l (Tables 1 and 2). It seems that naked-barley wastewater has more biodegradable tCOD than others. The THAR resulted in an average tCOD

Table 2. THAR performance summary on tCOD removal[a].

Raw material	Tapioca		Corn		Naked-barley	
Flow rate (m³/h)	300	408	300	408	300	408
$tCOD_{in}$ [mg/l]	37,713 (29,538~51,137)	37,442 (27,212~57,448)	51,973 (40,258~63,000)	46,819 (32,263~57,022)	76,645 (41,102~103,910)	58,620 (42,709~75,531)
$tCOD_{out}$ [mg/l]	8,716 (6,928~9,969)	9,811 (7,675~12,094)	10,939 (8,813~14,438)	11,753 (9,073~15,118)	12,324 (7,238~19,600)	9,665 (9,495~9,783)
tCOD Loading [kg/m³/d]	5.45 (4.27~7.39)	7.36 (5.35~11.29)	7.51 (5.82~9.10)	9.20 (6.34~11.21)	11.08 (5.94~15.02)	11.52 (8.39~14.84)
$tCOD_{rem.}$ [kg/m³/d]	4.31 (2.94~6.15)	5.43 (3.34~8.91)	6.26 (4.36~7.64)	6.89 (4.02~9.28)	9.03 (4.24~12.64)	9.78 (6.48~12.95)
Rem. Eff. [%]	78 (66~84)	72 (62~80)	79 (72~84)	74 (63~83)	84 (71~87)	83 (77~87)
Rem. Rate [kg/m³/d]	4.31	5.43	6.26	6.89	9.03	9.78

[a] Values were obtained from the running condition as shown in Fig. 2.

removal rate of 4.31 to 5.43, 6.26 to 6.89, and 9.03 to 9.78 kg tCOD/m^3 reactor/d for a decanted wastewater that generated from fermentation of tapioca, corn, and naked-barley, respectively.

Soluble COD Removal

Naked-barley wastewater had the highest sCOD concentration while tapioca and corn wastewater had almost the same sCOD concentration (Table 3). After the anaerobic treatment, the average sCOD concentration of tapioca wastewater was about 3,700 mg/l while corn and naked-barley wastewater had an effluent sCOD concentration of 3,975 to 4,191 mg/l and 3,927 to 5,145 mg/l, respectively. In other words, naked-barley wastewater was treated successfully by having the same effluent quality as either corn or tapioca wastewater. Increasing influent flow rate from 300 to 408 m^3/d did not cause any loss of the sCOD removal efficiency when either corn or tapioca wastewater was treated. When naked-barley wastewater was treated, the sCOD removal efficiency decreased slightly. However, the sCOD removal rate per reactor volume increased with an increasing flow rate and an increasing sCOD loading rate regardless of the raw materials (Table 3).

Insoluble COD Removal

Insoluble organic materials (as indicated by the difference between total and soluble COD) in decanted naked-barley wastewater were the most biodegradable anaerobically (76 to 78.3% vs. 56.7 to 70.4% for corn wastewater and 34.4 to 46.7% for tapioca wastewater). That is, out of the insoluble COD loading of about 4.55 kg/m^3/d, the hybrid reactor removed 3.46 to 3.57 kg/m^3/d of the insoluble COD. Decanted tapioca wastewater had the least amount of biodegradable insoluble organic materials. The insoluble COD loading with a decanted corn wastewater was 3.53 to 4.23 kg/m^3/d and 56.7 to 70.4% was converted to biogas (Table 4).

Continuous Treatment of Naked-Barley Wastewater

Decanted naked-barley wastewater was treated for 26 days continuously with operating at a flow rate of 300 m^3/d and an average tCOD loading rate of 11.08 kg/m^3/d. Effluent characteristics never deteriorated throughout this period. Average removal efficiencies of SS, tCOD, sCOD, and insoluble COD ranged from 60 to 71%, 83 to 84%, 86 to 91%, and 76 to 78%, respectively. Gas production rate varied from 6.61 to 7.57 m^3/m^3 reactor/d and 0.57 to 0.69 m^3 biogas/$tCOD_{rem}$. Maximum daily gas production rate was 19,574 m^3/d (Table 5).

Naked-barley wastewater, which is generally more difficult to treat than others under the conventional reactors, has a high concentration of biodegradable COD (Tables 1, 2, and 3). If there are any effective means to digest naked-barley wastewater, the rate of COD removal and biogas production from naked-barley wastewater may show better results than those from corn or tapioca wastewater. The

Table 3. THAR performance summary on sCOD removal[a].

Raw materials	Tapioca		Corn		Naked-barley	
Flow rate (m^3/h)	300	408	300	408	300	408
$sCOD_{in}$ [mg/l]	29,434 (20,697~36,235)	28,003 (22,677~36,984)	25,127 (21,296~30,375)	28,872 (26,346~31,748)	45,193 (26,075~59,613)	35,426 (29,859~41,648)
$sCOD_{out}$ [mg/l]	3,783 (1,462~6,960)	3,624 (3,024~5,314)	4,191 (2,250~5,063)	3,975 (2,361~5,234)	3,927 (2,667~6,881)	5,145 (4,063~5,823)
sCOD Loading [kg/m^3/d]	4.25 (2.99~5.24)	5.50 (4.46~7.27)	3.63 (3.08~4.39)	5.67 (5.18~6.24)	6.53 (3.77~8.61)	6.96 (5.87~8.19)
$sCOD_{rem.}$ [kg/m^3/d]	3.75 (2.48~4.88)	4.79 (3.71~6.65)	3.28 (2.44~4.00)	4.89 (4.15~5.35)	5.57 (3.28‘8.12)	6.21 (5.07~7.04)
Rem. Eff. [%]	87 (78~95)	87 (79~91)	85 (79~91)	86 (80~91)	91 (87‘94)	86 (85~88)
Rem. Rate [kg/m^3/d]	3.75	4.79	3.28	4.89	5.57	6.21

[a]Values were obtained from the running condition as shown in Fig. 2.

Table 4. THAR performance summary on insoluble COD removal[a].

Raw materials	Tapioca		Corn		Naked-barley	
Flow rate(m^3/h)	300	408	300	408	300	408
Ins. COD Loading [kg/m^3/d]	1.20	1.86	4.23	3.53	4.55	4.56
Ins. $COD_{rem.}$ [kg/m^3/d]	0.56	0.64	2.98	2.00	3.46	3.57
Ins. COD Rem. Eff. [%]	46.7	34.4	70.4	56.7	76.0	78.3

[a]Values were obtained from the running condition as shown in Fig. 2.

Table 5. Summary of gas production[a].

Raw materials	Tapioca		Corn		Naked-barley	
Flow rate (m^3/h)	300	408	300	408	300	408
Gas Production (m^3/d)	7,191 (4,971~8,036)	6,599 (4,184~8,026)	10,083 (9,401~11,894)	10,200 (7,420~12,336)	15,708 (11,430~19,574)	13,721 (11,725~15,700)
$tCOD_{rem}$ (kg/d)	8,947	11,273	13,003	14,307	18,743	20,299
Gas Production Rate (m^3/m^3 reactor/d)	3.46	3.18	5.22	4.91	7.57	6.61
Gas Production at 55°C	0.83 (0.59~1.27)	0.64 (0.43~0.95)	0.85 (0.68~1.26)	0.74 (0.54~0.89)	0.83 (0.61~1.98)	0.73 (0.55~0.87)
$tCOD_{rem.}$ (m^3/kg) at 0°C, 1atm	0.69	0.53	0.71	0.62	0.69	0.57

[a] Values were obtained from the running condition as shown in Fig. 2.

THAR was designed to operate without experiencing the unknown toxicity of naked-barley wastewater and performed as designed. Immediately after it was known that THAR could handle naked-barley wastewater successfully, the alcohol production rate increased to 20%, and thus the wastewater flow rate became 480 m^3/d. Although we have no available evidences to explain the reason why THAR works well to naked-barley wastewater, it is thought that distribution of wastewater to the biofilm of cellmass on the media [14] in THAR is one of the critical factors. Further work is necessary.

Biogas Production Rate

Biogas production during the 10-months period of operation is summarized in Table 5. The biogas had a methane content of 59 to 68% and CO_2 content of 32 to 41%. Gas was not analyzed for H_2S but sulfate levels in the raw wastewater were typically low [7]. The biogas production rate per reactor volume increased in the order of tapioca (3.18 to 3.46 $m^3/m^3/d$), corn (4.91 to 5.21 $m^3/m^3/d$), and naked-barley (6.61 to 7.57 $m^3/m^3/d$). For all raw materials, the average biogas production per unit of tCOD removed was 0.64 to 0.85 m^3/kg $COD_{rem.}$ at 55 and 0.53 to 0.71 m^3/kg $COD_{rem.}$ at standard conditions of 0°C and 1 atm.

When distillery wastewater was treated in a fully packed anaerobic filter operating at 40 to 80 kg $COD/m^3/d$ organic loading rate, Silverio *et al.* [15] reported an organic removal efficiency of 45 to 65% and a maximum gas production rate of 3.2 l/l/d. Assuming the biogas is 60% methane in which gas 1 was equivelant to a 0.4385 l of bunker oil with 9,750 kcal/l, the theoretical amount of gas production at a standard condition is equivalent to 0.58 m^3 biogas/kg $tCOD_{rem.}$ In mesophilic hybrid reactors, biomass accumulates and SS concentration in the sludge bed increases. Every 6 to 18 months, a mesophilic high-rate anaerobic reactor needs to have an anaerobic sludge withdrawal [20, 21]. However, the THAR seems to achieve a steady state of the SS concentration in the sludge bed of 3,520 to 10,250 mg/l. This means that biodegradation of influent SS and decay of the thermophilic biomass in the hybrid reactor was too fast for an accumulation of more than about 11,000 mg SS/l to take place. This phenomena seemed to contribute to the high gas production experienced with THAR.

Unfortunately, gas production before the start-up of the THAR was not measured and, therefore, direct comparison of gas amount production before and after the THAR operation was not possible. The boiler used in this process had a capacity of use for 15,000 m^3/d of biogas and was changed in July 1995 so that a maximum of 20,000 m^3/d of biogas could be used.

REFERENCES

1. Braun, R. and S. Huss. 1982. Anaerobic digestion of distillery effluents. *Process Biochem.* **35:** 425-434.
2. Cho, K. M. and Y. J. Yoo. 1999. Novel SSF process for ethanol production from microcrystalline cellulose using the δ-integrated recombinant yeast, *Saccharomyces cerevisiae. J. Microbiol. Biotechnol.* **9:** 340-345.
3. Fischer, A. J. and R. A. Greene. 1945. Plant scale tests on thermophilic digestion. *Sewage Works J.* **17:** 718-724.
4. Garber, W. F. 1954. Plant-scale studies of thermophilic digestion at Los Angeles. *Sewage Ind. Wastes* **26:** 1202-1213.
5. Kim, J. S., K. K. Oh, S. W. Kim, Y. S. Jeoung, and S. I. Hong. 1999. Ethanol production from lignocellulosic biomass by simultaneous saccharification and fermentation employing the reuse of yeast and enzyme. *J. Microbiol. Biotechnol.* **9:** 297-302.
6. Kim, K. and J. Y. Lee. 1998. Strain improvement of yeast for ethanol production using a combined treatment of electric field and chemical mutagen *N*-methyl-*N*'-nitro-*N*-nitrosoguanidine. *J. Microbiol. Biotechnol.* **8:** 119-123.
7. Kim, K. R., K. J. Oh, K. Y. Park, and D. K. Kim. 1999. Removal of hydrogen sulfide and methylmercaptan using thiobacillus in a three phase fluidized bed bioreactor. *J. Microbiol. Biotechnol.* **9:** 265-270.
8. Lettinga, G., S. W. Hobma, L. W. Hulshoff Pol, W. De Zeeuw, P. De Jong, P. Grin, and R. Roersma. 1983. Design

operation and economy of anaerobic treatment. *Wat. Sci. Tech.* **15:** 197-210.

9. Maiorella, B. L., H. W. Blanch, and C. R. Wilke. 1983. Distillery effluent treatment and by-product recovery. *Process Biochem.* **24:** 96-104.
10. Ono, H. 1965. Utilization of materials derived from treatment of wastes from molasses distilleries, Discussion of Bhaskaran, T. R. p. 100. *In* J. K. Baars (ed.), *Advances in Water Pollution Research*, vol **2**. Pergamon Press, New York, U.S.A.
11. Rudolfs, W. and H. Heukelekian. 1930. Thermophilic digestion of sewage solids-I. Preliminery paper. *Ind. Eng. Chem.* **22:** 96-104.
12. Ryu, S. R. and K. H. Lee. 1997. Comparison of immobilization matrix for ethanol fermentation by *Zymomonas mobilis* and *Saccharomyces cerevisiae*. *J. Microbiol. Biotechnol.* **7:** 438-440.
13. Sanchez Riera, F., P. Cordoba, and F. Sineriz. 1985. Use of the UASB reactor for the anaerobic treatment of stillage from sugar cane molasses. *Biotechnol. Bioeng.* **27:** 1710-1719.
14. Sheehan, G. J. and P. F. Greenfield. 1980. Utilisation, treatment and disposal of distillery wastewater. *Water Res.* **14:** 257-277.
15. Silverio, C. M., P. G. Anglo, G. V. Montero, Ma. V. Pacheco, M. L. Alamis, and V. S. Luis Jr. 1986. Anaerobic treatment of distillery slops using an upflow anaerobic filter reactor. *Process Biochem.* **21:** 1200-1211.
16. Stander, G. J. and J. F. Elsworth. 1950. Effluents from fermentation industries. Part III— The influence of high concentrations of sulphates on the anaerobic digestion method of treatment at thermophilic (55°C) and mesophilic (33°C) temperatures. *J. Inst. Sewage Purif.* **3:** 303-309.
17. *Standard Method for Examination of Wastewater.* 1992. 18th Ed. American Public Health Association, New York, U.S.A.
18. Yoon, K. P. 1998. Isolation and characteristics of *Pseudomonas* sp. KM10, a cadmium and mercury-resistant, and phenol-degrading bacterium. *J. Microbiol. Biotechnol.* **9:** 340-345.
19. Young, J. C. 1991. Factors affecting the design and performance of upflow anaerobic filter. *Wat. Sci. Tech.* **24:** 133-155.
20. Young, J. C. and B. S. Yang. 1989. Design considerations for full-scale anaerobic filters. *J. Wat. Poll. Cont. Fed.* **61:** 1576-1587.
21. Young, J. C. and H. W. Young. 1991. Full-scale treatment of chemical process wastes using anaerobic filter. *J. Wat. Poll. Cont. Fed.* **63:** 153-159.