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PILOT-SCALE EXPERIENCES ON ANAEROBIC FLUIDIZED-BED TREATMENT OF BREWERY WASTES

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ABSTRACT

This paper covers the results of a pilot-plant study on the Anaerobic Fluidized-Bed Reactor (AFBR) treatment of brewery wastes. The AFBR was operated over a wide range of organic and hydraulic loading rates for a study period of more than eight months. The reactor consisted of a clear PVC column with a diameter of 165 mm and 3 m in height. Sand having a median diameter of 0.5 mm was used as the medium. The AFBR was fed with wastewaters collected from a local brewery. A COD removal efficiency of greater than 75% was observed at an organic loading rate (OLR) of 8.9 kg COD/m^3 of expended bed/day for 82 days from start-up. The OLR was increased to greater than 14 kg COD/m^3.d and a COD to methane conversion of 87% was achieved. Effects of OLR and COD removal efficiency on gas flowrate and on gas composition as well as concentrations of suspended solids (SS) and volatile acids (VA) were investigated. It was observed that biomass distribution along the height of the AFBR was not uniform and a strong stratification of biomass exists between the upper and lower parts of the system. The ecological structure of biomass was examined by SEM and clumps of methanogenic bacteria were identified. The Monod kinetic parameters were determined using steady-state operating data and compared to similar results given in the literature for the same waste.

KEYWORDS

Anaerobic fluidized bed; brewery waste; biomass hold-up;bioenergy recovery; Monod kinetic coefficients;high-rate anaerobic industrial waste treatment.

INTRODUCTION

Anaerobic digestion processes in their various forms are being increasingly applied to a broad spectrum of industrial wastewaters throughout the world. The advantages of anaerobic biological treatment over aerobic processes for partial treatment or pretreatment of high- and medium-strength industrial wastewaters are well documented (McCarty 1968; Anderson and Saw 1984). The most significant advantages of this process are the production of methane, the minimal production of excess biological solids, and the comparatively low energy requirement. For anaerobic treatment to be economically attractive in terms of minimizing the capital costs, it is also important that such treatment should take place in one of the new generation of anaerobic reactors, such as a contact digester, a packed-bed digester, an upflow sludge blanket digester or a fluidized-bed reactor.

The anaerobic fluidized-bed reactor (AFBR) as illustrated in Figure 1 is a recent process innovation in anaerobic biotechnology which retains the growth-supporting medium in suspension by drag forces exerted by the upflowing wastewater. In the fluidized state each medium provides a large surface area for biofilm formation and growth. Unlike fixed-bed reactors, bed fluidization results in little or no short-circuiting and small pressure gradients.

The AFBR has been investigated for the treatment of a wide variety of industrial wastewaters as summarized in Table 1. Some full-scale AFBRs are currently in use in the U.S. and Europe for the treatment of wastewaters from agro-industry (Heijnen 1983, Sutton et al, 1982).

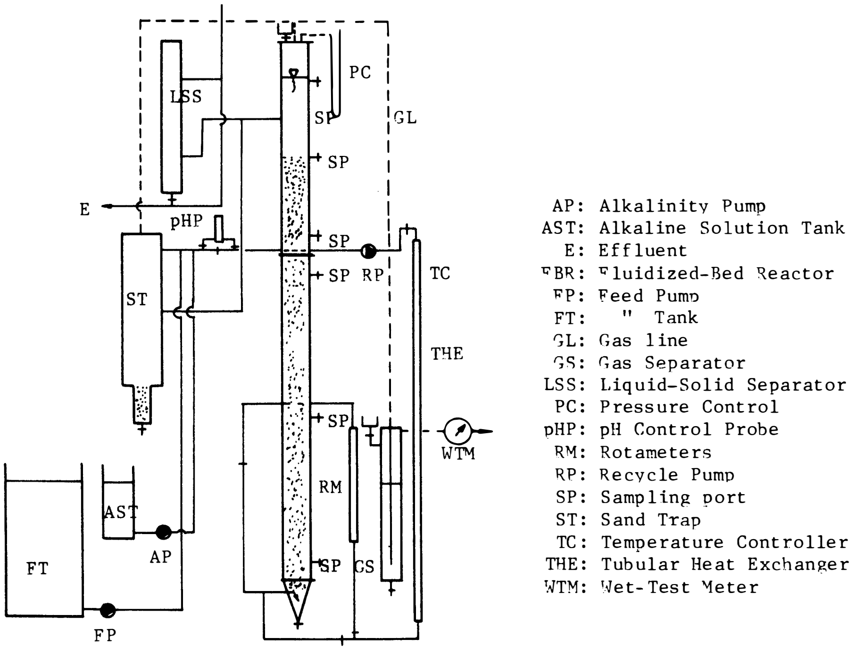
Although the AFBR has been known for more than ten years, there are still many important factors which need to be clarified concerning this process, and research efforts are required to gain a better insight the process in order to develop a more rational design and control procedure. This paper presents a pilot-plant study on the anaerobic fluidized-bed treatment of brewery wastes. A significant amount of data was obtained on the AFBR over the study period for a wide range of organic loading rates and operating conditions.

MATERIALS AND METHODS

Pilot Plant. The fluidized-bed reactor consisted of a clear PVC column having a diameter of 165 mm. The height of the reactor to the top liquid level was approximately 3 m.The fluidized-bed height was controlled to below 2.75 m. The pilot plant included a feed tank, feed and recycle pumps, a means for foam control, a sand trap, a gas–liquid separator, a wet-test meter for gas flow measurement, and other instrumentation. Temperature control of the pilot plant was achieved by adjusting the temperature of the recycled stream using an electrically controlled heat exchanger. The flow scheme of the pilot plant is shown in Figure 1.

Feed. Brewery waste collected from a local brewery was used as the feed. Concentrated feed which was in fact spoilt beer had a mean COD of 90,000 mg/l which was diluted with tap water to obtain the desired COD concentration.

Media. Sand having a specific gravity of 2.54, a median diameter of 0.5 mm and an initial porosity 0.41 was used as the media.



AP: Alkalinity Pump
AST: Alkaline Solution Tank
E: Effluent
FBR: Fluidized-Bed Reactor
FP: Feed Pump
FT: " Tank
GL: Gas line
GS: Gas Separator
LSS: Liquid-Solid Separator
PC: Pressure Control
pHP: pH Control Probe
RM: Rotameters
RP: Recycle Pump
SP: Sampling port
ST: Sand Trap
TC: Temperature Controller
THE: Tubular Heat Exchanger
WTM: Wet-Test Meter

Fig. 1. Flow Scheme of the AFBR

Start-Up of the Pilot Plant

Prior to start-up, the reactor was filled with 33 l of sand and longitudinal dispersion in the reactor was analyzed using tracer response curves. The results of the tracer study indicate that completely mixed flow conditions occur both in the case of a nonbiological and biological fluidized bed, and the conical flow distributor with an angle of about 20 degrees supplies a uniform fluidization along the height of the column.

After the dispersion and fluidization studies with tap water, 8.5 l seed sludge was put into the reactor, the reactor filled with tap water and operated by batch feeding for the first two weeks of the study. The initial bed expansion was controlled at about 40%. The use of a heavy seed sludge caused wash-out of the media due to the decrease in bulk density in the reactor. The media leaving the column blocked the sand trap by settling to the bottom. This experience indicated that digester supernatant should be used for starting up fluidized-bed reactors instead of using heavy seed sludge. $NaHCO_3$ solution was added to the reactor directly, in order to maintain a pH of 6.8-7.4. The reactor temperature was controlled at 35-1^{o}C while NH_4HCO_3 and KH_2PO_4 were used to provide the nutrient balance in the system.

Continuous operation was then started after two weeks of batch feeding. During the start-up period, hydraulic retention times and organic loading rates were kept above 10 days and 1.6 kg COD/m^3 of expanded bed volume per day or 1.0 kg COD/m^3 of liquid volume per day respectively. This operation was continued to the 47th day, after which the OLR was increased to beyond 1 kgCOD/m^3.d.

TABLE 1 Summary of AFBR Operating Data For The Treatment of Industrial Wastewaters

Wastewater	Feed COD (mg/l)	OLR (kgCOD/m^{3}d)	Temp (^{o}C)	HRT (hr)	COD Removal(%)	CH_4 yield (m^3/kgCOD rmd.)	Reference
Acid whey	50000-56000	10.8-23.5	35	36-120	72-84	-	Hickey and Owens(1981)
	52000-55000	9.4-23.0	24	36-84	65-71	-	
Acid whey	52000	6.6	35	120	94	0.36	
Chemical	12000	2.9-17.0	35	-	79-93	0.38-0.44	
Food Processing	7200-9500	2.2-15	35	7.5-49	75-86	0.40	
Soft drink Bottling	6000	2.5-11.5	35	-	66-89	0.41	
Heat Treatment liquor	10000	2.7-13.4	30	-	52-75	-	
Whey Permeate	9400	5.2-6.5	30-35	23.3	88	-	Li et al.(1982)
	13000	9.5-10.8	30-35	16.6	85	0.30	
	12000	11.2-14.9	30-35	14.5	84	0.28	
Whey Permeate	35000	9.9-13.4	30-35	43.6	76	0.27	
	9500	5.5-8.4	30-35	20.9	94	-	
Sweet whey	10000	5.6-37.4	25-31	4-27	27-93	-	Switzenbaum and Danskin(1982)
Whey permeate	3000-10000	5.0-17.2	35	2.4-14	70-95	0.35-0.395	Boening and Larsen(1982)
	3500-4200	5.0-13.1	25	5-10	40-75	0.27-0.37	
	2200-3100	3.1-7.5	15	2-14	25-55	0.10-0.23	
Molasses	8700-9500	12.8-14.9	30	8	43	0.348	Frostell(1982)
Sucrose	1500-16000	4.2-9.6	55	5-5.2	30-90	-	Schraa and Jewell(1984)
Glucose	480-9000	5.8-108	35	0.45-8	75-95	0.33	Chen et al(1982)
Sulfite liquor evaporator condensate	8250-16000	17-102	35	2.4 -15	69-90	0.29-0.36	Mueller et al (1985)
Soft-drink bottling	500-1200	1.0-3.8	20	20	85-93	-	Yoda et al. (1987)
Yeast factory waste	4500	80	37	1.4-2.4	25	-	Heijnen(1983)
		55	37	1.0-3.0	92	0.39	
	3150	56-70	37	1.2-1.8	90	0.35	

Experimental Design

The experimental procedure involved in this investigation is summarized in Table 2. In the first part of the study (Run I), the initial feed COD was 3220 mg/l and was then increased step by step to 12,000 mg/l in order to minimize the transient impact on the reactor performance. The hydraulic retention times ranged from 7 to 1.7 days in Run I. In the second series of tests the feed COD concentrations were varied from 1000 to 3500 mg/l and the hydraulic retention time decreased to 5 hours. Upflow velocity in the column was kept below 30 m/h during the second part of the study. The samples were collected and analyzed at least 3 times per week. The results between the 83rd and the 124th days are not given in Table 2, due to some mechanical problems with the feed pump.

TABLE 2 Experimental Procedure

Parameter	Run I 0 - 82 Days	Run II 125 Days
Hydraulic retention time, HRT (days)	7-1.7	1.4-0.2
Feed COD concentration, (mg/l)	3220-12000	1000-3500
Upflow velocity, (m/h)	< 30	30
OLR (kgCOD/m^3.d)	1-8.9	2.5-14.9

RESULTS AND DISCUSSION

Substrate Utilization

One major advantage claimed for an AFBR is its ability to retain a very high biomass holdup in the reactor which increases substrate utilization to an order of magnitude greater than in conventional anaerobic processes. Evidence of this may be seen in Figures 2 and 3 in which the percent COD removal and the COD removal rates are plotted as a function of COD loading.

The results were obtained at two different operating conditions. In the first part of the study, a COD removal efficiency of more than 75 percent was achieved at an organic loading rate of 8.9 kg COD/m^3.d which corresponds to a feed COD of 10500 mg/l and a HRT of 1.7 days. The corresponding soluble COD removal rate, R_L, is about 4.7 kg/m^3. (Fig. 3).

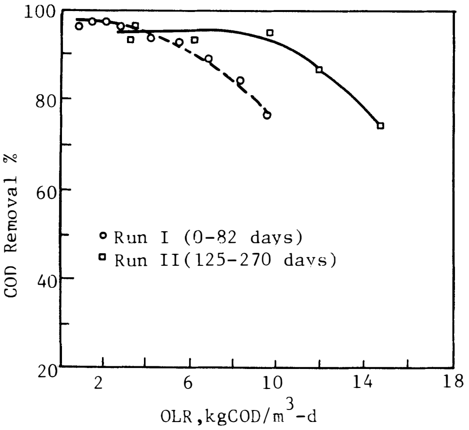


Fig. 2 Effect of COD loading on the percent COD removal of the FBR

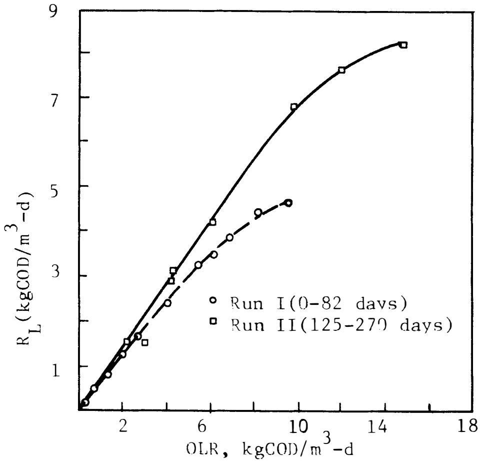


Fig. 3 Effect of COD loading on the COD removal rate (R_L) of the FBR

Starting from the 125th day the operating procedure was changed. The influent COD was decreased to levels of as low as 1000 mg/l. Organic loading rates were increased to 14.9 kgCOD/m^3.d and COD removal efficiencies greater than 74 percent were observed (Fig.2). COD removal efficiencies are about 95 percent for loading rates of less than 10 kg COD/m^3.d. The COD removal rates were as high as 8.25 kg COD/m^3.d (Fig.3). The effect of influent COD concentration on COD removal efficiency was analyzed by keeping the organic loading rate constant at around 4.1 to 4.5 kgCOD/m^3.d. The reactor was operated at four different hydraulic retention times (24, 17.5, 12 and 5 hours). The experimental results suggest that the COD removal efficiency of an AFBR is onlv a function of the COD loading rates, and neither the feed COD nor the HRT alone significantly affects the performance of the reactor. For example, about 93 to 95% of the feed COD was removed at a COD loading rate of 4.1 to 4.5 kg COD/m^3.d This loading was obtained at the following combinations of feed COD and HRT: (3200 mg/l, 24 h); (2390 mg/l, 17.5 h), (1680 mg/l, 12 h) and (943 mg/l, 5 h). Results obtained from this study have shown that lowstrength as well as high-strength soluble and biodegradable substrates can be equally treated in an AFBR with a high utilization efficiency, provided that the applied COD loading is maintained at a desirable level. This observations confirms the findings reported by Switzenbaum and Jewell (1980) and Chen et al. (1982).

Effluent COD and Volatile Acids

The effluent COD from the reactor increased with an increase in COD loading rate,as illustrated in Fig. 4. Such an increase in effluent COD is concomitant with a similar increase in the effluent volatile acids, as illustrated in the same figure. This observation seems to suggest that, at higher organic loadings, the effluent COD of an AFBR is largely exerted by the nonutilized volatile acid production in the reactor.

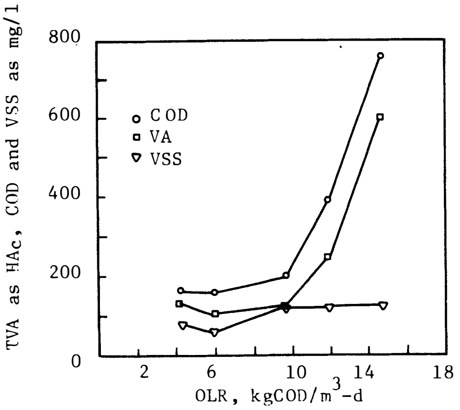


Fig. 4 Effect of COD loading on the effluent COD, TVA and VSS in the FBR for Run II

The accumulation of volatile acids was observed when the organic loading rate was increased to about 8.9 kgCOD/m^3.d in the first part of this study. At that OLR, the average effluent COD and volatile acids in the system were about 2400 mg/l and 1560 mg/l (as CH_3 COOH) respectively. The major reason for such high volatile acids was thought to be the insufficient amount of active methanogenic biomass, because the total volatile solids in the reactor were only around 320 g. In the second part of the study however, the total volatile acids in the reactor remained at around 595 mg/l as CH_3COOH, although the organic loading rate was increased to 14.9 kg COD/m^3.d.

Gas Production and Composition

Because the COD removal rate (R_L) in the AFBR increased with an increase in organic loading rate (Fig.3), a similar relationship may be observed between the daily gas production rate and the COD loading as illustrated in Fig.5. At high COD loadings, the percent CH_4 content of the gas produced decreased with increasing COD loadings because more CO_2 was produced in the acid forming stage (Fig.5). The observed CH_4 content of the gas decreased from 88 to 78% as the COD loading increased from 4 to 14.9 kg/m^3.d in the second part of the study. However, the CH_4 content of the gas decreased from 78 to 72% as the COD loading was increased from 1 to 8.9 kg/m^3.d in the first part of the research.

The observed methane production yields for the first and second part of the study were about 0.34 and 0.35 m^3 CH_4/kg COD removed respectively. Theoretically 0.395 m^3CH_4 is produced per kg COD removed at 35°C when the starting compound is glucose and the microbial yield is negligible (Metcalf and Eddy, 1979). This represents 87% recovery of energy value from the substrate used.

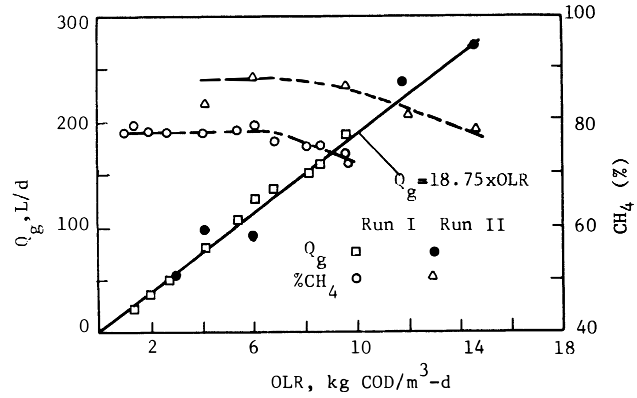


Fig. 5 Effect of COD loading on flowrate and CH_4 content of the Gas in the FBR

Biomass Holdup and Ecology

Biomass holdup measurements carried out on samples withdrawn from different heights in the AFBR revealed that the distribution of the biomass along the height of the reactor was not uniform. Bioparticles accumulated at the upper part of the bed as the thickness of the biofilm increased and the biomass holdup near the top part of reactor reached values of 22000 mgVS/l. However the bottom part of the reactor was occupied by the lightly coated media and the concentration of volatile solids in this part generally ranged from 2000 to 6000 mg/l. The ability of the AFBR to retain a very high biomass holdup was seen in Fig.6. The steady-state biomass holdup in the AFBR is strongly dependent on the COD loading applied. The biomass holdup increased at high organic loadings and caused over-expansion in the bed, consequently intentional media wasting was necessary in order to reduce the media lost from the reactor.

Another factor which has a negative effect on steady-state biomass holdup in the AFBR is gas bubbles. Therefore, it was expected that the effluent volatile suspended solids (VSS) concentration would increase with increased organic loadings. However, although the loss of biofilm at high COD loadings was relatively high, it was not severe enough to reduce the efficiency of the reactor.

A balance was established between the growth of biomass on the media and the removal of biofilm by gas production in the reactor. As a result of these two counter-balanced processes, the distribution of biofilm thickness and biomass holdup in the reactor was relatively stable.

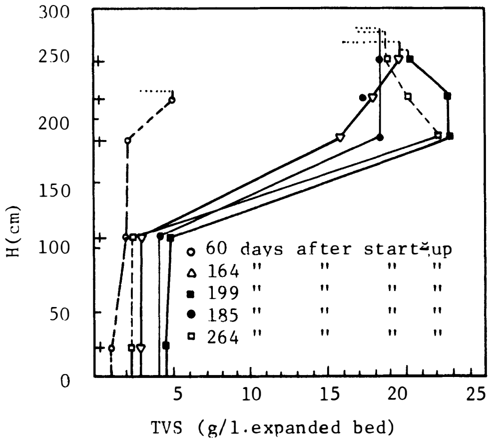


Fig. 6 Distribution of the biomass holdup along the height of the AFBR

The continuous biofilm sloughing process observed in this investigation also has a profound effect on sludge retention time, (θ_c). The SRT is calculated by:

$$\theta_c = \frac{XV}{Q.X_1+Q_wX_w} \tag{1}$$

Where X_1 is the effluent VSS concentration (mg/l), Q_w is the biomass wastage and X_w is the VSS concentration of the biomass removed. The experimental data illustrated in Fig.7 indicated that the SRT may decrease to around 10 days or even less, at high organic loading rates. By limiting the COD loading applied to an AFBR to a given level, one is able to maintain a desirable SRT in the reactor which, in turn, gives an acceptable COD removal efficiency.

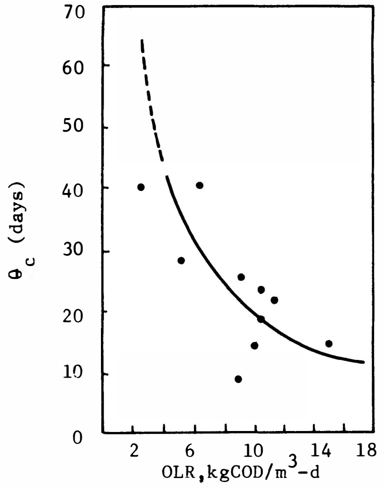


Fig. 7 Effect of OLR on the SRT

The biological structure of bioparticles withdrawn from the reactor was examined both by scanning electron and epifluorescence microscopes. It was observed that bacteria in the biofilm are mainly methanogenic and generally rods round in shape (Fig.8) although some clumps of methanogenic bacteria were identified (Fig.9).

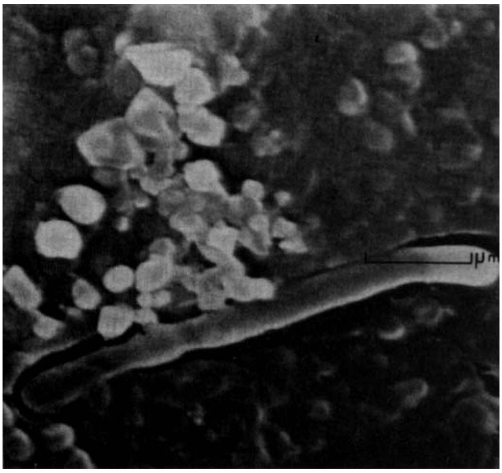


Fig. 8 SEM of biofilm cell in the AFBR.

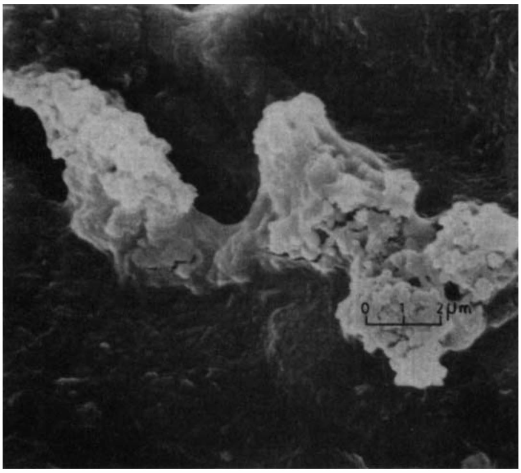


Fig. 9 SEM of clumps of methanogenic bacteria in the AFBR.

Kinetic Evaluation

Using Monod(1950) kinetics, the following final expressions can be obtained for effluent substrate (COD) concentrations from AFBR's:

$$\frac{X.\theta}{S_o-S_1} = \frac{K_s}{K}\cdot\frac{1}{S_1} + \frac{1}{K} \tag{2}$$

$$\frac{1}{\theta_c} = Y.\frac{S_o-S_1}{X.\theta} - b \tag{3}$$

where X : microorganism (VSS) concentration in the AFBR (mg/l)
S_o : influent substrate (COD) concentration (mg/l)
S_1 : effluent substrate concentration (mg/l)
θ : hydraulic retention time (d)
K : maximum rate of substrate utilization $(=\mu_m/Y)$
μ_m : maximum specific growth rate (l/d)
Y : microorganism growth yield (gVSS/g COD)
K_s : half-velocity constant (mg/l)
b : coefficient of endogeneous respiration (l/d).

Plots of equations (2) and (3) provide the necessary information for Monod kinetic coefficients in treatment of brewery wastes in AFBR. Steady-state operating results from the AFBR for brewery wastes are given in Table 4. Using the data given in Table 4, equations (2) and (3) are plotted in Fig.10 and 11 respectively.

TABLE 4 Steady-State Results From the AFBR

OLR (kgCOD/m^3.d)	S_o (mg/l)	S_1 (mg/l)	X (mgVSS/l)	θ (d)	θ_c (d)
8.87	11000	3000	4875	1.7	8.7
9.88	10000	3750	6295	1.4	14.0
4.97	5000	900	7590	1.4	28.2
2.50	2500	200	8155	1.44	39.8
14.94	2400	650	8855	0.21	14.3
10.40	1800	575	12225	0.21	17.85
9.86	3045	950	10460	0.44	25.3
6.33	2450	400	10460	0.5	41.0
10.30	3500	965	10440	0.44	23.4
11.30	4000	1350	11260	0.44	21.2

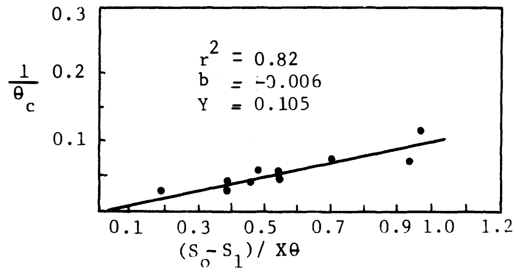


Fig.10. AFBR $\frac{S_o-S_1}{X\cdot\theta}$ versus $\frac{1}{\theta_c}$

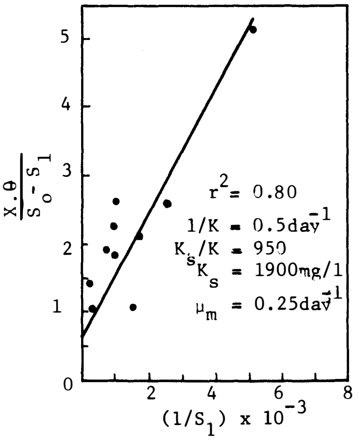


Fig. 11. AFBR $(\frac{1}{S_1})$ versus $(\frac{X\cdot\theta}{S_o-S_1})$

The results from the evaluation of Monod kinetic for AFBR treatment of brewery wastes show a good agreement with results given by Whiteman (1986) and Ghazali (1986) for the same waste (Table 5). The results also show that steady-state Monod kinetic evaluation for AFBR treatment of brewery wastes is an appropriate way to explain the treatment process.

TABLE 5 Comparative Evaluation of Monod Kinetics Parameters for Brewery Wastes

Reactor Type	Waste	Y (gVS/gCOD)	b (1/d)	μ_m (1/d)	K_s (mg/l)	Reference
Pilot ACR	Spoilt beer	0.057	0.0055	0.19	7137	Whiteman(1986)
Pilot ACR	Spoilt beer	0.032	0.004	0.28	21270	Ghazali(1986)
Pilot AFBR	Spoilt beer	0.105	0.006	0.25	1900	Present Study

CONCLUSIONS

The results of a pilot-scale AFBR investigation demonstrate that this process is highly effective for methane generation from soluble wastes. A COD removal efficiency of more than 75 percent can be achieved by an AFBR at an organic loading rate of 8.9 kg COD/m^3.d for less than 82 days from the start-up. About 340 l of methane is produced per kg COD removed. This represents 87% recovery of energy value from the waste treated. A significant increase in the organic loading rate has only slight effects on the methane content of the digester gas. The AFBR is capable of achieving a very high reactor biomass holdup throughout the biofilm on the fluidized-bed media but the distribution of the biomass along the reactor height is not uniform. The steady-state biomass holdup in the AFBR is strongly dependent on the COD loading applied. Biomass holdup increases at high organic loading rates which may cause over-expansion in the bed and intentional media wasting may be necessary to reduce media loss from the reactor. Rising gas bubbles may have a negative effect on the steady-state biomass holdup in the FBR. However, the loss of biofilms at high organic loadings is not severe enough to impair the efficiency of the reactor, even if it is relatively intensive. The continuous biofilm sloughing process has a profound effect on the SRT. The SRT may decrease to around 10 days or even less, at high organic loadings. By limiting the COD loading at a particular level one is able to maintain a desirable SRT in the system. The steady-state treatment process for the AFBR of brewery wastes can be explained by Monod kinetics.

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