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LOW TEMPERATURE TREATMENT OF MUNICIPAL SEWAGE IN ANAEROBIC FLUIDIZED BED REACTORS

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Abstract—The anaerobic fluidized bed reactor (AFBR) appears to be most promising for the treatment of low strength wastes, such as municipal sewage, at low temperature, since the process is able to maintain a large mass of active microorganisms and provides effective removal of TSS. The study is divided in three parts. The objective of the first part is to characterize the effect of decreasing temperature on the performance of two mature AFBR reactors. The second part presents the data from 220 days of operation at 10°C; and in the third part two start-ups, with and without inoculum at 15°C, are evaluated. A gradual temperature decrease from 20 to 5°C, allowing the microorganisms to acclimate to the new lower temperature, did not have a great effect on effluent quality. However a great accumulation of TSS was observed in the top of the fluidized bed. At 10°C, and a hydraulic retention time of 1.5 h, 70% of T_{COD} removal was achieved. It is possible to start-up the AFBR at 15°C without inoculation; however, at least 4 months is required to get good quality effluents.

Key words—anaerobic fluidized bed reactors, raw municipal sewage, low temperature treatment

NOMENCLATURE

T = temperature (°C)
$\bar{t}$ = hydraulic retention time (h)
$B_{V,T_{COD}}$ = total COD, volumetric loading rate (g/l.d)
S_{COD} = soluble COD (mg/l)
T_{COD} = total COD (mg/l)
T_{BOD_5} = total BOD_5 (mg/l)
TSS = total suspended solids (mg/l)
VSS = volatile suspended solids (mg/l)
TKN = total Kjeldahl nitrogen (mg N/l)
NH_3-N = ammonia nitrogen (mg N/l)
Org-N = organic nitrogen (mg N/l)
RE = T_{COD} removal efficiency (% T_{COD}).

INTRODUCTION

The successful application of anaerobic processes to domestic sewage, considering its particular characteristics, is a great challenge. First, the organic strength of sewage is relatively weak. Therefore, cell growth rate is limited, since the rate of growth of the organisms and the rate of substrate uptake are proportional to substrate concentration (Jewell, 1985). In addition, domestic sewage should be treated without heating, otherwise it is not economically feasible. This means the process should be able to operate over a wide range of temperatures (10–22°C) and occasionally lower than 10°C. In addition, domestic wastewater generally contains more particulate organics than soluble organic material. This slows the reaction rate, because the degradation rate of particles is slower than for soluble species, and the initial hydrolysis reaction can be relatively slow (Rittmann and Baskin, 1985). Some domestic sewages have a high sulphate concentration (> 100 mg/l). This can decrease methane production because some sulphate reducing bacteria use acetate as an electron source. The sulphide produced may cause serious odour problems.

The anaerobic fluidized bed reactor (AFBR) system appears to be most feasible for the treatment of domestic sewage. The process is able to maintain a large population of active microorganisms required to overcome the limit of slow growth of anaerobic microorganisms.

AFBR are extremely efficient in removing organic suspended solids. Most of the solids remain in the reactor until they are hydrolysed (Yoda *et al.*, 1985). It has been reported that the hydrolysing and acidifying communities are associated with entrapped suspended solids, whereas the methanogens are located in the film (Jewell, 1985). This can improve both particulate hydrolysis and rate of methanogenesis.

The main objective of this work is to *provide information* about the stability of the AFBR process treating domestic sewage at low temperature. Very few studies have been performed on anaerobic digestion at low temperature, and most of them do not contain data over long operation periods (over 100 days). The results from an experiment at decreasing temperatures, a restarting and long operating period at low temperature (220 days at 10°C) and a comparative start-up (with–without inoculum) are presented.

MATERIALS AND METHODS

Four laboratory anaerobic fluidized bed reactors were used to carry out the experiments. Figure 1 shows a schematic diagram of the AFBR-1 and AFBR-2. The reactors AFBR-3 and AFBR-4 are schematically represented in Fig. 2. Some of the reactor characteristics are

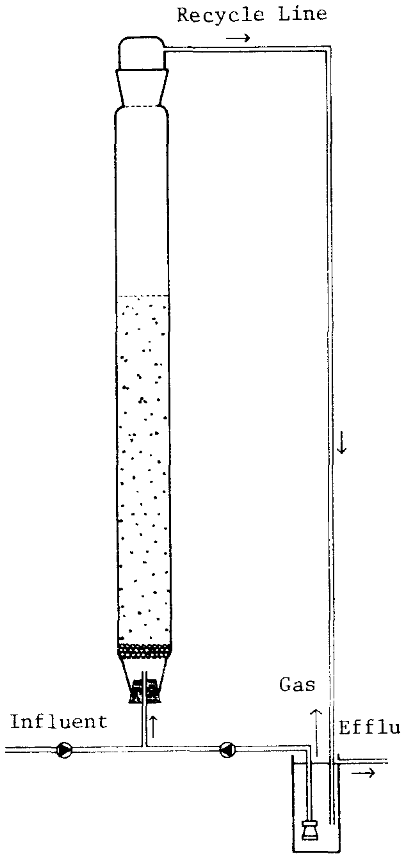

Fig. 1. Scheme of the reactors AFBR-1 and AFBR-2.

summarized in Table 1. Arlita® is an aluminium and iron silicate with traces of calcium carbonate and titanium, calcium, sodium and potassium oxides.

AFBR-1 and AFBR-2 were made of glass. Gas collectors were not installed. AFBR-3 and AFBR-4 consisted of a plexiglass tube with dimensions of 5.4 cm internal diameter by 63 cm high. The upper part of the reactors was equipped with a combined gas collector–settler device of 0.2 l. volume. Sampling points were arranged along the column at 15 cm intervals allowing samples of the media and accumulated solids to be taken.

The reactor effluent was drawn from the top and pumped into the bottom assembly at a constant flow rate to achieve a 20% bed expansion. The influent was pumped into the recycle line of the reactor using a peristaltic pump. A submerged membrane pump was used in the recycle line. The recirculation container (0.15 ml) was opened to the atmosphere in AFBR-1 and AFBR-2, but it was closed in AFBR-3 and AFBR-4.

The inlet system installed in AFBR-3 and AFBR-4 (Fig. 2) was an improvement of the system used in AFBR-1 and AFBR-2 (Fig. 1). It allowed better flow distribution, fewer possibilities for channeling and solved clogging problems in the inlet point during shut-downs which occurred very often with the system used in AFBR-1 and AFBR-2. The temperature was controlled by using a cryostatic bath.

The influent used was raw domestic sewage obtained from two different sewers having different wastewater characteristics. The experiment at decreasing temperature was carried out with raw sewage from Sewer-1. For the other experiments, wastewater from Sewer-2 was used. Some of the influent characteristics are presented in Table 2.

Organic loading rates ($B_{V,T_{COD}}$) and hydraulic retention time (t) are calculated based on the empty volume of the fluidized bed.

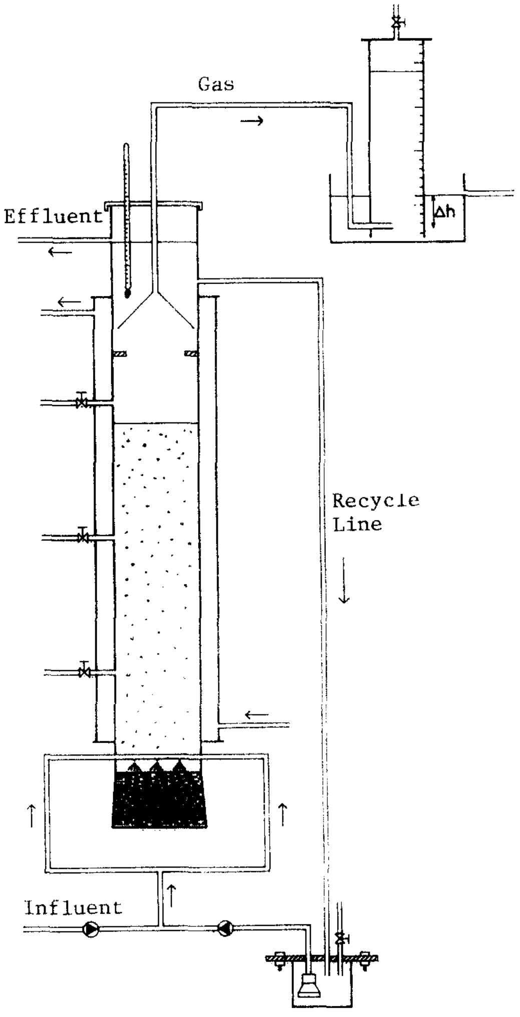

Fig. 2. Scheme of the reactors AFBR-3 and AFBR-4.

Influent and effluent analyses were determined according to *Standard Methods* (APHA *et al.*, 1985). Attached biomass was measured as indicated in Switzenbaum (1978). Nitrate, chloride, phosphate and sulphate were performed by ion chromatography with a Waters HPLC using the column Waters IC-PACK Anion Column P/N 07355. Elemental sulphur, carbon, hydrogen and nitrogen were determined with an elemental analyst Perkin–Elmer Model 240C. The biogas composition was measured with a Hewlett–Packard model 5790 Gas Chromatograph using Poropak Q as column packing.

Table 1. Reactor characteristics

	AFBR-1	AFBR-2	AFBR-3 AFBR-4
Diameter (cm)	3.0	3.0	5.4
Total volume (litres)	0.54	0.54	1.44
Active volume (litres)	0.23	0.16	0.96
Recirculation tank volume (litres)	0.15	0.15	0.15
Support material	Arlita	Red brick	Arlita
Diameter (mm)	0.14–0.28	0.14–0.28	0.21–0.50
Density (g/cm^3)	1.94	2.53	1.57
Porosity (%)	57	55	65
Expansion (%)	20	20	20
Superficial velocity (cm/s)	0.11	0.14	0.12
Temperature (°C)	10.0	10.0	15.0

Table 2. Wastewater characteristics

	Sewer-1		Sewer-2	
	Range	Average	Range	Average
S_{COD} (mg/l)	130–355	260	197–648	390
T_{COD} (mg/l)	150–590	475	295–1560	760
T_{BOD_5} (mg/l)	215–390	325	305–630	480
pH	6.9–8.2	7.7	7.2–8.0	7.5
Alk. (mg $CaCO_3$/l)	130–325	200	230–360	265
TSS (mg/l)	118–245	190	104–761	285
VSS (mg/l)	110–185	155	98–605	230
TKN (mg N/l)	25–38	30	31–67	43
N-NH_x (mg N/l)	10–16	14	9–46	19
Phosphate (mg PO_4^{3-}/l)	18–47	25	33–71	44
Sulphate (mg SO_4^{2-}/l)	99–184	155	167–230	200
Sulphide (mg S^{2-}/l)		Not detectable		

RESULTS AND DISCUSSION

To evaluate the general behaviour of the anaerobic fluidized bed reactor for treating a low-strength wastewater, such as raw municipal sewage at low temperature, three different experiments were carried out.

Performance at decreasing temperatures

This experiment was carried out with AFBR-1 and AFBR-2 which had previously been working for a period of 20 months at room temperature (20°C) achieving T_{COD} and T_{BOD_5} removals of 75 and 80%, respectively, when $\bar{t} = 2.7$ h and $B_{V,T_{COD}} = 2.5$–3.5 g/l.d with effluent $T_{COD} = 110$ mg/l, $T_{BOD_5} = 50$ mg/l and TSS = 20 mg/l.

Raw domestic sewage from Sewer-1 (Table 2) was used as influent. The goal of this experiment was to evaluate the effect of a gradual temperature decrease on process efficiency. The operating conditions of the last room temperature period were kept constant while the temperature was decreased step-by-step from 20 to 5°C.

Figures 3 and 4 show the evolution of T_{COD}, organic loading rates ($B_{V,T_{COD}}$), T_{COD} removal, gradual temperature decrease and mean hydraulic retention time ($\bar{t}$) for AFBR-1 and AFBR-2, respectively.

On day 68, the reactors were fed with an unusually high strength influent ($T_{COD} = 900$ mg/l) which provided a $B_{V,T_{COD}} = 9.0$ g/l.d. The effluent T_{COD} increased to 180 mg/l for AFBR-1 and 215 mg/l for AFBR-2. However, the reactors recovered quickly after the overloading.

Sudden and short temperature decreases had no significant impact on the performance of the reactors. They returned quickly to their habitual performance level.

When the reactors were operated at room temperature (20°C), a small amount of accumulated solids in

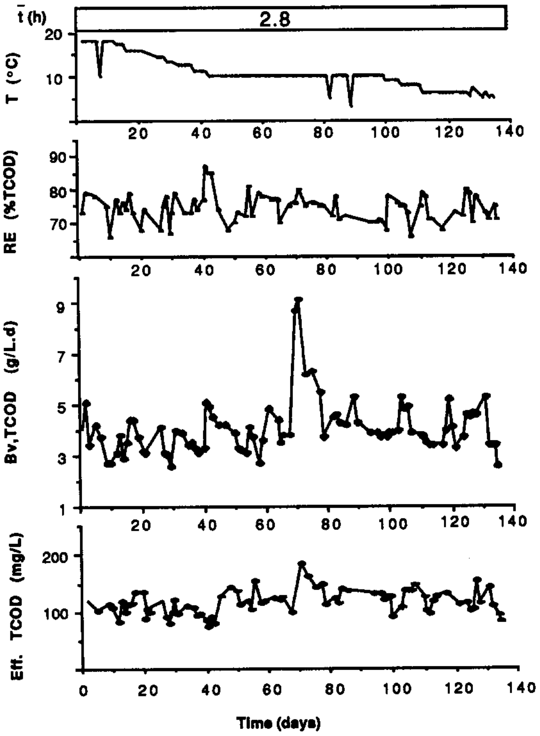

Fig. 3. Performance at decreasing temperatures, AFBR-1.

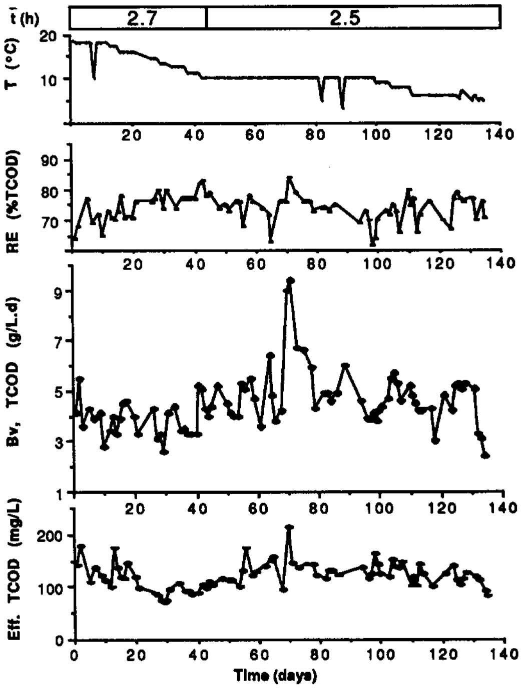

Fig. 4. Performance at decreasing temperatures, AFBR-2.

Table 3. Performance at decreasing temperatures. Operation conditions, influent and effluent characteristics (days 43–135)

	Influent		AFBR-1		AFBR-2	
	Range	Average	Range	Average	Range	Average
T (°C)	—	—	3.0–10.0	—	3.0–10.0	—
$\bar{t}$ (h)	—	—	2.4–3.3	2.8	2.0–2.9	2.6
$B_{V,T_{COD}}$ (g/l.d)	—	—	3.3–9.1	4.4	3.0–9.4	4.9
S_{COD} (mg/l)	130–355	260	—	—	—	—
T_{COD} (mg/l)	150–590	475	90–148	125	82–157	129
T_{BOD_5} (mg/l)	215–390	325	49–77	55	45–78	58
pH	6.9–8.2	7.7	7.6–7.9	7.7	7.4–7.9	7.6
Alk. (mg $CaCo_3$/l)	130–325	200	279–316	394	234–302	257
TSS (mg/l)	118–245	190	15–32	23	17-33	24
VSS (mg/l)	110–185	155	14–26	19	15–26	20
TKN (mg N/l)	25–38	30	25–30	29	25–31	29
NH_3-N (mg N/l)	10–16	14	18–29	25	18–26	24
Phosphate (mg PO_4^{3-}/l)	18–47	25	15–36	27	17–35	26
Sulphate (mg SO_4^{2-}/l)	99–184	155	45–137	89	50–138	95
Sulphide (mg S^{2-}/l)	Not detectable		Not detectable		Not detectable	
T_{COD} removal (%)	—	—	66–80	76	62–84	75
T_{BOD_5} removal (%)	—	—	71–86	85	82–88	84

the top of the fluidized bed was observed. These solids could be either non-attached biomass or suspended solids from the influent trapped in the reactor. During the period of operation at lower temperature (10°C), the accumulated solids increased considerably. Samples taken for analyses showed levels of TS = 30 g/l and VS = 15 g/l of compacted solids.

Table 3 summarizes the operating conditions, and some influent and effluent characteristics during the period 43–135 days, when the temperature was 10°C and lower.

Effluent T_{COD} as well as T_{BOD_5} had a tendency to increase when temperature decreased, but recovered gradually to previous concentrations after several days. With a hydraulic retention time of 2.7 h ($B_{V,T_{COD}} = 4.5$ g/l.d), a T_{COD} removal greater than 75% was achieved. The effluent TSS were quite stable and usually lower than 20 mg/l.

TKN and NH_3-N were periodically evaluated. The percentage of ammonia nitrogen (NH_3-N) was 53% in the influent and greater than 85% in the effluent, which shows that about 70% of Org-N turns into NH_3-N in the reactors. The effluent TKN concentration was slightly lower than that of the influent (3%) due to the nitrogen requirements of the microorganisms and physical removal of particulate Org-N.

Sulphide was not found in the effluent. A consistent relationship between influent and effluent sulphate concentrations was not found. On the other hand, small white granules containing a high percentage of sulphur (78%) were observed in the recirculation tank and in the effluent. A similar phenomenon was documented previously by Coulter *et al.* (1957) and Brown (1985), who concluded that the sulphate reduction by sulphate reducing bacteria has sulphur as the endproduct, since insufficient organic materials are available to reduce sulphate to sulphide. However, *Thiothrix* bacteria were found in the effluent. These microorganisms are able to use sulphide as an energy source and transform it into sulphur, which is deposited as sulphur granules in their cells. This indicates that part of the sulphates were reduced to sulphides, which may be used for the *Thiothrix* bacteria and converted into sulphur. Unfortunately there are not enough data to establish whether or not the sulphates were reduced to sulphides and subsequently reoxidized to elemental sulphur. Further research is needed.

After 93 days of operation at 10°C and lower, the attached biomass was 22 g VS/l for AFBR-1 and 25 g VS/l for AFBR-2.

Performance at 10°C

The goals of this experiment were to study the restart of anaerobic fluidized bed reactors at low temperatures (10°C) after a shut-down of 2.5 months, and to evaluate their performance during a long operating period (235 days) at low temperatures (10°C). This was carried out with AFBR-1 and AFBR-2 when the experiment at decreasing temperatures was concluded.

Raw domestic sewage from Sewer-1 was used during the restart; but since day 98, wastewater from Sewer-2 was used. This change allowed operation with higher loading rates and higher fluctuations in T_{COD}, T_{BOD_5} and TSS.

Figures 5 and 6 show the evolution of effluent T_{COD}, $B_{V,T_{COD}}$, T_{COD} removal and mean hydraulic retention time, for AFBR-1 and AFBR-2, respectively.

The initial $\bar{t}$ was 13.7 h for AFBR-1 and 10.1 h for AFBR-2. After 4-days, effluent T_{COD} was lower than 100 mg/l. Thereafter, hydraulic retention time was gradually decreased. After 20-days, the reactors were operating at conditions similar to those before the shut-down.

Table 4 summarizes the operation conditions and some influent and effluent characteristics when the reactors were operating at $\bar{t} = 1.5$ h with high $B_{V,T_{COD}}$ fluctuations, $B_{V,T_{COD}} = 6.0–35.5$ g/l.d. (days 60–235).

In spite of the organic loading rates applied (mean $B_{V,T_{COD}} = 8.9$ g/l.d for AFBR-1 and 10.4 for AFBR-2), and the great fluctuations in influent characteristics, the reactors performed in a very stable manner.

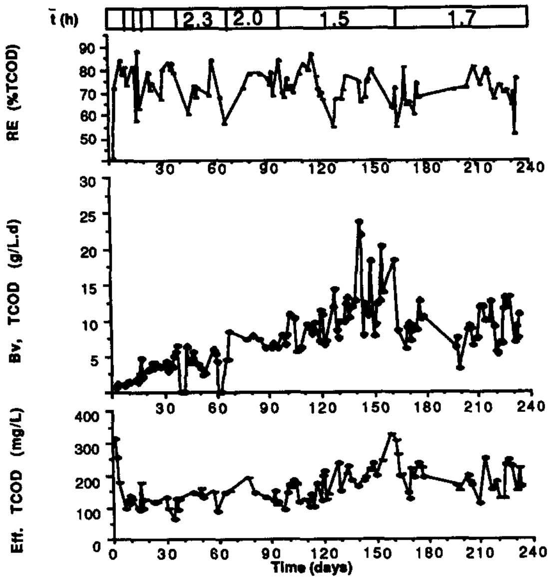

Fig. 5. Performance at 10°C, AFBR-1.

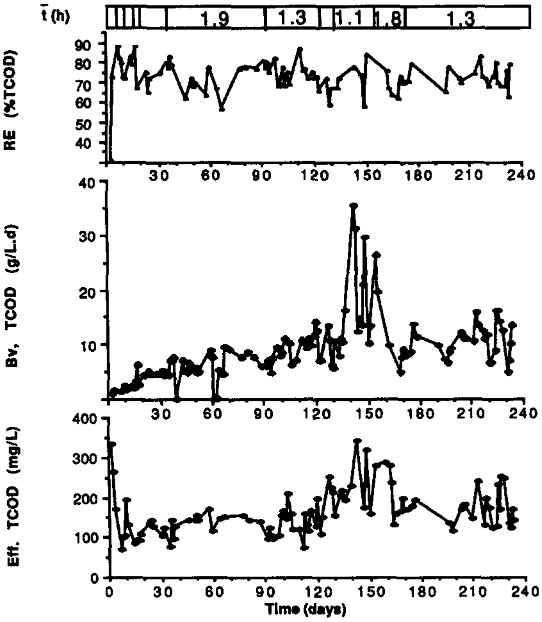

Fig. 6. Performance at 10°C, AFBR-2.

T_{COD} removal was usually higher than 70% and T_{BOD_5} removal about 80%, which shows the high efficiency of the anaerobic fluidized bed reactors treating low strength wastes at low temperatures. However, because the effluent quality is not sufficient for direct discharge, some kind of post-treatment must follow the anaerobic process.

TKN, Org-N and NH_3-N were analysed periodically. About 80% of the effluent TKN is NH_3-N, which shows that 70% of the influent Org-N is converted into NH_3-N in anaerobic conditions.

As in the experiment at decreasing temperatures, sulphide was never detected in the effluent, and white granules with a high percentage of sulphur (>70%) were present in the effluent.

After 230 days of operation the attached biomass was 31 g VS/l in AFBR-1 and 37 g VS/l in AFBR-2.

Comparative start-up

The start-up of anaerobic fluidized bed reactors is a very pivotal period in their operation. The challenge is to develop a well attached biolayer on the carrier. The usual procedure is to use anaerobic sludge from an operating anaerobic reactor as inoculum. This is quite expensive and generally the microorganisms need time to adapt to a new substrate and possibly to a new temperature. Inoculation is an obligatory step when the wastewater, such as some industrial wastes, lacks microorganisms. However, this is not a problem in domestic sewage. There is documentation of almost unseeded reactors having been started (Schellinkhout *et al.*, 1985).

AFBR-3 and AFBR-4 (Fig. 2, Table 1) were used to compare the start-up with and without seed. Anaerobic sludge from a UASB reactor which treats sugar beet wastewater (T_{COD} = 4000 mg/l) at 35°C was used as seed.

The reactors were filled with 0.8 l. of Arlita® and settled domestic sewage. AFBR-3 was seeded with 50 ml of anaerobic sludge (TS = 142 g/l, VS = 36 g/l).

Table 4. Performance at 10°C. Operation conditions, influent and effluent characteristics (days 60–235)

	Influent		AFBR-1		AFBR-2	
	Range	Average	Range	Average	Range	Average
T (°C)	—	—	9.5–10.5	10.0	9.5–10.5	10.0
$\bar{t}$ (h)	—	—	1.3–2.0	1.7	1.0–1.5	1.3
$B_{V,T_{COD}}$ (g/l.d)	—	—	6.0–23.7	8.9	6.9–35.5	10.4
S_{COD} (mg/l)	197–648	390	—	—	—	—
T_{COD} (mg/l)	295–1560	760	140–270	173	115–280	175
T_{BOD_5} (mg/l)	305–630	480	79–134	88	71–137	83
pH	7.2–8.0	7.5	6.3–8.2	7.3	6.9–8.1	7.4
Alk. (mg $CaCO_3$/l)	230–360	265	335–559	430	339–539	419
TSS (mg/l)	104–761	285	19–48	36	20–43	35
VSS (mg/l)	98–605	230	12–40	28	10–38	27
TKN (mg N/l)	31–67	43	26–58	37	26–56	37
NH_3-N (mg N/l)	9–46	19	22–50	30	22–44	30
Phosphate (mg PO_4^{3-}/l)	33–71	44	31–69	43	28–70	42
Sulphate (mg SO_4^{2-}/l)	167–230	200	143–213	177	83–194	160
Sulphide (mg S^{2-}/l)	Not detectable		Not detectable		Not detectable	
T_{COD} removal (%)	—	—	60–75	70	65–78	72
T_{BOD_5} removal (%)	—	—	74–84	80	72–85	80

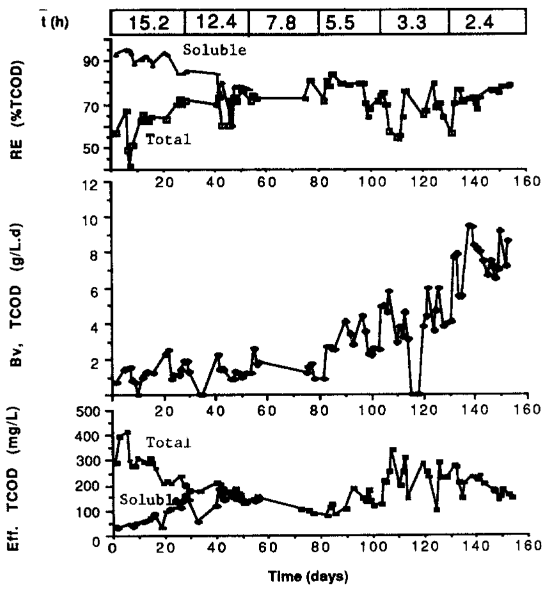

Fig. 7. Comparative start-up. Seeded reactor (AFBR-3).

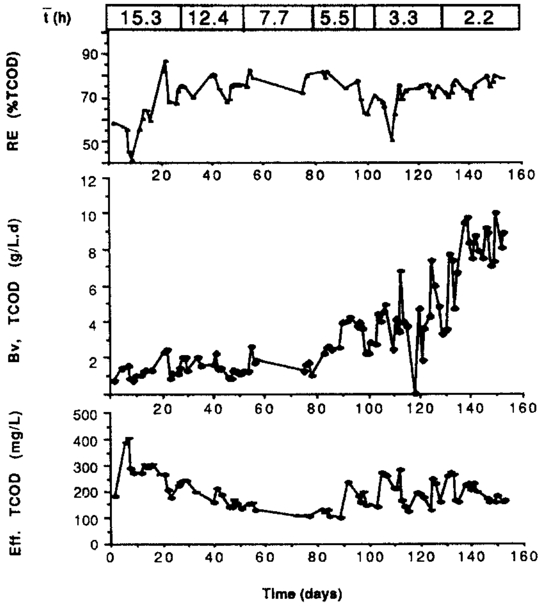

Fig. 8. Comparative start-up. Unseeded reactor (AFBR-4).

No seed was added to AFBR-4. Both reactors were maintained for 1 week in recirculating conditions before the pumping of raw domestic sewage from Sewer-2 was initiated. The temperature was controlled at 15°C.

Figures 7 and 8 show the evolution of effluent T_{COD}, $B_{V,T_{COD}}$, T_{COD} removals and the mean hydraulic retention time for the seeded (AFBR-3) and unseeded (AFBR-4) reactors. In Fig. 7 the effluent soluble COD and soluble COD removal are represented for the first 56-day period. From day 56, T_{COD} and S_{COD} values differed less than 5% and only T_{COD} is represented.

The initial $\bar{t}$ for both reactors was 15 h. At the beginning, the effluent of the seeded reactor had a large amount of black suspended solids (TSS = 410 mg/l) mainly sludge that had not been retained in the reactor and was responsible for the high values of T_{COD}. However the soluble COD was very low (50 mg/l). In the unseeded reactor, the effluent T_{COD} was very high, 375 mg/l, slightly lower than the soluble influent COD. However, a TSS removal of 90%, and effluent TSS lower than 25 mg/l, were usually achieved.

As shown in Figs 7 and 8 ($B_{V,T_{COD}} = 2.0$ g/l.d), about 70 days were required until both effluents reached similar characteristics, T_{COD} about 125 mg/l and TSS about 40 mg/l.

Table 5 summarizes the operating conditions and some of the influent and effluent characteristics during the period 135–153 days. Five months after the different start-up, both reactors were operating under similar conditions ($\bar{t} = 2.4$ h for AFBR-3 and $\bar{t} = 2.2$ h for AFBR-4) $B_{V,T_{COD}}$ ranged from 5.5 to 10.0 g/l.d, achieving T_{COD} removal higher than 75%. The effluent quality was slightly better in the unseeded reactor, effluent $T_{COD} = 178$ mg/l, TSS = 46 mg/l for AFBR-3 and effluent $T_{COD} = 170$ mg/l and TSS = 43 mg/l for AFBR-4.

Both reactors were equipped with a combined gas collector–settler device (Fig. 2) and a gas meter. For the last period of operation, $\bar{t} = 2.2$–2.4 h and $B_{V,T_{COD}} = 7.7$–8.3 g/l.d, the gas production rate observed was 1.0–1.5 l. of total gas/d. Biogas analysis showed a methane content always higher than 60%, with an average value of 80%, while the rest was made up of nitrogen (13%) and carbon dioxide (7%).

Table 5. Comperative start-up. Operation conditions, influent and effluent characteristics (days 132–153)

	Influent		AFBR-3 (seeded)		AFBR-4 (unseeded)	
	Range	Average	Range	Average	Range	Average
T (°C)	—	—	14.5–16.0	15.0	14.5–16.0	15.0
$\bar{t}$ (h)	—	—	2.2–3.2	2.4	2.1–2.4	2.2
$B_{V,T_{COD}}$ (g/l.d)	—	—	5.5–9.2	7.7	6.7–10.0	8.3
S_{COD} (mg/l)	197–648	390	—	—	—	—
T_{COD} (mg/l)	295–1560	760	143–237	178	158–230	170
T_{BOD_5} (mg/l)	305–630	480	63–93	77	64–71	70
pH	7.2–8.0	7.5	7.3–7.8	7.5	7.2–7.5	7.4
Alk. (mg $CaCO_3$/l)	230–360	265	395–510	430	395–495	425
TSS (mg/l)	104–761	285	37–52	46	32–55	43
VSS (mg/l)	98–605	230	30–47	38	29–49	33
T_{COD} removal (%)	—	—	71–80	75	73–80	76
T_{BOD_5} removal (%)	—	—	77–86	82	82-86	84

It would be reasonable to assume that the nitrogen gas initially dissolved in the influent was stripped from the liquid phase by methane gas in the anaerobic reactor (Lettinga *et al.*, 1985). Since the anaerobic treatment process for municipal sewage requires operation at high hydraulic loadings, a substantial part of the methane gas leaves the reactor in the dissolved phase. It has been reported that the methane collected represents only 10–30% of the entire methane produced (Yoda *et al.*, 1985). In this study 40–60% of the maximum possible methane produced was collected.

CONCLUSIONS

A gradual temperature decrease from 20 to 5°C, allowing the microorganisms to acclimate to the new lower temperature, had little effect on effluent quality. Though effluent T_{COD} and T_{BOD_5} had a tendency to increase when temperature was decreased, they recovered their previous concentrations after several days. At 10°C, $\bar{t} = 2.8$ h and $B_{V,T_{COD}} = 2.4$–3.3 g/l.d, a T_{COD} removal higher than 75%, T_{BOD_5} removal = 85%, effluent $T_{COD} = 125$ mg/l and TSS < 25 mg/l was achieved. However, at temperatures of 10°C or lower there was a large accumulation of suspended solids from the influent on the top of the fluidized bed.

The restarting at 10°C after a 2.5 month shut-down was very quick, achieving an effluent T_{COD} lower than 100 mg/l in 4 days. In spite of the high organic loading rates applied, $B_{V,T_{COD}} = 6.9$–35.5 g/l.d ($\bar{t} = 1.5$ h), and great fluctuations in the influent characteristics, the reactors operated very stably with T_{COD} removal > 70% and T_{BOD_5} removal = 80%.

With municipal sewage as the influent, it is possible to start-up anaerobic fluidized bed reactors without inoculum at 15°C. However, it requires at least 4 months to get good quality effluent.

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