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DEVELOPMENT OF ANAEROBIC MIGRATING BLANKET REACTOR (AMBR), A NOVEL ANAEROBIC TREATMENT SYSTEM

LARGUS T. ANGENENT* and SHIHWU SUNG

Department of Civil and Construction Engineering, Iowa State University, USA

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Abstract—A novel anaerobic treatment system, the anaerobic migrating blanket reactor (AMBR), was developed after completing a parallel study with upflow anaerobic sludge blanket (UASB) and anaerobic sequencing batch reactor (ASBR) processes. Using sucrose as the main component of a synthetic wastewater, the AMBR achieved a maximum chemical oxygen demand (COD) loading rate of 30 g.l^{-1}.day^{-1} at a 12-h hydraulic retention time (HRT). This resulted in a standard methane production rate (SMPR) of 6.5 l.l^{-1}.day^{-1} and an average methane-based COD (MCOD) removal efficiency of 62.2%. A key element in granular biomass formation was migration of the biomass blanket through the reactor. Although a carbohydrate-rich wastewater was used, no separate pre-acidification was required for the AMBR, because of high mixing intensities and wash out of acidogenic bacteria. In contrast, the absence of pre-acidification created "bulking" problems (caused by abundant acidogenic bacteria at the surface of granules) in a UASB reactor, operated under conditions similar to that of the AMBR. As a result, a maximum COD loading rate and SMPR of 21 g.l^{-1}.day^{-1} and 4.9 l.l^{-1}.day^{-1} were achieved, respectively, for the UASB reactor at a 12-h HRT. These values were 18 g.l^{-1}.day^{-1} and 3.7 l.l^{-1}.day^{-1}, respectively, for an ASBR at a 12-h HRT. Hence, the performance of the AMBR in treating a carbohydrate-rich wastewater was found to be superior in terms of maximum loading rate and SMPR. © 2001 Elsevier Science Ltd. All rights reserved

Key words—anaerobic, anaerobic migrating blanket reactor, upflow anaerobic sludge blanket reactor, anaerobic sequencing batch reactor, granulation, methanogenesis

INTRODUCTION

The upflow anaerobic sludge blanket (UASB) process and its derivatives have demonstrated excellent performance and stability in numerous full-scale operations worldwide (Lettinga *et al.* , 1980; Lettinga, 1995). These continuously fed processes rely on a feed-distribution system in the bottom of the reactor to evenly distribute substrate and create an upflow hydraulic pattern in the reactor. In addition, a gas–solids-separation system on top of the reactor prevents biomass from leaving with the effluent. The UASB reactor and its derivatives generally develop well-settleable granular biomass and are able to achieve high biomass levels. As a result, these processes can be operated at high organic loading rates (Lettinga, 1995). However, there is still a need for simpler and more economical technologies for wastewater treatment at small- and medium-sized industries (Hulshoff Pol *et al.*, 1997). Moreover, loss of biomass with the effluent due to excessive bed expansion or poor granulation (e.g., during shock-load conditions) needs to be addressed for single-vessel reactors, such as the UASB process (Guiot *et al.*, 1995). For continuously fed systems, this problem has been addressed through the development of compartmentalized reactor configurations.

Compartmentalization in anaerobic reactors was first described by Bachman *et al.* (1982), who developed the anaerobic baffled reactor. In the anaerobic baffled reactor, wastewater flows under and over vertical baffles in a uni-directional manner. The compartmentalized design allowed operation without a gas–solids-separation system, which simplified the process (Bachman *et al.*, 1985), while biomass retention during shock-load conditions was improved (Nachaiyasit and Stuckey, 1997). Recently, van Lier (1996) also developed a compartmentalized reactor, the upflow staged sludge blanket reactor. Instead of using a compartmentalized configuration,

*Author to whom all correspondence should be addressed. Current address: Department of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign, 205 N. Mathews Ave. MC-250, Urbana, IL 61801, USA. Tel.: +1-217-333-8121; fax: +1-217-333-6968; e-mail: angenent@uiuc.edu

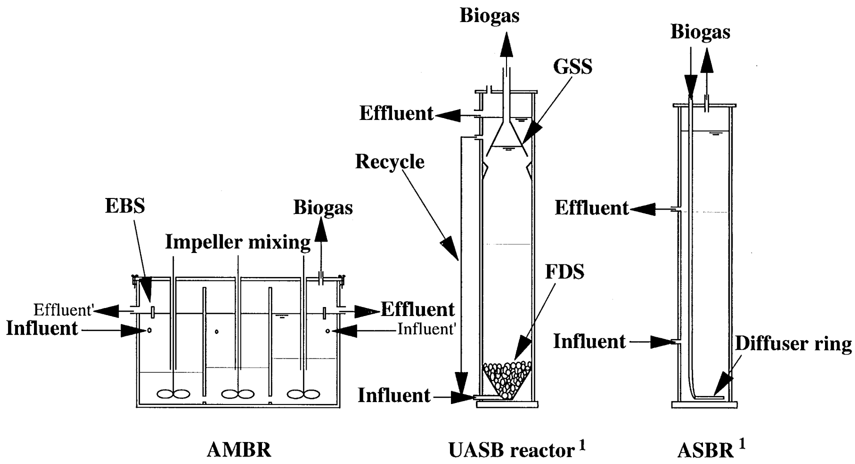

Fig. 1. Schematic diagram of the AMBR, UASB reactor, and ASBR; EBS = effluent-baffle system, GSS = gas–solids separator, FDS = feed-distribution system. Angenent and Dague (1995).

preventing excessive biomass loss in the effluent has also been addressed through the use of single-vessel batch-fed processes.

The anaerobic sequencing batch reactor (ASBR) is a batch-fed process that does not rely on an upflow hydraulic pattern. This design does not require feed-distribution and gas–solids-separation systems (Sung and Dague, 1995), which simplifies its configuration. Despite the absence of an upflow hydraulic pattern, Wirtz and Dague (1996) developed a granular blanket with an ASBR in five months after seeding the reactor with non-granular primary digester sludge. This showed that granulation is not dependent solely on an upflow hydraulic pattern. Vanderhaegen *et al.* (1992) also demonstrated formation of granules in the absence of an upflow hydraulic pattern in batch tests. A disadvantage of the ASBR is the non-continuous operating mode.

After performing a parallel study with UASB and ASBR processes (Angenent and Dague, 1995), problems observed with these two systems were addressed by developing a novel reactor. A detailed description of this novel reactor, the anaerobic migrating blanket reactor (AMBR) is presented in this study. A patent for the AMBR was issued on March 23, 1999 (US Patent No. 5,885,460). The performance of a laboratory-scale AMBR was studied by using a synthetic wastewater containing sucrose as the only substrate. The results were compared with results obtained with UASB and ASBR systems (Angenent and Dague, 1995), which were operated under conditions similar to those for the AMBR.

MATERIALS AND METHODS

AMBR

The AMBR consisted of a rectangular, Plexiglas reactor (inside dimensions: length = 45 cm, height = 25 cm, width = 15 cm) with an active volume of 12 l, which was divided into three compartments, as illustrated in Fig. 1. Round openings, with a diameter of 2.5 cm, were placed 0.5 cm from the bottom and 5 cm from the back side of the two Plexiglas sheets separating the compartments (one opening per sheet). These openings were placed at the bottom to create sufficient contact between biomass and substrate, ensure migration of biomass, and limit short-circuiting of substrate. The headspace of the AMBR was not compartmentalized. Effluent ports (diameter of 2.5 cm) were connected to a gas–liquid-separation tank. After 30 days of operation, baffles were glued in front of the effluent ports. Initially, the final compartment was not mixed. After two months of operation, all three compartments were mixed equally for 10 s every 15 min at 60 rotations min^{-1} to ensure gentle mixing (Mixers: Model 5vb, EMI Inc., Clinton, Connecticut, USA; Impellers: Lightnin A-310 axial flow, Rochester, New York, USA). At a rotational speed of 60/min, these impellers produced a root mean square velocity gradient, G of $22\,s^{-1}$ in a 4-l compartment, as determined by a rotating torque meter (Bex-O-Meter, Model 38, The Bex Company, San Fransisco, California, USA) described in Sajjad and Cleasby (1995). The flow over the horizontal plane of the reactor was reversed three times a day. After feeding the initial compartment for 6 h, the middle compartment was fed for 2 h before the flow was reversed. All pumps were Masterflex pumps of Cole Parmer Instrument Co., Chicago, Illinois, USA. The biogas collection system consisted of an observation bottle, a bottle packed with steel wool to scrub hydrogen sulfide from the biogas, a gas sampling port, and a wet-test gas meter (GCA, Precision Scientific, Chicago, Illinois, USA). Programmable timers (ChronTrol Corporation, San Diego, California, USA) were used to control the reactor operation.

The initial inoculum for the AMBR was collected from the ASBR described by Angenent and Dague (1995). The biomass had been stored at 4°C for 4 months before inoculation. At the start of the operation, the mixed liquor volatile suspended solids (MLVSS) concentration was approximately $6\,g\,l^{-1}$ with a volatile suspended solids (VSS) to total suspended solids (TSS) ratio of 0.84.

Operating conditions

The operating parameters for the AMBR are summarized in Table 1. The AMBR was operated in an incubator at 35 ± 1°C. A concentrated feed solution, containing sucrose, nutrients, trace elements, sodium bicarbonate (0.5 g $NaHCO_3\,g^{-1}$ chemical oxygen demand (COD) of the concentrated feed solution), yeast extract ($1\,mg\,g^{-1}$ COD of the

Table 1. Operating parameters

Operating parameters	units	AMBR	UASB[a]	ASBR[a]
HRT	day	0.5	0.5	0.5
Reactor volume	L	12	12	12
Temperature	°C	35	35	35
pH minimum	units	6.25	6.5	6.5
Upflow velocity	$m\,h^{-1}$	0	0.7–1	0
Recycle-to-feed ratio	day^{-1}	—	10	—
No. of reversals in flow	day^{-1}	3	—	—
Initial COD loading rate	$g.l^{-1}.day^{-1}$	8	6	6
Final COD loading rate	$g.l^{-1}.day^{-1}$	30	21	19
COD concentration at inlet	$g\,l^{-1}$	4–15.5	3–11.5[b]	3–9.5

[a] Angenent and Dague (1995).
[b] COD concentration without diluting by recycling effluent

concentrated feed solution), and tap water, was stored at 4°C to prevent pre-acidification, and was mixed to keep all components in solution. Make-up water (City of Ames tap water), pre-heated to 35 ± 1°C, was added to the concentrated feed solution just before feeding to the reactors. The nutrient stock solution consisted of $290\,ml\,l^{-1}$ 29.4% NH_4OH and $68.75\,g\,l^{-1}$ K_2HPO_4. The amount of nutrient stock solution supplemented was dependent on the COD of the concentrated feed solution ($0.886\,ml\,g^{-1}$ COD). The NH_4OH provided extra alkalinity and buffering capacity. The trace-element stock solution was prepared by adding: 50 g $FeCl_2 \cdot 4H_2O$, 1.25 g $ZnCl_2$, 12.5 g $MnCl_2 \cdot 4H_2O$, 1.25 g $(NH_4)_6Mo_9O_{24}.4H_2O$, 3.75 g $CoCl_2 \cdot 6H_2O$, 2.5 g $NiCl_2 \cdot 6H_2O$, 0.75 g $CuCl_2 \cdot 2H_2O$, and 1.25 g H_3BO_3 to 1 l tap water. This stock solution was added to the feed solution at a rate of 0.089 ml/g COD. The make-up water contributed additional essential nutrients, such as calcium, magnesium, and sulfate.

Analyses

The composition of the biogas was measured using gas chromatography (Model 350 Gow-Mac Instruments Co., Bridgewater, New Jersey, USA) with thermal conductivity detector (Column: 1.7 m × 3 mm stainless steel Poropack Q 80/100 mesh). The total alkalinity, concentration of total volatile fatty acids (VFA), total COD (TCOD) and soluble COD (SCOD), and concentrations of TSS and VSS were determined according to procedures described in *Standard Methods* (APHA, 1985).

Biomass characteristics

The specific methanogenic activity (SMA) of biomass was determined using the "headspace method" described by Rinzema *et al.* (1988). The biomass migration rate was determined by the decline in MLVSS from the initial compartment during the time of feeding (no solids were present in the influent). The sludge loading rate was calculated by dividing the mass of COD fed per day with the total VSS in the reactor. The sludge retention time was determined by dividing the total VSS in the reactor with the daily loss of VSS in the effluent. The sludge retention time can be controlled by periodically wasting biomass from the reactor. The biomass growth yield was obtained by dividing the net biomass production with the soluble COD removed from the system.

To analyze the mean size of granules, the arithmetic mean diameter was calculated with automated image analysis. Biomass samples were mixed and diluted to obtain samples with clearly visible, non-overlapping particles. Next, 1.75 ml of sample was added to a glass cell, which consisted of two 3-mm thick glass sheets cemented together, with a 2.5-cm diameter hole in the top sheet. This cell was covered with a cover slip to avoid air bubbles from entering. The automated image analysis setup contained a black and white video camera (Dage-MTI series 68, Michigan City, Indiana, USA), a microscope (Olympus SZH, Melville, New York, USA), and a PC with Quartz PCI Imaging software. Particles smaller than 0.1 mm were not included in the calculations of the size distribution (Grotenhuis *et al.*, 1991).

Assessment of reactor performance

To obtain information on the reactor performance, COD removal efficiencies were based on COD measurement of the influent and effluent, and methane production. Effluent samples were obtained at the midpoint of the time interval between reversals in flow. Thus, the effluent was sampled after feeding the initial compartment for 4 h. At this point, the effluent quality was assumed to be representative of the overall effluent quality. The COD loading rate was calculated as the mass of COD fed per reactor volume per day ($g.l^{-1}.day^{-1}$). The standard methane production rate (SMPR) was determined as follows. First, the biogas production (measured by gas meter) was corrected to standard temperature and pressure (STP). Second, the biogas production at STP was converted to SMPR by correcting for the wet volume of the reactor and the methane percentage that was present in the biogas. Third, the dissolved methane present in the effluent was estimated using Henry's law (Perry *et al.*, 1997), corrected to STP and the wet volume of the reactor, and added to the SMPR converted from the biogas production. Therefore, the SMPR was expressed as liters of methane per reactor volume per day ($l.l^{-1}.day^{-1}$). Theoretically, 0.35 l methane is produced per g COD utilized at STP (ignoring biomass growth), since 0.35 l of methane reacts with 1 g of oxygen in a complete oxidation, and thus represents 1 g COD. Hence, the methane-based COD (MCOD) removal efficiency was calculated by the methane production using the following formula:

$$\text{MCOD removal,} \quad (\%) = \frac{\text{SMPR}}{\text{COD loading rate} \times 0.35} 100$$

RESULTS AND DISCUSSION

Description of AMBR

The AMBR is a continuously fed, compartmentalized reactor without the requirement of elaborate gas–solids-separation and feed-distribution systems (Fig. 1). Effluent recycling is not necessary, but gentle intermittent mixing is needed to maintain sufficient contact between biomass and substrate due to the absence of an upflow hydraulic pattern. The influent flows horizontally into one end of the reactor and the effluent leaves from the other end. Consequently, the final compartment receives the lowest substrate concentration, and therefore the substrate utilization rate of the microbes in this compartment is low. This results in low biogas production, which enables the final compartment to serve as an internal clarifier preventing biomass loss in the effluent. Due to the flow pattern and the observed biomass migration, biomass accumulates in the final compartment. To prevent excessive accumulation of biomass in this compartment, the flow needs to be reversed periodically. Thus, after reversing the flow, the final compartment becomes the initial compartment and the earlier initial compartment serves as the internal clarifier (final compartment). To prevent a breakthrough of substrate when the flow is reversed, at least three compartments are required in a continuously fed AMBR. The influent is fed for a short period of time into the middle compartment before the flow is reversed.

Granulation

The AMBR was seeded with granules originally obtained from an ASBR (Angenent and Dague, 1995) and stored at 4°C for 4 months. The arithmetic mean diameter of the granules during start up was 0.78 mm and the MLVSS concentration was approximately 6 g l^{-1} throughout the AMBR (VSS to TSS ratio of 0.84). During start up, large granules were lost from the reactor with the effluent due to flotation, resulting in a decrease in the arithmetic mean diameter of the granules. The placement of baffles in front of the effluent ports on day 30 helped to prevent granules from washing out of the AMBR and temporarily reversed the decrease in the arithmetic mean diameter of the granules (Fig. 2). However, flocculent biomass continued to accumulate in the final compartment, which was not mixed for the first 60 days of operation. This resulted in a decrease of the arithmetic mean diameter to 0.4 mm (Fig. 2). On day 60, mixing of the final compartment was initiated, causing most flocculent biomass to be washed out with the effluent and a gradual increase in the arithmetic mean diameter of the granules (Fig. 2), while total biomass levels increased as well (Fig. 3). At the end of the experiment, the arithmetic mean diameter of the granules was 0.74 mm with an MLVSS of 16 g l^{-1}. Hence, after some modifications in design and operation, the AMBR was capable of maintaining and growing a well-settling granular biomass. A key element in maintaining granular

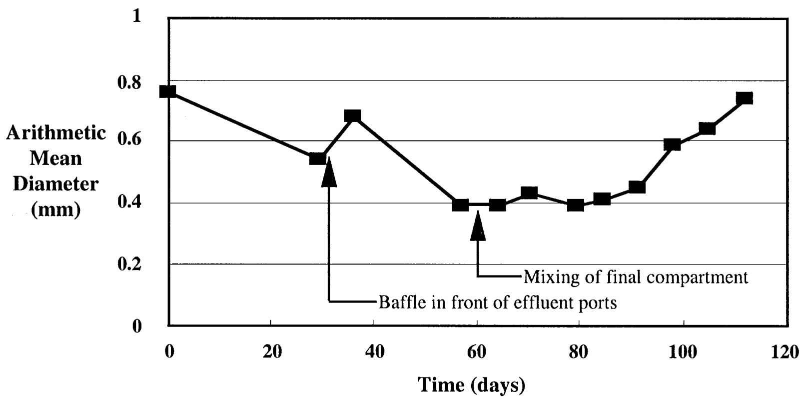

Fig. 2. Arithmetic mean diameter of granules.

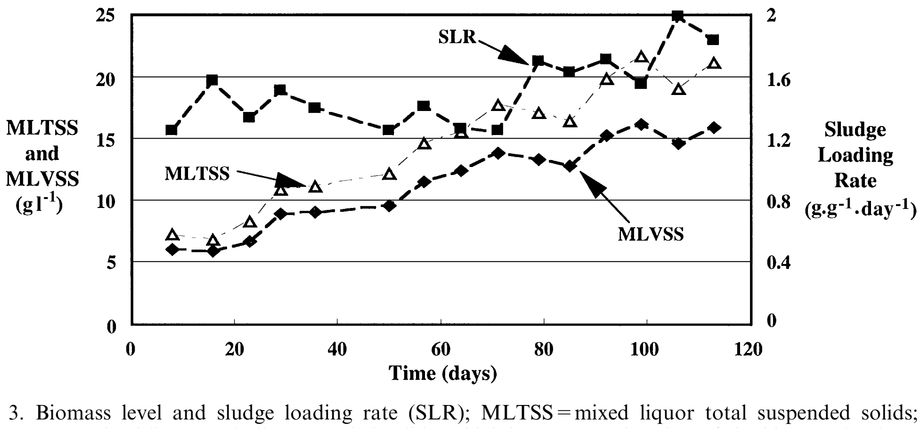

Fig. 3. Biomass level and sludge loading rate (SLR); MLTSS = mixed liquor total suspended solids; MLVSS = mixed liquor volatile suspended solids, which is an approximation of the biomass level.

biomass for the AMBR was the migration of the biomass blanket through the reactor. A higher migration rate of flocculent biomass, relative to the migration rate of granular biomass, was critical for the selection of well-settling biomass, as relatively more flocculent sludge migrated to the final compartment. Selection of well-settling biomass occurred, because of increased wash out of flocculent biomass from the final compartment due to lower settling characteristics of flocculent sludge over granular sludge.

Reactor performance

During this study, the COD loading rate was increased in a stepwise manner by increasing the sucrose concentration in the feed as soon as the effluent total VFA concentration, effluent pH, and MCOD removal were lower than 300 mg l^{-1}, higher than 6.5, and approximately 70%, respectively. After an increase in the COD loading rate, the system was only given a short time to adjust to new conditions (10 hydraulic retention times (HRTs)). Thus, the system was stressed to obtain a maximum COD loading rate in a short period of time. The experiment was ended when the COD loading rate could not be increased further, while satisfying the criteria mentioned above.

The SCOD, TCOD, and MCOD removal efficiencies, and the COD loading rate are shown in Fig. 4. After the reactor modifications discussed above were implemented on day 60, the SCOD removal increased to an average value of 94.9% ($n = 4$; standard deviation (SD) = 1.6) for a COD loading rate between 17 and 25 g.l^{-1}.day^{-1}. Meanwhile, the MCOD and TCOD removal fluctuated around 70 and 80%, respectively. Since the COD used for biomass growth does not end up as methane, the fraction of COD utilized for biomass synthesis is not included in the MCOD removal. Whenever biomass accumulation in a system is small, the difference between MCOD and TCOD removal becomes small. The MCOD and TCOD removals were not anticipated to become very close, because the SMPR and MCOD removals were lowered due to COD removal by sulfate-reducing bacteria. Meanwhile, a majority of produced sulfide was anticipated to be stripped out from the reactor due to biogas production and low pH levels of 6.6 ($n = 109$; SD = 0.18) in the initial compartment, and hence would not add COD to the effluent (and not lower TCOD removal). On the other hand, dissolved methane in the effluent (on average 0.28 l day^{-1} ($n = 109$; SD = 0.02)) added COD to the effluent, and hence lowered the TCOD removal, while dissolved methane was included in the MCOD removal. Between days 60 and 105, surplus biomass was washed out with the effluent and accumulation of biomass in the reactor was minimal. Hence, the MCOD and TCOD removals were relatively close (Fig. 4), because surplus biomass wash out with the effluent is also not included in the TCOD removal. For full-scale operation of the AMBR, however, surplus biomass is anticipated to be wasted from the reactor periodically, to decrease the effluent solids concentration. Biomass levels (MLVSS) in the reactor increased during the entire run, but the MLVSS did not exceed 16 g l^{-1} (Fig. 3) due to a high biomass migration rate and subsequent wash out of biomass. Consequently, the AMBR was operated at a sludge loading rate exceeding 1.5 g COD.g^{-1} VSS.day^{-1} between days 75 and 105.

When the COD loading rate was increased to 30 g.l^{-1}.day^{-1} on day 105, the SCOD removal decreased to approximately 87% on day 112 (Fig. 4). At this COD loading rate, the average 5-day MCOD removal (average removal of five adjacent days) was 62.2% ($n = 5$; SD = 3.7) and the average 5-day SMPR was 6.5 l.l^{-1}.day^{-1} ($n = 5$; SD = 0.4). Figure 5 shows the total VFA concentration in the effluent, which was approximately 600 mg l^{-1} as acetic acid. Hence, according to criteria mentioned above, the COD loading could not be increased any further without instigating unstable performances. The loading rate increase at day 105 had increased the sludge loading rate to approximately 2 g COD.g^{-1} VSS.day^{-1} (Fig. 3), which resulted in an SMA of 2.1 g COD.g^{-1}

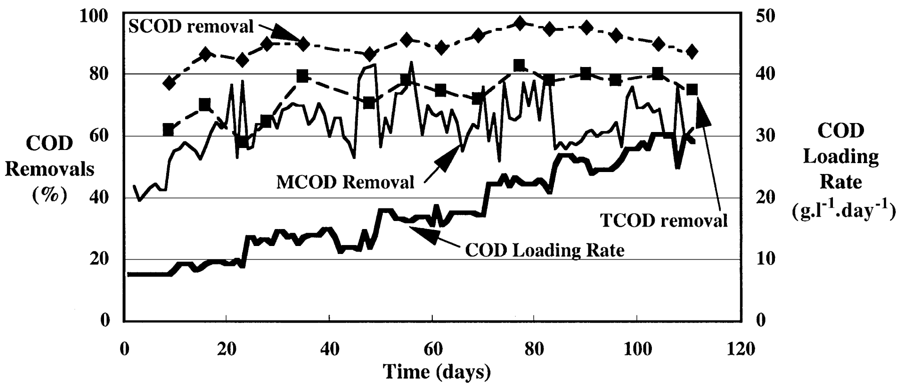

Fig. 4. Total COD (TCOD), soluble COD (SCOD), and methane-based (MCOD) removal efficiencies and COD loading rate.

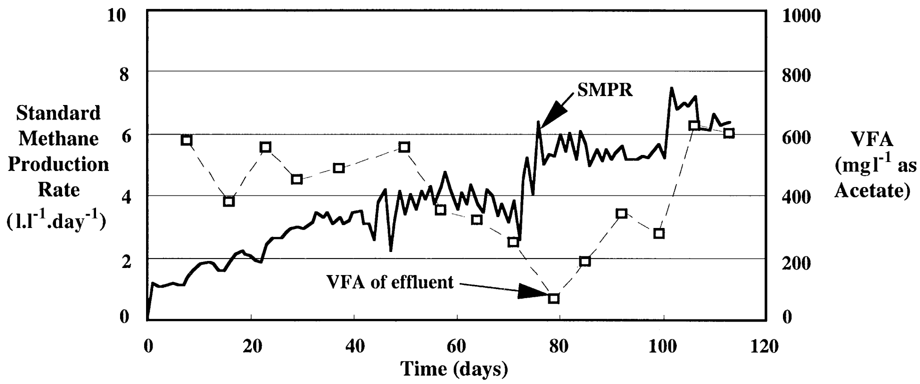

Fig. 5. Effluent total volatile fatty acids (VFA) concentration and standard methane production rate (SMPR).

VSS.day^{-1} at the end of the operational period. As non-acidified sucrose substrate was fed to the system, we believe that the SMA had reached a maximum and that without more biomass build up in the system the loading rate could not be increased further. Sludge loading rates for the biomass in the initial compartment during feeding were on average three times higher than the overall sludge loading rates for all three compartments.

Unique operational features of AMBR

Previous research indicated that acidogenic conditions in a first phase negatively impacted granular growth in the methanogenic reactor conditions of a two-phase treatment system (Vanderhaegen *et al.*, 1992). Hence, we developed the AMBR to accomplish partial phase separation (staging), rather than total phase separation (phasing) of acidogenesis and methanogenesis. In staged processes all steps of the anaerobic food chain are present (but acidogenic activities are higher in the initial compartments), while in phased processes a complete separation of hydrolysis/acidogenesis and acetogensis/methanogenis is desired. Advantages of staged processes were postulated by Fox and Pohland (1994) and Lettinga (1995). Total phase separation in the AMBR process was prevented by regularly reversing the flow over the horizontal plane of the reactor. Thus, reversing the flow provided another advantage in addition to preventing accumulation of biomass in the final compartments. Reversing the flow kept the pH above 6.2 and maintained methanogenesis in the initial compartments, without recycling of effluent or addition of large amounts of buffer. Ideal conditions for methanogens were created in the final compartments and less settleable acidogens were washed out of the system.

Because of high migration of granular biomass (the biomass migration rate for the initial compartment was 30 g VSS.l^{-1}.day^{-1} at the end of the operational period), the flow was reversed three times a day. Due to migration of granules and reversing the flow, the methanogenic activity of the biomass was very similar in the three compartments; the average SMA for the three compartments was 2.07 g COD.g^{-1} VSS.day^{-1} ($n=3$; SD = 0.12). Nevertheless, the SCOD and VFA concentrations were quite different in the three compartments at the midpoint in time between reversals in flow, indicating that staging had been accomplished (Fig. 6). Moreover, average pH levels in the initial, middle, and final compartments at the midpoint between reversals in flow were 6.62 ($n=109$; SD = 0.18), 6.92 ($n=109$; SD = 0.15), and 7.03 ($n=109$; SD = 0.18), which also indicates staged reactor conditions. Reversing the flow three times per day also helped accomplish the higher removal efficiencies at COD loading rates exceeding 25 g.l^{-1}.day^{-1} for the AMBR compared with the anaerobic baffled reactor. Bachman *et al.* (1985) found an SMPR of approximately 6 l.l^{-1}.day^{-1} at a COD loading rate of 36 g.l^{-1}.day^{-1} for an anaerobic baffled reactor treating sucrose, while the AMBR achieved a higher SMPR of 6.5 l.l^{-1}.day^{-1} at a lower COD loading rate of 30 g.l^{-1}.day^{-1}.

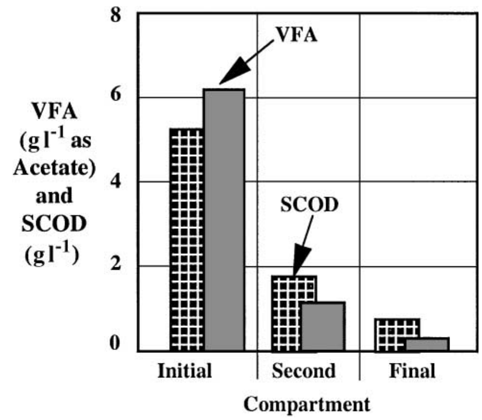

Fig. 6. Volatile fatty acids (VFA) and soluble COD (SCOD) concentration per compartment at a COD loading rate of 30 g.l^{-1}.day^{-1}; samples taken at the midpoint in time between reversals of flow.

The length of one cycle or the time the AMBR needs to be operated with its flow in one direction can be determined by evaluating either the hydraulic loading rate or the COD loading rate. If the hydraulic loading rate is controlling the cycle length (e.g., at a low HRT for low-strength wastewater), the biomass level in the initial compartment should be the regulating factor in determining cycle length. At higher COD loading rates, the pH and the VFA concentration in the initial compartment should be the regulating factor, since VFA production takes place mainly in the initial compartment and accumulation of VFA over time decreases the pH. This indicates that the easy-to-measure biomass level or pH in the initial compartment could be used to determine the cycle length necessary to obtain optimal operating conditions.

Migration of biomass in the AMBR needs to be limited to constrain the frequency of reversing the flow, especially at high hydraulic or COD loading rates. A high COD loading rate increased turbulence due to biogas production in the initial compartments, and subsequently increased the biomass migration rate. Increasing the size of openings in the bottom of inside walls or placement of baffles between compartments reduced the biomass migration rate (Angenent and Dague, 1996). Openings in the bottom of the walls between compartments could be used for systems designed with a long HRT. At short HRTs, baffles should be used to reduce migration of biomass and short-circuiting of substrate. However, the biomass migration rate for the AMBR should be sufficiently high to generate wash out flocculent biomass and select for a granular biomass.

Comparison with UASB and ASBR processes

The AMBR was developed and its operation was evaluated after a parallel study was completed with UASB and ASBR processes (Angenent and Dague, 1995). The operational parameters, such as HRT, active volume, temperature, and influent characteristics, were chosen for the AMBR to be identical to those of the UASB and ASBR systems to make a comparison possible. The three systems were anticipated to have different biomass concentrations governed by individual reactor configurations (Fig. 1). Hence, biomass levels were not controlled. Indeed, at the end of the operational periods, biomass levels for the AMBR, UASB, and ASBR systems were 15, 12, and 30 g VSS l^{-1}, respectively. Biomass levels for the ASBR were high and after 55 days of operation the top of the sludge blanket had reached the effluent decant port. Meanwhile, biomass levels were relatively low for the UASB reactor due to an upflow pattern and a resulting fluidized character of a low-density granular blanket. In fact, the fluidized granular blanket reached the gas–solids-separation system and surplus biomass needed to be wasted by opening a valve from the UASB reactor to prevent clogging (Angenent and Dague, 1995).

Table 2 summarizes operational information and performance data for the three systems for a COD loading rate of approximately 20 g.l^{-1}.day^{-1}. The SCOD removal for the UASB reactor was 98%, the SMPR was 4.8 l.l^{-1}.day^{-1}, MCOD removal was 70.9%, and the VFA concentration in the effluent was 120 mg l^{-1} as acetic acid (Table 2). Low VFA levels indicated a stable reactor performance, and thus the opportunity to increase the COD loading rate. However, persisting "fluffy" granular biomass and biogas production caused "bulking" problems (rising of the entire blanket as clumps of granular biomass), which prevented an increase in the loading rate. The fluffy granular biomass was defined as granules with a low density, hairy surface structure due to the accumulation of filamentous microorganisms (Alphenaar, 1994).

During this period, the arithmetic mean diameter of the granules in the UASB reactor was 2.9 mm and more than three times as large as for the granules in the AMBR and ASBR systems, which achieved arithmetic mean diameters of 0.7 and 0.8 mm, respectively. The ash content of the mixed liquor

Table 2. Performance data for the AMBR, UASB reactor, and ASBR at a COD loading rate of approximately 20 g.l^{-1}.day^{-1}; data with the standard deviations in parentheses are 5-day averages. For data comparison between systems, TCOD removal cannot be used, because surplus biomass left the AMBR and ASBR in the effluent, while surplus biomass was removed from UASB reactor

Parameters of performance	units	AMBR	UASB[a]	ASBR[a]
COD loading rate	g.l^{-1}.day^{-1}	22.6 (3.6)	19.5 (0.7)	18.6 (0.5)
Time after start	days	78	63	63
Av. daily loading increase	g COD.l^{-1}.day^{-1}	0.19	0.19	0.18
Effluent VFA (as acetic acid)	mg l^{-1}	190	120	360
SCOD removal	%	97	98	94
TCOD removal	%	82	96	80
Average MCOD removal	%	69.0 (5.6)	70.9 (4.3)	57.1 (3.7)
Average SMPR	l CH_4.l^{-1}.day^{-1}	5.4 (0.4)	4.8 (0.1)	3.7 (0.2)
MLVSS	g l^{-1}	14	12	30
Effluent VSS	g day^{-1}	35.3	4.3	34.7
Sludge retention time	day	5	NA	10
Sludge loading rate	g COD.g^{-1} VSS day^{-1}	1.6	1.6	0.4
Growth yield	g VSS g^{-1} COD removed	0.16	NA	0.16

[a] Angenent and Dague (1995) .

from the AMBR varied between 15 and 25% and increased slightly over the operational period (the differnce between MLTSS and MLVSS increased slightly over time, Fig. 3), while the particulate matter in the effluent consisted of 15% ash at a constant level. No large difference in these values between the reactor systems was found. However, granules in the AMBR and ASBR systems were denser than granules in the UASB reactor and freezing of the mixed liquor content destroyed the structure of granules from the UASB reactor completely, while granules from AMBR and ASBR systems remained intact. This indicated that granules from the latter systems were stronger than from the UASB reactor. Another possible indication of a less dense granular structure in the UASB reactor was the gray color of the granules, indicating the presence of a higher level of acidogens at the surface of the granules (Daffonchio *et al.*, 1995), while granules in AMBR and ASBR systems were black. The filamentous microorganisms at the surfaces of the UASB granules that caused fluffy biomass are believed to be acidogens since other studies observed similar phenomena and identified the filaments in their studies as acidogens (Guiot *et al.*, 1992; Vanderhaegen *et al.*, 1992). We believe that these differences in granular structure and appearance were a result of exposure of the granules to higher shear stresses in AMBR and ASBR reactors (intermittent mixing) that caused the sloughing off of acidogens. Indeed, increased wash out of the acidogens explains the bigger difference between SCOD and TCOD removal for the AMBR and ASBR systems compared with the difference between SCOD and TCOD removal for the UASB reactor (Table 2). This was observed before surplus biomass was wasted from the UASB reactor, which can also explain a higher acclimation of biomass, and hence lower levels of particulate matter in the UASB reactor effluent (Zilverentant, 1996).

Alphenaar (1994) reported that pre-acidification (acidification before the anaerobic reactor, such as the UASB reactor) of sucrose was necessary to avoid bulking problems due to fluffy granules in UASB reactors operated at high loading rates. The maximum sludge loading rate resulting in stable operation for non-acidified sucrose was 0.5 g COD.g^{-1} VSS.day^{-1}. Not surprisingly, fluffy biomass was found in the UASB reactor, which was operated at a much higher sludge loading rate of 1.6 g COD.g^{-1} VSS.day^{-1}. No bulking problems were observed in the ASBR, which was operated at a lower sludge loading rate of 0.4 g COD.g^{-1} VSS.day^{-1} (Angenent and Dague, 1995). However, no bulking or biomass flotation due to the overabundance of acidogenic bacteria was found in the AMBR, which was operated with a sludge loading rate as high as 1.6g COD.g^{-1} VSS.day^{-1}. This indicates that high-rate anaerobic systems with increased shear, such as the AMBR, are less dependent on a pre-acidification step.

Despite excellent removal efficiencies for the UASB reactor, a maximum COD loading rate of 20 g.l^{-1}.day^{-1} was achieved due to bulking problems. Meanwhile, the COD loading rate for the ASBR was limited to 19 g.l^{-1}.day^{-1} due to insufficient organic removal rates. At the end of the operational time, the SCOD removal for the ASBR was 94%, the SMPR was 3.7 l.l^{-1}.day^{-1}, and the VFA concentration in the effluent was 360 mg l^{-1} as acetic acid (Table 2). Therefore, based on the criteria outlined above, it was concluded that the maximum COD loading rate was achieved for the ASBR. Table 2 shows that MCOD removals were 69.0% for the AMBR, compared with 70.9 and 57.1% for the UASB reactor and ASBR, respectively. The relationships between SMPRs and COD loading rates for the entire operational runs were linear. The slope gives an indication of the methane yields, which were 0.23, 0.25, and 0.18 l CH_4 g^{-1} COD fed for AMBR, UASB, and ASBR systems, respectively (R^2 of 0.90, 0.92, and 0.94, respectively).

CONCLUSIONS

Based on information obtained with laboratory studies with UASB and ASBR systems used to treat a non-acidified carbohydrate substrate, a novel anaerobic treatment system was developed. The AMBR is a compartmentalized system operated by reversing the flow of the wastewater on a regular basis. The final compartments are intermittently mixed and baffles are present in front of the effluent ports. Granules in a laboratory-scale AMBR tended to be darker in color, smaller, and denser than granules in an UASB reactor operated under conditions similar to those in the AMBR. Granules in the UASB reactor were light gray and fluffy due to the presence of filamentous bacteria. Problems related to fluffy biomass, such as bulking and biomass flotation, were noticed in the UASB reactor and were likely the result of operating the UASB reactor at high loading rates with non-acidified sucrose. These problems were not observed in the AMBR, indicating that pre-acidification in a separate treatment system was superfluous.

In terms of stabilization of organic matter, the AMBR was very efficient with SCOD removals of 94.9% for loading rates up to 25 g COD.l^{-1}.day^{-1} at an HRT of 12 h. Furthermore, an SMPR of 6.5 l.l^{-1}.day^{-1} was found at a COD loading rate of 30 g.l^{-1}.day^{-1}. UASB and ASBR processes achieved lower maximum COD loading rates compared with the AMBR. Hence, it was concluded that in terms of maximum COD loading rates and SMPR, the AMBR was superior to the UASB reactor and the ASBR.

If operated semi-continuously, the AMBR system should consist of a minimum of two compartments. However, if plug-flow conditions are desired, three, four or even five compartments should result in more favorable conditions for operation. Detailed design choices will depend heavily on wastewater characteristics, economics, and the need for a flexible operation. Possible advantages of an AMBR with more than three compartments include smaller biomass migration rates, less chance of short-circuiting, and operation in a step feed mode for high-strength wastewater during shock loads. In addition, difficult-to-degrade compounds, such as propionate, would be degraded more efficiently in a system with more compartments, as acetate concentrations and hydrogen levels are anticipated to be lower in the final compartments of a multi-compartment AMBR (in which the headspaces are compartmentalized as well). Hydrogen concentrations in the final compartment are anticipated to be low due to hydrogen stripping from the initial compartment and fast hydrogen utilization in the final compartments (Fox and Pohland, 1994; van Lier, 1996). Furthermore, a multi-compartment AMBR might be ideal for treating sulfate-rich wastewater, as produced hydrogen sulfide is stripped from the initial compartment at lower pH levels, which curtails hydrogen sulfide levels in the final compartments and reduces possible inhibition of methanogenesis.

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