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The effect of organic loading rate on the performance of UASB reactor treating slaughterhouse effluent

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Abstract

Organic loading rate (OLR) is an important parameter significantly affecting microbial ecology and characteristics of UASB systems. In this study, UASB performance was evaluated in a 1000 1 reactor receiving feed from a traditional medium-size slaughterhouse. The initial seed for granules formed earlier was from a mesophilic municipal anaerobic digester sludge with a VSS content of 29 g l^{-1}. The temperature of influent was adjusted by an inline thermostat around 33 °C. The reactor was started with an OLR of 5 kg SCOD m^{-3} d^{-1} with gradual increase to 10 kg SCOD m^{-3} d^{-1} over a 2-week period. Examination of VSS data showed that on the average $89.3 \pm 11.3\%$ of bioparticle mass was present at the lower 30% of the reactor height. Under steady state conditions, experiments were conducted at OLRs of between 13 and 39 kg SCOD m^{-3} d^{-1} and hydraulic retention times (HRT) of 2–7 h. Removal efficiencies in the range of 75–90% were achieved at feed SCOD concentrations of 3000–4500 mg l^{-1}. A reduction in removal efficiency to as low as 67% could have been related to a combined effect of high OLR and low HRT. Up to 300 l of methane were produced per kilogram of SCOD removed at OLR values of less than 30 kg COD m^{-3} d^{-1} but methane production rate seemed to decline to below 200 at higher OLR values. No sign of cell washout was observed at high OLRs and sludge loading rates (SLR) of up to 2.7 kg SCOD kg^{-1} VSS d^{-1}. Elimination capacity of the reactor consistently increased from 9 to 25 kg SCOD m^{-3} d^{-1} corresponding to 1–2 kg SCOD kg^{-1} VSS d^{-1}. Solids retention time (SRT) calculations for the reactor indicated a range of 3.3 days at high upflow velocity of 1 m h^{-1} to 60.3 days at low upflow velocity of 0.33 m h^{-1} s during different phases of the study.

Keywords: Upflow anaerobic sludge blanket; Industrial wastewater; Slaughterhouse; Upflow velocity; Anaerobic treatment

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1. Introduction

The slaughterhouse industry poses a significant environmental impact by discharging effluent to receiving waters containing high concentration of biodegrad-able organic matter. Aerobic processes are not regarded as a suitable treatment option because of high energy requirements for aeration, limitations in liquid-phase oxygen transfer rates, and large quantities of sludge production. Traditional anaerobic processes are also limited by low rates of organic matter removal, long hydraulic retention times (HRT), accumulation of excessive residual organic matter and intermediate products, and large reactor volume requirements. Recent developments in anaerobic treatment processes, especially high retention of biomass in the reactor, has made it possible to decouple solids retention time (SRT) and hydraulic residence time in high-rate anaerobic reactors. This has resulted in increased treatment efficiency of these processes and gradual but steady improvement of the common perception that anaerobic processes are not suitable for treatment of various industrial effluents.

The upflow anaerobic sludge blanket (UASB) process is one of the recently developed high-rate systems. It has been widely adopted for treatment of medium to high-strength industrial wastewaters (Lettinga and Hulshoff Pol, 1991; Fang et al., 1995). Recent research studies indicate feasibility of this process to treat domestic effluents as well (Behling et al., 1997; Singh and Viraraghavan, 2000). The key feature of this system is the microbial aggregation into a symbiotic multilayer structure called a granule. Improved process knowledge and operational details on formation and retainment of stable granules has made high loading possible, resulting in a more sustainable operation of these systems.

A wide range of organic and hydraulic loading rates has been reported in the literature for UASB reactors, depending on the substrate used and the quality and quantity of the microbial community. Syutsubo et al. (1997) reported a COD loading of 30 kg COD m^{-3} d^{-1} with a COD removal efficiency of 85% at sludge loading rates (SLRs) of up to 3.7 g COD g^{-1} VSS d^{-1} for thermophilic reactors (Syutsubo et al., 1998). Organic loading rates (OLR) of up to 104 kg COD m^{-3} d^{-1} have been reported for anaerobic digestion of sugar substrate under thermophilic conditions (Wiegant and Lettinga, 1985). According to Soto et al. (1997), excellent stability and high treatment efficiency was achieved with hydraulic residence times as low as 2 h at an OLR of 6 kg COD m^{-3} d^{-1}, the percent COD removals being 95% (30 °C) and 92% (20 °C).

Slaughterhouse wastewater contains high amounts of organic matter with a soluble fraction in the range of 40–60%. The suspended and colloidal components in the form of fats, proteins, and cellulose can have an adverse impact on the performance of UASB reactors, leading to deterioration of the microbial activity and washout of active biomass (Lettinga et al., 1997; Núñez and Martínez, 1999). This may limit the operation to OLRs of 4–6 kg COD m^{-3} d^{-1} (Lettinga and Hulshoff Pol, 1991). Ruiz et al. (1997) reported sludge floatation and increased effluent solids concentration at OLR values higher than 5 kg COD m^{-3} d^{-1}. Others (Sayed et al., 1988; Sayed and De Zeeuw, 1988) have shown satisfactory treatment of slaughterhouse effluent with OLR values as high as 11 kg COD m^{-3} d^{-1} at a process temperature of 30 °C; Borja and Banks (1994) reported COD removal efficiencies of 64–99% at OLR values of 12–17 kg COD m^{-3} d^{-1}. Higher OLR values of up to 45 kg COD m^{-3} d^{-1} have been reported only for hybrid reactors using a combination of UASB reactor and a bentonite packing as a biomass support (Borja et al., 1995).

In this study, the effect of loading rate on UASB reactor treating slaughterhouse effluent was investigated. This is an important parameter and only limited information is available about the steady-state performance of UASB reactors under high OLRs. Biomass gradient along the height of reactor and methane production rate during different operational conditions were also examined.

2. Materials and methods

2.1. Experimental setup

A 1000 l effective volume square (50 × 50 cm) Plexiglas pilot used in this study is shown in Fig. 1. It was set up downstream of a medium-sized traditional slaughterhouse. A perforated piping system was used at the bottom of the reactor to ensure homogenous distribution of flow into the reactor. Nine sampling ports (20 and 30 cm apart at bottom and top, respectively) were provided to quantify sludge characteristic at different elevations along the reactor. The temperature of influent was adjusted by an inline thermostat prior to reactor entry. No recirculation of effluent was practiced.

2.2. Feed

The wastewater stream from a traditional slaughterhouse used in this study consisted of effluent from a combination of several stages. It included blood from killing operations, wash waters from stomach and intestines, and wastewater from the refrigerated chambers

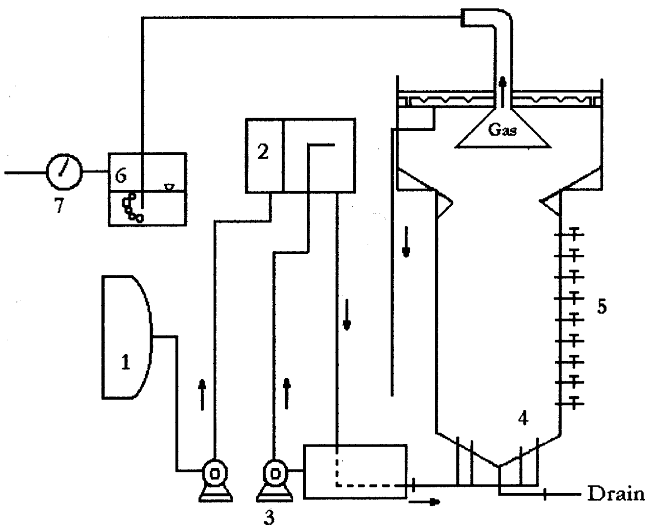

Fig. 1. Schematic diagram of UASB system (1, feed tank; 2, flow control weir; 3, recycle pump; 4, influent distribution; 5, sampling taps; 6, water seal; 7, gas meter). See text for operational details.

Table 1
Wastewater characteristics of UASB reactor at different periods of study

Parameter	Range	Average ± Std. Dev.
BOD_5 (mg $^{l-1}$)	914–1917	1748 ± 541
SCOD (mg l^{-1})	2258–4956	3799 ± 429
TCOD (mg l^{-1})	3265–14285	6037 ± 1092
P–PO_4^{3-} (mg l^{-1})	7–26	17 ± 12
N–NH_3 (mg l^{-1})	35–104	89 ± 50
Temperature (°C)	27–36	33.3 ± 2.8
PH	6.8–7.8	7.2 ± 0.3
Alkalinity as $CaCO_3$ (mg l^{-1})	1208–1713	1351 ± 181
VFA as acetic acid (mg l^{-1})	309–565	440 ± 124

and toilets. There was no separation of effluent from these operations and because of the inherent nature of the process, characteristics varied at different times (Table 1). Addition of nutrients was not deemed necessary since wastewater characteristics indicated an adequate concentration of essential proteins and trace elements. No dilution or recycling of feed was made in the beginning or at any of the phases of the study.

2.3. Operation

The reactor contained granulated sludge formed previously in the reactor. The initial seed was from a mesophilic municipal anaerobic digester sludge with a VSS content of 29 g l^{-1}. The temperature of influent was adjusted by an inline thermostat prior to reactor entry. Slaughterhouse effluent was pumped into a reservoir from the main slaughterhouse sewer containing composite effluent from different units. After separating inert particles in a cyclonic grit chamber, effluent was pumped into a container at the top and then fed by gravity into the influent distribution line of thereactor.

Two schemes of operation were selected. In the first three phases of the study, feed reservoir was filled at different times during the day to allow different concentrations to be investigated at constant HRT. In the subsequent two phases, both OLR and HRT were changed simultaneously by increasing inflow to the reactor. Temperature was maintained around 33 °C. There was no need to externally regulate pH of the reactor since it remained relatively constant throughout the study period.

2.4. Analytical methods

Routine analyses including soluble (filtered sample with a 0.45 μm pore size glass microfiber filter) and total BOD_5 and COD, alkalinity, nitrogen, and phosphorus were performed using procedures outlined in Standard Methods (APHA, 1985). Samples were centrifuged prior to volatile fatty acid analysis using distillation method. Gas evolution was measured by a cumulative gas flow meter located downstream of a water trap and analyzed by Schimadzu (5A with molecular sieve and carbon active columns and FID and ECP detectors) gas chromatograph. Most of the parameters were monitored daily during the start up phase and every other day during the normal operations.

2.5. Experimental design

The experimental protocol was designed to examine the effect of different OLRs on the operational (e.g. efficiency of COD removal) and performance (e.g. volumetric and microbial elimination capacity as defined in the next section below) indicators. All experiments were performed under steady state conditions. The attainment of the steady state was verified by checking whether the mean of the effluent characteristics for the last two measurements done within $5 \times$ HRT were remaining relatively constant. All the performance and operation results reported are the average values of at least two measurement data.

2.6. Operational and performance parameters

Operational and performance parameters include OLR, SLR, elimination capacity, and detention time. Loading rates can be looked at from the pollution indicator, empty reactor bed volume, and microbial mass. OLR takes into account the liquid flow rate and contaminant concentration and is defined as the mass of pollutant introduced in a unit volume of UASB reactor per unit time (e.g. kg COD $m^{-3}\,s^{-1}$). As such, this parameter integrates reactor characteristics, operational characteristics, and bacterial mass and activity into the volume of media. SLR or food to microorganism ratio (F/M) integrates contaminant concentration and microbial mass and is the mass of pollutant applied to a unit mass of microbial mass per unit time (e.g. kg COD kg^{-1} VSS d^{-1}).

Elimination capacity is related to OLR and SLR in that it is defined as the fraction of the organic load biodegraded in a unit volume of the UASB reactor or a unit mass of microbial mass. This parameter can be expressed either volumetrically (EC_V, kg pollutant removed per unit volume of reactor per day) or on the basis of microbial mass (EC_m, kg pollutant removed per unit mass of microorganisms in the reactor per day).

Methanogenic activity (MA) can be expressed on the basis of pollutant (liter biogas produced per unit mass of pollutant removed, MA_{scod}) or on the basis of microbial mass (liter biogas produced per unit mass of microbial population, MA_{vss}).

Mass loading rate ($kg\,m^{-3}\,d^{-1}$), SLR ($kg\,kg^{-1}\,d^{-1}$), and elimination capacity ($kg\,m^{-3}\,d^{-1}$ or $kg\,kg^{-1}$ VSS d^{-1}) were determined using the relationships between influent and effluent contaminant concentration, effluent flow rate, the effective volume of UASB reactor, and applying appropriate conversion factors as follows:

$$\mathrm{OLR} = \left(\frac{Q}{V_r}\right) C_{in} \tag{1}$$

$$\mathrm{SLR} = Q\left(\frac{C_{in}}{\mathrm{VSS}}\right) \tag{2}$$

$$\mathrm{EC_V} = \left(\frac{Q}{V_r}\right)(C_{in} - C_{out}) \tag{3}$$

$$\mathrm{EC_m} = \frac{\mathrm{EC_V}}{\mathrm{VSS}} \tag{4}$$

$$MA_{scod} = \frac{V_{CH_4}}{Q(C_{in} - C_{out})} \tag{5}$$

$$MS_{VSS} = \frac{V_{CH_4}}{Q(VSS)} \tag{6}$$

where Q is the effluent flow rate ($m^3\,h^{-1}$); V_r, the effective volume of reactor bed (m^3); VSS, the microbial concentration of the reactor (mg VSS l^{-1}), V_{CH_4}, the volume of biogas produced per day ($l\,d^{-1}$); and C_{in} and C_{out} are the contaminant concentrations (mg SCOD l^{-1}) in the influent and effluent stream, respectively.

3. Results and discussion

3.1. Startup

The startup of the reactor was rapid because the system had been adapted to the slaughterhouse effluent previously. The reactor was started with an OLR of 5 kg SCOD $m^{-3}\,d^{-1}$ to keep the initial loading rate below approximately 50% of the intended loading after the start-up period (Lettinga et al., 1997). The loading rate was gradually increased over a 2-week period to 10 kg SCOD $m^{-3}\,d^{-1}$.

3.2. Steady state performance

The total and soluble COD of the feed and of the effluent during the operation period, and the results for different organic and hydraulic loading rates along with performance indicators are presented in Table 2.

3.2.1. Removal efficiency

The performance of UASB reactor based on soluble COD removals at various upflow velocities and OLRs is shown in Fig. 2. At the initial three phases of the study, V_{up} was maintained relatively constant at 0.33–0.35 $m\,h^{-1}$ while OLR was increased from around 10 to 18 kg SCOD $m^{-3}\,d^{-1}$. As illustrated in the figure, SCOD removal efficiencies showed an increasing trend from a low 62% to a maximum of 92%. At the beginning of each phase where OLR was increased, there was a corresponding decrease in removal efficiency but the system recovered shortly and adapted to the new conditions with time.

At the beginning of phase 4 of the study, OLR was increased to 27 kg SCOD $m^{-3}\,d^{-1}$. Upflow velocity was also increased to 0.57 $m\,h^{-1}$ to further promote the selective process in the cultivation of more active biomass (Campos and Anderson, 1992). The system behavior was similar to earlier stages in that a transient decrease in performance was observed but the system performance reached the same conditions existing before the change. The 50% increase in OLR and 80% increase in V_{up} did not seem to have any adverse effect on organics removal and SCOD removal efficiency reached 93%.

In the next phase of study, OLR was increased another 30% to above 40 kg SCOD $m^{-3}\,d^{-1}$ and V_{up} to 1 $m\,h^{-1}$. Removal efficiency was drastically decreased to below 70%

Table 2
Summary of the conditions during the operation period of the UASB reactor

Variable	Unit	Phase of study				
		1	2	3	4	5
Time	day	1–38	39–64	65–91	92–112	113–136
Upflow velocity, V_{up}	$M\,h^{-1}$	0.33	0.34	0.35	0.57	1.0
Hydraulic residence time, HRT	H	7.1	6.8	6.7	4.1	2.3
SRT	day	60.3	23.4	14.0	14.4	3.3
SCOD in	$Mg\,l^{-1}$	3143 ± 661	3695 ± 662	4153 ± 364	4288 ± 564	3290 ± 722
TCOD in	$Mg\,l^{-1}$	8201 ± 3937	5719 ± 1280	5256 ± 589	5495 ± 622	5514 ± 1469
TSS	$G\,l^{-1}$	11.6 ± 2.2	10.9 ± 6.8	11.6 ± 1.3	12.8 ± 1	18.3 ± 1.2
VSS	$g\,l^{-1}$	10.2 ± 1.9	9.9 ± 6.7	10.5 ± 1	11.9 ± 1.2	14.9 ± 0.9
VSS out	$g\,l^{-1}$	0.09 ± 0.09	0.16 ± 0.13	0.36 ± 0.20	0.24 ± 0.14	0.59 ± 0.36
SCOD removal	%	76 ± 9	75 ± 12	85 ± 6	85 ± 8	68 ± 8
TCOD removal	%	78 ± 14	73 ± 11	77 ± 15	83 ± 7	68 ± 10
OLR	kg SCOD $m^{-3}\,d^{-1}$	13 ± 2.9	16.7 ± 3.3	17.4 ± 1.1	27.4 ± 4.8	39.5 ± 9
SLR	kg SCOD kg^{-1} VSS d^{-1}	1.3 ± 0.2	1.7 ± 0.3	1.7 ± 0.1	2.4 ± 0.3	2.7 ± 0.6
Elimination capacity, EC_v	kg SCOD $m^{-3}\,d^{-1}$	9.5 ± 1.8	12.6 ± 3.6	15 ± 1.7	25 ± 4.8	27 ± 6.9
Elimination capacity, EC_M	kg SCOD kg^{-1} VSS d^{-1}	1.0 ± 0.2	1.3 ± 0.4	1.4 ± 0.2	2.1 ± 0.4	1.8 ± 0.5
Methanogenic activity, MA_{vss}	$l\,kg^{-1}$ VSS	222 ± 32	347 ± 66	458 ± 54	464 ± 58	395 ± 68
Methanogenic activity, MA_{scod}	$l\,kg^{-1}$ SCOD	213 ± 21	254 ± 54	283 ± 23	201 ± 38	199 ± 36

and there was no indication that a recovery was to ensue. As a result, OLR was decreased to try a more gradual increasing trend but V_{up} was maintained around 1 m h^{-1}. Variation of OLR in the 30–40 kg SCOD $m^{-3}\,d^{-1}$ did not improve SCOD removal efficiencies from the 65 to 68% range. As such, OLR value of about 30 kg SCOD $m^{-3}\,d^{-1}$ was regarded as the upper limit for satisfactory performance for this type of wastewater under the conditions of this study. Considering the fact that HRT at this phase was low at 2.3 h, the decrease in performance could have also been attributed to insufficient time available for substrate transfer from the liquid to biomass.

The results obtained in this study showed better performance when compared with the values of 92% SCOD removal at 5.2 kg SCOD $m^{-3}\,d^{-1}$ and HRT of 1.2 day (Ruiz et al., 1997) and 93.4% COD removal at 20.8 kg SCOD $m^{-3}\,d^{-1}$ and HRT of 0.5 days for this type of wastewater under similar operating conditions and 87% SCOD removal at 30 and HRT of 7.2 h for alcohol distillery wastewater under thermophilic conditions (Syutsubo et al., 1997). This could have been due to a combination of factors including lack of blood separation in the slaughterhouse operations, high solids content, and long adaptation of granules to the slaughter-house effluent prior to this study.

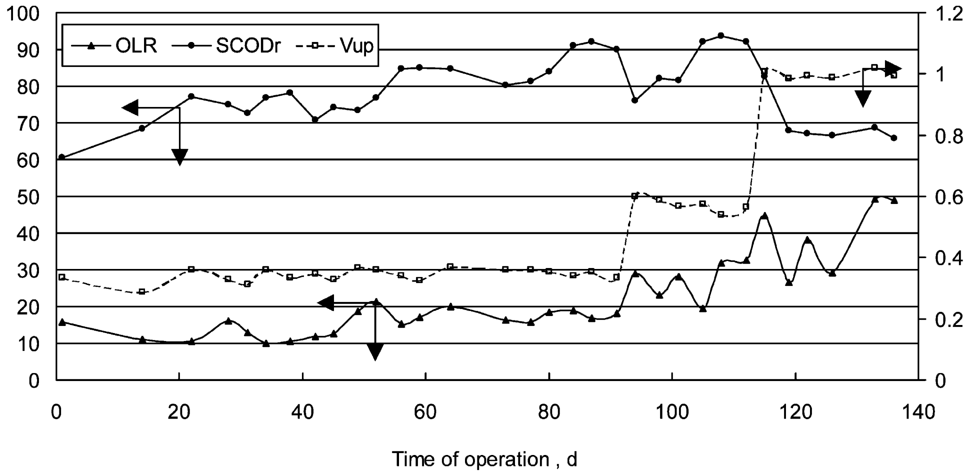

Fig. 2. Variation of SCOD removal efficiencies (%) at different OLRs (kg SCOD $m^{-3}\,d^{-1}$) and upflow velocities ($m\,h^{-1}$).

3.2.2. Sludge loading rate

Fig. 3 illustrates performance of the reactor at different SLRs. As shown in the figure, the SLR practiced in this study ranging from 1 to above 2.5. This was in line with the recommended range of 0.1–1 kg COD kg^{-1} VSS d^{-1} for anaerobic processes (Ndon and Dague, 1997). Another important aspect of the performance is to prevent anaerobic microorganism washout and to provide a margin of safety under transient inhibitory conditions in the reactor. This is assured by maintaining a minimum value of biological SRT even at low hydraulic residence times. SRT calculations for the reactor indicated a range of 3.3 days at high upflow velocity of 1 $m\,h^{-1}$ to 60.3 days at low upflow velocity of 0.33 $m\,h^{-1}$ s during different phases of the study. This was within the recommended range of 4–10 days to prevent washout of hydrolytic anaerobic bacteria (Eastman and Feguson, 1981) for cases where hydrolysis of insoluble organic matter is the rate-limiting step (Parkin and Owen, 1986) and 2.5–5 days for soluble wastewaters containing acetate as the primary organic (Stronach et al., 1986) constituent.

3.2.3. Methane production

Fig. 4 illustrates MA based on microbial capacity and SCOD conversion. The figure shows more fluctuation of methane produced on the basis of unit SCOD removed than unit VSS mass. This may be due to seasonal variability of biological degradability of effluent and potential presence of various organic and inorganic materials inhibiting treatment performance (Kroeker, 1979). Table 1 shows a steady increase in methane production capacity up to an OLR of 27 kg SCOD $m^{-3}\,d^{-1}$. As OLR was increased, MA_{vss} (at 25 °C and 1 atm) increased to a maximum of 283 l kg^{-1} VSS at organic load of 17.4 kg SCOD $m^{-3}\,d^{-1}$. From there on, incremental increase in MA_{vss} declined and eventually decreases to 199 l $CH_4{\cdot}kg^{-1}$ VSS d^{-1} at an OLR value of 39.5 kg SCOD $m^{-3}\,d^{-1}$ corresponding to SLR

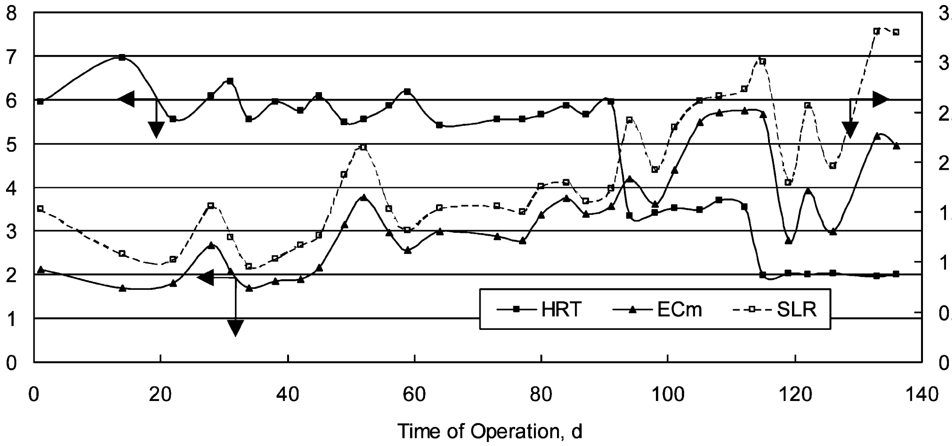

Fig. 3. SLRs (kg COD kg^{-1} VSS d^{-1}) applied and microbial elimination capacities (kg SCOD kg^{-1} VSS d^{-1}) at different HRTs (days).

of 2.7 kg SCOD kg^{-1} VSS d^{-1}. This apparent instability was manifested in Fig. 4 by the widening and erratic behavior of MA_{vss} and MA_{scod} curves at high organic loads.

Attachment of gas bubbles is a usual problem of ordinary UASB systems at high OLR values leading to biomass suspension and cell washout as methane production rate increases. Even though the system experienced a lower efficiency at high OLR values, there was no drastic increase in effluent VSS. The maximum effluent solids concentration of 590 mg VSS l^{-1} observed at the highest OLR studied, was around 3.3% of the reactor biomass concentration. The fact that no special gas separation system was used in the enlarged

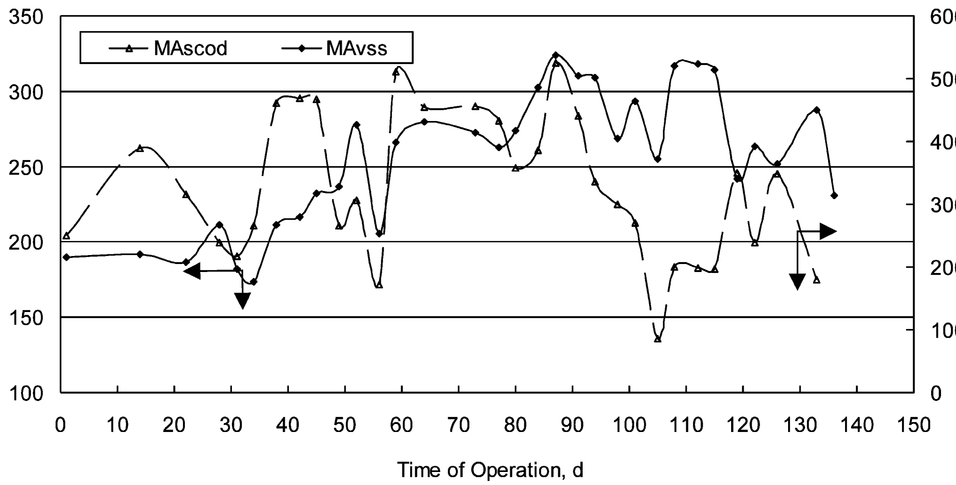

Fig. 4. Methane production per unit mass of biomass (l CH_4 kg^{-1} VSS d^{-1}) and SCOD removal (l CH_4 kg^{-1} SCOD) throughout the study period.

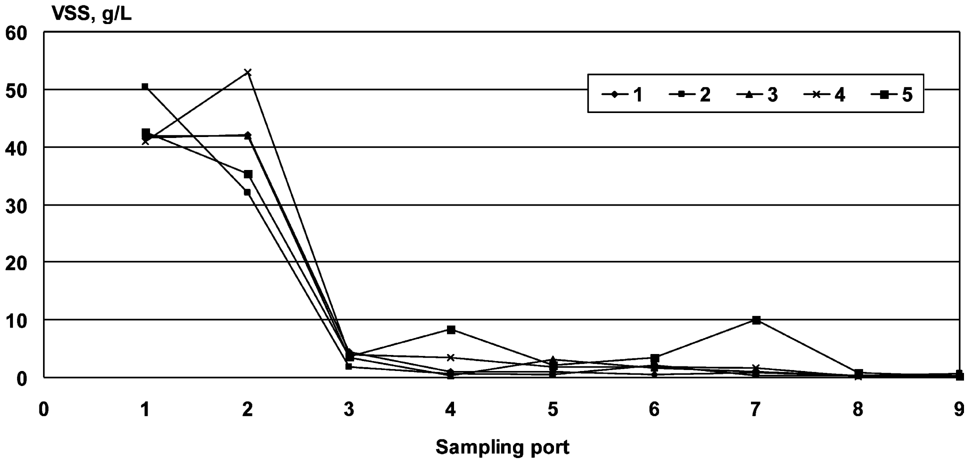

Fig. 5. Profile of solids content along the reactor height.

settling zone suggested good granule stability and characteristics. This was in conformity with the data on the profile of sludge behavior along the reactor height during the study.

3.2.4. Sludge gradient along the reactor height

As illustrated in Fig. 5, a distinct stratification of solids was maintained through the experimental period with larger solids (granules) settling down to lower part of the reaction zone and smaller ones in the upper part. Solids concentration at sampling ports 1 and 2 had a range of 41–51 and 32–52 mg l^{-1}, respectively. Examination of VSS data showed that on the average 89.3 ± 11.3% of bioparticle mass was present at the lower 30% of the reactor height (sampling ports 1–3) and the remaining aggregates were suspended due to the mixing by flowing liquor and rising gas bubbles. Reports in the literature indicate that cell washout is attributed exclusively to sludge blanket erosion (De Zeeuw, 1987) that is selective for well-aggregated granules. The combined effect of high substrate load and good granule characteristics along with the physical selection brought about by high OLR and upflow velocity played a positive role in maintaining stable and efficient solids in thelower part of the reactor.

4. Conclusions

The results of this study showed slaughterhouse wastewater can be satisfactorily treated by means of high-rate anaerobic processes, specifically with the use of USAB reactor. High SCOD removals of between 75 and 90% at OLRs of 13–30 kg COD m^{-3} d^{-1} were achieved in this study. Indication of erratic behavior was observed at organic loads higher than 30 kg COD m^{-3} d^{-1}. There was no sludge washout even at OLR values above 30 kg COD m^{-3} d^{-1} at HRT values as low as 2.3 h. Methane yields of 200–280 l CH_4 kg^{-1} $SCOD_{removed}$ were in the same order of magnitude as the rates achieved in earlier studies.

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