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Effects of Hydraulic Retention Time on Anaerobic Digestion of Domestic Wastewater at Low Loading Rates

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Effects of hydraulic retention time on anaerobic digestion of domestic wastewater at low loading rates

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Abstract

The hydraulic retention time has been identified as the key operating parameter that affects the performance of the UASB reactor. For low-strength wastewaters such as the domestic wastewater, it is the limiting design parameter. Hydraulic retention times that are too long or too short would adversely affect the performance of the UASB reactor. The highly fluctuating flow rates of domestic wastewater, which corresponds to fluctuating hydraulic retention times, have been cited as one of the inherent difficulties for application of the UASB reactor in domestic wastewater treatment. The generally low organic loading of domestic wastewaters further compounds the challenges of treatment by anaerobic digestion. This paper reports the effect of highly fluctuating hydraulic retention times on the performance of a UASB reactor in treating domestic wastewater at low loading rates with the aim of gaining a better understanding of its application. From the results obtained, conclusions derived are that the hydraulic retention time does not affect the effluent COD; fluctuating hydraulic retention times within the range in this study did not adversely affect the performance of the UASB reactor; longer hydraulic retention times give better COD degradation rates; and generally, for very similar volumetric loading rates, COD removal efficiency is lower at shorter hydraulic retention times.

Keywords: Upflow anaerobic sludge blanket, domestic wastewater, hydraulic retention time, low loading rates

1. Introduction

Anaerobic digestion has increasingly been recognised as the core for natural resource conservation and environmentally sustainable development (Foresti, 2001; McCarty, 2001; Seghezzo et al., 1998; Lettinga et al., 1993). One of its attractions is the production of energy in the form of biogas. In domestic wastewater treatment, however, this is impossible, as the rate of gas production has been found to be too low (Noyola et al., 1988). This is largely due to the low organic loadings of most domestic wastewaters (van Lier et al., 2001; Verstraete et al., 1996). Nevertheless, the application of anaerobic digestion in domestic wastewater treatment promises savings in energy consumption, rendering it highly viable to be considered seriously.

To date, the upflow anaerobic sludge blanket (UASB) reactor system has been the most popularly employed anaerobic system in anaerobic domestic wastewater treatment. The key to the success of the UASB system is the retention of highly active biomass with good settling abilities in the reactor (Schmidt and Ahring, 1996). Although the solids retention time is the fundamental parameter of the anaerobic treatment process (Cavalcanti, 2003, cited by van Haandel et al., 2006), the hydraulic retention time has been recognised as the more practical parameter to be used to control the performance of the UASB reactor (van Haandel et al., 2006). For low-strength wastewaters such as the domestic wastewater, the hydraulic retention time has been identified as the limiting design parameter (Foresti, 2001; Souza, 1986).

Since there is no sludge recycle, the solids retention time is equal to the hydraulic retention time. Long hydraulic retention times are known to be unfavourable for sludge granulation in UASB reactors (Alphenaar et al., 1993), whereas very short hydraulic retention times give rise to possibility of biomass washout. Both scenarios are unfavourable to good performance of the UASB reactor, although granulation has been reported to be unnecessary for successful anaerobic domestic wastewater treatment in UASB reactors (van Haandel et al.,

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2006; Aiyuk et al., 2004). The highly fluctuating flow rates of domestic wastewater, which corresponds to fluctuating hydraulic retention times, has been cited as one of the inherent difficulties for application of the UASB reactor for domestic wastewater treatment (van Lier et al., 2001). The generally low organic loading of domestic wastewaters further compounds the challenges of treatment by anaerobic digestion, since granulation is aided by high organic loading rates (Francese et al., 1998). Sludge degranulation during low organic loading rates has been observed by Ahn et al. (2002) and Aiyuk and Verstraete (2004). Grotenhuis (1992; cited in Aiyuk et al., 2006) attributed similar incidences in domestic wastewater treatment to the low substrate concentration.

This paper reports the effect of highly fluctuating hydraulic retention times on the performance of a UASB reactor in treating domestic wastewater at low loading rates. A better understanding of this would enable more effective application of the UASB reactor in treating low-strength domestic wastewater.

2. Methods

Figure 1 shows the experimental setup used. A UASB reactor with a working volume of approximately 13.0 L was operated at 37°C on domestic wastewater, which was fed into the reactor using a peristaltic pump (Watson Marlow, 323 E/D, U.K.) via 1.6-mm ID platinum-cured silicon tubing. Pinch corks were used to divert the influent and effluent flows during sampling for analysis.

Wastewater was initially fed at the lowest flow rate, i.e., 3.68 mL/min. When COD removal increased, the pumping rate was increased stepwise by 20% or 5 rpm, whichever was higher. Feed rate and biogas production were monitored daily, whereas influent and effluent temperature, pH, and COD concentrations were measured daily whenever possible, or otherwise after the process was deemed to have stabilized after any interruption. For the experiment described herein, the reactor was operated on domestic wastewater for 194 days.

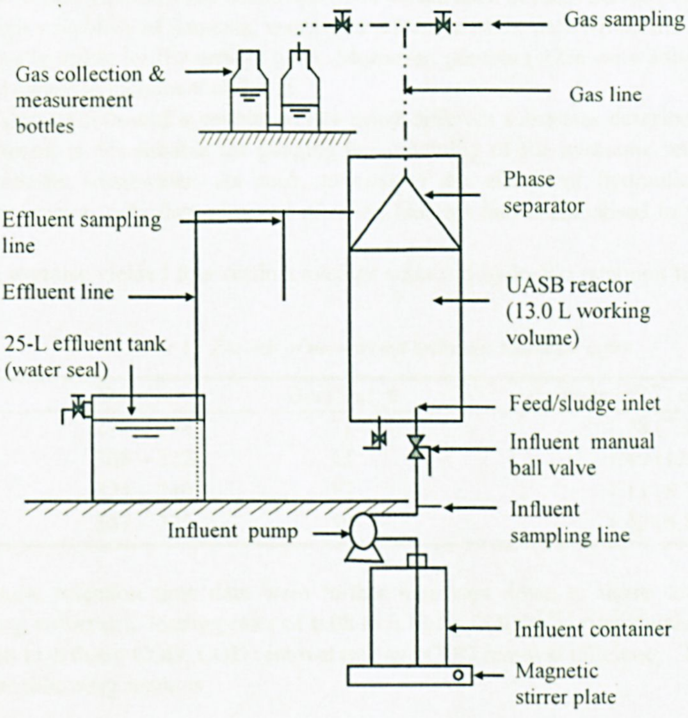

Figure 1. Experimental setup

2.1 Analytical Methods

The actual feed rate of wastewater into the reactor was irregular due to interruptions caused by various reasons such as clogging of the tube by fine suspended solids, influent sample withdrawal for analyses, power failures, maintenance works on the reactor and other unavoidable circumstances in the laboratory. As such, the actual feed rate was calculated from the wastewater volume fed and the corresponding time measured over as long a period as possible. The feed rates reported were averaged from the various feed rates obtained in the course of the day, regardless of the extent of fluctuations throughout. This was to give the best representation of the actual reactor operation considering the various interruptions mentioned above.

Biogas was collected by water displacement and the volume read from a calibrated gas collection bottle. Gas volumetric readings were recorded in mL. From the last 44 days of the experimental period onwards, the gas readings were recorded only after 4 h from the start of collection to allow the water displacement to normalise. Reported results are also the average readings of the day.

Temperature and pH were measured using a pH/temperature probe (Thermo Orion, 9107BN, U.S.A.) with automatic temperature compensation.

For COD analysis, a method equivalent to Standard Method 5220D: Closed Reflux, Colorimetric Method (Clesceri et al. 1998), i.e. Hach's Method 8000, was used. It is a combination of Reactor Digestion Method and Colorimetric Method (DR/890 colorimeter procedures manual, 1997–2000) where samples were digested at 150°C for two hours with potassium dichromate to form green chromic ion (Cr^{3+}). The amount of green Cr^{3+} was measured using a calibrated, pre-programmed colorimeter (Hach, DR/890, U.S.A.).

3. Results

The hydraulic retention time was found to fluctuate highly throughout the experiment due to the irregular feed rates caused by reasons mentioned above. Thus, for meaningful analysis of the results, the data were grouped into periods of similar hydraulic retention times within a range of 20 ± 1%, omitting anomalies that occurred for relatively insignificant durations (e.g. 1 d in a period of 17 d). The corresponding parameters were then normalised by re-calculating them using the average hydraulic retention time for each period respectively. Care was taken that each period exceeds ten times the average hydraulic retention times and not shorter than 14 d, slightly modifying Noyola et. al's (1988) definition of steady state period for domestic wastewater. It had been established that the reactor had achieved stable operation during each of these period (Tan, unpublished).

Considering the high variability of domestic wastewater characteristics, data within the range of 20 ± 1% can be taken to be sufficiently stable for the present work. Moreover, pumping rates were adjusted based on the higher value of 20 percent stepwise increment or 5 rpm.

Since the reactor start-up followed a certain regime using different substrates described in detail in Tan et al., (2006), this experiment is not suitable for gauging the suitability of the hydraulic retention times applied for granulation in domestic wastewater. As such, to analyse the effects of hydraulic retention time on the performance of the reactor, only data obtained after the biomass had acclimatised to the domestic wastewater were considered.

The normalisation exercise yielded four distinct average values of hydraulic retention times as shown in Table 1 below.

Table 1. Periods of normalised hydraulic retention times

Period	Day Nos.	Duration, d	Average HRT, d (RSD, %)
A	274 – 294	21	1.78 (7.10)
B	308 – 322	15	1.40 (12.4)
C	324 – 340	17	1.11 (5.72)
D	341 – 379	39	1.42 (6.77)

Normalised hydraulic retention time data were further narrowed down to those corresponding to the most frequently occurring volumetric loading rates of 0.08 to 0.13 kg COD/m^3/d (unpublished data). They were then analysed in relation to effluent COD, COD removal rate and COD removal efficiency. The main results obtained are discussed in the following sections.

3.1 Effects of hydraulic retention time on effluent COD

A plot of effluent COD for the selected range of volumetric loading rates, i.e. 0.080 to 0.13 kg COD/m^3/d in Figure 2 shows that there are no distinct differences among all the different average hydraulic retention times. It can thus be surmised that the hydraulic retention time does not affect the effluent COD in this study.

3.2 Effects of hydraulic retention time on COD removal

Considering only volumetric loading rates of similar range for all the periods of study, i.e. 0.080 to 0.13 kg COD/m^3/d, the following observations can be made from Figure 3:

1. Volumetric loading rates for average hydraulic retention times of 1.40 d (Period B) and 1.42 d (Period D) happened to fall into two distinct ranges that seemed to follow a consecutive incremental pattern. As such, it would be appropriate to consider them as one set of data with similar hydraulic retention times, say of average 1.41 d.
2. COD removal rates achieved at the average hydraulic retention times of 1.78 d, 1.41 d and 1.11 d were generally in decreasing order respectively. This agrees with the fact that longer hydraulic retention times give longer contact time between biomass in the reactor and the wastewater, and thus better COD degradation rates.

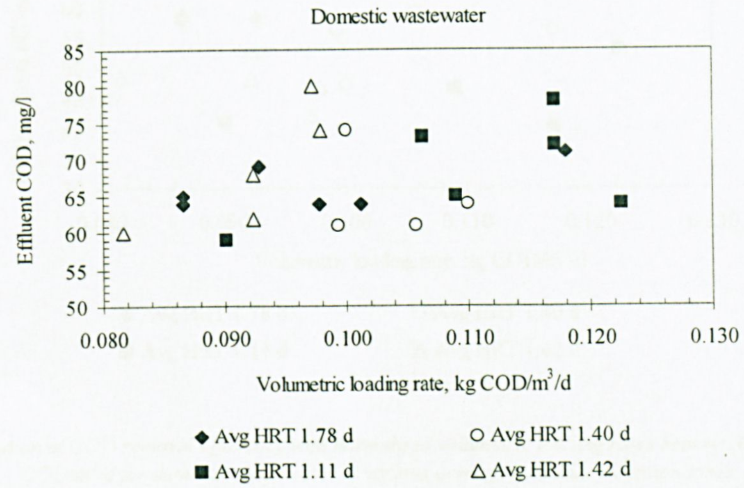

Figure 2. Variation of effluent COD with normalised volumetric loading rates between 0.08 and 0.13 kg COD/m^3/d for domestic wastewater at various average hydraulic retention times

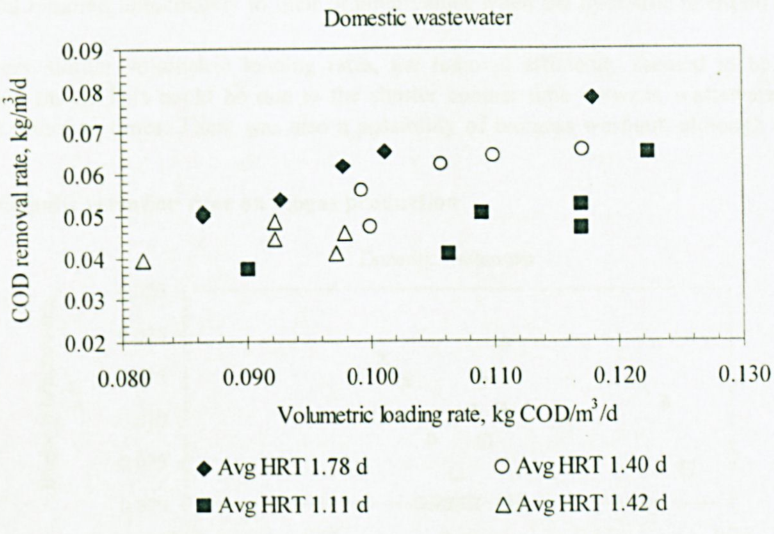

Figure 3. Variation of normalised COD removal rate with normalised volumetric loading rates between 0.08 and 0.13 kg COD/m^3/d for domestic wastewater at various average hydraulic retention times

When COD removal efficiency was similarly compared for the three hydraulic retention times (Figure 4), it followed a similar trend as for COD removal rate but tapered towards a plateau for the two longer hydraulic retention times. The plateau value indicates that at a certain higher volumetric loading rate, the removal efficiency reached a constant maximum value. For the shortest hydraulic retention time of 1.11 d, it shows an increasing trend with increasing volumetric loading rate; the higher liquid upflow velocity then could have caused more washout of solids that gave a lower COD removal efficiency overall. As such, higher volumetric loading rates were required to achieve the maximum COD removal efficiency. Thus the graphs seem to be shifting to the right as the average hydraulic retention time decreases. It is possible that the graph for 1.11 d would also taper off towards a plateau at higher volumetric loading rates.

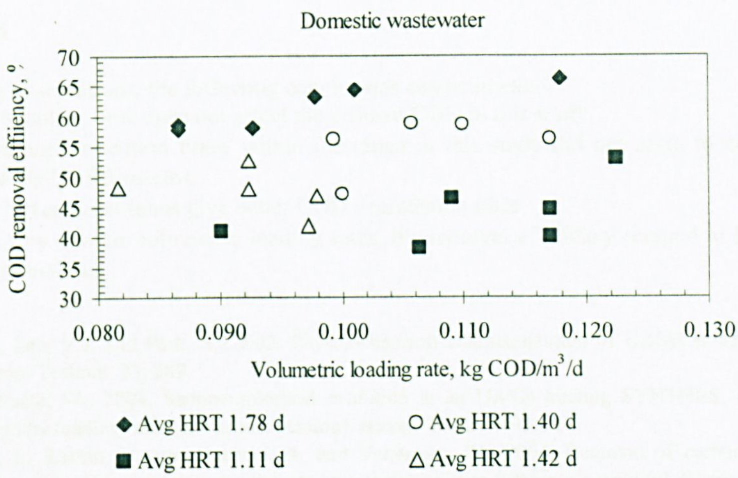

Figure 4. Variation of COD removal efficiency with normalised volumetric loading rates between 0.08 and 0.13 kg COD/m³/d for domestic wastewater at various average hydraulic retention times

It is interesting to note that although there was an interval with a short hydraulic retention time between Periods B and D, which had very similar hydraulic retention times, the COD removal rate for both periods were still consecutively proportionate to the volumetric loading rates. This shows that the reduced hydraulic retention time of 1.11 d did not disturb the stability of the reactor in any way. The reduced COD removal rates and efficiencies during the interval returned immediately to their original values when the hydraulic retention time increased to its earlier value.

Generally, for very similar volumetric loading rates, the removal efficiency seemed to be lower at shorter hydraulic retention times. This could be due to the shorter contact time between wastewater and biomass at shorter hydraulic retention times. There was also a possibility of biomass washout, although it might not have been obvious.

3.3 Effects of hydraulic retention time on biogas production

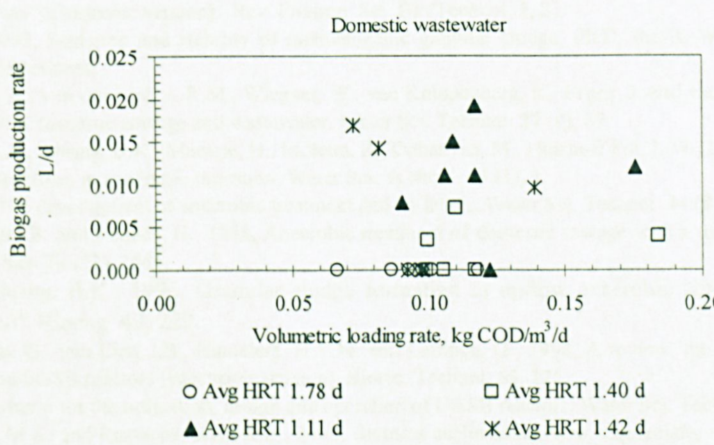

Figure 5. Variation of biogas production rate with normalised volumetric loading rate for domestic wastewater.

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As seen in Figure 5, biogas production rates show neither any correlation with volumetric loading rates nor any distinct differences among the different average hydraulic retention times. This could be attributed to the following reasons:

- the use of the degraded organics for maintenance and growth of cells, and thus no biogas was produced, and
- loss of gas through the effluent, either in the form of byproducts washout from the reactor, or dissolution in the liquid effluent.

4.0 Conclusions

From the preceding observations, the following conclusions can be made:

1. The hydraulic retention time does not affect the effluent COD in this study.
2. Fluctuating hydraulic retention times within the range in this study did not seem to adversely affect the performance of the UASB reactor.
3. Longer hydraulic retention times give better COD degradation rates
4. Generally, for very similar volumetric loading rates, the removal efficiency seemed to be lower at shorter hydraulic retention times.

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