Temperature effect on UASB reactor operation for domestic wastewater treatment in temperate climate regions

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Abstract The performance of an upflow anaerobic sludge blanket (UASB) reactor was investigated for the treatment of domestic wastewater at different operational temperatures (28, 20, 14 and 10°C) and loading rates. For each temperature studied a constant CODt removal was observed as long as the upflow velocity was lower than 0.35 m/h: 82% at 28°C, 68% at 14°C and 44% at 10°C. At 20°C the COD removal increased with the HRT, reaching similar values as at 28°C for long HRT. At upflow velocities higher than 0.35 m/h, a reduction in total COD removal was observed due to washout of influent TSS. At 28°C, a constant 200 g sludge mass was observed and COD removal was attributed to biological degradation only. At lower temperatures, COD removal resulted from degradation and solids accumulation in the reactor. The increase in reactor sludge was greater as the temperature decreased and explains the similar overall COD removal efficiency at 28°C, 20°C and 14°C. During the transition from winter to summer conditions (10°C to 28°C), methane production initially increased due to the degradation of accumulated solids. Afterwards, methane production gradually declined and an increase in COD removal was observed, indicating that the TSS accumulated during the winter was exhausted and influent degradation remained.

Keywords Anaerobic treatment; domestic wastewater; temperature effect; UASB; upflow velocity

Introduction

The UASB reactor is an attractive technology for wastewater treatment. The high costs of aeration and sludge handling associated with aerobic sewage treatment are dramatically lower as no oxygen is needed and the production of sludge is 3–20 times lower. However, its use is usually limited to high strength industrial wastewater with soluble substrates.

Domestic wastewater has typically low concentrations of COD, resulting in relatively small methane production that is insufficient to heat the reactor to more favorable mesophilic temperatures. The relatively high concentration of particulate matter present in domestic wastewater requires an initial hydrolysis step, which is significantly affected by temperature and is usually the rate-limiting step in sub-tropical climate regions.

In tropical countries the UASB reactor for domestic wastewater has found wide acceptance. There are several full-scale plants already in operation in Colombia, Brazil, Indonesia, India and Egypt and COD removals above 70% have been observed by several authors (Souza and Foresti, 1996; Chernicharo and Cardoso, 1999; Kalogo and Verstraete, 2000). The effluent quality at these installations is reported to be 140 mg COD/l, 75 mg BOD/l and 30 mg TSS/l.

At low temperatures the low hydrolysis rate and a decrease in the degradable organic matter fraction were found to cause the deterioration of the overall UASB reactor performance (Elmitwalli et al., 2001). COD removals of ~65% at 20°C and of 55–65% at 13–17°C were observed by several authors (Lettinga et al., 1981; Grin et al., 1983; Vieira and Souza, 1986; Elmitwalli et al., 1999; Seghezzo, 2000). A decrease in the effluent quality was also observed, together with a decline in the gas production rate. Agrawal et al.
(1997) observed a 78% decrease in the gas production rate when the temperature was reduced from 27°C to 10°C. The low gas production coincided with a 25% lower COD removal at 10°C than at 27°C, indicating suspended solids accumulation in the reactor.

This project concentrates on the effect of temperature on domestic wastewater treatment, using an UASB reactor at different upflow velocities, hydraulic retention times (HRT) and organic loading rates.

Material and methods
A UASB reactor was constructed of plexiglass with a working volume of 5.3 litres (8.0 cm diameter, 107.5 cm high). A diagram of the reactor is given in Figure 1. The reactor was outfitted with a gas/solid separator to prevent biomass washout. Four sampling ports were placed at different heights and an inflow manifold was used at the bottom of the reactor to ensure even influent distribution. The reactor was filled with 2 litres of granular sludge taken from a full scale UASB reactor treating food wastewater. The TSS concentration in the reactor immediately after inoculation was 130 g TSS/l. The reactor was fed with domestic wastewater after primary sedimentation from the Neve Sha’an neighborhood, Haifa. The wastewater can be classified as a medium strength domestic wastewater (Metcalf and Eddy, 1991).

Samples of the reactor effluent and methane production readings were taken one hydraulic retention time after inflow sampling. All samples were tested on a regular basis for pH, BOD, TSS, VSS, COD\textsubscript{t}, COD\textsubscript{s}, and VFA. Every 20 days 50 ml sludge samples were taken from the two lower sample ports and were tested for SVI, TSS and VSS. All analyses were performed according to Standard Methods for the Examination of Water and Wastewater (APHA, 1995). Effluent COD was characterized in two ways: well mixed samples were used for COD\textsubscript{t} and samples allowed to settle 10 minutes for COD\textsubscript{s} samples. COD removal was calculated on the basis of influent COD\textsubscript{t}. The volatile fatty acids concentration was measured using the five-point titration method (Moosbrugger et al., 1992). The methane gas produced was collected and measured as described by van Haandel and Lettinga (1994). The dissolved methane in the effluent was calculated according to Henry’s law and added to the methane gas actually measured.

During start-up, the reactor was operated at 28°C with a retention time of 24 hours to allow sludge adaptation to domestic wastewater. Afterwards, the retention time was gradually shortened with the corresponding increase in organic load. At every new retention time, the reactor was allowed to adjust to the higher load. After the performance reached steady state for a number of days, the retention time was shortened further. When the experimental regime was completed at 28°C, the same procedure was carried out for reactor temperatures of 20°C, 14°C and 10°C. The reactor was operated at a temperature of 28°C for 6 months and 2 months for each of the other temperatures.

![Figure 1](https://iwaponline.com/wst/article-pdf/48/3/25/423177/25.pdf)

**Figure 1** Laboratory scale (5.3 litres) UASB reactor equipped with a gas/solid separator at the top.
Results and discussion

During the start-up period, the reactor operated efficiently and the effluent TSS was constant with an 86.6% removal. The COD\text{t} removal increased with time, starting at 79.2% and reaching 88.5% at the end of the period. The effluent pH was very similar to the influent pH indicating that VFA was not accumulating in the reactor. At the conclusion of the start-up period, the reactor was operated at 28°C for six months and the hydraulic retention time (HRT) was gradually reduced from 24 hours to 1 hour only, with the corresponding increase in organic load from 0.2 to 31.8 g COD/l/day.

The effect of the decrease in HRT with the corresponding increase in organic load is given in Figure 2. For HRTs from 24 to 3 hours (0.04–0.35 m/h upflow velocity), a stable effluent COD concentration was observed even with the high fluctuation in influent COD\text{t} concentration (200–1,300 mg COD/l). The average total and settleable effluent COD were 102 (±43) and 81 (±26) mg/l respectively, corresponding to a COD\text{t} removal of about 82% and a COD\text{s} removal of about 83.5%. The effluent COD concentrations observed even at long HRT (24 hours) are probably of a non-biodegradable COD nature. Similar effluent COD concentrations and COD removal were observed by Vieira and Garcia (1992) (83 mg COD/l/day and 65%), Souza and Foresti (1996) (58 mg COD/l/day and 86%), El-Gohary and Nasr (1999) (145 mg COD/l/day and 77%) and Kalogo and Verstraete (2000) (97.4 mg COD/l/day and 71%) for the same temperature.

For HRTs shorter than 3 hours (corresponding to upflow velocities and influent organic load higher than 0.35 m/h and 5.0 g COD/l/day, respectively) the effluent quality deteriorated. While at longer HRTs (from 3 to 24 hours) the COD removal was always constant (around 82%), it decreased to 54.3% for COD\text{t} and 73.8% for COD\text{s} at 2 hours HRT and 37.9% for COD\text{t} and 59.2% for COD\text{s} at 1 hour HRT. The decrease in COD\text{s} removal rate can be explained by too short HRT to complete COD degradation. Results of effluent VFA concentration support this observation: at longer HRT the effluent VFA concentration was close to zero, however, at short HRTs (shorter than 3 hours) the effluent VFA concentration increased when VFA was present in the influent.

The COD\text{t} removal had a much more accentuated decrease than the COD\text{s} removal. A maximum COD\text{t} removal of between 6.0 and 8.8 g COD/l/day was observed at influent loadings between 16.4 and 23.8 g COD/l/day. At the highest organic load of 31.8 g COD/l/day, a decrease to 5.4 g COD removed per litre per day was observed. The decrease in COD\text{t} removal can be explained by the sharp increase in effluent TSS from about 20 mg/l, at HRTs longer than 3 hours, to about 100 mg/l and 220 mg/l, at 2 and 1 hour HRT respectively (Figure 3). It appears that the higher upflow velocity caused influent suspended solids washout, as opposed to a gradual increase that would be expected if the retention time was limiting. Batch tests also suggested that the effluent TSS originated from the influent because of the absence of gas production from the effluent particulate material.
When the reactor was submitted to two different influent TSS concentrations (150 mg TSS/l and 300 mg TSS/l) at different HRTs, the same upflow velocity limitation (0.35 m/h) was observed. In both cases, the reactor demonstrated a linear relationship between TSS removal (82%) and TSS loads for HRTs longer than 3 hours, even though the influent TSS load was much higher for the second case. At shorter HRTs, the TSS removal began to decrease in both cases, leading to the conclusion that the high upflow velocity was the limiting rate for both CODt and TSS removal, and not the retention time. The critical upflow velocity where CODt removal decreased is similar to the range reported by other authors, 0.33 to 0.67 m/h (Collivignarelli et al., 1991; Lettinga and Hulshoff Pol, 1991; Maaskant et al., 1991; Vieira and Garcia, 1992; Chernicharo and Cardoso, 1999; Kalogo and Verstraete, 2000).

The same upflow velocity limitation was observed at all temperatures studied (28, 20, 14 and 10°C), with an almost constant CODt removal for lower upflow velocities (Figure 4). For each temperature studied the CODt removal decreased with the decrease in the temperature, except in the case of 20°C, where at the longest HRT, the CODt removal reached similar values as at 28°C (~80%). Usually, decreasing the temperature negatively affects the kinetics and therefore increasing the HRT results in removal efficiency improvement. However, the HRT did not improve COD degradation at upflow velocities lower than 0.35 m/h (constant 68% and 44% at 14°C and 10°C, respectively). These results suggest a much lower biodegradability at lower temperatures of a range of compounds comprising the heterogeneous composition of domestic wastewater. In addition, it is possible that lower temperatures induced shifts in the bacterial population with predominantly slower kinetics. The COD removal rates observed at 20°C, 14°C and 10°C are in accordance to results observed by others (Lettinga et al., 1981; Grin et al., 1983; Vieira and Souza, 1986; Elmitwalli et al., 1999; Seghezzo et al., 2000).

The methane production rate showed a similar pattern at 28°C, 20°C and 14°C. At these temperatures the methane production increased with increasing influent COD organic load, up to 10.0 g COD/l/day for 28°C and 5.0 g COD/l/day for 20°C and 14°C. At higher loads a constant methane production of 1,100, 225 and 85 ml CH₄/l/day was observed for 28°C, 20°C and 14°C, respectively. At 10°C a very low methane production was observed for all the inflow organic loads, 25 ml CH₄/l/day.

The calculated temperature activity coefficient based on the maximum methane production was 1.220 (R² = 0.95), which was in the upper range of reported values for anaerobic processes (Gujer and Zehnder, 1983; Haandel and Lettinga, 1994). Moreover, the experimental temperature activity coefficient is higher than the one observed for methanogenic bacteria in batch experiments with granular sludge, 1.066 (R² = 0.92). Based on these results, it can be concluded that the hydrolytic bacteria were more affected by temperature changes than the methanogenic bacteria. As seen, the methane production rate showed a
decrease with temperature, as with the COD\textsubscript{t} removal (Figure 4). However, the decrease in the maximum methane production was much more pronounced than the decrease in the COD\textsubscript{t} removal. This phenomenon can be explained by suspended solids entrapment (accumulation) in the reactor, which resulted in better COD removal, but did not improve methane production.

The phenomenon of suspended solids accumulation in the reactor was not apparent at 28°C. The sludge mass in the reactor during summer conditions (28 °C) had a constant value of 200 g and a constant SVI value of 10 ml/g. In contrast, at lower temperatures solids of different appearance than the normal granular sludge accumulated in the reactor. As the temperature decreased and the rate of hydrolysis decreased, the daily increase in the reactor sludge was greater. The increase in the accumulation of particulate matter in the reactor roughly equalled the decrease in the biological degradation rate with temperature and explains the similar overall COD removal efficiencies obtained at 28°C, 20°C and 14°C, as observed in Figure 4. In addition, a number of observations regarding solid accumulation were made.

1. On visual examination, the particulate matter accumulated at the top of the sludge blanket had a floc-like appearance with a brown color different from the rest of the typically black granular sludge. The brown color and floc characteristics are probably due to the influent feedstock characteristics.

2. VSS/TSS ratio of the particulate matter was the same as the influent suspended solids, 84%.

3. In batch tests conducted with this particulate matter, zero gas production was observed. Seghezzo et al. (2000) studying a UASB reactor at 15°C also observed lower methanogenic activity in the upper part of the sludge blanket.

4. The SVI of the upper sludge was 38.8 ml/g, which was significantly higher than the typical SVI of the sludge. The difference in SVI can explain the accumulation of the particulate material on top of the typical bacterial granules. Due to the higher SVI value, the flocculent type sludge had a greater sensitivity to upflow velocities than the granular sludge. This fact can explain the increase in the effluent TSS concentration at longer HRT with the decrease in temperature. At 28°C the average effluent TSS concentration was 17.7 mg TSS/l, which increase to 26.6 mg TSS/l at 20°C, 60.3 mg TSS/l at 14°C and reached 120 mg TSS/l at 10°C.

During the transition from winter to summer conditions (10°C to 28°C) the methane production initially increased and then gradually declined over time, reaching values similar to the previous summer (28°C). In contrast, COD\textsubscript{t} removal at the beginning of the new warmer season was very low (59%) in comparison to the previous summer. The low COD\textsubscript{t} removal suggests that the high gas production observed was due to the degradation of the accumulated suspended matter and not the influent organic matter. An improvement in
CODₜ removal was observed with time, reaching again 82% after 40 days. The improvement in CODₜ removal together with the reduction in the gas production indicates that the accumulated matter was exhausted and influent degradation reached the values observed in the first summer season.

Conclusions
Based on the results of this investigation, it can be concluded that the UASB reactor can be a good alternative for domestic wastewater treatment even in temperate climates. During winter conditions when many municipal wastewater temperatures are about 14°C and the bacterial hydrolytic activity is lower, solids accumulation in the reactor will be more pronounced and COD removal performance will continue to be good (68%). The accumulated sludge from the winter is subsequently digested in the following summer, as is evidenced by a large gas production at the beginning of the new warm season.

References


