Impact of temperature on performance, microbiological, and hydrodynamic aspects of UASB reactors treating municipal wastewater

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Abstract
The present study examined the feasibility of treating municipal wastewater by a UASB system under low-temperature conditions. Two reactors were started-up at 20°C and subsequently operated at temperatures of 32, 20, 15, 11, and 6°C applying several hydraulic retention times (HRTs) ranging from 48 to 3 h during an operational period of approximately 900 days. Chemical oxygen demand (COD) removal efficiency ranged from 70 to 90% up to an HRT of 6 h and 11°C. The performance of the reactor was not very satisfactory during 6°C operation (average COD removal 40%). Sulfate reduction played an important role in COD reduction. Digital image analysis and scanning electron microscopic observations of sludge samples revealed aggregation of biomass in the form of irregular shaped granules (mean size ranged from 1.5 to 3.0 mm). The hydraulic regime in the reactor was impacted by the change in operating temperature. This study demonstrated that the UASB system could be applied successfully for pre-treatment/treatment of municipal wastewater under low-temperature conditions.

Keywords
Aggregated biomass; low temperature; municipal wastewater; performance; UASB reactor

Introduction
Upflow anaerobic sludge blanket (UASB) reactors are used successfully for several types of industrial (high to medium strength) wastewaters and low-strength wastewaters (Lettinga et al., 1984; Singh et al., 1996; Agrawal et al., 1997; Seghezzo et al., 1998). The success of the UASB process lies in its capability to retain a high concentration of immobilized active biomass because of the granulation of sludge particles (Hulshoff Pol, 1989). At present, the UASB technology has been applied to a lesser extent in temperate and cold climates. However, it has been reported that anaerobic bacteria can adapt quite easily to low temperatures, and a high-rate anaerobic treatment can be achieved at psychrophilic conditions (Kato et al., 1994; Rebac et al., 1995; Dague et al., 1998). A study was needed to examine the application of UASB reactor systems in cold regions (average temperature of municipal wastewater ranges from 6 to 15°C). The main aim of the present study was to investigate the performance and feasibility of a UASB system in the treatment of municipal wastewater in North American climates.

Methods
Two reactors (each of 8 l volume) made of polyacrylic column (height of 1.0 m and internal diameter of 10 cm) were used in this study (Figure 1). Other details related to the reactor, seed sludge, and operation can be found elsewhere (Singh and Viraraghavan, 1998). The feed to each reactor was raw municipal wastewater (COD: 350–600 mg/L; BOD5: 150–200 mg/L; SS 150–200 mg/L; sulfate as S: 50–100 mg/L), collected at the City of Regina Wastewater Treatment Plant.

All chemical analyses were conducted according to Standard Methods (APHA, AWWA
and WEF, 1992). Volatile fatty acids (VFAs) and gas compositions were determined by a gas chromatograph (Varian GC 3600) using flame ionization and thermal conductivity detectors, respectively. Helium was used as a carrier gas for both detectors at a head pressure of 30 psi. Granulation of sludge particles (biomass) was investigated using a digital image analysis system (Singh et al., 1997). The mechanism of aggregation was explored by morphological observations and elemental composition of the surface of aggregated biomass. Morphological observations were made using scanning electron microscopic techniques (Singh et al., 1996) and elemental composition was determined by X-ray electron diffraction technique. Mass balances on COD and sulfur compounds were made based on equations described by Singh and Viraraghavan (1998).

The hydraulic regime was investigated using stimulus-response techniques. Bromocresol green dye (an inert tracer; Sigma Chemical Co.) was used as the tracer. The concentration of dye in the effluent was determined by measuring its absorbance at a wavelength of 610 nm using a spectrophotometer (Baush and Lomb Spectronic). A mathematical analysis of the tracer response curve was made to determine the fraction of dead space and by-pass flow fractions in the reactor (Singh, 1999).

Results and discussion
Impact of temperature on performance aspects
The COD removal efficiency achieved after 20 days of start-up was in the range of 40–60%. COD removal continued to improve steadily during the whole period of operation. The start-up lasted for about 60 days with a COD removal efficiency of 80 to 85% at the end of the start-up period.

The effect of HRT and temperature on COD, BOD and SS removal was investigated through the data point observations made during the stable period of operation (Figure 2). It was observed that at an HRT of 6 h, there was an average reduction of 84% (SD 2.14), 87% (SD 2.5), 81% (SD 3.18), 79% (SD 0.97), and 60% (SD 2.8) COD at temperatures of 20, 32, 15, 11 and 6°C, respectively. The BOD removals at 6 h HRT were 88%, 86%, 79%, 75% and 58% at temperatures of 20, 32, 15, 11, and 6°C, respectively. From data point observations it was found that up to the temperature of 11°C and HRT of 6 h, reactors performed well in
terms of removal efficiency. When HRT was reduced from 6 h to 4 h and 3 h, a decrease in removal efficiency of COD and BOD was observed, which was more severe at low temperatures. Similarly, when temperature was reduced from 11°C to 6°C, the reactor exhibited very unstable conditions with a significant reduction in COD and BOD removal efficiencies (30 to 40%). Suspended solids (SS) concentration in the effluent was considerably lower, ranging from 10 to 30 mg/L (SD 5) with VSS/SS ratio of 0.8 (SD 0.15). SS removal efficiency varied between 56 and 90% during the stable periods. It was observed that when HRT was reduced to 3 h at temperatures of 20 and 30°C, the SS in the effluent increased to 56 and 38 mg/L, respectively, possibly because of an increase in the upflow velocity (0.25 m/h at 4 h to 0.33 m/h at 3 h). At all temperatures studied except at 6°C, 80 to 90% SS removal efficiency was achieved (HRT of 10 h to 6 h). It was found that temperature did not affect significantly the SS removal efficiency. This was mainly due to formation of well settling biomass aggregate (granulated sludge particles) in the sludge bed and entrapment of influent SS particles. As a result of biomass aggregation, the value of sludge

Figure 2 Effect of HRT and temperature on removals of COD, SS, and BOD₅ during steady state operation
volume index (SVI) also decreased from 60 to 18 mL/g-SS. This reflected a considerable (3 fold) improvement in the settling characteristics of aggregated sludge particles. The results obtained in the present investigation were in good agreement with those determined by other researchers (Agrawal et al., 1997; Behling et al., 1997). Higher removal efficiency achieved in this study up to 11°C operation was mainly due to the proper selection and enrichment of sludge particles in the reactor.

Figure 3 shows that the gas production increased with a decrease in HRT and decreased with a decrease in temperature. In this investigation, the organic loading rate was not constant and it increased with a decrease in HRT resulting in increased gas production at lower HRTs during operation at all temperatures. The percentage of methane in the total biogas increased with a decrease in temperature and HRT (up to 4 h). This can be also ascribed to the increased solubility of gases that is associated with a decrease in temperature, as well as to the different extents of these solubility increases between methane, carbon dioxide and the other biogas components. Because of increased solubility of gases at reduced temperature, approximately more than 50% methane produced could be estimated (by Henry’s law) to be lost as dissolved methane. Methane yield was estimated to be 166, 150, 182, and 199 mL-CH$_4$/g-COD removed at standard temperature and pressure (STP) at temperatures of 20, 32, 15, and 11°C, respectively compared with a theoretical yield of 350 mL-CH$_4$/g-COD removed. The reason for a comparatively lower methane yield was due to a high fraction of particulate COD (30 to 50%), low-temperature operation and COD consumed in sulfate reduction. Sulfate reduction ranged from 10 to 90% showing a decreasing trend with a decrease in temperature at each HRT. This was due to the reduced metabolic activity of sulfate reducing bacteria (SRB) in the absence of sufficient energy source such as hydrogen and acetate at low temperatures. A general increase in sulfate reduction with a decrease in HRT was observed possibly due to the competition between SRB and methane producing bacteria (MPB) for substrate consumption. If methanogenic activity is low, SRB might out-compete MPB for a suitable substrate. The ratio of total volatile fatty acid and alkalinity ranged from 0.032 to 0.14 during the operation. This indicated that reactors were quite stable (Switzenbaum et al., 1990).

Sludge retention times (SRT) at each temperature were estimated by dividing the total biomass measured as volatile suspended solids retained (g-VSS) in the reactor by the effluent VSS (g-VSS/d). Total VSS retained in the reactor was estimated from the VSS profiles determined along the height of the reactor. It was found that as the HRT decreased so did the SRT. At an HRT of 4 h maximum COD removal efficiency (80–85%) was achieved. At this HRT (4 h), SRTs obtained were 169 ± 20, 79 ± 6, 118 ± 14, 179 ± 25, and 183 ± 14 days at the temperatures of 32, 20, 15, 11, and 6°C, respectively. However, at the temperature of
6°C only 30 to 40% COD removal efficiency was achieved. Based on the COD mass balance, retained biomass, effluent VSS, and neglecting biomass decay, an SRT of about 45 ± 10 days was estimated to be critical for the accumulation of biomass in the reactor under conditions used in the present study. Jewell (1985) reported a minimum SRT of about 130 days to achieve 80% soluble COD removal in an anaerobic attached film expanded bed (AAFEB) reactor at 30°C with a soluble substrate concentration between 200 and 600 mg-COD/L. To be successful, a biological treatment process must have an SRT higher than the critical value; otherwise the reactor would eventually lose all the retained active biomass in the effluent.

Specific methane formation potential (SMFP) based on recovered methane in biogas increased from 0.065 kg-methane-COD/kg-VSS-d (at an HRT of 48 h) to 0.39 kg-methane-COD/kg-VSS-d (at an HRT of 6 h) during the operation at 20°C. SMFP showed a decreasing trend with a decrease in temperature. SMFP decreased by approximately 10%, 28% and 94% when temperature was reduced from 20°C to 15, 11, and 6°C, respectively.

Bacteriological performance in terms of fecal coliform reduction was clearly demonstrated. Fecal coliform reduction in general became less obvious with a decrease in temperature. High temperature and HRT were found to be more favourable for the reduction of fecal coliforms.

Impact of temperature on granulation and morphology of biomass
Digital image analysis and scanning electron microscopic observations of sludge samples from the UASB reactor demonstrated that biomass granulation (aggregation) progressed over time during 20°C operation. Biomass aggregates were found to be of irregular shape (mostly with uneven and rough surfaces). Fractal dimension analysis of sludge aggregates (Bellouti et al., 1997) based on results obtained through digital imaging software suggested that aggregated sludge particles were between the category of granular and flocculent type of sludge aggregates (pellets). Enrichment of rod type, segmented filamentous type and cocci-type anaerobic bacterial cells were observed. Filamentous Methanothrix-type of bacteria predominated on the surface of aggregated biomass. A significant amount of polymeric substance was present, possibly excreted by microorganisms. These substances probably acted as a bridging or adhesive material to form biomass aggregates or help in attaching cells on the inert surface. Moreover, surface roughness also influenced microbial cell attachment, by providing shelter for small particles from shear forces, and by increasing the available surface area for attachment. No significant differences were observed in the bacteriological composition of aggregated biomass with a decrease in temperature. The mean size of granulated biomass (1.8 mm to 3.0 mm) at a low temperature of 11°C was slightly higher compared with that of 20°C (1.5 mm to 2.5 mm). Surface elemental composition of the granulated biomass measured by X-ray diffraction analysis indicated that divalent cations such as calcium and magnesium facilitated the adhesion of cells resulting in the formation of pellets and granular type of aggregation. The atomic percentage of the sodium ion on the surface increased with a decrease in operating temperature which possibly resulted in a more fragile type of aggregated biomass matrix at a low temperature of 11°C compared with 20 and 32°C. Iron and sulfur (as ferrous sulfide precipitate) were also present on the surface of granules in a significant amount which also possibly contributed to the aggregation of biomass (Hulshoff Pol, 1989).

Impact of temperature on flow pattern
A Bromocresol Green Tracer (MW 720) experiment was conducted on UASB reactors at 20, 32, 11, and 6°C and at 10 hour HRT. Residence time distribution (RTD) normalized curves of the tracer suggested that the flow pattern at higher temperatures (20 and 32°C)
follow a more complete mix flow pattern than a plug flow pattern. The flow pattern in the reactor shifted towards a plug flow regime with decrease in temperature from 20 to 11 and 6°C. The reason for this shift can be ascribed to insufficient gas mixing because of a low gas production resulting in dead zone formation and by-pass flow. UASB reactors treating municipal wastewater could be characterized as tank-in-series reactors. At 20 and 32°C operation it can be segmented into a series of completely mixed regions. At lower temperatures (11 and 6°C) reactors can be segmented as mixed flow zones (sludge bed zone) followed by plug flow dispersion zones (blanket and settler zones) in series.

Table 1 shows the impact of temperature on the by-pass flow fraction and dead zone fraction at each temperature (HRT = 10 h). It was found from the mathematical analysis of tracer response curves that the dead zone fraction increased with a decrease in operating temperature. It showed that the slow-mixing unit was not able to provide sufficient mixing to avoid completely the formation of dead zones in the reactor. It indicated that inherent biogas mixing plays a crucial role in ensuring a near total elimination of dead space in the UASB reactor, though this cannot be avoided in a reactor treating municipal wastewater under low temperature conditions. Similarly, the by-pass flow fraction also increased when the operating temperature was reduced from 20 to 6°C.

**Conclusions**

This study concluded that a UASB reactor could be started-up successfully for application at low temperatures for municipal wastewater treatment/pre-treatment in cold regions (average summer temperature 15 to 20°C). UASB reactors can be optimally designed for 6 to 10 h HRT for a low temperature operation up to 11°C with a reasonable COD, BOD, and SS removal efficiency (70 to 90%). Compared with typical effluent quality requirements of 30 mg/L BOD and 30 mg/L of SS, the UASB system in this study was able to meet SS requirements in effluent (less than 30 mg/L) but could not meet the effluent BOD requirements. The high residual BOD (35 to 75 mg/L) in the effluent was possibly due to the presence of anaerobic soluble microbial products in the effluent which could not be completely degraded under low-temperature conditions at low HRTs. Incorporation of a simple aerobic biological post-treatment unit may be required to meet the effluent discharge criteria.

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**References**


