Problems encountered during the start-up of up flow anaerobic sludge blanket reactors (UASB) at 20 ⁰C & 15 ⁰C

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**KEYWORDS**

- Biogas accumulation
- Low temperature operation
- Synthetic wastewater
- Up flow anaerobic sludge blanket (UASB)
- Wastewater solids

**ABSTRACT**

UASB technology has been widely adopted for the treatment wastewaters in warm climates. Operation at low temperature wastewaters still present some challenges. When working at lower temperatures a number of operational problems were experienced associated with the accumulation of biogas and wastewater solids in or below the sludge bed. Physical entrapment of the biogas produced formed a buoyant plug, which had a tendency to float the sludge bed. An operational solution to this problem was found which involved fluidising the bed once a day to ensure better distribution of organic solids and allow the release of any trapped biogas. This was achieved by pumping biogas directly from the reactor headspace back up through the bed for a period of ~4 minutes, then allowing the bed to settle for a short period (< 10 minutes) before allowing the effluent to discharge. This mode of operation has not been previously been reported and represents a valuable low-energy approach to dealing with high solids wastewaters of this type at low operating temperatures. The results confirmed that full flow treatment under ambient conditions, without heating of the UASB reactor, was feasible.

**Introduction**

Despite the extensive literature dealing with wastewater treatment using UASB reactors, several aspects needed to be elucidated. For example, only limited data are available for UASB reactors treating sewage under extreme conditions: most of the reported results refer to anaerobic systems operated at temperatures above 20 ⁰C and HRT from 4 to 10 hours (Seghezzo et al. 1998; Foresti, 2001). The operational limits of UASB reactors in many situations and for many wastewater types are still unclear (Leitão, 2004). Thus, several challenges remain to be solved if the UASB process is to be implemented for the treatment of wastewater on a worldwide basis. The up flow anaerobic sludge blanket (UASB) reactor is now a common type of high-rate reactor for treatment of industrial and domestic wastewaters. It has a simple design, can be easily built and maintained, is relatively low cost, and can cope with a range of pH, temperature, and influent substrate concentrations (Lettinga and Pol, 1991; Cronin and Lo, 1998; Alvarez et al. 2006; Tiwari et al., 2006).

Low temperature causes an increase in water viscosity, and reduces the interchange between the organic matter in the effluent and the sludge bed (Driessen and Yspeert, 1999; Uemura and Harada, 2000; Price and Sowers, 2004). To solve this problem, it is necessary to improve the contact between the wastewater and the sludge bed (Kato et al. 1994; 1997; Rebac, 1998). Temperature shocks may affect the operation of UASB reactors. Van Lier et al. (1990) carried out a study in which temperature shocks of 45, 55, 61, and 65 ⁰C were applied to a UASB operating on synthetic wastewater at 39 ⁰C. No adverse effects were seen at 45 ⁰C but higher temperatures led to a sharp drop in the activity of the microbial consortium. Ganidi et al. (2009) carried out an extensive study of foaming in aerobic and anaerobic reactors and identified a range of causes and factors affecting severity. It was noted, however, that there was very little information in the literature relating to foaming in UASB this may indicate either that this type of reactor is potential advantageous with respect to foam formation, or that the types of substrate used are less liable to foaming. Cuervo-López et al. (1999) studied the effect of carbon source and nitrogen loading on UASB reactors and found foaming occurred at nitrogen loading rates...
above 500 mg N/L/day with glucose as the carbon source.

Foaming has also been reported for specific wastewater types: Koster and Lettinga (1985) reported foaming when treating potato starch wastewaters at low temperatures (14 and 20 °C), and other researchers have experienced similar issues with this wastewater (Kalyuzhnyi et al., 1998; Parawira et al., 2006). Foaming occurred in the UASB component of a combined packed bed reactor followed by a UASB treating oily wastewater (Jeganathan et al., 2007). In a comparative study of EGSB and UASB treating palm oil mill effluent, however, foaming and biomass washout was observed in the EGSB reactor but not in the UASB (Fang, 2011). To avoid foaming during the digestion of high lipid or protein wastewaters Lettinga and Pol (1991) recommended low loading rates and special attention to providing good contact between the granular sludge and the wastewater, as well as spray nozzles and skimmers for foam reduction and removal. In this work, operational problems during the operation of UASB reactors are discussed. Major problems encompass the gas entrapment in the granular sludge bed, formation of scum and crustation. This led to operational difficulties, as any biogas produced in this area was unable to escape, leading to floating of all or part of the sludge bed. The problem was solved by recycling the reactor headspace gas once per day, at a flow rate and time period sufficient to disrupt the bed and redistribute the accumulated solids throughout it. In this way, the applied solids loading could be dealt with effectively even at lower operating temperatures used.

Research Methods
The experiment used eight 4-litre continuously fed UASB reactors Figure 1. The reactors were operated in two sets of four, the first set (R1-4) working at 20 °C and the second set (R5-8) at 15 °C. Influent COD concentration was kept constant at about 750 mg COD/L, and the OLR was increased by reducing the HRT from a nominal 24 hours to 18, 9 and 6 hours. Operating conditions during the experimental are shown in Table 1. The reactors started up at an OLR of 0.5 g COD/L/day (synthetic sewage strength 500 mg COD/L) to allow re-acclimatisation. After two weeks the strength of the synthetic sewage was increased to 750 mg COD/L, as shown in Table 1 for more details. The granular sludge was then removed from the reactors, and about 2 kg of stored granular sludge from the original source was added to make up the required quantity. The material was thoroughly mixed, and 2 kg wet weight of granular sludge was added to each reactor for the start of the current experiment. The composition of the synthetic wastewater used is given in Table 2. The synthetic wastewater was based on one used by Whalley (2008) which was designed to resemble municipal wastewater in a range of relevant properties, as shown in Table 3.

Analytical methods
Total suspended solids
Total suspended solids (TSS) content was measured by passing a sample of known volume through a 0.4 μm pore size glass fiber filter paper (GF/C, Whatman, UK) of known dry weight (~ 0.1 mg). After drying at 105 °C for 24 hours, the paper was again weighed and the difference determined.

COD measurement
COD was measured by the closed tube reflux method with the titrometric determination of the endpoint (APHA, 2005)

Gas Composition
Biogas composition was quantified using a Varian Star 3400 CX gas chromatograph (Varian Ltd, Oxford, UK). The GC was fitted with a HayeSep C column and used either argon or helium as the carrier gas at a flow of 50 ml min⁻¹ with a thermal conductivity detector. The biogas composition was compared with a standard gas containing 65 % CH₄ and 35% CO₂ (v/v) for calibration. A sample of 10 ml was taken from a Tedlar bag used for sample collection and was injected into a gas-sampling loop.

Gas Volume
Biogas was collected in a gas-impermeable sampling bags and volume was measured using a weight-type water displacement gasometer (Walker et al., 2009).
Figure 1. UASB digesters – revised configuration

Table 1. Reactors operating conditions

| Reactor | Day From | Days To | No | Target temp. °C | Target Inf. COD mg/L | Target OLR g COD/L/day | Target HRT Hours |
|---------|----------|--------|----|-----------------|----------------------|------------------------|-----------------|
| R1-4    | 0        | 88     | 89 | 20              | 750                  | 0.75                   | 24              |
|         | 89       | 161    | 73 | 20              | 750                  | 1                      | 18              |
|         | 175      | 246    | 72 | 20              | 750                  | 2                      | 9               |
|         | 247      | 352    | 106| 20              | 750                  | 3                      | 6               |
| R5-8    | 0        | 111    | 112| 15              | 750                  | 0.75                   | 24              |
|         | 112      | 161    | 50 | 15              | 750                  | 1                      | 18              |
|         | 175      | 246    | 72 | 15              | 750                  | 2                      | 9               |
|         | 247      | 260    | 14 | 15              | 750                  | 3                      | 6               |
|         | 261      | 352    | 92 | 15              | 750                  | 2                      | 9               |

Table 2. Composition of synthetic wastewater concentrates. (Diluted to give a working solution) (Based on Whalley, 2008)

| Component                        | Unit | Quantity |
|----------------------------------|------|----------|
| Yeast (block bakers form)        | g    | 23       |
| Urea                             | g    | 2.14     |
| Full cream milk (UHT sterilised) | mL   | 144      |
| Sugar (granulated white)         | g    | 11.5     |
| Dried blood                      | g    | 5.75     |
| Ammonium phosphate (NH₄)₂HPO₄    | g    | 3.4      |
| Tap water                        | L    | Make up volume to 1 L |
Table 3. Characteristics of synthetic wastewater as used by Whalley (2008) at 1:100 dilution

| Parameter          | Unit   | Average | Range (In 5 Samples) |
|--------------------|--------|---------|----------------------|
| TS                 | mg/L   | 772     | 746-813              |
| VS                 | mg/L   | 498     | 449-541              |
| TSS                | mg/L   | 170     | 140-202              |
| VSS                | mg/L   | 118     | 83-138               |
| Fixed SS           | mg/L   | 52      |                      |
| TDS                | mg/L   | 556     | 522-587              |
| VDS                | mg/L   | 329     | 310-349              |
| Fixed DS           | mg/L   | 227     |                      |
| Settleable solids  | mL     |         |                      |
| 1hr                | 0.1    |         |                      |
| 2hr                | 0.2    |         |                      |
| 3hr                | 0.3    |         |                      |
| 4hr                | 0.4    | 0.3-0.3 |                      |
| 6hr                | 0.4    | 0.4-0.4 |                      |
| 24hr               | 0.5    | 0.5-0.5 |                      |
| 5d                 | 1.4    | 1.3-1.5 |                      |
| TC                 | mg/L   | 221     | 213-238              |
| TOC                | mg/L   | 195     | 175-221              |
| COD                | mg/L   | 460     | 450-474              |
| BOD                | mg/L   | 220     | 187-247              |
| COD:BOD ratio      |        | 2.1     |                      |
| Settled COD        | mg/L   | 345     |                      |
| Settled BOD        | mg/L   | 195     |                      |
| TN                 | mg/L   | 33      | 29-36                |
| TKN                | mg/L   | 24      | 21.8-26              |
| Nitrate            | mg/L   | 0.38    | 0.21-0.56            |
| Ammonia            | mg/L   | 9.8     | 9.1-10.6             |
| Orthophosphate     | mg/L   | 5.2     | 4.8-5.5              |
| Total Phosphorus   | mg/L   | 7       | 6.9-7.2              |
| Alkalinity         | mg CaCO₃/L | 147     | 127-164              |
| pH                 |        | 7.34    | 7.32-7.36            |
| Chloride           | mg/L   | 49      | 44-54                |
| Sulphate           | mg/L   | 43      | 37-47                |
| Copper             | mg/L   | 0.161   | 0.158-0.162          |
| Zinc               | mg/L   | 0.066   | 0.060-0.07           |
| Lead               | mg/L   | 0.043   | 0.038-0.047          |
| Iron               | mg/L   | 0.285   | 0.278-0.296          |
| Fats & oils        | mg/L   | 44      | 41.5-47.5            |
| Anionic detergents | mg/L   | 0.21    | 0.21-0.21            |

Results and Discussion

**Operational aspects**

Operation at 15 and 20 °C presented some difficulties, in the form of repeated blockages of the influent and gas lines and floating of the sludge bed, probably associated with the slower rate of degradation of organic solids present in the synthetic wastewater. A number of steps were taken to address these issues. On day 162 the contents of the effluent container were pumped rapidly through the reactor to mix the bed. This released trapped biogas but was not an effective approach as the
whole bed dispersed and gas and granular sludge were able to escape with the effluent.

From day 162-175 the reactors were not fed to allow conversion of accumulated undegraded organic material in the bed. From day 176-196 on alternate days, each reactor was lifted out of its insulated box and shaken 2-3 times. This was reasonably effective in releasing trapped gas, and thus probably reduced the occurrence of floating, but was time-consuming and physically demanding, and could also lead to blockages of the gas line due to sludge remaining in the gas separator (see below).

To clarify the nature of the problem and identify effective methods for resolving it, tests were carried out in a clear open-topped Perspex column 100 mm in diameter with a volume of approx. 4 litres, similar to that of the UASB reactors used in this investigation. The column was filled with 2 kg wet weight of granular sludge and fed with synthetic wastewater from the feed tank used to supply R5-8, at an OLR equivalent to that in the reactors. In all cases after operation for a few days, the sludge bed rose in the column as a result of bubbles trapped within and underneath it, and a layer of accumulated solids could be seen at the base of the bed (Figures 2, 3, 4 and 5).

A variety of strategies were trialled to determine the most effective way to break up the consolidated bed. Pumping of liquid was found to be much less effective than pumping gas or a gas/liquid mixture: with liquid only the flow tended to find a single pathway through or around the material, with the majority of the sludge bed remaining intact.

From day 196-314, based on the results of the Perspex column trials, the system was operated by attaching the gas bag containing the previous day's biogas production to the feed line, and pumping the gas through at the maximum feed pump speed in order to break up the sludge bed. Emptying of the gasbag took around 3-4 minutes, with gasbag volumes in this period ranging from 2.6-4.0 litres (uncorrected, i.e. not STP). At the maximum pump, speed of 400 rpm the gas flow was about 570 ml biogas per minute. The pumped gas together with any escaping from the bed was collected in a second gasbag attached to the gas outlet, and measured and analysed as usual. This method was effective in disturbing the bed without approximately linear, with slopes of -3.3 % per g COD/L/day at 20 °C (R2 = 0.8991, n = 16, p < 0.001) and -5.6 % per g COD/L/day at 15 °C (R2 = 0.9184, n = 20, p < 0.001). Biogas methane content appeared to decline slightly at 15 °C at a rate of allowing granular sludge to escape, and in preventing or reducing occurrences of floating. It had the disadvantage, however, of requiring disconnection of the feed line and of leaving it full of gas, both of which could allow small amounts of granular sludge to enter the feed line. This can be seen in the large number of full and partial blockages occurring in this period, especially in R1 and 5.

On day 276 the filter material at the bottom of the UASB reactors was removed. This had originally been provided to support the sludge bed and improve distribution of the incoming feed. With the new mode of operation, the filters tended to become detached and rise to the top of the reactor, or even into the gas separator: however, removal of the filter may have exacerbated the problem of granular sludge blocking the feed line.

From day 314 the procedure was therefore modified so that the gas was recirculated directly from the gas separator headspace, via a three-way valve connection into the feed line. The recirculation pump speed was kept at the maximum value, but the gas flow appeared to be higher than before due to removal of the constriction caused by the gasbag valve. Gas was recirculated for approximately 4 minutes as before, but this was adjusted by the operator based on sighting of granular sludge in the gas separator and sometimes continued for longer to ensure the bed was mixed. After gas recirculation, the sludge bed was allowed to settle for 5-10 minutes while other daily maintenance tasks were carried out, before feeding recommenced. This procedure proved easy to operate and highly effective, as can be seen from the small number of blockages occurring in the final stages of the trial, and was therefore maintained for the rest of the experimental period and in all subsequent experiments.

**Overall performance**

Overall performance. Table 4. and Figure 6 summarise the results for operation at 15 and 20 °C. It can be seen that although volumetric biogas and methane production increased with increasing OLR the relationship was no longer linear, with a distinct drop-off at OLR above 2.5 g COD/L/day, especially at 15 °C. COD removal showed a slight decline with increasing OLR and reducing HRT: this was around -1.7 % per g COD/L/day (R2 = 0.7974, n = 20, p < 0.001).

These results indicated that an OLR of 2.5 g COD/L/day, corresponding to a HRT of around 8 hours based on modified reactor volume, was the maximum before the performance started to
deteriorate. At OLR 2.5 g COD/L/day the digesters at 20 °C performed as well as those in the baseline study in terms of COD removal and gas production, while at 15 °C COD and OLR 2 g COD/L/day removal had declined to 85 % and SMP to 0.24 l CH₄ /g COD added, representing a reduction in energy recovery and an increased requirement for treatment downstream.

![Figure 2. Part of sludge bed broken away](image2)

![Figure 3. floating sludge beds](image3)

![Figure 4. Gas trapped beneath sludge bed](image4)

![Figure 5. Sludge bed after floating](image5)

| Table 4. The results for operation at 15 and 20 °C |
|-----------------------------------------------|
| Average OLR | COD removal | VMP | CH₄ | SMP added | SMP removed | Actual/ ThCH₄ |
| g COD/L/day | % | L/L/day | % | L CH₄ /g COD added | L CH₄ /g COD removed |
| 20 °C | | | | | | |
| 0.7 | 0.94 | 0.2 | 0.87 | 0.28 | 0.3 | 0.87 |
| 1 | 0.95 | 0.24 | 0.86 | 0.25 | 0.26 | 0.74 |
| 2 | 0.91 | 0.53 | 0.86 | 0.27 | 0.3 | 0.85 |
| 2.5 | 0.89 | 0.62 | 0.85 | 0.24 | 0.27 | 0.78 |
| 15 °C | | | | | | |
| 0.7 | 0.94 | 0.16 | 0.88 | 0.24 | 0.26 | 0.74 |
| 1 | 0.94 | 0.23 | 0.88 | 0.24 | 0.25 | 0.73 |
| 1.9 | 0.88 | 0.44 | 0.87 | 0.24 | 0.27 | 0.77 |
| 2 | 0.85 | 0.48 | 0.87 | 0.24 | 0.28 | 0.79 |
| 3 | 0.82 | 0.55 | 0.84 | 0.18 | 0.22 | 0.63 |
Figure 6. Kinetics of key parameters at 15 and 20 °C

Conclusion

At 15 and 20 °C, a number of operational problems were experienced associated with the accumulation of biogas and wastewater solids in or below the sludge bed. These are known issues for the UASB treatment of low temperature, low-strength wastewaters, but in this case were probably exacerbated by the very low upflow velocities being trialled in the current work. A solution for these problems was found, based on fluidising the bed once a day to ensure better distribution of organic solids and allow the release of any trapped biogas. This was achieved by pumping biogas directly from the reactor headspace back up through the bed for a period of ~4 minutes, then allowing the bed to settle for a short period (< 10 minutes) before allowing the effluent to discharge. This mode of operation has not been previously been reported and represents a valuable low-energy approach to dealing with high solids wastewaters of this type at low operating temperatures.

Conflict of interest

The authors have no conflicts of interest to declare.

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