ANAEROBIC TREATMENT OF AN APPLE PROCESSING WASTEWATER

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ABSTRACT

The new generation of anaerobic digestion systems provide a high level of performance under optimal conditions (~37°C). However, in practice many influents will be at lower temperatures – heating of digesters presents problems, particularly in developing countries where technical backup is limited. This paper reports on a study of the treatment of a low/medium strength apple juicing waste in an upflow anaerobic sludge blanket reactor (UASB) at temperatures less than optimal (25°C and 30°C). Maximum loading rates of approximately 12 and 16 kg COD m⁻³ d⁻¹ were attained at 25°C and 30°C, respectively, for influent concentrations in the range 2500 to 5000 mg COD l⁻¹. The comparative treatment capacity is in accord with the reported temperature sensitivity of mesophilic anaerobic processes. Formation of pelletised (granular) sludge enabled high upflow velocities and low hydraulic retention times.

KEYWORDS

Anaerobic digestion, upflow anaerobic sludge blanket, UASB, loading rate, volatile acids, granular sludge, pelletised sludge, temperature sensitivity.

INTRODUCTION

Over the past decade there has been an upsurge of interest in the new generation of anaerobic digestion systems such as the upflow anaerobic sludge blanket and the anaerobic attached film expanded bed systems. These systems have been applied principally in the treatment of medium to high strength industrial and agricultural wastes, of an essentially soluble nature. The reason for their success is that with these systems a solution has been found for one of the major problems that beset the traditional systems (e.g. clarigester, anaerobic contact process); namely, retaining sludge within the system without having to resort to low sludge concentrations demanding excessively large reactors and settlers. The sludge in the new systems separates readily with virtually no loss in the effluent even though very high concentrations of sludge can be maintained, in excess of 100 kg m⁻³ (Pette and Versprille, 1981). As a consequence it is possible to reduce the hydraulic retention time in the system substantially; times as short as 1.5 to 2 hours for low strength influents (1500 mg COD l⁻¹) have been reported (Lettinga et al. 1983; Schraa and Jewell, 1984).

Of the various "new" systems the upflow anaerobic sludge blanket (UASB) system is the least complex, and simplest to operate. In the other popular system, the anaerobic attached film expanded bed (AAFEH), the biological mass is attached to a support medium (e.g. sand) and it is necessary to recycle from above the bed to keep the medium/biological particles in suspension; no such recycle is required in the UASB process. This lack of complexity...
constitutes a significant advantage for the UASB, particularly for small systems and in regions where technical supervision is deficient.

Anaerobic systems generally are very sensitive to the system operating temperature, the maximum treatment capacity and process efficiency (to a lesser degree) increasing as the temperature increases, up to about 37°C. The reduction in capacity with reduction in temperature is so severe that for the traditional systems, with minor exceptions, the experimental investigations and practical applications have been confined principally to the near-optimal temperature range. It is not surprising therefore that the majority of investigations into the new systems have been carried out at temperatures above 30°C. However, in practice many influents will be at temperatures less than 30°C and in these instances heating of the reactors is required if optimal performance is to be attained.

Heating of anaerobic systems always presents problems of cost, operation and maintenance; these are particularly onerous for small units, and in regions where technical backup is not so readily available. However, the new generation systems have shown such remarkable performance at optimal (high) temperatures that even with a substantial reduction in performance at lower temperatures these may still present a viable method for treatment without heating. It is important therefore that the performance characteristics of these systems be known at lower temperatures.

From the discussion above, the UASB system appears to have the highest expectation of successful implementation and operation in regions where technical backup is inadequate. Of particular value would be information on the response of this system at temperatures less than optimal, say at 30°C and 25°C. This paper describes the results of such a study, on the temperature aspect of a UASB system treating a low to medium strength waste from an apple juicing plant. Specific objectives were:

1. Evaluate the performance at 25°C and at 30°C.
2. Ascertain if acceptable organic loading rates can be attained at 25°C.
3. Investigate the interaction of waste COD concentration and hydraulic retention time in the low/medium influent concentration range.
4. Ascertain if granular/pelletised sludge formation would take place in the UASB system operated under these conditions - this has an important bearing on practical implementation of the process.

MATERIALS AND METHODS

Apparatus: Two identical laboratory-scale upflow anaerobic sludge blanket reactors were constructed. Each reactor consisted of a perspex cylinder with a gas/liquid/solid separator arrangement at the top. The configuration of the two reactors is shown schematically in Fig 1, and in a photograph in Fig. 2. The inside diameter of the reactors was 10.0 cm and the height 120.0 cm, giving a total effective reactor volume of 9.0 litres.

Feed was made up each day and pumped to the reactor from a refrigerated vessel using a variable speed peristaltic pump. The feed line was split into four and connected to four inlet ports at the bottom of the reactor wall. During the start-up period an axially-mounted flat impeller was positioned 10 cm above the reactor base to allow mixing of the lower section of the reactor contents and to improve feed distribution, as suggested by Lettinga (1980).

The gas collection system at the reactor top was by means of a hollow cone. Rising gas bubbles were deflected into the cone by a collar on the inside wall of the reactor below the cone. Effluent gas flow was measured by a wet gas meter. Liquid passed out of the reactor through the annular space between the cone and the reactor wall to enter a small solid/liquid separator (volume less than 500 ml); clarified liquid flowed over a launder to the collection vessel. The volume provided for solid/liquid separation was small relative to the reactor volume; however, this did not pose a problem because in operation the sludge blanket only rose to a level of approximately two-thirds of the reactor height.

Temperature in the reactors was maintained at 25 or 30°C (± 0.2°C) by on/off control of a heating wire wrapped around the length of the reactor.
Wastewater characteristics: The influent feedstock was of two types:

1. Apple juice concentrate; and
2. Batches of the apple processing wastewater from the factory.

The characteristics of these wastes are listed in Table 1.

Initially the substrate utilised in the study was 'synthetic' in that it was made up by diluting the apple concentrate. Important characteristics of the apple concentrate were: (1) high COD concentration; (2) deficiency in nutrients such as nitrogen and phosphorus; and (3) highly acidic with little buffering capacity. Based on filtration, the COD of the apple concentrate was 99 percent soluble. The feed utilised during the initial period was prepared by diluting the apple concentrate with tap water to the required influent concentration as dictated by the selected organic loading rate and hydraulic retention time.

Apple processing wastewater from the plant was utilised once the laboratory units had been acclimatised. The concentration of this wastewater can change substantially over the course of a production season, the COD ranging from 1500 to 4000 mg COD/l. In this study concentrations of 2500 and 5000 mg COD/l were selected; these were achieved either by dilution with tap water or supplementation with concentrate.

The wastewater is deficient in the nutrients nitrogen and phosphorus; therefore, these were supplemented by chemical addition, by adding 50 mg NH₄Cl and 10 mg K₂HPO₄ per 1000 mg COD. With this addition the influent COD:N:P ratio was approximately 100:4:1. In addition to N and P a trace metal solution, as suggested by Zehnder and Wuhrmann (1977) for enrichment cultures of methanogenic bacteria, was added to the feed.

The buffer capacity of the waste was increased by the addition of 2.5 mg NaHCO₃ per mg COD. This was sufficient to maintain the pH in the reactor close to 7.

<table>
<thead>
<tr>
<th>TABLE 1: Apple Wastewater Characteristics</th>
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<tr>
<td>COD (mg/l)</td>
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<tr>
<td>Apple concentrate source</td>
</tr>
<tr>
<td>Apple wastewater</td>
</tr>
</tbody>
</table>

Start-up and loading program: The reactor at 30°C was seeded with three litres of sludge from a clarifester treating a glucose-starch waste. The 25°C reactor was started a month later by seeding with three litres of sludge drawn from the existing anaerobic pond treating the apple wastewater.

To acclimatise the sludge to the substrate the feed initially was applied at a COD concentration of 500 mg/l of diluted apple concentrate and a flow rate of 8 l/day. Thereafter the feed rate was maintained at 8 l/d and the feed concentration increased stepwise until the design COD concentration of 2500 mg/l had been reached. At each "step" the concentration was held constant for approximately one week. Once the design feed concentration had been reached i.e. 2500 mg/l the flow rate was increased stepwise to increase the loading on the reactors. Steady state performance was examined at each "step" in load; the "steady state" data quoted later are those measured once the COD removal efficiency and the gas production had been near-constant for a period of several days. Figure 3 (for the 30°C reactor) demonstrates the time-loading sequence; in particular the slow rate of increase in load over the initial period should be noted.

The objective of the first stage of the study was to establish the capacity of the UASB systems at 25 and 30°C for a fixed influent waste concentration of 2500 mg COD/l; this concentration corresponded to the mean concentration of the actual waste to be treated. The data was collected over a six month period during which the load was increased progressively until the COD reduction in the systems declined appreciably, and failure appeared imminent. Once the load/response up to failure had been established the flow to each system was halved.
Fig 1: Schematic diagram of the laboratory-scale UASB reactors.

Fig 2: Photograph of the two laboratory-scale UASB reactors.

Fig 3: Sequence of increase in loading rate for the 30°C UASB reactor (influent COD = 2500 mg/L).
and a period was allowed for the systems to stabilise.

The second phase of the study was concerned with the interactive effect of hydraulic retention time/influent concentration on system response. This was achieved by increasing the waste concentration progressively in the range 2500 to 5000 mgCOD/l (i.e. doubling concentration) while maintaining the flow at half of the maximum value attained during the first phase. When the concentration reached 5000 mgCOD/l the load would be equal to that where failure occurred for an influent concentration of 2500 mgCOD/l, but now with the hydraulic retention time doubled. The objective here was to assess the interaction between influent concentration and retention time in the low/medium concentration range.

**Analytical methods:** Reactor performance was assessed by measurement of the following parameters on a daily basis, using the methods listed:

1. COD reduction  
   - Dichromate reflux method
2. Gas production  
   - Wet gas meter
3. pH  
   - Digital pH meter
4. Alkalinity  
   - Gran titration
5. Effluent VFA concentration  
   - Gas chromatography

**RESULTS AND DISCUSSION**

**Performance - Influent COD 2500 mg/l:** Figures 4 and 5 illustrate the performance of the 30°C and 25°C UASB systems, respectively, over the first phase of the project when the influent COD was held constant at 2500 mg/l and the load was increased by increasing the flow rate. The treatment efficiency was calculated in terms of percentage removal of the influent COD on the basis of the filtered effluent COD (effluent VS levels are discussed later). Organic loading rate was measured in terms of the mass of substrate COD fed per day per unit total reactor volume (kg COD/m³/day); these values should be seen as conservative as the sludge blanket occupied only one third to half of the reactor volume.

A summary of the COD removal efficiencies at "steady state" organic loading rates is given in Table 2; the corresponding hydraulic retention times and the effluent VFA concentrations are listed as well. From the results in Table 2 and in Figs 4 and 5 it is apparent that the maximum viable loading capacities for the UASB systems at 25 and 30°C were approximately 10 and 15 kg COD/m³/day, respectively; beyond these loads failure is approached rapidly. The results conform to the pattern of efficiency versus loading rate observed in many studies on anaerobic digestion; that is, at low loading rates the efficiency is high, and remains so until above some loading rate there is a rapid fall-off and failure of the system is approached.

**Hydraulic retention time/Influent concentration interaction:** Figures 6 and 7 illustrate the performance of the 30°C and 25°C UASB systems, respectively, over the second phase of the project when the influent flow rate was held constant, and the load was increased by increasing the influent COD concentration in the range 2500 to 5000 mg/l. The influent flow rate for each reactor was fixed at half the maximum attained in the first phase; that is, when the concentration reached 5000 mg COD/l the load would be equal to the maximum attained in phase one. Comparison of Figs 6 and 4 (for 30°C) and Figs 7 and 5 (for 25°C) show that the COD removal versus loading rate were closely similar for each temperature, and the maximum loading rate apparently is independent of concentration. Although the data show that reactor performance was related to loading rate not enough information is provided by these results to ascertain the relationship between performance, influent concentration and retention time. Also, no information as to the cause of failure is evident. However, the results do conform to those reported elsewhere; Lettinga et al. (1983) maintained the load on a UASB reactor constant while varying the influent feed (VFA's) concentration; the performance remained near constant in the range 2600 down to 1000 mg COD/l (with corresponding retention times of 1.9 down to 0.8 hours). Only when the concentration dropped below 1000 mg COD/l (and the retention time decreased below 0.8 hours) was there a decline in COD removal efficiency. Schraa and Jewell (1984) noted similar behaviour in a thermophilic anaerobic attached film expanded bed system - data for COD removal efficiency versus loading rate was closely similar, independent of influent concentration, in the range 1500 to 1600 mg COD/l. It would appear that identification of the controlling mechanism in respect with retention time and influent COD concentration demands monitoring of parameters more directly related to
Fig 4: Effect of organic loading rate on organic removal efficiency; fixed influent COD, variable flowrate (temperature = 30°C; influent COD = 2500 mg/l).

Fig 5: Effect of organic loading rate on organic removal efficiency; fixed influent COD, variable flowrate (temperature = 25°C; influent COD = 2500 mg/l).
system failure than the global COD parameter; for example, specific volatile fatty acid concentrations. To this end, experiments presently are being conducted to monitor the concentrations of VFA's through the bed for a range of influent concentrations and retention times.

**VFA production:** The results listed in Table 2 confirm the observation that the propionic acid concentration serves as an instability or stress indicator for anaerobic systems (COWI, 1981; Mosey, 1981). Under stable conditions at temperatures of 25°C and 30°C the concentrations of acetate and propionate essentially were non-detectable above the bed (≤ 5 mg/l) for loading rates of less than 7.5 and 12.5 kg COD m⁻³ d⁻¹, respectively. However, as the loading rate was increased further (and the hydraulic retention time decreased) for the fixed influent concentration, so the short-chain volatile acid concentrations increased. It would appear from the data that the generation of acetate under the stress condition occurs at approximately the same rate as the generation of propionate.

The observed behaviour provides partial corroboration of Mosey's (1983) model for short-chain volatile acid production and utilization in anaerobic systems. Mosey postulates that hydrogen partial pressure (or redox potential) regulates the production of the various acids; in processes operating near maximum capacity the model predicts increased concentrations of propionic acid and hydrogen. Specific experiments are now being conducted in an effort to obtain information on the mechanisms and kinetics of acid production and utilization. These involve monitoring the concentration profiles of the various VFA's up the sludge bed for different influent concentrations and retention times. It is hoped to ascertain from the studies what practical control procedures (such as recycling) may be adopted to enhance system performance under various operating conditions.

**Effluent solids concentration:** The magnitude of the effluent solids concentration from the experimental study has little practical relevance as the solids/liquid separator was undersized for the reactor volume compared with a separator in a full-scale plant. However, it is worth noting the trends in the data of Table 3. The effluent solids concentration showed

### Table 2: Steady State Operating Results for UASB Reactors at 25 and 30°C with an Influent COD Concentration of 2500 mg/l

<table>
<thead>
<tr>
<th>Loading rate (kg COD/m³/d)</th>
<th>25°C Reactor</th>
<th>30°C Reactor</th>
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<tbody>
<tr>
<td></td>
<td>Rem Rₜ COD</td>
<td>Rem Rₜ COD</td>
</tr>
<tr>
<td></td>
<td>Ac Pr</td>
<td>Ac Pr</td>
</tr>
<tr>
<td>1.4</td>
<td>89 24.0 126  nd nd</td>
<td>96 24.0 46  nd nd</td>
</tr>
<tr>
<td>2.0</td>
<td>93 20.0 126 15 nd</td>
<td>98 20.0 58  nd nd</td>
</tr>
<tr>
<td>2.5</td>
<td>94 18.8 121  nd nd</td>
<td>98 20.0 64  nd nd</td>
</tr>
<tr>
<td>5.0</td>
<td>96 12.6 101  nd nd</td>
<td>95 12.5 76  nd nd</td>
</tr>
<tr>
<td>6.0</td>
<td>96 8.9 78    nd nd</td>
<td>-    -    -    -</td>
</tr>
<tr>
<td>7.5</td>
<td>91 9.0 176   nd nd</td>
<td>93 8.0 169  nd nd</td>
</tr>
<tr>
<td>10.0</td>
<td>86 6.4 349   110 27</td>
<td>89 6.1 282  6 19</td>
</tr>
<tr>
<td>12.0</td>
<td>76 5.5 654   231 69</td>
<td>-    -    -    6 10</td>
</tr>
<tr>
<td>12.5</td>
<td>-    -    -    -    -    -    -    -    -    -</td>
<td></td>
</tr>
<tr>
<td>13.5</td>
<td>-    -    -    -    -    -    -    -    -    -</td>
<td></td>
</tr>
<tr>
<td>16.0</td>
<td>-    -    -    -    -    -    -    -    -    -</td>
<td></td>
</tr>
</tbody>
</table>

Rem: COD removal efficiency (%)
Rₜ: hydraulic retention time (hours)
COD: filtered effluent COD concentration (mg/l)
Ac: acetate concentration (mg/l)
Pr: propionate concentration (mg/l)
nd: non-detectable (< 5 mg/l)
**Fig 6:** Effect of organic loading rate on organic removal efficiency: fixed influent flowrate; variable influent COD (temperature = 30°C; influent COD = 2500-5000 mg/l).

**Fig 7:** Effect of organic loading rate on organic removal efficiency: fixed influent flowrate; variable influent COD (temperature = 25°C; influent COD = 2500-5000 mg/l).
approximately the same increase with decreasing hydraulic retention time for both the 25°C and 30°C reactors. The increase principally was due to two factors: (1) With decreasing retention time (and increasing upflow velocity) a larger quantity of fine particles were "pushed" out of the reactor. (2) The decrease in retention time was accompanied by an increase in load, increased gas production and a larger degree of turbulence; this also caused fine particles to rise in the reactor.

**Table 3: Effect of Hydraulic Retention Time (R_h hours) on Effluent Solids Concentration (VS measured as mg COD/l) with an Influent COD of 2500 mg/l (difference between unfiltered and filtered effluent COD)**

<table>
<thead>
<tr>
<th>R_h (d)</th>
<th>Loading rate (kg COD/m^3/d)</th>
<th>Effluent solids concentration (mg COD/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>24</td>
<td>2.5</td>
<td>24</td>
</tr>
<tr>
<td>12</td>
<td>5.0</td>
<td>9</td>
</tr>
<tr>
<td>8</td>
<td>7.5</td>
<td>48</td>
</tr>
<tr>
<td>6</td>
<td>10.0</td>
<td>113</td>
</tr>
</tbody>
</table>

**Granular (pelletised) sludge formation:** In UASB operation the formation of granular or pelletised sludge is essential for efficient operation. Problems of biomass retention have never been encountered where granular or pelletised sludge has formed, the excellent settling and thickening properties allowing high loading rates. Considerable efforts are underway to identify the causes and environmental factors involved in formation of pelletised sludge (e.g. Lettinga et al. 1983; Ross, 1984) as yet, however, the reasons for this phenomenon are not clearly understood.

Formation of pellets has been observed in the digestion of a number of soluble wastes in full-scale and pilot-scale plants. The size of the pellets has varied between 0.5 and 5 mm. However, on laboratory-scale systems the formation of pellets has been reported only in a few instances: In 1980 Lettinga reported that at laboratory scale formation of pellets had been observed but only with composite volatile fatty acid or acetate-only substrates. In this investigation significant pelletisation of the sludge occurred in the UASB reactors operated at both 25°C and 30°C even though the VFA concentration of the waste was only about 4 percent of the total COD, the principal constituents being sugars. The process of pelletisation, once started, was very rapid. Over the first ten weeks of operation, as the load was increased, there appeared to be a gradual change in the sludge consistency from very fine to a more "grainy"/flocculated form. After this period there was a rapid change in the sludge morphology. (This change coincided with the load attaining a level of approximately 5 kg COD/m^3/day.) Over a period of six or seven days roughly half the sludge bed was transformed into pellets. The remainder of the sludge bed (the upper portion) continued to comprise flocculent sludge with good settling properties.

The first pellets that formed ranged in size from approximately 0.5 to 2 mm in diameter, but in time the pellets grew significantly larger; after six months' operation some of the pellets at the base of the reactor had grown to 5 mm in diameter, the size of the pellets decreasing gradually with reactor bed height. Figure 8 shows a photograph of a sample of pelletised sludge; the pellets are roughly spherical and have well-defined surfaces. Very fine sludge particles are to be found in the spaces between the pellets in the sludge bed. The pellets show no propensity to attach to each other. The pellets are greyish-white in colour with a soft spongy consistency and break up readily if handled; however, even with intense gasification the pellets do not break up within the bed.

Sampling problems caused difficulties in measurement of solids concentration at different points in the sludge bed. On the basis of the total reactor volume the volatile and total solids concentrations in the 30°C reactor were approximately 36 and 47 kg m⁻³, respectively. As the sludge bed occupied between a third and half of the total volume, the solids concentration in the bed was approximately 100 kg m⁻³.
Nutrient requirements: The mass ratio of COD:N:P utilised in the system was roughly 1000:8:1, the excess N and P appearing in the effluent.

Sensitivity to shock loads: A general impression from the study is that the UASB system is reasonably robust with respect to shock loads (provided the peak loading rate during the shock does not exceed the maximum system capacity). The data in Table 4 show the COD removal efficiency of the 30°C reactor when subjected to a shock load (caused by increasing concentration, while maintaining flow rate constant) of one day's duration. Prior to the shock the reactor had been loaded at a rate of 8 kg COD m\(^{-3}\) d\(^{-1}\) for approximately three weeks; during the shock load this was almost doubled, to 14.5 kg COD m\(^{-3}\) d\(^{-1}\), (for 24 hours) after which the load was reduced to approximately 10 kg COD m\(^{-3}\) d\(^{-1}\). From Table 4 the reduction in COD removal efficiency caused by the shock load was almost negligible.

<table>
<thead>
<tr>
<th>Days after shock</th>
<th>Loading rate (kg COD/m(^3)/d)</th>
<th>COD Removal (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>~20 to 0</td>
<td>~8</td>
<td>~93</td>
</tr>
<tr>
<td>0</td>
<td>14.5</td>
<td>86.7</td>
</tr>
<tr>
<td>1</td>
<td>9.7</td>
<td>86.1</td>
</tr>
<tr>
<td>2</td>
<td>11.4</td>
<td>83.1</td>
</tr>
<tr>
<td>3</td>
<td>11.5</td>
<td>82.0</td>
</tr>
<tr>
<td>4</td>
<td>10.3</td>
<td>84.9</td>
</tr>
<tr>
<td>5</td>
<td>9.2</td>
<td>88.4</td>
</tr>
<tr>
<td>6</td>
<td>9.2</td>
<td>88.3</td>
</tr>
</tbody>
</table>

Temperature sensitivity: The comparative treatment capacity at 25°C and 30°C appears to be in accord with the reported temperature sensitivity of mesophilic anaerobic processes. Henze and Harremoës (1983), in reviewing data on the temperature dependency, found that in the range 10°C to 30°C the relationship between the process rate, \(r_x\), at temperatures \(T_1\) and \(T_2\) may be estimated from the equation:

\[
r_{x,T2} = e^{K(T_1-T_2)}
\]

where \(K = 0.10\ °C^{-1}\).

It is of interest to note that if the rate is accepted as being linearly related to the maximum loading capacity at a given temperature, then the capacity at 25°C should be 61 percent of that at 30°C. The observed maximum capacity at 25°C was approximately (10/15) \(= 67\) percent of that at 30°C.

Conclusions

The problem of heating anaerobic treatment systems can be overcome in certain instances by utilizing one of the new generation systems. Even at temperatures less than optimal (down to 25°C here) the organic loading rate capacity is sufficient, negating the need for heating. This makes these systems an attractive treatment option, particularly for developing regions where technical backup is limited. Of the various systems the upflow anaerobic sludge blanket (UASB) reactor is the least complex and simplest to operate; these factors favour the selection of this system where technical and operator expertise are not established.
Apple processing wastewater

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References


Fig. 8: Photograph of a sample of the pelleted sludge taken from the UASB reactor operated at 25°C.