Sludge granulation and efficiency of phase separator in UASB reactor treating combined industrial effluent

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Received 15 May 2006; revised 16 August 2006; accepted 22 September 2006

Abstract

Sludge granulation and the effect of gas-liquid-solid separator (GLSS) design on the efficiency of upflow anaerobic sludge blanket (UASB) and upflow anaerobic sludge filter (UASF) reactors, operating at HRTs ranging from 3 to 12 h were investigated. VSS/TS ratio gradually increased in both the reactors with increasing sludge age (from 0.5 to more than 0.7 for UASB reactor and 0.012 to 0.043 for UASF reactor). X-Ray diffraction analysis of the UASF sludge showed the presence of expanding clays revealing its additional absorption capability. Fuoraphyllite and albite precipitation related to exocellular polymers of the microbial shell structure, showed the extended growth of microorganisms during sludge granulation. A gradual decrease (82%–69%) in COD removal with decreasing HRT was apparent in UASF reactor. In case of UASB reactor, this decrease was marginal because addition of GLSS device significantly improved (14%–20%) the overall efficiency of the UASB reactor. GLSS enhanced the efficiency of the UASB reactor by increasing the settleability of suspended particles and accelerating the coagulation of colloidal particles due to the velocity gradient.

Key words: sludge granulation; gas-liquid-solid (GLS) phase separator; UASB; microbial growth

Introduction

The success of the upflow anaerobic sludge blanket (UASB) reactor lies in the development of dense sludge bed at the bottom of the reactor, where biological digestion takes place. The sludge bed is basically formed due to aggregation of suspended solids and bacterial population into flocs and granules (Hulshoff, 1989). These dense aggregates have good settling properties and are not susceptible to washout from the system under practical conditions. The granulation of sludge enables the treatment system to show good treatment performance at high organic loading rates (El-Mamouni et al., 1997; Mahadevaswamy et al., 2004). It also leads to the reduction in the reactor size, which renders the treatment system cost effective. Nevertheless, parameters like temperature and upflow velocity substantially affect the sludge granulation (Barbosa and Sant Anna, 1989). Many researchers (Barbosa and Sant Ann, 1989; Singh and Viraraghavan, 1998) investigated the formation of sludge granulation at ambient temperatures (19–28°C) and an upflow velocity (V_up) of 0.478 m/h. They observed spherical granules after one month of operation. Where as the size of the granules was increased up to 8 mm in diameter after a period of 9 months.

For a well performing biological wastewater treatment system (UASB reactor) it is extremely essential to ensure good contact between the incoming substrate and the sludge mass in the system and to maintain a large sludge mass in the system. In order to qualify these conditions, the treatment system (UASB reactor) is equipped with a gas-liquid-solid (GLS) phase separator, a column and effluent draw-off facilities (Kansal et al., 2003). The GLS device also helps to improve the overall treatment efficiency of the reactor by dividing it into a settling zone (upper part) and a digestion zone (lower part). The wastewater is introduced uniformly through the bottom of the reactor, it passes through the sludge bed (digestion zone) and then enters into the settling zone. The enlarged part of the reactor causes substantial decrease in the upflow velocity, which in return facilitates the flocculation of suspended sludge and enhances its settling. With the time, mass of accumulated sludge on the slopes of phase separator exceeds the frictional force and slides back into the digestion zone and supplement the digestion of the organic matter of incoming wastewater. Various types (designs) of phase separators have been investigated for treatment efficiency (Cavalcanti, 2003; Sayed and Fergalal, 1995). The introduction of proper phase-separator design into the conventional UASB can significantly improve its treatment efficiency under comparable conditions (El-mitwalli, 2000; Cavalcanti, 2003). According to El-mitwalli (2000), an addition of vertically oriented reticulated polyurethane foam sheets in the upper part of the UASB reactor offers relatively higher efficiency because the presence of foam sheets prevents sludge bed flotation. Cavalcanti (2003) demonstrates that a UASB reactor having parallel plates
along with conventional phase separator can give better performance as compared with a reactor equipped with only conventional phase separator because addition of plates resulted in enhanced settlements of the suspended particles.

In this research an attempt was made to investigate the process of sludge granulation at various sludge ages (30, 60, 90, 120 and 150 d) and to study the effect of phase separator design on the treatment efficiency of UASB reactor at various HRTs and corresponding up-flow velocities.

1 Materials and methods

1.1 Wastewater characteristics and analytical approach

Wastewater used in this study was obtained from the combined industrial effluent drain carrying the effluents of more than one hundred mainly textile units along with domestic sewage. Integrated samples were prepared by mixing the water samples taken across the drain at varying depth. Wastewater samples were analyzed in terms of chemical oxygen demand (COD), biochemical oxygen demand (BODs), conductivity, turbidity, dissolved oxygen (DO), total dissolved solids (TDS), total suspended solids (TSS), total solids (TS), total hardness (TH), chlorides and pH. All the tests were carried out in accordance with standard methods for the examination of water and wastewater (APHA, 1998). The wastewater characteristics are given in Table 1.

Table 1 Characterization of wastewater

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Wastewater</th>
<th>Parameter</th>
<th>Wastewater</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>7.90 (0.08)</td>
<td>TDS (mg/L)</td>
<td>993 (22.2)</td>
</tr>
<tr>
<td>COD (mg/L)</td>
<td>514.6 (29.4)</td>
<td>TS (mg/L)</td>
<td>1233.4 (27.3)</td>
</tr>
<tr>
<td>BODs (mg/L)</td>
<td>262.8 (19.1)</td>
<td>SO(_2)(^{-}) (mg/L)</td>
<td>235.7 (13.5)</td>
</tr>
<tr>
<td>TSS (mg/L)</td>
<td>236 (24.6)</td>
<td>NO(_3)(^{-}) (mg/L)</td>
<td>57 (5.4)</td>
</tr>
</tbody>
</table>

Values in parenthesis represent standard deviation; * mean of five values.

1.2 Description of experimental system

A bench scale anaerobic experimental setup shown in Fig 1 was used for the wastewater treatment. The experimental assembly is divided into four parts: (1) fixed bed UASB reactor; (2) feed tank; (3) gas collection arrangement; and (4) effluent (treated) collection tank. The UASB/UASF reactor was made of Perspex tubular column (tubing) with an inside diameter (ID) of 7 cm, a length of 120 cm, and a volume of 5.3 L.

1.3 Design features of GLSS

To capture suspending particles and reduce their washout efficiently, an enlarged portion termed as gas-liquid-solid separator (GLSS) was added at the top of the column, giving the reactor a total height of 160 cm and a total volume of 15.5 L. Lower half of the GLSS was inclined entity with a slope angle (θ) of 60°, whereas upper half was a tubular section with an outside diameter (OD) of 23 cm and an inside diameter (ID) of 22 cm. A canopy was fixed with the top lid of GLSS (Fig 2) to (1) facilitate capturing of biogas generated during the wastewater treatment; (2) enhance the mixing and allow coagulation of suspended/colloidal particles (unsettled particles of the lower slant portion of GLSS). The mixing of suspended particles is promoted by providing a narrow gap (1 cm) between the lower edge of the canopy and wall of tubular section of GLSS (Fig 2). This gap enhances inlet velocity and causes turbulence in effluent; (3) facilitate the settlement of the coagulated particles due to a rapid drop in upward velocity (V\(_{up}\)) caused by enlarged portion above the bottom edge of canopy; (4) ease the sliding down of the settled coagulated particles back into the reactor. The reactor was equipped with six sampling probes placed at various heights from bottom to top. The reactor is mounted on a rectangular Perspex plate of dimension 2.5 ft\(^2\) (Fig 2).

1.4 Development of the sludge bed

The reactors (UASB/UASF) were seeded with sludge from two different sources. The UASF reactor was seeded with anaerobic sludge of the Hudiara drain bed (sediments), which was mainly comprised of sand particles with attached microbial growth and organic matrix. The
content of TS and volatile suspended solids (VSS) of the seed sludge were 890 and 10.5 g/L, respectively. A substantially higher level of TS as compared to VSS was due to the inert material and sand particles (Fig.3d) with higher specific gravity (Malina and Pohland, 1992). Anaerobic sludge mass for UASB reactor was developed by stabilizing the aerobic waste sludge (activated sludge) of a dairy wastewater treatment plant. During stabilization, the reactor was fed with synthetically prepared water with C:N:P ratio of 300:5:1. Color of activated sludge started changing from white to grey in the first week and then it became dark grey in the fourth week. Decomposition of the activated sludge resulted in the release of cellular material into the liquid, which was consumed by the anaerobic bacteria as food. The volume of the sludge was reduced about 33% due to the settlement of the sludge bed during the first 30 d. Wastewater was then introduced into the reactor to acclimatize the sludge. After 60 d, sludge granulation appeared. Sludge granulation was very well developed after seventy-eight days (Fig.3a).

### 2 Results and discussion

The effect of aging on sludge composition was monitored at sludge ages varying between 30–150 d. The average contents of TS and VSS were found to be approximately 39.2 and 20.9 g/L, respectively in UASB reactor at sludge age of 30 d (Table 2). While TS and VSS contents were 918.1 and 11.3 g/L, respectively in case of UASF reactor (Table 2). At sludge age of 60 d an over all increase in TS and VSS concentrations from 39.2 and 20.9 g/L to 53.7 and 31.7 g/L for UASB and from 918.1 and 11.3 g/L to 925.1 and 18.9 g/L for UASF reactors was observed. The increase in TS concentration was mainly due to settling of the sludge while VSS concentration clearly demonstrated the production of biomass. Actually, the maximum specific growth rate of bacteria depends upon the food over microorganism ratio (F/M) and is directly related to maximum specific substrate utilization rate (Baily and Ollis, 1986). Nevertheless, due to favorable temperature and appropriate availability of nutrients there was an appreciable increase in the TS and VSS concentrations (up to 66.7 and 48.6 g/L, respectively) in UASB reactor at sludge age of 120 d. TS concentration in UASF was appeared to be slightly dropped (from 925.1 to 919.1 g/L), whereas VSS content was increased from 18.9 to 35.4 g/L due to enhanced microbial growth attached with sand particles. However, a slight drop in TS content can best be explained due to bed expansion caused by the entrapment of the gas

<table>
<thead>
<tr>
<th>Table 2 Sludge composition at different sludge ages</th>
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<tbody>
<tr>
<td>Reactor</td>
</tr>
<tr>
<td>UASB</td>
</tr>
<tr>
<td></td>
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<tr>
<td></td>
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<tr>
<td></td>
</tr>
<tr>
<td>UASF</td>
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</tbody>
</table>

Fig. 3 Photographs of sludge granulation at the day 78 (a); microscopic view of sludge liquidation at the day 50 (b and c); and microscopic view of inert material in UASF sludge bed (d).
bubbles within the sludge bed. The bed expansion in such
cases may go up to 20% of the height of the bed (Young
and Yang, 1989; Metcalf and Eddy, 2003). Beyond the day
120, TS and VSS contents approached to 66.7 and 48.6
g/L for UASF and 919.1 and 35.4 g/L for UASF reactors,
respectively. A substantial increase in average VSS content
as compared to TS is associated with the growth of active
biomass. In fact, more than 90% of VSS content can be
attributed to active biomass, and rest (10%) can be referred
to non-biodegradable volatile solids and dead cell debris
(Metcalf and Eddy, 2003). At sludge age of 150 d, a drop
in TS and VSS content in case of UASF reactor is evident.
This drop could be owed to the liquidation of granules due
to temperature drop (Fig.3b, c). The sludge granules may
also be deteriorated due to some other factors, including
the effect of long chain fatty acids and the adsorption of
colloidal matter on the surface of sludge (Sayed et al.,
1987; Rinzema, 1988). Negative effect of these factors may
also be augmented due to reduced metanogenic activity at
lower temperatures (Ligero and Soto, 2002).

VSS/TS ratio reflects biomass growth and its quality. For
UASF reactor, VSS/TS ratio gradually increases from 0.5
to more than 0.7 with increasing sludge age. This steady
increase in VSS/TS ratio also reflects a steady increase in
the granules size (Amata, 1996). Beyond sludge age
of 90 d, the increase in VSS/TS ratio is marginal, even
slightly decreasing trend is evident at the day 150. In the
case of UASF reactor, the VSS/TS ratio also appears to be
gradually increased (from 0.012 to 0.042) with increasing
sludge age. Although the VSS content in the sludge of both
the reactors is comparable but the VSS/TS ratio in the case
of UASF sludge is strikingly very low. This is because
of the characteristics of the UASF sludge which contains
maximum mass of inert material.

2.1 X-ray diffraction analysis

X-ray diffraction analysis of UASF sludge shows that it
is mainly composed of clays like Illite, montmorillonite
and kaolinite along with the other non clay minerals such
as quartz, albite, calcite and gypsum (Fig 4a). The presence
of different clay minerals and quartz indicates that they are
detrital component of the sample and the presence of well
crystallize albite, calcite and minor gypsum indicate that
these minerals have been precipitated by the reaction of
different free cations present in the sludge, e.g. calcium
and PO\(_4\) generated by the microbiological growth in the
sludge has resulted in precipitation of gypsum, rest of the
calcium in the presence of CO\(_2\) generated during anaerobic
digestion has resulted as calcite. Similarly release of Na,
Al and silica from clay minerals has resulted in the
formation of well crystallized albite. The clay mineral Illite
and expanding clay montmorillonite have the absorption
capability of the heavy metals.

UASF sludge samples analysis taken at early stage of
day 60 and on the final day (day 150) show that its domi-
nant components are quartz and illite (Figs.4b and 4c). In
the sludge sample of 60 d faujasite (Na\(_2\)Al\(_2\)Si\(_4\)O\(_{12}\)·8H\(_2\)O)
and albite appeared to be formed authogenically by
leaching out of cations like Si and Al from illite.

However, in the sample of the day 150, fuoraphyllite
(KCa\(_2\)(Si\(_4\)O\(_{10}\))FO\(_{20}\)·8H\(_2\)O) along with albite seems to be
precipitated authogenically in reaction with available cal-
cium related to excelluar polymers of the microbial shell
structure, which shows the extended growth of microor-
ganisms during sludge granulation (Gonzalez et al., 2001;
Torkian et al., 2003).

2.2 Contribution of GLSS in UASB reactor efficiency

Table 3 shows the efficiency of the phase separator at
HRT varying between 3 to 12 h. A gradual increase in COD
and TSS removal efficiency of UASB (tubular portion of
the reactor) with an increasing HRT is apparent (Ragen
et al., 2001). COD and TSS removals were 56% and 39%,
respectively. Whereas COD and TSS removal due to GLSS portion of the reactor appeared to
be 20% and 26% at HRT of 3 h; about 14% and more
than 16% at HRT of 12 h, respectively. Overall removal
efficiency of the reactor (both tubular and GLSS portions)
for these parameters was then 76% and 65% at HRT of 3 h;
about 14% and more than 16% at HRT of 12 h, respectively. It demonstrated that addition of gas-liquid-
solid separator has substantially improved the overall

Fig. 4 X-Ray analysis of UASF sludge at day 150 (a); UASB sludge at
day 60 (b); UASF sludge at day 150 (c).
efficiency of the reactor. The contribution of GLSS portion in the overall efficiency of the reactor predominated up to HRT of 6 h. This could be explained by the fact that with the decrease in HRT, removal efficiency of the reactor portion decreases and in return resulting into an increase in the load of untreated particles (TSS) in the GLSS, which enabled GLSS to work in full swing furnishing maximum efficiency.

The mechanics of particles settling in the GLSS can be explained in the light of the changes in liquid upflow velocity, which is the function of the inlet area (van Haandel and Lettinga, 1994). The upflow velocity of the influent varies along the reactor because of changing the inlet areas as depicted in the Table 4.

As HRT was reduced from 12 h to 3 h corresponding increase in upflow velocities from 10 to 45 cm/h was evident. To facilitate the particle settling and to evaluate the efficiency of the GLSS for each upflow velocity inlet area at different points of the GLSS was varied. The area of the GLSS was gradually increased from 38.4 to 380 cm² and then sharply decreased to its minimum (34 cm²) by fixation of inverted canopy with outer diameter 21 cm and area 346 cm² (Fig.2). This arrangement reduced the available area ($A_2 - A_3 = 34$ cm²) for the influent upflow velocity. The available area was then again gradually increased to 342 cm² to facilitate the settling of coagulated particles. In first step, due to the enlarged area (380 cm²) of the GLSS the upflow velocity 45 cm/h was decreased to 4.5 cm/h for the minimum HRT of 3 h. At this stage critical settling velocity ($S_c$) became much higher than upflow velocity which made particles to settle down. It is also apparent from the results that within the GLSS removal of COD, TSS and turbidity was contributed by both, the lower enlarged portion and upper portion fixed with inverted canopy. The reason for the contribution of the upper portion was the removal of remaining suspended and coagulated colloidal particles. Coagulation of the colloidal particles due to the higher up flow velocity was achieved as water flowed through the narrow gap (1 cm) between the lower edge of the canopy and walls of tubular section of GLSS.

### Table 3 Removal efficiency (%) of various components of UASB reactor at HRT of 3–12 h corresponding to the up-flow velocities of 45 to 10 cm/h

<table>
<thead>
<tr>
<th>Removal efficiency</th>
<th>Sludge bed portion</th>
<th>GLSS lower portion</th>
<th>GLSS upper portion</th>
<th>GLSS (overall)</th>
<th>UASB (overall)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HRT (h)</td>
<td>3 h</td>
<td>6 h</td>
<td>9 h</td>
<td>12 h</td>
<td>3 h</td>
</tr>
<tr>
<td>COD(%)</td>
<td>56</td>
<td>61</td>
<td>66</td>
<td>70</td>
<td>11</td>
</tr>
<tr>
<td>TSS(%)</td>
<td>39</td>
<td>52</td>
<td>58</td>
<td>60</td>
<td>15</td>
</tr>
<tr>
<td>Turbidity(%)</td>
<td>37</td>
<td>53</td>
<td>55</td>
<td>57</td>
<td>22</td>
</tr>
<tr>
<td>Conductivity(%)</td>
<td>8</td>
<td>11</td>
<td>11</td>
<td>12</td>
<td>2</td>
</tr>
</tbody>
</table>

### Table 4 Upflow velocities in different portions of reactor

<table>
<thead>
<tr>
<th>Reactor portions</th>
<th>Area (cm²)</th>
<th>Available area (cm²)</th>
<th>Upflow velocity (cm/h) for varied HRTs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Column portion</td>
<td>$A_1=38.4$</td>
<td>38.4</td>
<td>10</td>
</tr>
<tr>
<td>GLSS</td>
<td>$A_2=380$</td>
<td>380</td>
<td>1</td>
</tr>
<tr>
<td>Lower portion of canopy</td>
<td>$A_1=346.2$</td>
<td>$A_2-A_3=33.8$</td>
<td>11</td>
</tr>
<tr>
<td>Upper portion of canopy</td>
<td>$A_4=38.4$</td>
<td>$A_2-A_4=341.6$</td>
<td>1.1</td>
</tr>
</tbody>
</table>

### 3 Conclusions

The steady increase in VSS/TS ratio is associated with the development of sludge granules. Beyond sludge age of 90 d, the increase in VSS/TS ratio was marginal, which leads to the conclusion that for the treatment of combined industrial wastewater proper granulation of seed sludge (dairy plant waste activated sludge) requires a period of three months. XRD analysis shows the presence of calcium and phosphate related to excellular polymers of the microbial shell structure, which shows the extended growth of microorganisms during sludge granulation. Addition of gas-liquid-solid separator (GLSS) substantially improved the overall efficiency of the UASB reactor, and due to the innovative designing of the phase separator, the overall removal efficiency of the reactor is not declined even at shorter HRT (3 h), and higher upflow velocities (45 cm/h).

### Acknowledgements

The authors thank the Higher Education Commission, Government of Pakistan, for extending support to this work under the indigenous Ph.D. Scholarship Scheme.

### References


