Comparisons Between the UASB and the EGSB Reactor

Seung J. Lim

ABSTRACT

Some characteristics of Upflow Anaerobic Sludge Blanket (UASB), Expended Granule Sludge Blanket (EGSB), and Static Granular Bed Reactor (SGBR) were investigated in order to compare performances of the three and recognize advantages and disadvantages, respectively. The UASB reactor is developed in the late 1970s and became rapidly widespread due to great performances. With granules, this reactor is able to treat various high-strength industrial wastewaters and most soluble wastewater could be applied in this reactor. The EGSB reactor was also developed to give more chances to contact between wastewater and granules. Besides, this reactor is able to separate dispersed sludge from mature granule using rapid upward velocity. Then, it is possible to treat high-strength and low-strength wastewater such as domestic wastewater, especially low temperature. The SGBR is innovated at IOWA state University and good performances have been reported for various wastewaters similar to the UASB and the EGSB reactor. This reactor is downflow unlike other reactors. And, it is very simple so that additional parts are not needed for this process. Sludge granulation process is not clearly understood yet, but EPS is very important a role to make a granule. Moreover, its structure and granulation process have been researched continuously.

KEYWORDS

anaerobic digestion, granule, UASB, EGSB, SGBR

INTRODUCTION

Anaerobic treatment was the history of wastewater treatment itself. Anaerobic treatment has been used for the treatment of concentrated industrial wastewater as well as domestic wastewater (McCarty and Smith, 1986). Jewell (1987) told that the septic tank was the simplest, the oldest, and the most widely used process. Anaerobic treatment has a lot of advantages such as low energy consumption, low production of waste biological solids, storage ability unfed for many months, low nutrients and chemicals requirements, great removal at even high loading rate, pathogen removal, improving dewaterability and producing energy gases. In comparison, it has some disadvantages like sensitive and vulnerable process, odor problem, long period needed for start-up the process and necessity of post treatment for discharge standards. However, lots of knowledge about xenobiotic compounds and toxic compounds has been researched gradually. And, as a matter of fact, anaerobic digestion process is very stable process if the system operated is understood well. When a starting-up full scale anaerobic treatment process, the sufficient inoculation is provided due to overcome its drawback. In case of odor problem, it can be prevented using physicochemical or biological process (Lettinga, 1996). Lettinga (1996) told that anaerobic treatment process makes mineral compounds such as ammonium, phosphate, or sulfide and needs additional post treatment for a sustainable environmental protection can be met.

The anaerobic treatment has been rapidly developed since the late 1960s. The anaerobic sludge bed reactors have three concepts as follows (Lettinga, 1996). First, the immobilized balanced micro-ecosystem is formed. Second, the immobilized anaerobic aggregates have high settleability. Third, mass transport is prevalent between granule and bulk solution. Since Young and McCarty (1969) developed the anaerobic filter, there have been a lot of research on the high rate anaerobic treatment. In Europe, however, the reactor which could be obtained greater performance was developed, i.e. UASB reactor in Netherlands in the late 1970s.
The aim of this article is to compare between the UASB and the EGSB reactor, and present not only application but also research trends each reactor. Besides, this article handles with sludge granulation before reactors contents and gives the information of SGBR which is one of modified processes.

SLUDGE GRANULATION

Introduction. Sludge granulation is a so complex and affected by many factors. Besides, this process is not clearly understood yet. Although there have been so many results of research on the granulation of sludge, they have already lots of hypotheses to make theories and understand observations (Wu et al., 1991; Thaveesri et al., 1994; Fang et al., 1994; Schmidt and Ahring, 1996). Most microorganisms of granules are denitrifying, nitrifying, acidogenic, and methanogenic bacteria. However, several factors determine characteristics of granules. For instance, there are characteristics of organisms, growth rate of organisms, and death rate and decay rate of the organisms in granules (Lett inga, 1996). Nicolella et al. (2000) proposed the concentration-flow rate plane to design criteria applicable to different reactor.

![Figure 1. Concentration-flow diagram for sludge granulation (Nicolella et al., 2000).](image)

Inorganic composition. The inorganic composition of sludge granule changes according to wastewater, process condition, and so on. However, some generalizations could be made from research results. Ash contents in a granule grown on complex wastewater were lower than those in a granule grown on simple wastewater, i.e., acetate, propionate, or butyrate (Ross 1984; Dolfing et al., 1985; Alibhai and Forster, 1986; Hulshoff Pol et al., 1986; Wu et al., 1991; Alphenaar et al., 1992; Schmidt et al., 1992; Ahring et al., 1993). In addition, granules grown on complex substrate are bigger than those grown on simple substrate.

The differences in shape and density under various conditions could be determined due to the low porosity of the granules when the density is high. It could make the inhibitions of transportation of substrate, gases, metabolites, and so on between cells and bulk solution if the granule had a lot of ash. The relationship between the density and the ash contents shows that an increase in density is related with an increased in ash contents (Hulshoff Pol et al., 1986).
Table 1. Minimum effective diameter for spherical granules with a settling velocity of 20 m/hr estimated using Stock’s law (Hulshoff Pol et al., 1986).

<table>
<thead>
<tr>
<th>Density (mg/mL)</th>
<th>37°C</th>
<th>55°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>1010</td>
<td>1.2</td>
<td>1.0</td>
</tr>
<tr>
<td>1020</td>
<td>0.8</td>
<td>0.7</td>
</tr>
<tr>
<td>1030</td>
<td>0.6</td>
<td>0.5</td>
</tr>
<tr>
<td>1040</td>
<td>0.5</td>
<td>0.4</td>
</tr>
<tr>
<td>1050</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>1060</td>
<td>0.4</td>
<td>0.3</td>
</tr>
<tr>
<td>1070</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>1080</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>1090</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>1100</td>
<td>0.3</td>
<td>0.2</td>
</tr>
<tr>
<td>1200</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>1300</td>
<td>0.2</td>
<td>0.1</td>
</tr>
<tr>
<td>1400</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>1500</td>
<td>0.1</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Stokes law:

If \( \text{Re} < 2 \):

\[
V = \frac{D^2 g (\rho_p - \rho)}{18 \rho},
\]

If \( 2 \leq \text{Re} \leq 400 \):

\[
V_s = 0.153 \left[ \frac{(\rho_p - \rho)D^{1.6}g}{\eta \rho^{0.5} \rho^{0.4}} \right]^{0.714}
\]

Where; \( \text{Re} \) = Reynolds number \((V_s \rho D/\eta)\), \( V_s \) = setting velocity \((\text{m/s})\), \( g \) = gravimetric constant \((\text{m/s}^2)\), \( D \) = diameter of granule \((\text{m})\), \( \rho \) = density of granule \((\text{kg/m}^3)\), \( \eta \) = viscosity of liquid \((37^\circ\text{C}: 0.73, 55^\circ\text{C}: 0.51\) for water) \((\text{kg/m}^\ast\text{s})\)

The ash is mainly consisted of calcium, potassium, iron (Dolfing et al., 1985; Fukuzaki et al., 1991a and 1991b; Wu et al., 1991; Shen et al., 1993). Some researchers believe that FeS might be contributed to make granules black color (Dolfing et al., 1985). However, Kosaric et al. (1990) showed that something else other than FeS could be of importance of the granule black color. Besides, there was no relationship between ash contents and the strength of granule (Hulshoff Pol et al., 1986).

**EPS contents.** It is very important to understand Extracellular Polymer Substances (EPS) to make and maintain granules. Especially, the surface charge of microorganisms was negative consistently so that it needs some positive charges or other means such as EPS and polymers in order to make granules. Zhou et al. (2006) showed that EPS contents and surface charges of substrates were very important to form granules based on the Derjaguin-Landau-Verwey-Overbeek (DLVO) theory in a UASB reactor. EPS contained organic debries, phages, lysed cells and is consisted of polysaccharides, proteins, lipids, phenols, and nucleic acids (Stal et al., 1989).
Several research on EPS showed that bacteria from surroundings were protected by EPS and the interaction with granules was contributed to make a sludge granulation (Dolfing, 1986; Morgan et al, 1991; Forster, 1992). The organic contents of EPS are about 0.6 to 20% of the volatile suspended solid contents and it is dependent upon the analysis procedures and granule conditions (Ross, 1984; Dolfing et al., 1985; Morgan et al, 1990; Grotenhuis et al., 1991; Shen et al., 1993). The amount of EPS in the thermophilic condition is smaller than that of in the mesophilic condition (Schmidt and Ahring, 1994). EPS is also affected by wastewater. Shen et al. (1993) reported that concentration of carbohydrate was increased by adding iron and yeast. However, it is not clear whether specific species produce EPS or all microorganisms could extract it to make granule (Schmidt and Ahring, 1994).

**Structure of granules.** In granule studies, cavities and holes have been usually seen on the granule surfaces (Macleod et al., 1990; Morgan et al., 1991). The cavities may be channels for transport of gases, substrate, or metabolites. From the study transmission electron microscopy, microcolonies of syntrophic bacteria were often observed in internal structure of granules (Macleod et al., 1990; Morgan et al., 1991). A distinct localization of acidogenic bacteria and hydrolytic bacteria in the outer layer of granule grown on lactate or propionate was observed; meanwhile methanogenic bacteria were dominated in the inner part of granule (Fukuzaki, 1991a, 1991b). Other research supported this result. Macleod et al. (1990) reported that the there were syntrophic bacterial consortia. And, they told that acidogenic bacteria and hydrogen consuming bacteria existed in the outer of granules and most acetate utilizing bacteria were located in the core of granules. However, Grotenhuis et al. (1991) showed that there was no spatial orientation of microorganisms.

![Figure 2](image)

**Granulation Process.** Granulation process is not clearly understood yet so that so many research have been doing continuously (Schmidt and Ahring, 1996). The four steps of concept for granulation are as follows (Costerton et al., 1987). First, transporting of cell to the surface of an uncolonized inert material or other cells; second, initial reversible adsorption to the substratum by physicochemical forces; third, irreversible adhesion of cells to the substratum by microbial appendages and/or polymers attaching cells to the substratum; fourth, multiplication of cells and development of granules.

The transportation of cells could be diffusion (Brownian motion), advection (convection), or active transport by flagella. Initial adsorption is usually described by the Derjaguin-Landau-Verwey-Overbeek (DLVO) theory. In this theory, there is a weak substratum attraction when cells are located a certain distance from the substratum, first. Next, repulsion occurs when electrostatic interactions dominate. Finally, a strong irreversible attraction is obtained when van der Waals forces are dominating. The irreversible adhesion is established by bacterial holdfast or polymers. However, it is not clear whether bacteria are first adhere reversely and then produce EPS or make EPS first and adhere irreversibly. After adhering, cells divide within granules and trap with EPS.
UASB REACTOR

Introduction. The Upflow Anaerobic Sludge Blanket (UASB) reactor was developed by Lettinga and his colleagues in Netherlands (Wageningen University) in late 1970s. The granule was reported by Young and McCarty (1969) in their anaerobic filter system first and was observed in South Africa during Lettinga’s trip before developing the first UASB reactor. However, the UASB reactor was not developed at that time due to the lack of fund and experience for granules. The first UASB reactor was applied for a beet sugar refinery in the Netherlands. It was successfully applied as a pilot system and there were lots of full-scale UASB reactors for various industrial wastewaters afterwards. The first publication about the UASB reactor was Dutch in the late 1970s and the official international journal is appeared in the year of 1980 (Lettinga et al., 1980).

There had been some USB reactors in the early 1970s, but these reactors had no attention at those times (Lettinga et al., 1980). However, there are several types of full scale-reactors operated all over the world, especially Europe, South America, South Asia, and South East Asia (Kato et al., 1994; Lettinga, 1995). Lettinga (1995) told that only the United States did not stubbornly adopt the high technology of UASB for a long time. Besides, in a survey, 1215 full-scale high rate anaerobic reactors have been operated throughout the world since 1970s and most reactors were consisted of UASBs and EGSBs which were developed by Lettinga (Franklin, 2001). Most application wastewaters were brewery and beverage industry, distillery and fermentation, food industry, pulp, and paper wastewaters. These wastewaters accounted for about 90% of the whole application.

This reactor is extremely simple and has a set of Gas-Liquid-Solids Separator (GSS) in order to separate solids from effluent as well as to ease to withdraw gas out of the reactor. The typical upflow velocity is 0.5 ~ 1.0 m/hr and the height to depth is 0.2 ~ 0.5. This reactor is usually able to treat 10 ~ 15 kg/m²*d high-strength organic wastewater. Moreover, there are no particular mixing instruments without gas produced and upflow shear force. The UASB reactor usually starts with 10 ~ 30% of the reactor volume inoculated granules. The greater it is inoculated, the greater amount of loading rate can be treated initially (Hickey et al., 1991). Another modification is called the UASB filter system or hybrid anaerobic reactor (Guiot et al., 1985). Solids in influent could be accumulated in the UASB so that they give latent effect to the quality of effluent continuously. In order to this drawback, the EGSB reactor was developed (Nicolella et al, 2000).

Lettinga and Holshoff Pol (1991) organized the information of design factors and sources for various concentration wastewaters. In comparison, Tiwari et al. (2005) reported that the design of UASB is not established well and it is depended on empiricism.

Singh et al., (2006) reported that the dead space of the UASB reactor was 10 ~ 11%. Additionally, the mixing zone was smaller and the bypass flow increased much more in the reactor when temperature was dropped. Some researchers considered that the flow of UASB reactor was between completely mixed and plug flow (Heertjes et al., 1982; Bolle et al., 1986). Figure 3 is the schematic diagram of the UASB reactor.
Application and development trends. Mijaylova-Nacheva and Canul-Chuil (2006) reported that the anaerobic packed bed reactor which packed with granular activated carbon and inoculated by UASB granules had good removal efficiency for aliphatic compounds. COD removal efficiency was up to 94% at organic loading rate 1.24 kg/m³•d. Leal et al. (2006) applied the UASB for treating oil and grease of dairy wastewater. Hydrolytic enzyme was added to the UASB reactor in this test in order to estimate the performance of enzyme on oil and grease. COD removal efficiency was averaged 90% in this test when the enzyme was applied.

There were some research on hydrogen production in the UASB rather than the Completely Stirred Tank Reactor (CSTR). Gavala et al. (2006) showed that the amount of hydrogen produced in the mesophilic UASB reactor was greater than that in the mesophilic CSTR. So was the thermophilic CSTR.

Leitao et al. (2006) tested for both the organic and hydraulic shock on the robustness of the UASB. Not until was HRT around 6 hours, the efficiency of UASB reactor was affected. The concentration of influent was about 800 COD mg/L.

Some researchers have shown that UASB reactors were feasible to treat domestic wastewater (Draaijer et al., 1992; Vieira et al., 1994; Seghezzo et al., 1998). Vieira and Souza (1986) reported that the cost involved in installing a system, labor fee and materials was about US $300/m³ reactor or US $10/capita for a 200L/capita•day sewage contribution.

The detoxifying performances of UASB reactors are very great. Anaerobic granules could degrade biocides up to 99% by the glucose supplemented continuous UASB reactor (Wu et al., 1993). Donlon et al. (1996) also showed that UASB reactors were applied to rapidly detoxify nitroaromatic compounds.
In order to enhance granule size in the UASB reactor, some natural or artificial additives were added (Yu et al., 2000; Tiwari et al., 2005). When using natural additives, UASB reactors could enhance both the granule size and COD removal efficiency. Unlike usual UASB reactor, this reactor could be applied to the low-strength wastewater (organic loading rate: 1.48 kg/m³•d) and COD removal efficiency was obtained 95 ~ 98% after adding natural ionic polymer additives. Artificial materials on preparing for deficit granules have been continuously studied for some decades. When starting the UASB reactor after the inoculation, the digested sludge concentration was at least 10,000 ~ 20,000 mg/L (Lettinga et al., 1983; Wu et al., 1987). However, when granules are not available for start up of reactors, anaerobic digested sludge, waste activated sludge, and cow manure are could be used instead of the granules inoculation (Hulshoff Pol et al, 1982, 1983). Table 2 summarizes the using of artificial material for inoculation (Hickey et al., 1991).

Table 2. Summary of reports of successful formation of granules using non-granular inoculum materials

<table>
<thead>
<tr>
<th>Wastewater</th>
<th>Reactor Volume (m³)</th>
<th>Temperature (°C)</th>
<th>Inoculum</th>
<th>Granulation Period (months)</th>
<th>COD Loading Rate (kd/m³•d)</th>
<th>COD Removal Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>VFA mixture</td>
<td>0.030</td>
<td>30</td>
<td>Digested sludge</td>
<td>&gt;3.0</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>Acetate + Yeast extract</td>
<td>0.00575</td>
<td>55</td>
<td>Digested sludge</td>
<td>3.6</td>
<td>31</td>
<td>&gt;93</td>
</tr>
<tr>
<td>Acetate + Yeast extract</td>
<td>0.00575</td>
<td>55</td>
<td>Cow manure</td>
<td>3.6</td>
<td>51</td>
<td>&gt;96</td>
</tr>
<tr>
<td>Glucose</td>
<td>0.02</td>
<td>35</td>
<td>Digested sludge</td>
<td>5.0</td>
<td>15 ~ 20</td>
<td>&gt;90</td>
</tr>
<tr>
<td>Glucose</td>
<td>0.03</td>
<td>35</td>
<td>Activated sludge</td>
<td>1.5</td>
<td>12</td>
<td>&gt;85</td>
</tr>
<tr>
<td>Brewery</td>
<td>0.02</td>
<td>35</td>
<td>Digested sludge</td>
<td>1.5</td>
<td>26 ~ 32</td>
<td>&gt;90</td>
</tr>
<tr>
<td>Brewery</td>
<td>607</td>
<td>19 ~ 23</td>
<td>Digested sludge + Activated sludge</td>
<td>12</td>
<td>3 ~ 8</td>
<td>&gt;90</td>
</tr>
<tr>
<td>Citrate</td>
<td>0.048</td>
<td>35</td>
<td>Activated sludge</td>
<td>2</td>
<td>22</td>
<td>&gt;90</td>
</tr>
<tr>
<td>Citrate</td>
<td>6</td>
<td>35</td>
<td>Activated sludge</td>
<td>4</td>
<td>12 ~ 15</td>
<td>&gt;85</td>
</tr>
<tr>
<td>Distillery</td>
<td>24</td>
<td>30</td>
<td>Digested sludge</td>
<td>6</td>
<td>12 ~ 24</td>
<td>&gt;85</td>
</tr>
<tr>
<td>Slaughterhouse</td>
<td>21</td>
<td>15 ~ 27</td>
<td>Digested sludge</td>
<td>9</td>
<td>3 ~ 4</td>
<td>&gt;90</td>
</tr>
<tr>
<td>Terephthalate Production</td>
<td>20</td>
<td>35</td>
<td>Digested sludge</td>
<td>6</td>
<td>12 ~ 20</td>
<td>&gt;90</td>
</tr>
<tr>
<td>Sugar molasses</td>
<td>0.0114</td>
<td>30</td>
<td>Digested sludge</td>
<td>1.5</td>
<td>13</td>
<td>&gt;90</td>
</tr>
</tbody>
</table>

**EGSB REACTOR**

**Introduction.** The EGSB reactor is the family of UASB reactor. With a high recycle ratio, the upflow of this reactor is typically maintained higher than 6 m/hr; meanwhile the general range of the UASB reactor is 0.5 to 1.0 m/hr. The height to width of EGSB is 4 ~ 5 so that it enables the EGSB reactor to contact granules with wastewater enough. Additionally, due to the high velocity, granules are expended and the hydraulic mixing is intensified as to also give granules more chances to contact with wastewater. Thus, this reactor is able to treat high-strength organic wastewater (up to loading rate about 30 kg/m³•d). The definitive feature of EGSB reactor is the rapid upflow velocity. It enables this reactor to separate dispersed sludge from mature granules in the reactor. It makes a lot of contacts between granules and wastewater and withdraws suspended sludge out of the reactor. Influent concentration of COD is often less than 1000 ~ 2000 mg/L so that this reactor is also used to treat low-strength wastewater, especially low to mid temperature (Lettinga, 1996; Lettinga et al, 1997).
There are not many models of EGSB reactors like the UASB reactor. But based on the UASB reactor and AF models, some models have been attempted (Saravanan and Sreekrishnan, 2006). The biofilm model is expected to be similar to or the same with UASB models. Then, there are no definite differences between UASB and EGSB models, yet. In case of flow, the flow is expected between completed mixed and dispersed plug flow. Besides, the exact pattern is dependent upon the recycle ratio. Figure 4 is the schematic diagram of the EGSB reactor.

![Figure 4. Schematic diagram of the EGSB reactor.](image)

**Application and development trends.** There was a research result of treating the slaughterhouse wastewater by the EGSB reactor (Nunez and Martinez, 1999). In this study, removal efficiencies of COD, TSS, and fats were 67, 90, and 85%, respectively. And, there was no accumulation of fats in the reactor. In the results of anthranilic acid treatment test, the removal feasibility was shown below the upflow velocity of 5m/hr because of granules washout (Razo-Flores et al, 1999).

In the test of removing the milk fat by the EGSB reactor, most fats were adsorbed on the granules and slowly decomposed (Petruy and Lettinga, 1997). It means that the EGSB reactor also has a filtration effect by controlling the recycle ratio. The anaerobic ammonium oxidation (ANAMMOX) process was tested by the EGSB reactor. In this test, removal efficiencies of total nitrogen, ammonium, and nitrite were 54.3, 21.7 and 99.9%, respectively. COD removal efficiency was 84% at the influent concentration of 500mg/L (Jianlong and Jing, 2005).
Chu et al. (2005) reported that a membrane-coupled EGSB could treat domestic wastewater under moderate to low temperature. In this study, the cake layer on the membrane was the most serious problem due to the highest resistance in total resistance of the hollow fiber membrane. COD removal efficiency was proportional to upflow velocity.

dos Santos et al. (2003) showed that it was possible to treat a triazine contained azo dye by the thermophilic EGSB reactor. In order to activate this reaction, anthraquinone-2,6-disulfonate was used as a redox mediator and color removal efficiency was up to 95% in this test.

In case of long-chain fatty acids, COD removal efficiencies of 66 ~ 73% in the thermophilic condition and 44 ~ 69% in the mesophilic condition were obtained (Hwu et al., 1998). However, the white-absorbed granules were also observed in this test due to the using of long-chain acids. Dinsdale et al. (2000) reported that short the mixture of chain organic acids such as maleic, oxalic, or fumaric acid could be removed and COD removal efficiency was 98% when an organic loading rate was 10 kg COD/m³·day. In comparison, when a mixture of acetic, propionic, butyric, maleic, glyoxylic, and benzoic acids was removed, COD removal efficiency was 90% at loading rate of 3 kg COD/m³·day.

Toxicity test in the EGSB reactor showed industrial streams containing formaldehyde can still be treated anaerobically, if combining the good granules and recycle ratio (Gonzalez-Gil et al., 1999). The hydrogen and methanol could be obtained as intermediate products and formaldehyde toxicity was in part reversible because the methane production rate recovered after formaldehyde conversion.

Nowadays, there have been lots of research on psychrophilic anaerobic treatments by the EGSB reactor (Rebac et al., 1999; Collins et al., 2003, 2005a, and 2005b; Enright et al., 2005; Connaughton et al., 2006a). It is because the EGSB reactor has been shown to be a feasible system for anaerobic treatment at low temperature. Under psychrophilic conditions, chemical and biological reactions proceed much slower than under mesophilic so that most reaction in the biodegradation of organic matter requires more energy to proceed (Lettinga et al., 2001). However, Connaughton et al. (2006b) showed that there has no difference between the mesophilic EGSB reactor and the psychrophilic one. The influent was brewery wastewater and COD loading rate was 4.47 kg/m³·d. Both reactors had good COD removal efficiencies (85 ~ 93%). Specific methanogenic activities and gas production rates were also similar.

**Comparison between UASB and EGSB.** Both the UASB reactor and the EGSB reactor make use of granules, but differ in term of geometry, process parameters, and applications, and so on.

There are two dominant commercial processes in Europe. The Biothane® UASB process has been an impressive track record for kind of wastewater in the UASB market; meanwhile the Biobed® EGSB technology was developed lately and overrun it. There is a comparison between two processes in Table 3 (Zoutberg and Eker, 1999).

<table>
<thead>
<tr>
<th></th>
<th>Biothane® UASB</th>
<th>Biobed® EGSB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loading (kg COD/m³·day)</td>
<td>10</td>
<td>30</td>
</tr>
<tr>
<td>Height (m)</td>
<td>5.5 ~ 6.5</td>
<td>12 ~ 18</td>
</tr>
<tr>
<td>Toxic</td>
<td>+/-</td>
<td>++</td>
</tr>
<tr>
<td>Components</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$V_{\text{liquid settler}}$</td>
<td>1.0</td>
<td>10</td>
</tr>
<tr>
<td>$V_{\text{liquid reactor}}$</td>
<td>&lt;1.0</td>
<td>&lt;6.0</td>
</tr>
<tr>
<td>$V_{\text{gas reactor}}$</td>
<td>&lt;1.0</td>
<td>&lt;7.0</td>
</tr>
</tbody>
</table>
Zoutberg and Frankin (1997) gave an example of installing and operating case of Biobed® EGSB. It was possible to treat effluent of the factory producing formaldehyde from methanol by the Biobed® EGSB. The effluent was mainly consisted of formaldehyde 5,000 mg/L and methanol 10,000 mg/L. The removal efficiency was 99% for both compounds. Another factory was also showed the similar removal efficiency (98%) when formaldehyde 10,000 mg/L and methanol 20,000 mg/L (Zoutberg and de Been, 1996).

Figure 5 is schematic diagram of the Biotehan® UASB process and the Biobed® EGSB process. In addition, it presents pictures installed in the field.

![Figure 5](image)

There have been some tests for comparison between the UASB and the EGSB reactor. Jeison and Chamy (1999) reported that both the UASB and the EGSB reactor were shown great performances. They tested with low-strength influent as well as high-strength and could observe the similar size granules of the two. In the results of this test, there was no great difference and removal efficiencies of COD and SS, even the results of sludge activity, and sludge ash contents were similar each other. Kato et al. (1997) showed that the removal efficiency of the UASB reactor was affected below 200 mg COD/L. The EGSB reactor could be sustained up to 154 mg/L (7.4 kg/m³·d) without any detrimental effects.

**SGBR REACTOR**

**Introduction.** The SGBR was developed at Iowa State University (Mach and Ellis, 2000). It is one of modified granule reactors by accepting downflow (U.S. Patent No. 6,709,591). This reactor is good for treatment of low to mid-strength wastewater. The structure of this system is very simple and there are needed no additional equipments. And, effluent often retains very low concentration according to the influent and the operation parameters.
The flow of SGBR was certainly not understood. It was presumed that granule bed was fixed, and liquid passed throughout a lot of holes (channels) which gases produced in the SGBR. Even though there were some movements in this reactor, this effect was not to be completely mixed flow (Evans and Ellis, 2004). Figure 6 is the schematic diagram of the SGBR process.

Figure 6. Schematic diagram of SGBR Process (Park and Ellis, 2004).

Advantages and disadvantages as a high-rate anaerobic reactor. The SGBR process has been performed at room temperature and achieved high organic removal efficiency by a dense bed of anaerobic granules. Without any additional mixing system or power such as the recirculation pumping, gas/liquid/solids separation (GSS) devices and complex under drain systems or influent distribution systems, or backwashing systems, this reactor is able to remove effectively organic wastewater and separated solids/liquid/gas by the elevation energy (Mach and Ellis, 2002; Roth and Ellis, 2003). The most advantage of this system is very simple. This system has only a feed pump and the bypass line as to dislodge any granules trapped in the under drain system. And it could have long SRT (greater than 300 days), which is greater than similar system (Evans and Ellis, 2004).

However, this system would be clogged or granules level would be flooded if influent containing high solids concentration were provided or granules rapidly grew due to the high organic concentration. To repeated, the rate of removal of solids in the SGBR should be faster than the rate of input of influent solids in order to operate continuously this system without any trouble. Besides, this system needs periodically backwashing for solids withdrawal out of the reactor. The backwashing process means the additional cost and the instant quality deterioration of effluent.

Application and development trends. March and Ellis (2000) compared two reactors at room temperature. In this test, performances of a larger height to width reactor were superior to those of a smaller height to width, due to the plug flow at former reactor. When treating the wastewater containing high sulfate concentration, there was no harmful effect. It was hypothesized that hydrogen sulfide produced was separated in the top of the reactor and it didn’t affect granules (Evans and Ellis, 2004).
Park and Ellis (2004) reported that the SGBR reactor could effectively treat leachate. Evans and Ellis (2004) treated the synthetic wastewater made of non-fat dry milk (COD: 1000 mg/L) by the SGBR reactor. In this test, COD removal efficiency was very great and was maintained over 90%.


<table>
<thead>
<tr>
<th>Wastewater</th>
<th>HRT (hr)</th>
<th>Organic Loading Rate (kg COD/m³•d)</th>
<th>COD Removal Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-fat dry milk</td>
<td>5 ~ 36</td>
<td>0.7 ~ 4.8</td>
<td>91.7 ~ 97.3</td>
</tr>
<tr>
<td>Non-fat dry milk</td>
<td>5 ~ 36</td>
<td>0.7 ~ 4.0</td>
<td>93.9 ~ 96.6</td>
</tr>
<tr>
<td>Sucrose + non-fat dry milk</td>
<td>18 ~ 48</td>
<td>2.5 ~ 5.0</td>
<td>93.5 ~ 95.3</td>
</tr>
<tr>
<td>Slaughterhouse (pilot)</td>
<td>16 ~ 48</td>
<td>1.3 ~ 4.6</td>
<td>91.8 ~ 94.2</td>
</tr>
<tr>
<td>Slaughterhouse (lab.)</td>
<td>8 ~ 48</td>
<td>0.4 ~ 7.1</td>
<td>83.7 ~ 95.7</td>
</tr>
<tr>
<td>High sulfate waste stream</td>
<td>18</td>
<td>4.0</td>
<td>97.3</td>
</tr>
<tr>
<td>Domestic wastewater</td>
<td>12 ~ 48</td>
<td>0.08 ~ 0.8</td>
<td>56.5 ~ 81.6</td>
</tr>
</tbody>
</table>

**CONCLUSIONS**

The anaerobic treatment is practical and useful process to treat various industrial and domestic wastewaters. Although this process had numberless advantages, a lot of designers and operators have preferred to use aerobic processes than to anaerobic processes. It was because there were some misunderstandings for anaerobic processes as well as the lack of knowledge, experience, and skills. However, there have been continuously studying so many research on high-rate anaerobic treatment processes and accumulated technologies and know-how obtained in the fields do not make the anaerobic process useless any more.

As the representative high-rate anaerobic process, characteristics and applications of both the UASB reactor and the EGSB reactor are investigated and their performances are also compared. The UASB reactor have overwhelmed with its great performance for decades and its various applicability and data, experience, and skills in the fields are the main reasons why this reactor became the most widespread. The EGSB reactor was also treat efficiently high-strength wastewater by expending granules. In addition, this reactor is also able to apply to low-strength wastewater (< 1,000 COD mg/L), especially low temperature. The SGBR which was innovated at IOWA state university showed great performances like the UASB and the EGSB reactor. This reactor adopted downflow and the system is extremely simple so that there are no additional equipments.

**REFERENCES**


