Comparisons Between the UASB and the EGSB Reactor

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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 dewaterbility 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 (Lettinga, 1996). Nicolella et al. (2000) proposed the concentration-flow rate plane to design criteria applicable to different reactor.

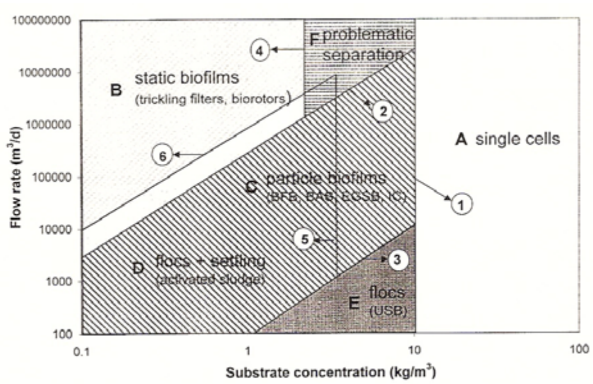


Figure 1. Concentration-flow diagram for sludge granulation (Nicolella et al., 2000).

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).

Density (mg/mL)	Diameter (mm)	
	37°C	55°C
1010	1.2	1.0
1020	0.8	0.7
1030	0.6	0.5
1040	0.5	0.4
1050	0.4	0.4
1060	0.4	0.3
1070	0.3	0.3
1080	0.3	0.3
1090	0.3	0.3
1100	0.3	0.2
1200	0.2	0.2
1300	0.2	0.1
1400	0.1	0.1
1500	0.1	0.1

Stokes law:

$$\text{If } \mathrm{Re} < 2:\ V = \frac{D^2 g(\rho_p - \rho)}{18\rho},$$

$$\text{If } 2 \le \mathrm{Re} \le 400:\ V_s = 0.153\left[\frac{(\rho_p - \rho)D^{1.6} g}{\eta^{0.5}\rho^{0.4}}\right]^{0.714}$$

Where; Re = Reynolds number ($V_s\rho_p D/\eta$), Vs = setting velocity (m/s), g = gravimetric constant (m/s^2), D = diameter of granule (m), ρ = density of granule (kg/m^3), η = viscosity of liquid (37°C: 0.73, 55°C: 0.51 for water) (kg/m•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.

(a) 

(b) 

Figure 2. Scanning electron micrographs of showing several cavities (a) Wiegant and de Man, (1986); (b) Hickey et al, 1991).

Granulation Process. Granulation process is not clear 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/m^3•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.

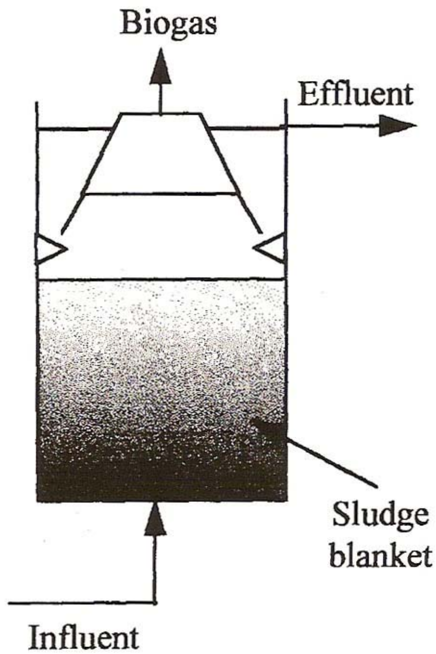


Figure 3. Schematic diagram of the UASB reactor .

Application and development trends. Mijaylova-Nacheva and Canul-Chuil (2006) reported that the anaerobic packed bed reactor which packed with granular activated carbon and inoculed by UASB granules had good removal efficiency for aliphatic compounds. COD removal efficiency was up to 94% at organic loading rate 1.24 kg/m^3•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 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 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/m^3 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/m^3•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

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

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/m^3•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.

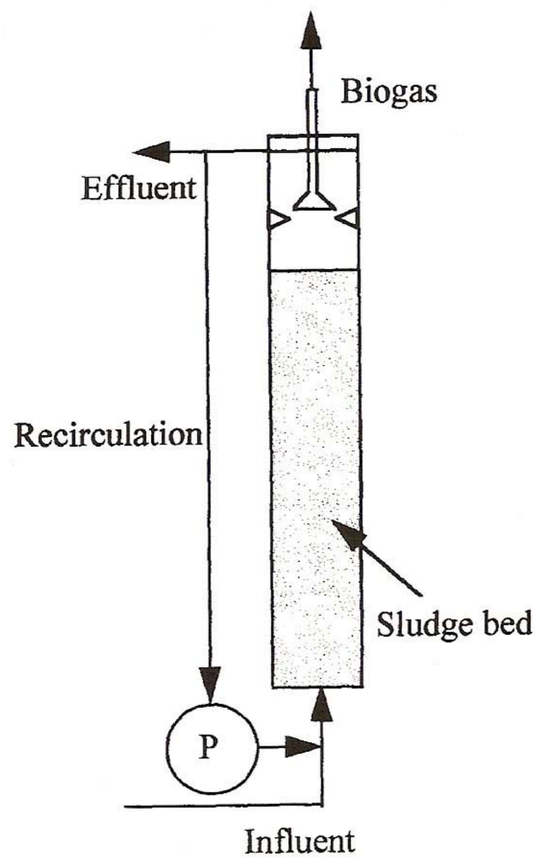


Figure 4. Schematic diagram of the EGSB reactor .

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/m^3·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/ m^3·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/m^3·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.

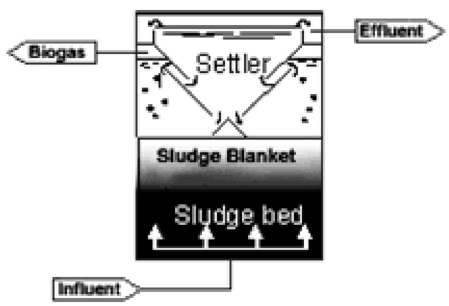
There are two dominant commercial processes in Europe. The Biothane® UASB process has been an impressive track record for kind of wastewater in the UASB market; meanwhile the Biobed® EGSB technology was developed lately and overrun it. There is a comparison between two processes in Table 3 (Zoutberg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

Table 3. Comparison between the main characteristics parameters of Biothane® UASB and Biobed® EGSB

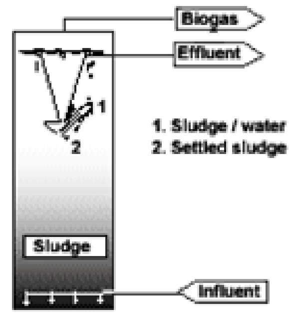
	Biothane® UASB	Biobed® EGSB
Loading (kg COD/m^3·day)	10	30
Height (m)	5.5 ~ 6.5	12 ~ 18
Toxic	+/-	++
Components		
V_{liquid} settler	1.0	10
V_{liquid} reactor	<1.0	<6.0
V_{gas} reactor	<1.0	<7.0

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 Biothane® UASB process and the Biobed® EGSB process. In addition, it presents pictures installed in the field.



(a)



(b)

(c)

(d)

Figure 5. Schematic diagram of (a) the Biothane® UASB process; (b) the Biobed® EGSB process and pictures installed in the field (c) the Biothane® UASB process; (d) the Biobed® EGSB process.

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/m^3•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.

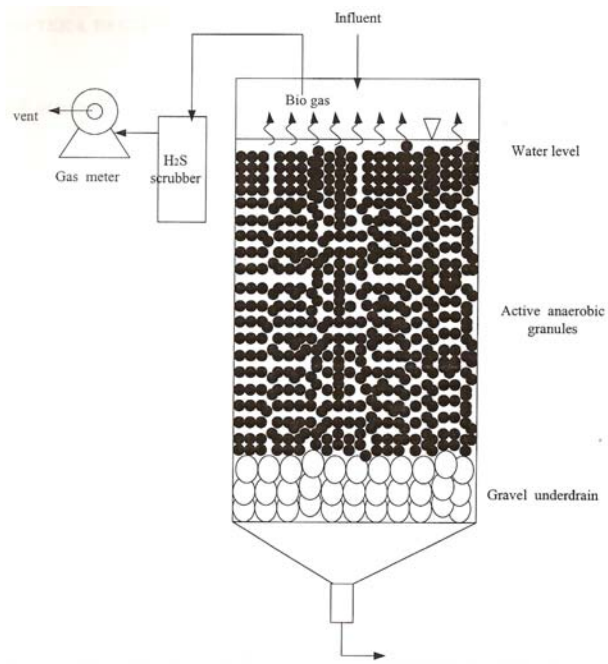


Figure 6. Schematic diagram of SGBR Process (Park and Ellis, 2004).

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%.

Evans and Ellis (2004) organized the results of SGBR process for various wastewaters in table 4.

Table 4. Some operating results of the SGBR process for various wastewaters (Evans and Ellis, 2004)

Wastewater	HRT (hr)	Organic Loading Rate (kg COD/m^3•d)	COD Removal Efficiency (%)
Non-fat dry milk	5 ~ 36	0.7 ~ 4.8	91.7 ~ 97.3
Non-fat dry milk	5 ~ 36	0.7 ~ 4.0	93.9 ~ 96.6
Sucrose + non-fat dry milk	18 ~ 48	2.5 ~ 5.0	93.5 ~ 95.3
Slaughterhouse (pilot)	16 ~ 48	1.3 ~ 4.6	91.8 ~ 94.2
Slaughterhouse (lab.)	8 ~ 48	0.4 ~7.1	83.7 ~ 95.7
High sulfate waste stream	18	4.0	97.3
Domestic wastewater	12 ~ 48	0.08~0.8	56.5 ~ 81.6

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 rector adopted downflow and the system is extremely simple so that there are no additional equipments.

REFERENCES

Ahring, B.K.; Schmidt, J.E.; Winther-Nielsen, M.; and Macario, A.J.L. (1993) Effect of Medium Composition and Sludge Removal on the Production, Composition, and Architecture of Thermophilic (55^oC) Acetate-utilizing Granules from an Upflow Anaerobic Sludge Blanket Reactor. *Appl. Environ. Microbiol*., **59**, 2538.

Alibhai, K.R.K. and Forster, C.F. (1986) An Examination of the Granulation Process in UASB Reactors. *Environ. Technol. Lett*., **7**, 193.

Alphenaar, P.A.; Perez, M.C.; and Lettinga. G. (1993) The Influence of Substrate Transport Limitation on Porosity and methanogenic Activity of Anaerobic Sludge Granular. *Appl. Microbiol. Biotechnol*., **39**, 279.

Bolle, W.L.; van Breugel, J.; van Eyebergen, G.C.; Kossen, N.W.F.; and Zoetemeyer, R.J. (1986) Modelling the Liquid Flow in Upflow Anaerobic Sludge Blanket Reactor, *Biotechnol. Bioeng*., **28**, 1615.

Colllins, G.; Woods, A.; McHugh, S.; Carton, M.W.; and O'Flaherty, V. (2003) Microbial Community Structure and Methanogenic Activity during Start-up Psychrophilic Anaerobic Digesters Treating Synthetic Industrial Wastewaters. *FEMS Microbiol. Ecol*., **46**, 159.

Collins, G; Foy, C.; McHugh, S.; Mahony, T.; and O'Flaherty, V. (2005a) Anaerobic Biological Treatment of Phenolic Wastewater at 15 ~ 18^{o}C. *Water Res*., **39**, 1614.

Collins, G.; Foy, C.; Mchony, T.; and O'Flaherty, V. (2005b) Anaerobic Treatment of 2,4,6-trichlorophenol in an Expended Granular Sludge Bed-Anaerobic Ffilter (EGSB-AF) Bioreactor at 18^{o}C. *FEMS Microbiol. Ecol*., **53**, 167.

Connaughton, S.; Collins, G.; and O'Flaherty, V. (2006a) Development of Microbial Community Structure and Activity in a High-Rate Anaerobic Bioreactor at 18^{o}C. *Water Res*., **40**, 1009.

Connaughton, S.; Collins, G.; and O'Flaherty, V. (2006b) Psychrophilic and Mesophilic Anaerobic Digestion of Brewery Effluent: A Comparative Study. *Water Res*., **40**, 2503.

Costerton, J.W.; Cheng, K.J.; Geesey, G.G.; Ladd, T.I.; Nickel, J.C.; Dasgupta, M.; and Marrie, T.J. (1987) Bacterial Biofilms in Nature and Disease*. Annu. Rev. Microbiol*., **41**, 435.

Grotenhuis, J.T.C.; Kissel, J.C.; Plugge, C.M.; Stams, A.J.M.; and Zehnder, A.J.B. (1991) Role of Substrate Concentrate in Particle Size Distribution of Methanogenic Granular Sludge in UASB Reactors. *Water Res*., **25**, 21.

Guiot, S.R. and van den Berg, L. (1985) Performance of Upflow Anaerobic Reactor Combining a Sludge Blanket and a Filter Treating Sugar Waste. *Biotechnol. Bioeng*., **27**, 800.

Dinsdale, R.M.; Hawkes, F.R.; and Hawkes, D.L. (2000) Anaerobic Digestion of Short Chain Organic Acids in an Expended Granular Sludge Bed Reactor. *Water Res*., **34**, 2433.

Draaijer, H.; Mass, J.A.W.; Schaapman, J.M.; and Khan, A. (1992) Performance of the 5 MLD UASB Reactor for Sewage Treatment at Kanpur, India. *Water Sci. Technol*., **25**, 123.

Dolfing, J. (1986) Granulation in UASB Reactors. *Water Sci. Technol*., **18**, 25.

Dolfing, J.; Griffioen, A.; van Neerven, A.R.W.; and Zevenhuizen, L.P.T.M. (1985) Chemical and Bacteriological Composition of Granular Methanogenic Sludge. *Can. J. Microbiol*, **31**, 744.

Donlon, B.A.; Razo-Flores, E.; Lettinga, G.; and Field, J.A. (1996) Continuous Detoxification, Transformation, and Degradation of Nitrophenols in Upflow Anaerobic Sludge Blanket (UASB) Reactors. *Biotechnol. Bioeng*., **51**, 439.

dos Santos, A.B.; Cervantes, F.J.; Yaya-Beas, R.E.; and van Lier, J.B. (2003) Effect of Redox Mediator, AQDS, on the Decolourisation of a Reactive Azo Dye Containing Triazine Group in a Thermophilic Anaerobic EGSB Reactor. *Enzyme Microbial Technol*., **33**, 942.

Enright, A.M.; McHugh, S.; Collins, G.; and O'Flaherty, V. (2005) Low-temperature Anaerobic Biological Treatment of Solvent-containing Pharmaceutical Wastewater. *Water Res*., **39**, 4587.

Evans, K.M. and Ellis, T.G. (2004) Fundamentals of the Static Granular Bed Reactor. Ph D’s Thesis, Iowa State University, IA.

Fang, H.H.P.; Chui, H.K.; and Li, Y.Y. (1994) Microbial Structure and Activity of UASB-granules Treating Different Wastewater. *Water Sci. Technol*., **30**, 87.

Forster, C.F. (1992) Anaerobic Upflow Sludge Blanket Reactor: Aspects of Their microbiology and Their Chemistry. *J. Biotechnol*., **17**, 221.

Franklin, R.J. (2001) Full Scale Experience with Anaerobic Treatment of Industrial Wastewater. *Water Sci. Technol*., **44**, 1.

Fukuzaki, S.; Chang, Y.; Nishio, N.; and Nagai, S. (1991a) Characteristics of Granular Methanogenic Sludge Grown on Lactate in a UASB Reactor. *J. Ferment. Bioeng*., **72**, 465.

Fukuzaki, S.; Nishio, N.; and Nagai, S. (1991b) Chemical Composition and kinetic Properties of Granular Methanogenic Sludge Grown on Propinate. *J. Ferment. Bioeng*., **72**, 405.

Gavala, H.N.; Skiadas, I.V.; and Ahring, B.K. (2006) Biological Hydrogen Production in Suspended and Attached Growth Anaerobic Reactor Systems. *Int J. Hydrogen Energy*, **31**, 1164

Gonzalez-Gil, G.; Kleerebezem, R.; van Aelst, A.; Zoutberg, G.R., Versprille, A.I.; and Lettinga, G. (1999) Toxicity Effects of Formaldehyde on Methanol Degrading Sludge and Its Anaerobic Conversion in BioBed® Expended Granular Sludge Bed (EGSB) Reactors. *Water Sci. Technol*., **40**, 195.

GrotenHuis, J.T.C.; Smit, M.; Plugge, C.M.; Yuansheng, X.; Lammeren, A.A.M.; van Stam, A.J.M.; and Zehnder, A.J.B. (1991) Bacterialogical Composition and Structure of Granular Sludge Adapted to Different Substrates. *Appl. Environ. Microbiol*., **57**, 1942.

Heertjes, P.M.; Kuijvenhoven, L.J.; and van der Meer, R.R. (1982) Fluid Flow Pattern in Upflow Reactors for Anaerobic Treatment for Beer Sugar Factory Wastewater. *Biotechnol. Bioeng*., **24**, 443.

Hickey, R.F.; Wu, W.M.; Veiga, M.C.; and Jones, R. (1991) Start-up, Operation, Monitoring and Control of High-rate Anaerobic Treatment systems. *Water Sci. Technol*., **24**, 207.

Hulshoff Pol, L.W.; de Zeeuw, W.; Velzeboer, C.T.M.; and Lettinga, G. (1983) Granulation in UASB reactor. *Water Sci. Technol.*, **15**, 291.

Hulshoff Pol, L.W.; Dolfing, J.; de Zeeuw, W.; and Lettinga, G. (1982) Cultivation of Well adapted Pelletized Methanogenic Sludge. *Biotechnol. Lett*., **4**, 329.

Hulshoff Pol, L.W.; van de Worp, J.J.M.; Lettinga, G.; and Beverloo, W. A. (1986) Physical Characterization of Anaerobic Granular Sludge. In *Anaerobic Treatment. A grown-up Technology*., RAI Halls, Amsterdam.

Hwu, C.S.; Lier, J. B.; and Lettinga, G. (1998) Physicochemical and Biological Performance of Expended Granular Sludge Bed Reactors Treating Long-chain Fatty Acids. *Process Biochem*., **33**, 75.

Jeison, D. and Chamy, R. (1999) Comparison of the Behaviour of Expended Granular Sludge Bed (EGSB) and Upflow Anaerobic Sludge Blanket (UASB) Reactors in Dilute and Concentrated Wastewater Treatment. *Water Sci. Technol*., **40**, 91.

Jewell, W.J. (1987) Anaerobic Sewage Treatment. *Environ. Sci. Technol*., **21**, 14.

Jianlong, W. and Jing, K. (2005) The Characteristics of Anaerobic Ammonium Oxidation (ANAMMOX) by Granular Sludge from an EGSB Reactor. *Process Biochem*., **40**, 1973.

Kato, M.T.; Field, J.A.; Kleerebezem, R.; and Lettinga, G. (1994) Treatment of Low Strength Soluble Wastewater in UASB Reactors, *J. Ferment. Bioeng*., **77**, 679.

Kato, M.T.; Field, J.A.; and Lettinga, G. (1994) The Anaerobic Treatment of Low Strength Wastewaters in UASB and EGSB Reacters. *Water Sci. Technol*., **36**, 375.

Kosaric, N.; Blaszczyk, R.; Orphan, L.; and Valladares, J. (1990) The Characteristics of Granules from Upflow Anaerobic Sludge Blanket Reactors. *Water Res*., **24**, 1473.

Leal, M.C.M.R.; Freire, D.M.G.; Cammarota, M.C.; and Sant'Anna Jr., G.L. (2006) Effect of Enzymatic Hydrolysis on Anaerobic Treatment of Dairy Wastewater. *Process Biochem*., **41**, 1173.

Leitao, R.C.; Santaellla, S.T.; van Haandel, A.C.; Zeeman, G.; and Lettinga, G. (2006) The Effects of Hydrauli and Organic Shock Loaads on the Robustness of Upflow Anaerobic Sludge Blanket Reactors treating Sewage. *Water Sci. Technol*., **54**, 49.

Lettinga, G. (1995) Anaerobic Digestion and Wastewater Treatment Systems. *Antonie van Leeuwenhoek*, **67**, 3.

Lettinga, G. and Holshoff Pol, L. (1991) UASB-process Design for Various Types of Wastewaters. *Water Sci. Technol*., **24**, 87.

Lettinga, G.; Homa, S.W.; Hulshoff Pol, L.W.; de Zeeuw, W.; de Jong, P.; Grin, D.; and Roersma, R. (1983) Design, Operation and Economy of Anaerobic Treatment. *Water Sci. Technol*., **15**, 177.

Lettinga, G.; Field, J.; van Lier, J.; Zeeman, G.; and Hulshoff Pol, L.W. (1997) Advanced Anaerobic Wastewater Treatment in the near Future. *Water Sci. Tech*., **35**, 5.

Lettinga, G.; Rebac, S.; and Zeeman, G. (2001) Challenge of Psychrophilic Anaerobic Wastewater Treatment. *TRENDS in Biotechnol*., **19**, 363.

Lettinga, G.; van Nelsen, A.F.M.; Hobma, S.W.; de Zeeuw, W.; and Klapwijk, A. (1980) Use of the Upflow Sludge Blanket (USB) Reactor Concept for Biological Wastewater Treatment, Especially for Anaerobic Treatment. *Biotechnol. Bioeng*., **22**, 699.

Mach, K.F. and Ellis, T.G. (2000) Development of the Static Granular Bed Reactor. Master's Thesis, Iowa State University, IA.

Macleod, F.A.; Guiot, S.R.; and Costerton, J.W. (1990) Layered Structure of Bacterial Aggregates Produced in an Upflow Anaerobic Sludge Bed and Filter Reactor. *Appl. Environ. Microbiol*., **56**, 1598.

McCarty, P.L. and Smith, D.P. (1986) Anaerobic Wastewater Treatment. *Environ. Sci. Technol*., **20**, 1200.

Mijaylova-Nacheva, P. and Canul-Chuil, A. (2006) Anaerobic Biodegradation of Chlorinated Aliphatic Compounds using Packed Bed Reactors. *Water Sci. Technol*., **54**, 193.

Morgan, J.W.; Evison, L.M.; and Forster, C.F. (1991) The Internal Architecture of Anaerobic Sludge Granules. *J. Chem. Technol. Biotechnol*., **50**, 211.

Morgan, J.W.; Forster, C.F.; and Evison, L.M. (1990) A Comparative Study of the Nature of Biopolymers Extracted from Anaerobic and Activated Sludge. *Water Res*., **6**, 743.

Nicolella, C.; van Loosdrecht, M.C.M.; and Heijnen, J.J. (2000) Wastewater Treatment with Particulate Biofilm Reactors. *J. Biotechnol*., **80**, 1.

Nunez, L.A. and Martinez, B. (1999) Anaerobic Treatment of Slaughterhouse Wastewater in an Expended Granular Sludge Bed (EGSB) Reactor. *Water Sci. Technol*., **40**, 99.

Park, J. and Ellis, T.G. (2004)Evaluation of Leachate Treatment and Recycle Options using the Static Granular Bed Reactor. Master's Thesis, Iowa State University, IA.

Petruy, R. and Lettinga, G. (1997) Digestion of a Milk-fat Emulsion. *Bioresour. Technol*., **61**, 141.

Razo-Flores, E.; Smulders, P.; Prenafeta-Boldu, F.; Lettinga, G.; and Field, J.A. (1999) Treatment of Anthranilic Acid in an Anaerobic Expended Granular Sludge Bed Reactor at Low Concentrations. *Water Sci. Technol.*., **40**, 187.

Rebac, S.; van Lier, J.B.; Lens, P.; Stams,A.J.M.; Dekkers, F.; Swinkels, K.T.M.; and Lettinga, G. (1999) Psychrophilic Anaerobic Treatment of Low Strength Wastewaters. *Water Sci. Technol*., **39**, 203.

Ross, W.R. (1984) The Phenomenon of Sludge Pelletisation in the Anaerobic Treatment of a Maize Process Waste. *Water SA*, **4**, 197.

Roth, M.J. and Ellis, T.G. (2003) Development of the Static Granular Bed Reactor for Full-scale Application. Master's Thesis, Iowa State University, IA.

Saravanan, V. and Sreekrishnan, T.R. (2006) Modelling Anaerobic Biofilm Reactor – A Review. *J. Environ. Management*, **81**, 1.

Schmidt, J.E. and Ahring, B.K. (1994) Extracellular Polymers in Granular Sludge from Different Sludge Upflow Anaerobic Sludge Blanket (UASB) Reactors. *Appl. Microbiol. Biotechnol*., **42**, 457.

Schmidt, J.E. and Ahring, B.K. (1996) Granular Sludge Formation in Upflow Anaerobic Sludge Blanket (UASB) Reactors. *Biotechnol. Bioeng.*, **49**, 229.

Schmidt, J.E.; Macario,A.J.L.; Ahring, B.K.; and Conway de Macario, E. (1992) Effect of Magnesium of on Methanogenic Subpopulations in a Thermophilic Acetate-degrading Granular Consortium., *Appl. Environ. Microbiol*., **58**, 862.

Seghezzo, L.; Zeeman, G.; van Lier, J.B.; Hamelers, H.V.M.; Lettinga, G. (1998) A Review: The Anaerobic Treatment of Sewage in UASB and EGSB Reactors. *Bioresour. Technol*., **65**, 175.

Shen, C.F.; Kosaric, N.; and Blaszczyk, R. (1993) Properties of Anaerobic Sludge as Affected by Yeast Extract, Cobalt and Iron Supplement. *Appl. Microbiol. Biotechnol*., **39**, 132.

Shen, C.F.; Kosaric, N; and Blaszczyk, R. (1993) The Effect of Selected Heavy Metals (Ni, Co and Fe) on Anaerobic Granules and Their Extracellular Polymeric substance (ECP). *Water Res*., **27**, 25.

Singh, K.S.; Viraraghavan, T.; Bhattacharyya, D. (2006) Sludge Blanket Height and Flow Pattern in UASB Reactors: Temperature Effects. *J. Environ. Eng*., **132**, 895.

Stal, L.J.; Bock, E.; Bouwer, E.J.; Douglas, L.J.; Gutnick, D.L.; Heckmann, K.D.; Hirsh, P.; Kolbel-Boelke, J.M.; Marshall, K.C.; Prosser, J.I.; Schutt, C.; and Watanabe, Y. (1989) Cellular Physiology and Interactions of Biofilm Organism. *In Structure and Function of Bioflm*, Wiley, Chichester.

Thaveesri, J.; Gernaey, K.; Kaonga, B.; Boucneau, G.; and Verstaete, W. (1994) Organic and Ammonium Nitrogen in Lab-scale UASB in Relation to Granular Sludge Growth Reactors. *Water Sci. Technol*., **30**, 43.

Tiwari, M.K.; Guha, S.; Harendranath, C.S.; and Tripathi, S. (2005) Enhanced Granulation by Natural Ionic Polymer Additives in UASB Reactor Treating Low-strength Wastewater. *Water Res*., **39**, 3810.

Vieira, S.M.M. and Souza, M.E. (1986) Development of Technology for the Use of the UASB Reactor in Domestic Sewage Treatment. *Water Sci. Technol*., **18**, 109.

Vieira, S.M.M.; Carvalho, J.L.; Barijan, F.P.O.; Rech, C.M. (1994) Application of the UASB Technology for Sewage Treatment in a Small Community at Sumare Sao Paulo State. *Water Sci. Technol*., **30**, 203.

Wiegant, W.M. and de Man, A.W. (1986) Granulation of Biomass in Thermophilic Upflow anaerobic Sludge Blanket Reactors Treating Acidified Wastewaters. *Biotechnol. Bioeng*., **28**, 718.

Wu, W.M.; Bhatnagar, L.; and Zeikus, G. (1993) Performance of Anaerobic Granules for Degradation of Pentachlorophenol. *Appl. Environ. Microbiol*., **59**, 389.

Wu, W.M.; Hickey, R.F.; and Zeikus, J.G. (1991) Characterization of Metabolic Performance of Methanogenic Granules Treating Brewery Wastewater – Role of Sulphate Reducing Bacteria. *Appl. Environ. Microbiol*., **57**, 3438.

Wu, W.M.; Hu, J.C.; Gu, X.S.; Zhao, Y.Z.; and Gu, G.G. (1987) Cultivative of Anaerobic Granular Sludge in UASB Reactors with Aerobic Activated Sludge as Seed. *Water Res*., **21**, 789.

Young, J.C. and McCarty, P.L. (1969) The Anaerobic Filter for Wastewater Treatment. *J. Water Poll. Control Fed*., **4**, 160.

Yu, H.Q.; Fang, H.H.P.; and Tay, J.H. (2000) Effect of Fe^{2+} on Sludge Granulation in Upflow Anaerobic Sludge Blanket Reactor. *Water Sci. Technol*., **41**, 199.

Zhou, W.; Imai, T.; Ukita, M.; Sekine, M.; and Higuchi, T. (2006) Triggering Forces for Anaerobic Granulation in UASB Reactors. *Process Biochm*., **41**, 36.

Zoutberg, G.R. and de Been, P. (1997) The Biobed® EGSB (Expended Granular Sludge Bed) System Covers Shortcomings of the Upflow Anaerobic Sludge Blanket Reactor in the Chemical Industry. *Water Sci. Technol*., **35**, 183.

Zoutberg, G.R. and Eker, Z. (1999) Anaerobic Treatment of Potato Processing Wastewater. *Water Sci. Technol*., **40**, 297.

Zoutberg, G.R. and Frankin, R. (1996) Anaerobic Treatment of Chemical and Brewery Wastewater with a New Type of Anaerobic Reactor; The Biobed® EGSB Reactor. *Water Sci. Technol*., **34**, 375.