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Doctor Thesis of Tohoku University

Development of an Innovative Self-Agitation Anaerobic Baffled Reactor (SA-ABR) for Organic Waste Treatment and Biogas Production

（有機性廃棄物処理とバイオガス生成のための新規自動攪拌式嫌気性バッフルドリアクターの開発）

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Chapter 1 Introduction and problem statement

Abstract: Rising crude oil prices force us to think about alternative energy source. Overall, the basic knowledge of biogas production, the microorganisms involved, and the biochemical processed was widely extended. A lot of experience was gained, leading to a continuous process optimization of anaerobic fermentation and the development of now and more efficient applications. This study contributes to the consolidation of knowledge in the food waste treatment fields, so that learning can be accessed more easily and applications can be harmonized.

1.1 General perspective

Anaerobic digestion is a waste and wastewater treatment technology that includes a number of physical, chemical and biological processes. The advantages of this type of digestion are that it does not require aeration, the construction costs are low, and large amount of biogas is produced.

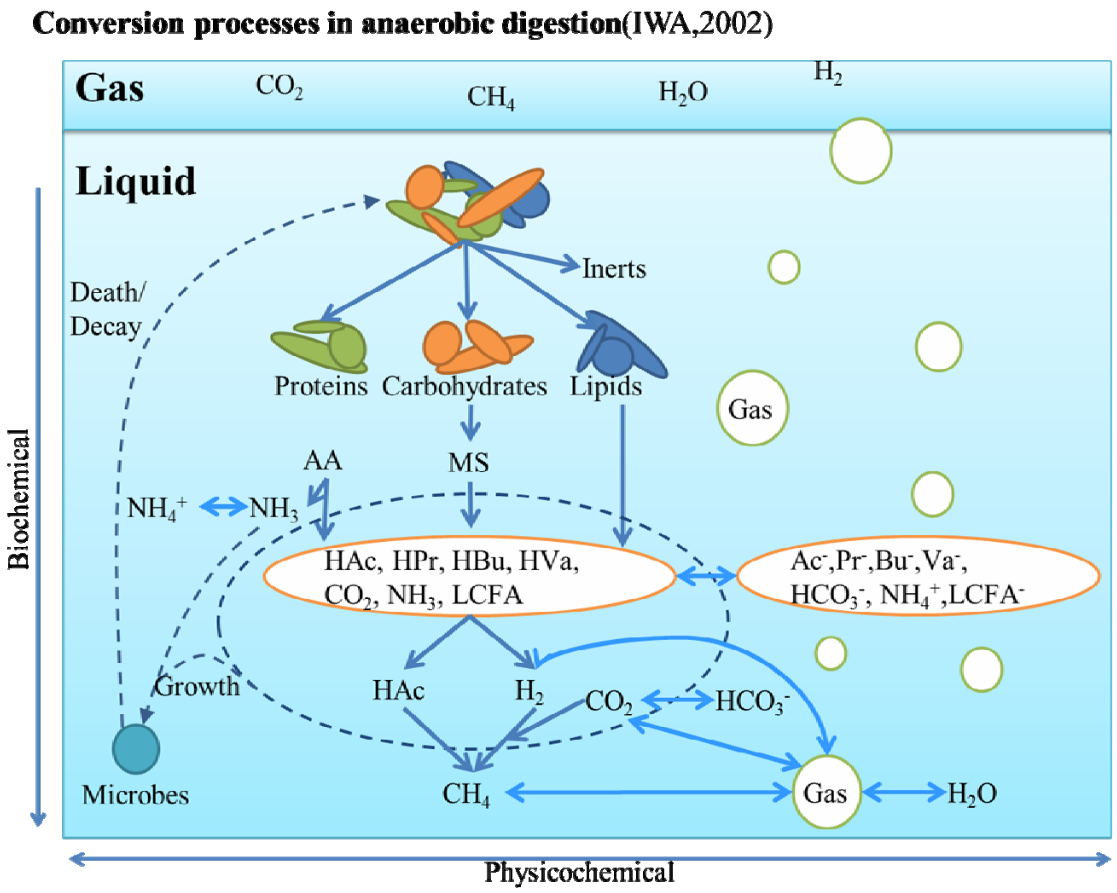

Fig. 1-1 Conversion processes in anaerobic digestion.

1.2 Benefits of waste fermentation

There are many benefits to be derived from the fermentation process of converting substrates (Ghosh and Pohland 1974, Van Starkenburg 1997).

1.3 Research objectives

The continuous operation of an innovative self-agitation anaerobic baffled reactor (SA-ABR), which requires no electricity for the agitation, was investigated (Kobayashi and Li 2011, Qi et al. 2013). The improved reactor retained the advantage of separate the different bacteria and digestion phases, while its design allows for the treatment of a high strength substrate at a high loading rate mixing parts of the reactor without electricity in a the low-cost reactor which has already been shown (Table 1-1). Thus, this research topic focuses on the development of SA-ABR.

Table 1-1 The performance of SA-ABR and compare with other reactors (Kobayashi et al. 2013)

Performance	SA-ABR	Normal anaerobic reactor
Flow state	One or several CSTR(s)	CSTR
Agitation	Non-mechanical	mechanical
Electricity	No need	Amount
Shortage	-	Operation cost high
HLR (kg/m^3/day)	1-18	1-10

1.4 Dissertation outline

The whole thesis structure was illustrated in Fig. 1-2

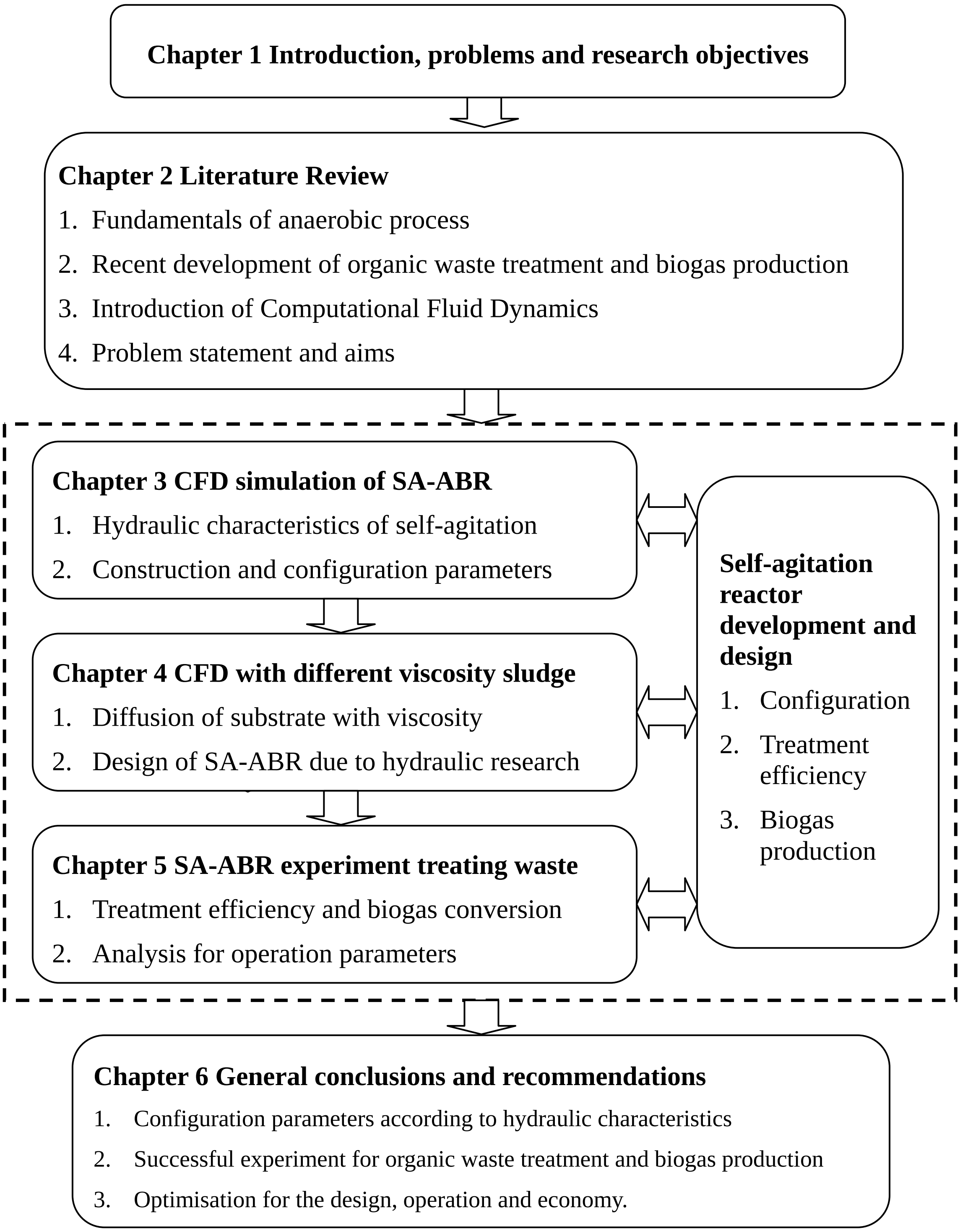

Fig. 1-2 The whole thesis structure

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Chapter 2 Preliminary review: Methane fermentation of organic solid wastes.

Abstract: Anaerobic conversions are among the oldest biological process technologies. They have been applied and developed over many centuries. In organic waste treatments, high organic loading rates and low sludge process are among the many advantages anaerobic processes exhibit over other biological unit operations. More important, this technology has a positive net energy production and the biogas produced can also replace fossil fuel sources, therefore, has a direct positive effect on greenhouse gas reduction. This will ensure the ongoing, popularity of anaerobic digestion processes for waste treatment in the future. The research is hoped to introduce a new anaerobic digestion reactor. An innovative self-agitation reactor which no needs the mechanical mixer or other recirculating equipment for mixing has been studied.

2.1 Substrate and biogas

The formation of methane is a biological process that occurs naturally when organic material (biomass) decomposes in a humid atmosphere in the absence of air but in the presence of a group of natural microorganisms which are metabolically active, i.e. methane bacterial. In natural, methane is formed as arch gas (or swamp gas), in the digestive tract of ruminants, in plants for wet composting, and in flooded rice field. Biomass which is suitable to be fermented is named “substrate” (Deublein and Steinhauser 2010).

In general, all type of biomass can be used as substrates as long as they contain carbohydrates, proteins, fats, cellulose, and hemicellulose as main components. However, lignin and most synthetic organic polymers (plastic) simply decompose slowly.

Biofuel production from agriculture, municipal, and industrial wastes is efficiently accomplished through conversion to biogas, a mixture of mostly methane (CH_4) and carbon dioxide (CO_2), via anaerobic digestion. Anaerobic digestion is a process by which a complex mixture of symbiotic microorganisms transforms organic materials under oxygen-free conditions into biogas, and additional cell matter, leaving salts and refractory organic matter. In practice, microbial anaerobic conversion to methane is a process for both effective waste treatment and sustainable energy production. In waste treatment, this process can provide a source of energy while reducing the pollution and odor potential of the substrate. Unlike fossil fuels, use of renewable methane represents a closed carbon cycle and thus does not contribute to increases in the atmospheric concentration of carbon dioxide(Smith et al. 1988).

2.2 Fundamentals of methane fermentation

2.2.1 Four phases bioreaction of degradation

Methane fermentation is a complex process, which can be divided up into four phases of degradation, named hydrolysis, acidogenesis, acetogenesis, and methanation, according to the main process of decomposition in this phase (Fig. 2-1).

The first and second as well as the third and fourth phase are linked closely with teach other. Therefore, one can accomplish the process well in two stages. In both stages the rates of degradation must be equal in size. If the first stage runs too fast, the CO_2 portion in the biogas increases, the acid concentration rises and the pH vale drops below 7.0. Acidic fermentation is then also carried out in the second stage. If the second stage runs too fast, methane production is reduced. There are still many bacteria of the first stage in the substrate. The bacteria of the second stage must be inoculated (Gujer and Zehnder 1983).

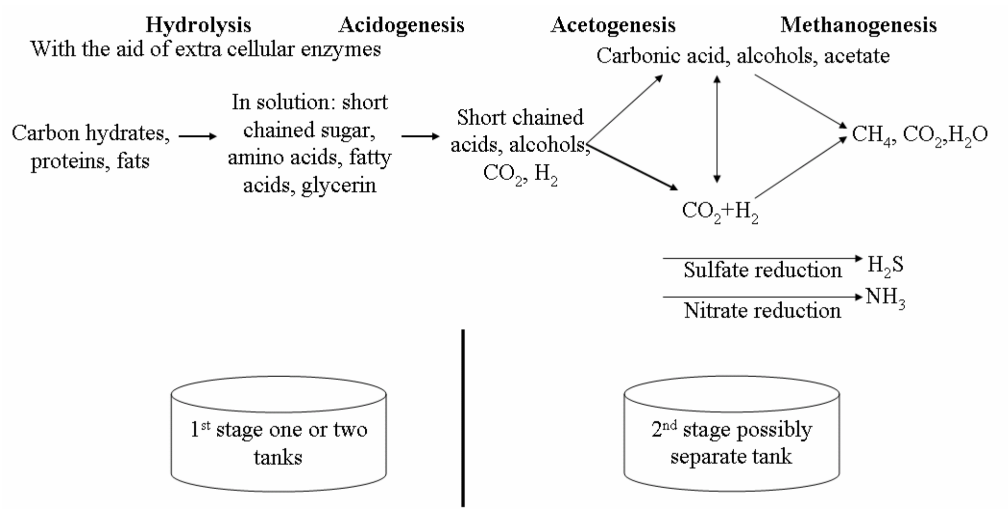

Fig. 2-1 Biochemistry of the methane gas production

2.2.2 Process parameters

With all biological processes, the constancy of the living conditions is of importance. The microbial metabolism processes are dependent on many parameters (Table 2-1), so that, for an optimum fermenting process, numerous parameters must be taken into consideration and be controlled, by which the hydrolysis and acidification of the substrate occur, differ from the requirements of the methane-forming microorganisms.

Table 2-1 Environmental requirements

Parameter	Hydrolysis/acidogenesis	Methane formation
Temperature	25-35^{o}C	Mesophilic 32-42^{o}C
		Thermophilic 50-58^{o}C
pH value	5.2-6.3	6.7-7.5
C:N ratio	10-45	20-30
DM content	<40% DM	<30% DM
Redox potential	+400 to -300 mV	<-250mV
Required C:N:P:S ratio	500:15:5:3	600:15:5:3
Trace elements	No special requirements	Essential: Ni, Co, Mo, Se

2.2.3 Biogas production potential

Wastes from food processing are high in organic matter and are therefore ideal for methane fermentation. Biomethane production potential varies from one type of organic waste to another, depending upon the release of volatile solids during AD, digester type, and digester operating conditions (pH, temperature, loading rate, etc.). Methane production of a specific crop residue is affected by the chemical composition of the residue, which changes as the plant matures as affected by the timing and conditions of harvest (Nallathambi Gunaseelan 1997, Lehtomäki et al. 2008)

2.3 Evaluation of substrate for biogas production

A test could be in principle continuous or batch-wise. Conventional methane fermentation takes place in the batch, semi-continuous, or continuous modes of operation. In the latter two modes, the digester is intermittently or continuously supplied with aqueous slurry of the substrate and an equal amount of fermentor broth is withdrawn. Individual and multistage digesters, in which all phases of methane fermentation occur, are used. In batch systems, steady-state conditions can not be achieved because the components within the digester are constantly changing. In the semi-continuous and continuous modes, methane fermentation can take place in the steady state as the organisms grow at the maximum rate permitted by the inflow of substrate and nutrients. (Parkin and Speece 1982, Mata-Alvarez et al. 2000, Hoffmann et al. 2008).

2.4 Computational Fluid Dynamics

Computational Fluid Dynamics (CFD) is a powerful approach that provides detailed spatial distribution of flow fields (Klusener et al. 2007). CFD can also provide a three-dimensional visualization of a system. Recent advancements in CFD have significantly enhanced the understanding of flow fields in wastewater treatment plants. CFD allows a computational model to be used under many different design constraints and is an effective tool in water treatment device design and optimization (Fan et al. 2008). Some studies have also focused on using CFD to evaluate the important parameters of water treatment reactors, examples include plate settlers (Salem et al. 2011), countercurrent pulsed sieve plate extraction columns (Din et al. 2010), horizontal cross-flow bubble column reactors (Klusener et al. 2007), and the CW (García et al.

2005, Qi et al. 2013). Simulation produced a good match with the measured data for water flow, tracer experiments and pollutant removal processes (Qi et al. 2013) and have significantly improved the understanding of flow fields in wastewater treatment plants (Liu 2012).

2.5 Problems statement

The advantages of organic waste anaerobic digestion treatment are that it does not require aeration, the construction costs are low, and large amounts of biogas is produced (Ji et al. 2012). Unstirred plug-flow digesters often exhibit problems due to the accumulation of organic acids and the resulting pH decrease in the front part of the reactor (Barber and Stuckey 1999). In a continuous stirred tank reactor (CSTR) reactor, the mass transfer in the liquid phase is affected not only by the applied stirring frequency but also by the agitation method; higher reaction rates of anaerobic digestion are obtained under conditions with higher agitation frequency (Cubas et al. 2011). Karim et al. (2005) noted that mixing by naturally produced gas may be sufficient for the treatment of low solids concentration substrates such as 5% manure, while the effect of additional mixing became important in the case of treating 10% manure. However, the need for additional agitation means that the low-cost benefit is partially lost.

The performance of anaerobic digesters is affected primarily by the HRT of substrate in the reactor and the degree of contact between incoming substrate and a viable bacterial population. These parameters are primarily a function of the hydraulic regime (mixing) in the reactors. The importance of mixing in achieving efficient substrate conversion has been noted by many researchers, although the optimum mixing pattern is a subject of much debate. Mixing of the substrate in the digester helps to distribute organisms uniformly throughout the mixture and to transfer heat. Mixing can be accomplished through various methods, including mechanical mixers, recirculation of digester contents, or by recirculating the produced biogas using pumps (Karim et al. 2005).

One digestion reactor is the anaerobic baffled reactor (ABR). Very little mixing occurs between one compartment and the next because of the baffle arrangement. The ABR may be represented as a series of ideal stirred tanks corresponding to the number of compartments, where a higher number of compartments makes the reactor approach closer to plug (Liu et al. 2007, Sarathai et al. 2010). Perhaps the most significant advantage of the ABR is its ability to separate acidogenesis and methanogenesis longitudinally within the reactor, allowing the reactor to behave as a two-phase system without the associated control problems and high costs (Weiland and Rozzi 1991). However, unstirred plug-flow digesters often have problems because of the accumulation of organic acids and the associated pH decrease arising from a high organic loading rate in the first part of the reactor.

2.6 Research aims

As one development of the ABR reactor, the SA-ABR could help us to solve the problems. The operation parameters must be analyzed in a laboratory test and in a pilot plant as well before the construction of a production plant. In a first simple fermenting test, the basically degradability of a substrate, the graph of the degradation, and the biogas yield has to be determined. Sometimes the maximum recommendable volume load and the changes of the concentrations of certain materials have to be measured. These are important if the large-scale installation is to be continuously operated. In a test, possible and practical substrate mixture can be determined. Therefore a test station with an agitated bioreactor with a capacity of more than 40 L is used.

For the tests in the laboratory or in the pilot plant, the following measurements are recommended. The appropriate measuring devices can be fixed to the reactor or installed separately.

- pH value and redox potential
- dry matter, water content
- content of organic dry matter
- degradability as total content of organic acids/acetic acid equivalent and inhibitors
- content of short chain fatty acids, principally acetic acid, propionic acid, butyric acid, and iso-butyric acid

The measurements give, among other things, information on the biogas yield, the nutrients which can be expected, the extent of decomposition of the biomass which can be provided during the fermentation, the fertilization value of the residue, and also the preferable type, dimensions, and mode of operation of the production plant.

2.7 Summary

In the future, anaerobic digestion will be one of the main solutions for the treatment and valorization of solid waste. It reduces quantities of waste and leads to the production of methane. In fact anaerobic digestion systems are highly stable, provided they are designed, operated and controlled properly. However, poor operational stability still prevents anaerobic digestion from being widely commercialized.

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Chapter 3　CFD simulation of SA-ABR and hydraulic characteristics analysis of self-agitation process

Abstract: An innovative self-agitation anaerobic baffled reactor (SA-ABR) was designed for treating waste substrate. The compound in the reactor is mixed without the use of any mechanical equipment and electricity. Instead, the system uses the produced biogas to create a level difference in the chambers. Computational fluid dynamics (CFD) models were used to investigate the hydraulic characteristics in the reactors. The results show that each self-agitation cycle is separated into the energy storage process, exergonic process and buffer stage. The compound transition phenomenon mainly occurs during the energy exergonic process and buffer stage. The SA-ABR can be regarded as a combination of CSTR and PFR due to the length of the U-tube. The technology is applicable for the waste substrate fermentation treatment.

3.1 Introduction

Good engineering design demands a detailed understanding of the flow pattern within a system (García et al. 2005, Fan et al. 2008). An accurate estimate of sludge rheological properties is required for the design and efficient operation of digestion, including mixing and pumping (Baudez et al. 2011, Jiang et al. 2014). To obtain and research an accurate knowledge of mixing behavior in the SA-ABR, the CFD software, Fluent®, was used to create numerical simulations and to visualize the water flow status in the self-agitation reactors. The predominant structure parameters and operation conditions were investigated.

3.2 Material and methods

3.2.1 The SA-ABR structure and model

Fig. 3-1 (a) illustrates the schematics of four chambers SA-ABR in this study. The reactors consisted of a container with partition plates; the operation principle is the same as that in Qi et al. (2013). The size (length × width) of four chambers (one or two -stage) reactors was 0.8 m × 0.8 m. The reactor was composed of four chambers (chamber 1, chamber 2, chamber 3 and chamber 4, from left to right). Chambers 1 and 2 (the first stage) were linked through the attached U-tube. The substrate was fed from the middle of first half reactor bottom. The height and length of the first U-tube are 15 to 35 cm. The headspace of the chamber 1 was closed, and the biogas produced was stored until being transported to chamber 2 via the U-tube. By contrast, the headspace of the chambers 2 to 4 weren't close. Inside the reactor, the continual change in the liquid level and the self-agitation distributed the organic load from near the inlet port of the reactors and provided a nutrient supply to the bacteria in the SA-ABR system.

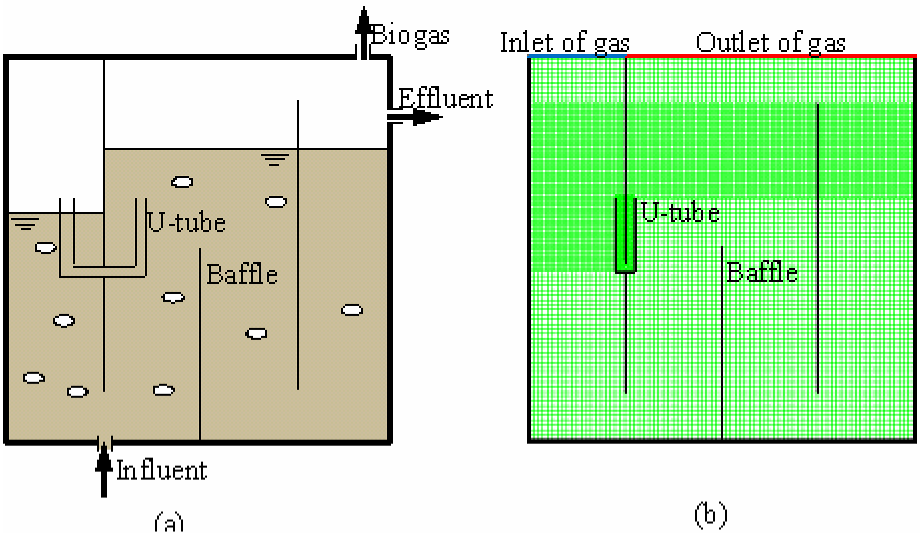

Fig. 3-1 Schematics of the SA-ABR (a) and the CFD model (b). It is composed of four chambers (the chamber 1, 2, 3 and 4, from left to right)

3.3 Conclusions

To simulate the mixing behaviors in the SA-ABR, several CFD models in Fluent® were used to investigate the influence of different configurations on the diffusion of an inlet substrate and the agitation of the whole liquid. The necessary periodical mixing is performed by the biogas generated during the process. The blast of the produced gas and the sudden change of flow characteristics in the liquid levels resulted in the vigorous mixing of the liquid. The SA-ABR can be regarded as a combination of CSTR and PFR due to the length of the U-tube. The technology is applicable for the waste substrate fermentation treatment, especial for medium and small scale reactor.

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Chapter 4 Effect study of different substrate concentration and sludge viscosity on the self-agitation by CFD simulation

Abstract: Computational fluid dynamics (CFD) models were used to investigate hydraulic characteristics and substrate diffusion in the self-agitation reactors with different viscosity of sludge and substrate. The self-agitation is affected by variations of viscosity properties. Design and operation of the reactor were discussed for optimisation in the anaerobic digestion process.

4.1 Introduction

Significant differences in sludge viscosity were found for sludge of different origins (Seyssiecq et al. 2003). For example, anaerobic granular sludge seem to have a lower viscosity than aerobic granular sludge and active sludge (Pevere et al. 2009). Viscosity was strongly influenced by the TSS of sludge (Tixier et al. 2003, Lotito and Lotito 2014). High TSS results in tremendous augmentation of viscosity and induces difficulty of pumping and mixing, which affects mass transfer and anaerobic digestion (Baudez et al. 2013, Eshtiaghi et al. 2013, Ratkovich et al. 2013, Jiang et al. 2014). Besides the sludge management inside the wastewater treatment chain, rheology is also important for further sludge handling like dewatering or biogas production from sewage sludge. To increase biogas production, it is necessary to recycle and recalculate digested sludge in order to mix it with incoming sludge. The flow rate in the recirculation circuits has to be very large and rheology is needed to calculate head losses and pumping power (Ratkovich et al. 2013).

For enhancing mass transfer and efficient anaerobic digestion, mixing is a crucial operation, which is directly conditioned by the rheology of sludge. To obtain and research the effect of viscosity on mixing behavior in the SA-ABR, CFD simulation was used to study the effect of viscosity on the agitation.

4.2 Simulation conditions and preferences

The structure of reactor and model are same with in Chapter 3. To provide a visualization of the hydraulic characteristics, when the liquid level of the primary simulation reached the top of the U-tube, two other phases were used to represent the inlet substrate (around the inlet at the bottoms of the chamber 1 and chamber 2) and the sludge (at the bottoms of the chambers 3 and 4). The two phases were defined as the "inlet substrate" and "tracer". The qualities of the tracer were the same as that of the mixed liquor. Different colors in the reactor are defined as different types of material at the start of simulation. The part near the inlet (red) is defined as the substrate; the liquid in the bottom of chambers 3 and 4 is defined as the tracer (green), and the gas blue.

The higher the mixed liquor suspended solid (MLSS) concentration, the more significant rheological properties and their impact on energy consumption and process control become (Ratkovich et al. 2013). The mixture can be concentrated to a much higher solid content than would be possible for the excess sludge alone (Pevere et al. 2009). The viscosity in the research is set from 1 to 100 mPa·s, corresponding to solid concentration from 0 to 100 g/L.

4.3 Conclusions

When the viscosity of the liquid is 1 mPa·s, the whole self-agitation is almost a completely mixing reactor. The diffusion of substrate and the tracer become low after every self-agitation as the viscosity increase from 1 to 100 mPa·s. As the viscosity increases, the substrate is difficult to be agitated. After the viscosity is higher than 25 mPa·s, the substrate and tracer couldn't be mixed in whole of the reactor.

The necessary periodical mixing is performed by the biogas generated during the process. High TSS is not good for the diffusion of influent and liquid in one self-agitation process. So the mixing results of high TSS influent maybe not better than the low TSS. With a longer U-tube, the maximum turbulence intensity increases may be sufficient to agitate a high viscosity compound.

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Chapter 5　Experiment of food organic waste treatment by SA-ABR

Abstract: A 60 L self-agitation anaerobic baffle reactor of food waste fermentation was operated for 190 days to evaluate process stability. The HRT of substrate increased from 100 days to 30 days. Many indexes were detected and analysis, e.g., alkalinity, biogas components, solid contents, organic material (COD, carbohydrate, protein and liquid), VFAs and alcohols, which were used to estimate the performance of reactor, e.g. waste reduction rate and biogas production. The results show that the biogas production rate gradually decreases as the HRT of substrate decreases; the waste degradation rate is stable within all of state. There is not obvious inhibition or acidification in the reactor.

5.1 Introduction

Microbial methane production has the potential for reducing the demand for fossil fuels like coal, oil, and natural gas that have provided the power for developing and maintaining the technologically advanced modern world. Biogas production from agriculture, municipal, and industrial waste can contribute to sustainable energy production. The technology for methane production is scalable and has been applied globally to a broad range of organic waste feedstocks, most commonly animal manures (Smith et al. 1988). Biogas can be made from most biomass and waste materials regardless of the composition and over a large range of moisture contents, with limited feedstock preparation. Implementation of digestion technology at agricultural, municipal, and industrial facilities allows efficient decentralized energy generation and distribution to local markets.

Residual waste is the term used for waste generated by households. Several decades ago, Japan government introduced a system for waste management. This makes it possible to collect the organic bio-waste suitable for composting or fermentation separately from the inorganic waste. The self-agitation reactor is thought to have much potential for use in small-scale digesters. The fluid dynamics analysis has shown a significant improvement in sludge mixing when the reactor is mixed by the U-tube. As such, this mixing system is expected to enhance digestion performance and avoid stratification, without creating excessive costs. There is a need to examine the experiment treatment efficiency.

5.2 Experiment material and method

5.2.1 Experimental process

The digester used in this study was a 64 L reactor (height: 80 cm; width: 80 cm; thickness: 10 cm) with a working volume of 40 L, which was composed of four chambers (the chamber 1, 2, 3 and 4 from left to right), with chamber 1 and the chamber 2 linked by two hollow U-tubes attached in parallel. Each U-tube was 2 cm in inner diameter, 19 cm in width and 25 cm in vertical length.

Substrate stored in a feed tank (4 ^{o}C) was fed to a reactor by a time-controlled pump (Furue science, Roller pump RP-LV2). The substrate was fed from the port at the bottom center of chamber 1and chamber 2. The diameter of the inlet port from the feed pump to the reactor was 10 mm. No significant agitation caused by feeding was observed by visual contact in this study because the substrate used was high in strength and viscous. The effluent including residual substrate and biomass produced was passed through a same pump with influent.

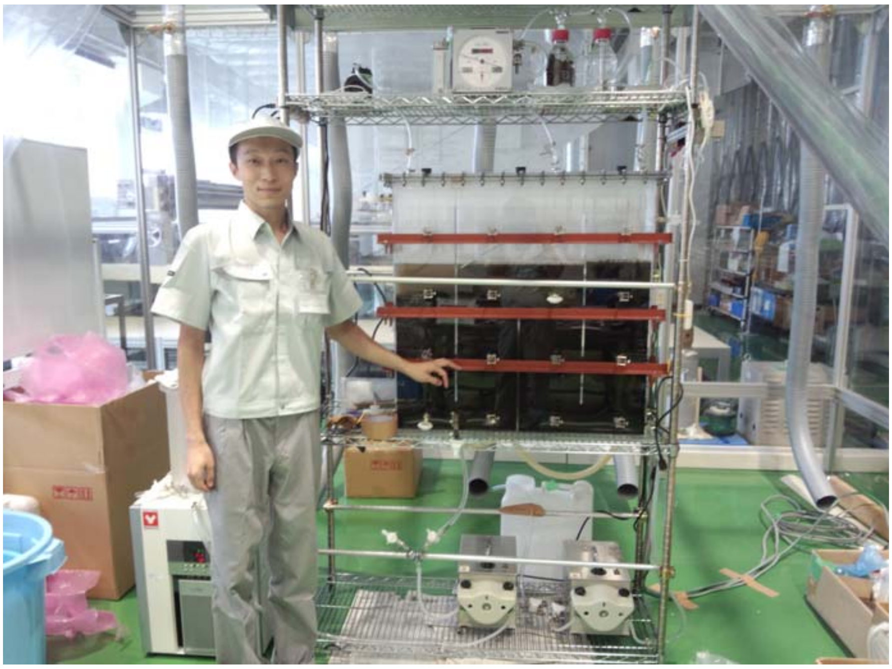

Fig. 5-1 Experiment system cooperating with Panasonic Company

5.2.2 Livestock co-substrate components and content

The food waste used in this study was composed of fruits (30%), vegetables (36%), meat & fish (14%), and staple foods (20%), which is selected based on the typical component of the in Japan (Li et al. 2006). Once a or two weeks, the food described above was freshly prepared and shredded below 3 mm in diameter with a blender. The slurry food was diluted with tap water to approximately 100 g/L TS. For survival, microorganism needs certain minimum concentration of trace elements Fe, Co, Ni etc. Thus, 100 mg/L $FeCl_2$, 10 mg/L $CoCl_2$ and 10 mg/L $NiCl_2$ was added as a supplementary mineral for methanogenesis.

5.2.3 Analysis

The samples used for measuring the alkalinity, ammonium nitrogen (NH_4^+-N), VFA and soluble components were prepared by centrifuging digested sludge samples at 3000 rpm for 20 min and filtrating them through a 0.45 lm pore size filter. Alkalinity, total solids (TS), volatile solids (VS), suspended solids (SS) and volatile suspended solids (VSS), was measured in accordance with the examination methods for wastewater (Japan Sewage Works Association), and COD with APHA Standard Methods (APHA 2005). NH_4+-N concentration was measured by the indophenol blue absorptiometry method. The VFAs were measured by a gas chromatograph (Agilent, 6890) with a flame ionization detector (FID) and a 30 m column (Shimadzu, DB-WAXetr), and pH was measured by a glass pH meter (TOA DKK, HM-30 V). The components of the biogas were measured by a gas chromatograph (Shimadzu, GC-8A) equipped with thermal conductivity detector (TCD) and a stainless steel column packed with Porapack Q (Shimadzu GLC). The temperatures of the detector and column were maintained at 100 and 70 ^oC, respectively. The H_2S concentration in the biogas was determined using Gastec H_2S detector tubes (GASTEC) after sampling the effluent biogas from the sampling port between the gas meter and the reactor.

5.2.4 Operation condition choose

The original seed microorganisms used for mesophilic methanogenesis and thermophilic acidogenesis were taken from a full-scale sewage sludge digester operated at mesophilic or thermophilic condition, respectively in the Senen wastewater treatment plant.

The HRT for the substrate was gradually shortened from 100, to 60, to 30 days. The flow-rate of the feed pump was fixed. The turn-on amount of pump in one day changed due to the influent substrate every day. The temperature should be kept exactly within a range of ± 2 ^oC. Otherwise, gas losses of up to 30% have been taken in consideration.

5.3 Conclusions

Average pH value at steady state of the reactor was very stable at 7.3-7.6 during the experiment, even substrate HRT shortened from 100 days to 30 days. TS values in the reactor at steady state were 14.0±2.58 g/L at HRT 100 d, 17.2±1.82 g/L at HRT 60 d and 22.0±1.43 g/L at HRT 30 d, which were gradually increased with the HRT of substrate. As the HRT reduced from 100 days to 30 days, the conversion rate decreased from 1.09 to 0.94 L-biogas/g-TS and from 2.02 to 1.50 L-biogas/g-VS. The biogas production yield of substrate gradually decreased due to the shorten HRT, from 83.1±7.97 to 73.2±5.59 L-Gas/L-Sub. The average biogas composition at HRT 30 d was within the following range: 61.1 ± 2.01 % methane, 36.3 ± 2.71 % carbon dioxide.

Soluble and insoluble organic material concentrations were very stable at stable state as different HRT. Carbohydrate, protein and liquid concentrations of the effluent were almost the same within HRT from 100 to 30 days. Shortening the retention led to an increase in the VFA and alcohols concentration; however, it had a limited effect on the VFA concentration in the effluent. According to these results, these indicate that the reactor can be kept stable at the desirable condition levels over the entire steady state operation periods.

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Chapter 6 General conclusions and recommendations

6.1 General conclusions

To provide a visualization of the hydraulic characteristics, the CFD software, Fluent®, was used to create numerical simulations and to visualize the water flow status in the self-agitation reactors. The self-agitation reactor was analyzed in a laboratory test as well before the construction of a production plant. In the fermenting test, the basically degradability of a substrate, the graph of the degradation, and the biogas yield has to be determined.

Every cycle of the self-agitation process could be separated the pressure energy storage process, exergonic process and buffer stage. The agitation is stronger when the U-tube is longer. The viscosity of the substrate has great effect on the diffusion in every self-agitation or the mixing between substrate at different location. Our self-agitated reactor allows the successful continuous operation of treating food waste with not less than 10 kg/m^3/d COD volumetric loading rate.

6.2 Recommendations

The SA-ABR is innovative due to the periodic process of liquid and the gas through the U-tube. The most important feature of the reactor design is to maintain self-agitation ability. The self-agitation frequency or number relates to the gas production rate and the volume for storage gas in the chamber 1.

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