Comparison of Dairy Manure Anaerobic Digestion Performance in Gas-lift and Bubble Column Digesters

Jing Tang

Thesis submitted to the Faculty of
Virginia Polytechnic Institute and State University
in partial fulfillment of the requirements for the degree of

Master of Science
In
Biological Systems Engineering

Zhiyou Wen
Binxin Wu
Jactone Arogo Ogejo

December 04, 2009
Blacksburg, VA

Keywords: dairy manure, anaerobic digester, CFD, RTD, gas recirculation mixing

Comparison of Dairy Manure Anaerobic Digestion Performance in Gas-lift and Bubble Column Digesters

Jing Tang

Abstract

Anaerobic digestion is one of the most promising management options for dairy manure treatment. Manure wastewater from dairy farms has been used for methane production for decades. However, performance failure due to inadequate mixing is routine. In general, the mixng of anaerobic digester is achived throguh mechnical stirring, liquid circulation, and gas circulation, among which the gas circulation proves to be the most effcient way. In this work, we studied the liquid flow pattern of two differetn type of gas-circualtion based anaerobic digesters, with the aim to understand the effects of hydrodynamic behavior of the digesting liquid on the anaerobic digestion performance, so a better mixing strategy can be provided.

We used two 20-L gas circulation based anaerobic digesters with confined (gas-lift) and unconfined (bubble column) design. The anaerobic digestion performance and mixing behaviors were studied at different gas recirculation rate. It was found that the biogas production from the bubble column was constantly higher than that from gas-lift digester. However, the overall flow of the two digesters, which is indicated by residence time distribution (RTD), showed a similar pattern. Furhter investigation of local liquid flow behavior using Computational Fluid Dynamic (CFD) indicate that the bubble column accumulated higher portion of sludge in the bottom of the digester, which has a higher TS and VS, COD, and biomethane production potential than those from the gas-lift digester. This is the reason that the biogas production from the bubble column is higher than the gas-lift digester. Through this study, a thorough characterization of the flow behavior of the anaerobic digester were developed, and provided a deep insight of its influence on the anaerobic digestion performance.

Attribution

Author Jing Tang is the major contributor and writer of this thesis. Co-author Dr. Zhiyou Wen was the committee Chair. Co-author Dr. Binxin Wu served as a committee member and contributed Computational Fluid Dynamics (CFD) simulation analysis.

Jing Tang, Dr. Wen and Dr. Arogo are with the Department of Biological Systems Engineering, 200 Seitz Hall, Virginia Tech, Blacksburg, VA 24061.

Dr. Wu is Sr. Research Engineer, Philadelphia Mixing Solutions Company, 1221 East Main Street, Palmyra, PA 17078

Acknowledgements

I would like to thank my advisor, Dr. Zhiyou Wen, for his guidance and support throughout this research. I would like to thanks my committee member, Dr. Binxin Wu, for his wonderful work on CFD simulation, and his guidance in my research. And Dr Jactone Arogo Ogejo for his encouragement during my academic career.

I am grateful to all of the members of my lab for their help and companionship while performing this research. Special thanks go to Lifeng Li and Yanjuan Hong who gave me the guidance on laboratory skills. Also, I would like to thank Michael (Ben) Johnson and Ying Jing for encouraging and supporting me during my research.

Most importantly, I would like to thank my family and all my friends. Thanks for supporting me wholeheartedly throughout my academic career.

Table of Content

List of Figures

List of Tables

1. Introduction

1.1. Background

Anaerobic digestion (AD) is an effective way to recovery energy (methane) from animal manure, but it is still an evolving technology in which several technical hurdles need to be overcome. One of these challenges is to design an effective mixing system to ensure anaerobic digesters function properly and generate high level of biogas. Mixing enhances digestion performance by promoting contact between substrate and microorganism, eliminating thermal stratification, minimizing solid deposition, eliminating dead zones, and reducing the formation of scum (Cheremisinoff 1989; Wheatley 1991). The importance of mixing in achieving efficient digestion performance has been noted by many studies. To date, various researches have been conducted to investigate the effect of mixing mode, intensity, and duration on anaerobic digestion performance (Hashimoto 1982; Svendsen, Jakobsen et al. 1992; Karim, Hoffmann et al. 2005; Karim, Klasson et al. 2005).

Mixing of an anaerobic digester is usually achieved by mechanical stirring, liquid recirculation, and gas recirculation. Mechanical stirring uses internal impellers or propellers to agitate the digester contents and achieve a uniform distribution of substrate and temperature. This type of mixing requires high energy input (Wheatley 1991; Varma 2007), and may injury the microbial population during digestion (Whitmore 1987; Stroot, McMahon et al. 2001; Ong 2002). The internal mechanical stir fittings are also not accessible for maintenance during operation. The liquid-recirculation digesters use pumps and associated pipe work to circulate liquid near the top of the digester and discharge it at the base of the sidewalls or *vice verse*. The main disadvantage of this type of mixing is that it often causes short cut channeling of the digester with high solid content, which resulted in a large dead space with the digester (Cheremisinoff 1989; Wheatley 1991). Compared with mechanical stirring and sludge recirculation, gas recirculation has been proven to be the most efficient mixing method (Garrison 1980; Lee, Cho et al. 1995; Ghosh 1997). This mixing system does not have moving parts within the digester, thus, the capital and maintenance costs were low (Carroll and R.D.Ross 1984). Gas recirculation is also less prone to gas leaking than mechanical stir which requires more mechanical seals.

Gas circulation-based anaerobic digesters have two types of configurations: gas-lifting type (confined) and bubble column type (unconfined) (Tekippe 1982). A gas-lift digester has a concentric draft tube within the cylindrical digester; circulated gas is introduced into the bottom of the draft tube, rises inside the tube. The liquid between the draft tube and the digester wall is "sucked" into the draft tube from the bottom of the digester. The rising of the liquid inside the draft tube, and down-flow of the liquid outside the draft tube cause the liquid circulation of the entire digester. In the bubble column type digester, the gas is introduced at the bottom of the digester. Contrast to gas-lifting mechanism, mixing in the bubble column occurs as the bubbles rise along the digester. Gas-lift and bubble column bioreactors have an increasing application in chemical industry, especially suitable for sensitive cell culture and biochemical fermentation. In aerobically-based fermentation or cell culture processes, gas-lift bioreactor has proved a better performance than bubble column in terms of lower stress forces, better mixing and higher mass transfer rate (Asterio S´anchez Mir´on 09/2000; Wood and Thompson 1987; Choi, Chisti et al. 1996). In anaerobic digestion process, however, recirculated gas is simply for mixing, rather than providing mass transfer for microorganism growth. Therefore, the performance of an anaerobic digester with gas-lifting or bubble column design may be significantly different from that of an aerobic fermentation process.

Baumann (1982) reported that the draft tube system in gas-lift bioreactor was not effective in controlling floating solids as energy input was confined to a limited area. While Carroll (1984) found that confined gas-lift system had superior mixing with a 98% actively mixed volume compared with unconfined systems with a 57% mixed volume. Karim (2007) and Vesvikar (2005) used computational fluid dynamics (CFD) to study the digester configuration effects on gas-lift mixing effectiveness.

To date, there has been a lack of head-to-head comparison of these two types of gas-circulation based digesters. Furthermore, although people have realized the advantage of the gas-circulation systems, there lacks a detailed study of the hydrodynamic behaviors of the fluid inside the reactor. The current research on anaerobic digestion mixing still treats the reactor as a "black box". The digestion performance is based on the measurement of superficial parameters such as, biogas production and solid destruction. What happens inside the reactor and how it influences the results is still in question.

1.2 Objectives

The objective of this work is to compare the digestion performance of these two types of digesters when treating dairy manure wastewater, and to provide an insight of the flow pattern of the reactors through experimental residential time distribution (RTD) and computational fluid dynamics (CFD). So a deeper insight of anaerobic digester performance can be obtained.

2. Literature Review

2.1. Animal Manure Production and Treatment

2.1.1. Current Status of Animal Manure Production

Growth in livestock industries has resulted in large amounts of animal waste (manure) production. It is reported that the US dairy industry is currently raising about 9 million milking cows, and with more than 335 million tons of dairy manure generated every year (Sheffield 2002; Nennich 2004; USDA 2005 ; USDA 2006). The US Dairy Practices Council defines manure as the feces and urine from farm livestock (Barber 1979). The characteristics of manure vary widely depending on the health, diet, species, age and genetics of the animals. The American Society of Agricultural Engineers (ASAE) has a standard (D384.2) that defines the average quantities and characteristics of different types of animal manures (ASABE 2005). Table 1 shows the typical characteristics of dairy manure as excreted.

Table 1. Estimated typical dairy manure characteristics as excreted. (ASABE 2005)

Animal Type	Total Manure[1]		Moisture[2]	Total Solids	Volatile Solids	Nitrogen	Phosphorus	Potassium
	lb/d-animal	ft^2/d-animal	%wet basis	lb/d-animal				
Dairy								
Lactating Cow	150	2.4	87	20	17	0.99	0.17	0.23
Dry Cow	83	1.3	87	11	9.2	0.5	0.066	0.33
Heifer (970 lb)	48	0.78	83	8.2	7.1	0.26	--	--

[1] Total manure is calculated from total solids and manure moisture content.
[2] Manure moisture contents ranging from 75 to 90 percent. At these moisture levels as excreted manure has a density equal to that of water and specific gravity of 1.0 was assumed in calculation of manure volume.

In general, animal manure can be utilized as a source of fertilizer for pastureland, cropland and hay production. Manure is recognized as an excellent nutrient source of nitrogen, phosphorus, potassium and other nutrients such as calcium, magnesium and sulfur which benefit plant growth and add organic matter to improve soil structure and quality. Manure can also be used as source of energy to produce biomethane, heat or electricity. It is reported that one billion tons of animal waste is equivalent to approx 100 Mt coal (Sheffield 1999). Developing an appropriate manure management practice is the key in order to increase the sustainability and social acceptance of intensive livestock production.

2.1.2 Current Dairy Manure Treatment Methods

With the expansion in livestock industries, developing appropriate manure disposal methods has been a challenge faced by the industry and the animal industry is facing strict legislation scrutiny. Inappropriate disposal of animal manure can cause serious environmental problems such as pathogens contamination of waster body, nutrient enrichment in surface water, odor problems, airborne ammonia, and greenhouse gas emission (Loehr 1984). As a result, animal manure management has been of increasing concern all around the world. Current manure treatment technologies are based on physical/chemical processes and biological processes. Below are some examples for different manure treatments.

Direct Combustion

One way of treating animal manure is to directly burn it in a furnace to produce heat and thus, recover the greatest amount of energy. This method, however, has several limitations. In general, wet manure with solids content below 30% requires additional fuel to sustain the incineration. In addition, the ash content of manure is usually high, and the appropriate methods for using the ash has yet to be available (Veenhuizen 1992). The incineration also needs a large scale operation in order to keep the process economical; therefore, it is unsuitable for use on a small scale.

Aerobic treatment system for manure treatment

For a confined dairy farm operation, a flushing system is one way used to collect the manure, i.e. dairy manure on the concrete pat of animal pens is flushed into a temporary storage pit, the large volume of slurry is then pumped into separator to be separated into solid and liquid phases (Vanhorn, Wilkie et al. 1994). Separation of coarse solids from manure slurry removes large particles that could interfere irrigation equipment, reduce the organic loading on liquid storage lagoons, and capture fibrous by-products that can be used as agricultural resources such as bedding and fertilizers. The liquid is flushed into a storage lagoon for stabilization, with or without aeration, and then reused as flushing water. In aerobic process, aerobic microorganisms oxidize organic compounds (Figure 1). Removal of these organic compounds reduces odor and ammonia emissions. Aerobic treatments are usually only suitable for separated slurry or dilute effluents.

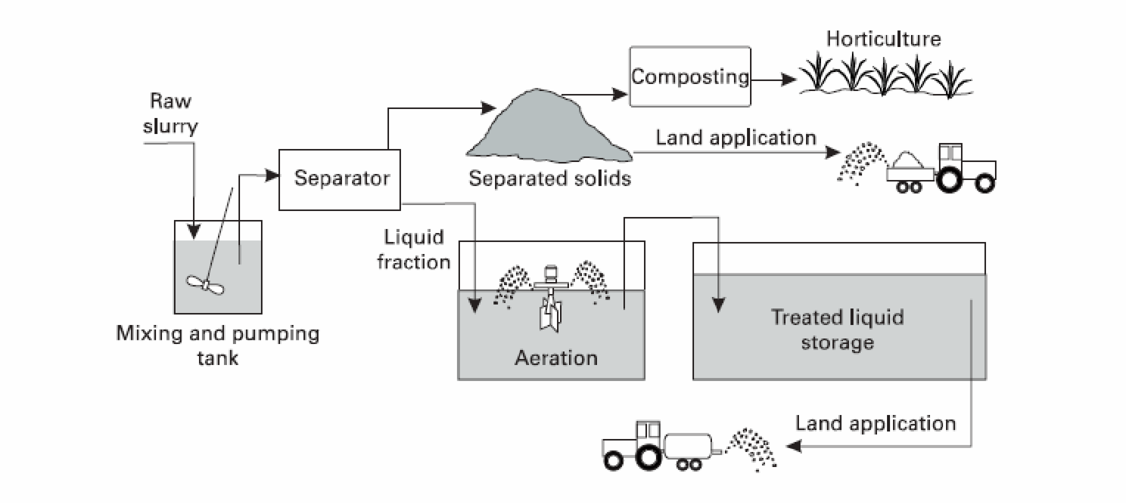


Figure 1. Aerobic Treatment System (Jacobson 2000)

The main drawbacks to aerobic treatment are high cost for aeration equipment, higher biosolids production than anaerobic systems, and potential release of ammonia if the system is aerated at an incorrect level. Since complete aerobic manure treatment is normally not economically(Westerman, 1997), lower aeration rate has been recommended for odor control purpose.

Anaerobic treatment:

Anaerobic treatment of animal manure has several advantages such as it produces methane and odor-free solid residues which can be used as fertilizers. Anaerobic digestion processes can also reduce solids content, and eliminate pathogens and weed seeds from the biomass (Wheatley 1991). Currently, this technology is widely recognized as a pollution control method as well as an alternative energy source. The biogas produced can be used for heating and other purposes, and also perhaps provides surplus energy for use on the farm to diminish the process cost. As a result, anaerobic manure treatment provides an attractive alternative to conventional, energy-consuming aerobic treatment systems. Over the past 25 years, anaerobic digestion has been widely applied to industrial and agricultural waste treatment (Speece 1996; Ghosh 1997). Figure 2 shows a typical anaerobic digestion system for animal manure.

Anaerobic degradation of animal manure produces methane biogas, which is resulted from degradation of organic matter (mainly carbohydrates, proteins and lipids) by the bacteria and archaea. The major composition of the biogas are methane (typically 60-65%) and carbon dioxide (Hill 1984). Methane is a clean energy source which according to Clean Air and Energy Policy Act represents fuel source that can reduce the emissions of SO_X, NO_X and methane into the atmosphere (Robinson 1988). Methane generated from anaerobic digestion of manure can be collected as used as a source of sustainable and renewable energy, while uncontrolled CH_4 emissions from natural degradation of manure during storage is undesirable because of the global warming effects resulting from the release of greenhouse gases (Steed J 1994). Considering the dual benefits of environmental pollution control and renewable energy production, there is a great potential for methane generation from manure anaerobic digestion.

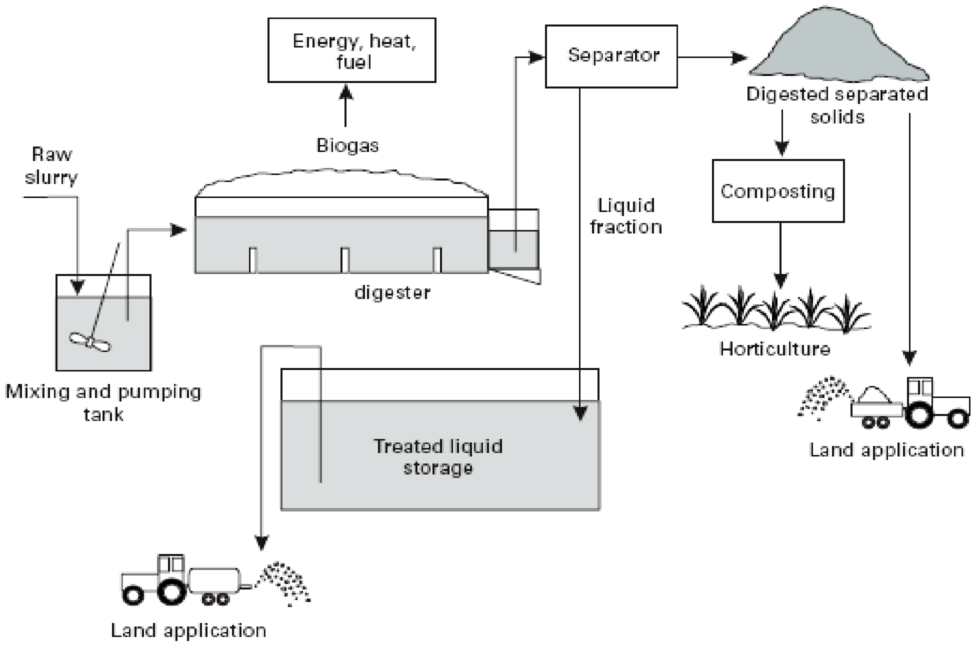


Figure 2. Typical Anaerobic Digestion System (Jacobson 2000)

2.2 Roles of mixing in anaerobic digesters performance

Among various manure treatment technologies, anaerobic digestion is the most promising technology. As it can efficiently process manure and collect the methane biogas a renewable energy. Very little odor is produced from the anaerobic digester if properly managed (Jacobson 2000). In general, the performance of animal manure anaerobic digestion is affected by a variety of parameters such as retention time of manure stream, the degree of contact between the substrate contained in the manure and the viable microorganism population in the digester (Cheremisinoff, 1989, Karim, 2005). Mixing plays an important role in controlling these parameters. Recent studies have shown that mixing is the crucial parameters determining the successful operation of a digester, and the importance of mixing in achieving efficient digester performance has been noted by many researchers (Karim, 2005, Rajneesh Varma, 2007, Ong, 2002, Smith, 1996). While there is still a lack of understanding of mixing mechanisms. For example, U.S. Department of Energy conducted a survey for 95 large anaerobic digesters implemented for animal waste treatment and methane production. It revealed that the about half of these digesters was failed (Lusk 1998) and the majority of failures were attributed to inadequate mixing, which resulted in stratification, local overloading, and insufficient gas production. The inappropriate management of the digester was another major reason for reactor failure

The effect of mixing on anaerobic digesters was initiated in the 1930's when the use of mixing equipment was to break up the floating scum layers formed in the digester. Later study showed that digesters with heating and mixing could treat four times as much sludge as a conventional digester (Torpey 1954). Mixing of the digester is required as it enhanced the digestion performance by (1) dispersing sludge, promoting contact between substrate and microorganisms, (2) eliminating thermal stratification and distributing buffering alkalinity, and (3) minimizing solid deposition while eliminating any dead zones and reducing the formation of scum and grit (Cheremisinoff 1989; Wheatley 1991).

2.2.1 The Mixing Mode Used in Anaerobic Digestions

In general, mixing of anaerobic digesters can be accomplished mainly by mechanical stirring, sludge recirculation, and gas recirculation (Figure 3, Table 2):

Mechanical stirring

This design incorporates internal mechanical mixers such as impeller and propeller to achieve good mixing of the contents in the digester. Mechanical mixing is widely used and considered to be the most efficient in terms of power consumed per gallon of liquid (Casey 1986). It ensures a uniform distribution of liquid content and temperature throughout the digester, and it is capable of processing sludge with a high solid content.

However, mechanical mixing also has several disadvantages. For example, the internal fittings of the digesters are not accessible for maintenance during operation, and the internal maintenance has to interrupt the operations of the digesters. On the contrary sludge or biogas recirculation mixing could have more flexibility as there are no moving parts inside (Casey 1986). Moreover, the power requirement for high speed mixers is high and thus, the energy consumption per unit of liquid is less effective (Wheatley 1991). Very high mixing rates may also injure the microbial population and negatively affect digestion performance, by disturbing microheterogeneity of flocs and hence synergistic interactions between organisms (Stroot, 2001; Whitmore, 1987). Ong (2002) pointed that mechanical mixing is detrimental to the biomethanation process, as mixing was found to decrease the production of extracellular polymeric substances, which aid in maintaining the structural integrity of microbial aggregates.

Liquid recirculation

In this mixing system, pumps and associated pipework are used to withdraw sludge near the top of the digester and discharge it at the base of the sidewalls or *vice versa*. Mixing is produced by sludge recirculation. This type of mixing, however, has been reported to be the least effective and has been rarely used as the sole method of digester mixing. In general, it is difficult to mix the sludge thoroughly, and short circuiting and dead space are commonly happened in the digesters (Cheremisinoff 1989; Wheatley 1991). Therefore, sludge recirculation is usually combined with other types of mixing mechanisms such as mechanical stirring to achieve the best performance of anaerobic digestion (U.S.EPA 09/1979).

Gas recirculation

This type digester circulates the biogas generated in the digester to mix the content of the digester. In general, gas is collected from the headspace of the digester, and then subdivided into two streams. One stream of biogas is compressed and recirculated by air pumps back to the base of the digester for mixing; the other is conveyed to gas storage.

Depending on the configuration of the internal design of the digesters, gas mixing in the digesters can be achieved through confined and unconfined types. In confined digester, a concentric draft tube is located within the cylindrical digester; circulated gas is introduced into the bottom of the draft tube, rises inside the tube. The liquid between the draft tube and the digester wall is “sucked” into the draft tube from the bottom of the digester. The rising of the liquid inside the draft tube, and down-flow of the liquid outside the draft tube causes the liquid circulation of the entire digester. For instance, for a “gas piston” type, a bubble generator produces a large gas bubble within the draft tube where the action of the bubble within the draft tube creates piston pumping. In unconfined type digester, the gas is introduced at the bottom of the digester and simply released at the base of the digester. Contrast to gas-lifting mechanism in the confined digester, mixing in the unconfined digester occurs as bubbles rise to the surface of the tank. In one type of unconfined gas-lift system, small-diameter pipes are suspended from the roof and operated sequentially. The total gas flow for mixing is pumped through each pipes for a set period of time (Carroll and R.D.Ross 1984; Cheremisinoff 1989; Wheatley 1991).

Gas recirculation has been proven the most efficient mode of mixing for anaerobic digesters (Garrison 1980; Lee, Cho et al. 1995; Ghosh 1997). The design of gas mixing systems is relatively simple, without the need of any moving parts within the digester. The capital and maintenance cost of this type of digester is lower than mechanical stirring (Carroll and R.D.Ross 1984). In addition, anaerobic digestion has a requirement for air tight, and gas recirculation mixing is less prone to gas leaking than mechanical stir digesters which need more mechanical seals and proper installation.

Table 2. Comparison of Different Mixing Patterns.

	Advantage	Disadvantage
Mechanical Stirring	● Internal mixer ● Widely used ● Uniform distribution ● High solids level	● Internal fittings inaccessible for maintenance ● High power requirement ● Injury the microbial population
Sludge Recirculation	● No moving part inside	● Least effective ● Circulate sludge rather than mix ● Short circuiting and dead space
Gas Recirculation	● No moving part inside ● Widely used ● Most efficient for anaerobic digesters ● Lower capital and maintenance requirement ● Less prone to gas leaking	● More research concerning optimization needed

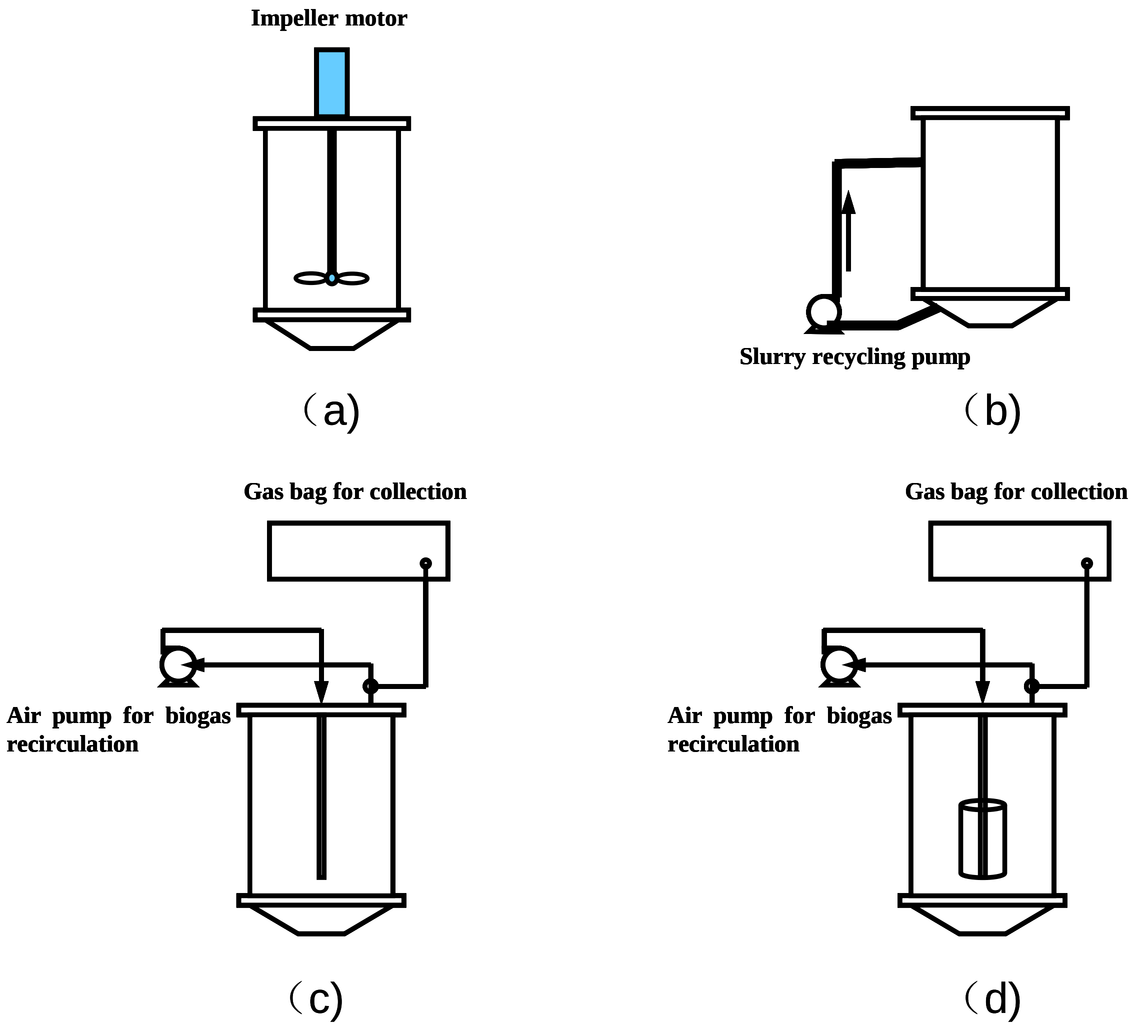


Figure 3. Different Mixing Modes; (a) Mechanical Stirring; (b) Sludge Recirculation; (c) Unconfined Gas Recirculation; (d) Confined Gas Recirculation (with draft tube)

2.2.2 Factors affecting gas-recirculation digester efficiency

Rheological Properties of Liquid

In the design and operation of manure handling and treatment systems, rheological properties of manure are as important as biological and chemical parameters. For instance, the degree of mixing, the power consumption and the choice of the pump are greatly affected by the manure slurry's rheological properties ({Chen, 1981;Chen, 1986;Oneil, 1985). Increased solids content requires more power consumption to ensure adequate mixing performance. Unless the volatile fraction of the sludge was greater than 65%, it is usually impractical and uneconomical to thicken sludge to more than 8% of solid content (Sawyer 1960).

Previous studies have shown that liquid manure slurry is a non-Newtonian fluid, i.e. the relationship between shear stresses and shear rates is nonlinear (Kumar M 1972; Chen 1986; Achkaribegdouri and Goodrich 1992; Landry, Lagu et al. 2004 ; El-Mashad, van Loon et al. 2005) when the solid content is above 5%. The viscosity of manure slurry usually decreases with increasing temperature (Kumar M 1972). For example, Liquid manure with 10% TS behaves with non-Newtonian flow properties at different shear rates (2.38-238 s^{-1}) (El-Mashad, van Loon et al. 2005). Moroccan dairy cattle manure has been determined to be a pseudoplastic fluid in the range of 2.5-12% TS at temperatures between 20 and 60^{o}C (Achkaribegdouri and Goodrich 1992). As most sludge are non-Newtonian fluids, intermittent mixing results in considerable inertial power inputs to start mixing (Brade 1981). If the sludge is shown to be a Bingham plastic fluid, continuous mixing is recommended, rather than intermittent mixing (Lever 1987)

Digester Configuration

Designing an appropriate digester configuration is a key element. The performance of biogas recirculation type digesters is affected by a variety of parameters including the depth to diameter ratio of the digester, draft tube to tank diameter ratio, bottom clearance of the draft tube, slope of the hopper bottom, and sparger design.

The most commonly used anaerobic digesters are cylindrical tanks, with the ratio of depth to diameter ranging from 0.4:1-2:1. The mixing efficiency of centrally-located mixers decreases with the increases of cylindrical tanks diameter (U.S.EPA 09/1979; Brade 1981). Conical bottoms have been proven effective in reducing solid sedimentation and improving mixing efficiency than flat bottoms (Mooyoung, Daugulis et al. 1979; Choi, Chisti et al. 1996). Karim (2007) reported that 45° conical bottoms reduced the poorly mixed zone by 2.3% than 25°conical bottom. However, Vesvikar and Al-Dahhan (2005), reported that flow pattern of the reactor bottom zone with 25°and 60° had no significant difference. It was also noted that a change in bottom shape did not affect the velocity profiles as much as the increased D/T ratio (draft tube diameter to tank diameter).

The draft tube requires specific design parameters such as diameter, height, and clearance from bottom. The observation about draft tube's effect on digester performance is not quite consistent due to different digester configurations and emphasis on different performance parameters. For instance, the dead volume of a flat-bottom digester decreased by 60% when the D/T ratio changed from 0.21 to 0.7 (Vesvikar 2005). Koide and Iwamoto (1983) found that within the D/T range from 0.5 to 0.75, a decrease in D/T resulted in an increase in the volumetric gas-liquid mass transfer coefficient. However, Weiland (1984) reported an opposite observation. Moreover, Pironti *et al*.(1995) found that no liquid circulation was observed when the bottom of the draft tube was located at the transition between the conical and cylindrical regions; whereas liquid circulation started and its magnitude increased as the draft tube was lowered further into the conical region. Kojima *et al*.(1999) observed the liquid circulation velocity increasing with the increase of draft tube height.

Power Input

The degree of mixing is also determined by the power delivered by the mixers to the digesting sludge. For the anaerobic systems with gas mixing, a power input ranging 5-8W/m^3 is recommended (U.S.EPA 1979). On the contrary, an aerobic reactor with gas mixing requires 3000-2000W/ m^3 power input (Chisti 1998). This huge difference is due to the fact that gas in anaerobic process is only used for mixing purpose, while gas in aerobic process is needed for providing oxygen for cell growth in addition to mixing purpose (Varma 2007). Casey (1986) has developed an equation to express the relation between power input and gas recirculation rate. For a given power input and gas flow rate, mixing efficiency depends on the sparger design configuration. For a gas recirculation anaerobic digester with a conical bottom, Rajneesh (2007) reported that a multi-orifice ring sparger performed better than single orifice sparger in terms of enhancing the liquid recirculation and reducing the poorly mixed zone.

2.2.3. Effect of Mixing Intensity on the Anaerobic Digestion Performance

Mixing plays an important role in the anaerobic digestion performance, it is well accepted that thorough mixing of the substrate in the digester is essential in high-rate anaerobic digester. For instance, Hashimoto (1982) found higher biogas production in continuously mixed digesters than those mixed for 2 h per day with cattle manure. Ho and Tan (1985) found higher biogas production for continuously mixed digesters than unmixed ones with palm oil mill effluents. A pilot scale study on a digester with dairy manure also showed that with mixing, continuous methane production is obtained, while digester performance deteriorates soon without mixing(Borole, Klasson et al. 2006). Karim *et al*.(2005) concluded that mixing becomes more critical with thicker manure slurries (10%). On the contrary, there are also some reports that more biogas was produced in unmixed conditions than mixed conditions (Ben-Hasson 1985; Ghaly 1989; Chen 1990; Ghaly and Echiegu 1992). Similarly, Hamdi (1991) and Fischer *et al*.(1983) found that mixing did not improve gas production in olive mill wastewater and pig waste treatment respectively. Intermittent mixing is also recommended over continuous mixing for anaerobic digesters (Mills 1979; Smith, Hein et al. 1979). It is suggested (Lettinga 1981; Whitmore 1987; Dolfing 1992) that incomplete mixing provided a quiescent environment for bacteria, such as flocs, biofilms and granules which are ideal conditions for formation of new spatial associations among different microbial populations, while rapid mixing disrupts the structure to disturb the syntrophic relationships between organisms.

All these studies indicated that the effect of mixing on anaerobic digestion performance is a complex process. Moreover, although people have realized the advantage of the gas-circulation systems, there still lacks a detailed study of the hydrodynamic behaviors of the fluid inside the reactor. The current research on anaerobic digestion mixing still treats the reactor as a “black box”. The digestion performance is based on the measurement of superficial parameters such as, biogas production and solid destruction. What happens inside the reactor and how it influences the results is still in question. Therefore, in-depth research is needed to investigate the flow patterns inside the reactor so a deeper insight of anaerobic digester performance can be obtained.

2.3 Techniques of Determining Mixing Efficiency of Anaerobic Digesters

Various techniques have been developed to investigate the mixing efficiency of anaerobic digesters by measuring the liquid velocity profile within the tank. Such as streak photography, velocity probes, CARPT (computer automated radioactive particle tracking technology) and laser doppler velocimeters. These methods are mainly applied to lab scale digesters with visible liquid, but not suitable for anaerobic digesters of dark liquid animal manure samples. For instance, the walls of the digester and the fluid needs to be transparent for techniques such as streak photography and laser doppler velocimeters. These experimental techniques used for visualizing flow patterns cannot be used for digesters treating animal wastes due to their opaque and complex flow nature. In addition, these methods are time-consuming and expensive.

At present, residence time distribution (RTD) and computational fluid dynamics (CFD) are two major methods used for investigating the hydrodynamics of a reactor, especially industrial complex processes. The RTD study characterizes overall flow pattern behavior (mixing, channeling and recirculation), while CFD can be used for characterizing the local flow behaviors.

2.3.1 RTD Techniques

RTD is used to evaluate the overall characteristic of the flow pattern that occurs in the reactor. It is assumed that fluid with different flow routes takes different amounts of time to pass through the reactor; the distribution of these times is the residence time distribution (RTD) of fluid. RTD can be measured using tracer method, i.e. a tracer is added as a step, pulse, or oscillation into the inlet stream and the concentration of the tracer in the outlet is monitored with time. The response curve from the outlet is the residence time distribution (RTD) of the reactor. Mixing efficiency is determined by calculating the statistical properties of the distribution or by comparing the observed RTD with the RTD of reactor of various mixing model (Cheremisinoff 1989; Levenspiel 1999).

Tracer:

The tracer for RTD studies should be conservative, nontoxic and cost effective. Three types of tracers have been employed to conduct RTD studies: radioactive isotopes such as Tc-99m(Borroto, Dominguez et al. 2003) and sodium-24; salt such as potassium chloride (Janekeh 1991), lithium chloride; and fluorescein such as methylorange (Gavrilescu and Tudose 1999). Currently, lithium chloride is widely used in RTD studies in anaerobic laboratory and pilot-scale digesters (Grobicki and Stuckey 1992; SMITH, ELLIOT et al. 1993; Smith, Elliot et al. 1996; Liu, Ren et al. 2007). Previous work has shown that lithium is not absorbed by sludge particles and micro-organisms (Chambers 1979), and has no harmful effects on the microorganisms even at relative high concentrations (Anderson, Campos et al. 1991).

Determination of RTD:

In the determination of RTD, samples should be collected for at least two theoretical hydraulic residence times (HRT) following tracer injection. The analysis of the tracer concentration distribution includes estimating tracer recovery, meaning hydraulic retention time, and variance. For instance, if the mean hydraulic residence time is shorter than HRT, it indicates the existence of channeling or dead space inside the reactor (Levenspiel 1972). Furthermore, the RTD experimental data needs to be fitted into a mixing model to describe the flow pattern and degree of mixing. A number of mixing models have been developed. For instance, Cholette (1959) developed a model to visualize the reactor to consist of an ideal mixed zone and a stagnant zone. Levenspiel (Levenspiel 1972; 1999) developed the dispersion model and the tank-in-series model which are widely used in RTD studies (Grobicki and Stuckey 1992; SMITH, ELLIOT et al. 1993; Smith, Elliot et al. 1996; Liu, Ren et al. 2007). This model provided a useful method to estimate the fraction of dead space within the reactor

2.3.2 CFD Simulation

RTD study can be used to characterize the flow pattern (mixing, channeling and recirculation) and various hydrodynamic parameters. However, it cannot visualize the flow pattern inside the reactor, and the local flow behavior is unknown. A more detailed description of fluid mechanics and mixing can be obtained using computational fluid dynamics (CFD) simulation.

CFD simulation can be performed by commercially available software such as FLUENT (Fluent Inc. Lebanon, NH, USA). It develops a mathematical solution from the fundamental mass, momentum, and energy conservation equations for known geometrical configuration in 3-dimensional space. CFD simulation can be used to predict hydrodynamic parameters such as velocity, turbulence, hold-up profiles, dead space, etc, and create flow maps of velocity vectors, streamlines, and iso-value contours. These quantified parameters are widely used in the design selection and optimization of anaerobic digesters (Vesvikar and Al-Dahhan 2005; Wu and Chen 2008; Mitsuharu Terashimaa April 2009). Vesvikar (2005) used the CFD simulation to evaluate different geometric designs of the anaerobic digester by varying the air flow rate, draft tube diameter, height and clearance from the bottom, and the shape of the digester bottom.

The results from RTD studies and CFD simulation on anaerobic digesters have been widely reported in the literature, because they provide experimental and numerical approaches to obtain reliable quantitative results.

3. Material and Method

3.1. Raw materials

Dairy manure was collected from Virginia Tech Dairy Center in Blacksburg, Virginia. This barn uses a flush system to remove manure from the pen floor. Manure is flushed four times a day. In our study, the manure was scraped manually from the pen floor when it is accumulated on the floor between consecutive flushing times. The manure was mixed with tap water at a ratio of 1:1 (w/w) and blended with a heavy duty blender (Model CB15, Waring Commercial). The slurry was then screened through a standard US # 10 (2 mm openings) sieve to remove coarse solids. The liquid was stored in a refrigerator at 4°C and diluted with top water to achieve the desired solids content (~1%, w/w) prior to use. Several batches of manure were used throughout the experiments.

3.2 Digester Design and Operation

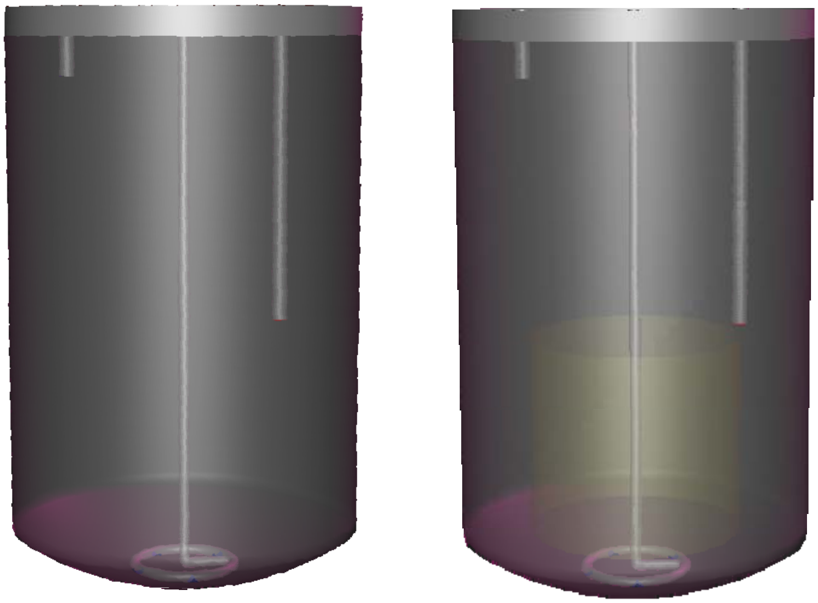
Two anaerobic digesters with an identical dimension were used in the experiments (Figure 4). The digesters were made of PVC and had a round bottom. Each digester had 18L working volume and 3.5 L headspace. The gas-lift digester containes a draft tube inside the reactor, with the diameter ratio of the draft tube to the digester being 0.6. The bubble column digester did not contain the draft tube. Digesters were maintained at 35℃ with a water bath circulator. The water bath circulation was wrapped with insulation to reduce heat loss. During anaerobic digestion, part of biogas was circulated by an air pump and introduced into the digester through a gas diffuser. The gas diffuser was an O-ring (7.4 mm diameter) made of a 4 mm I.D. stainless steel tube and located 1 cm above the digester bottom. Four holes (down face) with 1mm×4mm opening were equidistantly cut along the O-ring. The gas circulation rate was set at 0.5, 1 and 3 L/min, respectively. Other details can be referred to Table 4, Figure 5.

Each digester was fed with 4 L seed sludge (obtained from the sedimentation basin of Virginia Tech dairy farm) and 14 L liquid manure. The digesters were operated as a batch mode for 4 days and then switched to a continuous operation with a hydraulic retention time (HRT) of 12.5 days. Each day, 1.44 L influent was added to the digesters with 24 hour cycles. At each cycle, 60 ml influent was added to the digester within the first 23 second through a time-controlled peristaltic pump (Masterflexes with Easy-load, Cole Parmer Instrument Company, Vernon Hills, Ill.); the feeding was then stopped for the rest of the hour. The operation was repeated at the beginning of next hour cycle. The effluent removal from the digester was kept at the same operation procedure as the influent addition so liquid volume of the digester was maintained consistent.

Manure influent was stored in a reservoir which was mixed continuously to keep a homogenous condition. The digesters were presumed to reach steady-state when the coefficient of variation for daily biogas production was less than 10%. T-test was performed using JMP software (SAS 2009) to test whether the two different gas recirculation systems (bubble column and gas-lift) have any effect on biogas generation, TS, VS and RTD profiles, with statistical significance (P) of 0.1.

Table 3. Main Geometrical Specifications for Digesters

Digester height	44 cm
Digester diameter	25.4cm
Draft tube height	23cm
Draft tube diameter	15.4cm
Working volume	18L
Headspace	3.5L
Sparger tube diameter	4mm
Ring sparger diameter	7.4cm
Liquid height	38cm
Ring sparger above bottom	1cm
Draft tube bottom above ring	5cm
Slurry in/out tube I.D	1/2inch
Hole number on the sparger	4
Hole area	1mm×4mm
End of the influent tube	Right below liquid level
End of the effluent tube	Middle of the slurry height



(a) (b)

Figure 4. 3D Diagram of Lab Scale Digester. (a : Bubble column; b: Gas-lift)

Figure 5. Part of the Lab Experimental Set-Up

3.3. Tracer Response Experiment and Determination of Residential Time Distribution (RTD)

Tracers were used to investigate the mixing behavior and residential time distribution (RTD) of the digesters. Lithium chloride was used as tracer because lithium ion was reported no harmful effects on anaerobic digestion performance (Anderson, Campos et al. 1991) and not absorbed by sludge particle and microorganisms (Chambers 1979). At steady state of the digester, 5ml of lithium chloride solution (110g/L) was instantly injected into the digester with the influent (5 mg Li^+/L of digester working volume); the tracer concentration in the effluent was then continuously monitored (the volume of tracer used was kept small in relation to the total volume within the digester and the injection took place over a very short period compared to the residence time so as to assume to be an "instantaneous" input). Samples are collected from the effluent of the digester every hour. Samples were also collected prior to injection to establish background tracer concentrations and for at least two HRT following injection(NCASI Sept.1983).

Normalized tracer concentration (C) and the time (θ) was used to compare with other RTD studies, i.e.

$$\text{Normalized time } \theta = \frac{time(h)}{HRT(h)}$$

$$\text{Normalized concentration } C = \frac{concentration(mg/L)}{initial\ conc.(mg/L)}$$

3.4. Model Development for CFD Simulation

Liquid manure behaves as a pseudoplastic fluid in the range of 2.5-12% TS and temperature between 20 and 600 C (Achkari-Begdouri, 1992). In this thesis, however, liquid manure was treaded as a Newtonian fluid (water) for TS < 2%. The slurry recirculation mixing flow inside an anaerobic digester is very complex, which is governed by mass and momentum conservations, and turbulence transport. To develop a theoretical model describing the mixing process, the following assumptions were made:

- Fluid flow in the digester is 3-D, gas-liquid two-phase, and steady.
- Liquid manure is incompressible and isothermal fluid.
- The model is limited to flow model without considering the heat flow, the manure temperature is constant at 35℃. Thus, the effect of temperature on the viscosity is negligible.
- The coupling between the phases is strong.
- Different phases move at different velocities (slip velocities).

Continuity Equation

The continuity equation for the mixture is expressed as

$$\frac{\partial \rho_m}{\partial t} + \nabla \cdot (\rho_m \vec{v}_m) = 0 \tag{1}$$

Where, ρ_m is the mixture density given by:

$$\rho_m = \sum_{k=1}^{n} \alpha_k \rho_k \tag{2}$$

And $\vec{v}_m$ is the mass-averaged velocity given by:

$$\vec{v}_m = \frac{\sum_{k=1}^{n} \alpha_k \rho_k \vec{v}_k}{\rho_m} \tag{3}$$

α_k is the volume fraction of phase *k*.

Momentum equations

The momentum for the mixture can be obtained by summing the individual momentum equations for all phase, which can be expressed as:

$$\frac{\partial}{\partial t}(\rho_m \vec{v}_m) + \nabla \cdot (\rho_m \vec{v}_m \vec{v}_m) = -\nabla p + \nabla \cdot [\mu_m (\nabla \vec{v}_m + \nabla \vec{v}_m^T)]$$

$$+ (\rho_m \vec{g}) + \vec{F} + \nabla \cdot \left(\sum_{k=1}^{n} \alpha_k \rho_k \vec{v}_{dr,k} \vec{v}_{dr,k} \right) \qquad (4)$$

where, p is static pressure, $\vec{g}$ is gravity, n is number of phases, $\vec{F}$ is body force, μ_m is the mixture viscosity, and $\vec{v}_{dr,k}$ is drift velocity for second phase k.

Slip velocity and drift velocity

The slip velocity is defined as the velocity of a secondary phase (p) relative to the velocity of the primary phase (q) and expressed as:

$$\vec{v}_{pq} = \vec{v}_p - \vec{v}_q \qquad (5)$$

The drift velocity is expressed as:

$$\vec{v}_{dr,p} = \vec{v}_{pq} - \sum_{k=1}^{n} c_k \vec{v}_{qk} \qquad (6)$$

Volume fraction equation for secondary phases

The volume fraction equation for secondary phase p can be obtained from the continuity equation as:

$$\frac{\partial}{\partial t}(\alpha_p \rho_p) + \nabla \cdot (\alpha_p \rho_p \vec{v}_m) = -\nabla \cdot (\alpha_p \rho_p \vec{v}_{dr,p}) + \sum_{q=1}^{n} (\dot{m}_{qp} - \dot{m}_{pq}) \qquad (7)$$

Turbulence model (the standard k- ε model)

The standard *k*- ε model proposed by Launder and Spalding (1972) is a semi-empirical model based on model transport equations for the turbulent kinetic energy (*k*) and its dissipation rate (ε). *k* and ε are obtained from the following transport equations:

$$\frac{\partial}{\partial t}(\rho_m k) + \nabla \cdot (\rho_m \vec{v}_m k) = \nabla \cdot [(\mu_m / \sigma_k) \nabla k] + G_k + G_b - \rho \varepsilon \tag{8}$$

And

$$\frac{\partial}{\partial t}(\rho_m \varepsilon) + \nabla \cdot (\rho_m \vec{v}_m \varepsilon) = \nabla \cdot [(\mu_m / \sigma_\varepsilon) \nabla \varepsilon] + C_{1\varepsilon} \frac{\varepsilon}{k}\left(G_k + C_{3\varepsilon} G_b\right) - C_{2\varepsilon} \rho \frac{\varepsilon^2}{k} \tag{9}$$

In these equations, G_k represents generation of turbulent kinetic energy due to mean velocity gradient, G_b is generation of turbulent kinetic energy due to buoyancy, $C_{1\varepsilon}$, $C_{2\varepsilon}$ and $C_{3\varepsilon}$ are constants; and σ_k and σ_ε are turbulent Prandtl numbers for *k* and ε, respectively. The model constants have the following default values showed in table 4 (Launder and Spalding, 1972):

Table 4: Constants for turbulence transport model

$C_{1\varepsilon}$	1.44
$C_{2\varepsilon}$	1.92
$C_{3\varepsilon}$	0.09
σ_k	1.0
σ_ε	1.3

Table 5: Model inputs for CFD simulation

Water density	998.2 kg/m^3
Water viscosity	0.001 Pa.s
Water inlet velocity	0.1m/s
Gas inlet velocity	1m/s

3.5. Analyses

Total solid (TS), volatile solid (VS), were determined according to standard methods (APHA 1998). Chemical oxygen demand (COD) was measured using Hach method (Hach, chemical method DR/2000). The volume of biogas generated from each digester was measured by water displacement method through a wet tip meter (Rebel wet-tip gas meter company, Nashville, TN).

To measure the methane content of the biogas, a tedlar gas bag was used to collect biogas from the digester, then, 10 µL of collected gas was injected in duplicate into a Shimadzu 2014 gas chromatograph (Shimadzu Scientific Instruments, Inc. Columbia, MD) with a gas-tight syringe. The GC was equipped with a thermal conductivity detector with a ShinCarb-ST packed column (20m × 2.0mm). The temperature for injector, oven, and detector were 120℃, 110℃, and 160℃, respectively. The carrier gas (helium) flow rate through the column was maintained as 10 ml/min.

Lithium concentration was determined using flame atomic adsorption with standard procedures (APHA 1998). The atomic adsorption instrument is a Perkin-Elmer 5100 PC. The flame is air-acetylene, the wavelength is 670.8 nm, and the lamp is a hallow cathode with a current setting of 15 mA. Exit age distribution curves of effluent tracer concentrations with time were drawn for each study.

The samples for scanning electron microscopy (SEM) were fixed in a 0.1M phosphate buffer (pH7.2) containing 2% glutaraldehyde and then in a 1% OsO4 solution, and dehydrated through a graded series of water-ethanol mixtures. The ethanol was gradually replaced by the nonpolarsolvent amyl-acetate. The samples were dried by the critical point dry method and subsequently sputter-coated with gold. The SEM graphs were taken on a Hitachi S520 and Jsm35C at 15kV.

3.6 Statistical Analysis

T-test was performed using JMP software (SAS 2009) to test whether the two different gas recirculation systems (bubble column and gas-lift) have any effect on biogas generation, TS, VS and RTD profiles.

For example, when comparing the RTD profiles of the two gas recirculation mixing systems, samples collected from the two digesters were independent, and it was assumed that the sample measurements within each digester were normally distributed with equal variances. The hypothesis was as following:

Ho: The means of RTD profiles between bubble column and gas-lift digesters are the same.

Ha: The means of RTD profiles between bubble column and gas-lift digester are not same.

The biogas generation, TS, VS and RTD profiles of the two digesters were compared using JMP software according to the following statistical model:

$$y_{ij} = \mu + T_i + e_{ij}$$

Where,

y_{ij} is response for experimental unit j of treatment i,

μ is overall mean,

T_i is effect due to treatment i(bubble column or gas-lift digester treatment), i=1,2

e_{ij} is random error

A P value of 0.1 was chosen as significance level (α=0.1), corresponding to a confidence level of 90%. If the t-test returns a probability less than or equal to 0.1, then we reject the null hypothesis, and conclude that the means of RTD profiles between the two digesters were significantly different. If the t-test returns a probability greater than 0.1, we fail to reject the null hypothesis, and accept that the means of RTD profile between the two digesters were not significantly different.

4 Results and Discussion

4.1. Anaerobic Digestion Performance at 1L/min Gas Circulation Rate

4.1.1 Biogas Production

The performance of the gas-lift and bubble column digesters were first evaluated by the biogas generated from the digesters. The gas flow rate was first set at 1L/min. As shown in Figure 6. The two digesters started with the similar biogas production but gradually differentiated with bubble column generating a higher biogas level than the gas-lift reactor. This difference in biogas production was significant ($P<0.1$) and consistently observed during the 40 days operation.

The methane content of the steady state biogas produced by the two digesters was also compared. (Figure 8). Unlike the total biogas production, the methane content was maintained at a relative constant level (ca.70%) throughout all the experimental conditions.

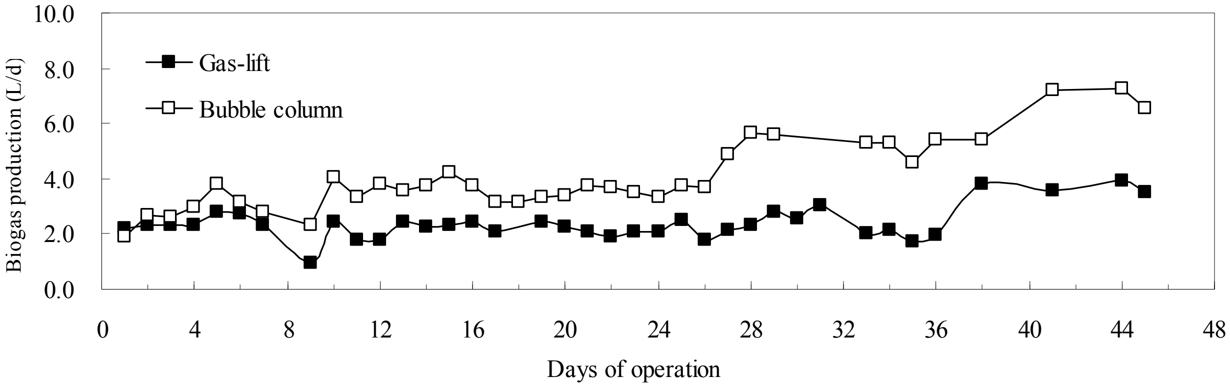


Figure 6. Plots showing daily biogas production from two digesters.

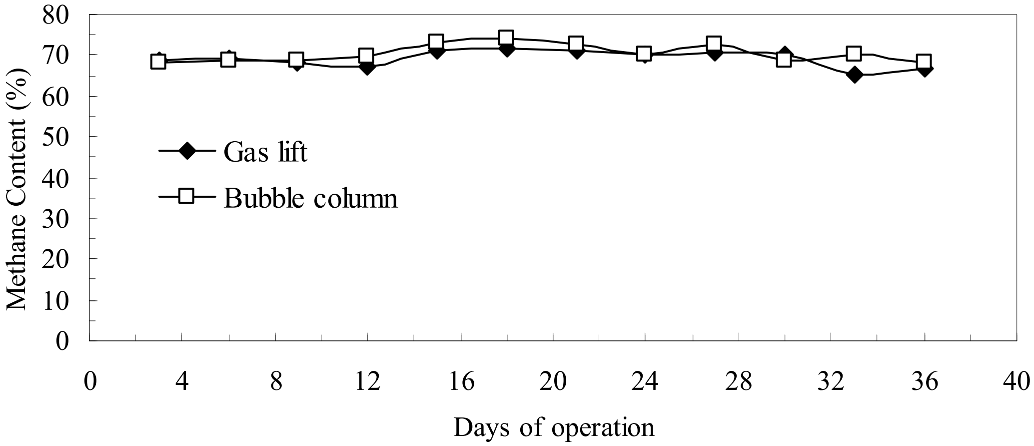


Figure 7. Methane content of the two digesters

4.1.2 Tracer Response and Solid Reduction of the Effluent

In general, gas-lift digesters have been known for its better mixing efficiency than bubble column digesters (Caroll 1984, Choi, 1996), while the results in this work shows that the biogas production rate of the gas-lift digester was consistently higher than that from the gas-lift digesters (Figure 7). To better understand the effects of mixing on the biogas production performance, we studied the flow pattern of the two types of digesters using residential time distribution (RTD) with trace experiment.

Tracer experiments were conducted at steady state with gas recirculation flow rate of 1 L/min. The two digesters resulted in a similar RTD profile; i.e. following the injection of tracer to the digester, the tracer concentrations in the effluents increased sharply, and then gradually decreased (Figure 8). This RTD pattern is similar to the complete mixed type reactor. The ANOVA analyses showed that the difference between the two digesters' RTD curves were statistically insignificant ($P > 0.1$: $P= 0.5821$).

The total solid (TS) and volatile solid (VS) content of the effluents of the two digesters were also characterized (Figure 10); the results shows that the TS and VS content between the two digesters were statistically insignificantly ($P>0.1$: TS: $P= 0.736$;. VS: $P= 0.843$;)

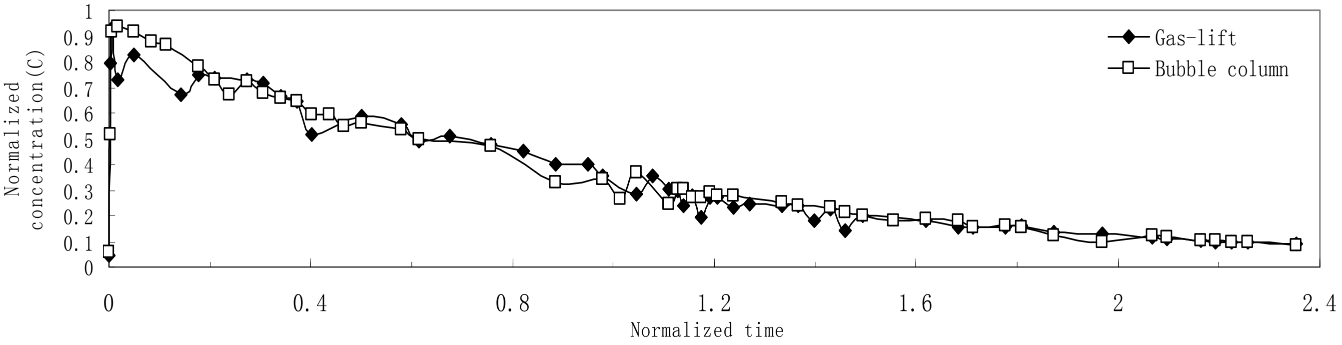
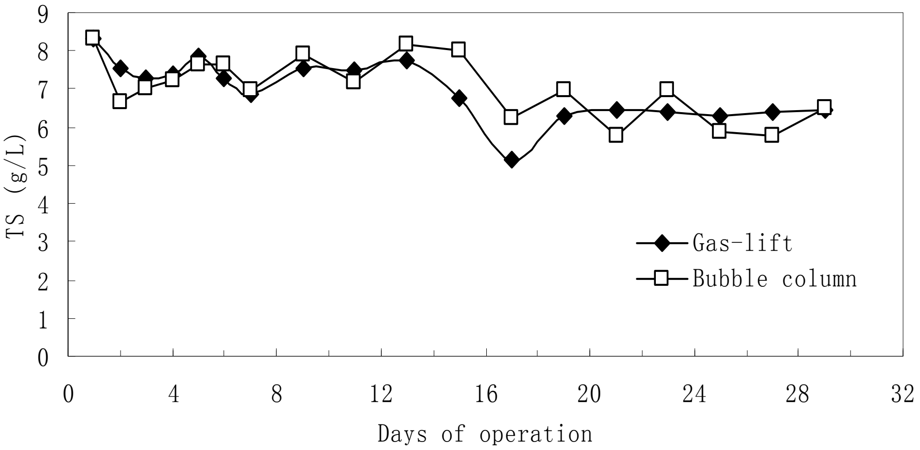
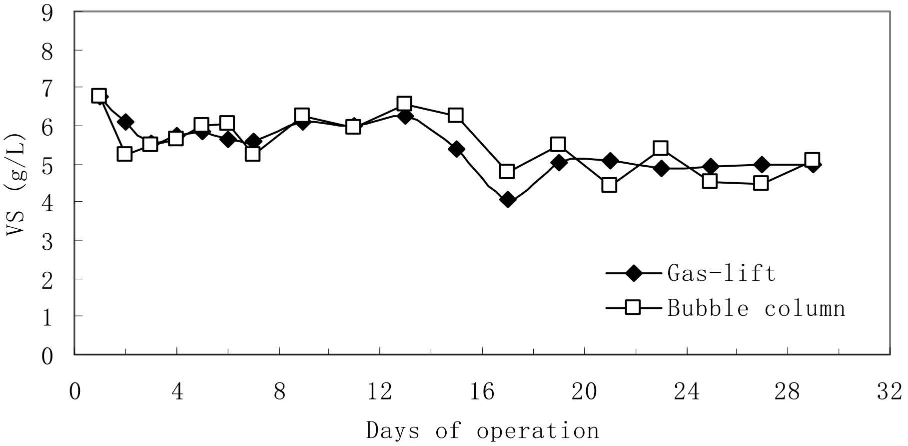


Figure 8. RTD curves obtained from two digesters at 1L/min gas flow rate



(a) TS characteristics in the effluent



(b) VS characteristics in the effluent

Figure 9. TS and VS characteristics in the effluent from the two digesters

2nd RTD test result different sampling position

In the RTD test above, the end of the effluent tube was in the middle height of the sludge level. Then the effluent tube was extended further to the bottom of the digester. RTD test was reconducted, as well as the TS and VS values of effluent samples.

The two digesters resulted in a similar RTD profile, and the ANOVA analyses showed that the difference between the two digesters' RTD curves were statistically insignificant ($P > 0.1$). As for the TS and VS result, the TS and VS values from the two digesters are significantly different. Given that previous study has shown that lithium is not absorbed by sludge particles and micro-organisms, and also tracer was injected at the steady state of the digesters, it is deduced that there were different dead spaces around the bottom part of the digesters. The accumulated sludge was withdrawn to the effluent samples occasionally, and they resulted in the fluctuation of the TS and VS value curves.

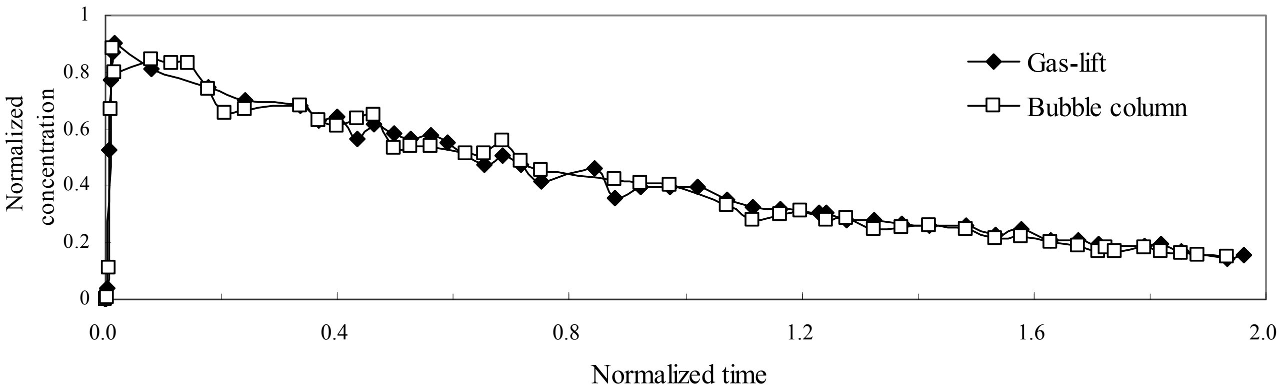
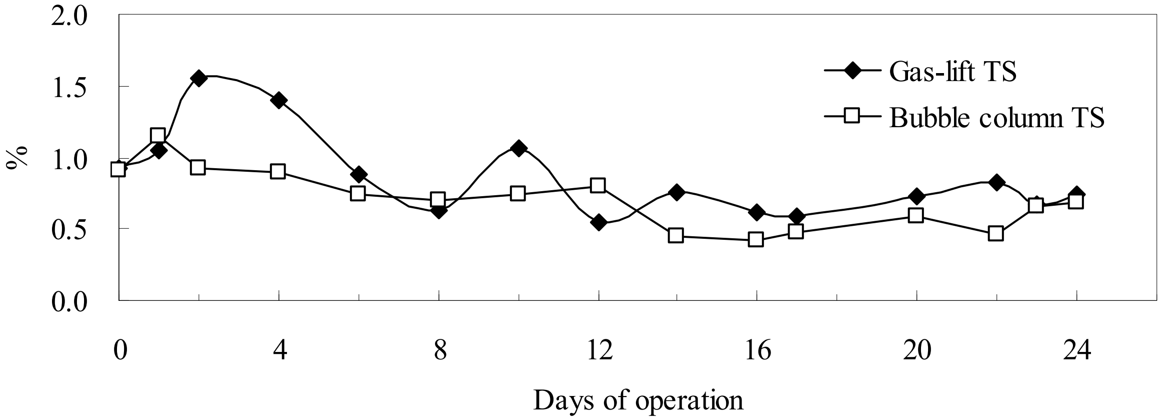
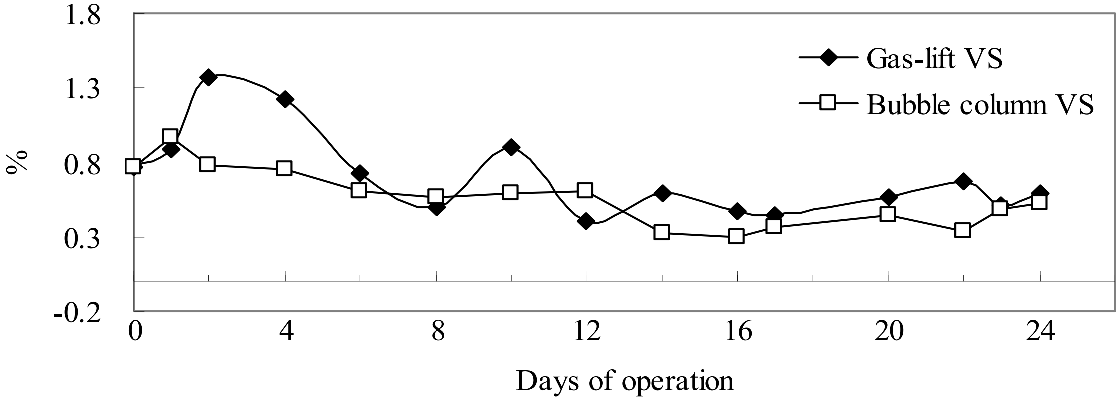


Figure 10. RTD curves obtained from two digesters at 1L/min gas flow rate (Effluent tubes reached to the digester bottom.)



(a) TS characteristics in the effluent



(b) VS characteristics in the effluent

Figure 11. TS and VS characteristics in the effluent from the two digesters

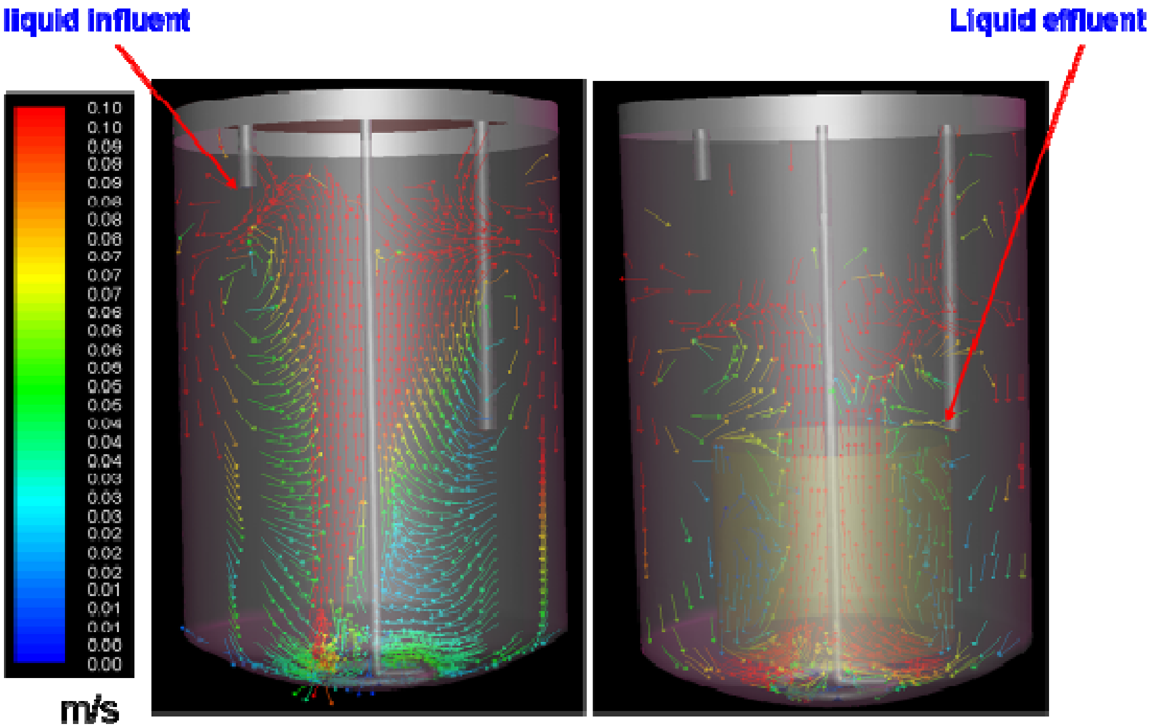
4.1.3 CFD Simulation of the Liquid Flow inside the Digesters

The above results indicated that the RTD test of the digesters cannot explain the difference in biogas production of the two types of digesters. Indeed, the RTD tests gave a similar result for the two digesters, while the biogas productions of the two digesters were significantly different (Figure 6). This may be due to the inherent limitation of the tracer experimental design and the RTD methodology that cannot provide an in-depth insight of local flow pattern of the digesters. To further investigate the effect of mixing and the consequent flow pattern of the digesters on the biogas production performance, the methodology of computational fluid dynamics (CFD) was used to characterize the two digesters.

Compared with RTD analysis which only characterizes overall features of the flow pattern (mixing, channeling and recirculation), CFD simulation can predict local hydrodynamic parameters such as liquid velocity distribution and dead space and create flow maps of velocity vectors. While CFD studies have been used in the design and optimization of various anaerobic digesters (Vesvikar and Al-Dahhan 2005; Wu and Chen 2008; Mitsuharu Terashimaa April 2009), a CFD analysis for comparing the gas-lift and bubble column digesters has not been reported.

In this study, Figure 12 presents vectors of velocity magnitude for the mixture phase. For this particular case, liquid velocity colored by velocity magnitude in which red color represents the velocity greater than or equal to 0.1m/s. Figure 13 shows the contour of liquid velocity from front view. The velocity at red area is greater than or equal to 0.3 m/s. The blue area represents low velocity (<0.06m/s), as indicated in the contour bar. From visual inspection, because of the fluid recirculation conducted by the draft tube, gas-lift digester has a higher velocity area at the bottom than bubble column. This illustration is helpful in anticipating that gas-lift digester has an advantage over bubble column in reducing solid accumulation and dead zones on the bottom. Also, the flow pattern of gas-lift is symmetrical because of the centrally located draft tube. From the density and color of the arrow in Figure 12, and the colored velocity contours in Figure 13, it can be seen that the distribution of liquid velocity in bubble column digester is more heterogeneous with higher value in the central of the body and the top than gas-lift digester, while leaves a large low velocity area at the bottom and in the corner. Comparatively, the distribution of liquid velocity of gas-lift digester is uniform in the main body except for the places near the wall. Also, due to the water recirculation conducted by the draft tube, the gas-lift digester has an active higher velocity area at the bottom than bubble column.

The CFD simulation revealed that the liquid velocity in the bubble column reactor, particularly in the bottom section, is much less than the gas-lift digester, indicating the mixing efficiency of the bubble column reactor is not as good as the gas-lift reactor. As a result, the solid sedimentation in the bubble column could be greater than gas-lift reactor, although both digesters have solid accumulation in the bottom compared to the bulky area (Figure 13).



(a) (b)

Figure 12. Vectors of velocity magnitude for the mixture phase

(a: Bubble column b: Gas-lift)

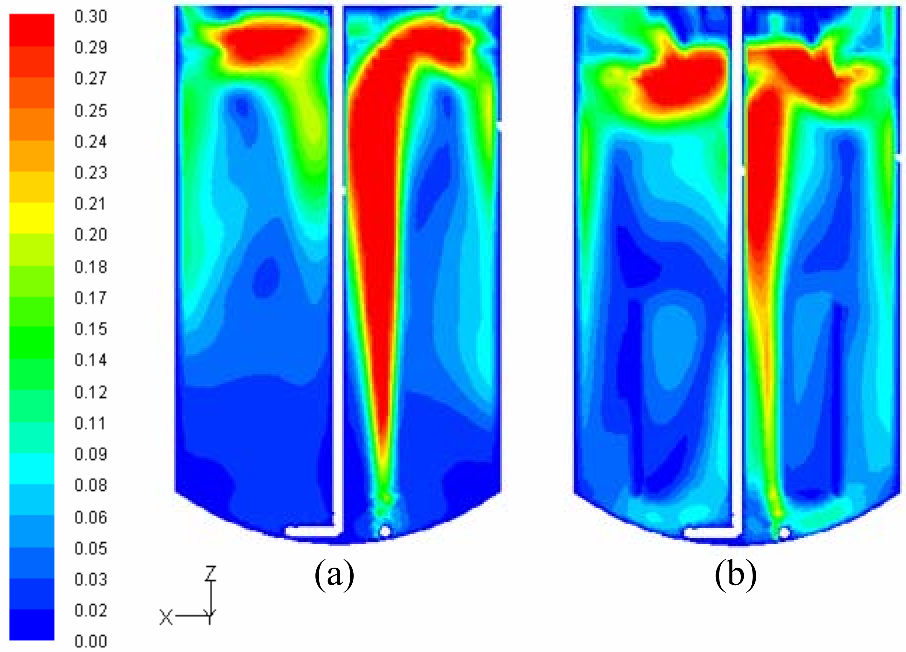


Figure 13. Contours of liquid velocity from front view

(a: Bubble column   b: Gas-lift)

4.1.4 TS and VS Distribution at the Bottom Part

CFD simulation of the digesters indicated that while the liquid flow in the bulk portion of the digester was similar, the flow velocity of the bubble column digesters around the bottom was lower than the gas-lift digester, i.e. the bubble column digester has more “dead” space than the gas-lift digester. To further confirm the CFD simulation result, liquid samples were taken at different depth of the digesters and the TS and VS content as a function of depth (from the gas-liquid interface to the bottom of the digester) were determined. As shown in Figure 15 and Figure 16, for each type digester, the trend of TS and VS with depth was similar, i.e. TS and VS was maintained at a relatively low but constant level at the bulky area of the digesters (from liquid surface to 9 inch deep), and increased with the depth when the depth approached to the bottom section (beyond 9 inch depth). Figure 15 and Figure 16 also show that the two digesters had a similar TS and VS profile at the bulky position; however, bubble column digester had higher TS and VS in the bottom region than the gas-lift digester, indicating more solid was accumulated in the bubble column as compared with the gas-lift digester.

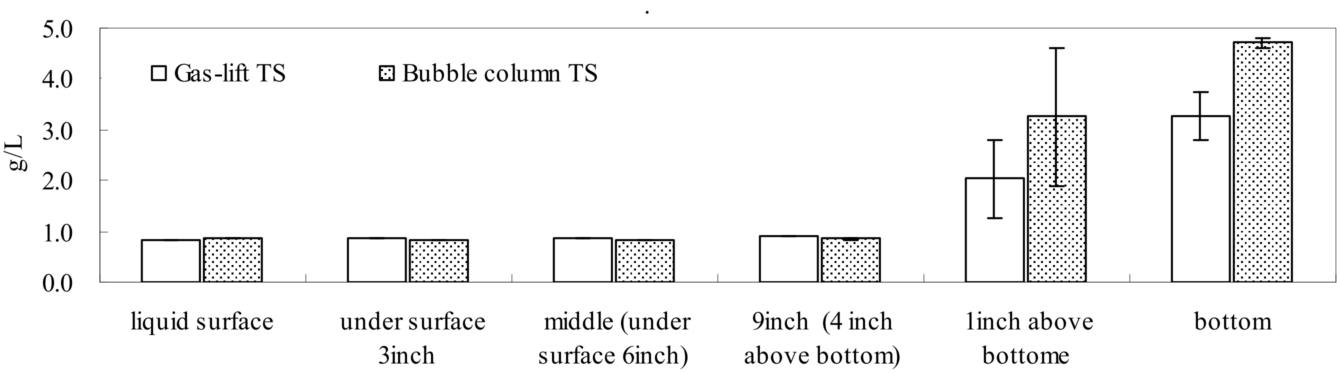


Figure 14. TS distribution with depth

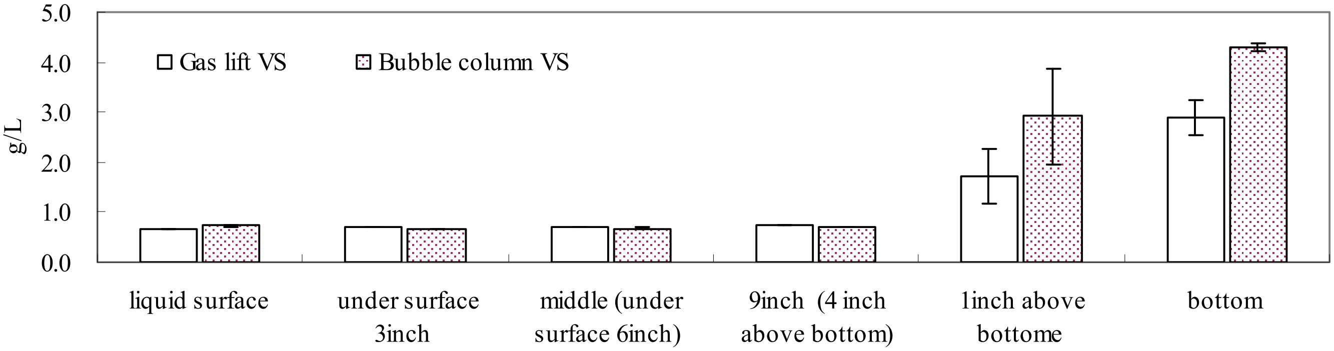


Figure 15. VS distribution with depth

4.1.5 COD and BMP Test of Different Portions of the Digester Liquid

From the CFD simulation, we can know that the gas-lift digester has a better mixing pattern (less stagnant space, comparatively uniform liquid velocity distribution, activated bottom region, and etc) than bubble column digester. The above TS and VS profiles of the two digesters (Figure 15 and Figure 16) were in agreement with the CFD simulation i.e. the bubble column accumulated more solid in the bottom region was due to the slow velocity/dead zone of this digester as indicated by the CFD simulation (Figure 13 and Figure 14). While in terms of biogas production performance, bubble column obtain higher biogas production than gas-lift.

The information available in the literature on the role of mixing in anaerobic digesters is confusing. On one hand, many research studies emphasized the importance of adequate mixing to improve the digestion performance. Initially, in 1930's, the use of mixing equipment for anaerobic digesters was to break up the floating scum layers formed inside. Then the test initiated in 1951 showed that a single digester with heating and mixing could treat the sludge as much as four conventional digesters (Torpey 1954). Currently, mixing of the digester is required for high rate AD design. Hashimoto (1982) found higher biogas production in continuously mixed digesters than those mixed for 2h per day with cattle manure. Ho and Tan (1985) found higher biogas production for continuously mixed digesters than unmixed ones with palm oil mill effluents. Pilot scale study on digester with dairy manure also showed that with mixing, continuous methane production is obtained, while digester performance deteriorates soon if without mixing(Borole, Klasson et al. 2006). Karim *et al.*(2005) concluded that mixing becomes more critical with thicker manure slurries (10%).

On the other hand, there have been some reports that more biogas was produced in unmixed or intermittent condition than mixed condition (Ben-Hasson 1985; Ghaly 1989; Chen 1990; Ghaly and Echiegu 1992). Hamdi (1991) and Fischer *et al.* (1983)found that mixing did not improve gas production in olive mill wastewater and pig waste treatment respectively. Stroot *et al.* (2001) confirmed that continuous mixing was not necessary for good digestion performance. Additional, intermittent mixing is recommended over continuous mixing for anaerobic digesters (Mills 1979; Smith, Hein et al. 1979). It is suggested that (Lettinga 1981; Whitmore 1987; Dolfing 1992) incomplete mixing provided a quiescent environment for bacteria, such as flocs, biofilms and granules which are ideal condition for formation of new spatial associations among different microbial populations, while rapid mixing disrupts the structure to disturb the syntrophic relationships between organisms.

To investigate the effect of the nonhomogeneous distribution of the digester content on the biogas production capacity, the sludge accumulated in the bottom of the digester was further characterized for their COD levels and biochemical methane potentials (BMP). 3 bottles with 200ml slurry taken from the bottom region respectively were prepared for each digester for BMP test. Results obtained from mean value of 3 bottles and were shown in Figure 17. For comparison purpose, the sludge taken in the middle of the digesters (the outlet position of effluent sampling tubes) was also characterized for these two parameters.

As shown in Figure 16, for each digester, the COD level increased when the sampling position was moved from the middle position to the bottom of the digester. When comparing the two digesters, the bubble column had a higher COD level in the bottom sludge than that of the gas-lift digester. The COD profile further confirmed that the liquid/sludge inside the digesters was inhomogeneous with the bottom tend to accumulate more sludge. As shown in Figure 17, the sludge at the bottom of the digester generated more biogas than the biogas produced from the bulk solution. The sludge from the bubble column bottom sludge generated more biogas than that from the gas-lift digester. The result in Figure 17 clearly explained the reason why the overall biogas production from the bubble column digester was higher than that of the gas-lift digester. Overall, the above result indicate that a better mixing does not necessarily mean generating more biogas, inefficient mixing and thus, a partial solid sedimentation may boost the biogas production.

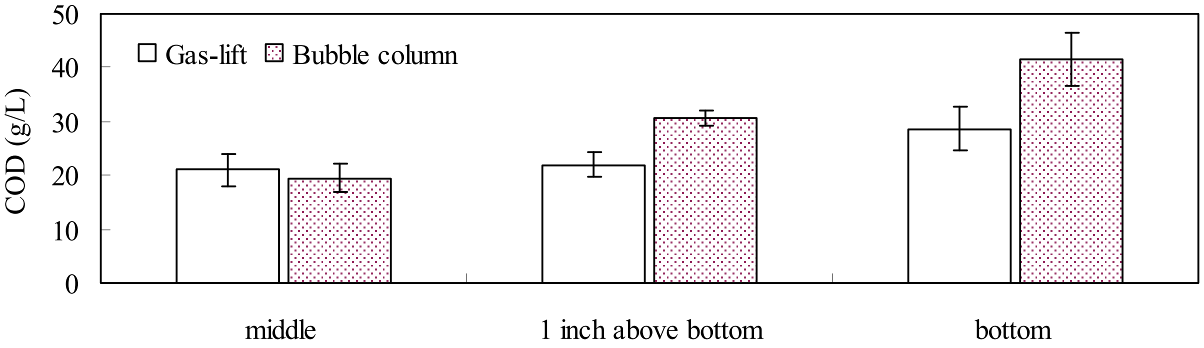


Figure 16. COD characteristics with depth of two digesters

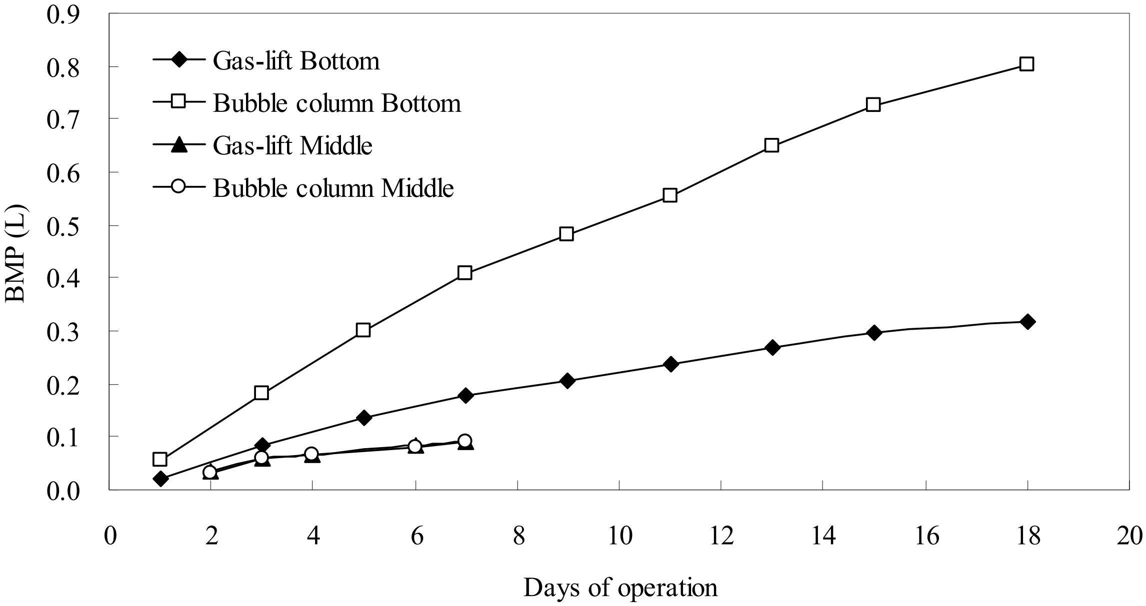


Figure 17. BMP test of sludge samples from middle and bottom depth of two digesters

4.2 Effect of Different Gas Flow Rate on Biogas Production

The above results indicate that at certain gas circulation rate, bubble column and gas-lift digesters had different biogas production performance due to the different flow pattern and sludge accumulation in these two types of digesters. Furthermore, it is suggested that(Lettinga 1981; Whitmore 1987; Dolfing 1992) incomplete mixing provided a quiescent environment for bacteria, such as flocs, biofilms and granules which are ideal condition for formation of new spatial associations among different microbial populations, while rapid mixing disrupts the structure to disturb the syntrophic relationships between organisms (Lettinga 1981; Whitmore 1987; Dolfing 1992). In this section, the two digesters were further operated at different gas-circulation rates to investigate the effect of mixing/flow pattern on the biogas production performance. We did the SEM (scanning electron microscopy) test on microbial population and the observation is showed in Figure 20. Also, we did the CFD simulation to explore the change of flow patterns at different gas recirculation rates (Figure 19).

As shown in Figure 19, the digesters were operated at 1L/min, when the gas flow rate was switched to 3L/min, the biogas production from both gas-lift digester and bubble column digester reduced. But the difference of the biogas production between the two digesters narrowed compared with that observed in 1/L min gas circulation rate. The gas flow rate was further switched to 0.5 L/min; both of the two digesters generated a high amount of biogas production. While, the biogas performance deteriorated soon, because gas spargers were clogged by too much solid accumulation. Throughout all the experiment, the bubble column digester consistently produced more biogas than gas-lift digester. Compared with the biogas production in 1 L/min, the increased gas flow rate decreased the biogas production and made the production curve less stable. .

To quantify the flow fields, three velocity areas are defined as low velocity area ($v<0.06$m/s), medium velocity area (0.06m/s$<v<0.2$m/s), and high velocity area ($v>0.2$m/s), as shown in Figure 19. we can see gas-lift digester keep a consistently stable and symmetrical flow pattern no matter at 0.5L/min or 3L/min gas recirculation rate: its liquid velocity distribution is uniform in the main body except for places near the wall; furthermore, the active medium velocity area at the bottom become more obvious due to the increased water recirculation velocity conducted by the draft tube. While in the bubble column digester, the effect of gas flow rate on the liquid flow pattern is significant. The high velocity area is in the central body and the top, and it is increased with the increased gas flow rate. At the 0.5L/min rate, almost half of the volume from the bottom falls into low velocity area, demonstrating poor mixing at low gas flow rate. The distinct low velocity boundary layers can be observed, and the corner of the bottom seems never been activated whether at 0.5L/min or 3L/min.

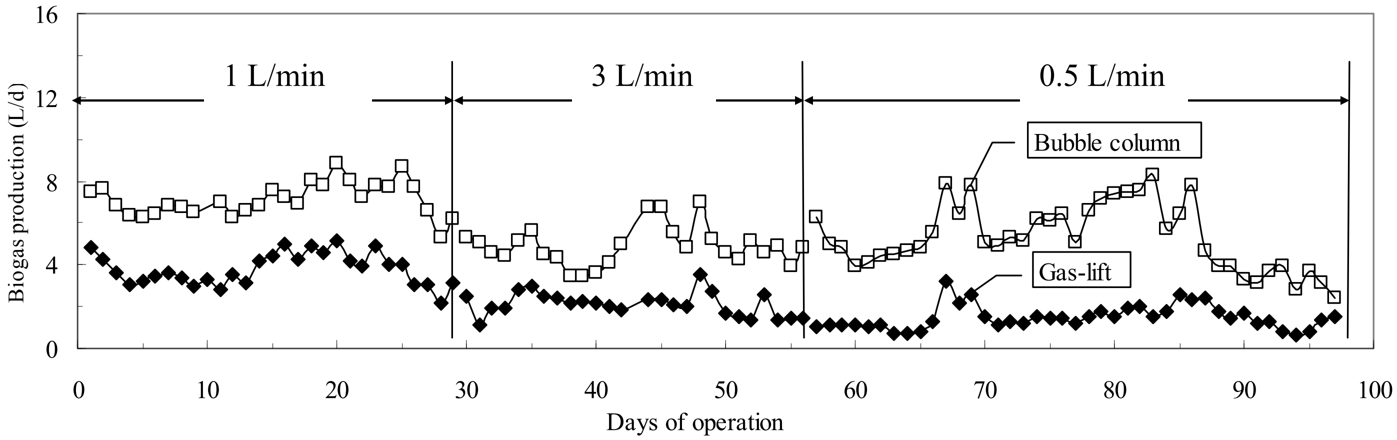
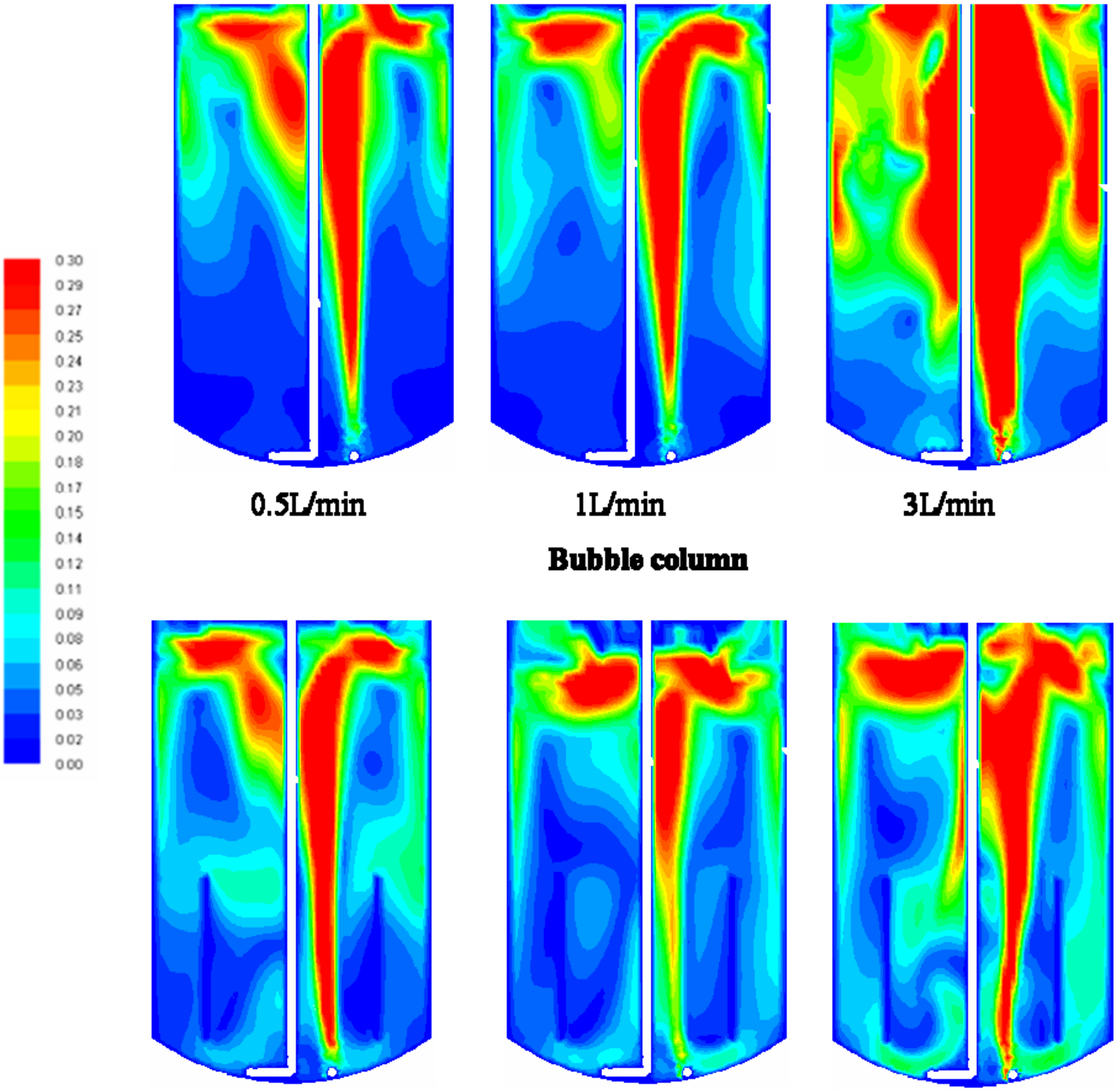


Figure 18. Biogas production at different gas recirculation rates



0.5L/min 1L/min 3L/min

Bubble column

0.5L/min 1L/min 3L/min

Gas-lift

Figure 19. Contours of velocity at different gas recirculation rate

4.3 SEM Test

In this work, we used SEM (scanning electron microscopy) to investigate the effect of mixing on the microbial population of the two digesters. A heterogeneous bacterial population and biofilms (Figures A1 and B1) were observed in both digesters. It should be noted that although the SEM images can provide some clue to recognize some methanogenic bacteric having distinct morphotypes(Zehnder 1981), the morphological observation of the bacteria through SEM could not provide precise information on microbial population. 16s-rDNA based techniques are needed to characterize the microbial communities.

SEM could be used to do a preliminary analysis on the microbial communities of the anaerobic digester. Kobayashi *et al.*(1988) used a combination of tests including SEM and immunologic methods to characterize the methanogenic flora of two turbulent, high-rate reactors. It demonstrated that species diversity and distribution was influenced by the concentration of substrate as well as the degree of turbulence inside the digester. Heppner *et al.* (1992) used light microscope and SEM to observe the growth of microbial communities in a fluidized-bed reactor. The study found that *Methanocorpusculum*-like and *Methanospirillum* –like microorganisms were present during the early start-up phase. And a much more complex population consisted of *Desulfobulbus*, *Methanothrix* and at least three different species of methanogens were observed in the mature biofilm during steady-state condition. Harper and Pohland (1997) used SEM to visually compare the microbial consortia in different reactor regimes, and found that, with increasing HRT, Rods and cocci decreased while filaments increased. And the trend was most pronounced in the gas separated reactor which appeared to produce a more plug flow regime inside of the reactor.

MAcLEOD *et al.*(1990) used SEM and TEM (Transmission Electron Microscopy) to examine the ultrastructure of bacterial granules and revealed its three-layered structures: a very heterogeneous population in the exterior layer; a predominance of bacterial rods in the middle layer; and the internal core consisting of large amounts of *Methanothrix*-like cells. Wu *et al.*(1996) used SEM and TEM to observe the formation of anaerobic granules. The study demonstrated the key role of *Methanosaeta sp.* and *Methanobacterium formicicum* in granulation and the importance of *Methanosarcina sp.* in the granules structure.

In the SEM observation of our study, excluding those that could not be identified confidently or the micro-organisms were infrequently observed, some most prevalent morphotypes were listed below:

- a: Bamboo-shaped rods with flat-ends showed the typical morphotype of *Methanothrix* described by Zehnder(1980), Patel(1984) and Zinder (1984)

- b: Two types of cocci resembling *Methanococcus* species were observed frequently in both digester: large cocci (b2)with a diameter of around 1 μm and a rough surface; smaller cocci (b1)with a diameter around 0.3-0.5μm and a smooth surface. While they also could be *Methanosphaera* species.

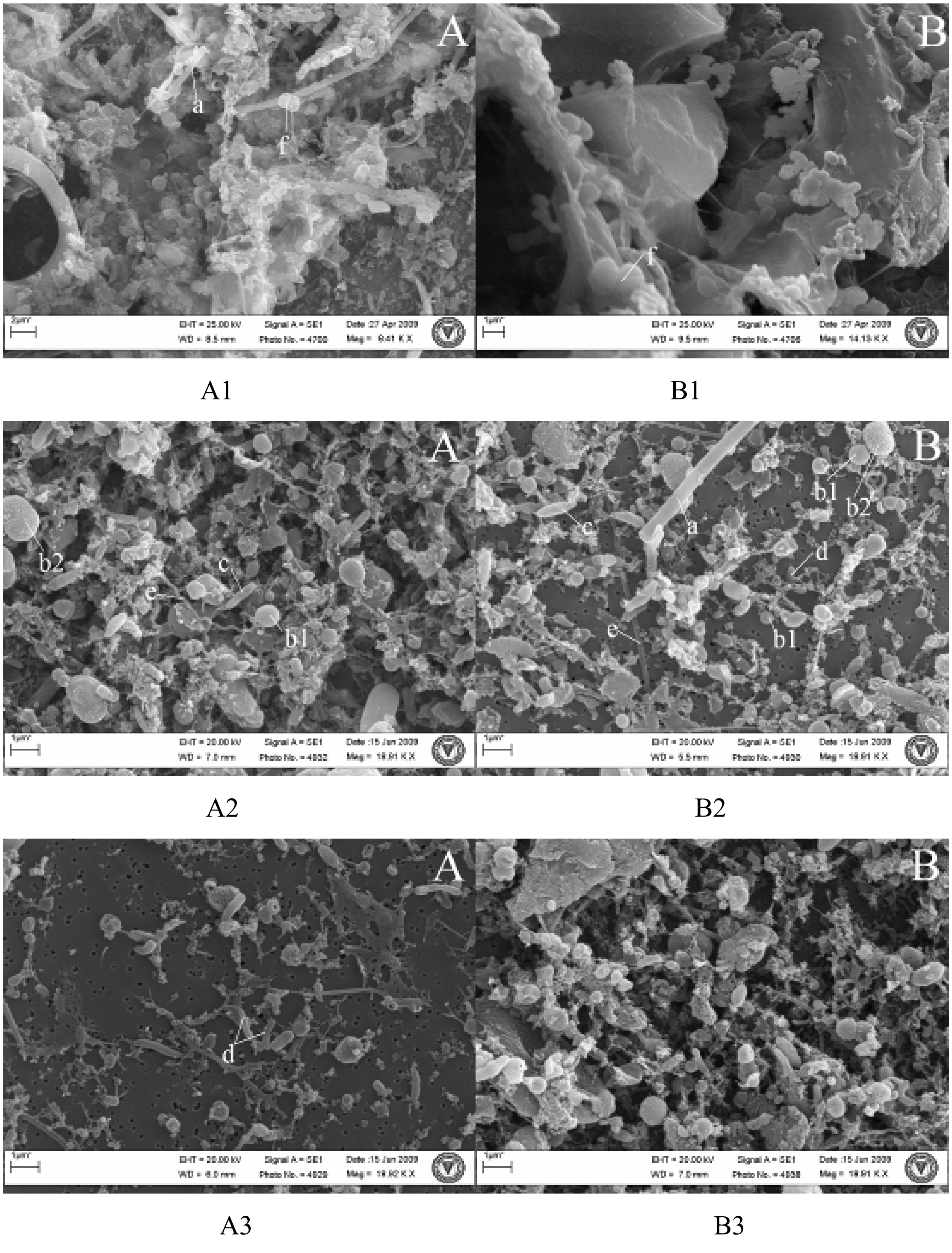
- c: This rod-shaped bacteria had a length around 1μm. It was similar with d below, but not as curved as d. By its size and shape, it could be related to *Methanobrevibacter, Methanomicrobium* and *Methanobacterium.*

- d: A slightly curvy slender rods similar with c was observed more frequently in air-lift digester than bubble column. It resembled the *Syntrophomonas* species, and it was also suggested to be a slender relative of *Desulfovibrio* or *Desulfomonas* (Harper. S.R. 1997)

- e: Long filamentous organisms resembled *Methanospirillum* species.

- f: Bacteria resembled *Methanosarcina* species, but it could also be a *Methanosphaera*.

The microbial populations of the two digesters were compared preliminarily by visual estimations. The sludge of the bubble column digester seemed to have more bacteria than the gas-lift digester. Additional, a more homogeneous bacterial population was observed from bubble column digester, where *Methanococcus* –like micro-organism was dominant in the population. It should be noted that the SEM only give a overall morphology of the bacteria/arches population in the digester, further study on the microbial community characterization using molecular based tool is needed.



A1 B1

A2 B2

A3 B3

Figure 20. SEM observation of the sludge samples from digester bottoms
(A) Gas-lift digester; (B) Bubble column digester

5. Conclusion

The effect of mixing on the biogas production performance is a complicated process; depending on the reactor configuration and operational condition. The effect of mixing on anaerobic digestion performance need to be evaluated based on specific cases. In this work, the biogas production rate from the gas-lift digester was consistently higher than that from the gas-lift digesters.

In this work, the RTD of the two digesters gave a similar result, while the biogas production shows a clear difference in terms of anaerobic digestion performance. This may be due to the inherent limitation of the tracer experimental design and the RTD methodology that cannot provide an in-depth flow pattern of the digester. This led us to use CFD to reveal the flow pattern of the digesters.

The CFD simulation revealed that the liquid velocity in the bubble column reactor, particularly in the bottom section, is much less than the gas-lift digester, indicating the mixing efficiency of the bubble column reactor is not as good as the gas-lift reactor. As a result, the solid sedimentation of the bubble column is more than that of the gas-lift reactor, although both of the two digesters had certain solid accumulation in the bottom as compared to the bulky solution. This sludge accumulation may result in a higher biogas production performance of the bubble column digester than the gas-lift digester. Overall, the above results indicate that a better mixing does not necessarily generate more biogas, inefficient mixing and thus, a partial solid sedimentation may boost the biogas production.

6 Future Work

In the SEM test, a more heterogeneous bacterial population was observed from the gas-lift digester than bubble column digester. The bacteria could not be identified definitively by using only morphology. Further study on the microbial community characterization is needed to elucidate this microbial distribution difference.

Our study revealed that complete mixing does not necessarily mean a good digestion performance, inefficient mixing with solid settling at the bottom encourages higher gas production. The intensity and duration of mixing should be further studied to provide a better operational strategy for anaerobic digesters. The relationship between digester mixing efficiency and the degree of digestion should be clarified. Also the effect of different solid level of the sludge on biogas productivity should be investigated in the future work.

Extensive work need to be done before scaling up the biogas recirculation mixing system to full scale application, such as a basic economic analysis should be provided in the future work to gain a more comprehensive understanding of the biogas recirculation mixing system.

References

Achkaribegdouri, A. and P. R. Goodrich (1992). "Rheological Properties of Moroccan Dairy-Cattle Manure." Bioresource Technology **40**(2): 149-156.

Anderson, G. K., C. M. M. Campos, et al. (1991). "Evaluation of the Inhibitory Effects of Lithium When Used as a Tracer for Anaerobic Digesters." Water Research **25**(7): 755-760.

APHA (1998). Standard methods for the examination of water and wastewater. Washington, DC, American Public Health Association.

ASABE (2005). 2005. Manure production and characteristics. ASABE Standard D384.2.American Society of Agricultural and Biological Engineers. St. Joseph, MI. .

Asterio S´anchez Mir´on, F. G. ı. C., Antonio Contreras G´omez, Emilio Molina Grima, and Yusuf Chisti (09/2000). "Bubble-Column and Airlift Photobioreactors for Algal Culture." AIChE Journal **46**(9): 1872-1887.

Barber, E. M. (1979). Canada animal manure management guide. Ottawa, Publication 1534, Agriculture Canada.

Baumann, P. G. and G. L. Huibregtse (1982). "Evaluation and Comparison of Digester Gas Mixing Systems." Journal Water Pollution Control Federation **54**(8): 1194-1206.

Ben-Hasson, R. M., Ghaly, A.E., Singh, R.K. (1985). Design and evaluation of no-mix energy efficient anaerobic digester. Proceedings, Annual Meeting, Canadian Society of Agricultural Engineering, Charlottetown, P.E.I.

Borole, A. P., K. T. Klasson, et al. (2006). "Methane production in a 100-L upflow bioreactor by anaerobic digestion of farm waste." Applied Biochemistry and Biotechnology **131**(1-3): 887-896.

Borroto, J. I., J. Dominguez, et al. (2003). "Technetium-99m as a tracer for the liquid RTD measurement in opaque anaerobic digester: application in a sugar wastewater treatment plant." Chemical Engineering and Processing **42**(11): 857-865.

Brade, C. E., Noone, G.P. (1981). "Anaerobic digestion—need it be expensive?" Wat. Pollut. Control **80**: 70-76.

Carroll, W. D. and R.D.Ross (1984). A Full Scale Comparison of the Confined and Unconfined Gas Lift Mixing Systems in Anaerobic Digesters Sewage Sludge Stabilisation and Disinfection. , Ellis Horwood Ltd. , Chichester, England 146-157.

Casey, T. J. (1986). Requirements and methods for mixing in anaerobic digesters. Anaerobic Digestion of Sewage Sludge and Organic Agricultural Wastes., Elsevier App. Sci. Pub.**:** 90–103.

Chambers, T. E. J. a. B. (1979). the effect of longitudinal mixing on the settleability of activated sludge Technical Report TR 122, Water Research Centre, Stevenage

Chen, T. H., P. Chynoweth and R. BIljetina (1990). "Anaerobic digestion of municipal solid waste in a nonmixed solids concentrating digestor." Applied Biochemistry and Biotechnology **24-25**: 533-544.

Chen, Y. R. (1986). "Rheological Properties of Sieved Beef-Cattle Manure Slurry - Rheological Model and Effects of Temperature and Solids Concentration." Agricultural Wastes **15**(1): 17-33.

Cheremisinoff, P. N. (1989). Wastewater treatment technology Gulf Publishing Company, Houston, Texas.

Chisti, Y. (1998). "Pneumatically agitated bioreactors in industrial and environmental bioprocessing: Hydrodynamics, hydraulics, and transport phenomena." Applied mechanics reviews **51**: 33.

Choi, K. H., Y. Chisti, et al. (1996). "Comparative evaluation of hydrodynamic and gas-liquid mass transfer characteristics in bubble column and airlift slurry reactors." Chemical Engineering Journal and the Biochemical Engineering Journal **62**(3): 223-229.

Cholette, A. a. L. C. (1959). "Mixing efficiency determinations for continuous flow systems." Canadian journal of chemical engineering **32**: 105.

Dolfing, J. (1992). "The Energetic Consequences of Hydrogen Gradients in Methanogenic Ecosystems." Fems Microbiology Ecology **101**(3): 183-187.

El-Mashad, H. M., W. K. P. van Loon, et al. (2005). "Rheological properties of dairy cattle manure." Bioresource Technology **96**(5): 531-535.

Fischer, J. R., D. M. Sievers, et al. (1983). "Energy-Consumption from Farm Animal Manure Methane Generation." Transactions of the Asae **26**(1): 223-&.

Garrison, W. E., C.A. Nagel, and R.S. Easley, (1980). Current Design and Operating Experience with Anaerobic Sludge Digestion. proceedings of the 7th U.S./Japan Conference on Sewage Technology, Tokyo EPA-600-9-80-047.

Gavrilescu, M. and R. Z. Tudose (1999). "Residence time distribution of the liquid phase in a concentric-tube airlift reactor." Chemical Engineering and Processing **38**(3): 225-238.

Ghaly, A. (1989). "Continuous production of biogas from dairy manure using an innovative no-mix reactor." Applied biochemistry and biotechnology **20**: 541.

Ghaly, A. E. and E. A. Echiegu (1992). "Performance Evaluation of a Continuous-Flow No-Mix Anaerobic Reactor Operating on Dairy Manure." Energy Sources **14**(2): 113-134.

Ghosh, S. (1997). "Anaerobic digestion for renewable energy and environmental restoration."

The 8th International Conference on Anaerobic Digestion, Sendai International Center,Sendai, Japan,.

Grobicki, A. and D. C. Stuckey (1992). "Hydrodynamic Characteristics of the Anaerobic Baffled Reactor." Water Research **26**(3): 371-378.

Hamdi, M. (1991). "Effects of Agitation and Pretreatment on the Batch Anaerobic-Digestion of Olive Mill Waste-Water." Bioresource Technology **36**(2): 173-178.

Hashimoto, A. G. (1982). "Effect of Mixing Duration and Vacuum on Methane Production-Rate from Beef-Cattle Waste." Biotechnology and Bioengineering **24**(1): 9-23.

Hill, D. T. (1984). "Methane productivity of the major animal waste types." Transactions of the ASAE **27**(2): 530-4.

Ho, C. C. a. Y. K. T. (1985). "Anaerobic Treatment of Palm Oil Mill Effluent by Tank Digesters." Journal of Chemical Technology and Biotechnology B-Biotechnology **35**(2): 155-164.

Jacobson, L., J. Lorimor, J. Bicudo, and D. Schmidt (2000). "Lesson 43: Emissions control strategies for manure storage facilities. Section 4 Biological Processes." Livestock and Poultry Odor Workshop I:Emissions,Measurement, Control and Regulation, from http://pubwiki.extension.org/mediawiki/files/8/85/L43_sec4.pdf.

Janekeh, M. K. a. M. (1991). "Two- and Three-Phase Mixing in a Concentric Draft Tube Gas-Lift Fermentor." Biotechnology and Bioengineering **38**: 1261-1270.

Karim, K., R. Hoffmann, et al. (2005). "Anaerobic digestion of animal waste: Effect of mode of mixing." Water Research **39**(15): 3597-3606.

Karim, K., R. Hoffmann, et al. (2005). "Anaerobic digestion of animal waste: Waste strength versus impact of mixing." Bioresource Technology **96**(16): 1771-1781.

Karim, K., K. T. Klasson, et al. (2005). "Anaerobic digestion of animal waste: Effect of mixing." Bioresource Technology **96**(14): 1607-1612.

Karim, K. T., G. J. Al-Dahhan, M. H. (2007). "Gas-lift digester configuration effects on mixing effectiveness." Water Research **41**(14): 3051-3060.

Kobayashi, Hester A. Everly Conway DE Macario, Regan S. Williams and Alberto J. L. Macario (1988). "Direct Characterization of Methanogens in Two High-Rate Anaerobic Biological Reactors." APPLIED AND ENVIRONMENTAL MICROBIOLOGY: 693-698.

Koide, K., Shinji Iwamoto (1983). " Gas holdup and volumetric liquid-phase mass transfer coefficient in bubble column with draught tube and with gas dispersion into annulus." Journal of chemical engineering of Japan **16**(5): 413-419.

Kojima, H., J. Sawai, et al. (1999). "Liquid circulation and critical gas velocity in slurry bubble column with short size draft tube." Chemical Engineering Science **54**(21): 5181-5185.

Kumar M, B. H., Mohsenin NN. (1972). "Flow properties of animal waste slurries " Transactions of the ASAE **15**(4): 718-722.

Landry, H., C. Lagu, et al. (2004). PHYSICAL AND RHEOLOGICAL PROPERTIES OF MANURE PRODUCTS Applied Engineering in Agriculture. **20** 277-288.

Lee, S. R., N. K. Cho, et al. (1995). "Using the Pressure of Biogas Created during Anaerobic-Digestion as the Source of Mixing Power." Journal of Fermentation and Bioengineering **80**(4): 415-417.

Lettinga, G. (1981). Anaerobic digestion for energy saving and production. In Energy from Biomass, Ist E.C. Conference. W. P. a. P. Chartier, Applied Science Publishers Ltd., London.

Levenspiel, O. (1972). Chemical reaction engineering., New York, Wiley

Levenspiel, O. (1999). Chemical reaction engineering New York : Wiley, .

Lever, H. C. K. a. M. L. (1987). "Mixing in anaerobic sludge digesters." Water **14**: 16-20.

Liu, X. L., N. Q. Ren, et al. (2007). "Hydrodynamic characteristics of a four-compartment periodic anaerobic baffled reactor." Journal of Environmental Sciences-China **19**(10): 1159-1165.

Loehr, R. C., Ed. (1984). Pollution Control for Agriculture. . Toronto Academic Press

Lusk, P. (1998). "Methane Recovery from Animal Manures: The Current Opportunities Casebook." NREL/SR-580-2545, National Renewable Energy Laboratory, Golden, CO.

Mills, P. J. (1979). "Minimization of Energy Input Requirements of an Anaerobic Digester." Agricultural Wastes **1**(1): 57-66.

Mitsuharu Terashimaa, R. G., Kazuya Komatsua, Hidenari Yasuic, Hiroshi Takahashid, Y.Y. Lie and Tatsuya Noikef (April 2009). "CFD simulation of mixing in anaerobic digesters " Bioresource Technology **100**(7): 2228-2233.

Mooyoung, M., A. J. Daugulis, et al. (1979). "Waterloo Process for Scp Production from Waste Biomass." Process Biochemistry **14**(10): 38-40.

NCASI (Sept.1983). A Review of Procedures for Conducting Conservative Tracer Studies in the Hydraulic Characterization of Effluent Treatment Basins.

Nennich (2004). CHARACTERIZATION OF MANURE EXCRETION AND ENVIRONMENTAL IMPACTS OF NUTRIENT MANAGEMENT IN DAIRY PRODUCTION SYSTEMS, Washington State University, Pullman, WA. **Ph.D. Thesis**.

Ong, H. K., P.F.Greenfield and P.C. Pullammanappallil (2002). "Effect of mixing on biomethanation of cattle-manure slurry." Environmental Technology **23**(10): 1081-1090.

Pironti, F. F., V. R. Medina, et al. (1995). "Effect of draft tube position on the hydrodynamics of a draft tube slurry bubble column." Chemical Engineering Journal and the Biochemical Engineering Journal **60**(1-3): 155-160.

Robinson, A., Baxter, L., Junker, H., et al. (1988). "Fireside Issues Associated with Coal-Biomass Cofiring." NREL/TP-570-25767, National Renewable Energy Laboratory, Golden, CO.

Sawyer, C. N., Grumbling, A.M. (1960). "Fundamental consideration in high-rate digestion." Inc. Sew. Engng. Div. ASCE,: 86–92.

Sheffield, J. (1999). Summary Report of the Workshop on Opportunities to Improve and Benefit from the Management of Animal Waste. JIEE Research Paper,Joint Institute for Energy and Environment. Knoxville, TN.**:** 99–01.

Sheffield, J. (2002). Financial approaches to animal manure management.In: Animal Residuals 2002 Conference and Workshop Report. **(No: JIEE 2002-04)**.

Smith, L. C., D. J. Elliot, et al. (1996). "Mixing in upflow anaerobic filters and its influence on performance and scale-up." Water Research **30**(12): 3061-3073.

SMITH, L. C., J. ELLIOT, et al. (1993). "Characterization of mixing patterns in an anaerobic digester by means of tracer curve analysis." Ecological modelling **69**: 267-285.

Smith, R. J., M. E. Hein, et al. (1979). "Experimental Methane Production from Animal Excreta in Pilot-Scale and Farm-Size Units." Journal of Animal Science **48**(1): 202-217.

Speece, R. E. (1996). Anaerobic Biotechnology for Industrial Wastewaters. Vanderbilt University, Arachae Press.

Steed J, H. G. (1994). "Methane emissions from typical manure management systems." Bioresource Technology **50**: 123-30.

Stroot, P. G., K. D. McMahon, et al. (2001). "Anaerobic codigestion of municipal solid waste and biosolids under various mixing conditions - I. Digester performance." Water Research **35**(7): 1804-1816.

Svendsen, H. F., H. A. Jakobsen, et al. (1992). "Local Flow Structures in Internal Loop and Bubble Column Reactors." Chemical Engineering Science **47**(13-14): 3297-3304.

Tekippe, C. A. B. a. R. J. (1982). Current Anaerobic Digester Mixing Practices. 55rt Annual Water Pollution Control Fed. Conf. St. Louis, Missouri.

Torpey, W. N. (1954). "High-Rate Digstion of Concentrated Primary and Activated Sludge " sewage and industrial wastes **26** (4): 479-494.

U.S.EPA (09/1979). process design manual for sludge treatment and disposal, EPA 525/1-79-011.

U.S.EPA (1979). Process design manual for sludge treatment and disposal.

USDA (2005). USDA, Agricultural Statistics, National Agricultural Statistics Service. United States Government Printing Office, Washington, DC

USDA, U. A. R. S. (2006). " FY-2005 Annual Report Manure and Byproduct Utilization."

Vanhorn, H. H., A. C. Wilkie, et al. (1994). "Components of Dairy Manure Management-Systems." Journal of Dairy Science **77**(7): 2008-2030.

Varma, R. a. A. M. A.-D. (2007). "effect of sparger design on hydrodynamics of a gas recirculation anaerobic bioreactor " Biotechnology and Bioengineering **98**(6).

Veenhuizen, M. A. (1992). "Ohio livestock manure and wastewater management guide. Bulletin 604." Bulletin **604**

Vesvikar, M. S. and M. Al-Dahhan (2005). "Flow pattern visualization in a mimic anaerobic digester using CFD." Biotechnology and Bioengineering **89**(6): 719-732.

Weiland, P. (1984). "Influence of draft tube diameter on operation behaviour of airlift loop reactors." Chemical engineering & technology **7**: 374-385.

Wheatley, A. (1991). Anaerobic Digestion: A Waste Treatment Technology New York, NY, Elsevier Applied Science.

Whitmore, T. N., D. Lloyd, G. Jones, and T.N. Williams (1987). "Hydrogen-Dependent Control of the Continuous Anaerobic-Digestion Process." Applied Microbiology and Biotechnology **26**(4): 383-388.

Whitmore, T. N., Lloyd, D., Jones, G. and Williams, T.N. (1987). "Hydrogen-dependent control of the continuous anaerobic digestion process." Appl. Microbiol. Biotechnol. **26**: 383-388.

Wood, L. A. and P. W. Thompson (1987). "Applications of the Air Lift Fermenter." Applied Biochemistry and Biotechnology **15**(2): 131-143.

Wu, B. X. and S. L. Chen (2008). "CFD simulation of non-Newtonian fluid flow in anaerobic digesters." Biotechnology and Bioengineering **99**(3): 700-711.