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A Systematic Analysis of Foam Drainage and Stability: Measurements, Mechanisms, and Implications for Anaerobic Digester Foaming

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A Systematic Analysis of Foam Drainage and Stability: Measurements, Mechanisms, and Implications for Anaerobic Digester Foaming

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Abstract

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The formation of a substantial foam layer has severe impacts on the overall digestion process that is responsible for the major portion of waste stabilization. An understanding of dynamics of foam produced by three primary causes – dispersed gas bubbles, surface-active materials, and hydrophobic compounds – provides insight into the prevention of the foam layer and into the control of the foam stability. To better understand the mechanisms in three-phase foam dynamics, we developed a systematic methodology to characterize foam drainage behavior using electrical conductance measurements.

With no sludge conditions, all tested sodium dodecyl sulfate (SDS) foams exhibit a node-dominated drainage regime with high mobility at bubble surfaces. Drainage regime under similar foaming conditions was consistent with existing drainage studies using other measurement techniques in the literature.

The drainage of sodium dodecylbenzenesulfonate (SDBS) surfactant solution, a commercial form of linear alkylbenzene sulfonate (LAS) that is most frequently found in anaerobic sludge, was studied in detail by several approaches. Two complementary methods of macroscopic drainage investigations (forced and free drainage) were conducted to gain confidence in its validity. The experimental data can be fitted using a power law with an exponent of 1/3 for forced drainage and of 1.0 for free drainage. These data indicate the following drainage behavior: mobile bubble surfaces, causing plug-like flow within Plateau borders, thus dissipation mainly occurs inside the nodes.

With the drainage studies for a variety of aqueous surfactant solutions, experimental and theoretical studies to include wastewater sludge are important for understanding the stability of three-phase foams, and therefore foaming in anaerobic digesters. The drainage behavior of sludge-containing foams was characterized by our developed method. The presence of anaerobic sludge at total solid (TS) concentrations of approximately 2.5-2.8% induced a transition from the node-dominated regime to a Plateau-border (PB)-dominated

regime. This apparent transition was verified in both forced and free drainage experiments. These drainage studies supported a more detailed estimation of foam stability in relation to its structure.

In summary, our developed method using the electrical conductance measurements was applied to understand the key aspects of foam stability required for prediction and control of foaming in anaerobic digesters. A systematic methodology for assessing foam dynamics was proposed and discussed in two- and three-phase foams.

This dissertation is dedicated to my wife for all of her support and sacrifices that made my doctoral studies possible

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List of Notation

Alphabetic Symbols:

Symbol	Meaning
a	diameter of the probe, cm
b	diameter of column from probe center to wall, cm
A	cross-sectional area of the foam column, cm^2
A_H	Hamaker constant
AE	alcohol ethoxylates
APE	alkyl phenol ethoxylates
C_{el}	electrolyte concentration, M
CMC	critical micelle concentration
d	distance between two electrode segments, cm
DLVO	Derjaguin-Landau-Verwey-Overbeek
DTDMAC	ditallowdimethylammonium chloride
e	electric charge
H	foam height, cm
$H_{1/2}$	half of initial foam height, cm
g	gravitational acceleration, m/s^2
k	permeability, m^2
K_c	dimensionless Plateau border – dominated permeability number
K_n	dimensionless node – dominated permeability number
K_x	dimensionless parameter in free drainage
l	length of electrode on foam probe, cm
L	length of Plateau border, m
LAS	linear alkylbenzene sulfonate
MATH	microbial adherence to hydrocarbons
MLSS	mixed liquor suspended solids, mg/L
MLSS_f	MLSS concentration after emulsification
MLSS_i	MLSS concentration before emulsification
N_A	Avogadro's number
PB	Plateau border
PBS	phosphate buffered saline
Q	controlled flow rate, ft^3/hr
R	resistance, ohms
RAS	return activated sludge
SBR	sequencing batch reactor
SDS	sodium dodecyl sulfate
SDBS	sodium dodecylbenzenesulfonate
SI	scum index, %
SRT	solid retention time, d
SS	suspended solids, mg/L
t	time, s

t_{i}	average drainage time between electrodes
$t_{1/2}$	foam half-life time, s
TS	total solids, mg/L
TSS	total suspended solids, mg/L
v_{f}	front velocity, cm/s
v_{s}	superficial liquid velocity, cm/s
$\mathrm{V}_{\mathrm{foam}}$	volume of foam, cm^3
$\mathrm{V}_{\mathrm{liquid}}$	volume of liquid, cm^3
VSS	volatile suspended solids, mg/L
WAS	waste activated sludge
z	vertical coordinate, cm

Greek Symbols:

Symbol	Meaning
α	power-law exponent in forced drainage experiment
β	power-law exponent in free drainage experiment
χ	free drainage parameter
ε	liquid fraction
ε_0	initial liquid fraction
ε_{r}	electric constant of water
γ	surface tension
κ^{-1}	debye length
λ	conductance, siemens
μ	bulk viscosity of foaming solution, Pa·s
θ	cell constant
ρ	density, kg/m^3
σ	specific conductivity
σ_{f}	specific conductivity in the foam phase
σ_{l}	specific conductivity in the liquid phase
σ_{r}	relative conductivity
ψ	electrical potential
Π	interfacial forces in films
Π_{el}	electric double layer forces
Π_{vw}	van der Waals forces
Π_{other}	other forces such as hydrophobic, hydration and steric forces

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1. Introduction

Concerns about climate are driving a search for alternatives to fossil fuels. Wastewater has drawn considerable attention as a potential source of renewable energy (Kim *et al.* 2011). Whereas most treatment processes are consumers of energy, anaerobic treatment processes produce energy in the form of biogas. Anaerobic treatment processes are employed at numerous municipal wastewater treatment plants, and are responsible for the major portion of waste stabilization (McCarty 1964, McCarty and Bae 2011). While complete anaerobic sludge digestion has the potential to produce biogas as a useful energy source, many digesters are plagued with foaming problems associated with gas production (Murk *et al.* 1980, van Niekerk *et al.* 1987, Ross and Ellis 1992). Foaming in wastewater sludge refers to the accumulation of floating suspended solids on the surface of the sludge (Jenkins *et al.* 1993). The formation of excessive foam layer induces a decrease in solids content within the active volume of digesters and decrease biogas recovery. The first type of foaming is associated with low levels of active biomass during start-up and is caused by the presence of partially degraded organic matter in the mixed liquor or digesting liquor. Start-up foams are usually transient and unstable, dissipating within a few weeks of their first appearance (Pitt 1988). The second type is the stable foam that occupies a significant volume of the digester. These foams can tip or overflow floating digester covers, and create visual and odor nuisances causing safety hazards (van Niekerk *et al.* 1987, Pagilla *et al.* 1997). These detrimental effects ultimately result in an increase in operation and maintenance costs (Westlund *et al.* 1998, Ganidi *et al.* 2009). Recent surveys reported that 50% to 80% of anaerobic digesters have experienced intermittent or continuous foaming problems within the previous ten years (CSWEA 2011, Subramanian *et al.* 2012).

Considerable effort has been made to understand the causes and controls of foaming in aerobic activated sludge, but much less is known about foaming in anaerobic sludge digesters. In most cases, the appearance of foam in activated sludge was thought to be associated with the filamentous organisms with highly hydrophobic cell walls, particularly *Gordonia amarae* (de los Reyes *et al.* 1998, Oerther *et al.* 2001). These are primarily aerobic microorganisms, but have been commonly identified in anaerobic digesters treating waste activated sludge (WAS), and have been implicated as a cause of foaming because some cells remain viable (Hernandez and Jenkins 1994, Pagilla *et al.* 1997, Westlund *et al.* 1998). Several solutions have been developed to eliminate foam-causing filamentous microorganisms in full-scale anaerobic digesters, including thermal pre-treatment and chlorination (Pagilla *et al.* 1998, Jolis and Marneri 2006). It is likely that microbial factors contribute to foam formation, but are not the sole cause because dissolved gases and surface active agents are necessary for foam initiation (Davenport and Curtis 2002). Thus, fundamental studies of physicochemical surface properties within the foam are necessary for a better understanding of foaming and its stability.

Foams are thermodynamically unstable structures (Vardar-Sukan 1998). One of the main characteristics of foams is that they irreversibly evolve in time because they are not in equilibrium under normal gravity conditions (Weaire *et al.* 1997, Saint-Jalmes and Langevin 2002). When freshly formed, liquid drains out of the foam and flows down from the upper to the lower foam layers due to gravitational and capillary forces. As a result, the liquid films become thinner (coarsen) and eventually collapse (Kruglyakov *et al.* 2008, Biance *et al.* 2011). Fast drainage rates are expected to indicate less stable foams, leading to a quick breakdown of foam structure. Such changes in the liquid content and the drainage rates are important for predicting foam stability, but suitable methods for measuring the drainage rates and stability of foaming wastewater sludge have not been reported.

There are few techniques available for the study of foam drainage (Barigou *et al.* 2001). Foam optical properties strongly depend on the liquid content, and used in the liquid drainage based on the measurements of the transmitted light, recorded by a CCD digital camera (Saint-Jalmes *et al.* 2000, Vera *et al.* 2001, Saint-Jalmes 2006). This light transmission technique is possible to determine liquid fraction gradients and front drainage velocity, but it remains difficult to use it regarding the quantitative estimation of liquid fraction, as the details of light transport in foams are not yet well understood (Koehler *et al.* 1999, 2000). Foam electrical properties are also used to study the drainage of foams. Early measurements of foam drainage involved a segmented capacitance resistor which requires the foam to be non-conducting (Hutzler *et al.* 1995), but the difficulties associated with calibration and the lack of reproducibility represent drawbacks for this method (Barigou *et al.* 2001). An improved method extensively used electrodes, which consisted of two parallel plates, or two stripped wires, and measured the local electrical resistance in electrically conducting foams (Chang and Lemlich 1980, Datye and Lemlich 1983, Weaire *et al.* 1995, Wilde 1996, Phianmongkhol and Varley 1999). The change in electrical current is important for the continuous monitoring of the rate of foam formation and collapse (Lemlich 1978). Recent technique has been developed and tested for a multi-point foam probe, which allows measurement of the electrical current across a foam phase at multiple locations (Brown *et al.* 2001, Varley *et al.* 2004a, Varley *et al.* 2004b). Such techniques are particularly valuable in processes where foams cannot easily be visualized, for example, foam formation in bioreactors (Phianmongkhol and Varley 1999, Brown *et al.* 2001). However, measurement and analysis of conductivity profiles has not been investigated to determine the appropriate drainage properties in biological foams.

This study focused on the development of a systematic methodology for the characterization of foam drainage rate, regime and stability by an electrical resistance measurement technique. Data were compared with existing drainage studies using other measurement techniques and validated by two types of drainage experiments based on the foam drainage model. Application of a new method developed using specific multi-point probes revealed new knowledge about liquid variations of difficult-to-measure within biological foams and comprehensive description of foam stability in anaerobic digester systems.

2. Literature Review

2.1 Biological Foaming in Wastewater Treatment Plants

2.1.1 Overview of Wastewater Treatment Process

Municipal wastewater has four primary components: domestic wastewater, industrial wastewater, infiltration and inflow to the sewage system. Standard practice for municipal wastewater treatment includes primary, secondary treatment, and the treatment of sludge that is generated by wastewater treatment (Figure 2-1). The influent wastewater is fed to a primary sedimentation basin to remove settable solids. The primary effluent runs continuously into the aeration basin together with return activated sludge (RAS) in order to sustain a certain biomass concentration. In the secondary treatment, biodegradable organic matter and suspended solids (SS) are significantly reduced by aerobic microbial degradation. An activated sludge that contains a variable and mixed community of aerobic microorganisms in common uses for the treatment of municipal wastewater. Afterwards, the activated sludge is sent to a secondary sedimentation basin for solid-liquid separation. The conventional sludge treatment process consists of a heated digestion tank and an anaerobic consortium. The input to the anaerobic digester is typically a mixture of settled materials from primary, secondary treatment and surface scums from sedimentation basins. Sometimes the digested sludge passes to the second reactor where the suspended material is allowed to settle and concentrate for more efficient disposal. The settled sludge is then dewatered to reduce the sludge volume.

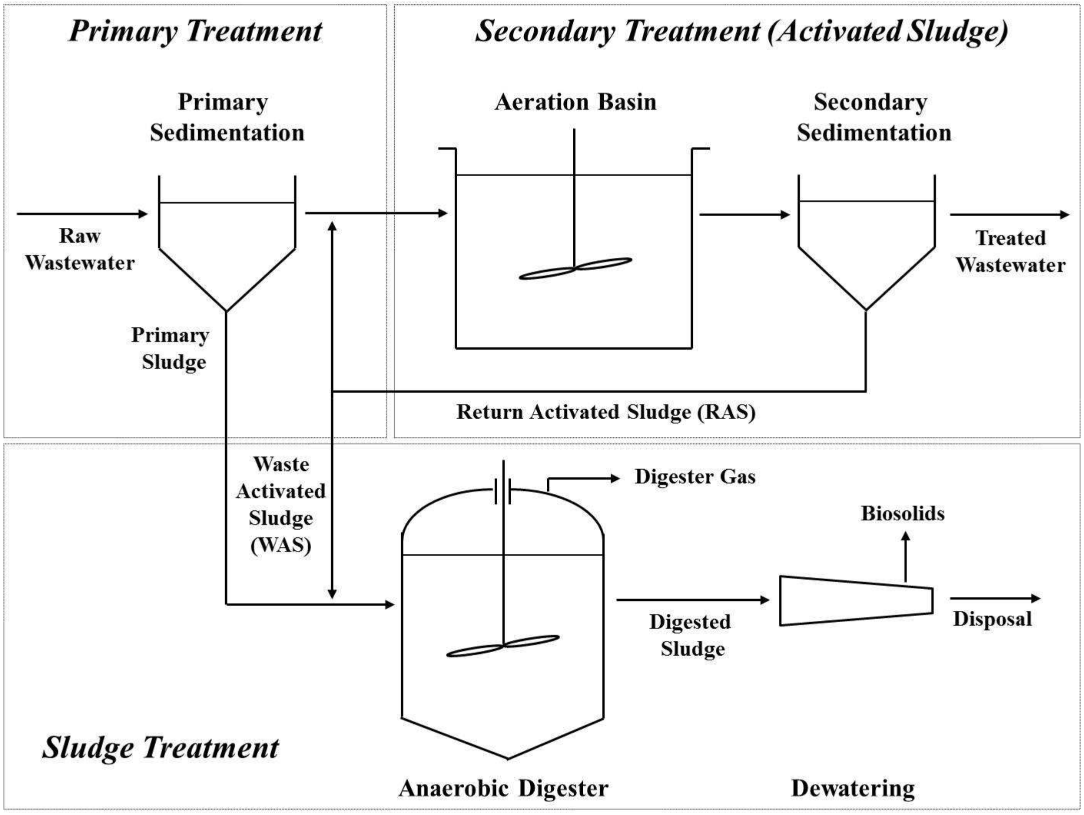

Figure 2-1 A schematic description of conventional wastewater treatment processes

2.1.2 Solids Separation Problems

Solid-liquid separation is one of the most important unit operations in wastewater treatment processes. Most activated sludge solids separation problems can be related to the nature of the sludge floc (Table 2-1). The flocs are usually small, spherical and compact, but can be sheared in the turbulent environment of an activated sludge aeration basin. When an activated sludge culture contains filamentous microorganisms, large floc sizes are possible because these organisms form a network or backbone within the floc. This backbone provides the floc with enough strength not to break up in the turbulent environment of the reactor. As indicated in Table 2-1, pinpoint floc may be related to filamentous organism levels, but filamentous bulking and certain types of foaming are mainly related to the presence of excessive amounts of filamentous organisms.

Table 2-1 A summary of major solids separation problems and nature of the sludge floc (modified from Jenkins (1992))

Name of Problem	Effect of Problem	Nature of Sludge Floc
Dispersed growth	No settling of sludge and high turbidity effluent.	Small clumps or single cells in dispersed state.
Pin floc or Pinpoint floc	Weak settling of sludge and a cloudy, turbid effluent.	Small, compact, weak, roughly spherical microflocs. Weak structure of macroflocs. Smaller aggregates settle slowly.
Bulking	Weak settling of sludge due to large buoyancy. Low RAS and WAS concentration.	Filamentous organisms extent from flocs into the bulk solution and interfere with compaction and settling of activated sludge.
Foaming / Scum formation	Foams with sludge solids on the surface of treatment units. Sometimes foams and solids overflow tank.	The presence of hydrophobic microorganisms and surfactants.

2.1.3 Foaming Caused by Filamentous Microorganisms

In biological foam, a three-phase system consists of gas, liquid and solid in the form of the certain types of filamentous microorganisms (Jenkins *et al.* 1993). Gas bubbles can attach to the particles and can lift the solids to the surface of the tank. This reaction is controlled by the hydrodynamics of the system and the degree of hydrophobicity of the particles. Particles that do not exhibit some hydrophobicity are reported to be incapable of successful flotation except by chance entrainment in the sludge layer on the surface (Gochin and Solari 1983). This appears to vary with culture conditions and sludge ages.

The main features of foam-causing filamentous microorganisms are aerobic, gram-positive filaments and hydrophobic cell surfaces due to the presence of long-chain lipids called mycolic acids (Mori *et al.* 1988, Blackall and Marshall 1989, Stratton *et al.* 1998). The cell wall of all validly classified members of the *Corynebacterineae* (a suborder of the order *Actinomycetales*) contains mycolic acids with long alkyl chains (Stach *et al.* 2004). Among the suborder *Corynebacterineae*, the first microbial isolates from scum layers in the activated sludge were classified as *Nocardia amarae* (Lecheval and Lecheval 1974) and was believed to be the most common filaments associated with activated sludge foaming (Blackall *et al.* 1988). Later, *Nocardia amarae* was reclassified as *Gordonia amarae* based on rRNA sequence information (Klatte *et al.* 1994, Blackall *et al.* 1995). As another member of the class *Actinobacteria*, *Candidatus Microthrix Parvicella* was identified as a predominant microorganism in biological foams worldwide (Blackbeard *et al.* 1986, Lemmer 1986, Seviour *et al.* 1990, Pujol *et al.* 1991).

2.2 Problems Associated with Foaming in Anaerobic Digesters

2.2.1 Description and Extent of Anaerobic Digester Foaming

Foaming in anaerobic digesters has been identified for over a decade with severe impacts on the overall digestion process (Hernandez and Jenkins 1994, Barjenbruch *et al.* 2000). Digester foams have been known to overflow floating covers on digesters, foul gas collection systems, and invert total solids (TS) profiles within digesters (Murk *et al.* 1980, Tetreault and Diemer 1987, van Niekerk *et al.* 1987, Ross and Ellis 1992). Some digester foams can form stable layers that occupy a significant volume of the digester (Hernandez and Jenkins 1994). In many situations, the presence of a substantial foam layer can lead to serious operating problems and a decrease in process efficiency (Ghosh *et al.* 1995, Pagilla *et al.* 1997, Ganidi *et al.* 2009). For example, useful biogas production was reduced to 40% for 10-weeks by digester foaming in the Henriksdal plant (Stockholm, Sweden) with a total loss in biogas production valued at approximately $150,000 (Westlund *et al.* 1998).

Surveys have been conducted to define the extent of the problem and to correlate various process parameters with foaming occurrence. A survey by the American Society of Civil Engineers reported that 11% of plant operators cited foaming as the most persistent anaerobic digester operating problem, with a half of all digesters surveyed having experienced foaming problems at one time or another (Filbert 1985). Similarly, van Niekerk *et al.* (1987) surveyed 26 wastewater treatment plants in California to determine the frequency and occurrence of digester foaming problems. Of the respondents, 54% reported intermittent or continuous anaerobic digester foaming. A nationwide survey of 114 U.S. activated sludge plants conducted by Pitt and Jenkins (1990) to quantify the extent of foaming found that 41 plants (36%) experienced foaming problems. The most recent survey of anaerobic digester foaming conducted by the Central States Water Environment Association (CSWEA) reported that 50% to 80% of anaerobic digesters have experienced intermittent or continuous foaming problems within the previous ten years (CSWEA 2011, Subramanian *et al.* 2012). These numbers clearly indicate that digester foaming is a major problem facing anaerobic sludge treatment facilities.

Foaming observations of full-scale anaerobic digesters were firstly reported at the Encina Water Pollution Control Facility (Carlsbad, CA) (Murk *et al.* 1980). In the fall of 1985, foaming was observed in the city of Winnipeg’s North End Water Pollution Control Centre (NEWPCC, Manitoba, Canada) primary anaerobic digesters (Ross and Ellis 1992). They indicated that high organic loading rates, short hydraulic retention times and high volatile acid concentrations were responsible for the periodic foaming events. Meanwhile, when the NEWPCC plant was modified from an activated sludge secondary process to pure oxygen activated sludge process, anaerobic foaming increased. In the middle of 1980s, experience at the East Bay Municipal Utility District (EBMUD, Oakland, CA) supported the finding that waste activated sludge containing *Gordonia* is a key factor related to digester foaming (Tetreault and Diemer 1987, van Niekerk *et al.*

1987). The presence of excessive levels of *Gordonia* in the feed sludge increased the surface depth of the foam layer at the full-scale anaerobic digesters of Sacramento Regional Wastewater Treatment Plant (SRWTP, Sacramento, CA). The Oceanside Water Pollution Control Plant (OSP, San Francisco, CA) experienced the accumulation of *Gordonia* species in the mixed liquor during the summer of 2001, which was associated with substantial foaming in the egg-shaped digesters (Jolis and Marneri 2006). Other recent studies at biogas plants in England (Ganidi *et al.* 2009) and Germany (Moeller *et al.* 2010) also reported that digester foaming significantly impacts process efficiency and operational costs.

2.2.2 Primary Causes and Factors

a. Biogas Bubbles

Foams generated within anaerobic digester sludge are comprised of thousands of tiny bubbles of methane and carbon dioxide. If these bubbles rise and accumulate at the sludge surface faster than they decay, foaming occurs (Vardar-Sukan 1998). The amount of methane gas produced under anaerobic conditions is 0.35 L CH_4/g COD, however, a variety of factors affects the rate of digestion and biogas production (Metcalf & Eddy 2003). Higher gas production rates have been associated with increased foam formation in the reactor (Varley *et al.* 2004b). The key process conditions for gas bubble formation include gas production rate, gas composition, mixing method, and speed of agitation. At a more fundamental level, the number of bubbles and the bubble size distribution will have an important effect on foam properties. Mixing is critical to avoid the creation of dead zones, which reduces the active volume of the digester, and also affects bubble formation and size.

According to van Niekerk *et al.* (1987), fine bubble gas mixing of anaerobic digester contents produced more foams than coarse bubble mixing or mechanical mixing. Pagilla *et al.* (1997) also stated that a gas-mixed digester is more prone to foaming than a mechanically-mixed digester under similar conditions. This conclusion indicated that a gas-mixed digester provides greater foaming potential. Results from Scardina and Edwards (2006) showed that excessive mixing increases the amount of bubbles in the bulk phase, and thus leads to the foaming potential of the sludge samples. Decreasing the amount of bubbles and increasing the bubble size reduced the ability of the hydrophobic particles (foam-causing microorganisms) to be enriched at the gas-liquid interface (Wozniak *et al.* 1976).

b. Surfactants

Surfactants are employed in large quantities in household and industrial applications and as a result end up in domestic and industrial wastewater treatment plants. The average concentration of surfactants in the influent ranges from 10 to 20 mg/L for domestic wastewater and can be as high as 300 mg/L in industrial wastewater (Shcherbakova *et al.* 1999, Scott and Jones 2000). Surfactants can affect the operation of activated sludge plants by enhancing foam formation in the aeration basin and reducing the settling properties of sludge flocs (Therien *et al.* 1984). The non-biodegraded or partially degraded surfactants fed to the anaerobic digesters and may enhance the foaming by stabilizing the liquid films in the foam. Foam formation is favored when a surfactant is present because the surface tension of the liquid is lowered.

Surfactants mainly consist of three classes: anionic, non-ionic, and cationic. Anionic surfactants represent the major component used and form about 41% of all consumed surfactants (Liwarska-Bizukojc and Bizukojc 2006). Linear alkylbenzene sulphonates (LAS), characterized as anionic surfactants, are the most frequently used in both domestic and industrial applications worldwide (Prats *et al.* 1997). Among the non-ionic surfactants, the most important are the linear alcohol ethoxylates (AE), and the alkyl phenol ethoxylates (APE). The quaternary ammonium compound, ditallowdimethylammonium chloride (DTDMAC), is a cationic surfactant used as a fabric softening agent and has been measured in wastewater influent at average concentrations of 0.6 mg/L (Sullivan 1983).

Since surfactants are adsorbed onto particles and organic matter of sludge or attached to suspended solids (Prats *et al.* 1997, Jensen 1999), 26% of surfactants are typically removed in the primary sedimentation basin (Feijtel *et al.* 1996). Unsettled common surfactants are easily biodegradable in activated sludge treatment plants, however, degradation is not always complete (Turner *et al.* 1985, McEvoy and Giger 1986, Langford *et al.* 2005). Due to the high degradability under aerobic conditions (> 99% of the LAS influent load) (Temmink and Klapwijk 2004), primary settled sludge will contain substantial surfactant concentrations and fed to the anaerobic digesters. The LAS concentrations in the feed sludge to the anaerobic digesters can range from 100 mg/kg to 30 g/kg (Petrovic and Barcelo 2004), and the degradation of anionic surfactants (LAS) was only 7% and 27% for non-ionic surfactants during anaerobic digestion. Owing to the low removal tendency of surfactants and the subsequent treatment of primary and activated sludge in a digester, non- or partially degraded surfactants can lead to increased surface activity and contribute to foaming events in anaerobic digesters.

Another type of surfactant affecting foam formation is bio-surfactants, which are considered to be metabolic intermediates that are eventually biodegraded by the microorganisms. It is widely believed that microorganisms release bio-surfactants when they use hydrophobic substrates (e.g., hexadecane) as their carbon source (Khan and Forster 1990, Lemmer *et al.* 2000). The readily biodegradable hydrophobic substrates could increase bio-surfactant production, and the foaming problems in activated sludge were due to a bio-surfactant produced by *Gordonia amarae* (Pagilla *et al.* 2002). Although bio-surfactants are also generally biodegradable in activated sludge, they contribute to foaming in anaerobic digesters (Ganidi *et al.* 2009).

c. *Hydrophobic particles (microorganisms)*

The concentration of foam-causing microorganisms (hydrophobic particles) in the sludge fed to anaerobic digesters is a significant factor in preventing stable foam production. It is clearly demonstrated that concentrations between 0.05 and 0.1 g *Gordonia* per g TS resulted in severe foaming in anaerobic digesters (Hernandez and Jenkins 1994). *Gordonia* populations are associated with various process control factors such as solid retention time (SRT), temperature and pH. Firstly, the SRT is the average time the biomass resides in the biological system and determines the types of microorganisms that can grow in the bioreactor. It is controlled by the amount of sludge wasted intentionally from the reactor. To alleviate foaming in activated sludge processes, it is possible to wash *Gordonia* out by operating at a sufficiently low SRT (for 24°C at an SRT of 1.5 d) in the absence of foam trapping and recycle. When this was done, *Gordonia* populations were much lower (Pitt and Jenkins 1990, Cha *et al.* 1992). As a foam control strategy, 44 of 114 activated sludge plants used SRT reduction with 73% of success rate (Pitt and Jenkins 1990). The SRT reduction could be the best approach for reducing activated sludge foaming, but may not be applicable to anaerobic digesters because decreased SRT increases sludge. Sludge surfaces were significantly more hydrophobic at higher SRTs (16 and 20 d) in the sequencing batch reactors (SBRs) (Liao *et al.* 2001), which could lead to stable foam formation in digesters.

The abundance of *Gordonia* decreases in the winter so that most *Gordonia* isolates did not grow below 15°C (Pitt and Jenkins 1990, Oerther *et al.* 2001, de los Reyes and Raskin 2002). On the other hand, the growth of *Microthrix parvicella* was reported to occur even below 10°C (Slijkhuis 1983) and the abundance of *Microthrix parvicella* increased during the winter (Knoop and Kunst 1998). However, during mesophilic anaerobic digestion (30-35°C), the growth of filamentous bacteria cells was not influenced by the temperature range (Soddell and Seviour 1995). A thermophilic digestion could be effective in foam minimization because both *Gordonia amarae* and *Microthrix parvicella* isolates were usually not able to grow at high temperature (45-122°C) (Marneri *et al.* 2009). The microscopic observation identified the more efficient destruction of *Microthrix parvicella* in thermophilic conditions and a reduced susceptibility to foaming (Dohanyos *et al.* 2004).

The control of pH in anaerobic treatment is critical because methanogens are extremely pH sensitive. Their activity is seriously inhibited outside the pH range of 6.5 and 7.5. Although the results are reported under aerobic conditions, the level of *Gordonia* was maximum around pH 6.5 (Cha *et al.* 1992). This influence was greater at the 8 d SRT, but a similar trend was evident in the data at an SRT of 3 d. They suggest that a change in pH from about 7.0 to 6.5 would result in an increase in *Gordonia* count of about 20%. In contrast to the active pH of *Gordonia* and *Microthrix parvicella* requires a pH value above 7.1 when grown under conditions below 15°C. It is possible that anaerobic digester foaming caused by filamentous bacteria can be mitigated by pH control.

2.2.3 Plant Operation and Foam Control

Anaerobic digesters experience two types of foaming problems (Pitt 1988, Hernandez 1994). The first type of foaming is associated with low levels of active biomass during start-up and is caused by the presence of partially degraded organic matter in the mixed liquor or digesting liquor. Start-up foams are usually transient and unstable, dissipating within a few weeks of their first appearance. The second type of foaming occurs in mature digesters. The surface tension may lower and foams generally have higher suspended solids levels than the liquids from which they were produced. As a result, foam generation in anaerobic digesters cannot be attributed to a single characteristic. Several approaches have been taken to control biological foaming in activated sludge process, which can contribute to anaerobic digester foaming.

Chlorination of RAS is the most common and effective method for *Gordonia* control (Blackall 1986, Pitt and Jenkins 1990). The main purpose of chlorination of the surface foam layer is to kill the *Gordonia* and break up the foam. Several researchers recommended that Cl_2 should be applied to the foam layer because, if applied to the mixed liquor, the high Cl_2 doses can reduce activated sludge viability and may impair treatment capacity (Neethling *et al.* 1987). The use of chlorine sprays on the surface of aeration basins has been successfully implemented at the 23rd Avenue Plant in Phoenix, AZ (Albertson and Hendricks 1992). In anaerobic digesters, the chlorination method was also applied to control the foaming caused by the presence of *Gordonia* in the feed WAS, but the average WAS foaming potential and foam stability was increased by the chlorination (Pagilla *et al.* 1998).

A pre-treatment of the feed WAS has the possibility to destroy the foam-forming microorganisms. A lab test has shown that heating of WAS (70°C, 5 min) reduces the ability to foam (Westlund *et al.* 1998). The surface foam layer is considerably reduced by thermal pre-treatment at 120°C for 60 min due to the decrease in the hydrophobicity of sludge (Barjenbruch *et al.* 2000). Recently, a pilot-scale thermal hydrolysis test of secondary scum was conducted to destroy *Gordonia* and to reduce its foaming potential (Jolis and Marneri 2006). They indicated that thermal hydrolysis (170°C, 30 min) is capable of more than a seven-log reduction in *Gordonia* sp.

Selectors have been most commonly used to control the filamentous microorganisms by reducing or selecting out (Chudoba 1985, Shao and Jenkins 1989). The purpose of a selector is to enhance the desirable organisms, and to reduce the growth of undesirable organisms. Anaerobic selectors were applied at both bench-scale and full-scale with moderate success (Pitt and Jenkins 1990). In laboratory scale activated sludge process at different SRT, the control of *Gordonia* was investigated by an aerobic selector (Cha *et al.* 1992). At the short SRT, the aerobic selector was successful in controlling *Gordonia* populations. A recent study showed that classifying selectors are an effective approach for foam control at full-scale (Parker *et al.* 2003).

Furthermore, various physical and chemical foam control methods have been developed and applied. A mixing technique had a major effect on foam formation (van Niekerk *et al.* 1987). Mechanical mixing did not produce foaming in anaerobic digesters, but fine- and coarse-bubble mixing produced a modest amount of stable foam. Other solutions to control foam include lower digestion temperature, installation of foam separators and water spray scrubbers (Ghosh 1991, Pagilla 1997). Chemical antifoam agents can be added on demand when the reactor produces vigorous foaming. A synthetic cationic conditioning polymer has been used to investigate the effect of chemical antifoams on foam formation (van Niekerk *et al.* 1987). The chemicals were added to the WAS before it was fed into the anaerobic digesters, but they did not have a significant effect on digester foaming. However, another study indicated that defoamant chemicals in laboratory-scale digesters worked well over certain concentrations (Ross and Ellis 1992). Westlund *et al.* (1998) reported that polyaluminium salt (PAX-21, 3-6 g Al/kg TSS·d) could be used as an antifoam agent for the foaming digesters. The foam was mechanically destroyed with a mixer installed above the sludge level in the foam phase of the digester and this work was successful. Unfortunately, the majority of the published studies in this area have not attempted to investigate the foam destruction mechanisms in the anaerobic digesters.

2.3 Measurements and Analytical Methods for Biological Foams

2.3.1 Overview of Foam Tests

Ideally, foaming tests should describe a parameter independent of the apparatus and procedure used, and only reflect the nature of the solution tested (Bikerman 1972). Foam measurement and quantitative characterization are important to obtain basic information about the extent of foaming problems. Several methods for quantifying the degree of foaming have been proposed (Sezgin *et al.* 1978, Matsui and Yamamoto 1984, Pretorius and Laubscher 1987, Ho and Jenkins 1991), however, no such standard method exists. These methods are probably the most objective measure for quantifying the amount of foam formed in the bioreactor.

Two major parameters are widely used to characterize the typical properties of foams. Foaming potential is a measure of how easily a liquid foams, the foaming ability of a liquid and the factors that help to attain immediate foam stabilization. Foam stability is a measure of the foam persistence and depends on factors that lead to its breakdown and collapse.

2.3.2 Modified Aeration Method

Different types of foam tests based on the aeration method have been developed to measure the foaming potential of a particular sludge sample under reproducible laboratory conditions. The test procedures differ in the gas production method and the measurement scales. For activated sludge, Pretorius and Laubscher (1987) suggested the use of a Scum Index (SI), calculated as follows:

$$SI(\%) = \frac{biomass\ levels\ in\ foam}{total\ biomass} \times 100$$

The portion of biomass in foam is determined by fractionary flotation at a standard aeration rate of 10 L/hr for 15 min during which time a thick stable scum layer formed. SI values an the corresponding foaming extents observed in practice are shown in Table 2-2 (Pretorius and Laubscher 1987).

Table 2-2 Arbitrary comparison of scum index with the extent of foaming problems

Scum Index (SI) (%)	Extent of Foaming Problems
0 – 0.5	Insignificant
0.5 – 6	Low
6 – 10	Moderate
10 – 15	Serious
> 15	Disastrous

The foaming potential and foam decay in sludge samples was examined after stopping aeration (Goddard and Forster 1987). A sample of sludge was aerated for 30 min using a fine bubble diffuser at airflow of 1.5 L/min. After this, air was turned off and the foam depth was measured 1 min later. The Foam Index was quantified from the calculation of the foam ratio (foam depth / original liquor depth) at suspended solids concentration of 3.5 g/L.

$$Foam\ Index_{3.5} = \frac{Foam\ ratio\ at\ 3.5\ g/L}{3.5} \times 100$$

Similarly, Khan and Forster (1990) measured both foam height and stability with a pneumatic system. The samples were aerated for 30 min and the foam height measured one or five minutes after aeration was stopped. They also expressed foam stability using an index defined by the time it takes for foam to collapse to 50% of its initial value (T_{50}). Their system allowed air at a controlled pressure and flow rate to be dispersed into the sample at a constant temperature. They concluded that this method would be less time-consuming than the Scum Index method proposed by Pretorius and Laubscher (1987) and more precise than the Foam Index proposed by Goddard and Forster (1987). The foaming test method developed by Blackall *et al.* (1991) used a scale that combined the foaming potential and the foam stability. A foaming apparatus consisting of a glass cylinder (500 mm high, 40 mm diameter) and a sintered glass disc (max. pore size 40-90 μm) was used with compressed air at 200 mL/min. Foam generation and stability of sludge samples were recorded in terms of foam volume, bubble size, speed of formation and time until foam collapse. A classification system to assess the foam was developed as shown in Table 2-3 (Blackall *et al.* 1991).

Ho and Jenkins (1991) conducted aeration tests with a 1 L graduated cylinder and air at a flow rate of 4 ft^3/hr through a sintered silica sand diffuser. Instantaneous foam heights were measured every 10 sec for 10 min, and the average foam height was determined at 5 min. For high solids samples such as digested sludge, the aeration method was used to determine foaming potential (Hernandez 1994). The sludge was diluted with warmed (37.5°C) distilled water to a TS concentration of 1.5 % and a final volume of 200 mL. The diluted sample was transferred to 1 L graduated cylinder containing an air stone (ASTM 1745), and sparged with N_2 gas at a flow rate of 1,600 cm^3/min for 90 sec. When the foam layer reached its maximum height, the volume of foam layer and foam height was measured.

Results obtained with the aeration test methods usually varying over a wide range. It is often unclear whether the variation is caused by the test procedure or by unknown sludge characteristics. A recent study showed that the evaluation of foaming potential for activated sludge was affected by aeration test conditions (Fryer *et al.* 2011). Based on a repeatability and coefficient of variation analysis in each case, the optimum operating conditions for the sintered disc method were determined to be a porosity of 40 to 100 μm (i.e., porosity disc size 2), an airflow rate of 0.5 L/min and a sludge sample volume of 150 mL.

Table 2-3 Classification of foams generated in the laboratory (Blackall *et al.* 1991)

Foam Rating	Description
0	Reaction to aeration as for pure water. Bubbles break surface but are unable to foam or have no stability.
1	1.0-3.0 cm of foam with fragile, ill-formed bubbles. Insufficient stability to form films. Immediate collapse on aeration being halted.
2	Intermittent films sufficiently stable to last for > 5-10 seconds. Usually generated from a fragile foam structure of limited height. Films unstable on aeration being halted.
3	Foam of some substance (i.e., bubbles about 1.0 cm diameter) to 3-8 cm height. Infrequent to regular film formation, with both film and foam semi-stable on aeration being halted. Films have 10-30 seconds stability.
4	Initially 8-15 cm of foam (about 1 cm diameter bubbles) with stable films being formed at regular intervals. Body of the foam and films stable for 3-5 min once aeration ceases.
5	Condition of stable foam 5-10 cm in height in 2 min, after which collapse to 3-5 cm height, which is stable when aeration is halted. No films.
6	Stable foam 15-30 cm in height with no films. Bubble size about 0.5 cm during production and only increases to 2.0-3.0 cm diameter in 3-5 min from time that aeration is halted.
7	Dense stable foam > 30 cm over 2 min aeration. Bubble size about 0.3 cm during production of foam and max. 1.0 cm diameter in 3-5 min after aeration is halted. Foam is sufficiently stable to show no change in height in 10-15 min after aeration is halted.

2.3.3 Alka-Seltzer^{TM} Tablet Method

In another foaming potential test method, two tablets of Alka-Seltzer^{TM} were added into a 250 mL aliquot of mixed liquor in a 500 mL graduated cylinder to produce fine gas bubbles (Ho and Jenkins 1991). Each tablet contains aspirin (324 mg), heat treated sodium bicarbonate (1,916 mg), and citric acid (1,000 mg). The foam potential was recorded as the maximum volume of the foam generated during the test. Foam stability could be calculated by noting the foam half-life. This procedure of foam stability was later applied to activated sludge samples by Oerther *et al.* (2001). The diluted sludge samples were placed into 500 mL graduated cylinders and two tablets of Alka-Seltzer^{TM} (sodium acetylsalicylate 650 mg, heat treated sodium bicarbonate 3,832 mg, and citric acid 2,000 mg; Bayer Corp., Elkhart, IN) were added. The volume of foam generated from the evolution of CO_2 gas was measured as the maximum volume of sample in the cylinder minus the initial 250 mL. They demonstrated that a Alka-Seltzer^{TM} based test successfully quantified filamentous foaming by microscopic observations. The MLSS concentrations affected the foaming potential and the relationship between the foaming potential and MLSS could be described by linearized power functions. However, the Alka-Seltzer^{TM} method is not suitable for use with sludge samples containing high MLSS levels such as digester sludge (Jenkins *et al.* 2004). In the Alka-Seltzer^{TM} tests, two crucial factors of uncertainty were introduced (Hug 2006). First, the gas production rate increases with increasing high temperature, particularly due to higher dissolution rate and lower solubility of CO_2, thus the foaming potential could be measured at different conditions. The other is that tablets can start to float during dissolution, resulting in uncontrollable reduction of the effective gas production rate. Fryer *et al.* (2011) improved the precision of Alka-Seltzer^{TM} method by using a wire cage. A galvanized wire cage with 10 mm square holes was constructed to contain the tablets and reduce their movements within the sample.

2.3.4 Microscopic Examination

The appearance of foam in activated sludge was thought to be correlated to large numbers of filamentous bacteria and even non-filamentous bacteria as constituting the predominant microbial populations in some scum samples (Seviour *et al.* 1990, Lemmer *et al.* 1998). To count nocardioform actinomycetes in activated sludge, pour-plate technique with a serial dilution was firstly used (Pipes 1978). Later, more simple method was developed for quantifying nocardioform, known as filaments counting technique (Vega-Rodriguez 1983, Pitt and Jenkins 1990). This technique counts all intersections with Gram-positive filaments of greater than 1 μm in length across a microscopic slide with three equally spaced lines (Table 2-4).

The filament counting technique is subjective because number of intersections may not accurately assess changes in biomass of the filaments. Filaments can also lose their Gram-staining properties when they are subject to more competitive and environmental stress such as anaerobic selector and anaerobic digesters, which makes their identification difficult (Cha *et al.* 1992, Hernandez *et al.* 1994). The use of molecular techniques may reflect some of these problems. An immunofluorescent method was developed to estimate the quantity and viability of *Gordonia* filaments in activated sludge and anaerobically digested sludge on both a mass and volume basis (Hernandez *et al.* 1994). Using this technique, the *Gordonia* content was found to average 18% of the VSS in a full-scale activated sludge system and for 13% of the VSS in completely mixed anaerobic digesters.

Table 2-4 Nocardioform filament counting technique of Pitt and Jenkins (1990)

Step	Procedure
1	Blend 400-mL MLSS or diluted RAS of known concentration for 2 to 3 minutes at low power in a blender
2	Prepare several (5 to 10) clean frosted microscope slides by marking the edges with a glass scribe at three equally spaced points along their length
3	On each slide place 80-μL blended MLSS using a micropipette. Spread the liquid evenly over the entire slide
4	Air dry the slides
5	Microscopically examine the slides at a magnification of 100, using phase contrast, to check for even MLSS distribution over the slide. Discard slides showing uneven distribution such as clumping, bare spots, or accumulation of solids along the slide edge
6	If less than five slides remain, repeat Steps 1 through 5 to obtain five satisfactory slides
7	Gram stain using the Hücker modification
8	Count five slides at 1000× using oil immersion and normal illumination
9	Use a microscope eyepiece graticule with a line ruled on it
10	(a) Locate the scribe mark on the slide edge (b) Line up the eyepiece line with the scribe mark on the slide (c) Count any intersection with the eyepiece line of Gram positive branched filaments of greater than 1 μm in length (d) Move across the slide to the opposite edge counting all intersections with the Gram positive filaments greater than 1 μm in length (e) Repeat steps (a) through (f) at the two other scribe marks on the slide (f) Average the number obtained for the three counts and express the results as “number of intersections/g VSS” (g) Repeat procedure (a) through (f) for four more slides
11	Calculation: Number of intersections/g VSS = (Average # of intersections/80 μL) × (10^6 μL/L) × (1/MLVSS (g/L))

2.4 Physical Mechanisms of Foam Formation and Stability

2.4.1 Fundamental Principles of Foam Formation

The foam that may accumulate on the surface of an anaerobic digester is a three-phase system containing gas bubbles (methane, carbon dioxide, and small amounts of other gases), liquid (water) and solid particles (suspended solids or microorganisms). A three-phase foam can maintain its configuration only when the arrangement leads to the lowering of the energy contributed by each of the three phases comprising the foam (Aubert *et al.* 1986). The energy of the foam includes the energy of the gas, the chemical energy of the surfactants in the liquid films that form the walls of the bubbles, and the energy of the surfaces of the films. The energy can be measured as internal pressure, surface tension, film elasticity, and surface viscosity. Among the three factors for foam formation, gas production (gas bubbles) alone does not result in anaerobic digester foaming in the absence of surfactants (Vardar-Sukan 1998, Ganidi *et al.* 2011).

2.4.2 Foam Structure and Related Parameters

Foams have a complex disordered structure, the elements of which are individual liquid films (bubble faces), meeting in Plateau borders (bubble edge) (Figure 2-2) (Weaire *et al.* 1997). The Plateau borders are the regions between three touching bubbles. The nodes are junctions of at least four borders. Foam consists of bubbles compressed on each other and can be characterized by the liquid fraction (ε), which equals the volume of liquid (V_{liquid}) divided by the volume of the foam (V_{foam}). The liquid fraction is useful for distinguishing between dry and wet foams and for assessing the degree of packing. The liquid volume fraction may vary from less than one percent (dry) to around 35% vol. (wet). For low liquid volume fraction (dry foam), the bubbles are polyhedral, with slightly curved faces and well-defined edges. In the dry foam, the Plateau borders are narrow and extremely thin films of liquid separating the gas bubbles. Wet foams are generally characterized by nearly spherical gas bubbles, which are separated by relatively large amounts of liquid. These structures are best visualized as consisting of contacting soft spheres.

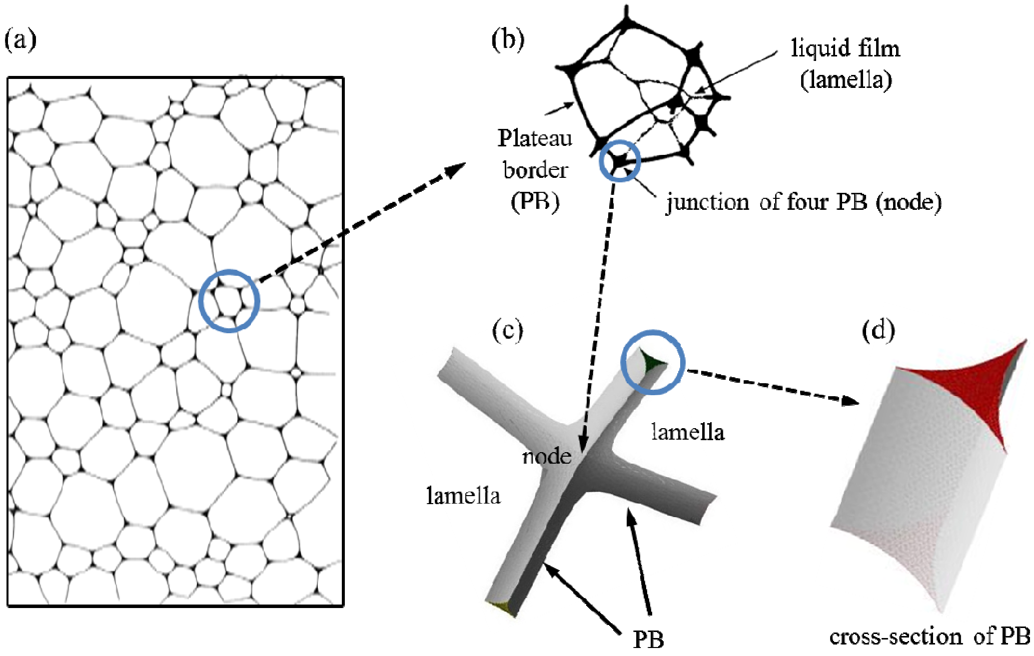

Figure 2-2 Foam elements of the network of channels in foam: (a) gas bubbles produced in the column, (b) shape and structure of the gas bubble, (c) four Plateau borders attached by a node, and (d) cross-section of a Plateau border with the three foam liquid films attached to it

2.4.3 Foam Drainage and Stability

One of the main characteristics of aqueous foams is that they irreversibly evolve in time: foams drain, coarsen, and finally completely collapse as the films between bubbles rupture (Weaire *et al.* 1997, Saint-Jalmes and Langevin 2002, Saint-Jalmes 2006). When foam is first formed, it is termed wet foam because the liquid film between the dispersed bubbles is relatively thick. As the foam matures, the liquid and gas in the foam tend to separate with time due to gravity and capillarity. Such liquid drainage leads to thinning of the films separating gas bubbles and to their eventual rupture (Figure 2-3).

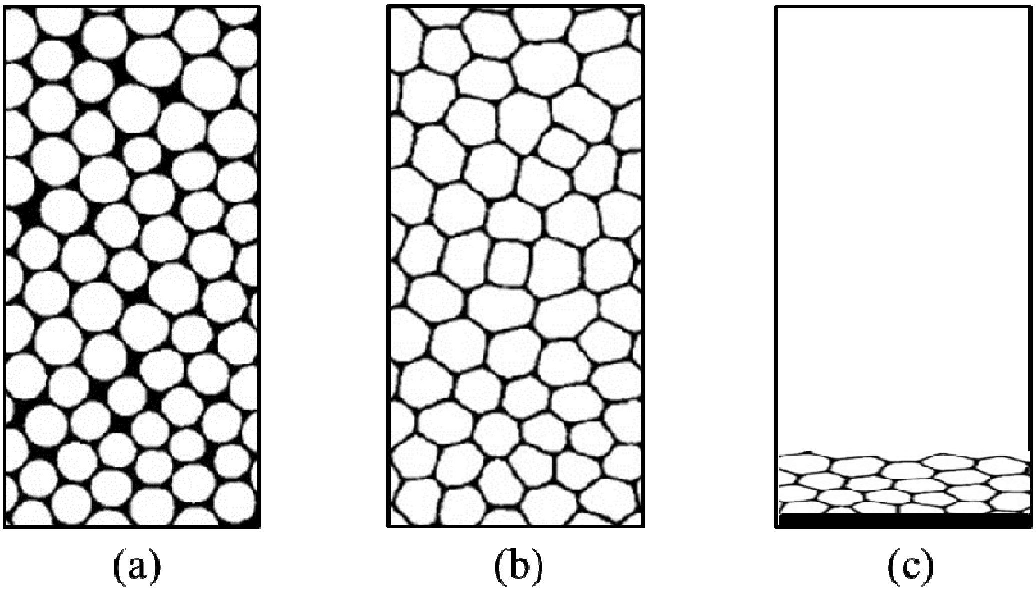

Figure 2-3 Two-dimensional disordered foams with different liquid volume fractions during the foam drainage: (a) wet foam (high liquid volume fraction), (b) dry foam (low liquid volume fraction), and (c) foam rupture and collapse (almost zero liquid volume fraction)

For any foam to be reasonably long lasting, the liquid phase must contain, in solution one, or more surfactants. The function of the surfactant is to stabilize the liquid films. A thin liquid film is formed around the biogas bubbles, preventing them from bursting (Figure 2-4(a)). Certain solid particles have hydrophobic properties that can attach to biogas bubbles formed during anaerobic treatment. They selectively partitioned into the foam trapping and carrying other solids or semi-solid particles with them (Mori *et al.* 1988, Hernandez 1994). These hydrophobic particles at the gas-liquid interface may create a bridge that impedes liquid drainage, and enhance foam stability (Figure 2-4(b)). Thus, drainage velocity is a major factor controlling foam stability and is often used as a diagnostic test.

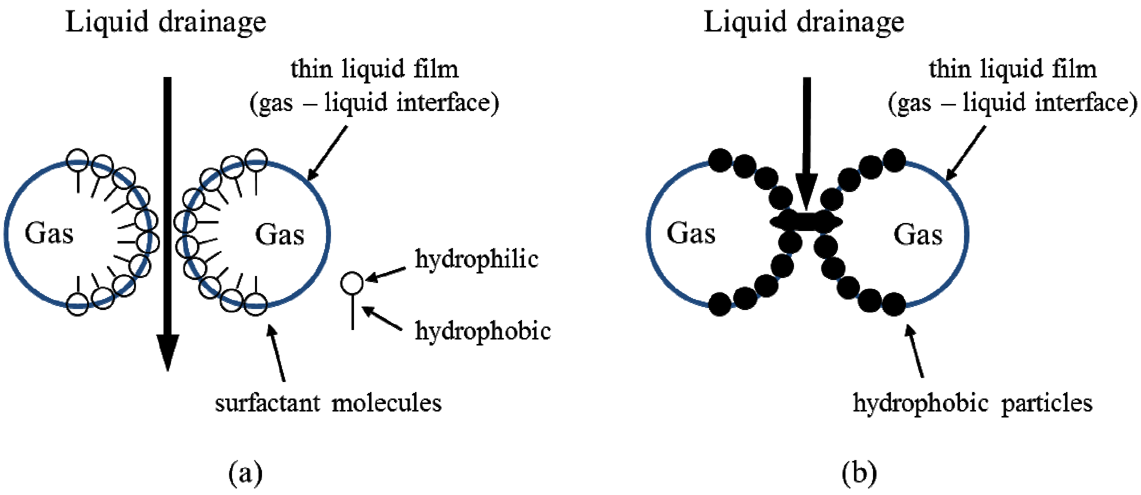

Figure 2-4 Physical mechanisms of foam formation and stabilization at the gas-liquid interface: (a) two-phase foam in the absence of particles and (b) three-phase foam in the presence of hydrophobic particles. Note that hydrophobic particles can bridge across the gas bubble and prevent drainage of foam liquid

Among the different stabilizing effects, the drainage plays a key role in the lifetime of the foam, as it irreversibly changes the foam's liquid content (Safouane *et al.* 2006). Foam drainage theory was pioneered by Leonard and Lemlich (1965). This theory describes the flow of a liquid through the Plateau borders, which are connected via nodes and form a network through which the liquid flows (Figure 2-5(a)). Macroscopic liquid drainage rates are inferred from microscopic flow descriptions at the scale of the elementary structure (a PB and a node). Drainage influences foam stability by thinning the liquid films between adjacent bubbles. The bubbles can then easily coalesce leading to foam destruction (Weaire *et al.* 1997, Stone *et al.* 2003, Neethling *et al.* 2005, Stevenson 2007). The main factors that influence the flow of foam liquids include mean bubble size, foam geometry, properties of gas and liquid phase, liquid volume fraction, and the physicochemical nature and concentration of surfactant and/or hydrophobic solid particles (Heller and Kuntamukkula 1987, Pagilla 1997, Neethling *et al.* 2002). A number of researchers have shown that the rate of drainage depends on the viscosity of the solution under the foam layer (Pugh 1996, Morey *et al.* 1999). In anaerobic digester sludge, an increase in the total solids contents resulted in an increase in sludge viscosity. Increased sludge viscosity can reduce the foam drainage rate and potentially result in the creation of stable foams (Goel *et al.* 2004).

Despite the complexity of fluid flow and bubble geometry, an overriding structure to fluid flow has been observed in many experiments (Koehler *et al.* 2004, Feitosa *et al.* 2005, Saint-Jalmes 2006, Carn *et al.* 2009). Conceptually, the macroscopic observation of liquid drainage of the standing foam (free drainage) is the most simple. Experimentally, the volume or height of liquid drained with time can be measured, but this requires a controlled and reproducible initial state. This means that the foam must be uniform with a constant liquid fraction all along its height. Such conditions are not easy to produce, especially for high liquid fractions. Furthermore, free drainage also requires long experimental times to follow the foam drainage to the final equilibrium state.

As opposed to free drainage, a forced drainage method turned out to be a simple and useful technique to study liquid transport in foams (Weaire *et al.* 1993, Saint-Jalmes 2006, Carn *et al.* 2009). The forced drainage experiment allows the rate of liquid drainage and the liquid fraction, which are directly related to the foam stability, to be quantitatively measured. The liquid drainage rates (v_f) could be measured in a wide range of injected superficial liquid velocity (v_s) and a power law relationship with $v_f \sim v_s^{\alpha}$ was determined both experimentally and theoretically (Saint-Jalmes *et al.* 2004) (Figure 2-5(b)). The drainage regime is determined by where the main hydrodynamic resistances to the liquid flow occur either in the PBs or in the nodes. The explanation of this behavior is given in terms of a transition between a node-dominated and a PB-dominated drainage regime, for which theory predicts respectively $\alpha = 1/3$ and $\alpha = 1/2$ (Durand *et al.* 1999, Safouane *et al.* 2001).

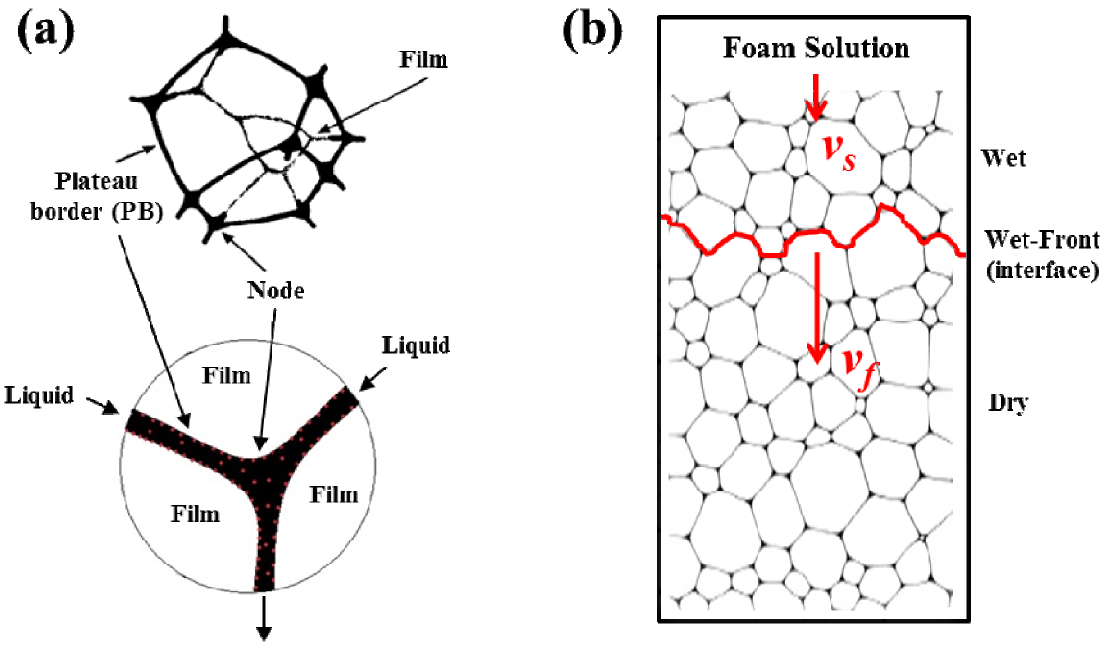

Figure 2-5 Schematic representation of the liquid flowing through the foam structure (a) microscopic descriptions in a single foam structure (a PB and a node) and (b) macroscopic drainage investigations (v_f) depending on injected liquid velocity (v_s) in a forced drainage experiment

2.4.4 Drainage Model and Boundary Conditions

A theoretical model of foam drainage focuses on gravity-driven flow through aqueous foams and describes the time and space evolution of the foam liquid fraction, ε (z, t) (Koehler *et al.* 2000, Saint-Jalmes 2006). The drainage equation is derived from averaging over the whole network of PBs and nodes. The foam is considered as a porous medium, but its permeability is not constant and is dynamically coupled to the liquid flow, unlike conventional porous media. Hence, the Darcy's law that relates the permeability (k) and the average front drainage velocity (v_f) through the foam is shown in following equation with permeability as an explicit function of $\varepsilon\,(z, t)$.

$$v_f = \frac{k(\varepsilon)}{\mu}\rho g$$

where μ is the bulk viscosity of foaming solutions, ρ is the liquid density, and g is the gravitational acceleration. The permeability of the porous medium (i.e., foam) to liquid flow is determined by the physicochemical properties of foaming solutions. A detailed derivation of a general expression for $k(\varepsilon)$ is presented in Koehler *et al.* (2000).

In the first limiting case (Figure 2-6(a)), assuming no-slip boundary conditions (less mobile) at the bubble surface, the liquid flowing inside the PBs is Poiseuille-like with high surface viscosity at the bubble surfaces and the permeability is $k(\varepsilon) = K_cL^2\varepsilon$. K_c is the dimensionless permeability number, which depends only on the PB (channel) geometry and L is the PB length. The front velocity is given by

$$v_f = \frac{K_c\rho g L^2}{\mu}\varepsilon = \left(\frac{K_c\rho g L^2}{\mu}\right)\cdot\left(\frac{v_s}{v_f}\right)^{1/2} = \left(\frac{K_c\rho g L^2}{\mu}\right)^{1/2}\cdot v_s^{1/2} = \tau\cdot v_s^{1/2}$$

In the second case (Figure 2-6(b)), assuming slip boundary conditions at the bubble surfaces, it is proposed that the main hydrodynamic resistance occurs in the nodes. The bubble surfaces are mobile, thus the surface velocity is non-zero, yielding another form for $k(\varepsilon) = K_nL^2\varepsilon^{1/2}$, leading to:

$$v_f = \frac{K_n\rho g L^2}{\mu}\varepsilon^{1/2} = \left(\frac{K_n\rho g L^2}{\mu}\right)\cdot\left(\frac{v_s}{v_f}\right)^{1/2} = \left(\frac{K_n\rho g L^2}{\mu}\right)^{2/3}\cdot v_s^{1/3} = \omega\cdot v_s^{1/3}$$

In node-dominated regime, K_n is a dimensionless number, describing the node permeability.

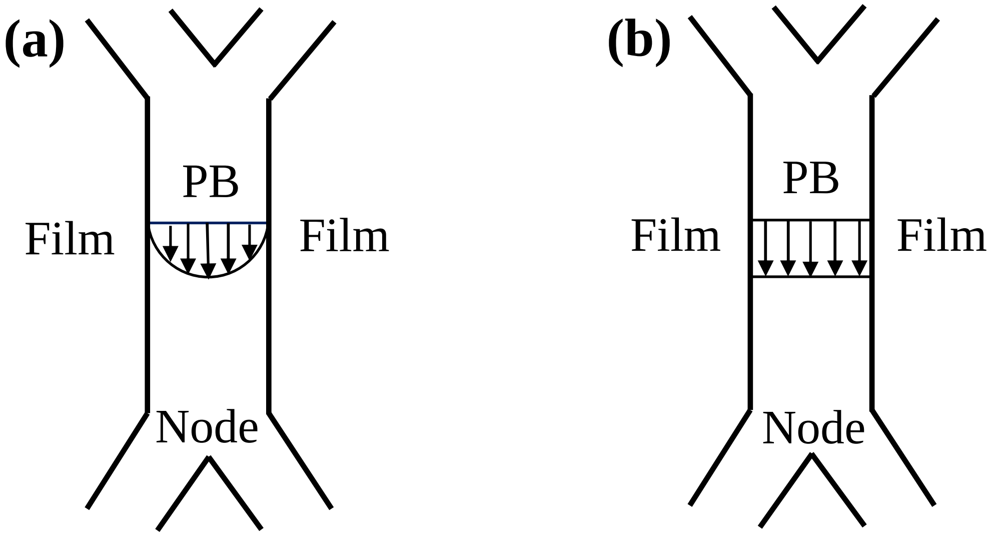

Figure 2-6 Liquid flow through the elementary foam structure: (a) PB-dominated drainage regime (high surface viscosity, zero surface velocity, and Poiseuille-like flow) and (b) node-dominated drainage regime (low surface viscosity, non-zero surface velocity, and plug-like flow)

In free drainage, we focused on the time variation of the liquid fraction within foams at multiple locations, which follow power laws: $\varepsilon(z) = t^{-\beta}$. The exponent β depends on the parameter $\chi = z/z_0\ (t_0/t)^{1/2}$ ($z = 0$ at the foam top) (Koehler *et al.* 2000). Here, z_0 and t_0 are the length scales and the typical time defined by $z_0 = C\gamma/2\rho gL$ and $t_0 = C\gamma\mu/2K_x(\rho g)^2L^3$. C is the constant, γ is the surface tension, K_x is the dimensionless parameter depending on the drainage regime: K_c for rigid surfaces and K_n for mobile ones.

$\varepsilon \sim t^{-2/3}$ for $\chi < 1$, $\varepsilon \sim t^{-1}$ for $\chi > 1$ (less mobile, PB-dominated)

$\varepsilon \sim t^{-1}$ for $\chi < 1$, $\varepsilon \sim t^{-2}$ for $\chi > 1$ (mobile, node-dominated)

In the transition range, the flow is in a single PB with interfaces that are neither perfectly rigid nor perfectly mobile.

2.5 Interfacial Forces Involved in Foam Drainage and Stability

Interfacial forces that arise in foam films confined between gas bubbles are critical to better understand the drainage properties and the stability. Numerous theoretical and experimental data indicate that the thermodynamic and kinetic properties of the liquid in thin films differ significantly from the properties of the bulk phase of the same solution (Khristov *et al.* 1993, Vilkova and Kruglyakov 2005, Kruglyakov *et al.* 2008). The classical Derjaguin-Landau-Verwey-Overbeek (DLVO) theory is commonly used to explain the stability of foams that related to the development of the thermodynamics of thin films (Lyklema and Mysels 1965, Exerowa *et al.* 1987). Later, Bergeron *et al.* (1993) identified discrepancy between DLVO theory and experiment, indicating that other forces such as hydrophobic force are also important in determining the stability of foam films, recognized as non-DLVO forces (Bergeron 1999, Sedev *et al.* 1999, Angarska *et al.* 2004). It is customary to assume that various contributions to the disjoining pressure that can calculated as the derivative of the Gibbs energy of interaction per unit area (Derjaguin 1936) are additive to express the interfacial forces in films (Bergeron 1999).

$$\Pi = \Pi_{el} + \Pi_{vw} + \Pi_{other}$$

where Π_{el} is electric double layer forces, Π_{vw} is van der Waals forces, and Π_{other} is other forces such as hydrophobic, hydration and steric forces.

The charged surface and the neutralizing diffuser layer of counter-ions form an electrical double layer. Due to the electrostatic repulsion, the counter-ions between two planar charge surfaces built up at each surface. The counter-ion concentration varies with distance, which can be calculated on the basis of Poisson-Boltzmann equation and Gouy-Chapman theory. An approximation for electrostatic forces between two planar surfaces is given by

$$\Pi_{el} = 64 C_{el} RT \Gamma_0^2 \exp(-\kappa H)$$

$$\Gamma_0 = \tanh\left(\frac{e\psi_s}{4kT}\right)$$

where C_{el} is the electrolyte concentration, R is the gas constant, e is the electric charge, ψ is the electrical potential, H is the film thickness, the Debye length (κ^{-1}) is given by

$$\kappa^{-1} = \left(\frac{\varepsilon_r \varepsilon_0 kT}{2e^2 N_A I}\right)^{1/2}$$

where ε_0 and ε_r are the permittivity of vacuum and the electric constant of water, respectively, and N_A is Avogadro's number. The Debye length decreases as electrolyte concentration (i.e., ionic strength in wastewater) increases, thus the electrostatic repulsion force reduces with increasing ionic strength in sludge liquids.

Van der Waals forces are always present between interacting planes. In foam films, they are attractive forces and depend on the geometry and nature of the surface interactions. For two parallel planes, the van der Waals disjoining pressure varies with the film thickness.

$$\Pi_{vw} = -\frac{A_H}{6\pi H^3}$$

where A_H is the Hamaker constant that expresses the non-retarded van der Waals interaction free energies based on pairwise additive (Hamaker 1937). For the symmetric case of two air phase (2) interacting across medium (3), the Hamaker constant A_{232} is within the order of 10^{-20} J for foam films.

The role of hydrophobic force in bubble coalescence was proposed, recognizing that gas bubbles are highly hydrophobic in view of high interfacial tension of air/water interface (72 mN/m) (Wang and Yoon 2006). In foam films, hydrophobic force may play a role, in which case the DLVO theory can be extended for the contributions of hydrophobic force (Yoon and Aksoy 1999).

$$\Pi = \Pi_{el} + \Pi_{vw} + \Pi_{hb}$$

$$\Pi_{hb} = -\frac{K_{232}}{6\pi H^3}$$

where K_{232} is the constant that can be directly compared with the Hamaker constant A_{232}. Hydrophobic particles present wastewater and their attraction forces associated with the surface interactions at the solid-liquid interfaces. The hydrophobic force may be two orders of magnitude higher than the van der Waals and electrostatic forces at short distances (< 2 nm) (van Oss 1994).

3. Research Objectives

The research objectives were to understand the fundamental principles of foam stability that are necessary to predict and control foaming in anaerobic digester systems. Even if the drainage of a variety of aqueous surfactant solutions has been investigated with experimental and theoretical studies in previous studies, extending these studies to include wastewater sludge is important for understanding the stability of three-phase foams, and therefore foaming in anaerobic digesters. In this study, the stability was considered on the basis of macroscopic drainage investigations, with the goal of developing a new method for determination of the liquid quantity that drains in the presence of anaerobically digested sludge. A multi-point electrical resistance measurement technique was used as a tool for the characterization of difficult-to-measure foam levels and liquid variations in wastewater treatment systems. Based on the foam drainage theory, a systematic methodology was introduced for the determination of drainage properties and a more detailed estimation of foam stability in various aqueous foams. As compared to existing drainage studies by other measurement techniques, our developed method was validated in the anionic surfactant foam column of large diameter. Several drainage experiments were conducted for the drainage properties of aqueous foams stabilized with sodiumdodecylbenzenesulfonate (SDBS), a commercial form of linear alkylbenzene sulfonate (LAS) that comprises the majority of anionic surfactants currently manufactured by the chemical industry and is the most frequently used in household detergents. To verify drainage regime, both forced and free drainage experiments were performed for SDBS foams, then application of a real-time electrical resistance measurement technique was used to understand foaming in anaerobic digesters.

The specific objectives of the study were:

- To develop a new method for measuring macroscopic drainage rates in two-phase and three-phase foam system
- To examine the macroscopic drainage rates and regimes by our developed method and to compare the results with previous techniques in the literature
- To validate a multi-point electrical resistance measurement technique and a methodology to characterize drainage behaviors
- To investigate the drainage regime of aqueous foams stabilized with SDBS
- To access the drainage regime of foams stabilized with anaerobically digested sludge and to investigate the properties of drainage behavior
- To estimate the surface mobility between bubbles in sludge-containing foams
- To determine the foam stability in terms of half-life time by a real-time foam measurement system
- To understand the role of sludge on the drainage and stability

4. Materials and Methods

4.1 Foaming Solutions

4.1.1 Anionic Surfactants

Sodium dodecyl sulfate (SDS) of high purity and sodium dodecylbenzenesulfonate (SDBS) were purchased from Sigma-Aldrich (St. Louis, MO) and were used as a foaming agent to represent common anionic surfactants. Although surfactants of biological origin are commonly implicated in anaerobic digester foaming, anionic solutions were used to provide reliable foam formation, but with a possible loss of similarity to real world foaming cases. In a typical preparation, an aqueous solution was prepared by dissolving powder surfactants in deionized (DI) water, followed by filtration through a 0.22 μm filter (Millipore Corp., Molsheim, France). A typical concentration was 1.2×10^{-2} mol/L (1.5 CMC) for SDS aqueous solutions, which is slightly above the critical micelle concentration (CMC) estimated at 8.2×10^{-3} mol/L (Bergeron and Radke 1992). To compare the existing results in the literature, concentrations of SDS were adjusted in the range of 8.2×10^{-3} mol/L (1.0 CMC) to 1.6×10^{-2} mol/L (2.0 CMC). The CMC of SDBS was equal to 1.2×10^{-3} mol/L (Carrier and Colin 2002), and this surfactant was particularly stable. SDBS concentration ranged 1.8×10^{-3} mol/L (1.5 CMC) for forced drainage and 1.2×10^{-2} mol/L (10 CMC) for free drainage to reduce coarsening effects.

4.1.2 Anaerobic Digester Sludge

Anaerobic digester sludge was taken from one of the full-scale anaerobic digesters operated by the Easy Bay Municipal Utilities District (EBMUD, Oakland, CA). In the wastewater treatment facility, WAS from the secondary clarifiers was pumped to the gravity belt thickener and then mixed with primary sludge prior to being fed to the anaerobic digesters. Sludge samples were collected in plastic containers and immediately transported to UC Berkeley for foaming tests. Collected digested sludge was mixed with prepared SDBS aqueous solutions at various concentrations to generate sufficient volume of foam. These sludge were diluted with warmed (37°C) deionized water to various TS concentrations ranged from 1.5 to 3.0%, if necessary, when we conducted both forced and free drainage experiments. All tests and analysis were performed within 24 hours of collection.

4.2 Batch Foaming Experiments

Prepared surfactant solution or mixture foaming solution (2 L) was transferred to an ethanol washed and dried plastic container fitted with an air stone centered at the bottom, and injected with nitrogen or carbon dioxide gas at a controlled flow rate of 4 ft^3/hr. The input of nitrogen or carbon dioxide gas into the foaming solution produced foams along the height of a cylindrical test column with a diameter of 15.2 cm (6 in.) and a height of 1.0 m (3.3 ft.). With the aeration on, instantaneous foam heights were recorded every seven seconds until foam heights obtain one meter. Foam consists of large quantities of liquid and gas, making it possible to use changes of electrical resistance to measure foam behavior.

4.3 Multi-Point Electrical Resistance Measurement System

All experiments for the foam formation and the study of drainage were performed with a multi-point electrical resistance measurement system (Figure 4-1). This measurement apparatus consisted of a stainless steel electrode placed around the inner edge of the column, a multi-point foam probe placed at the center of the column, and a controller connected to the main body of the foam probe.

Foam probe and controller were developed by Charis Technology Ltd. (Maidstone, Kent, UK), and they allowed for continuous monitoring and recording of total foam heights and electrical resistance. The probe consisted of 16 electrodes at regular intervals (7.5 cm). When a voltage (1.0 V) is applied to the electrodes the response of electrical currents at each electrode was logged in a PC every seven seconds by the controller. It provided a conductance reading that can be converted to a specific conductivity (σ) by means of the following equation (Zahn 1979).

$$\sigma = \lambda \cdot \theta = \frac{\ln(b/a)}{2\pi l R}$$

where λ is the conductance (siemens), θ is the cell constant which is equal to the distance between electrodes divided by the cross-section area of electrodes, R is the resistance (ohms) ($1/R$ = conductance) and b, a and l are the diameter of column from probe center to wall (here 15.2 cm), the diameter of the probe (here 1.2 cm), and the length of each electrode (here 7.5 cm), respectively.

Each electrode is electrically isolated from all other electrodes during measurement, which effectively ensures that the lines of conductance measured are perpendicular to the electrode surface. The measurement region of the probe is a circular slice through the headspace region and the shape of the regions is maintained by the interaction of the electric field from each electrode with that from neighboring electrodes. This technique measured electrical resistance that can be converted into the conductivity at multiple locations along the foam column, allowing changes in foam composition to be monitored with time. Foam electrical properties were used to measure liquid variations in real-time and are applicable for practical monitoring of anaerobic digesters.

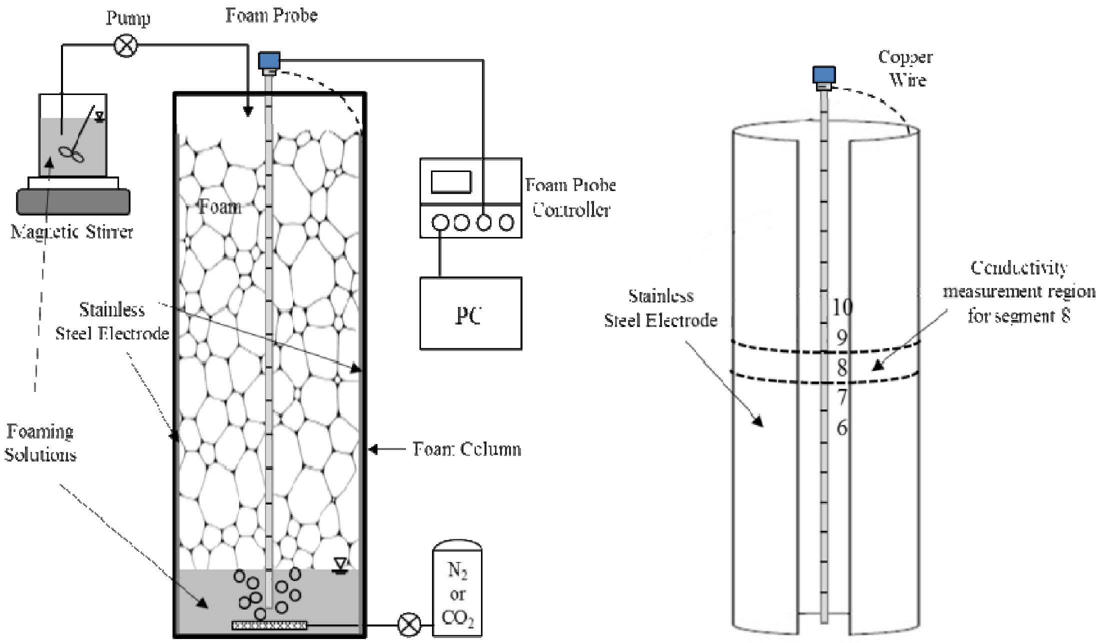

Figure 4-1 Schematic representations of a multi-point electrical resistance measurement system for characterization of foam development and its evolution for various foaming solutions

4.4 Foam Drainage Experiments

4.4.1 Forced Drainage Experiments

Forced drainage experiments were conducted to measure macroscopic drainage rates and to determine the drainage regimes in terms of the main hydrodynamic resistances to the liquid flow occurred either in the PBs or in the nodes. A series of forced drainage experiments were performed for the drainage properties of foams stabilized with anionic surfactants or mixtures of surfactants and digested sludge taken from full-scale anaerobic digesters. It allows for a more detailed estimation of foam stability in relation to its structure. The protocol for all forced drainage experiments comprised the following steps. First, a foam layer (80 cm) was prepared in the test column and was allowed to drain completely under normal gravity conditions to obtain a relatively uniform column of dry foam (typically liquid fraction $\varepsilon < 10^{-4}$). Once the foam was dry, the same foaming solution was added to the top of the column at a controlled flow rates (Q). As this solution migrated downward through the dry foam, a wet front traveled down the foam column at a steady velocity (v_f). The experiment was terminated when the wet front reached the bottom of the foam resulting in almost uniformly wet foam. Thus, the drainage front profile consisted of three regions: the drained region below the traveling wet front ($\varepsilon < 10^{-4}$), the transition region in the vicinity of the wet front, and the main body region with uniform liquid fraction. Electrical resistance, measured at multiple locations along the foam column, was used to follow the advancing wet front. This front propagated at a constant velocity (v_f) that can be estimated as $v_f = d/t_i$, where d is the known distance between two electrode segments (7.5 cm) and t_i is the average time it takes the front to migrate from one electrode segment to another.

The front velocity will depend on the injected superficial velocity (v_s) by mass conservation. Adding liquid for a time Δt at the top produced uniformly wetted foam behind the front spanning a volume ($v_f \cdot A \cdot \Delta t$) and the liquid fraction (ε) can be calculated as:

$$\varepsilon = \frac{Q \cdot \Delta t}{v_f \cdot A \cdot \Delta t} = \frac{v_s}{v_f}$$

With the theoretical works for the drainage (Chapter 2.4.4), experimental results can be also expressed as $v_f \sim v_s^{\alpha}$ or $v_f \sim \varepsilon^{\delta}$, where α and δ are fitting parameters. The PB-dominated regime ($\alpha \sim 1/2$) is characteristic of less mobile and solid-like surfaces, while the node-dominated regime ($\alpha \sim 1/3$) is characteristic of mobile and fluid-like surfaces. The regime type (PB- or node-dominated) is expected to influence foam stability.

4.4.2 Free Drainage Experiments

A free drainage experiment was conducted to improve the study of foam stability. Free drainage is the evolution of the liquid fraction of initially uniform foam of finite height. Foam dries first at the top, and a dry front propagates down through the foam, while the liquid emerges and accumulates at the bottom. The drainage dynamics were observed by the electrical resistance measurement system which allows to follow the liquid fraction as a function of time, $\varepsilon(t)$, in several points of the foam column. This provided the drainage curves of the liquid fraction in the foam at any time, which can be normalized by the initial liquid fraction (ε_0) obtained after complete foam formation. We presented the evolution of the liquid fraction over time at a fixed position in the foam, 10.0 cm from the top. Experimental results were expressed as $\varepsilon/\varepsilon_0 = t^{-\beta}$ (PB-dominated regime, $\beta < 1$, and node-dominated regime, $\beta > 1$).

4.5 Foam Stability Determination

Together with the drainage curves, we obtained continuous on-line profiles of total heights of the foam, then the foam stability could be characterized by its half-life time, defined as the time required for the foam to be reduced by half (Iglesias *et al.* 1995). The initial foam height was continuously decreased with time, thus the foam stability could be estimated by the time when the foam height reached its half height.

4.6 Relative Hydrophobicity

Relative cell hydrophobicity of anaerobically digested sludge samples was measured by the microbial adherence to hydrocarbons (MATH) test using hexadecane. This method is based on the degree of adherence of bacteria cells to various liquid hydrocarbons following a brief period of mixing (Rosenberg *et al.* 1980, Khan *et al.* 1991, Chang and Lee 1998). The sludge samples were placed in a 50 mL centrifuge tube, centrifuged at 3,000 g for 10 min, and washed with 0.1 M phosphate buffered saline (PBS) buffer (pH = 7.4 ± 0.1). In a 50 mL separatory funnel, 15 mL of hexadecane was added to 30 mL of washed sludge, and then agitated for 5 min. After allowing 30 min for the hydrocarbon phase to rise completely, the aqueous phase was transferred into other centrifuge tubes and measured suspended solid concentrations. Relative hydrophobicity could be calculated as a ratio of MLSS concentration in the aqueous phase after emulsification ($MLSS_f$) to MLSS concentration in the aqueous phase before emulsification ($MLSS_i$).

$$\text{Relative cell hydrophobicity (\%)} = (1 - MLSS_f/MLSS_i) \times 100$$

4.7 Total Solids (TS), Total and Volatile Suspended Solids (TSS/VSS)

Total solids (TS), total suspended solids (TSS) and volatile suspended solids (VSS) of all foaming solutions were measured according to Standard Methods 2540B, D and E, respectively (APHA *et al.* 1992). Sample volumes used were 2 mL of the prepared foaming solution. Glass filters (47 mm, type A/E glass fiber filters, P/N 61631, Gelman Sciences, East Hills, NY) were rinsed with deionized water, dried at 550°C for 1 h in a muffle furnace, stored in a desiccator until needed, and weighed immediately before use.

5. Results and Discussion

5.1 Multi-Point Electrical Resistance Measurement

Figure 5-1 presents the relationship between the relative conductivity and the liquid fraction of anionic surfactant (SDS) foams. Relative conductivity values were computed from electrical resistance measurement data obtained at multiple locations in the foam column. The error bars are the sample standard deviations. The liquid fraction was calculated according to equation discussed in Section 4.4.1 on page 38. This calculation was based on average values of the macroscopic drainage rate during the drainage through the foam column at individual injected superficial velocities. The lower detection limit for relative conductivity is 0.0017, corresponding to the liquid fraction of 0.0046. In a two-phase foam system, a similar relationship between the relative conductivity and the liquid fraction has been developed by Lemlich (1978). The following equation is particularly useful, as it requires only a measure of the relative conductivity for predicting the liquid fraction.

$$\varepsilon = 3 \times \sigma_r = 3 \times \frac{\sigma_f}{\sigma_l}$$

where σ_f and σ_l are the specific conductivities in the foam and bulk liquid phase, respectively. For our experimental setup, all parameters in equation (Section 4.3 on page 36) except λ were constant, and the relative conductance was therefore equal to the relative conductivity. The dotted line was fitted to Lemlich's equation in Figure 5-1 to demonstrate the capacity of continuous on-line measurements of the liquid fraction. The equation is only valid at lower values of liquid fraction ($\varepsilon < 0.1$) (Varley *et al.* 2004b) as the liquid remains largely in the PBs with the derivation of this equation (Lemlich 1978, Phelan *et al.* 1996). As the liquid fraction increases the relationship becomes sub-linear due to the increasing importance of nodes (Britan *et al.* 2009). For a wider range of liquid fractions, a simple empirical formula gave an excellent description of collected data (Feitosa *et al.* 2005), as shown by the nearly identical solid lines in Figure 5-1.

$$\varepsilon = \frac{3 \cdot \sigma_r \cdot (1 + 11 \cdot \sigma_r)}{(1 + 25 \cdot \sigma_r + 10 \cdot \sigma_r^2)}$$

When considering all the data conducted for SDS foams, the relative conductivity tends to be higher for our experimental data than for other two fitted lines. As the liquid fraction increases, particularly above approximately 0.007, there is closer agreement between some scatter in the data and the Lemlich equation. In free drainage, the variation of the liquid fraction along the foam column was computed from the Feitosa equation after the measurements of both the conductivity in the foam phase and the conductivity in the bulk liquid phase.

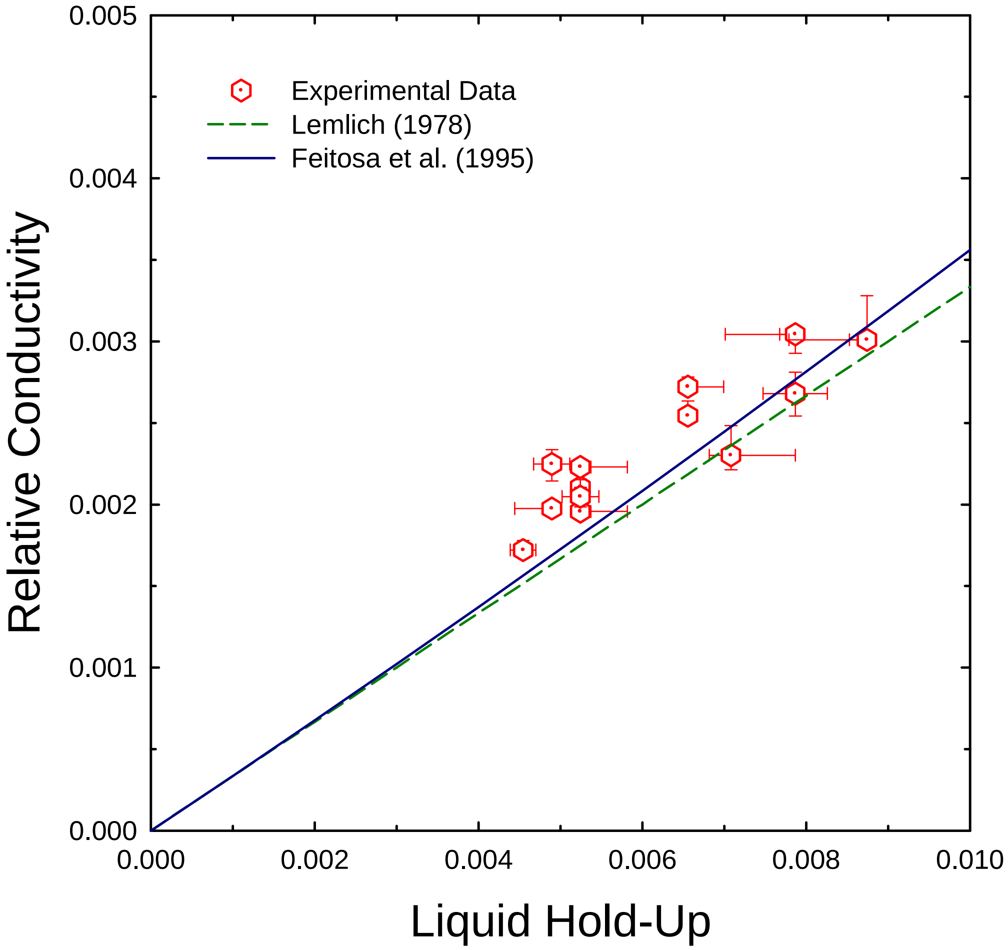

Figure 5-1 Relationship between the relative conductivity and the liquid fraction for anionic surfactant (SDS) foams. The liquid hold was computed from the macroscopic drainage rate obtained at individual injected superficial velocities during forced drainage experiments. The lower detection limit for relative conductivity is 0.0017, corresponding to the liquid fraction of 0.0046. The dotted lines were fitted to the Lemlich equation and the solid lines were fitted to the Feitosa equation

5.2 Macroscopic Drainage Observation

Electrode pairs located at multiple heights of the foam column measured the relative conductivity profiles with time (Figure 5-2). Foam was prepared and stabilized with sodium dodecyl sulfate (SDS) at the concentration of 1.2×10^{-2} mol/L (1.5 CMC). Nitrogen gas was added at a flow rate of 4 ft^3/hr. As the foam developed, the relative conductivity increased, reaching a maximum when gas input was terminated and the foam started draining. As expected, the relative conductivity was higher for electrodes closer to the bulk liquid surface during the foam formation. It could be visually observed that the relative conductivity varied with height, the foam being wettest at the bottom and driest at the top. The foam was allowed to reach a height of 80 cm before the gas was stopped, and then drained out until equilibrium was eventually reached between gravitational and capillary forces. In order to prepare the dried foam column, liquid drainage was continuously allowed until the relative conductivity had similar values at different heights along the foam column. The drainage rate's relationship to vertical location showed that drainage was fastest at the bottom of the foam column and slowest at the top. This observation can be attributed to the higher hydrostatic head at the top, which leads to more resistance to the liquid flow in the foam phase.

The forced drainage method allows an estimation of accurate liquid fraction of the foam. The relative conductivity profiles were enlarged for the forced drainage time in Figure 5-2 with the heights of 30.0, 37.5, 45.0 and 52.5 cm of the foam column (Figure 5-3). Once the added solution (9.37×10^{-4} cm/s) has passed each electrode the relative conductivity started increasing because the wet front traveled down the foam column, and in the limit of long times, approached an equilibrium state. This liquid fraction distribution becomes more and more uniform as drainage proceeds. The front moving down along the foam column did not spread out, but took the form of a solitary wave. This velocity is thus the same as the surface-averaged liquid velocity behind the wave and could be estimated as $v_f = l/t_i$, where t_i is the average time it takes the midpoint of the wet front to migrate from one electrode to another. This macroscopic front drainage velocity was measured in a series of experiments with different superficial velocities.

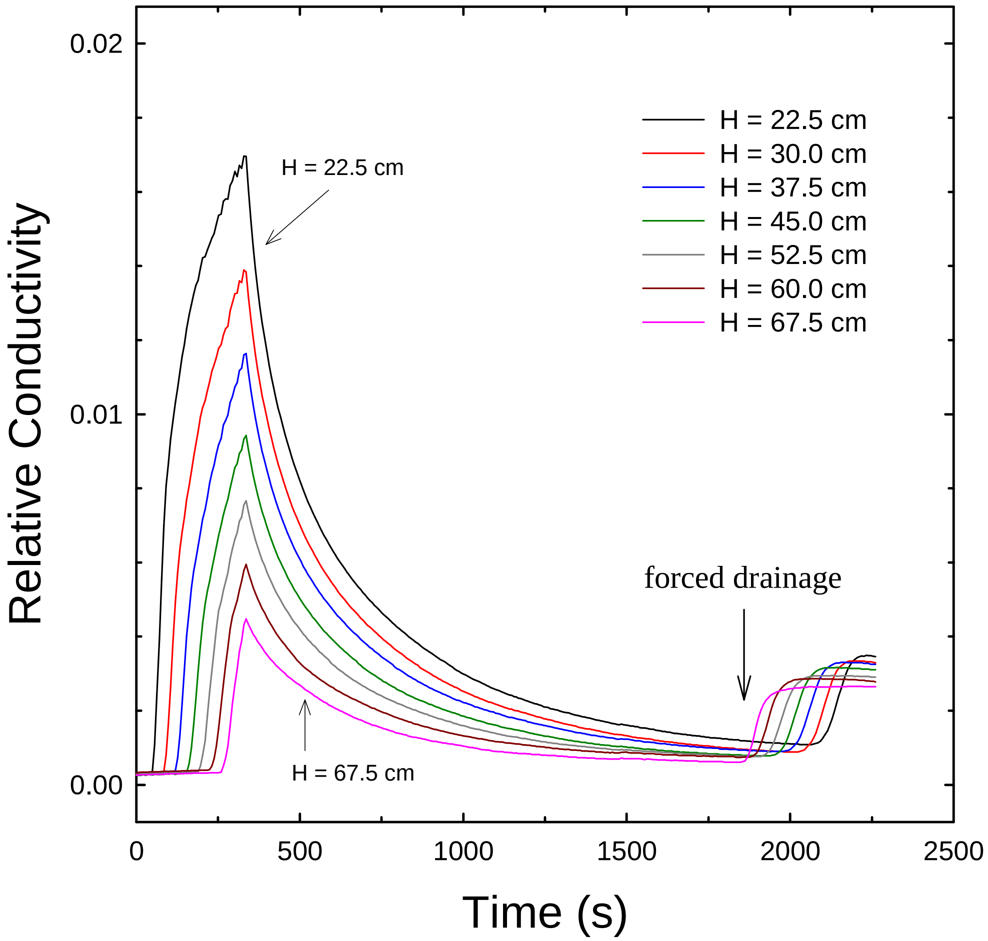

Figure 5-2 Representative relative conductivity profiles for foam probe electrodes from the bottom (*H* = 22.5 cm) to the top (*H* = 67.5 cm) during foam formation and forced drainage experiments

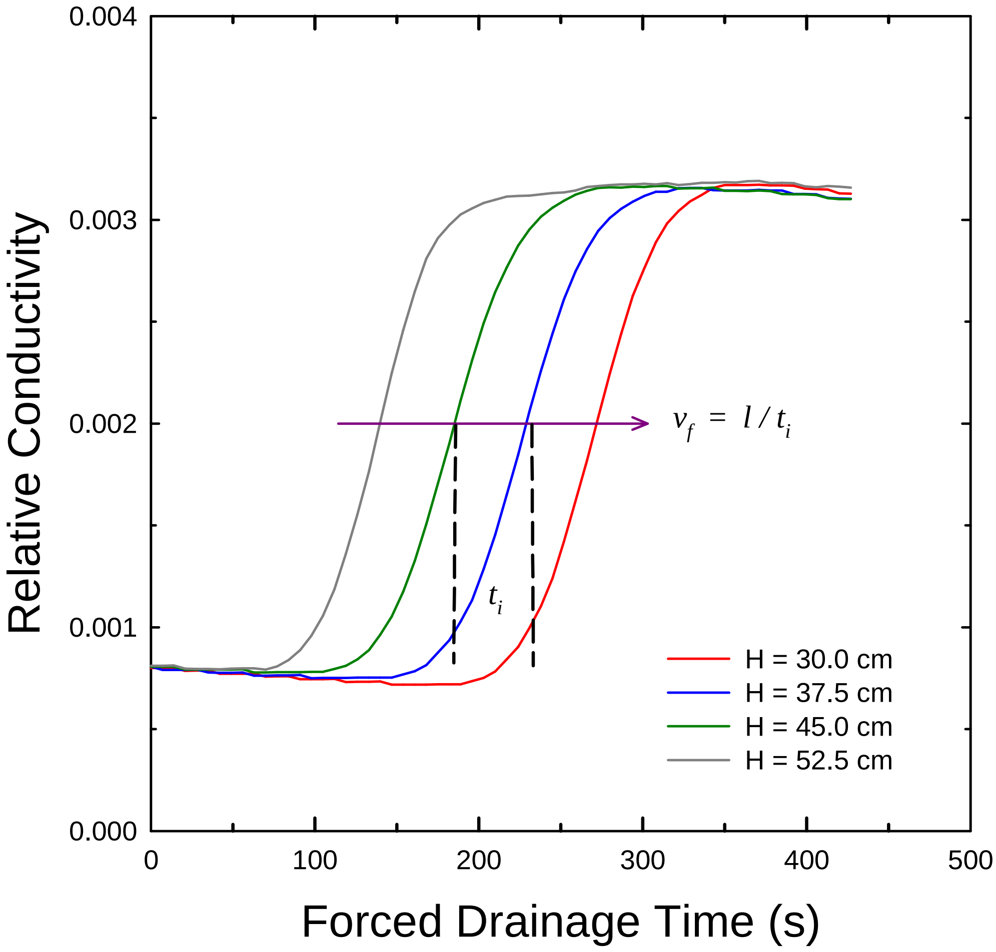

Figure 5-3 Representative relative conductivity profiles with time during forced drainage experiments. Average front velocity could be estimated as $v_f = l$ (=7.5 cm) / t_i through a series of drainage experiments with different superficial velocities for aqueous foam stabilized with sodium dodecyl sulfate (SDS) at the concentration of 1.2×10^{-2} mol/L (1.5 CMC). Superficial velocity was 9.37×10^{-4} cm/s

5.3 Method Validation

The capability of the technique was confirmed by the estimation of macroscopic drainage rates through a series of forced drainage experiments with different superficial velocities for aqueous foam stabilized with SDS. Simple surfactant foams were first tested at a range of injected superficial velocities. The concentrations of surfactant (SDS) solutions used in this experiments were 8.2×10^{-3} mol/L (1.0 CMC), 1.2×10^{-2} mol/L (1.5 CMC) and 1.6×10^{-2} mol/L (2.0 CMC), respectively. These values were selected to compare the performance of the drainage regime with the existing studies using other measurement techniques.

It was reported that a power law relationship between the front velocity and the superficial velocity was in a good agreement with experimental findings. We found that a simple power law yielded an exponent $\alpha = 0.35 \pm 0.04$ for 1.0 CMC, $\alpha = 0.38 \pm 0.03$ for 1.5 CMC and $\alpha = 0.30 \pm 0.04$ for 2.0 CMC, respectively (Figure 5-4). The power laws determined in this study were fitted to the foam drainage equation. Power-law relationships were analyzed by regression statistics with confidence level of 95%. P-values were less than 0.001 for all relationships. The estimated power laws as a fitting parameter indicated that the bubble surfaces are mobile, i.e. in the node-dominated, since the power-law exponent was close to its theoretical value ($\alpha = 1/3$).

The results obtained by the multiple light scattering techniques and the segmented capacitance sensors with two parallel plates were in good agreement with those used (Koehler *et al.* 2000, Vera *et al.* 2001, Neethling *et al.* 2005, Carey and Stubenrauch 2013). In two-phase foams, the electrical resistance measurement method developed in this work was validated, and thus could be used to characterize difficult-to-measure liquid variations and drainage rates within sludge foams, as the liquid flowing within brown foam is invisible. This method enables both real-time monitoring of and intervention in foam development.

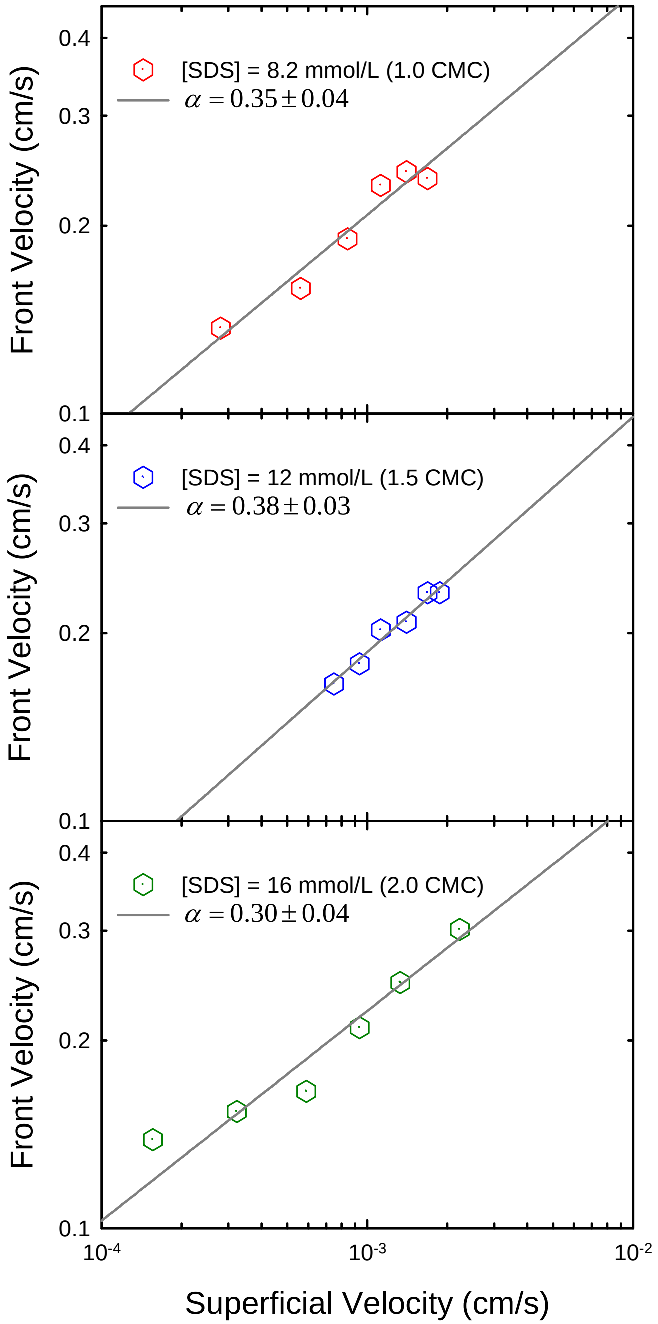

Figure 5-4 Relationship between the front velocity and the superficial velocity for aqueous foams stabilized with sodium dodecyl sulfate (SDS) at the concentration of 8.2×10^{-3} mol/L (1.0 CMC), 1.2×10^{-2} mol/L (1.5 CMC) and 1.6×10^{-2} mol/L (2.0 CMC), respectively. Each line indicated power-law relations with an exponent α

5.4 Drainage Behavior of Sodium Dodecylbenzenesulfonate (SDBS) Foams

Drainage regime of a column of draining aqueous foam stabilized with sodium dodecylbenzenesulfonate (SDBS) was characterized by both forced and free drainage experiments in which local drainage rates are measured by the electrical resistance technique. The SDBS is a commercial form of linear alkylbenzene sulfonate (LAS) that comprises the majority of anionic surfactants and is most frequently found in anaerobic sludge. Forced drainage experiments were carried out for the SDBS foam at the concentration of 1.8×10^{-3} mol/L (1.5 CMC). The variation of the front velocity with the superficial velocity of the injected fluid was investigated to determine the drainage regime (Figure 5-5). The data were fitted with power-laws over a range of almost two orders of magnitude of flow rates. The power-law exponent α (= 0.32 ± 0.05) was close to the theoretical value for the node-dominated regime, where dissipation mainly occurred in the nodes with the mobile PB surfaces.

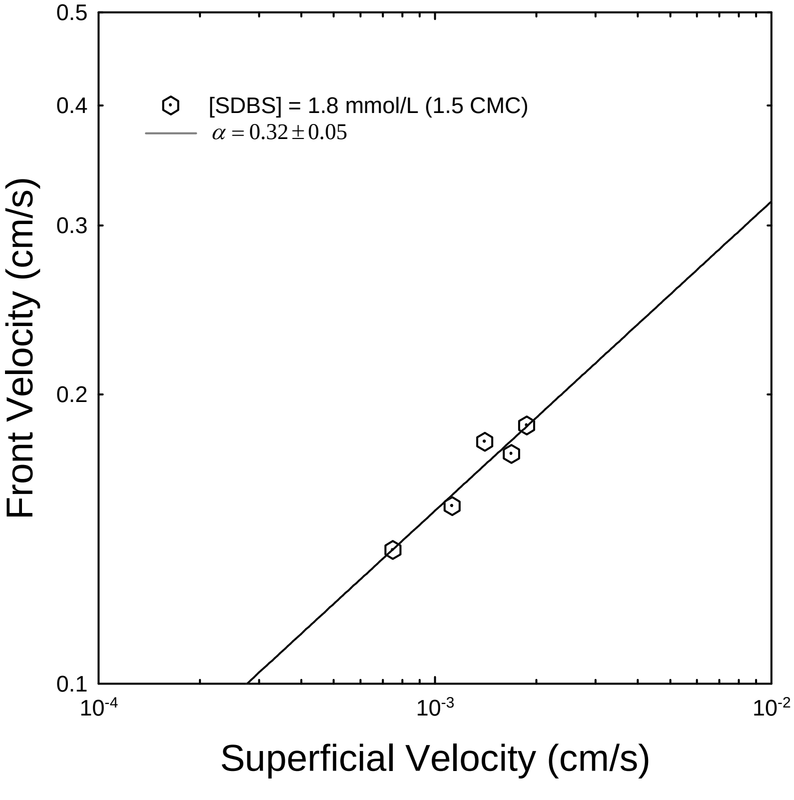

Figure 5-5 Relationship between the front velocity and the superficial velocity for aqueous foams stabilized with sodium dodecylbenzenesulfonate (SDBS) at the concentration of 1.8×10^{-3} mol/L (1.5 CMC). The line indicated power-law relations with an exponent α = 0.32 ± 0.05

Free drainage experiments were performed to verify the drainage properties (i.e. node-dominated regime) obtained from forced drainage experiments. At a concentration of 1.8 mmol/L, the forced drainage experiment presented a node-dominated drainage regime for aqueous surfactant foams. To validate the result obtained from forced drainage experiments, the same foaming solution was used in free drainage experiments. The evolution of the liquid fraction over time was followed at a fixed position in the foam, 10 cm from the top. The liquid fraction was calculated from the relative conductivity in Feitosa's empirical equation. The drainage curve could be normalized by the initial liquid fraction in foams (ε_0 = 0.002) obtained after the foam formation. Free drainage curves showed the power-law decay and the time scale on which power law behavior appears was of the order of 100 s (Figure 5-6). From the long time scale, the drainage regime can be determined from the exponent of a power law, $\varepsilon = t^{-\beta}$ discussed in Section 2.4.4 on page 30. The value of the exponent β was predicted to be 1.0 for low concentration of SDBS, evidencing the mobile surfaces in the PBs walls.

High concentrations of SDBS ([SDBS]/CMC$_{SDBS}$ = 10) were used to strongly minimize the coalescence-induced foam destabilization (Carn *et al.* 2009). At higher concentration, the liquid fraction was dramatically decreased after certain drainage times (Figure 5-6). This suggests that higher surfactant concentrations cause more stable foam for a long time, however the drainage regime was not changed with similar theoretical values of the power law exponent. The value of the power law exponent was estimated to be 1.4 for the SDBS concentration of 10 CMC and supports our expectation of high surface mobility in the PB walls during drainage. These results confirmed the previous experiment's results, showing that the node-dominated regime was found in forced drainage experiments.

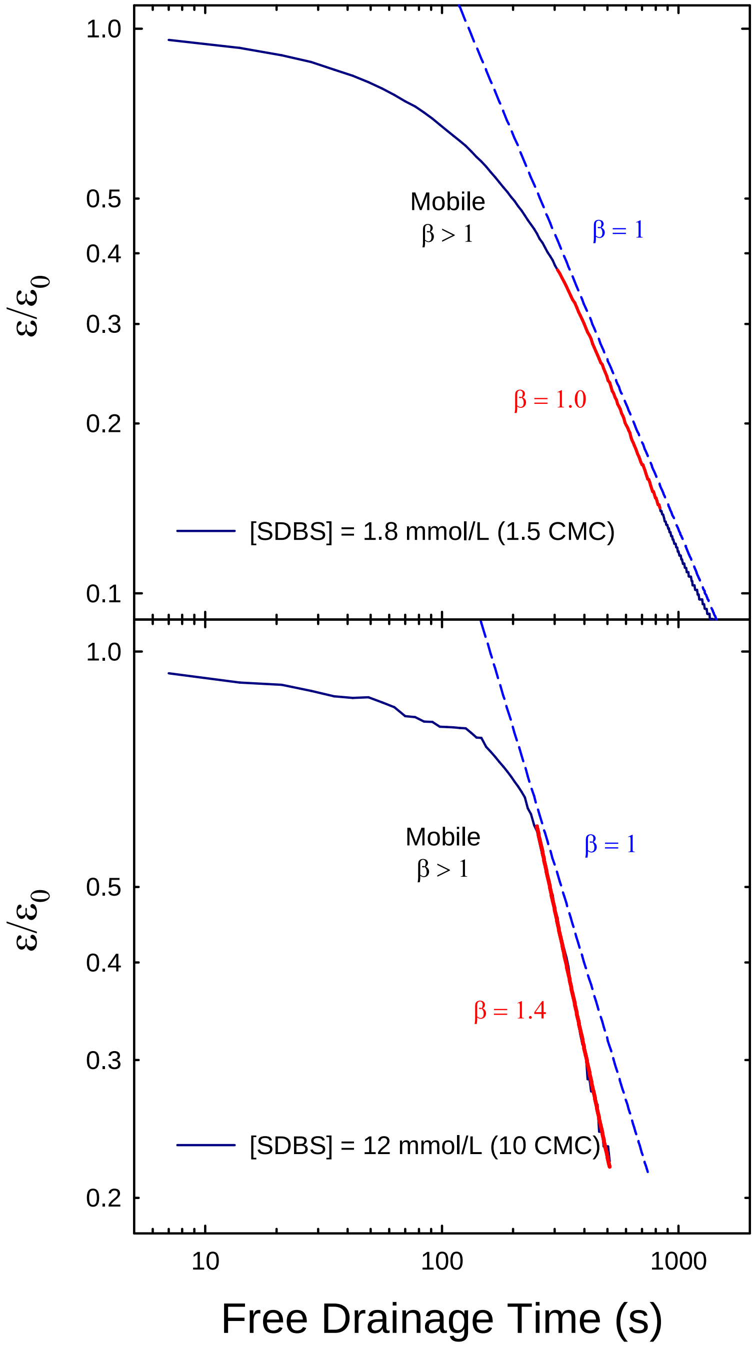

Figure 5-6 Normalized liquid fractions with free drainage time for aqueous foams stabilized with SDBS at the concentration of 1.8×10^{-3} mol/L (1.5 CMC) and 1.2×10^{-2} mol/L (10 CMC), respectively. Drainage curve corresponds to a fixed height, 10 cm below the top of the foam. The initial liquid fraction in foams was 0.002 and the exponent β was estimated to be 1.0 and 1.4, respectively

5.5 Foam Stability Determination

In the majority of studies where the drainage regime is predicted, no attempt was made to investigate foam stability. The time of rupture of half of the foam column, $t_{1/2}$, was commonly used to quantify foam stability. The initially produced foam column decayed to half of its height. The foam probe used in this study continuously measured the variation of total foam heights during the foam formation and drainage. The foam heights were plotted versus the corresponding elapsed time for the free drainage of SDBS foams (Figure 5-7). The concentration of SDBS was 1.2×10^{-2} mol/L (10 CMC) and the estimated $t_{1/2}$ was 33.6 min. The capability of this simple automated method to estimate the half-life time could be applied for testing and predicting of foams of extremely varying stability. The technique is relatively low-cost, easy to use, and is therefore useful for the study of foam drainage for both qualitative and quantitative description of various foaming systems, even bioreactors. However, important issues must be clarified for a complete understanding of the correlation between the drainage regime and foam stability.

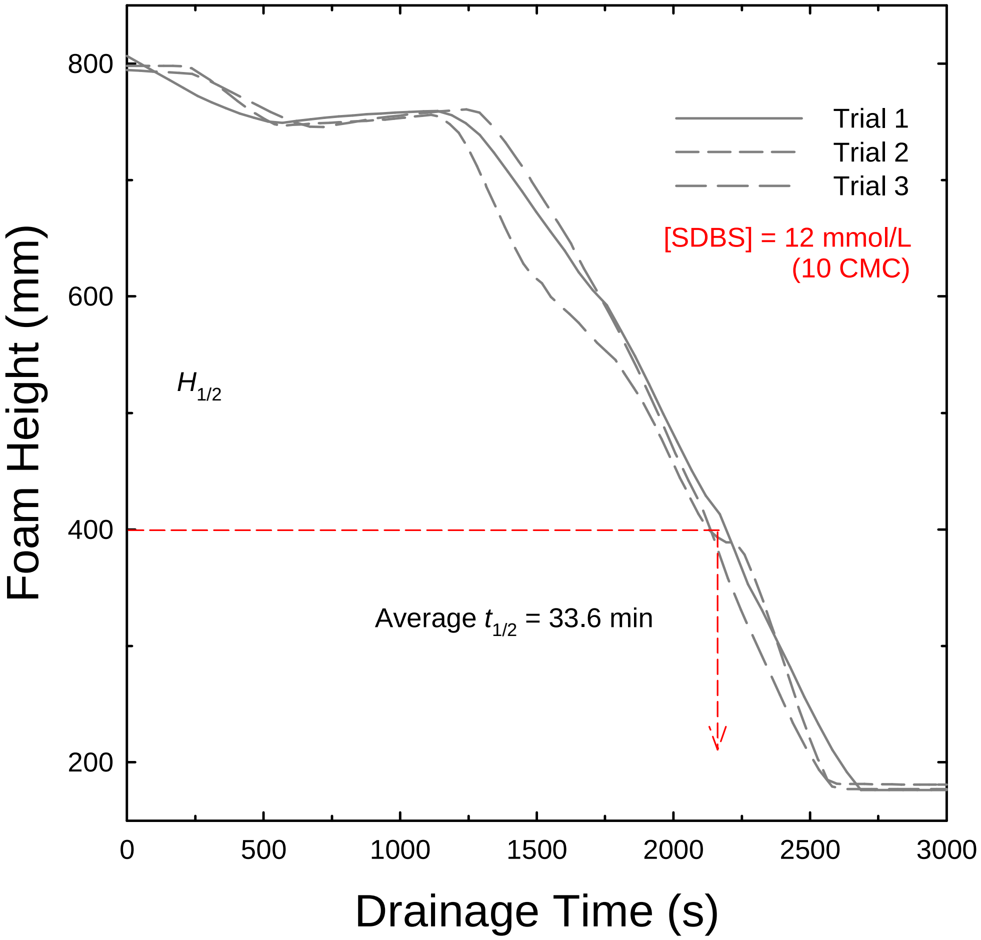

Figure 5-7 Representative variation of foam height with the corresponding elapsed time during free drainage of SDBS foams. Foam half-life time ($t_{1/2}$) was estimated when the height reached at half of initial foam height ($H_{1/2}$) and was around 33.6 min.

5.6 Drainage Behavior of Digested Sludge-Containing Foams

To ensure ability of the foaming, foaming solutions were prepared with mixtures of sludge samples and SDBS at different concentrations. Foam ability measures the maximum height of the foam column following a 15-minute injection of gas. Foam capacity was calculated from maximum foam height divided by total volume of gas injected over 15 min (Figure 5-8). Foam ability and capacity was significantly increased at the surfactant concentration of 2.9 mmol/L (2.4 CMC). Half-life time was also measured to estimate the stability, but foams were not stable when surfactants added up to the concentration of 1.4 mmol/L (1.2 CMC). All data were measured three times and presented average value of their measured data. Average total solid concentrations of digested sludge samples collected from the anaerobic digester ranged from 2.5 to 2.8%. Relative hydrophobicity of collected anaerobic sludge was ranged from 55 to 62%, indicating that the sludge has not a high foaming potential.

In forced drainage experiments, addition of anionic surfactants should be over 2.4 CMC to minimize coalescence effects of the drainage behaviors. Representative plots of relative conductivity profiles in the presence of anaerobically digested sludge are shown in Figure 5-9. General trends are similar to those for the pure surfactant foams as shown in Figure 5-3. The relative conductivity became more and more uniform at different heights as drainage proceeded. However, foam stabilized with anaerobically digested sludge was not completely uniform due to solid particles. In contrast to pure surfactant foams, the drainage rate was virtually constant and more scatter was observed in the sludge-containing foams. In the forced drainage experiments, the relative conductivity increased sharply when the wet front reached each electrode, however, the relative conductivity did not reach equilibrium at the final stage. Nevertheless, the front velocity can be estimated from midpoints of the conductivity jumps between the electrodes. These front velocities were measured in a series of experiments with different superficial velocities.

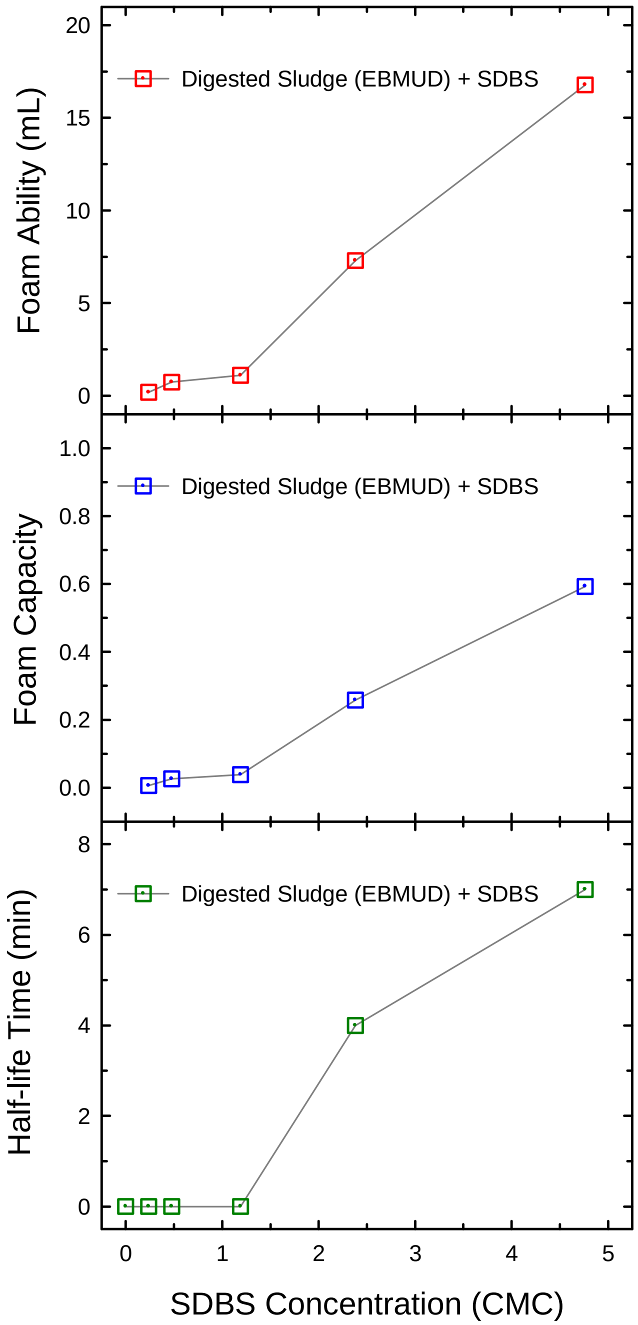

Figure 5-8 Foam ability, capacity and half-life time of foams stabilized with the mixture of digested sludge and SDBS at different concentrations

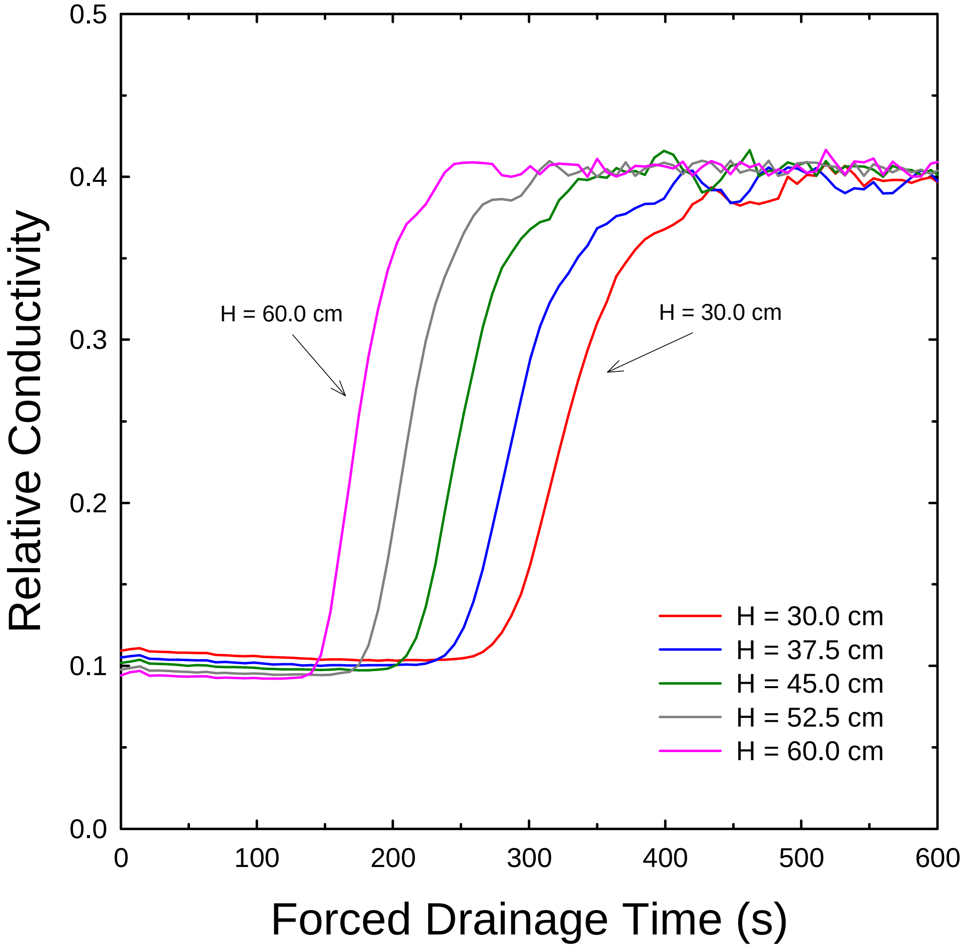

Figure 5-9 Representative relative conductivity profiles with time during forced drainage experiments. Average front velocity could be estimated through a series of drainage experiments with different superficial velocities for aqueous foam stabilized with the mixture of SDBS and anaerobically digested sludge. Superficial velocity was 1.37 × 10^{-3} cm/s

To assess whether surfactant concentrations prevented drainage of the anaerobically digested sludge foam, experiments were performed in which different concentrations of SDBS were mixed with sludge samples before the foam was formed. Power law relationships were similar in three sets of sludge samples with the significant difference in SDBS concentrations (Figure 5-10). In forced drainage experiments, TS concentrations for all foaming solutions were adjusted to 2.5% after the mixture with surfactants. A simple regression at a 95% probability level was applied to determine the power law exponent of the relationship between the front velocity and the superficial velocity. Power law exponents were different with pure SDBS solutions in the wide range of surfactant concentrations. The drainage regime was likely the PB-dominated because the power law exponent was close to the 1/2 of theoretical value in all experiments. Although power law exponents were not always fitted to the theoretical value, addition of sludge samples resulted in a transition of drainage regime from the node-dominated to the PB-dominated. Sludge solids may make bubble surfaces less mobile as surface viscosity increases.

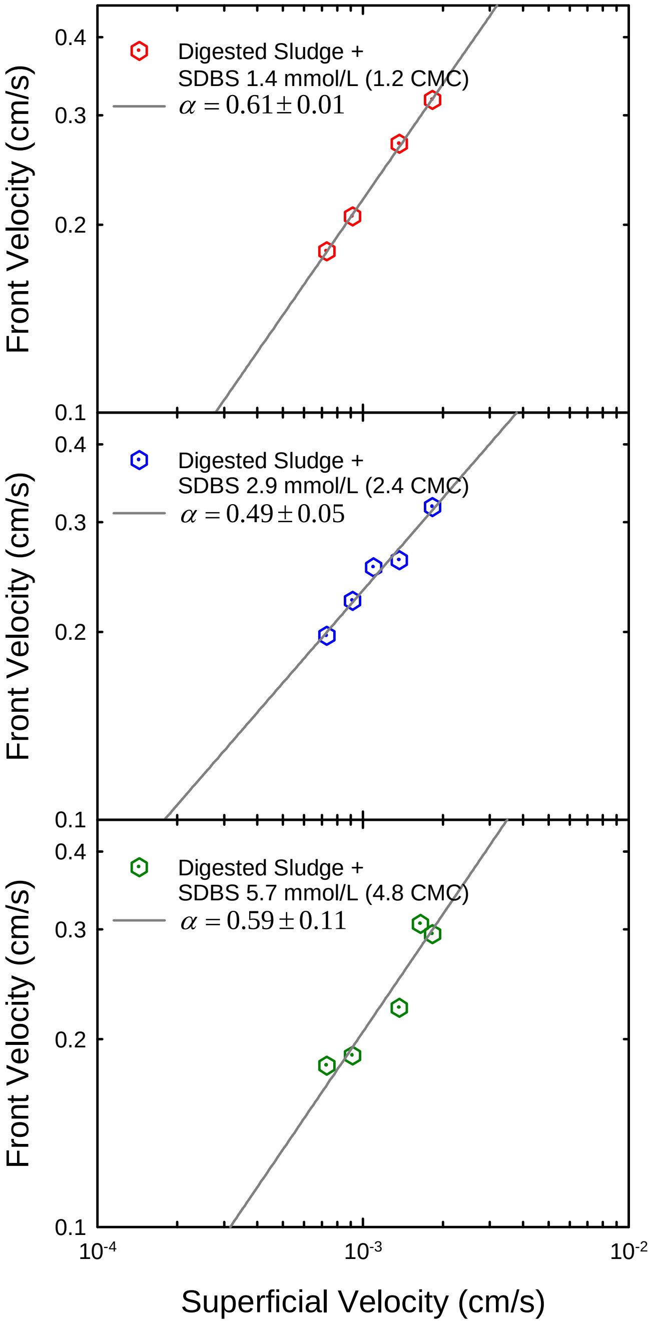

Figure 5-10 Relationship between the front velocity and the superficial velocity for aqueous foams stabilized with the mixture of digested sludge and sodium dodecylbenzenesulfonate (SDBS) at the concentration of 1.4, 2.8 and 4.7 mmol/L, respectively. Each line indicated power-law relations with an exponent α

To verify the PB-dominated drainage regime in the presence of anaerobically digested sludge, free drainage experiments were performed at different total solid concentrations of anaerobic sludge samples. In free drainage, total solid concentrations were adjusted in the range 1.4 to 2.8% by dilution with distilled water after collecting sludge samples. The power-law relationship between the liquid fraction and drainage time determines where the liquid mainly flows either in the nodes or in the PBs. The drainage curve corresponds to a fixed height, 10 cm below the top of the foam column. Normalized liquid fraction in lower total solid concentrations of sludge-containing foam resulted in a more rapid decrease during drainage (Figure 5-11(a)). When no digested sludge was diluted, the normalized liquid fraction still decreased with time, but much more slowly (Figure 5-11(b)). At the low total solid concentration (14,000 mg/L), they continued to decease throughout the duration of the experiment. Initial drainage rates were similar in both sets of drainage, but the exponent β is significantly different between the figures (Figure 5-11). Regression results of the relationship between the liquid fraction and time had an exponent of 1.11 for sludge-containing foams at low total solid concentration. The drainage regime within the foam is likely closely associated with high surface mobility because the exponent was over 1.0 of theoretical value (Section 2.4.4 on page 27). In contrast, a significant amount of sludge solids will prevent the drainage of liquid within the foam (25,000 mg/L), thus liquid fraction was more slowly decreased. The exponent of power law was approximately 0.44 which indicates PB-dominated drainage regime with low surface mobility between bubbles. This value indicated that sludge-containing foams were likely to behave in a PB-dominated drainage regime since the power law exponent obtained from both forced and free drainage experiments was close to its theoretical value. It also supports the hypothesis that sludge impedes liquid drainage and stabilizes foams. Typical total solid concentration of real anaerobic digesters is approximately 2.5-3.0%, so bubble surfaces would decrease their mobility caused by both surface viscosity and bulk viscosity of the foaming solution when a foaming occurs.

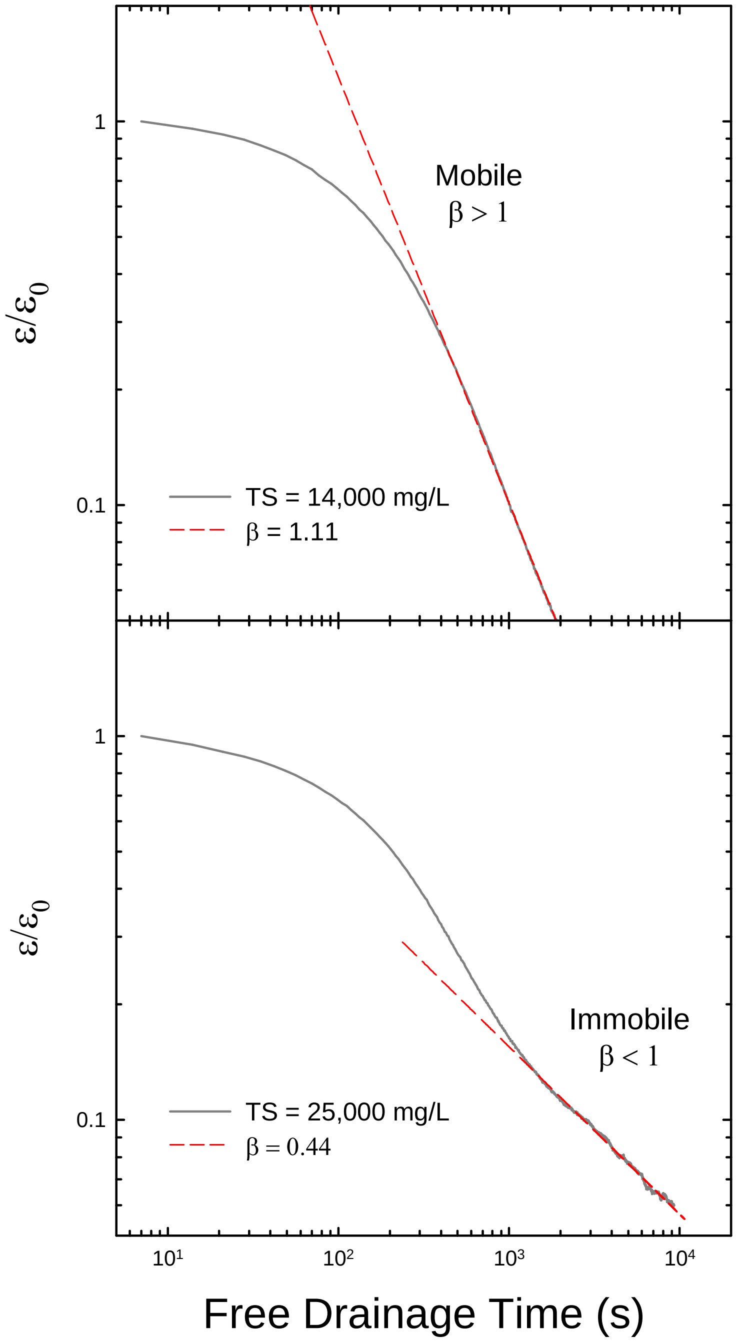

Figure 5-11 Normalized liquid fractions with free drainage time for foams stabilized with mixtures of SDBS and anaerobically digested sludge. SDBS concentration was 1.2×10^{-2} mol/L (10 CMC). The values of the exponent were estimated to be 1.11 and 0.44 for 14,000 mg/L and 25,000 mg/L of total solid concentrations of the foaming solutions, respectively

5.7 Foam Stability in Digested Sludge-Containing Foams

The time of rupture of half of the foam column is the commonly used quantity to characterize foam stability. This value is associated with the free-drainage time when the initially produced foam column has decayed down to half of its original height. The changes in foam height with time were presented for several solutions at different total solid concentrations (Figure 5-12 and Figure 5-13). General features of foam decay tend to decrease slowly at initial stage, but continuously increased the decay rate at final stage. Half-life time was estimated based on the variation of foam height, which usually is of particular interest in application. The half-life time reached its maximum value at total solid concentrations of approximately 2.0% (Figure 5-14). Since the original height was essentially the same in all cases, it was seen that the half-life time was considerably changed from 145.1 min for TS of 12,800 mg/L, up to 681.1 min when TS of 20,400 mg/L was added, and going down to 229.6 min in the presence of TS of 28,800 mg/L. The foam stability was variable with TS concentrations occurring at anaerobic digesters and no clear temporal trends. It is interesting to note that the analysis of drainage behavior allows a better comparison. At the TS concentration of 1.4%, the foam was not quite stable as bubble surface had high mobility as presented in Figure 5-11, while the foam stability increased due to low surface mobility, which is associated with viscous drag forces at the high TS concentration of 2.5%. The present results confirmed an earlier opinion that less mobile surfaces cause more stable foam. Further research is needed to determine the possible cause for the decrease in foam decay at much higher TS concentrations and their potential importance for drainage rate.

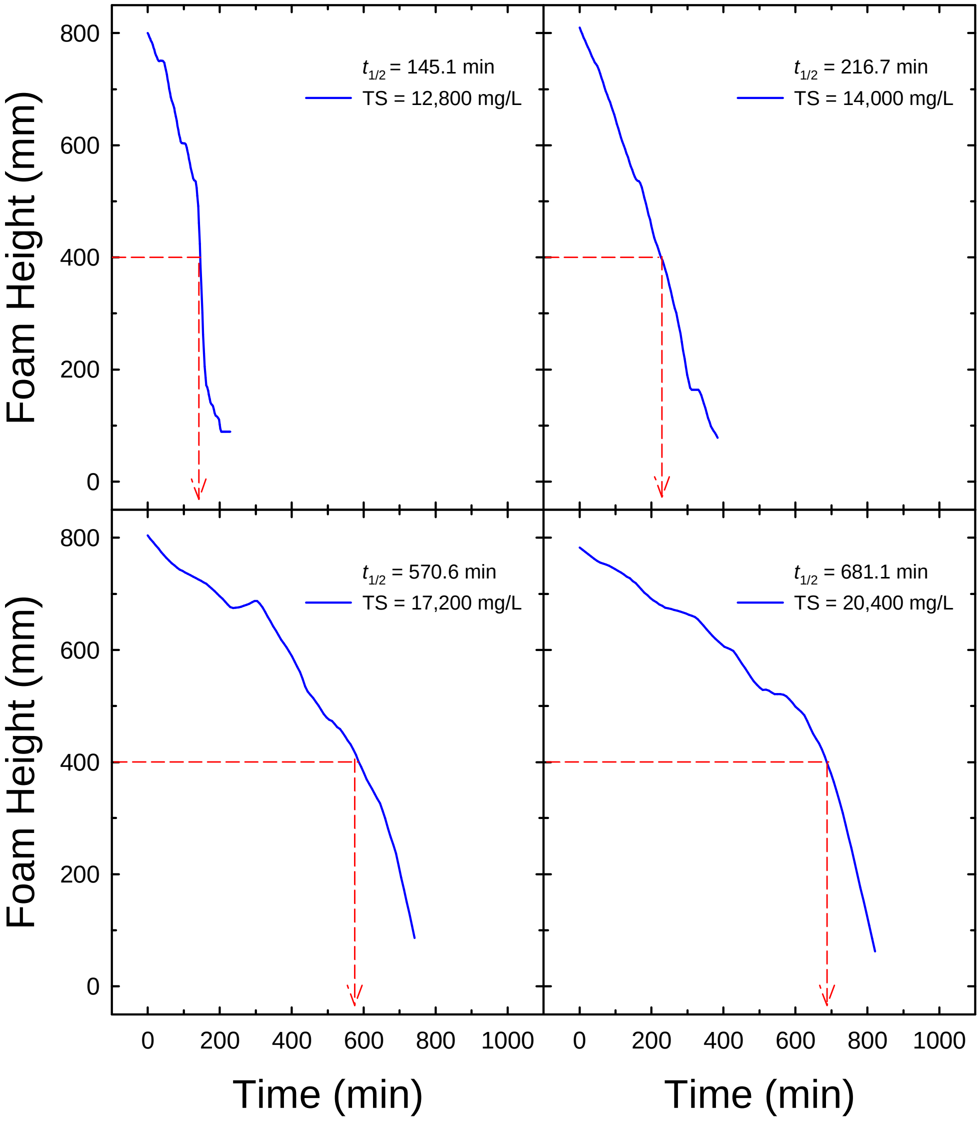

Figure 5-12 Foam height variations and estimated half-life time of the foam column, $t_{1/2}$, for several solutions of various TS concentrations of 12,800 mg/L, 14,000 mg/L, 17,200 mg/L and 20,400 mg/L, respectively

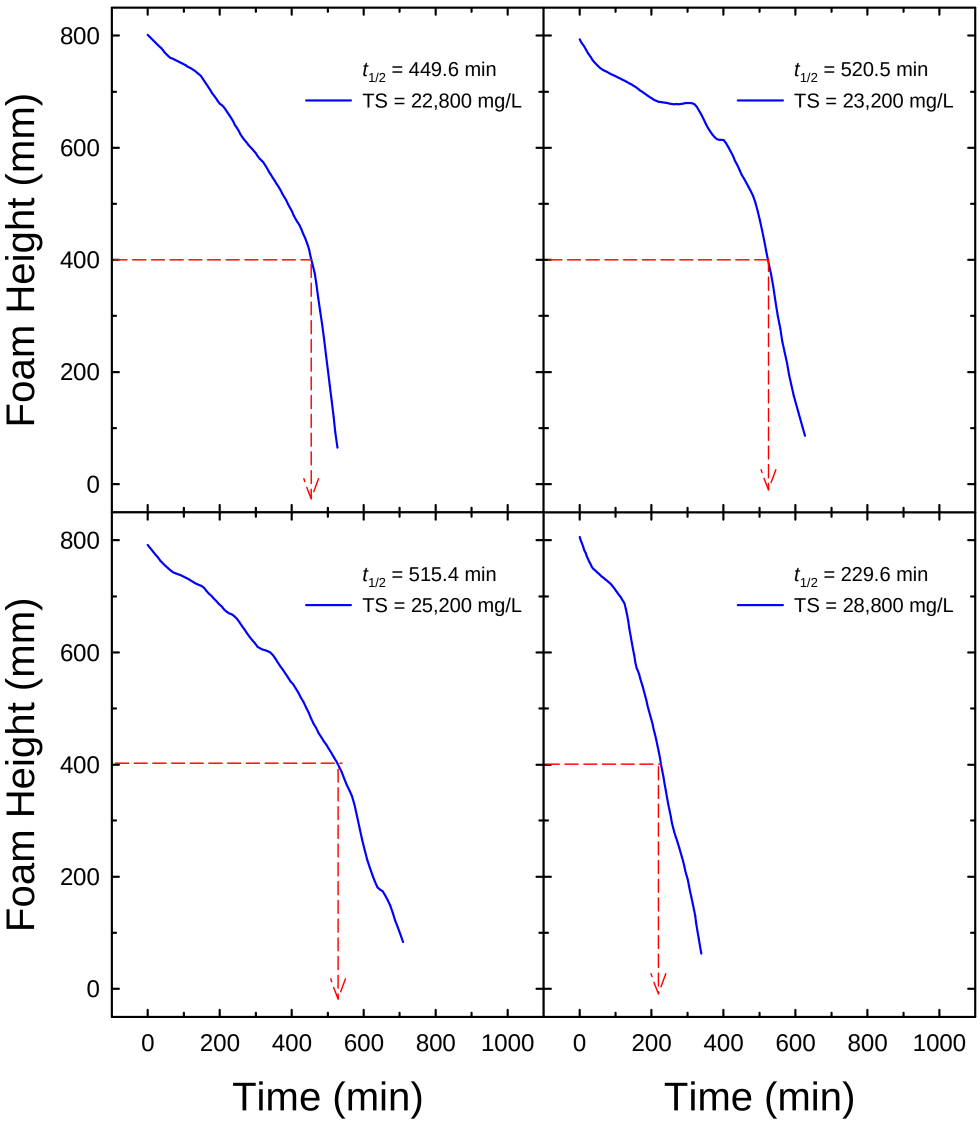

Figure 5-13 Foam height variations and estimated half-life time of the foam column, $t_{1/2}$, for several solutions of various TS concentrations of 22,800 mg/L, 23,200 mg/L, 25,200 mg/L and 28,800 mg/L, respectively

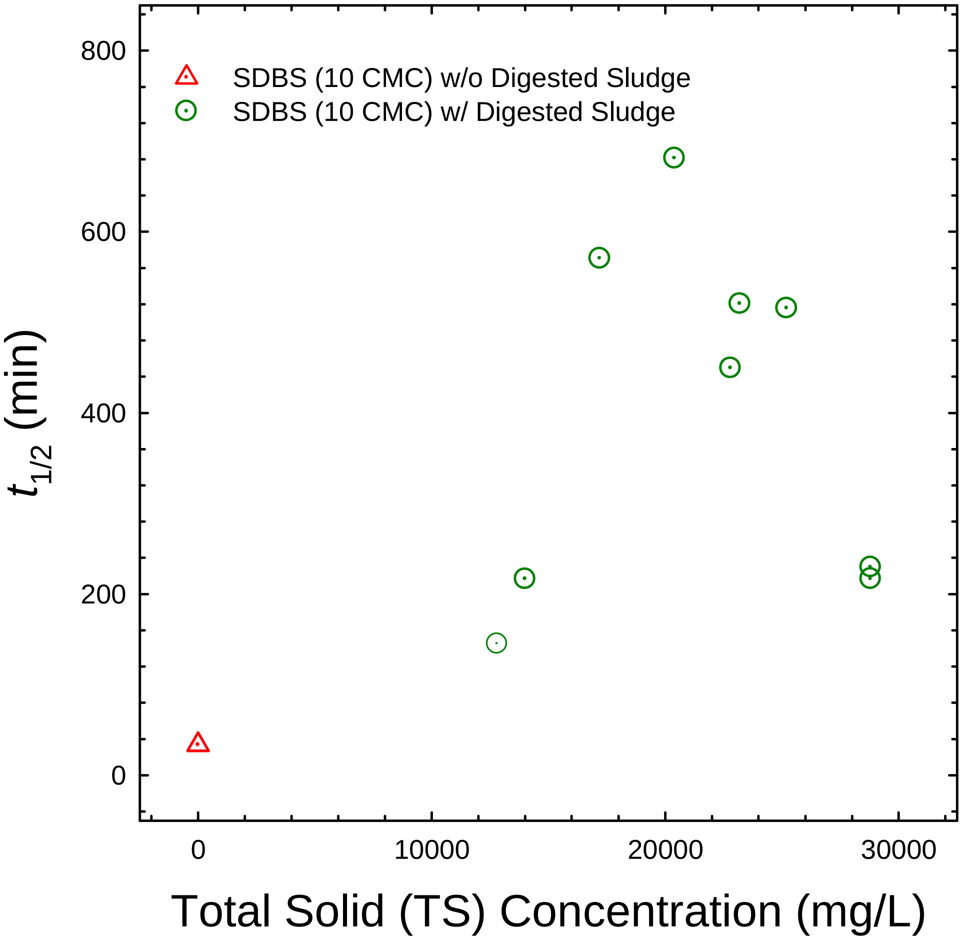

Figure 5-14 Estimated half-life time of the foam column as a function of total solid concentration in the mixture of SDBS and digested sludge. Triangle symbols indicate SDBS foam of 1.2×10^{-2} mol/L (10 CMC) and circle symbols indicate SDBS foam (10 CMC) in the presence of different TS concentrations

5.8 Discussion

The presence of wastewater sludge can affect liquid drainage rates in foam with both external and interfacial forces. First, wastewater sludge contains solid particles capable of foam drainage. Therefore, addition of wastewater sludge could increase gravitational and hydrodynamic forces, and introduce solid particles (microorganisms) capable of foam drainage. Similar effect has been proposed for activated sludge when microbial flocs are formed in biological wastewater treatment (Jenkins *et al.* 1993, Liao *et al.* 2001). Second, solid particles can affect bubble surface interactions in biological foams where they can influence on drainage behavior. The decrease in rates of liquid drainage when activated sludge presents in foams was proposed by the stabilizing effect of hydrophobic particles, particularly foam-causing microorganisms (Pitt and Jenkins 1990, Ho and Jenkins 1991, Pagilla *et al.* 1997).

In anaerobic systems, all of the liquids within foams were drained more rapidly at lower solid concentrations during the free drainage periods. This effect was presumably due to the reduced hydrodynamic force caused by the viscous effect. Density has apparently been largely neglected because it has been assumed that it is relatively constant which varied from 1.02 to 1.04 g/mL in sludge samples (Dammel and Schroeder 1991, Schuler *et al.* 2001). Both forced and free drainage experiments evidenced that the foam surfaces in the presence of digested sludge were likely to be mobile, resulting in low surface viscosity and an increase in drainage rates at low TS concentrations. The rate of foam decay decreased up to approximately TS of 2.0%, but they increased at much higher TS concentrations due to probably the transition of surface mobility.

While our drainage and stability experiment suggested the occurrence of this phenomenon for pure surfactant foams, this is the first time this finding has been documented under conditions relevant to anaerobically digested sludge. Carn *et al.* (2009) reported a decrease in drainage rates when the silica nanoparticle concentration increased. Our studies with real digested sludge, which contained about similar TS concentration studied by Carn *et al.* (2009), also exhibited a transition of drainage regime in the presence of anaerobic sludge where TS concentrations between 2.5 to 3.0% are common.

Under the relatively immobile conditions in the presence of digested sludge, the foams were generally stable. While there was a PB-dominated drainage regime accompanied by the exponent of 1/3 when the sludge were present, an node-dominated drainage regime was observed in the absence of digested sludge (Figure 5-15). The parameter β obtained in the free drainage experiments essentially changed (Figure 5-16). Other researchers have reported regime transition when solid particles contain surfactant foams (Carn *et al.* 2009). Hydrophilic suspended particles smaller than 1 μm shorten the lifetime of films in foams (Hudales and Stein 1990, Gonzenbach *et al.* 2006, Horozov 2008). The properties of cell surface hydrophobicity appear to play a role in the rate of drainage and stability. However, they were unable to identify the conditions responsible for the stability of the foams. Further research is needed to determine if other operating parameters such as solid retention time affect the cell surface hydrophobicity.

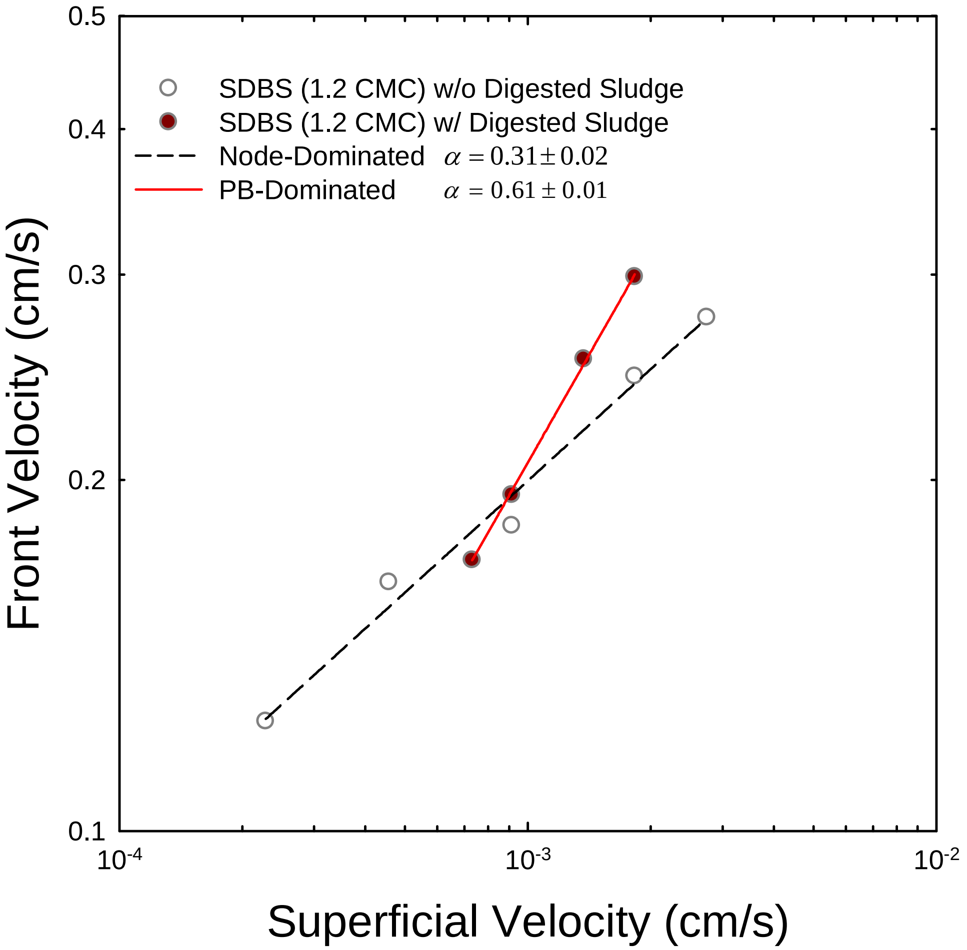

Figure 5-15 Relationship between the front velocity and the superficial velocity for aqueous foams stabilized with sodium dodecylbenzenesulfonate (SDBS) at the concentration of 1.4×10^{-3} mol/L (1.2 CMC). Opened symbols present foams stabilized in the absence of anaerobically digested sludge and full symbols present foams stabilized in the presence of anaerobically digested sludge. Dotted line indicates power law relations with an exponent $\alpha = 0.31 \pm 0.02$ (node-dominated) and solid line indicated power law relations with an exponent $\alpha = 0.61 \pm 0.01$ (PB-dominated), respectively.

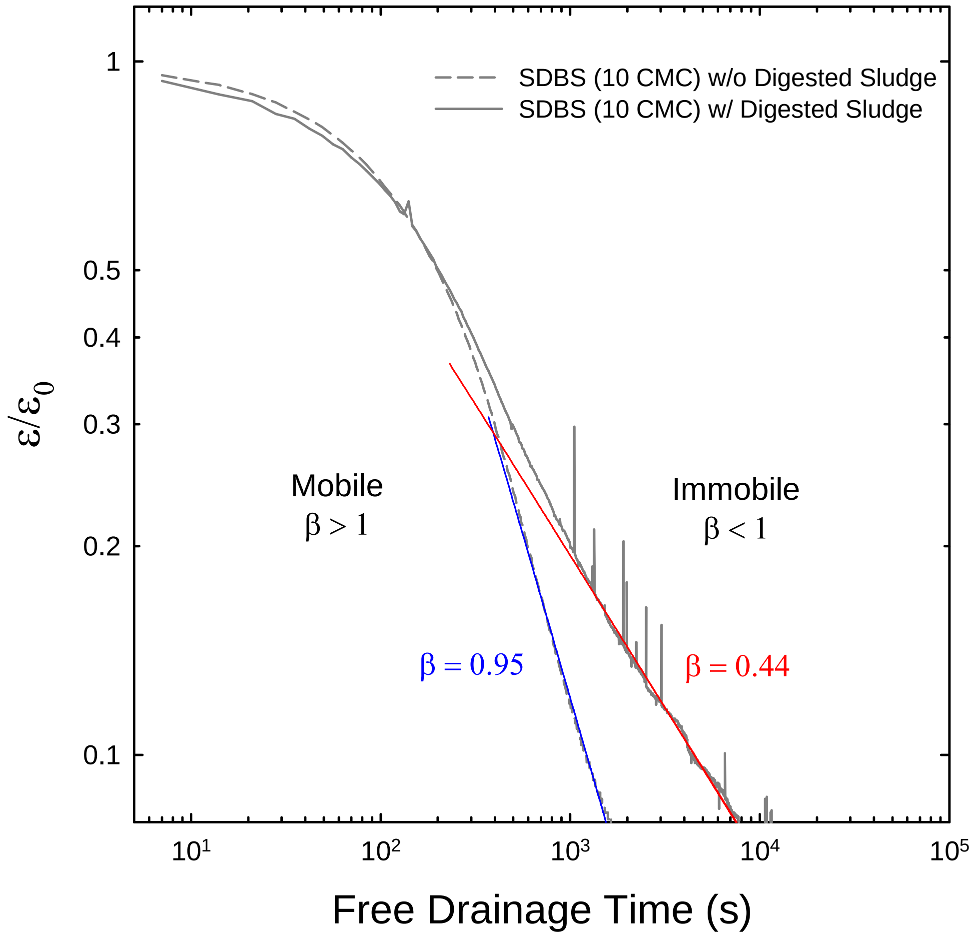

Figure 5-16 Normalized liquid fractions with free drainage time for foams stabilized with sodium dodecylbenzenesulfonate (SDBS) at the concentration of 1.2 × 10^{-2} mol/L (10 CMC). Dotted line presents the foam stabilized in the absence of anaerobically digested sludge and solid line presents the foam stabilized in the presence of anaerobically digested sludge. Blue line indicates power law relations with an exponent $\beta = 0.95$ (mobile, node-dominated) and red line indicates power law relations with an exponent $\beta = 0.44$ (immobile, PB-dominated), respectively.

6. Conclusions

The research described in this dissertation examined the measurements, mechanisms, and implications for anaerobic digester foaming. The capacity of a multi-point electrical resistance measurement technique for assessing drainage behaviors and quantifying foam stability was also examined. Additionally, as a fundamental understanding of foam stability is necessary to predict and control foaming in wastewater treatment plants, the principles of foam dynamics in two-phase and three-phase foam systems were analyzed.

Previous research had described that the node-dominated drainage regime for a variety of anionic surfactant solutions, which is determined by visual observations or light transmission techniques. However, these techniques are not suitable for sludge-containing foams, as the liquid flowing within brown foam is invisible and the mechanism of foam stability was not understood. Determination of drainage regime for sodium dodecyl sulfate (SDS) foams was first attempted by a multi-point electrical resistance measurement technique, which enables both real-time monitoring and intervention in foam development. This research developed the protocol for measuring macroscopic drainage rates during forced drainage experiments, and analyzed the drainage regime for SDS foams at various concentrations. In our experiments, all tested SDS foams were likely to exhibit the node-dominated drainage regime. This result was in a good agreement with the findings of existing drainage studies using other measurement techniques in the literature. Our developed method designed to characterize drainage regime was validated for SDS foams. This suggests that the drainage regime for other foams can be determined by our developed method.

The research further explored this result using sodium dodecylbenzenesulfonate (SDBS), a commercial form of linear alkylbenzene sulfonate (LAS) that is most frequently found in anaerobic sludge. Results showed that all tested SDBS foams were also likely to exhibit the node-dominated drainage regime based on forced drainage studies. The drainage regime of this anionic surfactant has not been measured. Experiments suggest that our developed technique was applicable for any other foams stabilized with surfactants to determine drainage regime. In addition, free drainage experiments were performed to verify the results obtained from forced drainage experiments. Based on foam drainage theory, the power law relationship between normalized liquid fraction and drainage time determines where liquid flows either in the nodes or in the Plateau borders. Since the power law exponent was close to its theoretical value of 1/2 in free drainage, liquid drainage in two-phase foams mainly occurs in the node with mobile surfaces, a finding that confirms data from forced drainage studies. In the majority of studies where the drainage regime is predicted, no attempt is made to investigate foam stability, and it is not possible to estimate stability based on the published data. This research introduced an accurate method for quantifying foam stability that can simultaneously measure variations of foam height with electrical resistance at multiple locations.

Many anaerobic digester operators have experienced foaming, but the causes and controls are not still understood. Almost all wastewater treatment plants employ anaerobic digesters to stabilize waste sludge, and much of this sludge exhibits significant foaming potential. Our experimental approaches include estimations of macroscopic drainage rates and analysis of drainage regimes for standing foams by our well-verified technique. Measuring macroscopic drainage rates and the regime can be applied to predict foam stability in anaerobic digester systems. This research examined the relative contribution of sludge to drainage regimes and stability of the foam. The reported results have been compared and discussed in the frame of the theoretical knowledge mainly developed for aqueous surfactant foams. Our results indicate that drainage is likely to observe a Plateau-border (PB) dominated regime by the theoretical meaning of the power law exponents obtained from both forced and free drainage experiments.

In forced drainage, the power law exponents suggest that the presence of digested sludge at TS concentrations of approximately 2.5% can induce a transition from a drainage regime, where dissipation mainly occurs in the nodes, to a PB-dominated regime. It is worth noticing that for several sludge-containing foams, α is greater than 0.5 in forced drainage, which is not physically comprehensible in the frame of existing theories, but the drainage regime is clearly changed in the presence of digested sludge.

At this point, it is important to note that this behavior is also observed in free drainage experiments, as checked via liquid fraction measurements in the top of the foam column. This qualitative observation suggests that drainage kinetics are drastically slowed down in the presence of sludge, as sludge can induce a transition from mobile to immobile surfaces. In the frame of these theoretical interpretations, it seems that the sludge solids induce an increase in the surface viscosity. However, it is difficult to claim this before surface tension measurements. Both forced and free drainage experiments suggested that drainage regime dependent on the surface mobility was responsible for the observed change in stability in the presence of digested sludge. This analysis could explain why wastewater sludge foams, especially digested sludge, are much more stable in bioreactors than surfactant-induced foams that show the node-dominated drainage regime

Interestingly, we have shown that a significant stabilizing effect arises when digested sludge present in the foam system for TS concentrations of approximately 2.0%. This stabilizing effect has been related to drainage kinetic slow-down strongly dependent on the TS concentration. Foams containing high TS concentrations (TS > 2.0%) were less stable than expected, together with lower half-life time. This suggests that sludge properties, such as cell surface hydrophobicity, can be influenced by internal forces within foams. From a practical perspective, this study suggests that the presence of stable foam, associated with lower drainage rates, could be controlled by the understanding of surface properties between bubbles, and may be prevented in anaerobic digester systems.

The question of how biological foams measure in real wastewater treatment plants and why wastewater sludge from anaerobic digestion makes stable foam layers has been unclear for the last decade. This research made a significant contribution towards understanding how three-phase foams cause stable foams and the factors controlling their stability. We determined that bubble surfaces were less mobile in the presence of digested sludge, and foam drainage regimes fit the generalized theory by using two complementary methods. This decreased surface mobility is likely what enables them to maintain stable foams. The results of this research will be useful to operators interested in minimizing the amount of stable foam layers. Our developed method used in this research may be particularly relevant to monitoring programs for unidentified foams in many industries.

7. Recommendations for Future Research

In this research, the foaming solutions were prepared with the mixture of surfactants in order to produce sufficient volume of foam for conducting both forced and free drainage experiments. Prior to practical application of various drainage studies, further research has to be conducted using digested sludge alone that has high foaming potential in order to obtain realistic drainage behaviors.

While this research showed that a relationship between foam stability and TS concentrations of digested sludge was not a clear link, our attempts to determine the cause of the observed stability were inconclusive. Further research is needed to determine the reasons for the observed stability at different TS concentrations. A better understanding of the microbial community in anaerobic digesters, and the sludge properties, such as cell hydrophobicity, responsible for internal forces within foams may be helpful in gaining insight into this phenomenon. Analyzing surface properties of sludge caused by foam-causing microorganisms known to be present in wastewater sludge could help determine why foam stability changes. These sludge properties at various operating conditions such as solid retention times (SRTs) could help determine the factors that control the drainage rates and foam stability.

Additional research is needed to understand the factors controlling drainage rates and regimes associated with the bubble surface mobility. Anaerobically digested sludge is a complex mixture of different kinds of organic matter that has varying drainage kinetics of foam and consists of particles of various sizes. A better understanding of how physical parameters, such as bubble size, particle size and bulk viscosity, affect drainage rates could help to better predict their foam stability. Studies to determine these parameters are needed to predict how drainage rates will interact with sludge and to modify drainage models for three-phase foams. This could be done by determining the individual parameters affecting the existing drainage model, and conducting drainage experiments looking at bubble surface interactions with individual parameters.

This research conducted for sludge samples collected from non-foaming anaerobic digesters. Digested sludge alone did not, thus the mechanisms of drainage and the factors controlling it are still not well understood. While it is known that different types of surfactants exist in digested sludge, and that some microorganisms capable of producing bio-surfactants exist, further research is needed to determine how much surfactants contain in anaerobic digesters to identify more accurate causes of foaming. This information could be useful in investigating surface interactions with digested sludge operated at various conditions.

8. References

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