Exploring the Effects of Salts on Gas Dispersion and Froth Properties in Flotation Systems

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Abstract

Several mineral flotation plants utilize process water with high soluble salt content. The processing of soluble minerals, the use of recycle streams, sea or well water give rise to this situation. It is unclear as to the overall effect on flotation response though there does seem to be evidence of bubble size reduction, increased froth stability and reduced reagent dosage. The present work aims to quantify the effects of salts commonly present in process water on gas dispersion (bubble size and gas holdup) and froth properties (solid and liquid overflow rates) and to compare to a typical frother, MIBC (methyl isobutyl carbinol). Three sets of experiments were run: 2-phase, 3-phase using talc and 3-phase using ore. All tests were run in a laboratory column. The salts examined in the 2-phase tests were NaCl, $CaCl_2$, Na_2SO_4, $Na_2S_2O_3$ and $Al_2(SO_4)_3$. Tests were conducted to determine the effects of salt type and concentration on gas holdup, bubble size distribution and foaming. The salts containing multivalent ions had a greater impact than did the monovalent ions, in keeping with the literature. A relationship between gas holdup and ionic strength was established. The effects of NaCl and MIBC on frothing and on solid and liquid overflow rates in 3-phase tests using 1%w/w talc were investigated. The results showed increased frothing and overflow rates upon the addition of NaCl, comparable to adding MIBC. Three-phase tests using ore (Falconbridge's Brunswick Mine) explored the effect of NaCl concentration. The results show reduction in bubble size and increased gas holdup in salt solutions comparable to those in the 2-phase tests. For each case, the concentration of MIBC giving equivalent gas holdup and frothing as the salt systems was determined. Proposed mechanisms for coalescence

inhibition and froth stability in salt solutions are briefly reviewed in light of the current

findings.

Résumé

Plusieurs usines de flottation de minerais utilisent de l'eau saliné dans leurs procédés. Le recyclage de l'eau, utilisation de l'eau de mer ou de puit ou le traitement des minerais soluble mène à ces circonstances. Les effets de l'utilisation de l'eau salée sur la performance ne sont pas clairs, mais, il y a preuve de la réduction dans la taille des bulles, des effets sur la stabilité de la mousse et le besoin d'utiliser moins de réactif dans le système. L'objectif de cet étude est de quantifié les effets des sels présent dans les eaux sur la dispersion de gaz (tailles de bulles et fraction gazeuse) et les caractéristiques de la mousse. Trois expériences ont été entrepris: 2-phase (air et solution), 3-phase (avec talc) et 3-phase (avec minerais). Toutes les testes ont été entrepris dans une colonne de laboratoire. Les sels examiner dans les tests de 2-phase étaient NaCl, CaCl$_2$, Na$_2$SO$_4$, Na$_2$S$_2$O$_3$ et Al$_2$(SO$_4$)$_3$. Les tests ont déterminé les effets de type de sel et concentration sur la fraction gazeuse et distribution de tailles de bulles. Les sels contenant des ions multivalent avaient un plus grand effet relatif aux ions monovalent. Une relation entre la fraction gazeuse et force ionique et la concentration de frother (MIBC) donnant une fraction gazeuse équivalent ont été établit. Les effets de NaCl et MIBC sur la mousse dans une système contenant 1%w/w talc a été investiguer. Les résultats ont démontré une augmentation dans la production de mousse après l'addition de NaCl au système, comparable à un système avec MIBC. Des tests de 3-phase utilisant des minerais (de la mine Brunswick de Falconbridge) démontre une réduction dans la tailles des bulles et une augmentation dans la fraction gazeuse dans les systèmes contenant du sel, comparable aux testes de 2-phase.

Les mécanismes pour l'inhibition de coalescence des bulles et la stabilité de mousse sont décris.

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Chapter 1 - Introduction

1.1 - Mineral Flotation

Flotation is a process which selectively separates solid particles originally developed to recover minerals from ores. Reagents known as collectors and frothers are generally added to a mineral-water slurry. Collectors alter the surface properties of desired minerals to render them hydrophobic (water repellent). Certain minerals (e.g. talc) are naturally hydrophobic in which case collectors may not be needed. Gas (air) is then injected into the slurry through a dispersing mechanism to form bubbles. Frothers are generally added to decrease bubble size and promote frothing. Air bubbles contact hydrophobic particle surfaces and adhesion (to form hydrophobic mineral-air bubble aggregates, Figure 1) occurs. The aggregates rise to the surface of the pulp phase and form froth. There is generally a distinct interface between the pulp and froth zones. The froth grows and overflows the vessel (flotation machine or cell), thus concentrating the hydrophobic particles in the overflow. The majority of the hydrophilic (water wetted) particles remain in the slurry and exit the flotation machine by an underflow. A schematic of a flotation system is shown in Figure 2.

Flotation systems, therefore, comprise two distinct zones: pulp and froth. Collection (collision and attachment, Figure 1) of the hydrophobic mineral occurs in the pulp zone, the lower portion of the machine where the minerals are in suspension. The froth zone is located in the upper section of the flotation machine and is characterized by high volume fraction of gas and a regime of upward flowing and coalescing bubbles coated with hydrophobic particles which stabilize the froth.

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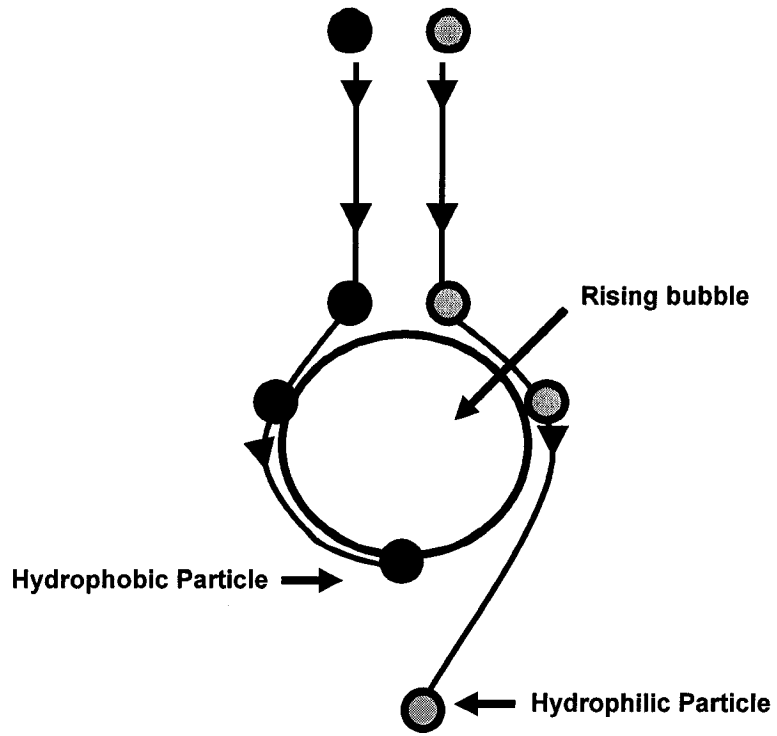
Figure 1 – Bubble interaction with a hydrophobic particle (black) and a hydrophilic particle (grey)
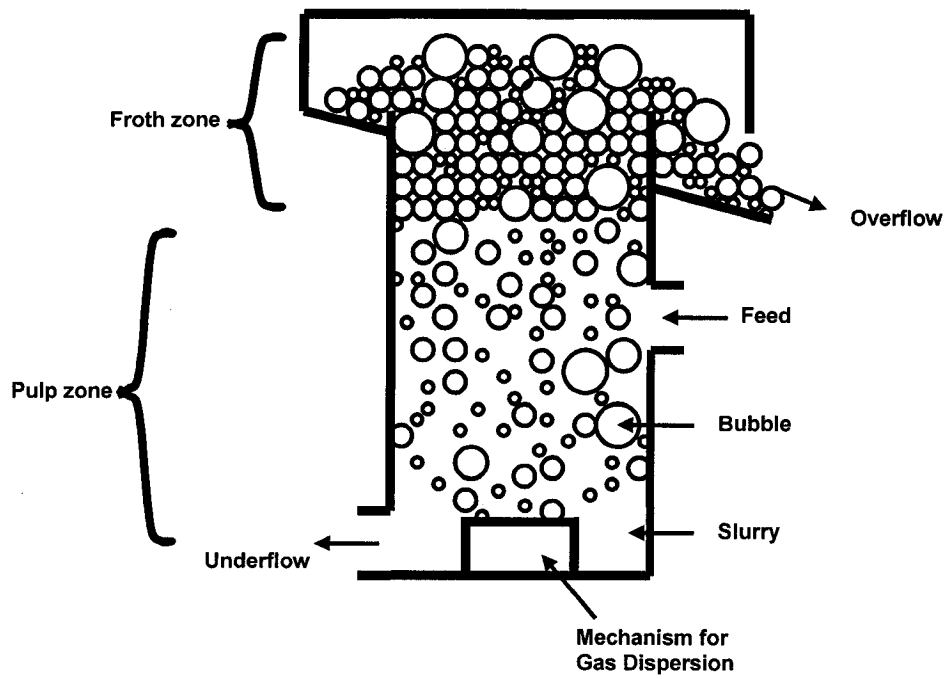
Figure 2 – Schematic of a flotation system

It has been well documented that gas dispersion and froth parameters are important factors contributing to flotation performance (Finch and Dobby, 1990; Vera et al. 2002).

1.2 - Issues Concerning Flotation Process Water Quality

Several mineral flotation operations utilize water with high inorganic salt content. The use of recycle water, artesian well water, sea water or the processing of soluble minerals give rise to this situation. The presence of certain soluble salts in process water seems to affect flotation performance significantly by changing gas dispersion properties and froth stability. This section will give a brief overview of flotation in salt water which is the focus of this thesis.

Issues concerning water quality in flotation systems have been addressed on several occasions (Rao et al., 1988; Rao and Finch, 1989; Liu et al., 1993; Rao and Leja, 2004). The majority of these works consider the presence of metal ions which chemically alter the interfacial characteristics of the mineral surfaces and affect selectivity. This paper will focus, rather on the effect of salts on gas dispersion and froth stability and through these properties their relationship to flotation performance.

1.3 – Salts: Gas Dispersion and Frothing

It has been well documented that many salts inhibit bubble coalescence (Marrucci and Nicodemu, 1967; Lessard and Zieminski, 1971; Craig et al., 1993; Hofmeier at al., 1995; Laskowski et al., 2003). Coalescence occurs when bubbles interact in such a way that the intervening water film ruptures, thus forming a larger bubble from two (or more) smaller ones. Ions appear to slow film drainage and hinder coalescence (Craig et al., 1993). There is evidence that specific ion hydration effects play a role in determining the

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magnitude of the anti-coalescence forces (Craig, 2004). Hofmeier et al. (1995) consider that elasticity due to surface tension gradients induced in the surface is another factor which determines coalescence behavior.

These properties are similar to those produced by frothers. There are, however, significant differences between inorganic salts and frothers. The first is the need for high salt concentrations for coalescence inhibition (Lessard and Zieminski, 1971; Craig et al., 1993; Zahradnik et al., 1999) compared to a few parts per million of frother. Inorganic ions are also generally unable to form a stable froth layer in two phase (liquid-gas) systems. Lekki and Laskowski (1975) state that only in the presence of hydrophobic particles will salt solutions form a stable froth. These researchers note that inorganic electrolytes fall into the category of surface inactive agents.

Researchers have attempted to determine transition concentrations at which salts begin to inhibit bubble coalescence (Lessard and Zieminski, 1971; Craig et al., 1993; Zahradnik et al., 1999). Zieminski and Whittemore (1970) have shown that many ions of high valence have a greater effect hindering bubble coalescence than monovalent ions. This valence effect will be studied here.

An example of a flotation plant with high inorganic salt concentration is Falconbridge's Raglan mine in northern Quebec. The mill utilizes a closed-loop recycle water system due to environmental restrictions regarding effluent water disposal as well as limitations regarding the use of fresh water. The only water bleeds are in the form of moisture in the filter cake and steam from drying. As an apparent consequence the flotation circuit is able to operate effectively without the use of frother. This observation

corresponds to previous evidence suggesting that flotation in salt water results in lower reagent consumption (Haig-Smillie, 1974, Yoon and Sabey, 1989).

The most highly concentrated ions present in Raglan process water are Na^+, Cl^-, SO_4^{2-}, and $S_2O_3^{2-}$. Total salt concentration can reach 20 000 - 25 000ppm (equivalent to 0.3M to 0.45M NaCl). The presence of sodium is due to the addition of soda ash for pH control. The chloride results from calcium chloride added to underground drilling water to prevent freezing. Calcium subsequently precipitates with carbonate ions so little calcium (or carbonate) remains in solution. Sulfate and thiosulfate are present due to the oxidation of sulfide minerals being processed. Tests were designed to examine and quantify the impact of these ions, initially in a two-phase (solution-gas) system. These results provide a foundation to understand the effect of salts in the more complex, three phase flotation system. The salts examined were NaCl, Na_2SO_4, $CaCl_2$ and $Na_2S_2O_3$ to cover the ions present at Raglan with $Al_2(SO_4)_3$ added to extend the range of ion charge, i.e., examples of 1-1, | 1-2, 2-1 | and 3-2 (cation-anion charge) salts were tested. Three-phase (solution-air-solids) tests were then run to compare with the salt effect on gas dispersion and froth properties in the 2-phase system.

1.4 - Hypothesis, Objectives and Thesis Organization

It has been shown that many inorganic electrolytes affect gas dispersion and frothing properties. At the Raglan concentrator flotation occurs in a saline solution without the use of frothers. The objective of this thesis is to explore the role of salts in 'replacing' frother functions, specifically gas dispersion (gas holdup and bubble size) and froth properties (froth height and solids and liquid overflow rates).

Chapter one introduces the concept of flotation, raising concerns over process water quality. Chapter two gives a summary of major findings from the literature regarding the effect of salts on gas dispersion properties, froth stability. The importance of gas dispersion and froth properties on process performance is also outlined. Chapter three outlines the equipment and test procedures utilized in the experiments and Chapter four the results obtained from the three sets of tests (2-phase, 3-phase with talc and 3-phase with ore). Chapter five summarizes the results obtained from all the experiments and gives an overview of the findings. Chapter six concludes the thesis and discusses the fulfillment of the project objectives and possible future work in this field of study.

Chapter 2 – Literature Review

2.1 - Gas Dispersion Properties in Inorganic Aqueous Solutions

Frothers (a class of surfactants) are commonly used in flotation systems to hinder bubble coalescence to control bubble size (Klassen and Mokrousov, 1963). Certain inorganic salts have a similar ability to hinder coalescence. The following text will discuss possible mechanisms involved in the suppression of bubble coalescence in inorganic electrolytes.

It should be noted that coalescence (determination of bubble size) occurs primarily, if not totally, at the point of bubble generation (Hofmeier et al., 1995). Marucci and Nicodemu (1967) studied coalescence behavior and stated that bubbles almost stop coalescing above the initial bubble production zone in a column. Bubble size is dictated by sparger characteristics, gas flow rate, pressure and the system rheological properties.

Many inorganic ions are able to inhibit bubble coalescence, there being several possible factors attributed to this behavior among them: ion valence, solution viscosity, surface tension, ion hydration, ion adsorption behavior and oxygen solubility.

Lessard and Zieminski (1971), Zahradnik et al. (1999), and Craig et al. (1993) have attempted to determine the transition concentration at which salts inhibit bubble coalescence. The tests consisted of contacting bubble pairs and determining the percentage of bubbles which coalesced. The concentration at which 50 % of the bubbles coalesced was termed the transition concentration. These tests were similar to early work by Foulk and Miller (1931). These researchers used a similar setup and measured the

'percentage film formation' which was equal to the percentage of bubbles which failed to coalesce.

Low salt concentrations seem to have little or no effect on bubble coalescence. There is an intermediate salt concentration range in which bubble coalescence is increasingly inhibited. Finally there is an upper concentration above which there is virtually no coalescence (i.e., no further decrease in average bubble size). Figure 3 depicts the general relationship between bubble size (diameter, D_b) and concentration of coalescence inhibiting salt. Chan and Tsang (2005) and Tsang et al. (2004) have shown that transition concentration is bubble size dependent, increasing with decreasing bubble size.
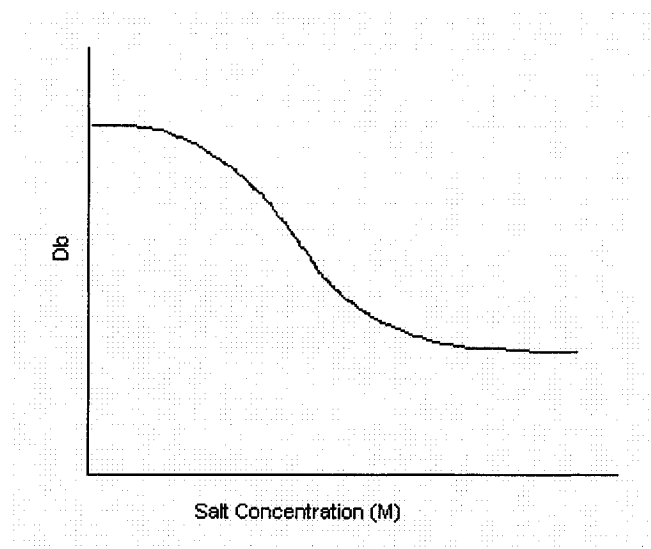
Figure 3 – Bubble diameter vs. coalescence inhibiting salt concentration

Zieminski and Whittemore (1971) have shown that salts containing polyvalent ions have a greater effect in hindering bubble coalescence with respect to monovalent salts. This means that ions of higher valence decrease bubble size at lower molar concentrations. This work also shows that for most salts there is a good correlation

between ionic strength and bubble size. Ionic strength is a function of ion concentration and valence.

The valence and size of an ion play important roles in ion hydration which affects the molecular arrangement of the water at the air / solution interface. Highly hydrated ions prefer to exist in the bulk solution in a fully hydrated state (Hey et al., 1981). This explains the increase in surface tension upon the addition of certain inorganic salts to water by the displacement of ions and their associated water of hydration from the interface (i.e., negative adsorption).

Ion hydration also plays a role in determining solution viscosity which affects the drainage of films from the surface of bubbles. Viscosity is a measure of a fluid's resistance to shear. Certain ions break the structure of water (reduce viscosity) while others are considered structure formers (increase viscosity). Unhydrated ions tend to create a looser structure and thus reduce viscosity (Zieminski and Whittemore, 1971, Rao and Leja, 2004). Conversely, a tighter ionic structure will increase viscosity. Cations such as Ca^{2+} tend to increase viscosity while Na^+ and Cl^- are structure breakers and reduce viscosity. However, Lessard and Zieminski (1971) showed that viscosity alone could not account for coalescence behavior in salt solutions. The discrepancy is evident in KCl solutions which effectively reduce viscosity but still inhibit bubble coalescence (Lessard and Zieminski, 1971). Bulk viscosity values were used in these studies. It is possible that the viscosity at the air/water interface differs from the bulk values. Lessard and Zieminski (1971) stated that small changes in bulk viscosity could possibly have a much greater effect near the surface.

Hofmeier et al. (1995) claimed that elasticity, development of a restoring force in the interface in response to a variation in surface composition, was a factor which determines coalescence behavior. The Gibbs elasticity (E) is given by:

$$E = \left(\frac{4c}{DkT}\right)\left(\frac{d\gamma}{dc}\right)^2$$

Equation 1

where c is concentration, D, interfacial thickness, k, Boltzmann's constant, T, temperature, and $d\gamma/dc$, the surface tension gradient (Hofmeier et al., 1995).

Elasticity, thus, is a function of the rate of change in surface tension with concentration squared. Weissenborn and Pugh (1996) measured various surface tension gradients and disproved this hypothesis by showing that solutions of inorganic electrolyte did not behave according to Gibbs elasticity. There is currently much discussion in the literature concerning this issue (Bhatt et al., 2004; Jungwirth and Tobias, 2002). Measured surface tension gradients do not correlate well with coalescence inhibiting transition concentrations from the literature.

It was once believed that a build up of charge on the bubble surface (Zieminski and Whittemore, 1971) could cause the inhibition of coalescence in electrolyte solutions. This seems unlikely as it does not follow conventional double layer theory: increasing salt concentration would compress the double layer and reduce electrostatic repulsion, theoretically promoting coalescence (Craig et al., 1993). Yang et al. (2001) and Li and Somasundaran (1991) have recently developed methods to determine the zeta potential on bubbles. Bubbles tend to have negative surface charge in solution. Increasing ion concentration tends to decrease surface charge (i.e., it tends towards charge neutrality),

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though it is important to note that surface charge is strongly dependent upon the ionic species present and pH of the solution.

Recent molecular dynamics simulations by Jungwirth and Tobias (2002) have suggested that heavier halide (I^-, Br^-) anions may exhibit surfactant-like activity. These models attempt to demonstrate that certain ions are attracted to the air/water interface. This notion of ion adsorption was discussed in detail by Foulk and Miller (1931) and correlated well to surface tension data. The Jungwirth / Tobias model shows that Cl^- is accumulated at the interface while Na^+ remains in the bulk. These findings of ion specific adsorption may be an important mechanism leading to coalescence inhibition.

Craig et al. (1993) created a combining rule (table) which assesses whether a given cation / anion pair in solution would inhibit bubble coalescence. This table does not predict the magnitude of anti-coalescence. They add that one must not overlook ion specific behavior because coalescence is strongly dependent upon the specific combination of ions present in solution.

Using Craig et al.'s (1993) work as a model, Weissenborn and Pugh (1995) created a table of cation / anion pairs to indicate whether a salt would positively or negatively adsorb at the interface and suppress coalescence. They determined positive or negative adsorption behavior by comparing the magnitude of change in surface tension with salt concentration ($d(\Delta\gamma)/dc$). High positive values of $d(\Delta\gamma)/dc$ are related to highly hydrated ions which have a tendency to remain in the bulk or negatively adsorb. The opposite is true for ions with little hydration. The results were interesting showing that salts which inhibited bubble coalescence had values of $d(\Delta\gamma)/dc$ less than -1 or greater than +1. Foulk and Miller (1931) also stated that both positive and negative adsorption

could lead to the formation of stable films. They also discussed the ability of mixtures of positively and negatively adsorbed ions to create non-foaming (most probably coalescing as well) solutions. This notion lends itself well to the Jungwirth and Tobias model as it addresses ion specific behavior at the interface.

Weissenborn and Pugh (1996) linked increased ion concentration to the accompanying decrease in oxygen solubility which may have an effect on bubble coalescence. The authors suggested that effects related to dissolved gas concentration are possibly important aspects to consider. There seems to be a fairly good correlation between oxygen solubility and surface tension. This result may be expected due to the fact that viscosity, gas solubility, ion concentration and hydration are all related phenomenon. It was suggested that the presence of micro-bubbles could induce a "bridging attraction" which leads to coalescence. Lower gas solubility would reduce the number of micro-bubbles present, suppressing bridging and hindering bubble coalescence (Weissenborn and Pugh, 1996).

Craig et al. (1993) and Weissenborn and Pugh (1996) suggested that attractive hydrophobic forces could influence coalescence behavior in salt solutions. Craig et al. (1993) discussed the possibility of reduced hydrophobic attraction between bubbles due to the presence of certain ions in solution. This could lead to bubble coalescence inhibition. There was little evidence to support these claims and Craig (2004) later ruled out this hypothesis. He measured hydrophobic forces and noticed no significant change upon the addition of electrolyte to water.

Understanding the specific nature of ions (Craig, 2004), their effects on the structure of water and the process of coalescence is complex. Researchers have attempted

to determine the mechanisms which control coalescence. To date, there has been no satisfactory explanation of the exact mechanism(s) controlling bubble coalescence in inorganic aqueous solutions.

2.2 - Aspects Related to High Inorganic Salt Concentrations

The major concern regarding the use of saline water in flotation is corrosion. Associated costs, most notably machine maintenance, can be major.

In terms of flotation performance, Paulson and Pugh (1996) noted that the presence of inorganic electrolytes does not cause flotation of minerals which are not hydrophobic. It was shown by Yoon and Sabey (1989) that increased sodium sulfate concentration had no effect on contact angle measurements on a hydrophobic coal surface. Laskowski and Iskra (1970) found that 0.1M KCl had practically no effect on contact angle measurements of methylated silica plates. It should be noted that high salt concentration may affect collector adsorption, thus affecting hydrophobicity. Salts seem to influence flotation performance, largely by altering gas dispersion and frothing properties.

2.2.1 - Particle–Particle Interactions (Solids dispersion)

The dispersion of particles within a slurry can be an important parameter affecting flotation performance. Particles with high like surface charge repel leading to a dispersed system. Increasing ion concentration tends to neutralize surface charge and eliminates the repulsive force resulting in coagulation. If coagulation occurs between the minerals separation will be more difficult (Rao and Leja, 2004).

Certain polyvalent cations like Mg^{2+}, Ca^{2+} or Al^{3+} can neutralize mineral surface charge by forming hydroxide species. This can lead to aggregation by charge neutralization and also by a bridging mechanism. Redispersion can occur at high pH or salt concentration if complete hydroxide coverage occurs and the associated high positive charge causes repulsion (Rao and Leja, 2004). However, under these conditions ionic species which precipitate would not affect gas dispersion because they are removed from solution.

Wellham et al. (1992) discussed improved dispersion due to electrostatics at high salt concentrations specifically when slime coatings are problematic. Reducing electrostatic interactions may help reduce the effect of slime coatings.

Winter and Moore (1926) performed tests on ores from Western Australia. Certain ores contained colloidal matter which readily floated and interfered with flotation. In contrast Wellham (1992) found that salts acted as a coagulant for colloidal matter and greatly improved flotation. Winter and Moore (1926) note that the use of salt water improved concentrate and residue settling rates.

2.2.2 - Bubble–Particle Interactions

As soluble salt concentrations increase electrostatic interactions are generally neutralized. This may allow hydrophobic forces to dominate bubble-particle interaction behavior. Li and Somasundaran (1991) have clearly shown that increasing NaCl concentration neutralizes the zeta potential on bubbles. This is also true for solids in salt solution (Paulson and Pugh, 1996; Laskowski and Iskra, 1970). Small ions of high valence tend to be more highly hydrated and thus remain in the bulk solution away from

the air/solution interface. Hey (1981) discusses the possibility of the presence of a salt free zone at the interface in inorganic solutions due to ion hydration.

Yoon and Sabey (1989) state that reduction in the double layer thickness, around hydrophobic particles, enhances bubble/particle adhesion. The hydration sheath around particles and bubbles is reduced by electrolytes, leading to reduction in the disjoining pressure and enabling improved bubble/particle contact. Enhanced bubble/particle adhesion would lead to higher flotation response (Yoon and Sabey, 1989). Laskowski (1966) pointed to the precipitation of microbubbles on hydrophobic surfaces in salt solutions as another possible explanation for improved flotation performance.

Authors have shown that increased KCl concentration leads to lower induction times and improved attachment efficiency (Laskowski and Iskra, 1970; Nguyen, 1998; Dai, 1999). Laskowski and Iskra (1970) state that lower induction times are due to destabilization of wetting films on hydrophobic material in salt solutions.

2.3 - Effects of Inorganic Ions on Foam/Froth Stability

Typically, the term foam is used for 2-phase (liquid, gas) systems while the term froths is used for 3-phase (liquid, solid, gas) system.

Lekki and Laskowski (1969) and Leja (1982) state that inorganic salt solutions produce poor 2-phase foam. It is only in the presence of hydrophobic solids that good frothing is achieved with salts.

Laskowski and Iskra (1970) found by increasing electrolyte concentration in foam stabilized by a surfactant, that they became drier and less voluminous. Apparently, the lack of free water makes the foam formed in such a system much less wet which affects its stability.

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Tan (2005) shows that the presence of salts destabilized polypropylene glycol (PPG) foams. The results show that foam retention time, or foamability, of a 0.24mM PPG400 solution decreases with an increase in salt concentration for NaCl, and for the divalent ions from $MgCl_2$ and $CaCl_2$, foamability is more depressed. Ion valence seems to be more important than salt type. These three salts had little effect on static surface tension (thus, apparently little effect on surfactant adsorption at the air-water interface). The authors attributed the decreased foamability in the presence of salt to a decrease in electrostatic repulsion between the negatively charged bubble surfaces resulting in less stable foam.

There is very little research into the effect of salts in frothing (i.e., the 3-phase system).

2.4 - Gas Dispersion and Foaming Properties

In the figures air flow rate, Q_g (cm^3/s), has been converted to superficial gas velocity, J_g (cm/s), calculated as follows:

$$J_g = \frac{Q_g}{A_{col}}$$

Equation 2

where A_{col} is the column cross sectional area (cm^2).

Industrial flotation cells generally operate at superficial gas velocities between 0.5 and 2.5cm/s (Finch and Dobby, 1990; Xu et al., 1991; Dahlke et al., 2005). All gas velocities have been corrected to account for the temperature and pressure under which the measurements were taken.

As a measure of gas dispersion, gas holdup was measured as a function of salt concentration and air flow rate. Gas holdup, ε_g, is the volume fraction of air in an aerated liquid or slurry in a given test section of a reactor, i.e.,

$$\varepsilon_g = \frac{V_{gas}}{V_{total}}$$

Equation 3

Where V_{gas} is the volume of gas in the test section and V_{total} is the total volume. Gas holdup is generally expressed as a percentage.

Gas holdup is an indirect measure of bubble size, increasing as bubble size decreases (for a given gas velocity), at least for bubble diameter $\leq$ 2mm. This reflects that smaller bubbles rise at lower velocities and thus gas residence time in the column increases (Clift et al., 1978). Bubble size is dictated by sparger characteristics, air flow rate and the system's ability to inhibit coalescence.[1]

In the 2-phase tests gas holdup was determined using a single differential pressure measurement as shown below. Equation 4 is used to calculate gas holdup in this situation:

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[1] It should be noted that any factor which affects bubble rise velocity in a swarm will contribute to the gas holdup value. Zhou et al. (1992) suggests this extends to the type of coalescence-suppressing agent present.
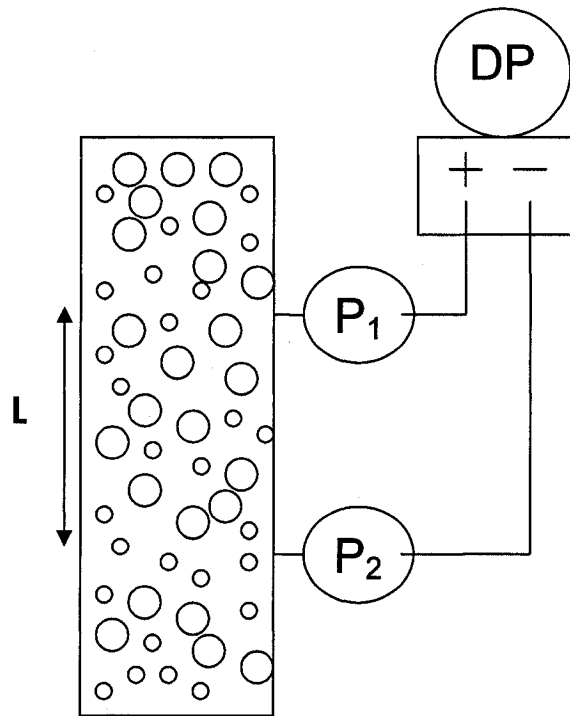
Figure 4 – Schematic of gas holdup measurement using a single differential pressure measurement

$$\varepsilon_g = \left(\frac{DP}{\rho_{sol} gL} \right)$$

<div align="right">**Equation 4**</div>

where DP is the differential pressure reading between the two taps, ρ_{sol} is the solution density, L is the distance between the taps and g is gravitational acceleration.

In the 3-phase tests gas holdup was determined using two pressure measurements made along the column. Equation 5 is used to calculate gas holdup in this situation:
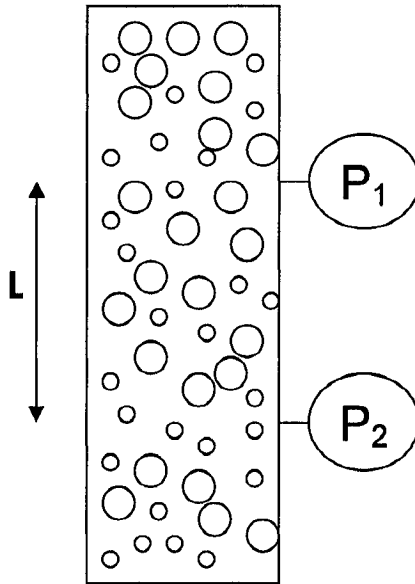
Figure 5 – Schematic of gas holdup measurement using 2 pressure measurements

$$\varepsilon_g = \left(\frac{P_2 - P_1}{\rho_{sl} g L} \right)$$

<div align="right">**Equation 5**</div>

where P_1 is the upper pressure reading, P_2 the lower pressure reading and ρ_{sl} the slurry density.

Bubble size (bubble diameter, D_b) distributions were determined using the McGill Bubble Size Analyzer. There are two average bubble diameters which are typically used to describe bubble size distributions, the number mean, D_{10}, and the Sauter mean, D_{32}, given by:

$$D_{10} = \frac{\sum D_b}{n}$$

<div align="right">**Equation 6**</div>

$$D_{32} = \frac{\sum D_b^3}{\sum D_b^2}$$

<div align="right">**Equation 7**</div>

The general trend is for average bubble size (D_{10} or D_{32}) and gas holdup to increase with increasing superficial gas velocity.

Once superficial gas velocity and Sauter mean bubble diameter are known bubble surface area flux, S_b, can be calculated from Equation 8. This is the total surface area of bubbles that passes through a cross section of cell per unit time.

$$S_b = \frac{6J_g}{D_{32}}$$

Equation 8

Bubble surface area flux increases with decreasing bubble size or increasing gas velocity.

Gas retention time, rt, was determined for each of the 2-phase systems tested. Retention time is the slope of the linear part of the total gas volume in solution and foam, V, plotted versus gas flow rate, Q, (Equation 9) (Pomianowski et al., 1973).

$$rt = \frac{\Delta V}{\Delta Q}$$

Equation 9

Retention time is defined as the average time needed for a unit gas volume to pass through the studied system (solution and foam) (Malysa and Pawlikowska-Czubak, 1975).

Chapter 3 - Experimental

3.1 - Two-Phase Tests

Two-phase (water-air system) gas dispersion tests were undertaken to determine the effect of salt type and concentration on gas holdup, bubble size and foaming properties. A 434 cm (419 cm above sparger) X 7.6 cm diameter bubble column was used for the tests. A cylindrical porous sparger bubble generator with nominal porosity 40μm was located at the base of the column (vertical position). A Bailey differential pressure transmitter was located between 162.5 cm and 288 cm above the sparger. The pressure measurements were used to determine gas holdup. Another pressure transmitter was located at the base of the column to record the pressure at the sparger. This pressure reading was used to correct the air flow rate to the test conditions. Bubble size measurements were made using the McGill Bubble Size Analyzer to capture images of the bubbles (Hernandez-Aguilar et al., 2002; Gomez and Finch, 2002). The bubble viewer (BV) (a sampling tube attached to a sealed viewing chamber) is inserted into the top of the column and filled with process water. Once air is introduced to the column bubbles rise by buoyancy through the sampling tube and into the viewing chamber which is backlit. Inside the viewing chamber the bubbles slide along an inclined window where images are captured using a digital camera. In-house image analysis software was utilized to determine bubble size distributions. The height of foam produced was measured for each test. The set-up is shown in Figure 6 .
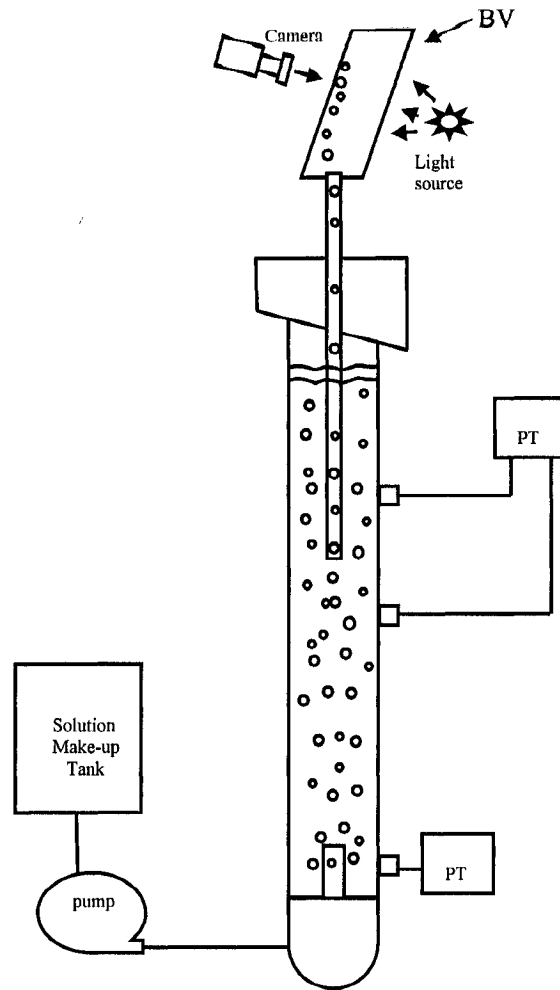
Figure 6 – Experimental set-up for gas holdup and bubble size measurements

Table 1 - Parameters for 2-phase tests

	Concentration Range	Jg (cm/s) Range	~pH
NaCl	0 - 0.5 M		6.7
Na_2SO_4	0 - 0.3 M		6.7
$CaCl_2$	0 - 0.2 M	0.7-1.7	6.7
$Na_2S_2O_3$	0 - 0.17 M		6.7
$Al_2(SO_4)_3$	0 - 0.07 M		3.3
MIBC	0 - 20 ppm		6.7

Tests were carried out using Montreal tap water doped with varying amounts of salt (NaCl, CaCl$_2$, Na$_2$SO$_4$, Na$_2$S$_2$O$_3$ and Al$_2$(SO$_4$)$_3$) and in one set of tests MIBC (methyl isobutyl carbinol) a common industrial frother. Air was introduced through the sparger at given air flow rates (2, 3, 4, 5 l/min). Once the system reached steady state (i.e., pressure signal traces remained constant) pressure readings and foam height were recorded and in selected tests bubble size was measured. Steady state was generally reached after 5-10 minutes. The column was emptied and cleaned after each test.

3.2 - Three-Phase Tests with Talc

The setup is shown schematically in Figure 7. Tests were run in a 320 cm X 10.16 cm diameter column provided with pumps to deliver feed and tails streams. The air flow rate was controlled using a mass flow meter. Superficial gas velocities ranged from 0.4 – 1.9 cm/s (gas holdup tests were extended to 2.4 cm/s). The column had two sets of three conductivity rings; one set above and one below the sparger for gas holdup measurements. There were two pressure transducers (WIKA) located immediately above and below the upper conductivity rings. Superficial slurry velocity (downwards), J_{sl}, was maintained at 1 cm/s (using the tails pump). One percent talc (by weight) was added to the system to allow froth to form.

The objective of the tests was to determine the effect of solution chemistry on overflow rate. Tests were run using Montreal Tap water with varying concentrations of NaCl and MIBC. Table 2 summarizes the test parameters (solution concentration and superficial gas velocity).

The experimental sequence was the following: air was introduced, the feed and tails pumps were kept at ~4.8 l/min, froth was allowed to form and overflow into the

launder and was collected over a 5 minute interval. The level in the column would start at a froth depth of 0 cm and would slowly drop according to the amount of material which overflowed the column. The samples were weighed wet, oven dried and the dry solids were then weighed. The amount of NaCl in the overflow was back calculated and subtracted from the solids overflow. From these results average slurry, solution and solids overflow rates per minute were determined as well as percent solids in the overflow. Gas holdup was determined using the pressure measurements.
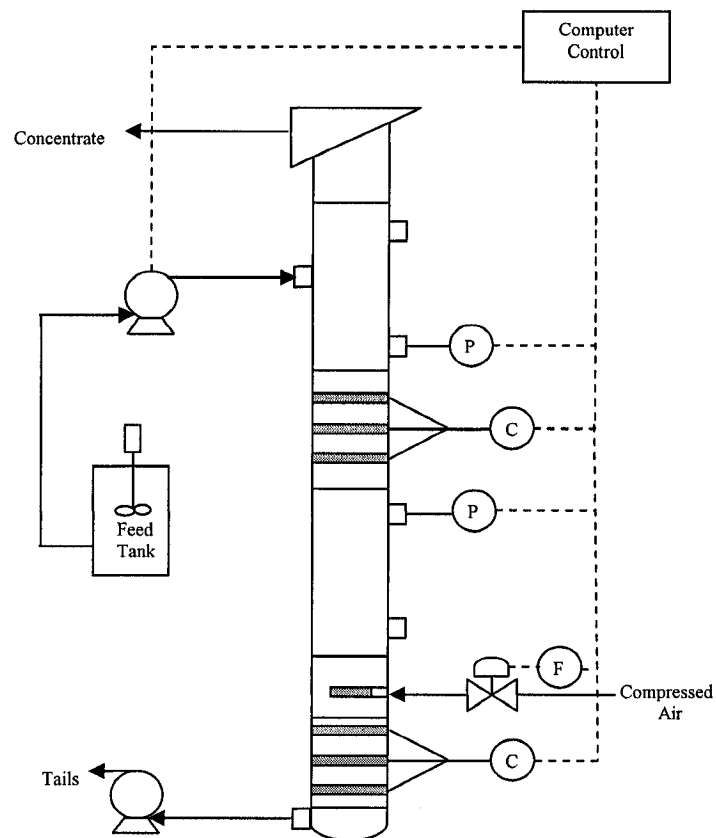
Figure 7 – Experimental setup for 3-phase test work with talc

Table 2 – Parameters for talc tests

Test #	Solution	Jg (cm/s)
1	water	0.4
2	water	1.0
3	water	1.4
4	water	1.9
5	0.1M	0.4
6	0.1M	1.0
7	0.1M	1.4
8	0.1M	1.9
9	0.2M	0.4
10	0.2M	1.0
11	0.2M	1.4
12	0.2M	1.9
13	0.4M	0.4
14	0.4M	1.0
15	0.4M	1.4
16	0.4M	1.9

Test #	Solution	Jg (cm/s)
17	5ppm MIBC	0.4
18	5ppm MIBC	1.0
19	5ppm MIBC	1.4
20	5ppm MIBC	1.9
21	10ppm MIBC	0.4
22	10ppm MIBC	1.0
23	10ppm MIBC	1.4
24	10ppm MIBC	1.9
25	15ppm MIBC	0.4
26	15ppm MIBC	1.0
27	15ppm MIBC	1.4
28	15ppm MIBC	1.9

3.3 – Three-Phase Tests with Ore

These tests were undertaken using the same experimental setup as shown in Figure 7. Figure 8 shows images of the column, bubble viewer and computer control. During these tests the column had automatic level control. The level was held at 5 cm ± 2 cm. Air flow rate was controlled using a Matheson rotameter (manual). Superficial gas velocities tested ranged from 0.4 – 1.5 cm/s. The test parameters are summarized in Table 3.

Selected conditions were repeated (some up to eight times) and a pooled estimate of standard deviation (s_p) was determined. Throughout the results section, error bars ($2s_p$) are used to indicate precision. More details are in Appendix (Reproducibility section).
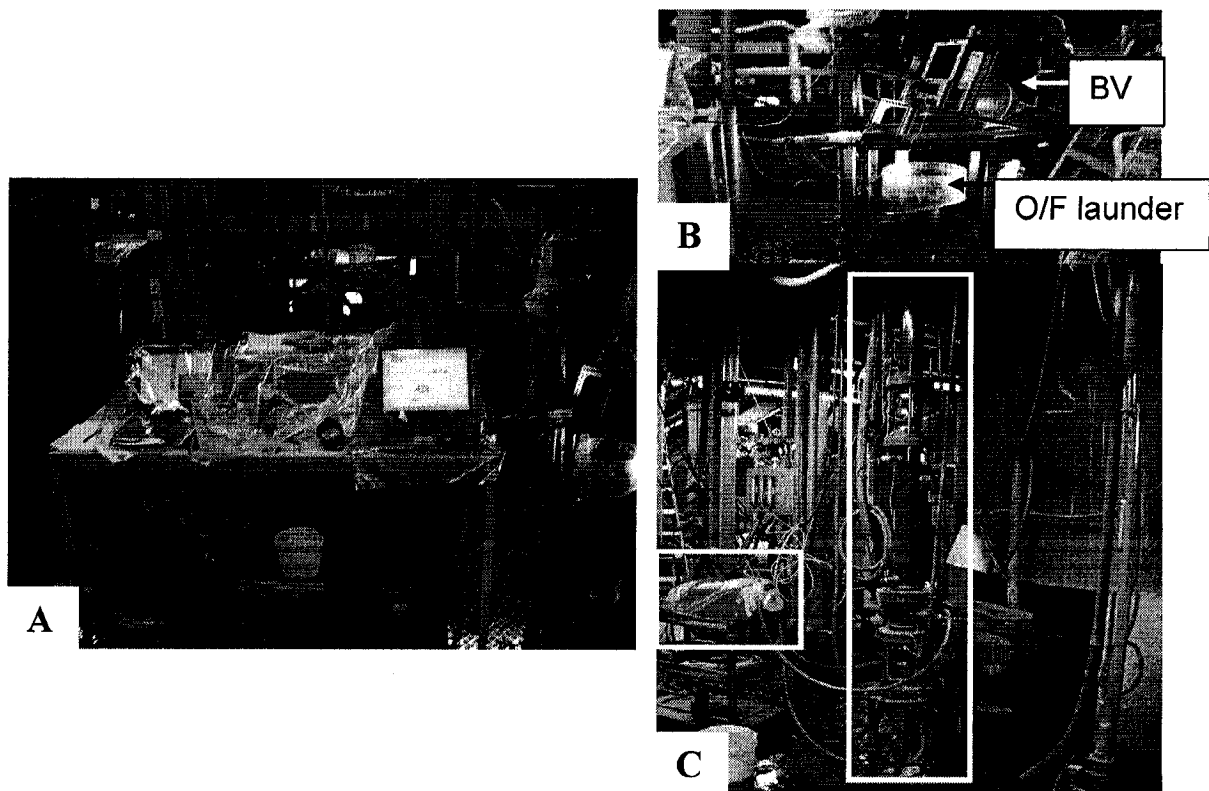
Figure 8 – Experimental setup for flotation tests: A- computer control (2nd floor), B- McGill bubble viewer (BV) above column (2nd floor), C- column and tails pump (1st floor - outlined in white).

Table 3 – Parameters for flotation tests

Test #	Solution	J_g (cm/s)
1	water	0.4
2	water	0.9
3	water	1.5
4	0.1M NaCl	0.4
5	0.1M NaCl	0.9
6	0.1M NaCl	1.5
7	0.2M NaCl	0.4
8	0.2M NaCl	0.9
9	0.2M NaCl	1.5
10	0.4M NaCl	0.4
11	0.4M NaCl	0.9
12	0.4M NaCl	1.5
13	10ppm MIBC	0.4
14	10ppm MIBC	0.9
15	10ppm MIBC	1.5

Chapter 4 –Results

4.1 - Two-Phase Tests

4.1.1 - Gas Holdup and Bubble Size

The range in superficial gas velocity, 0.7-1.7 cm/s, is typical of industrial practice and, as Figure 9 shows, the expected near linear response in gas holdup with an increase in superficial gas velocity is seen[2] (Finch and Dobby, 1990, Dahlke et al., 2005). Increasing sodium chloride concentration increased gas holdup over the range of gas velocities tested. This demonstrates the salt's ability to hinder bubble coalescence. It is noted that at 0.1M NaCl, gas holdup at low superficial gas velocities is similar to that of water while gas holdup increases over that of water at the higher superficial gas velocities. This seems to show that coalescence behavior can be gas rate dependent. This could be attributed to differences in initial bubble size created at the different air flow rates. Hofmeier et al. (1995) photographed bubble production at a frit in NaCl solution and noted the production of large quantities of very fine bubbles at high gas flow rates. Gas holdup increases with the production of these fine bubbles.

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[2] Linearity will break down eventually at high superficial gas velocity.
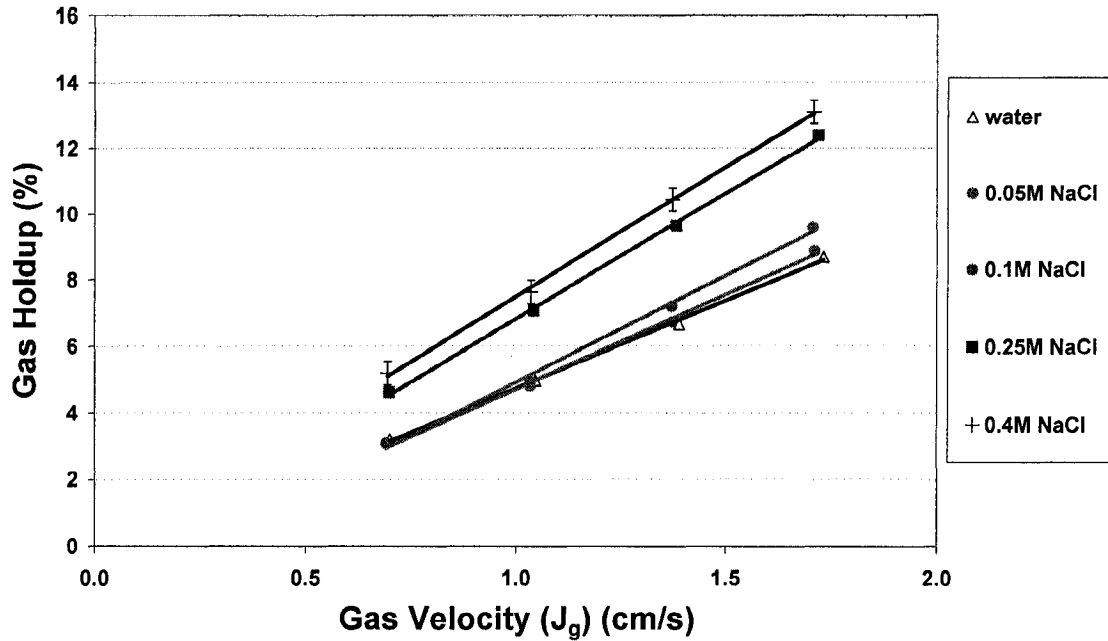
Figure 9 – Gas holdup vs. superficial gas velocity for varying concentrations of sodium chloride (Example error bars (±2s) shown for 0.4M NaCl)

Bubble size distributions were measured at various sodium chloride concentrations (0, 0.05, 0.1 and 0.25M NaCl) at a superficial gas velocity of 0.7cm/s. Typically, 2000 bubbles were counted per test.

As seen in Figure 10 the bubble size distributions are bi-modal. There seem to be two distinct size ranges: bubbles under 2mm and bubbles over 2mm. For water, 0.05 and 0.1M NaCl solutions the bubble size distributions are similar. The results show a significant decrease in bubble size in 0.25M NaCl with bubbles under 2mm now dominant. These results correspond to the substantial increase in gas holdup with an increase in NaCl concentration from 0.1 to 0.25M (Figure 9). Example error bars are shown in Figure 9 for the case of 0.4M NaCl corresponding to ±2 pooled standard deviations. In all figures, example error bars are given for selected cases only for the purpose of clarity.

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As a result of this inter-dependence and the fact that gas holdup is more easily measured on-line, this parameter is used to indicate coalescence inhibition in the remaining tests.
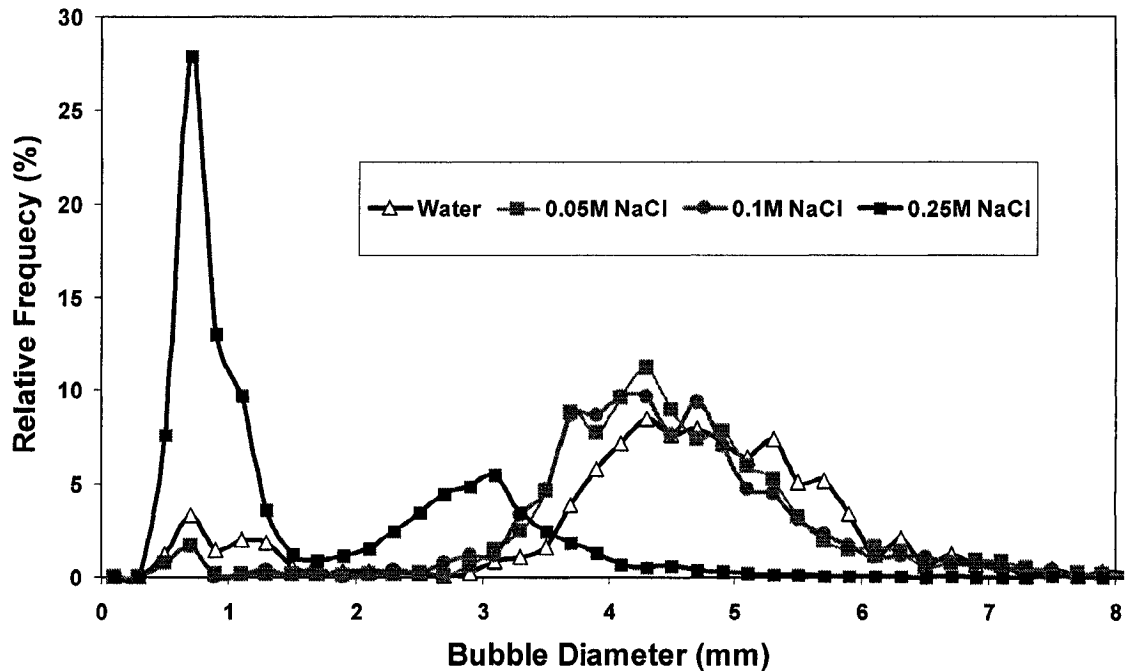
Figure 10 - Bubble size distributions in sodium chloride solutions (note, as more bubbles are counted the 'noise' in the data tends to decrease, i.e., it is a statistical effect (Hernandez-Aguilar and Finch 2005).)

4.1.2 - Effect of Salts

The results of gas holdup versus salt concentration are shown in Figure 11. It should be noted that the pH of the aluminum sulfate solution was adjusted to roughly pH 3 using sulfuric acid. This was done to ensure the aluminum did not precipitate. All other salts were tested at natural pH (6-7) with no acid addition. Although four superficial gas velocities were tested only two (0.7 and 1.7cm/s) are shown for clarity. Aluminum sulfate (3-2 salt) is able to increase gas holdup at relatively low molar concentrations. Each salt containing divalent ions (Na_2SO_4, $Na_2S_2O_3$ and $CaCl_2$) behaved similarly and were able

to increase gas holdup at intermediate molar concentrations. Relatively higher

concentrations of NaCl (monovalent ions) were needed to increase gas holdup.

In detail, $Na_2S_2O_3$ did not follow the same trend as the other 1-2 or 2-1 salts at the

low superficial gas velocity where the rate of increase in gas holdup with concentration

was higher. At the higher gas velocity all the 2-1 and 1-2 salts behaved similarly.

Compared to the other anions, thiosulfate is less stable (readily oxidizing to SO_4^{2-}) which

may be playing a role.
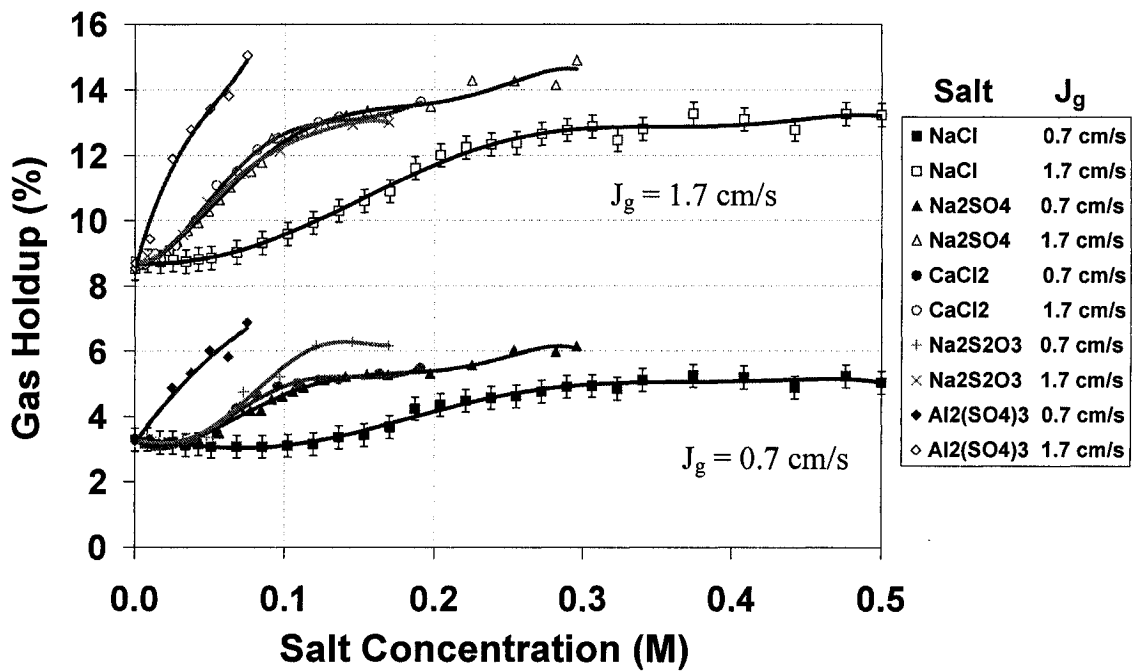
Figure 11 - Gas holdup vs. salt concentration (J_g = 0.7, 1.7 cm/s)

Data compression was achieved by introducing ionic strength in place of

concentration. Ionic strength (μ) is defined by

$$\mu = \tfrac{1}{2}\sum_i C_i Z_i^{\ 2}$$

Equation 10

where C_i is the molar concentration of the ith species and Z_i is the charge of the ith species. The summation is taken over all ionic species in solution. Figure 12 shows that the relationship between gas holdup and ionic strength appears to be independent of salt type.

Zieminski and Whittemore (1971) have demonstrated a correlation between total bubble surface area and ionic strength (for 11 salts tested). Total bubble surface area, like gas holdup, is a function of bubble size, both increasing as bubble size decreases. Keitel and Onken (1982) showed a good correlation between Sauter mean bubble diameter, D_{32}, and ionic strength (they also noted the possibility of using the diameter of hydrated ions to improve the correlation). It seems, therefore, that the higher the charge on the ionic species the more coalescence is inhibited. On one hand this seems counter intuitive as increasing charge neutralizes electrostatic repulsive forces though this may be offset as electrostatics also play a role in determining ion hydration. Zieminski and Whittemore (1971) noted that coalescence behavior was a function of ion-water interactions. Highly hydrated ions tend towards the bulk (away from the solution/air interface) and are termed 'structure makers'. It has been shown that both positive and negative adsorption can cause bubble coalescence inhibition (Foulk and Miller, 1931). The present results generally fall into the category of negatively adsorbed coalescence inhibitors though NaCl has a small structure breaking ability (Weissenborn and Pugh, 1995).

Salt	J_g
■ NaCl	0.7 cm/s
♦ NaCl	1.0 cm/s
▲ NaCl	1.4 cm/s
● NaCl	1.7 cm/s
□ Na2SO4	0.7 cm/s
○ Na2SO4	1.0 cm/s
△ Na2SO4	1.4 cm/s
○ Na2SO4	1.7 cm/s
✖ CaCl2	0.7 cm/s
♦ CaCl2	1.0 cm/s
▲ CaCl2	1.4 cm/s
● CaCl2	1.7 cm/s
▩ Na2S2O3	0.7 cm/s
♦ Na2S2O3	1.0 cm/s
▲ Na2S2O3	1.4 cm/s
⊛ Na2S2O3	1.7 cm/s
■ Al2(SO4)3	0.7 cm/s
♦ Al2(SO4)3	1.0 cm/s
▲ Al2(SO4)3	1.4 cm/s
● Al2(SO4)3	1.7 cm/s
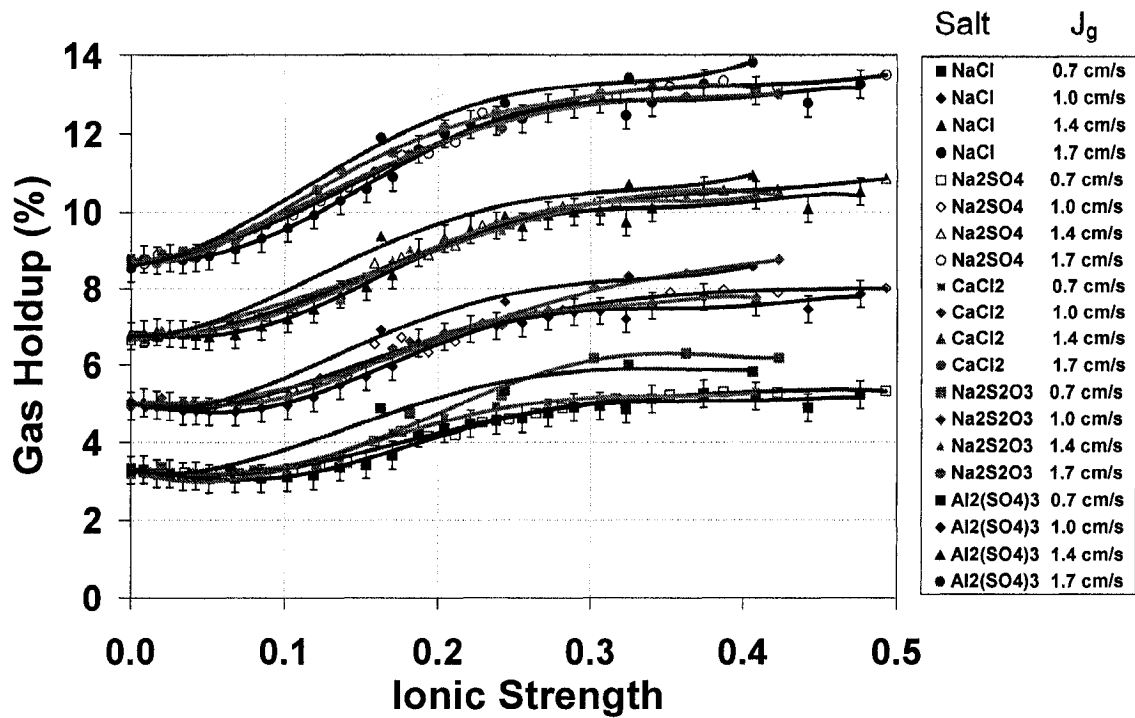
Figure 12 – Gas holdup vs. ionic strength for the four superficial gas velocities (all salts tested)

4.1.3 - Equivalent Frother Concentration

Further data compression was attempted by introducing the relative change in gas holdup with respect to the gas holdup in water, $\Delta\varepsilon_g/\varepsilon_{gH2O}$ (%). Using this 'reduced' gas holdup allows comparison of gas holdup results obtained at different superficial gas velocities. The $\Delta\varepsilon_g/\varepsilon_{gH2O}$ (Figure 13) follows a similar trend for all salts: initially a shallow decrease followed by an exponential increase asymptotic to $\Delta\varepsilon_g/\varepsilon_{gH2O} \sim 60\%$ (i.e., gas holdup is increased by a factor of 1.6). The trend-line in Figure 6 is a polynomial fitted to all the data.

Figure 13 includes $\Delta\varepsilon_g/\varepsilon_{gH2O}$ versus frother (MIBC) concentration (upper axis). It is evident that MIBC is capable of greater suppression of coalescence than salts (over the range of salt concentration tested), and certainly at much lower concentrations. Recycle

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water obtained from Raglan showed, on average, an ionic strength of 0.42 (vertical line on Figure 13). From this observation it can be estimated that salts at Raglan have the same effect, with respect to increased gas holdup, as roughly 7-10ppm MIBC in Montreal tap water (assuming the correlation with ionic strength holds for Raglan water). MIBC at such a concentration would be considered typical (Gélinas et al. 2005) and supports, in terms of gas dispersion, why Raglan is able to operate without the use of frother. In a study of the potash flotation system, which takes place in saturated brine (7M NaCl and KCl), Laskowski et al. (2003) have likewise shown that frother is not needed for bubble size control.
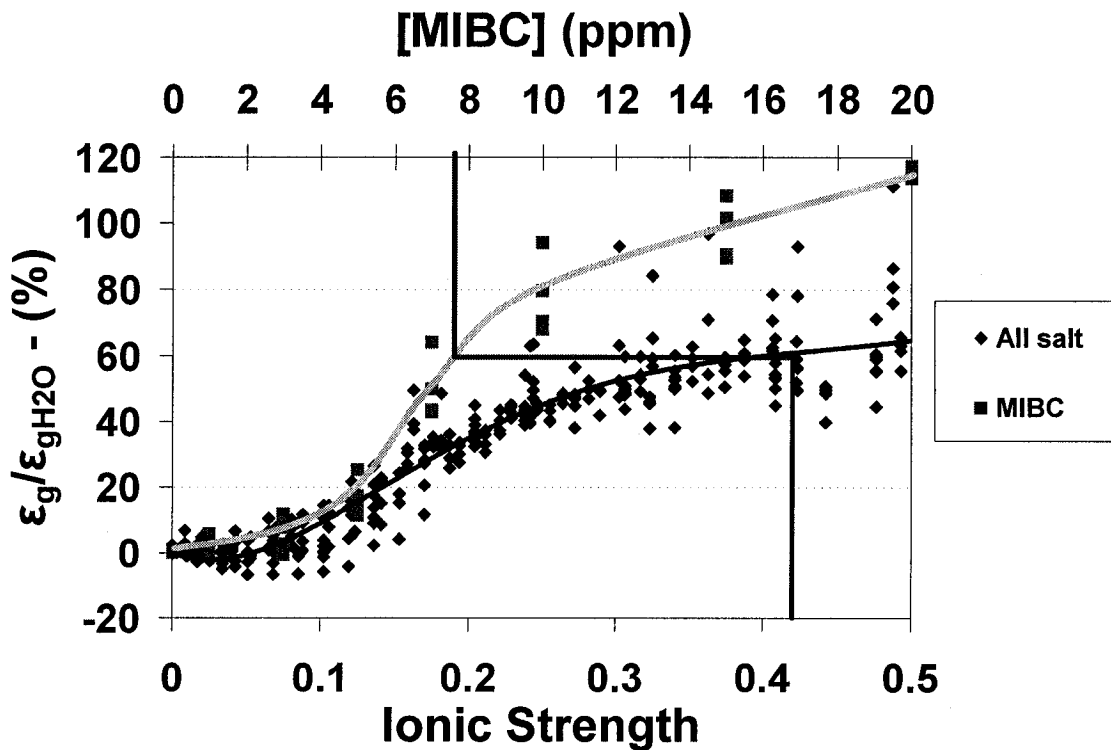
Figure 13 – $\Delta\varepsilon_g/\varepsilon_{gH2O}$ vs. ionic strength of salt (lower axis) and MIBC concentration (upper axis)

4.1.4 - Salt and Frother

Gas holdup tests were run as a function of MIBC concentration with and without 0.5M NaCl (roughly the ionic strength of Raglan process water). Figure 14 shows results obtained at superficial gas velocities of 0.7 and 1.7cm/s. Gas holdup in the presence of sodium chloride was higher. The presence of salt increased the rate of gas holdup change with concentration, suggesting a maximum effect at ca. 10-15ppm frother (for $J_g = 0.7$ cm/s), lower than in the absence of salt. This demonstrates the salt's continued ability to decrease bubble size and increase gas holdup in the presence of frother. Evidence for an additive effect is mixed: at 0.7cm/s MIBC alone reaches the same gas holdup as MIBC and salt while at 1.7cm/s gas holdup in the presence of salt remains consistently higher.

Sol'n	J_g (cm/s)
□ water	0.7
△ water	1.7
■ 0.5 M NaCl	0.7
▲ 0.5 M NaCl	1.7
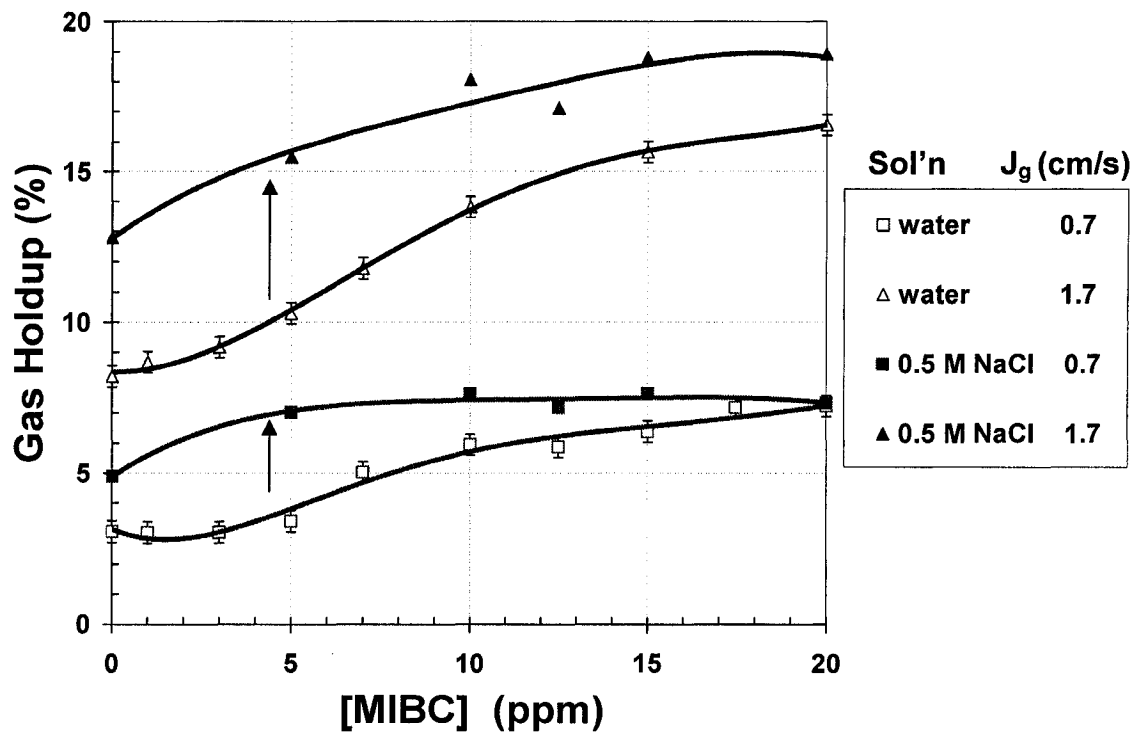
Figure 14 – Gas holdup vs. MIBC concentration in the absence and presence of 0.5M NaCl

4.1.5 - Foaming: Comparing Salts and Frother

Equilibrium foam heights were measured at the same time as the gas holdup tests were conducted. Figure 15 shows the results obtained at a superficial gas velocity of 1.7cm/s, the highest air flow rate tested. All the salt solutions produced shallow foams (<10cm). The same was true for the MIBC solutions below 10-15ppm (upper axis). Comparing at 0.4 ionic strength, foaming is equivalent to about 8-10ppm MIBC, as before when comparing on the basis of gas holdup.
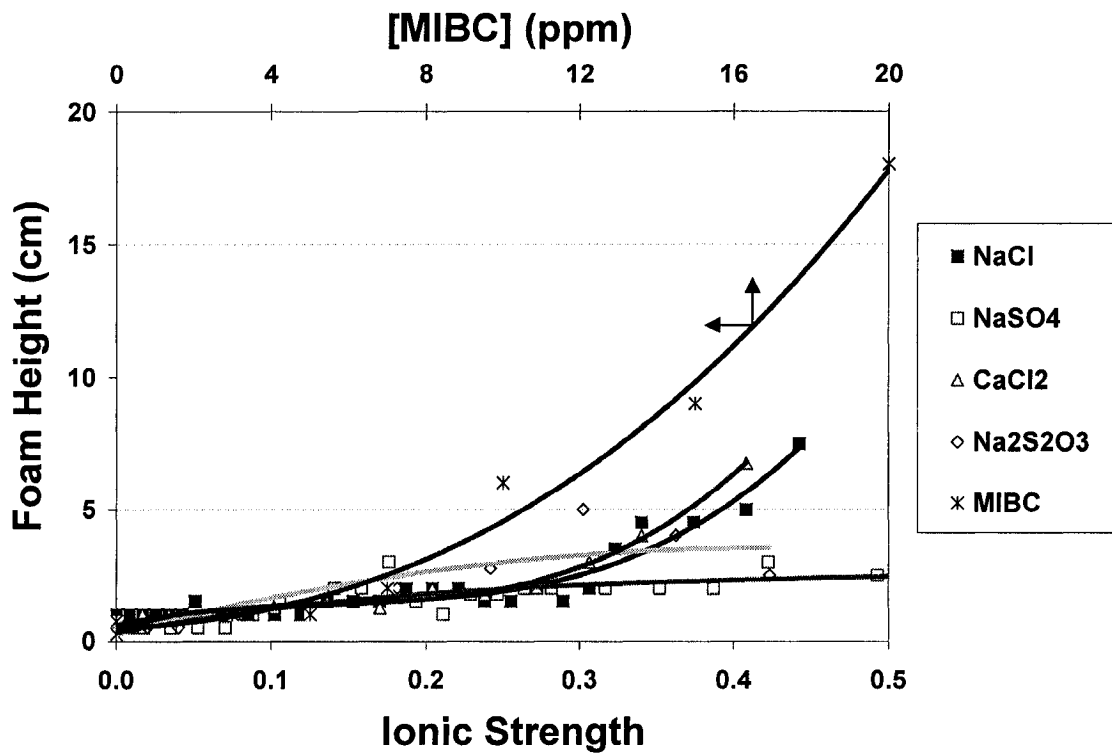
Figure 15 – Equilibrium foam heights for salt and MIBC solutions (J_g = 1.7cm/s)

4.1.6 - Foaming: Solutions Containing Both Salt and Frother

Figure 16 shows the foam height results obtained for MIBC solutions ranging from 0-20ppm (in water). The second data set shows foam heights for the same MIBC

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concentrations in 0.5M NaCl. The results show that below 10ppm MIBC the salt solution produces deeper foam while above 10ppm MIBC the salt reduces foam height.

This may be explained by the fact that at low MIBC concentrations the presence of salt produces finer sized bubbles, as shown in the gas holdup results. This encourages foam formation at low frother concentration. Above 10ppm the sodium chloride seems to destabilize the foam in relation to MIBC only.
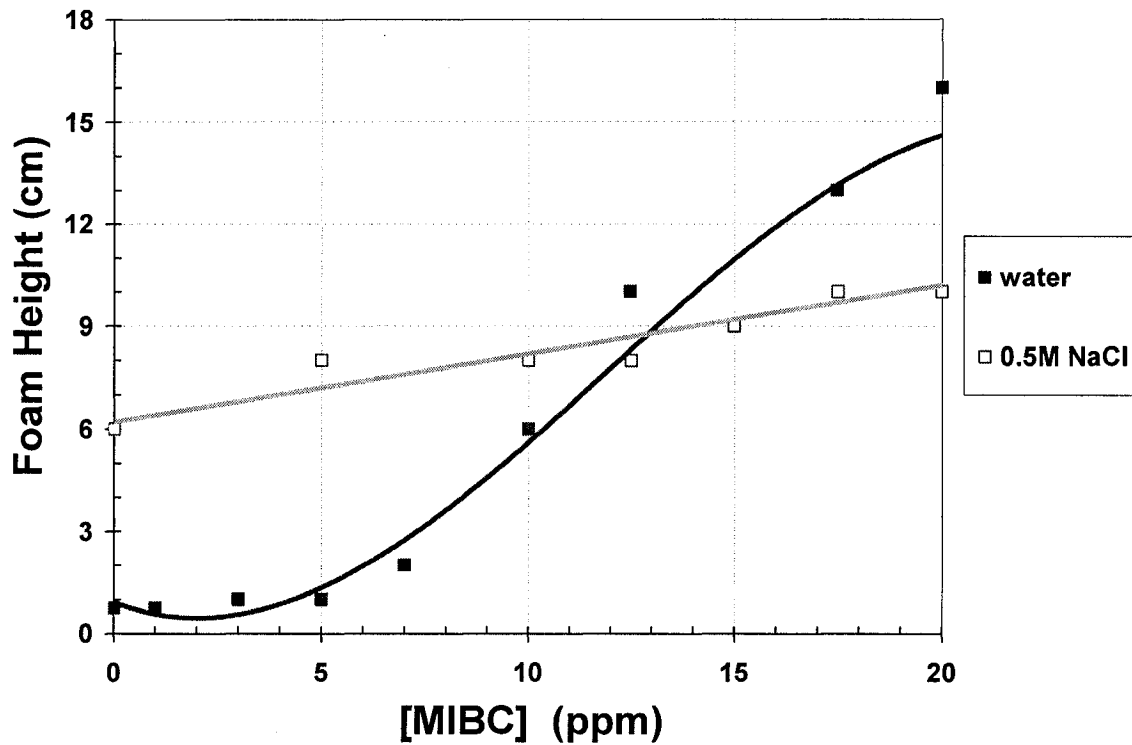
Figure 16 – Effect of 0.5M NaCl on foaming behavior in MIBC solutions (J_g = 1.7cm/s)

Figure 17 combines results from Figure 14-Figure 16. This shows that gas holdup is increased in the presence of salt, i.e., finer bubbles are produced, which help build the deeper foam, at least up to 10ppm MIBC. Above 10ppm despite the finer bubbles (higher gas holdup) in the presence of salt, foam is now destabilized. Laskowski et al. (2003)

showed a similar effect at much higher salt concentrations (NaCl, KCl saturated brine) with MIBC.
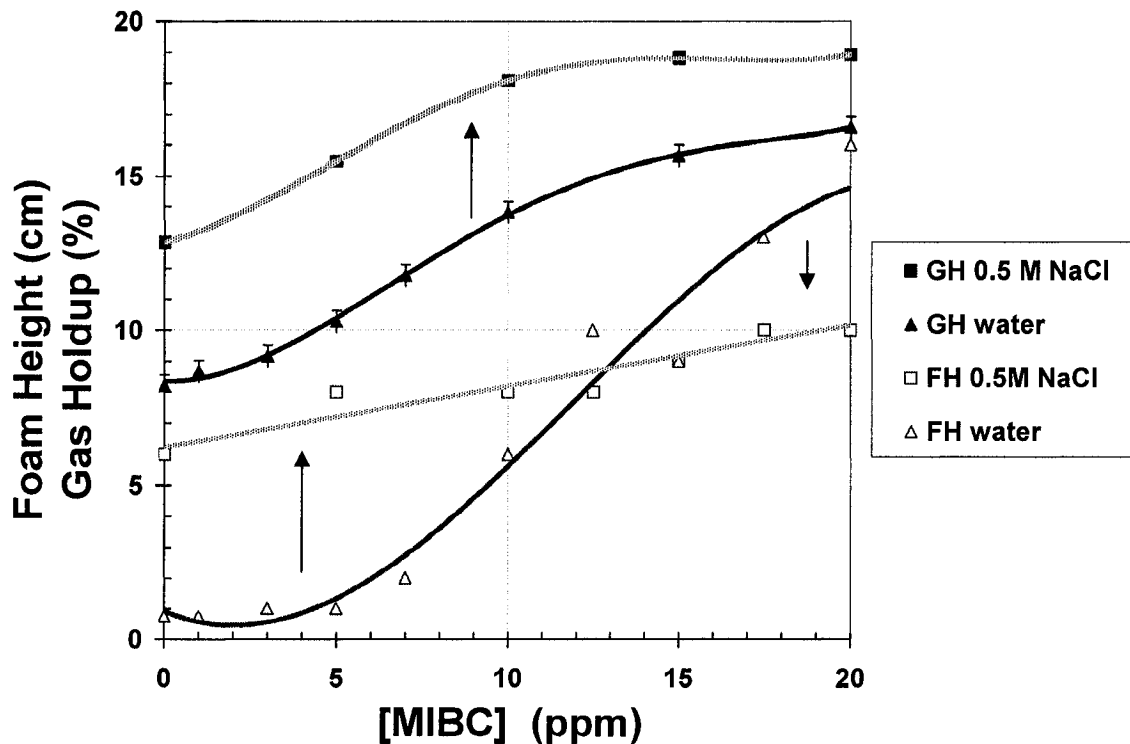
Figure 17 – Effect of MIBC concentration on Gas Holdup and Foam Height in water and 0.5M NaCl
(GH = gas holdup, FH = foam height)

4.1.7 - Retention Times

Retention times were determined for each of the systems tested. The salts produced shallow foams as shown in Figure 15. This means that retention time is largely dependent on the gas holdup (in solution) for the salt systems. MIBC solutions do produce some foam, especially at high air flow rates, and concentrations (>10ppm). The presence of foam will increase retention time.

The superficial gas velocities used (0.7-1.7cm/s), gave an approximately linear increase in gas holdup (Figure 9). Thus, it is assumed that we are working in the linear $\Delta V/\Delta Q$ region.

The results in Figure 18 follow similar trends as for gas holdup. The salts containing multivalent ions increased retention time at lower molar concentrations. The MIBC solutions produced higher retention times especially at the higher concentrations where foaming in present. In terms of frother equivalence, 0.4M NaCl (ionic strength 0.4) is equal to ca. 10-12ppm MIBC.

As in the gas holdup case, sodium thiosulfate shows a different trend, the retention times being consistently lower for the other |1-2| salts. This corresponds to the higher gas holdup for sodium thiosulfate at the low gas velocity (Figure 11). These higher gas holdup values decrease the slope ($\Delta V/\Delta Q$). The graphs used to determine rt values can be found in the appendix (Figures A1-A6).
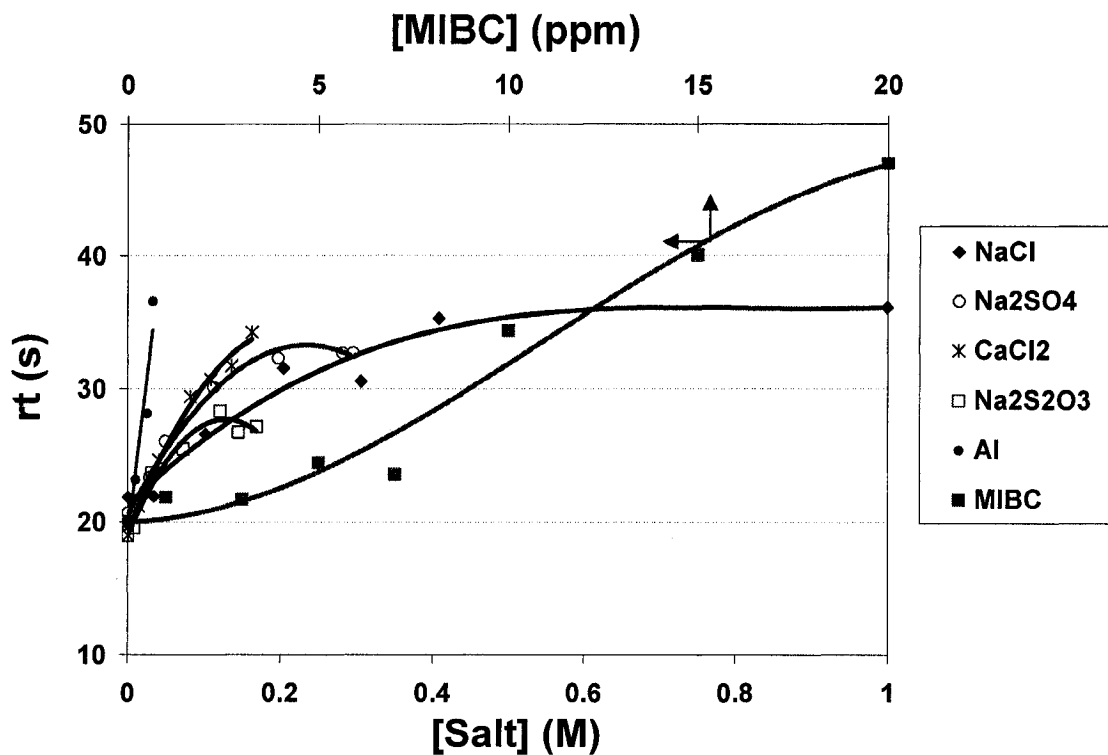
Figure 18 – Effect of salt or frother type and concentration on retention time

4.2 – Three-Phase Tests with Talc

Tests were run to complement the effect of sodium chloride concentration on gas holdup by including solids and liquid overflow rate. The results were compared to a system containing typical dosages of MIBC.

4.2.1 - Gas Holdup

Figure 19 and Figure 20 show the effect of NaCl and MIBC on gas holdup in the 1%w/w talc system, respectively. Both figures show the expected linear increase in gas holdup with increasing gas velocity. The results show increasing gas holdup with increasing NaCl or MIBC concentration. This is due to the production of finer sized bubbles which rise at lower velocities, thus gas residence time inside the column increases.
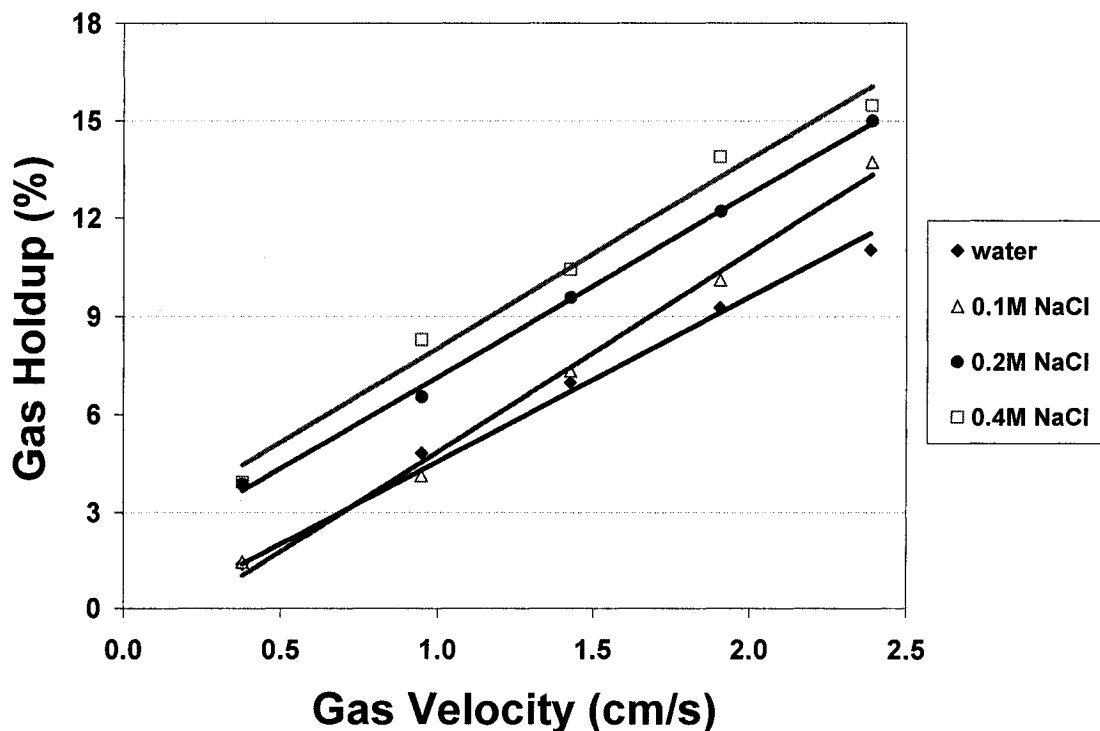
Figure 19 – Effect of NaCl concentration on gas holdup in a system containing 1%w/w talc
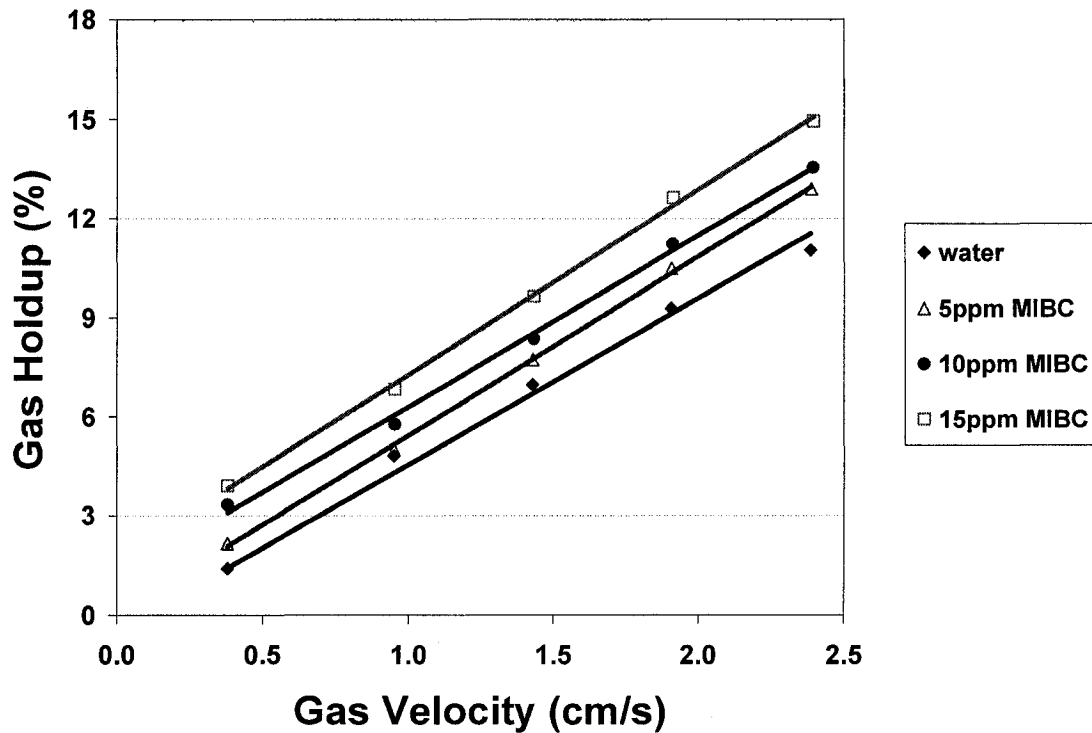
Figure 20 – Effect of MIBC concentration on gas holdup in a system containing 1%w/w talc

4.2.2 - Overflow Froth Images

Figure 21 is an overhead picture of the top of the column. The column is filled with water and 1%w/w talc and the air is off. Figure 22 depicts the case with air on, at three gas velocities. Bubbles form but quickly burst and there is no froth overflow into the launder. This system does not form a stable froth phase, regardless of the gas velocity.

Figure 23 depicts the 0.1M NaCl-talc system which does form a stable froth. The picture sequence also illustrates the increasing volume of froth which overflows into the launder with increasing gas velocity. This result shows that froth stability results from the presence of both salt and talc (recall with 0.1M alone, stable foam did not form). This seems to suggest a combination bubble size, chemistry and stabilization by solids is at play.

40
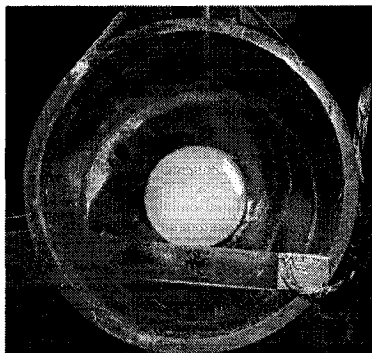
Figure 21 – Overhead picture of column and overflow launder (a 30 cm ruler is shown as a reference)
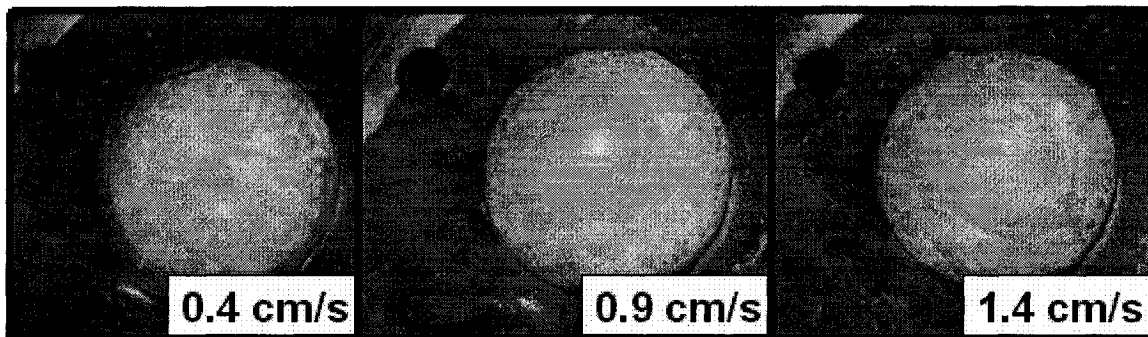
Figure 22 – Overhead pictures of froth formed in water with 1% w/w talc at 3 gas velocities (note: no overflow into launder)
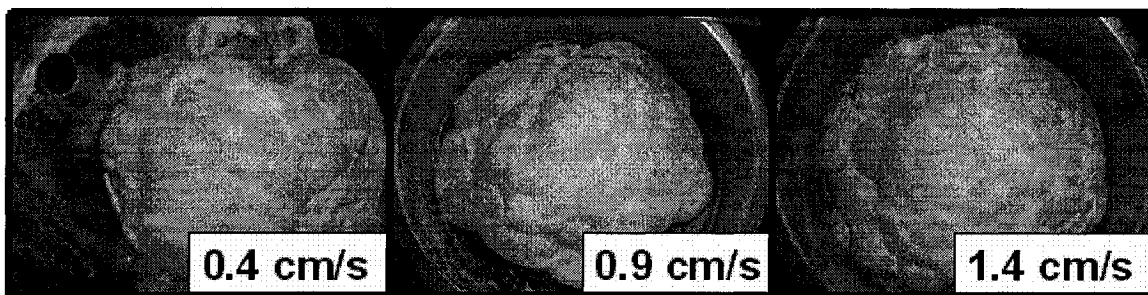
Figure 23 – Overhead pictures of froth formed in 0.1M NaCl with 1% w/w talc at 3 gas velocities (note: overflow into launder)

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4.2.3 - Comparing the NaCl and MIBC Systems

Figure 24 shows the effect of increasing gas velocity and NaCl concentration on total overflow rate of solids plus liquid. Increasing either salt concentration or gas velocity increases the overflow rate. The same effect can be seen in Figure 25 in the system containing MIBC. Increasing MIBC or NaCl concentration produces finer sized bubbles in the pulp which drives higher mass transfer (liquid and solids) into the froth and then over the lip of the cell. Increases in gas velocity likewise increase bubble surface area flux. There will be a tendency for bubble size to increase with gas velocity (Finch and Dobby, 1990) but this is not enough to offset the gas velocity contribution to bubble surface area flux.
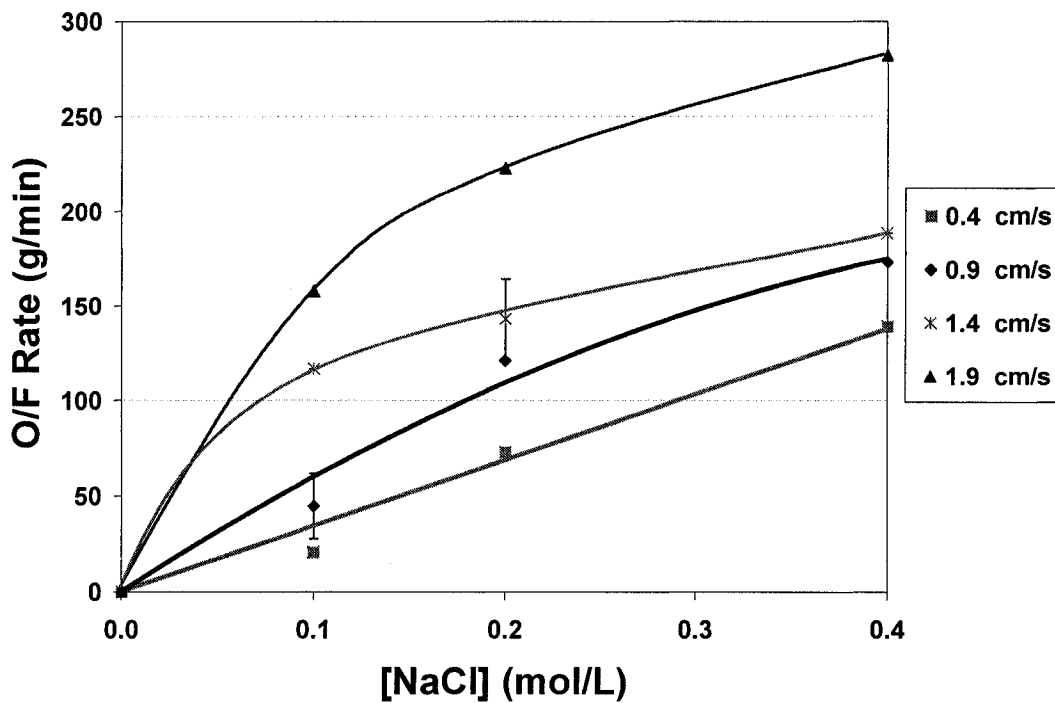
Figure 24 - Effect of NaCl concentration and gas velocity on overflow rate
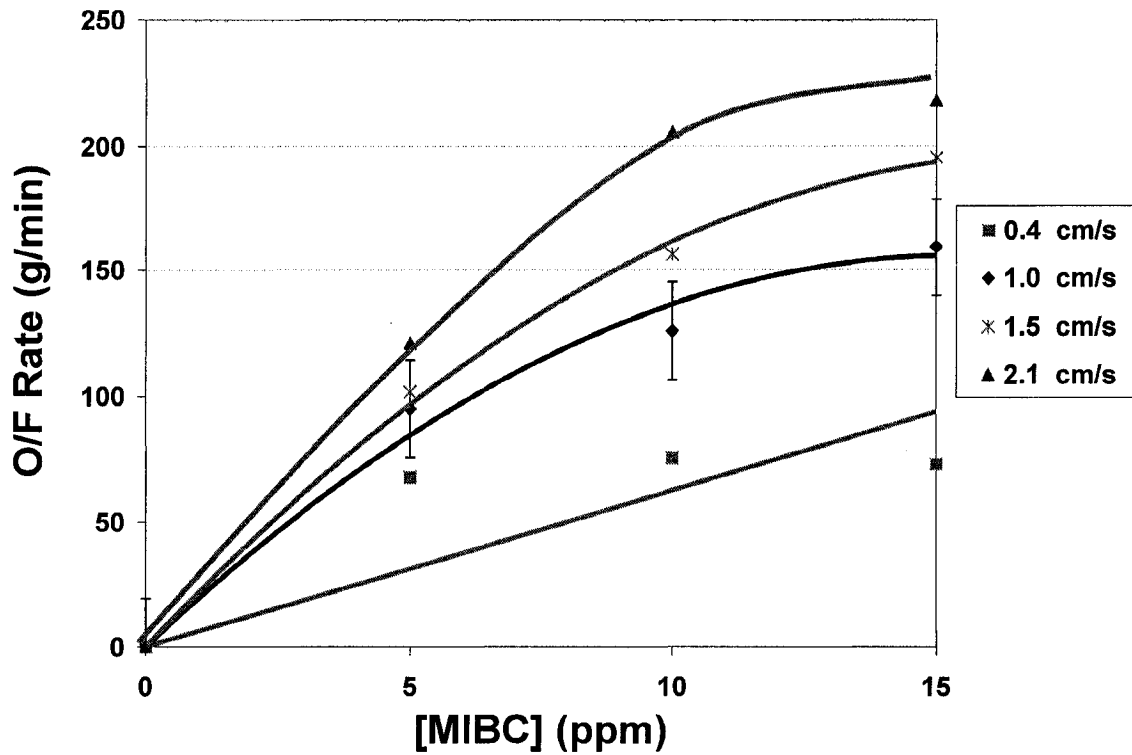
Figure 25 - Effect of MIBC concentration and gas velocity on overflow rate

Comparing the salt and frother systems (Figure 26) it can be seen that the 15ppm MIBC overflow lines lie higher than the 0.2M NaCl but lower than the 0.4M NaCl. These results suggest that the ionic strength of 0.4 (Raglan water $\approx$ 0.4) is equivalent to somewhat more than 15ppm MIBC. These results differ from the conclusion reached in the two-phase tests where, using gas holdup as the criterion, 0.4M NaCl was similar to 7-10ppm MIBC. One reason may be the adsorption of some MIBC onto the hydrophobic surface of the talc, thus reducing the actual MIBC concentration in solution.
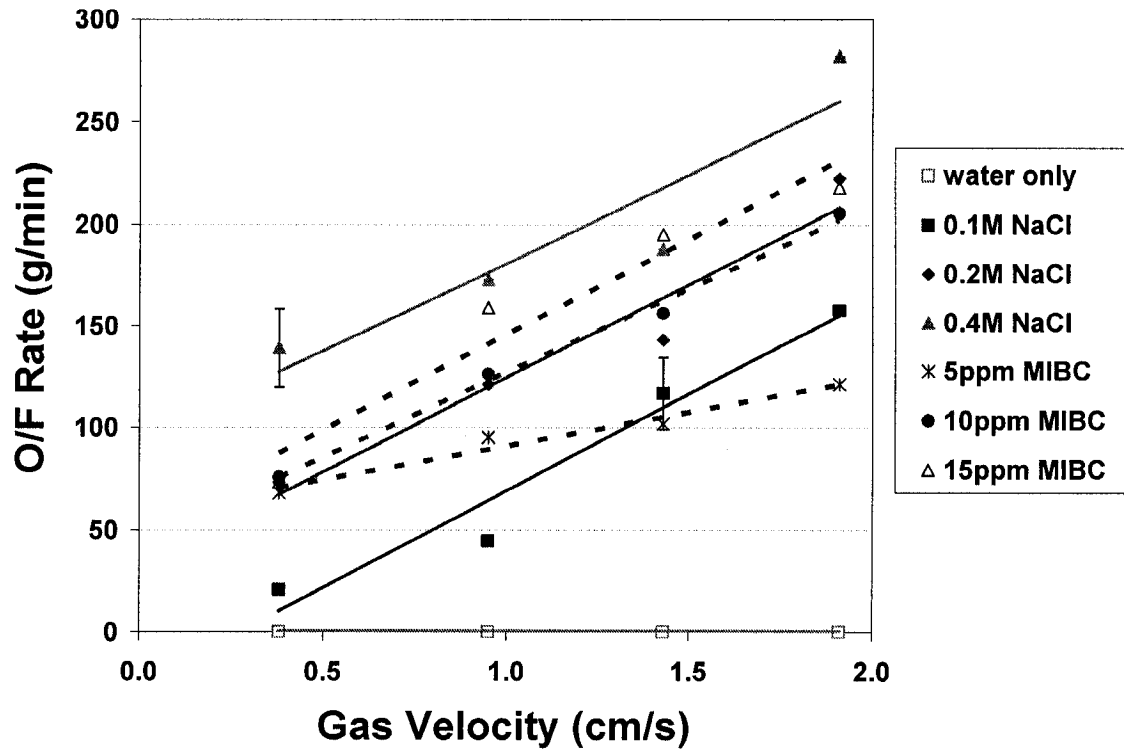
Figure 26 – Effect of gas velocity on overflow rates in NaCl (solid trend lines) and MIBC solutions (dashed trend lines)

Figure 27 shows the overflow rates versus gas holdup. The data are compressed somewhat (especially as gas holdup increases) compared to the dependence on gas rate (5ppm frother being a notable exception), suggesting gas holdup is closer to the unique independent variable. Gas holdup to a first approximation can be considered a surrogate for bubble surface are flux and some dependence on this variable is expected.
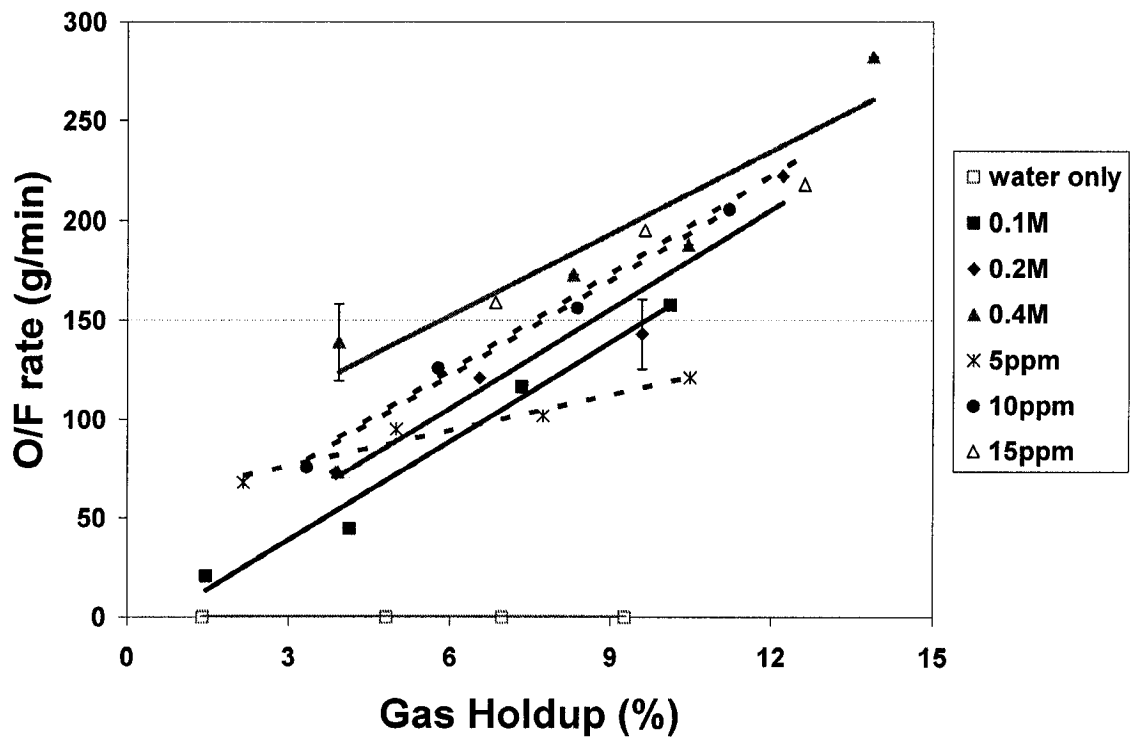
Figure 27 – Effect of gas holdup on overflow rates in NaCl (solid trend lines) and MIBC solutions (dashed trend lines)

Figure 28 divides the overflow rates into solids (talc) and solution starting with 0.1M NaCl. Note that the water rate always exceeds the solids rate and increases more rapidly with gas velocity, to exceed the solids by 6 times (120g/min to 20g/min) at 2cm/s. This is recorded by the (almost linear) decrease in percent solids.
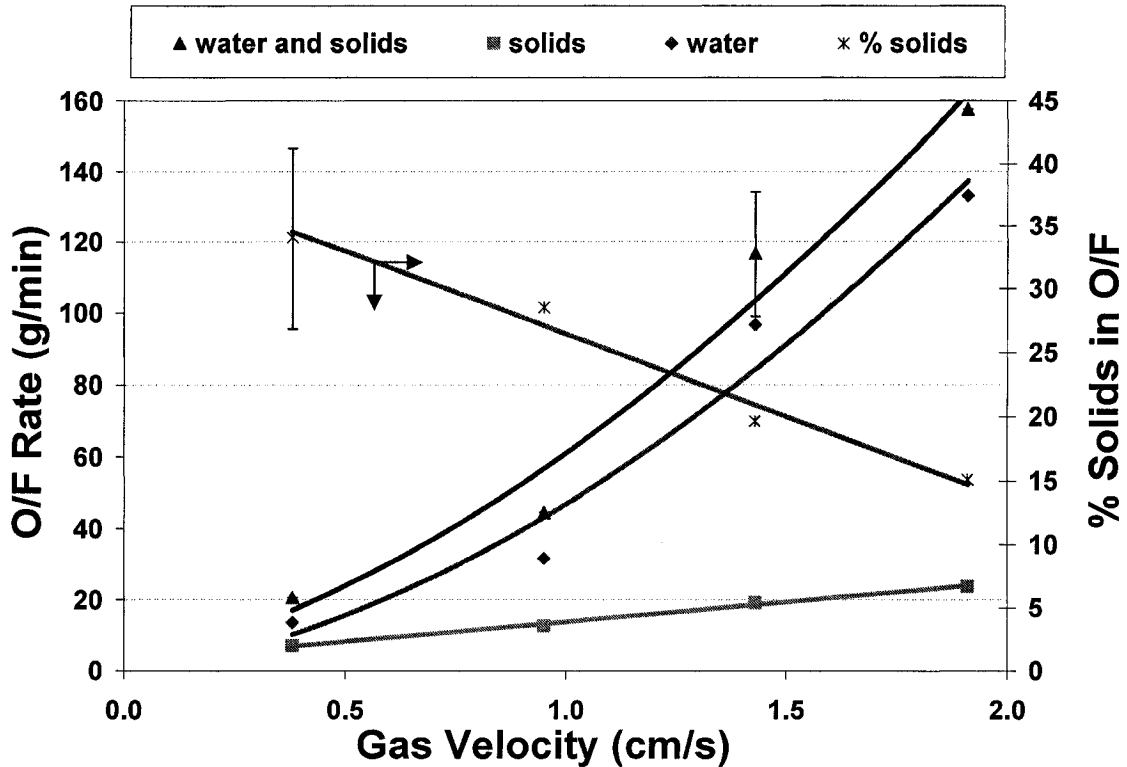
Figure 28 – Overflow rates and percent solids for 0.1M NaCl system

Figure 29 shows the results for the 0.4M NaCl tests. The results follow the same trends as the 0.1M NaCl tests but the overflow rates are higher due to the increased frothing in the salt solution. Figure 30 shows the results for the 15ppm MIBC test, the highest frother concentration tested. All the results show decreasing percent solids with increasing gas velocity. Results for the remaining salt and frother concentrations can be found in the appendix.
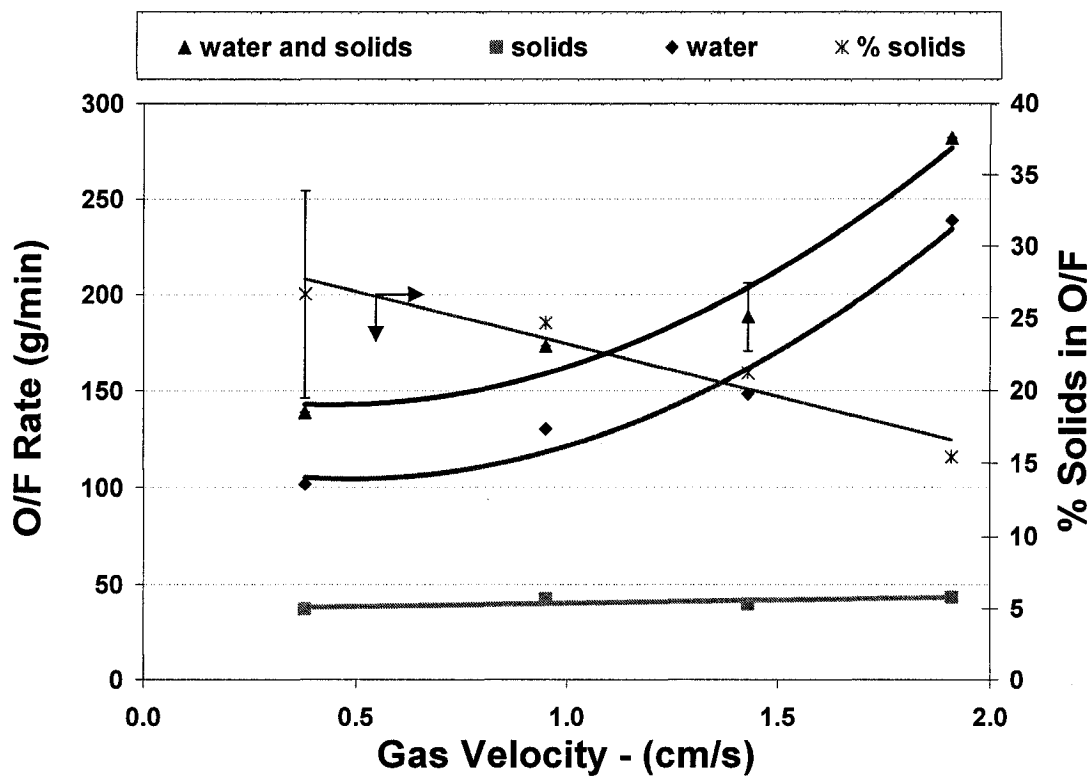
Figure 29 - Overflow rates and percent solids for 0.4M NaCl system
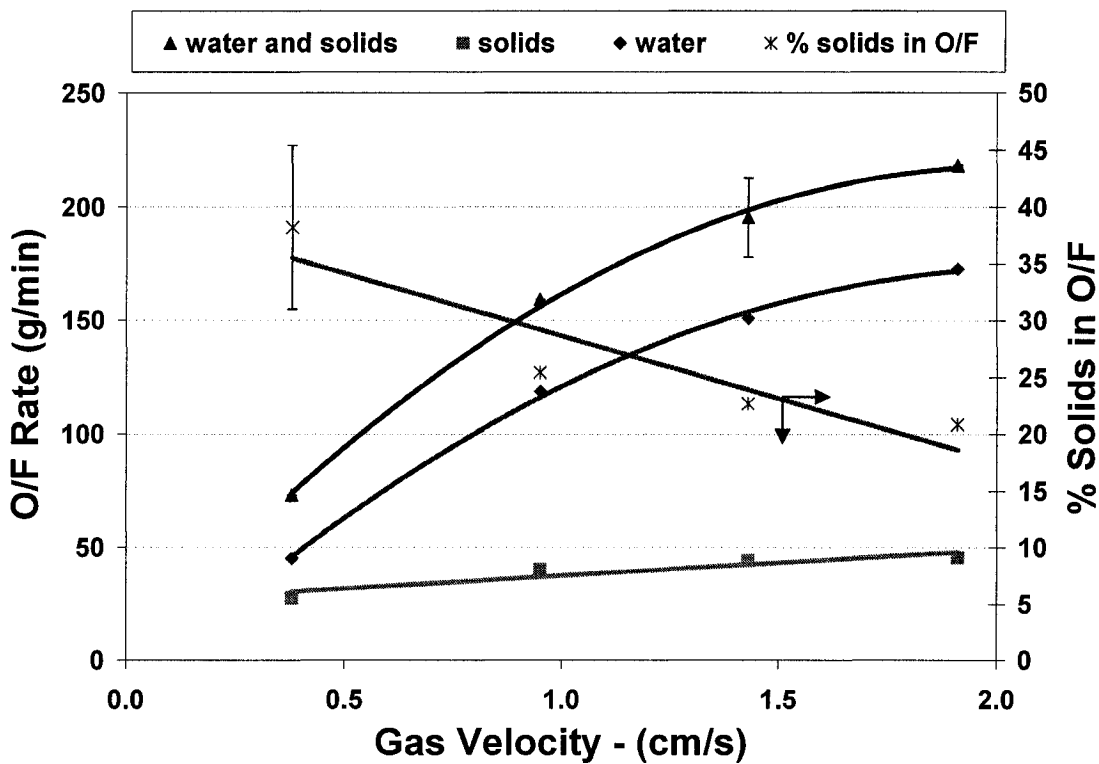
Figure 30 - Overflow rates and percent solids for 15ppm MIBC system

4.2.4 - Percent solids in the overflow

Rather than following the overflow rates the trend in percent solids may be revealing. This would be useful as in-plant percent solids is relatively easy to measure. Figure 31 shows the percent solids in the overflow as a function of NaCl (a) and MIBC (b) concentration. It is evident that all the tests show decreasing percent solids with increasing superficial gas velocity, i.e., a preferential transport of water, this can be attributed to the fact that almost all the solids present in the system are recovered, i.e., there is 'starvation' of talc. The recovery of talc does exceed 90 % at high salt or frother concentrations with high gas velocity as seen in Figure 32. However, the low salt and low frother also show the decreasing percent solids trend and solids do not appear to be 'starved' in these cases.
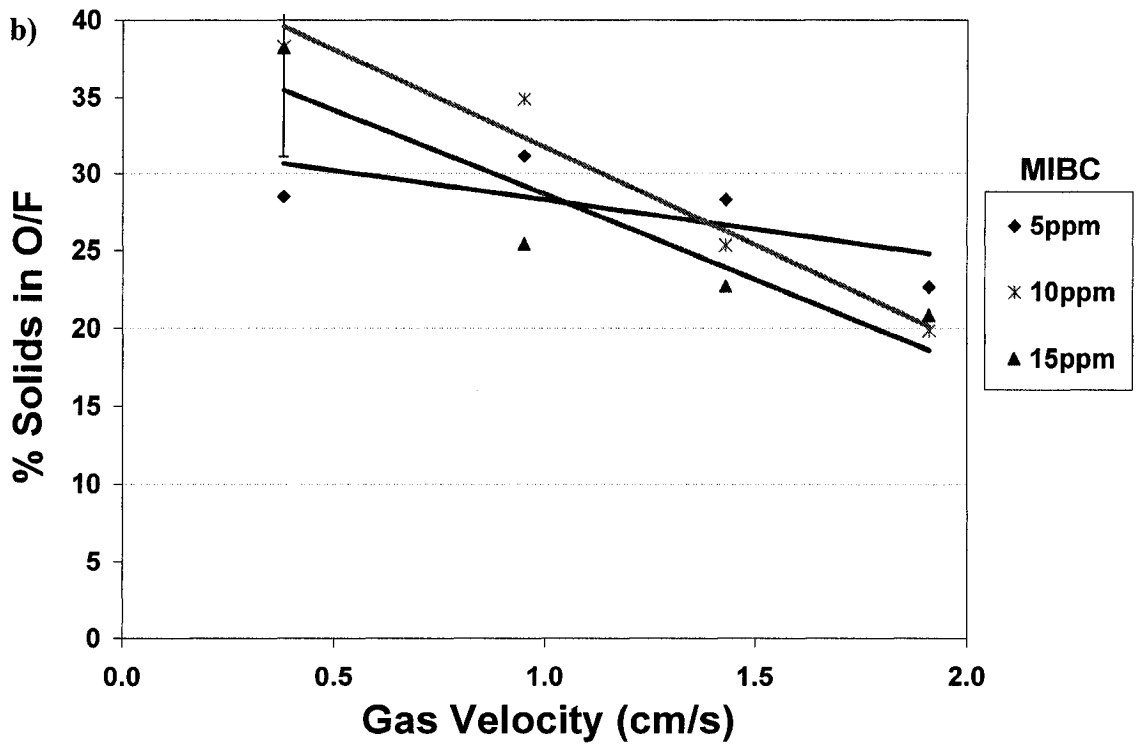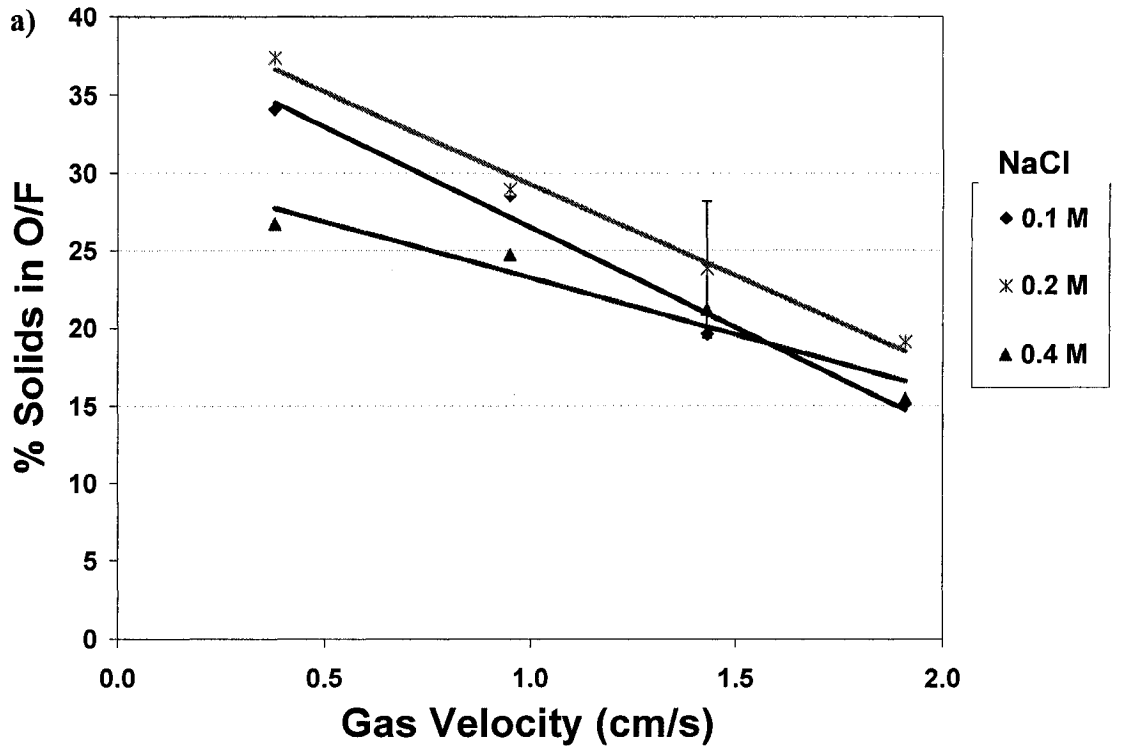
Figure 31 - Effect of a) NaCl and b) MIBC concentration and gas velocity on percent solids in the overflow
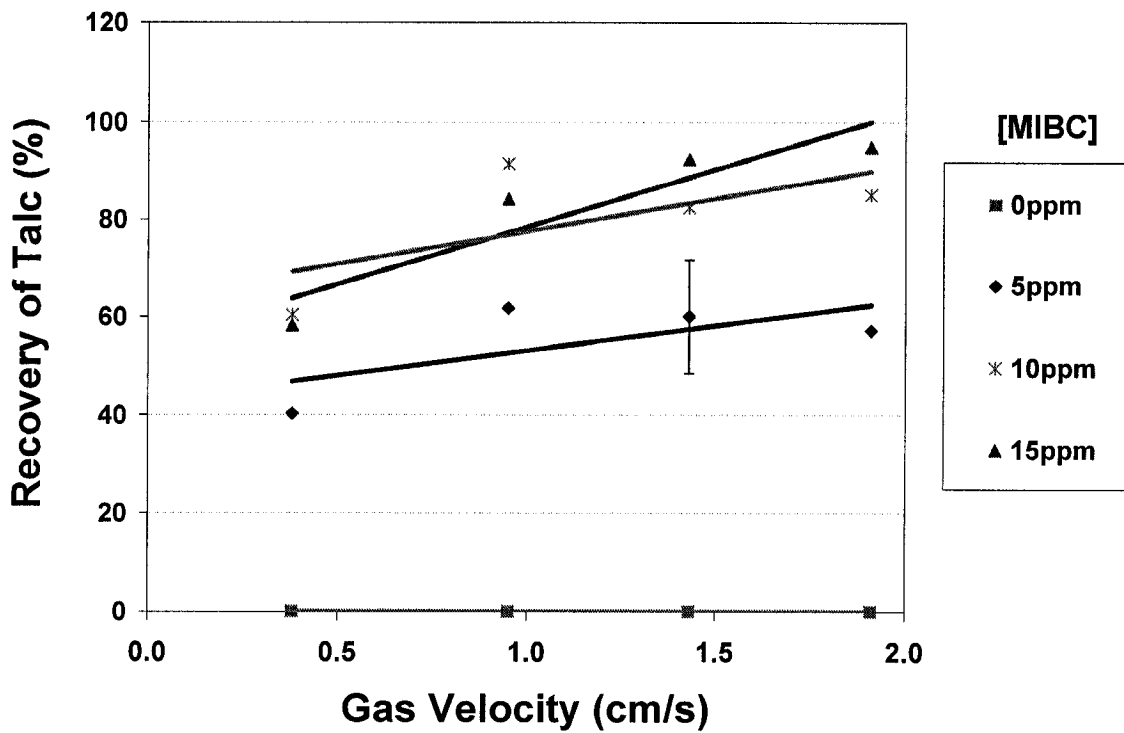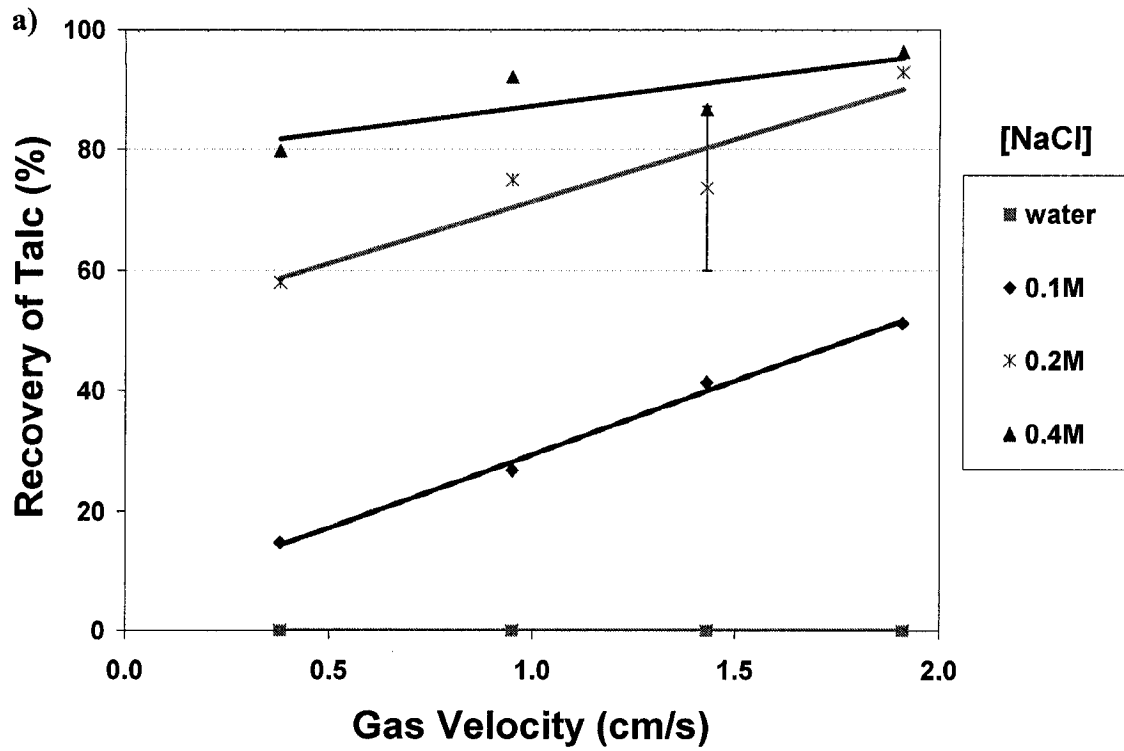
Figure 32 – Effect of a) NaCl and b) MIBC concentration and gas velocity on talc recovery

4.3 – Three-Phase Tests with Ore

4.3.1 - Effect of Salt and Frother on Gas Dispersion Properties

Table 4 summarizes the test conditions and results. For all gas velocities, the effect of increasing NaCl concentration or the addition of MIBC increases gas holdup and decreases mean bubble size (D_{10}, D_{32}) compared to water alone. The effect of increasing gas velocity was to increase gas holdup and bubble size for all (the exception is water alone which is discussed later).

Table 4 – Summary of selected gas dispersion results[3]

Test #	Solution	Jg (cm/s)	ε_g (%)	D_{10} (mm)	D_{32} (mm)	S_b (s^{-1})
1	water	0.4	2.80	3.36	4.45	5.05
2	water	0.9	6.59	4.04	5.10	10.28
3	water	1.5	12.95	3.05	5.05	17.31
4	0.1M NaCl	0.4	3.55	2.57	2.94	7.68
5	0.1M NaCl	0.9	8.35	3.04	3.66	14.38
6	0.1M NaCl	1.5	18.79	3.91	4.82	18.28
7	0.2M NaCl	0.4	4.42	0.89	1.16	19.50
8	0.2M NaCl	0.9	10.23	1.52	2.84	18.57
9	0.2M NaCl	1.5	15.82	3.04	4.19	20.96
10	0.4M NaCl	0.4	4.69	0.93	1.11	20.36
11	0.4M NaCl	0.9	10.86	1.40	2.44	21.58
12	0.4M NaCl	1.5	15.84	1.55	3.10	28.29
13	10ppm MIBC	0.4	4.29	1.04	1.18	19.30
14	10ppm MIBC	0.9	9.93	1.41	1.93	27.48
15	10ppm MIBC	1.5	18.79	2.17	3.15	28.09

The evolution of the bubble size distribution with NaCl concentration is seen in Figure 33. The distribution changes from bi-modal (water) to uni-modal ($\geq$0.2M NaCl). The 0.1M NaCl solution produced an intermediate condition: the large bubbles clearly

[3] Refer to - Note Concerning Bubble Size Results p.57

becoming smaller and the fine bubbles seen in water largely suppressed. The 0.2 and 0.4M sodium chloride solutions produced similar, quite narrow (single mode) distributions centered at ca. 1.2mm.
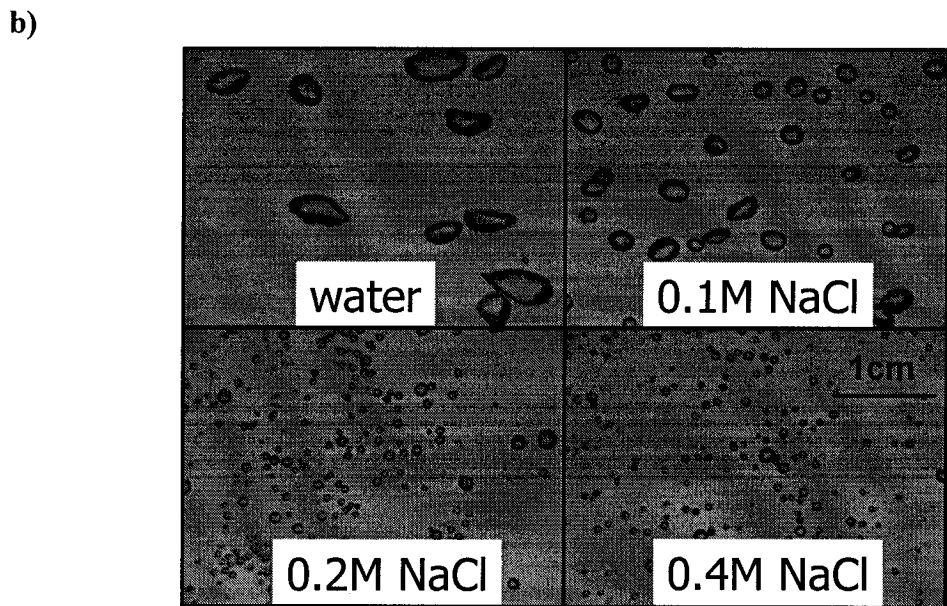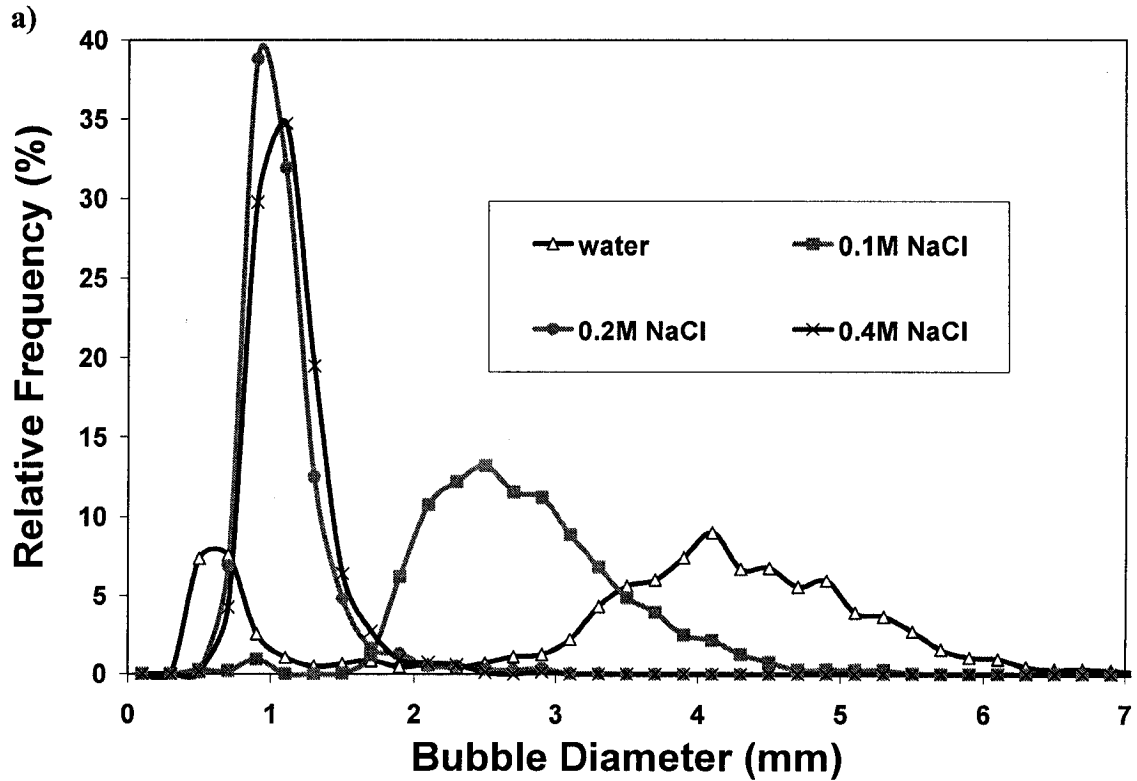
Figure 33 - a) Effect of NaCl concentration on bubble size distribution (J_g = 0.4 cm/s), b) Example images

Figure 34 includes the 10ppm MIBC results obtained at the same gas velocity. The results show similar bubble size distributions for 0.2M, 0.4M NaCl and 10ppm MIBC. This demonstrates that both salt and frother are able to produce equally fine sized bubbles in a flotation system. The results obtained at gas velocity 0.9 and 1.5cm/s are shown in the appendix, Figures A19-A20.
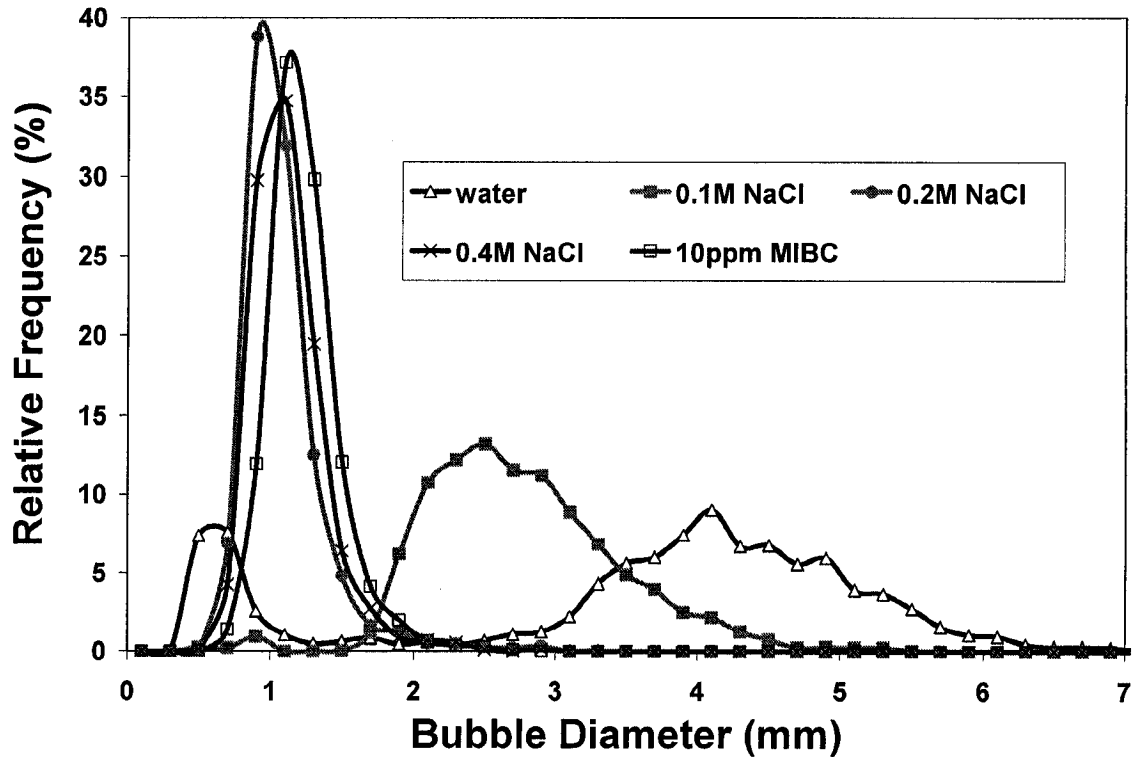
Figure 34 – Effect of NaCl concentration on bubble size distributions (Jg = 0.4cm/s)

Figure 35 shows the effect of NaCl, MIBC and superficial gas velocity on Sauter mean bubble diameter. There is a significant decrease in average bubble size upon addition of NaCl, the effect being evident at all 3 gas velocities (0.4, 0.9 and 1.5cm/s). The results obtained in a 10ppm MIBC solution are comparable to those obtained in 0.4M NaCl.
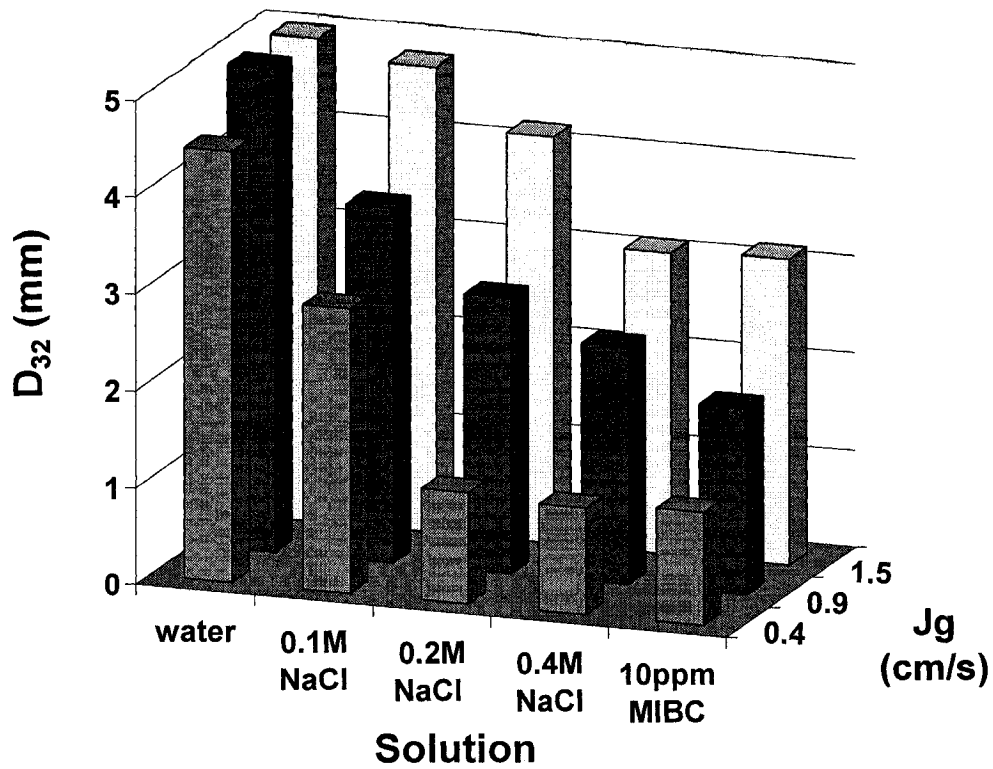
Figure 35 – Effect of NaCl, MIBC and J_g on Sauter mean bubble diameter (D_{32})

The effect of solution chemistry and gas velocity on bubble surface area flux (S_b = $6J_g/D_{32}$) is shown in Figure 10. The results show increasing bubble surface area flux with increasing salt concentration and gas velocity, with the largest surface area flux in the 0.4M NaCl being similar to that for the 10ppm MIBC case. The maximum S_b (ca. $30s^{-1}$) is on the low side of those seen in industrial applications (Nesset et al., 2006).
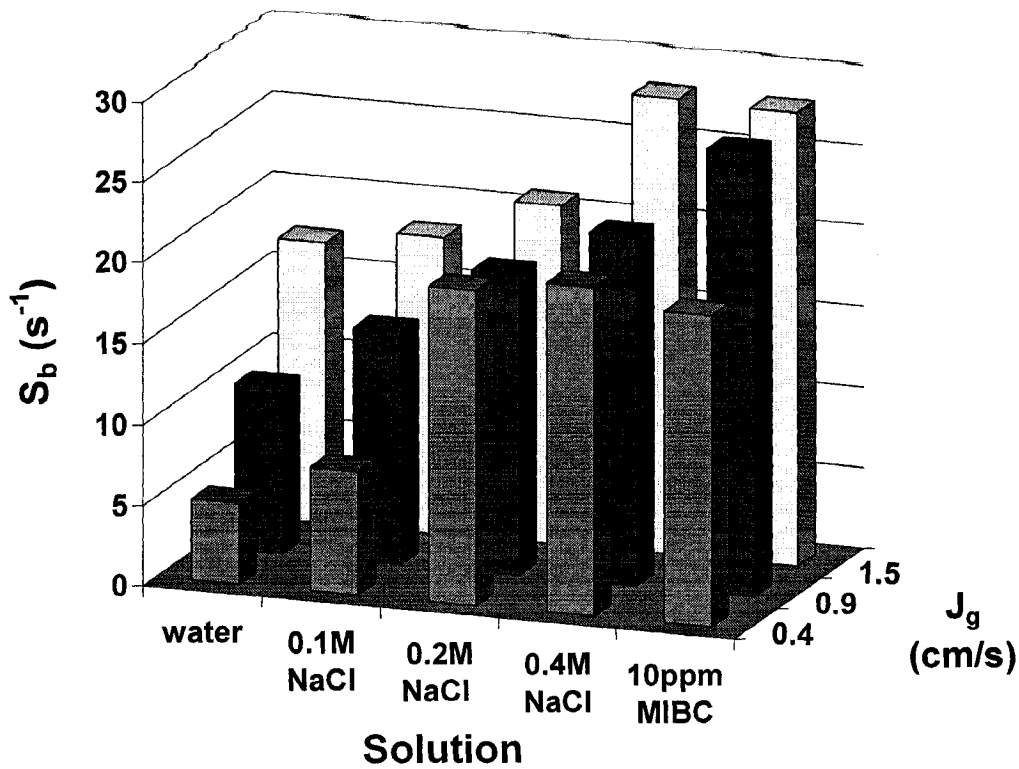
Figure 36 – Effect of NaCl, MIBC and gas velocity and surface area flux

Figure 37 shows the effect of NaCl and MIBC on gas holdup. The results show increasing gas holdup with increasing salt concentration which corresponds to the decreased bubble size. The 10ppm MIBC solution shows a comparable gas holdup to 0.4M NaCl as expected from the similar average bubble sizes (Figure 34 and Figure 35). The 0.2M NaCl gives similar gas holdup to 0.4M NaCl at lower gas velocities (J_g = 0.4–1.4cm/s), corresponding to similar bubble size distributions seen in Figure 34.
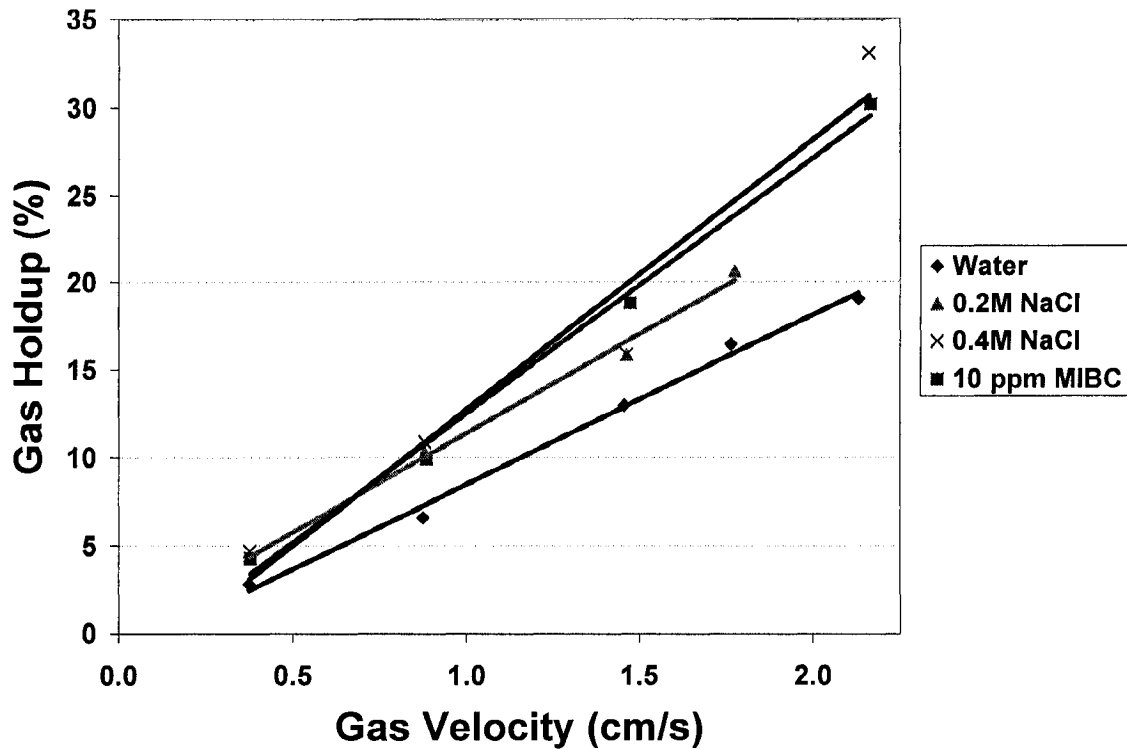
Figure 37 – Effect of NaCl and MIBC on gas holdup

4.3.2 - Effect of Gas Velocity

The effect of increasing gas velocity is to increase gas holdup and to increase mean bubble size (D_{10}, D_{32}). This effect can be seen in Figure 38 and Figure 39 which also show the distribution become wider at higher gas velocities.

The water system (Figure 38) shows a bi-modal bubble size distribution. There are two distinct bubble diameters: less than 1mm (peaking at 0.5mm) and greater than 1mm (peaking at 4 - 4.5mm). This system produced very large bubbles. Interestingly, there is a higher fraction of small bubbles at high superficial gas velocities. This is probably due to a bubble breakage mechanism which is subdued at higher salt (or frother)

concentrations (Shäfer et al., 2002). This effect can also be seen in Figure 34, the fine

bubbles present with water alone almost completely disappear as salt or frother is added.
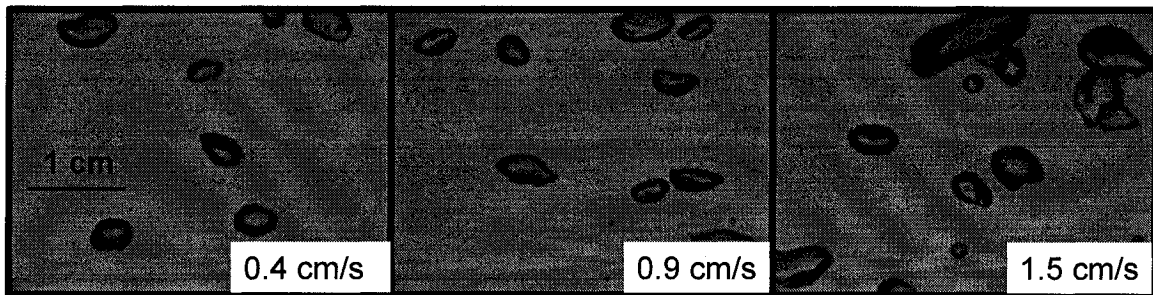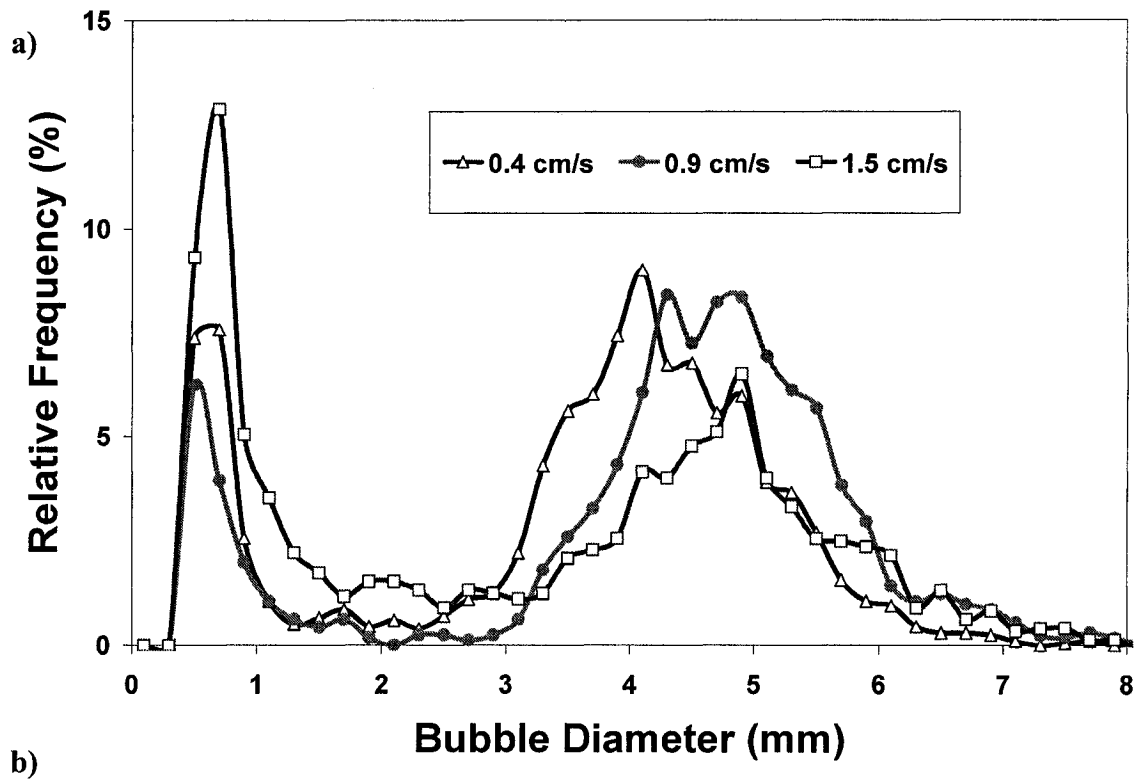
Figure 38 - a) Effect of superficial gas velocity on bubble size distribution in water,
b) Example images

At the other extreme from water, significantly smaller bubbles are produced in the

10ppm MIBC solution (Figure 39). The bubble size distribution for 0.4cm/s is narrow, all

the bubbles are between 0.5 and 2.5mm in diameter. Increasing the gas velocity to

1.5cm/s, the distribution becomes flat and wide with bubble diameters now ranging from

ca. 0.5 to 5.5mm in diameter. All the results obtained in this work followed consistent trends with increasing gas velocity.
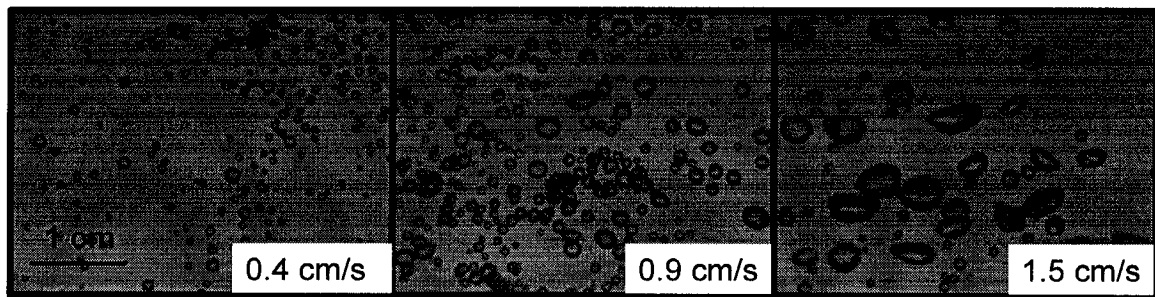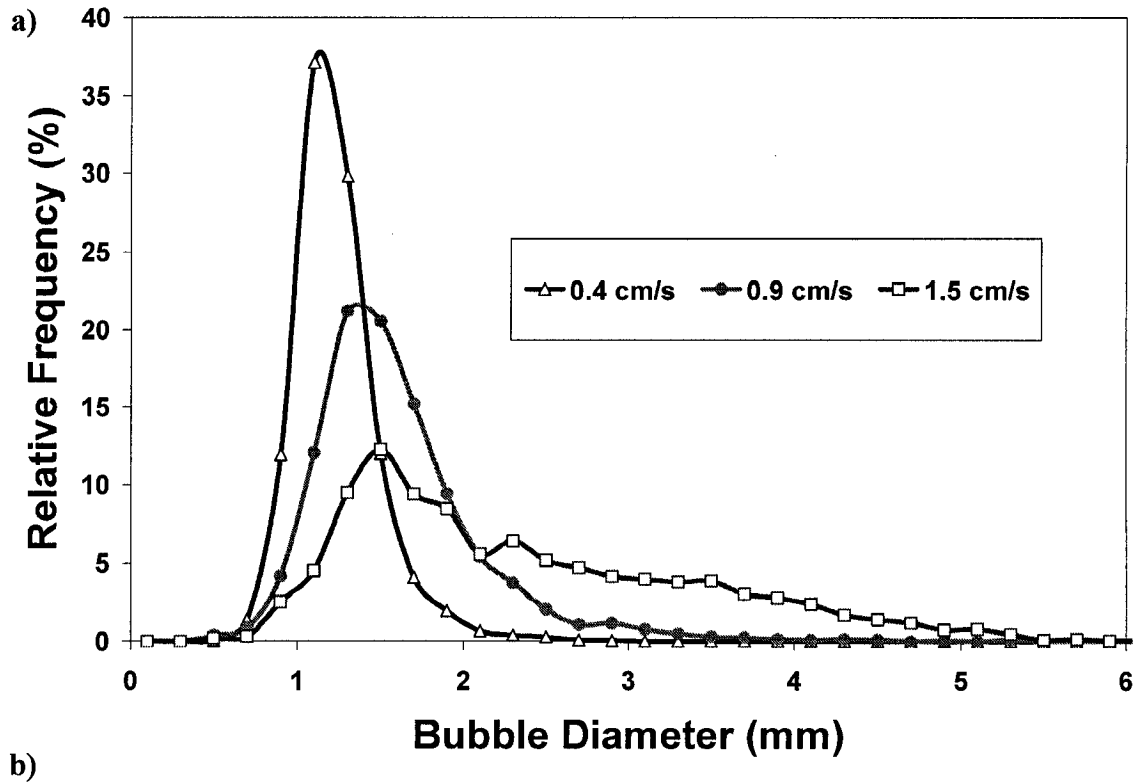
Figure 39 - a) Effect of superficial gas velocity on bubble size distribution in 10ppm MIBC solution, b) Example images

The effect of increasing gas velocity on Sauter mean bubble diameter can be seen in Figure 40. There is a consistent increase in average bubble diameter with increasing gas velocity. Figures A16-A18 (Appendix) show the effect of gas velocity on bubble size distribution in 0.1M, 0.2M and 0.4MNaCl,
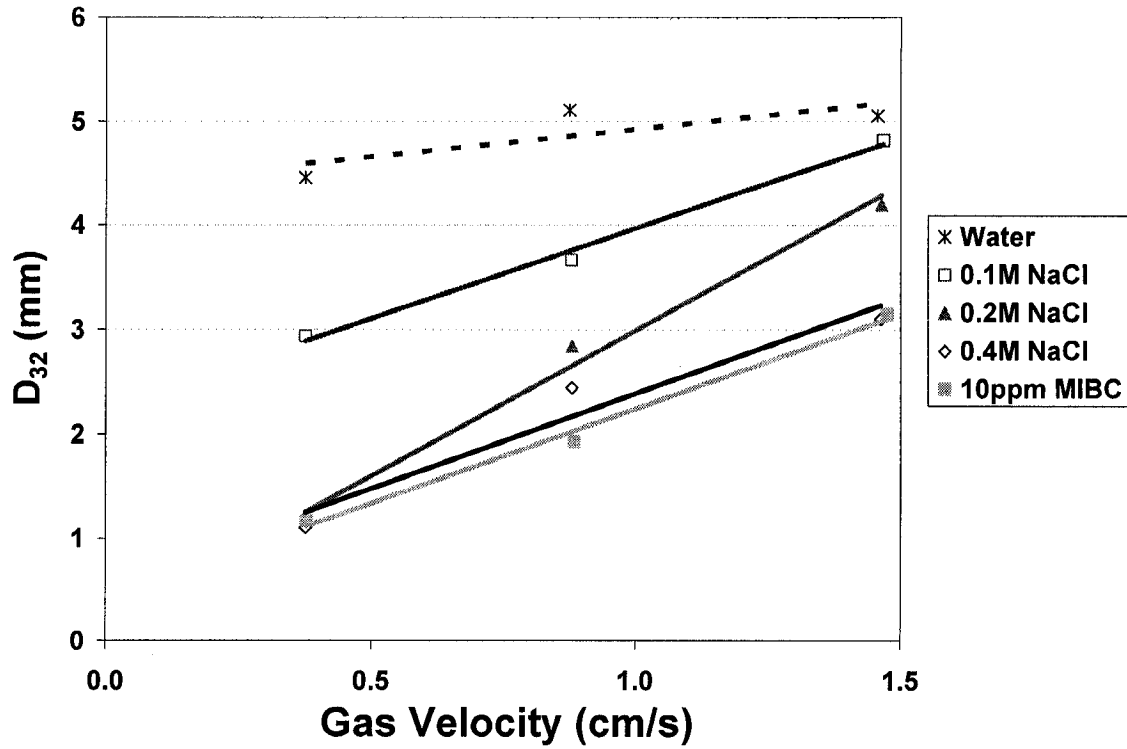
Figure 40 – Effect of superficial gas velocity on Sauter mean bubble diameter

4.3.3 - Note Concerning Bubble Size Results in Water

On analyzing the bubble size data it became clear that under certain conditions (water, low salt and high gas velocity) large bubbles were not all being counted because of the restricted viewing area of the images. The following are examples of large bubbles which were not counted because they were too large to fit in the viewing area (2.75cm (height) by ~3.80cm (width)).

Water 0.4 cm/s

Water 0.9 cm/s

Water 1.5 cm/s
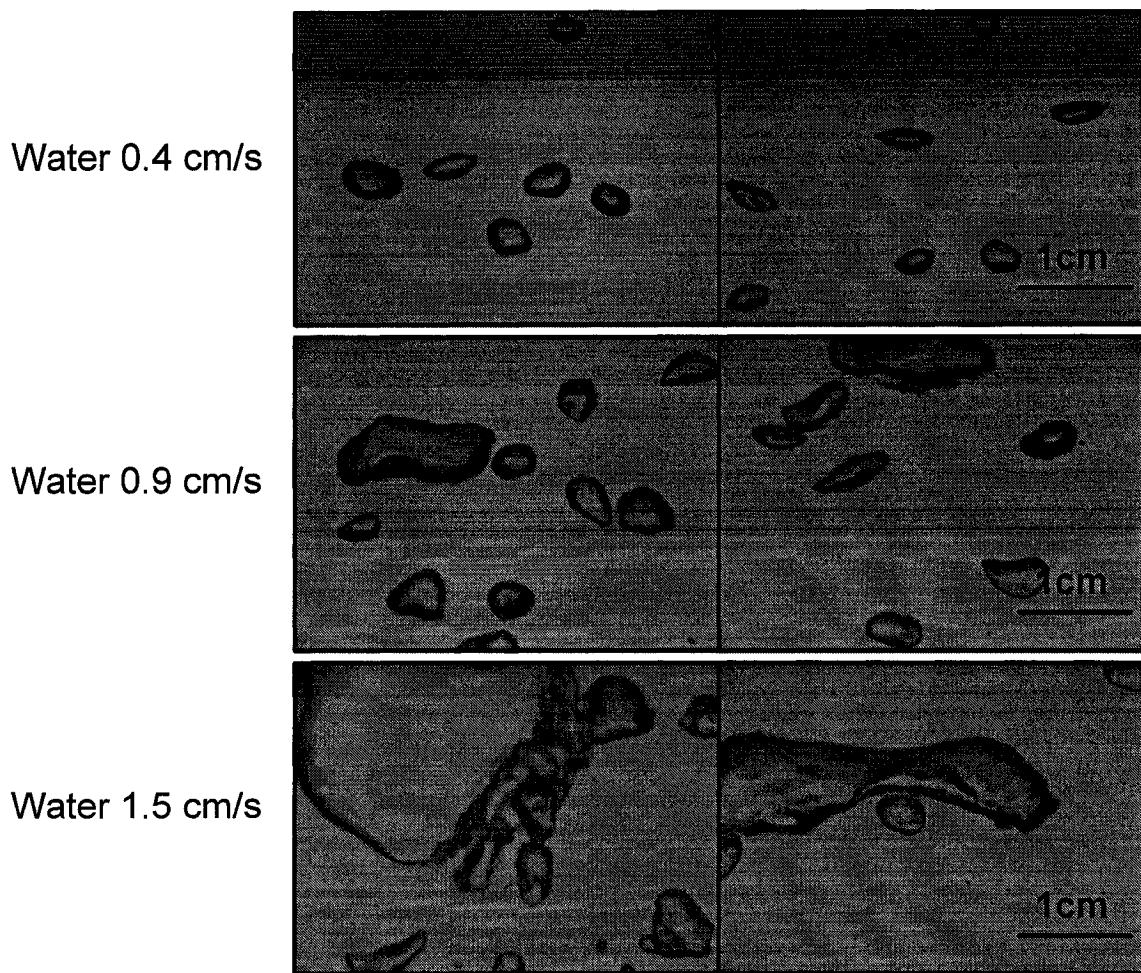
Figure 41 – Examples of large bubbles in water system at higher superficial gas velocities (lower picture) which were not counted in the bubble size distributions

Table 5 – Gas dispersion data for water

Solution	J_g (cm/s)	E_g (%)	D_{10} (mm)	D_{32} (mm)	S_b (s^{-1})
water	0.4	1.41	3.36	4.45	5.05
water	0.9	4.29	4.04	5.10	10.28
water	1.5	10.81	3.05	5.05	17.31

Calculated average bubble sizes (D_{10} and D_{32}) decrease at gas velocity of 1.5cm/s when in fact, they should (and do in actuality) increase the highest. To correct this problem a larger viewing area is needed. It should be noted that using a larger viewing area decreases resolution which means loss in ability to accurately measure small bubbles. A way to resolve this dilemma is being investigated. As Table 5 shows, gas

holdup is not affected by a 'large bubble problem' faithfully reporting the expected increase as gas velocity is increased.

4.3.4 - Frothing and Overflow Rates

Figure 42 shows the effect of gas velocity on concentrate (froth) overflow. Increasing gas velocity increases overflow rate. It should be noted that at the higher gas velocities (>1.5cm/s) the level fluctuated significantly and was not easily controlled. This may have led to overestimation of the overflow rates at these high gas velocities. The 0.4M NaCl and 10ppm MIBC systems showed that greatest overflow rates.
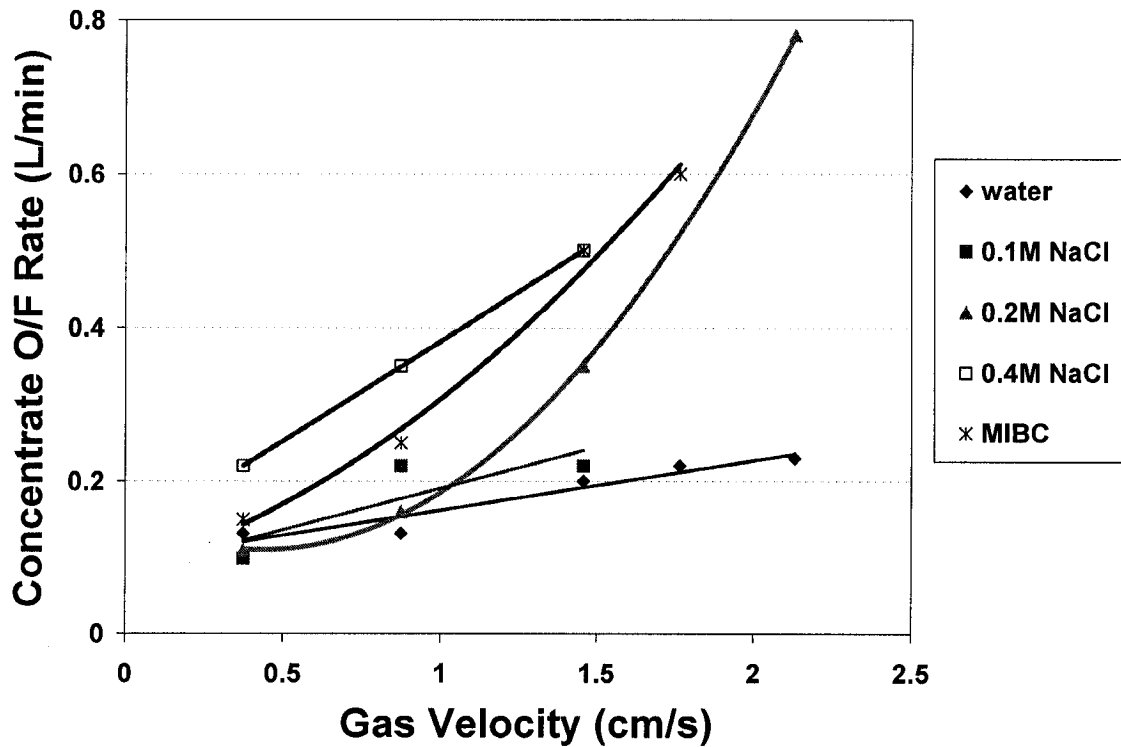
Figure 42 – Concentrate overflow rate vs. gas velocity for all systems tested

Figure 43 shows overhead images of the froth and bubbles sampled from the pulp. Along with the decrease in bubble size in the pulp there is a clear decrease in bubble size

on the surface of the froth when NaCl or frother is added to the system. In water alone the froth is unstable; bubbles readily coalesce and burst before overflowing into the launder. Unlike the talc system, there was limited froth overflow in the water. Overflow rates increase when gas velocity is increased or when salt or frother is present.
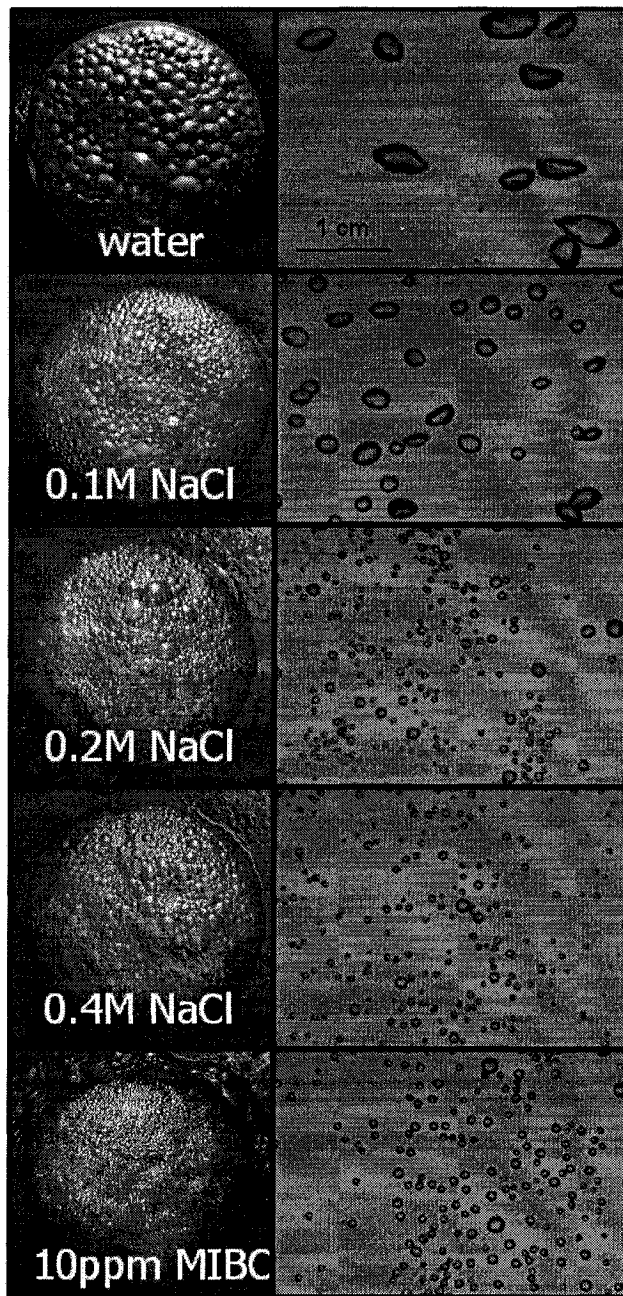
Figure 43 – Flotation tests - Overhead images of the surface of the froth (left) (as a reference, the diameter of the column is 10.16cm) and images of the bubbles sampled from the pulp (right)

Chapter 5 - Discussion

The results show that certain inorganic electrolytes are able to decrease bubble size governed by ionic strength. To illustrate, Figure 44 shows results from the 3-phase ore tests which demonstrate the effect of NaCl on D_{10}, D_{32} and gas holdup.
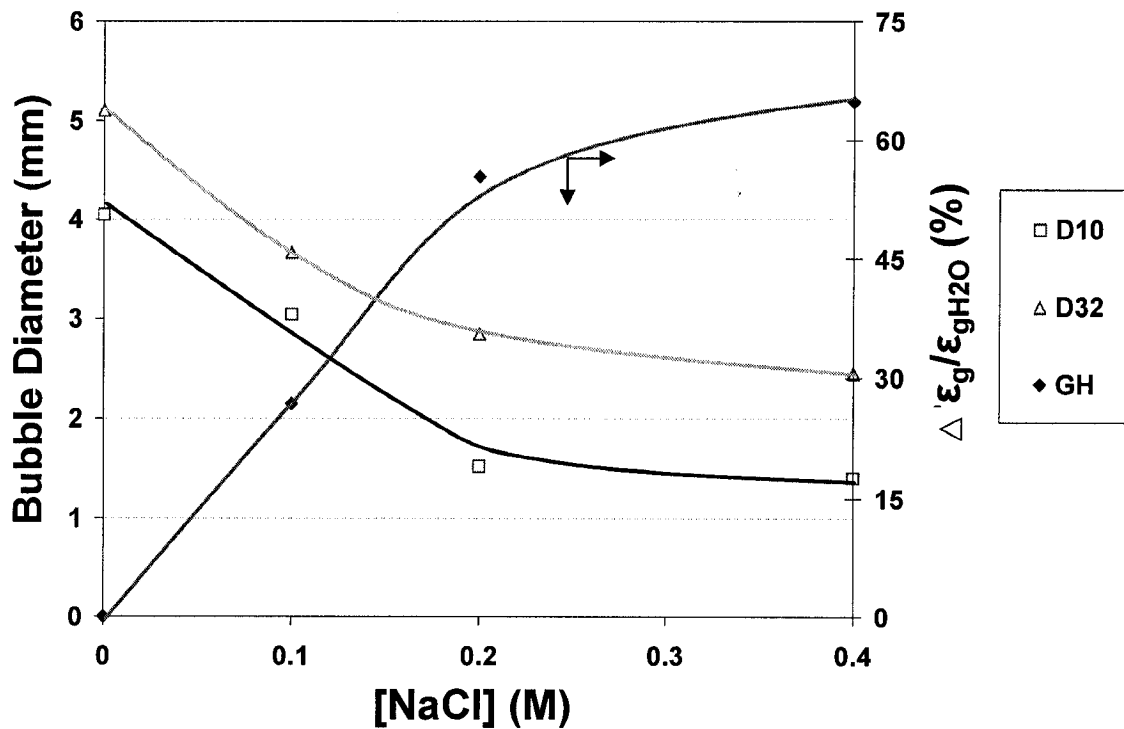
Figure 44 – Effect of NaCl concentration on D_{10}, D_{32} and gas holdup (GH) for 3-phase ore tests (J_g = 0.9 cm/s)

Figure 45 compares the change in gas holdup for the three sets of tests undertaken. The $\Delta\varepsilon_g/\varepsilon_{gH2O}$ parameter is used to try to allow for the different columns (diameters, spargers) used. The 3-phase talc and 3-phase ore tests show greater increases in gas holdup. This may be due to the presence of solids. The presence of solids has been shown to both increase and decrease gas holdup depending on the amount of solids

present (Pérez Garibay et al., 2002; Banisi et al., 1995). In this case the solids appear to have increased gas holdup. The solids being hydrophobic and attach to bubbles mal slow their rise and hence increase gas holdup to water alone. To help resolve, bubble size data are required.
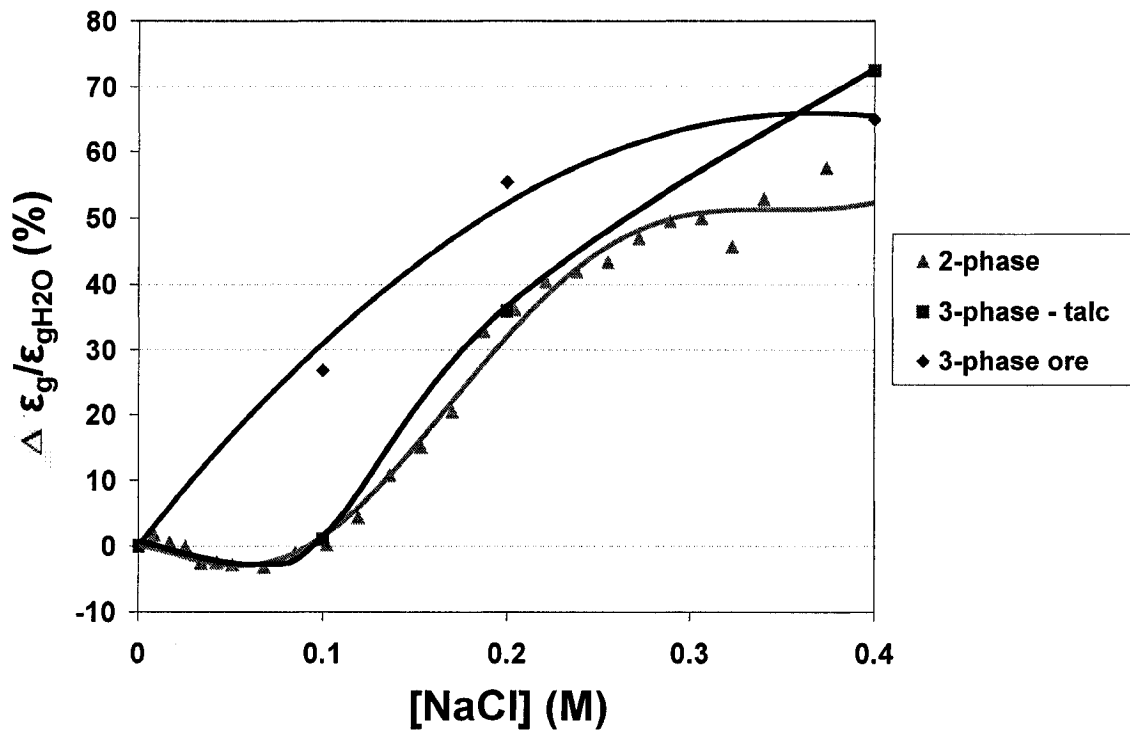
Figure 45 – Effect of NaCl on gas holdup for the three systems tested (J_g = 0.9-1.0 cm/s)

Figure 46 shows the effect of NaCl concentration on the relative decrease in Sauter mean bubble diameter compared to water. The 3-phase ore test at low gas velocity tested, 0.4cm/s, shows the greatest reduction in average bubble size. The 0.9cm/s showed an intermediate drop in average bubble size while the 2-phase tests showed the lowest change. This corresponds to the higher gas holdup shown in the 3-phase ore tests (Figure 45). The 2-phase tests produced relatively larger bubbles (at a given gas velocity) than

the 3-phase ore tests. It can also be seen that average bubble diameter increases with gas velocity as noted in the previous section.
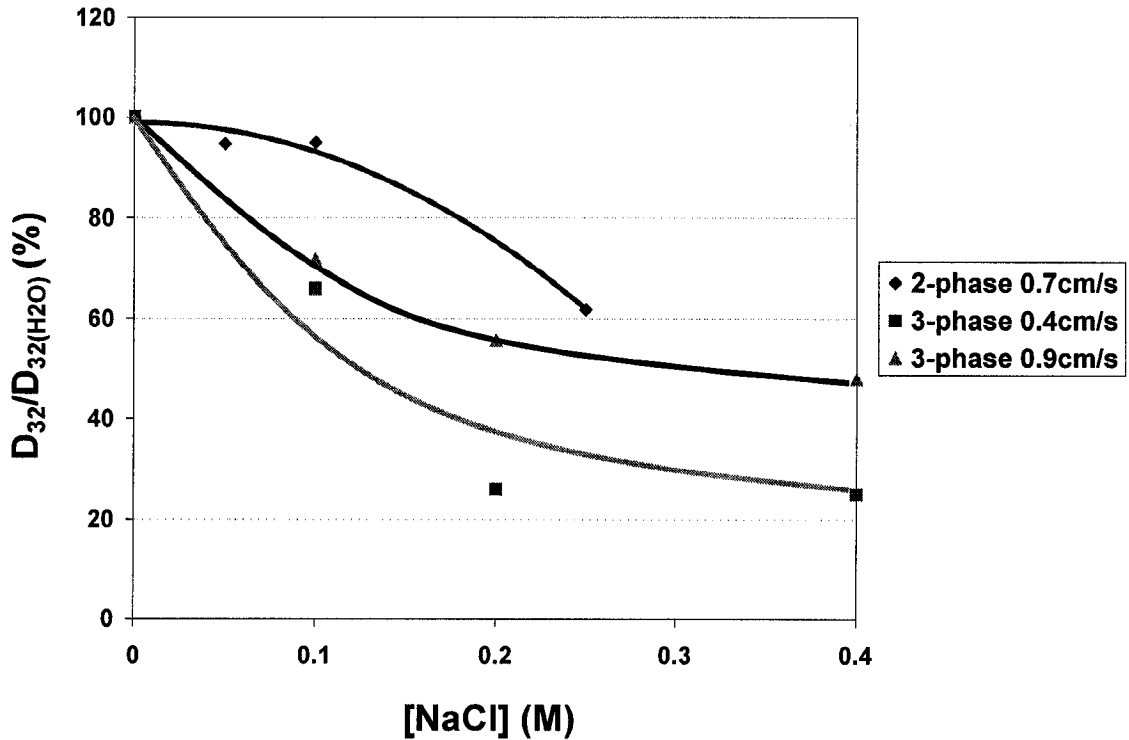
Figure 46 – Effect of NaCl concentration on $D_{32}/D_{32}(H_2O)$ in 2 and 3-phase ore tests at various gas velocities

In terms of bubble size distribution, there were similarities between the 2 and 3-phase work. Both systems produced bi-modal bubble size distributions in water or weak salt or frother solutions (Figure 10 and Figure 33). This may be due to a bubble breakage mechanism. As salt or frother was added the distributions became narrower and tended towards finer bubble sizes.

It has been noted (Lekki and Laskowski, 1975, Leja, 1982) as well as in these tests that salts are unable to produce substantial 2-phase foam. To investigate frothing, therefore solids were added (i.e., the 3-phase tests). From the 3-phae tests, there seems to

be a critical bubble size above which froth cannot be formed as it is unstable, even in the presence of solids. As bubble size in the pulp decreased, either due to the addition of salt or frother, frothing increased. The case with 0.1M NaCl is interesting: it provides little decrease in bubble size or increase in gas holdup but does support a froth in the presence of solids. This may imply a 'synergy' between solids and salt that stabilizes froth even with only a small effect on bubble size in the pulp phase.

To further compare the salt and frother systems the role of chemistry within the froth must be examined. Both systems are able to produce fine sized bubbles in the pulp but the question is whether there any differences in particle collection efficiency, water carrying rate (to the froth), bubble film stability which affect overall performance.

Certain authors have pointed to improved flotation performance in salt solutions (in relation to water only) (Pugh et al., 1997, Yoon and Sabey, 1989). In general, operations do not float in water without the use of frother. Few authors have attempted to compare salt water flotation to conventional flotation (the use of relatively clean water with added frother). Here it has been shown that relatively high salt concentrations have the same effect as frother, in terms of gas dispersion and frothing in presence of solids. Certain concentrators which employ saline process water have noted the need for reduced frother dosage and have even stopped using frother. It has also been noted that if frother is added to flotation cells with high soluble inorganic salt content froth properties change and may become persistent and possibly unmanageable. The effect of salt on collector adsorption is another important aspect to investigate as this could affect selectivity.

Many mining operations located in remote areas are facing water shortages. In certain of these situations recycling water was the solution. Others have implemented the

use of sea water or highly saline well water. These practices will most probably become increasingly common in the future.

There are two possible avenues operations can take: 1) learn how to process minerals in saline solutions and control the adverse affects or 2) implement desalination to alleviate the unwanted side effects of salt (e.g., corrosion). The outcome will be determined by economics. This study is a first step in understanding the effect these salts have on technical aspects of the process by a detailed analysis of gas dispersion and frothing characteristics.

Chapter 6 – Conclusions

This thesis attempts to interpret the role of salt in replacing frother by investigating gas dispersion and frothing properties in 2-phase (water only) and in 3-phase tests using talc (a naturally hydrophobic solid) and an ore (treated as for flotation).

In the 2-phase tests, the results show increasing gas holdup with increasing concentration of NaCl, $CaCl_2$, Na_2SO_4, $Na_2S_2O_3$ and $Al_2(SO_4)_3$. The effect increased with ion valence. A reasonable correlation between gas holdup and ionic strength for the salts tested was demonstrated. Gas holdup for salt solutions with ionic strength of 0.4-0.5, as at Raglan, is similar to that of ca. 7–10ppm MIBC, which is a typical concentration in plant. These findings suggest that flotation concentrators which utilize salt water with ionic strength ≥ 0.4 may be able to reduce frother dosage as part of the anti-coalescence function is derived from the inorganic electrolyte.

The effect of NaCl and MIBC on solid and liquid overflow rates from a system containing 1%w/w talc was investigated. The results showed increased frothing and overflow rates upon the addition of NaCl to the system. The system containing 15ppm MIBC behaved similarly in terms of gas dispersion and overflow rates as the 0.4M NaCl system (corresponding to Raglan process water ionic strength).

The 3-phase tests with ore showed decreasing bubble size and increasing gas holdup with increasing NaCl concentration. The 0.2M and 0.4M NaCl results are comparable to 10ppm MIBC solution in terms of reduction in bubble size and increased gas holdup.

The 3-phase tests confirm the 2-phase gas dispersion results and show solids promote stable froths with salt. From the gas dispersion / froth stability perspective it is shown that some salts can replace the functions of the frother.

6.1 - Recommendations

Extending the 2-phase tests to examine more salt types could help explain the characteristics associated with the salts which effect gas dispersion and foaming.

As previously noted, inorganic salts are unable to produce substantial 2-phase foam. For this reason solids were needed to create a frothing system. It would be interesting to further investigate this aspect by running tests with various types of solids (varying size and hydrophobicity). This setup may also prove useful for testing (characterizing) frothers over realistic concentration (<20ppm) compared to the dosages used in the absence of solid (Moyo, 2005; Finch et al., 2006).

Further work comparing salt and frother-produced froths could give insight into interactions taking place within the froth. Several authors (Laskowski et al., 2003, Tan et al., 2005) have noted that salts seem to create drier foams / froths. High water content in froth is generally associated with entrainment of gangue material though it may also lead to better particle drainage (reduced entrainment) (Melo and Laskowski, 2005). This aspect concerning the presence of salts and should be considered when diagnosing actual flotation (grade / recovery) results.

Chapter 7 - References

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Appendix

2-Phase Tests

Reproducibility

Repeat tests were conducted in water (8 repeats), 0.5M NaCl (3 repeats) and 10ppm MIBC (3 repeats) at the four superficial gas velocities tested (0.7, 1.0, 1.4 and 1.7cm/s). The tables below show the data sets, the mean, standard deviation (stdev) (Equation A1) and pooled standard deviation (Equation A2). All the tests involve the same type of measurement but each condition has a unique mean. The data sets are pooled to give a more accurate standard deviation. The pooled standard deviation of all the repeat tests (water, 0.5M NaCl and 10ppm MIBC) is 0.176%. The error bars shown in the thesis correspond to two pooled standard deviations.

$$s = \sqrt{\frac{\sum_{i=1}^{N_1}(x_i - \bar{x})^2}{n-1}}$$

Equation A1

$$s_p = \sqrt{\frac{\sum_{i=1}^{N_1}(x_i - \bar{x}_1)^2 + \sum_{j=1}^{N_2}(x_j - \bar{x}_2) + ... \sum_{k=1}^{N_m}(x_k - \bar{x}_m)^2}{N_1 + N_2 + ...N_k - m}}$$

Equation A2

Table A1 – 2-Phase repeat water tests

J_g (cm/s)	ϵ_g (%)	mean (%)	stdev (%)	Pooled std (%)
0.7	3.29	3.23	0.091	0.155
0.7	3.20			
0.7	3.20			
0.7	3.19			
0.7	3.29			
0.7	3.06			
0.7	3.37			
0.7	3.26			
1.0	4.94	4.90	0.211	
1.0	4.96			
1.0	5.05			
1.0	4.42			
1.0	5.02			
1.0	4.79			
1.0	5.00			
1.0	5.03			
1.4	6.75	6.74	0.097	
1.4	6.65			
1.4	6.79			
1.4	6.72			
1.4	6.89			
1.4	6.58			
1.4	6.82			
1.4	6.73			
1.7	8.53	8.61	0.185	
1.7	8.67			
1.7	8.76			
1.7	8.69			
1.7	8.75			
1.7	8.21			
1.7	8.73			
1.7	8.55			

Table A2 – 2-phase repeat 0.5M NaCl tests

J_g (cm/s)	ε_g (%)	mean (%)	stdev (%)	Pooled std (%)
0.7	5.03	5.05	0.169	0.262
0.7	4.89			
0.7	5.23			
1.0	7.70	7.68	0.189	
1.0	7.48			
1.0	7.86			
1.4	10.32	10.29	0.252	
1.4	10.02			
1.4	10.52			
1.7	13.85	13.32	0.501	
1.7	12.86			
1.7	13.26			

Table A3 – 2-phase repeat 10ppm MIBC tests

J_g (cm/s)	ε_g (%)	mean (%)	stdev (%)	Pooled std (%)
0.7	5.95	5.99	0.120	0.156
0.7	5.89			
0.7	6.12			
1.0	8.61	8.63	0.147	
1.0	8.50			
1.0	8.79			
1.4	11.21	11.21	0.200	
1.4	11.01			
1.4	11.41			
1.7	13.81	13.78	0.241	
1.7	13.53			
1.7	14.01			

Table A4 - 2-phase NaCl Results

Jg (cm/s)	[salt] (M)	FH (cm)	Gas Holdup Pressure (%)	delta Eg Eg H2O (%)	Air flow (L/s)	vol Tot. (L)	Jg (cm/s)	[salt] (M)	FH (cm)	Gas Holdup Pressure (%)	delta Eg Eg H2O (%)	Air flow (L/s)	vol Tot. (L)
0.69	0.0000	0	3.29	0.0	0.031	0.50	1.03	0.0000	0	4.94	0.0	0.047	0.68
0.69	0.0085	0	3.30	0.3	0.032	0.59	1.04	0.0085	0	5.02	1.7	0.047	0.87
0.70	0.0170	0	3.20	-2.7	0.032	0.48	1.03	0.0170	0	4.97	0.5	0.047	0.78
0.69	0.0255	0	3.20	-2.6	0.032	0.46	1.04	0.0255	0	4.94	-0.1	0.047	0.73
0.69	0.0340	0	3.12	-5.0	0.032	0.50	1.03	0.0340	0	4.81	-2.6	0.047	0.75
0.69	0.0425	0	3.14	-4.4	0.032	0.52	1.04	0.0425	0	4.81	-2.6	0.047	0.84
0.69	0.0510	0	3.06	-6.7	0.032	0.50	1.03	0.0510	0	4.80	-2.8	0.047	0.73
0.69	0.0680	0	3.07	-6.6	0.032	0.48	1.03	0.0680	0	4.78	-3.2	0.047	0.75
0.69	0.0850	0	3.07	-6.5	0.032	0.43	1.03	0.0850	0	4.89	-1.1	0.047	0.71
0.69	0.1020	0	3.09	-5.8	0.032	0.46	1.03	0.1020	0	4.95	0.2	0.047	0.78
0.69	0.1191	0	3.14	-4.3	0.032	0.52	1.03	0.1191	0	5.15	4.3	0.047	0.82
0.69	0.1361	0	3.36	2.3	0.032	0.55	1.04	0.1361	0	5.47	10.8	0.047	0.87
0.70	0.1531	0	3.42	4.2	0.032	0.55	1.04	0.1531	0.5	5.69	15.1	0.047	0.91
0.69	0.1701	0	3.67	11.6	0.032	0.59	1.03	0.1701	0	5.95	20.5	0.047	0.98
0.69	0.1871	0	4.23	28.8	0.032	0.57	1.03	0.1871	1	6.56	32.8	0.047	1.05
0.70	0.2041	0	4.35	32.4	0.032	0.62	1.04	0.2041	1	6.73	36.2	0.048	1.08
0.70	0.2211	0	4.47	36.2	0.032	0.62	1.04	0.2211	0.75	6.93	40.4	0.047	1.10
0.70	0.2381	0	4.57	39.0	0.032	0.62	1.04	0.2381	0.5	7.01	41.9	0.047	1.11
0.70	0.2551	0	4.61	40.4	0.032	0.66	1.04	0.2551	0.5	7.08	43.3	0.048	1.11
0.70	0.2721	0	4.76	44.8	0.032	0.69	1.04	0.2721	1	7.26	46.9	0.048	1.14
0.70	0.2891	0.5	4.90	49.2	0.032	0.77	1.04	0.2891	1	7.39	49.5	0.047	1.20
0.70	0.3061	0	4.93	50.1	0.032	0.80	1.04	0.3061	1	7.40	49.9	0.048	1.22
0.70	0.3232	0	4.85	47.6	0.032	0.72	1.04	0.3232	1.5	7.19	45.6	0.048	1.20
0.70	0.3402	0	5.11	55.6	0.032	0.78	1.04	0.3402	1.5	7.55	52.8	0.048	1.23
0.70	0.3742	0	5.24	59.6	0.032	0.78	1.04	0.3742	1.5	7.78	57.4	0.047	1.30
0.69	0.4082	0	5.19	57.9	0.032	0.78	1.04	0.4082	1.5	7.64	54.5	0.047	1.27
0.70	0.4422	0.5	4.89	48.7	0.032	0.77	1.04	0.4422	2.5	7.45	50.8	0.047	1.37
0.70	0.4762	0.5	5.23	59.0	0.032	0.83	1.04	0.4762	3	7.86	59.0	0.047	1.42
0.67	0.5	0	5.03	53.1	0.031	0.80	1.01	0.5	0.5	7.70	55.8	0.046	1.28

Jg (cm/s)	[salt] (M)	FH (cm)	Gas Holdup Pressure (%)	delta Eg Eg H2O (%)	Air flow (L/s)	vol Tot. (L)	Jg (cm/s)	[salt] (M)	FH (cm)	Gas Holdup Pressure (%)	delta Eg Eg H2O (%)	Air flow (L/s)	vol Tot. (L)
1.37	0.0000	0	6.75	0.0	0.063	1.09	1.71	0.0000	1	8.53	0.0	0.078	1.49
1.38	0.0085	1	6.81	6.8	0.063	1.24	1.71	0.0085	1	8.77	2.8	0.078	1.56
1.38	0.0170	1	6.86	-0.9	0.063	1.15	1.71	0.0170	1	8.74	2.4	0.078	1.52
1.38	0.0255	1	6.82	0.1	0.063	1.15	1.72	0.0255	1	8.80	3.2	0.079	1.49
1.37	0.0340	1	6.80	0.2	0.063	1.18	1.71	0.0340	1	8.75	2.5	0.078	1.49
1.38	0.0425	1	6.76	6.5	0.063	1.24	1.71	0.0425	1	8.81	3.3	0.078	1.61
1.37	0.0510	1	6.73	0.1	0.063	1.18	1.71	0.0510	1.5	8.86	3.8	0.078	1.58
1.37	0.0680	1	6.77	0.1	0.063	1.18	1.71	0.0680	1	9.02	5.8	0.078	1.59
1.37	0.0850	1	6.99	0.1	0.063	1.18	1.71	0.0850	1	9.31	9.1	0.078	1.59
1.37	0.1020	1	7.19	3.9	0.063	1.22	1.71	0.1020	1	9.58	12.3	0.078	1.68
1.37	0.1191	1	7.45	13.6	0.063	1.34	1.71	0.1191	1	9.93	16.4	0.078	1.75
1.38	0.1361	1	7.85	17.4	0.063	1.36	1.71	0.1361	1.5	10.30	20.7	0.078	1.85
1.38	0.1531	1	8.05	17.9	0.063	1.36	1.72	0.1531	1.5	10.60	24.3	0.078	1.85
1.37	0.1701	1	8.36	31.6	0.063	1.54	1.71	0.1701	1.5	10.90	27.8	0.078	1.99
1.37	0.1871	2.5	8.95	25.7	0.063	1.59	1.71	0.1871	2	11.61	36.1	0.078	2.01
1.38	0.2041	2	9.32	33.9	0.063	1.60	1.72	0.2041	2	12.01	40.7	0.079	2.08
1.38	0.2211	1.5	9.54	37.3	0.063	1.61	1.72	0.2211	2	12.24	43.5	0.078	2.11
1.38	0.2381	1	9.65	39.1	0.063	1.59	1.72	0.2381	1.5	12.34	44.6	0.078	2.13
1.38	0.2551	1	9.63	40.0	0.063	1.59	1.72	0.2551	1.5	12.39	45.2	0.078	2.12
1.38	0.2721	2	9.92	38.1	0.063	1.64	1.72	0.2721	2	12.66	48.4	0.078	2.14
1.38	0.2891	2	10.01	41.9	0.063	1.70	1.72	0.2891	1.5	12.77	49.7	0.078	2.17
1.38	0.3061	2	10.03	43.8	0.063	1.71	1.72	0.3061	2	12.89	51.0	0.078	2.21
1.38	0.3232	3	9.74	37.9	0.063	1.73	1.72	0.3232	3.5	12.47	46.2	0.078	2.23
1.38	0.3402	4	10.11	38.2	0.063	1.81	1.72	0.3402	4.5	12.80	50.1	0.078	2.37
1.38	0.3742	3	10.56	50.6	0.063	1.88	1.72	0.3742	4.5	13.27	55.6	0.078	2.46
1.37	0.4082	3	10.44	45.0	0.063	1.84	1.71	0.4082	5	13.10	53.6	0.078	2.40
1.38	0.4422	6.5	10.09	39.9	0.063	2.04	1.72	0.4422	7.5	12.78	49.8	0.078	2.51
1.38	0.4762	5	10.52	44.6	0.063	1.98	1.71	0.4762	9	13.26	55.4	0.078	2.74
1.33	0.5	3	10.32	37.1	0.061	1.89	1.66	0.5	7.5	13.23	55.1	0.076	2.66

Table A5 - 2-phase Na$_2$SO$_4$ Results

Jg (cm/s)	[salt] (M)	FH (cm)	Gas Holdup Pressure (%)	delta Eg Eg H2O (%)	Air flow (L/s)	vol Tot. (L)	Jg (cm/s)	[salt] (M)	FH (cm)	Gas Holdup Pressure (%)	delta Eg Eg H2O (%)	Air flow (L/s)	vol Tot. (L)
0.70	0.000	0.00	3.20	0.0	0.032	0.48	1.05	0.0000	0.00	4.96	0.0	0.048	0.75
0.70	0.004	0.00	3.24	1.2	0.032	0.48	1.04	0.0035	0.00	4.94	-0.4	0.048	0.78
0.70	0.007	0.00	3.17	-0.9	0.032	0.48	1.04	0.0070	0.00	4.93	-0.5	0.048	0.76
0.70	0.014	0.00	3.22	0.6	0.032	0.50	1.04	0.0141	0.00	4.99	0.7	0.048	0.76
0.70	0.021	0.00	3.18	-0.8	0.032	0.47	1.04	0.0211	0.00	4.88	-1.6	0.048	0.75
0.70	0.028	0.00	3.20	0.0	0.032	0.47	1.04	0.0282	0.00	4.97	0.2	0.048	0.76
0.70	0.035	0.00	3.22	0.6	0.032	0.49	1.04	0.0352	0.00	5.13	3.5	0.048	0.80
0.70	0.042	0.00	3.26	1.9	0.032	0.50	1.04	0.0422	0.75	5.35	7.8	0.048	0.89
0.70	0.049	0.75	3.41	6.5	0.032	0.57	1.04	0.0493	1.00	5.66	14.0	0.047	0.93
0.70	0.056	0.00	3.48	8.6	0.032	0.55	1.04	0.0563	0.75	5.71	15.1	0.047	0.95
0.69	0.063	0.00	4.03	25.7	0.032	0.60	1.04	0.0634	0.50	6.53	31.7	0.047	1.01
0.70	0.070	0.00	4.29	33.8	0.032	0.65	1.04	0.0704	0.50	6.71	35.2	0.047	1.07
0.69	0.077	0.00	4.16	30.0	0.032	0.65	1.04	0.0774	0.50	6.32	27.5	0.047	1.09
0.69	0.084	0.00	4.18	30.5	0.032	0.67	1.04	0.0845	0.50	6.60	33.1	0.047	1.12
0.69	0.092	0.00	4.52	41.1	0.032	0.70	1.04	0.0915	0.50	7.08	42.8	0.047	1.16
0.69	0.099	0.00	4.60	43.5	0.032	0.74	1.03	0.0986	0.50	7.22	45.6	0.047	1.21
0.70	0.106	0.00	4.75	48.3	0.032	0.71	1.04	0.1056	0.50	7.32	47.6	0.048	1.18
0.70	0.113	0.00	4.89	52.5	0.032	0.77	1.04	0.1126	0.75	7.44	49.9	0.048	1.17
0.70	0.127	0.00	5.12	59.8	0.032	0.75	1.04	0.1267	1.00	7.59	53.1	0.047	1.23
0.70	0.141	0.00	5.22	62.9	0.032	0.78	1.04	0.1408	0.75	7.90	59.3	0.048	1.29
0.70	0.155	0.00	5.29	65.0	0.032	0.76	1.04	0.1549	0.50	7.98	60.9	0.047	1.22
0.69	0.169	0.00	5.27	64.6	0.032	0.78	1.04	0.1690	1.00	7.89	59.2	0.047	1.27
0.70	0.197	0.50	5.31	65.8	0.032	0.84	1.04	0.1971	1.25	8.02	61.6	0.047	1.30
0.69	0.225	0.5	5.57	73.8	0.032	0.89	1.03	0.225288	1	8.45	70.3	0.047	1.33
0.69	0.253	0.5	6.03	88.1	0.032	0.93	1.04	0.253449	1	8.75	76.4	0.047	1.36
0.70	0.282	0.5	5.98	86.7	0.032	0.95	1.04	0.28161	1.75	8.78	76.9	0.047	1.39
0.69	0.296	0.5	6.14	91.8	0.032	0.93	1.04	0.29569	1.5	8.90	79.5	0.047	1.40

Jg (cm/s)	[salt] (M)	FH (cm)	Gas Holdup Pressure (%)	delta Eg Eg H2O (%)	Air flow (L/s)	vol Tot. (L)	Jg (cm/s)	[salt] (M)	FH (cm)	Gas Holdup Pressure (%)	delta Eg Eg H2O (%)	Air flow (L/s)	vol Tot. (L)
1.39	0.000	0.50	6.65	0.0	0.063	1.10	1.73	0.0000	0.50	8.67	0.0	0.079	1.43
1.39	0.004	0.50	6.62	-0.5	0.063	1.09	1.73	0.0035	0.50	8.65	-0.2	0.079	1.44
1.39	0.007	0.00	6.74	1.3	0.063	1.07	1.73	0.0070	0.50	8.89	2.5	0.079	1.46
1.39	0.014	0.00	6.81	2.3	0.063	1.09	1.73	0.0141	0.50	8.89	2.5	0.079	1.47
1.39	0.021	0.00	6.97	4.8	0.063	1.08	1.73	0.0211	0.50	9.09	4.8	0.079	1.51
1.38	0.028	0.00	7.13	7.2	0.063	1.13	1.72	0.0282	0.50	9.36	7.9	0.079	1.57
1.38	0.035	0.00	7.26	9.1	0.063	1.16	1.72	0.0352	1.00	9.68	11.6	0.079	1.65
1.38	0.042	0.75	7.48	12.4	0.063	1.26	1.72	0.0422	1.50	9.92	14.4	0.078	1.75
1.38	0.049	1.00	7.87	18.3	0.063	1.33	1.72	0.0493	1.25	10.28	18.6	0.078	1.79
1.38	0.056	1.50	8.11	21.9	0.063	1.42	1.72	0.0563	2.00	10.64	22.7	0.078	1.93
1.38	0.063	1.50	8.67	30.4	0.063	1.48	1.71	0.0634	2.00	11.02	27.1	0.078	1.97
1.38	0.070	2.00	8.82	32.6	0.063	1.59	1.72	0.0704	3.00	11.46	32.1	0.078	2.13
1.38	0.077	1.00	8.89	33.5	0.063	1.54	1.71	0.0774	1.50	11.50	32.6	0.078	2.04
1.38	0.084	0.75	9.14	37.4	0.063	1.56	1.71	0.0845	1.00	11.79	35.9	0.078	2.06
1.38	0.092	1.00	9.66	45.2	0.063	1.70	1.71	0.0915	1.75	12.53	44.5	0.078	2.24
1.37	0.099	1.00	9.69	45.6	0.063	1.70	1.71	0.0986	1.75	12.52	44.3	0.078	2.19
1.38	0.106	1.25	9.90	48.7	0.063	1.68	1.72	0.1056	2.00	12.62	45.5	0.078	2.20
1.39	0.113	1.25	10.15	52.5	0.063	1.64	1.72	0.1126	2.00	12.75	47.1	0.079	2.18
1.38	0.127	1.50	10.27	54.3	0.063	1.73	1.72	0.1267	2.00	12.95	49.3	0.078	2.23
1.38	0.141	1.50	10.44	57.0	0.063	1.81	1.72	0.1408	2.00	13.22	52.4	0.078	2.31
1.38	0.155	1.00	10.57	58.8	0.063	1.72	1.72	0.1549	2.00	13.36	54.0	0.078	2.27
1.38	0.169	2.00	10.58	59.0	0.063	1.77	1.71	0.1690	3.00	13.19	52.0	0.078	2.35
1.38	0.197	2.00	10.86	63.2	0.063	1.78	1.72	0.1971	2.50	13.50	55.6	0.078	2.35
1.37	0.225	1.5	11.20	68.3	0.063	1.83	1.71	0.2253	2.50	14.28	64.7	0.078	2.45
1.37	0.253	1.75	11.47	72.4	0.063	1.86	1.71	0.2534	2.75	14.27	64.5	0.078	2.45
1.38	0.282	2.5	11.66	75.3	0.063	1.94	1.71	0.2816	3.00	14.15	63.1	0.078	2.45
1.38	0.296	2.5	11.84	77.9	0.063	1.94	1.71	0.2957	3.00	14.90	71.7	0.078	2.44

Table A6 - 2-phase CaCl$_2$ Results

Jg (cm/s)	[salt] (M)	FH (cm)	Gas Holdup Pressure (%)	delta Eg Eg H2O (%)	Air flow (L/s)	vol Tot. (L)	Jg (cm/s)	[salt] (M)	FH (cm)	Gas Holdup Pressure (%)	delta Eg Eg H2O (%)	Air flow (L/s)	vol Tot. (L)
0.71	0.000	0	3.20	0.0	0.032	0.46	1.05	0.000	0	5.05	0.0	0.048	0.73
0.70	0.007	0	3.17	-1.2	0.032	0.47	1.05	0.007	0	4.90	-2.8	0.048	0.73
0.71	0.014	0	3.09	-3.5	0.032	0.45	1.05	0.014	0	5.04	-0.2	0.048	0.73
0.70	0.027	0.25	3.22	0.7	0.032	0.49	1.05	0.027	0.75	5.08	0.6	0.048	0.79
0.70	0.041	0.25	3.16	-1.3	0.032	0.50	1.05	0.041	0.5	5.15	2.0	0.048	0.82
0.70	0.054	0.5	3.49	9.0	0.032	0.55	1.05	0.054	0.5	5.51	9.1	0.048	0.88
0.70	0.068	0.5	4.25	32.7	0.032	0.66	1.05	0.068	1	6.42	27.2	0.048	1.08
0.70	0.082	1	4.64	45.0	0.032	0.77	1.05	0.082	2	6.81	35.0	0.048	1.22
0.70	0.095	1	4.94	54.2	0.032	0.83	1.05	0.095	1.5	7.09	40.5	0.048	1.27
0.70	0.109	1	5.02	56.6	0.032	0.86	1.05	0.109	3	7.43	47.1	0.048	1.39
0.70	0.122	1.25	5.12	59.9	0.032	0.91	1.04	0.122	2	7.52	49.0	0.048	1.36
0.70	0.136	1.5	5.13	60.2	0.032	0.90	1.04	0.136	2	7.62	50.9	0.048	1.26
0.70	0.163	2	5.30	65.4	0.032	0.95	1.04	0.163	4	7.75	53.5	0.048	1.45
0.70	0.190	2.5	5.49	71.3	0.032	1.05	1.04	0.190	6	8.11	60.6	0.048	1.60
1.40	0.000	0	6.79	0.0	0.064	1.04	1.75	0.000	0.5	8.76	0.0	0.080	1.36
1.40	0.007	0.5	6.77	-0.3	0.064	1.08	1.74	0.007	1	8.67	-1.0	0.079	1.48
1.40	0.014	0.5	6.84	0.7	0.064	1.09	1.74	0.014	1	8.99	2.6	0.080	1.45
1.40	0.027	0.75	7.04	3.7	0.064	1.14	1.74	0.027	1	9.24	5.5	0.079	1.53
1.40	0.041	1	7.50	10.5	0.064	1.22	1.74	0.041	1.25	10.02	14.3	0.079	1.66
1.39	0.054	1	7.72	13.7	0.064	1.30	1.73	0.054	1.5	11.08	26.5	0.079	1.78
1.39	0.068	1.25	8.70	28.2	0.063	1.47	1.73	0.068	1.25	11.52	31.5	0.079	1.92
1.39	0.082	2	9.29	36.9	0.063	1.65	1.73	0.082	2	12.17	38.9	0.079	2.15
1.39	0.095	2	9.74	43.5	0.063	1.71	1.73	0.095	1.75	12.53	43.0	0.079	2.18
1.39	0.109	3	10.02	47.7	0.063	1.79	1.72	0.109	2	12.70	44.9	0.079	2.31
1.39	0.122	3	10.06	48.2	0.063	1.80	1.72	0.122	3	13.02	48.6	0.079	2.31
1.39	0.136	3	10.43	53.7	0.063	1.76	1.72	0.136	4	13.18	50.5	0.079	2.38
1.39	0.163	6	10.40	53.3	0.063	2.01	1.72	0.163	6.75	13.16	50.2	0.079	2.54
1.39	0.190	12	10.86	60.0	0.063	2.44	1.72	0.190	15	13.64	55.7	0.079	3.18

Table A7 - 2-phase Na$_2$S$_2$O$_3$ Results

Jg (cm/s)	[salt] (M)	FH (cm)	Gas Holdup Pressure (%)	delta Eg Eg H2O (%)	Air flow (L/s)	vol Tot. (L)	Jg (cm/s)	[salt] (M)	FH (cm)	Gas Holdup Pressure (%)	delta Eg Eg H2O (%)	Air flow (L/s)	vol Tot. (L)
0.71	0.000	0	3.19	0.0	0.032	0.45	1.05	0.000	0.5	4.92	0.0	0.048	0.72
0.70	0.004	0	3.22	0.9	0.032	0.46	1.05	0.004	0.5	4.92	0.0	0.048	0.76
0.70	0.008	0	3.35	5.0	0.032	0.47	1.05	0.008	0.5	5.15	4.7	0.048	0.77
0.70	0.016	0	3.21	0.5	0.032	0.46	1.05	0.016	0.5	5.00	1.8	0.048	0.77
0.70	0.032	0	3.26	2.1	0.032	0.47	1.05	0.032	0.5	5.16	5.0	0.048	0.80
0.70	0.048	0.25	3.36	5.1	0.032	0.54	1.05	0.048	0.5	5.48	11.4	0.048	0.86
0.70	0.073	1	4.75	48.6	0.032	0.75	1.05	0.073	1	6.60	34.2	0.048	1.09
0.70	0.097	1	5.21	63.1	0.032	0.83	1.05	0.097	2.5	7.03	42.9	0.048	1.26
0.70	0.121	2.25	6.17	93.1	0.032	1.08	1.04	0.121	3.5	8.03	63.3	0.048	1.48
0.70	0.145	1	6.29	96.8	0.032	1.05	1.04	0.145	2.5	8.41	71.1	0.048	1.42
0.70	0.169	0.5	6.16	93.0	0.032	0.90	1.04	0.169	0.75	8.76	78.2	0.047	1.35
1.40	0.000	1	6.72	0.0	0.064	1.06	1.75	0.000	1	8.69	0.0	0.080	1.36
1.40	0.004	0.75	6.65	-1.1	0.064	1.07	1.74	0.004	0.75	8.75	0.7	0.079	1.44
1.40	0.008	0.5	6.92	2.9	0.064	1.09	1.74	0.008	0.5	8.92	2.5	0.079	1.39
1.40	0.016	0.5	6.79	1.0	0.064	1.08	1.74	0.016	0.5	8.82	1.5	0.079	1.41
1.40	0.032	0.75	7.22	7.5	0.064	1.16	1.74	0.032	1	9.57	10.1	0.079	1.60
1.39	0.048	0.75	7.91	17.7	0.064	1.27	1.74	0.048	1	10.57	21.6	0.079	1.70
1.39	0.073	1.25	9.02	34.2	0.063	1.48	1.73	0.073	2	11.47	31.9	0.079	1.95
1.39	0.097	2.5	9.51	41.4	0.063	1.65	1.73	0.097	2.75	12.14	39.6	0.079	2.12
1.39	0.121	5	10.26	52.6	0.063	1.97	1.73	0.121	5	12.82	47.5	0.079	2.39
1.39	0.145	4	10.39	54.5	0.063	1.87	1.72	0.145	4	12.94	48.8	0.079	2.29
1.38	0.169	2	10.52	56.5	0.063	1.73	1.72	0.169	2.5	13.01	49.7	0.079	2.19

Table A8 - 2-phase Al$_2$(SO$_4$)$_3$ Results

Jg (cm/s)	[salt] (M)	pH	FH (cm)	Gas Holdup Pressure (%)	delta Eg Eg H2O (%)	Air flow (L/s)	vol Tot. (L)	Jg (cm/s)	[salt] (M)	pH	FH (cm)	Gas Holdup Pressure (%)	delta Eg Eg H2O (%)	Air flow (L/s)	vol Tot. (L)
0.71	0	7.37	0	3.26	0.00	0.032353	0.478839	1.06	0	7.37	0.5	5.03	0.00	0.048364	0.802118
0.71	0	3.99	0	3.34	0.00	0.032334	0.478839	1.06	0	3.99	0.5	5.02	0.00	0.048336	0.792997
0.71	0.01	3.45	0.75	3.31	1.52	0.032355	0.530523	1.06	0.01	3.45	0.75	5.07	0.82	0.048356	0.813266
0.71	0.025	3.35	2	4.88	49.63	0.032174	0.896366	1.05	0.025	3.35	5	6.91	37.42	0.048146	1.344802
0.70	0.0375	3.25	2.5	5.33	63.59	0.032098	1.000747	1.05	0.0375	3.25	5.5	7.66	52.32	0.047976	1.540391
0.70	0.05	3.2	3	6.00	84.23	0.032029	1.068646	1.05	0.05	3.2	5.5	8.32	65.53	0.047838	1.608796
0.70	0.0625	3.18	3	5.82	78.65	0.031978	1.109689	1.05	0.0625	3.18	6.5	8.58	70.80	0.047809	1.667068
0.70	0.075	3.13	-	6.89	111.30	0.032019	1.15884	1.04	0.075	3.13	-	9.37	86.48	0.047825	1.847962

Jg (cm/s)	[salt] (M)	pH	FH (cm)	Gas Holdup Pressure (%)	delta Eg Eg H2O (%)	Air flow (L/s)	vol Tot. (L)	Jg (cm/s)	[salt] (M)	pH	FH (cm)	Gas Holdup Pressure (%)	delta Eg Eg H2O (%)	Air flow (L/s)	vol Tot. (L)
1.41	0	7.37	0.75	6.73	0.00	0.064268	1.11425	1.75	0	7.37	1	8.55	0.00	0.080072	1.426382
1.41	0	3.99	0.5	6.80	0.00	0.064228	1.089421	1.75	0	3.99	1	8.70	0.00	0.08	1.440063
1.41	0.01	3.45	1	7.17	6.59	0.064212	1.175561	1.75	0.01	3.45	2	9.44	10.45	0.079917	1.635145
1.40	0.025	3.35	5.5	9.37	39.25	0.063916	1.772969	1.74	0.025	3.35	7	11.90	39.29	0.079603	2.236607
1.39	0.0375	3.25	8	9.90	47.12	0.063708	2.103343	1.73	0.0375	3.25	10	12.79	49.66	0.079247	2.726086
1.39	0.05	3.2	9.8	10.72	59.24	-	-	1.73	0.05	3.2	-	13.42	57.00	-	-
1.39	0.0625	3.18	-	10.95	62.65	-	-	1.72	0.0625	3.18	-	13.82	61.72	-	-
1.39	0.075	3.13	-	12.17	80.88	-	-	1.72	0.075	3.13	-	15.04	76.06	-	-

Table A9 - 2-phase MIBC Results

Jg (cm/s)	[salt] (M)	FH (cm)	Gas Holdup Pressure (%)	delta Eg Eg H2O (%)	Air flow (L/s)	vol Tot. (L)	Jg (cm/s)	[salt] (M)	FH (cm)	Gas Holdup Pressure (%)	delta Eg Eg H2O (%)	Air flow (L/s)	vol Tot. (L)
0.70	0	0	3.29	0.0	0.032	0.48	1.05	0	0	5.02	0.0	0.048	0.76
0.71	0	0	3.06	0.0	0.032	0.46	1.06	0	0	4.79	0.0	0.048	0.71
0.71	1	0	3.04	-0.9	0.032	0.48	1.06	1	0	4.74	-1.1	0.048	0.73
0.71	3	0.25	3.04	-0.6	0.032	0.47	1.06	3	0.5	4.92	2.7	0.048	0.75
0.71	5	0.25	3.41	11.4	0.032	0.54	1.06	5	0.75	5.47	14.2	0.048	0.91
0.71	7	0.5	5.03	64.2	0.032	0.78	1.06	7	0.75	7.19	50.0	0.048	1.20
0.71	10	1	5.95	94.2	0.032	0.94	1.05	10	3	8.61	79.7	0.048	1.48
0.70	15	0.75	6.39	108.4	0.032	1.19	1.05	15	3	9.65	101.6	0.048	1.79
0.70	20	0.75	7.23	135.9	0.032	1.14	1.05	20	4.3	11.19	133.7	0.048	2.19

Jg (cm/s)	[salt] (M)	FH (cm)	Gas Holdup Pressure (%)	delta Eg Eg H2O (%)	Air flow (L/s)	vol Tot. (L)	Jg (cm/s)	[salt] (M)	FH (cm)	Gas Holdup Pressure (%)	delta Eg Eg H2O (%)	Air flow (L/s)	vol Tot. (L)
1.40	0	0	6.89	0.0	0.064	1.05	1.74	0	0.25	8.75	0.0	0.079	1.38
1.41	0	0.5	6.58	0.0	0.064	1.01	1.76	0	0.75	8.21	0.0	0.080	1.56
1.41	1	0.75	6.66	1.3	0.064	1.08	1.75	1	0.75	8.68	5.7	0.080	1.43
1.41	3	0.75	7.08	7.7	0.064	1.12	1.75	3	1	9.17	11.7	0.080	1.49
1.41	5	0.75	7.71	17.3	0.064	1.27	1.75	5	1	10.29	25.3	0.080	1.71
1.40	7	2	9.40	42.9	0.064	1.53	1.75	7	2	11.78	43.5	0.080	2.08
1.40	10	5.5	11.21	70.5	0.064	2.03	1.74	10	6	13.81	68.2	0.079	2.55
1.39	15	5.5	12.48	89.7	0.063	2.45	1.73	15	9	15.65	90.6	0.079	3.04
1.39	20	7	14.29	117.4	0.063	2.62	1.72	20	18	17.55	113.8	0.078	3.42

Table A10 - rt values for salt and MIBC tests

| [NaCl] (M)	rt (s)	[Na2SO4] (M)	rt (s)	[CaCl2] (M)	rt (s)	[Na2S2O3] (M)	rt (s)	[Al2(SO4)3] (M)	rt (s)	[MIBC] (ppm)	rt (s)
0	21.875	0	20.685	0	19.024	0	18.994	0	19.834	0	20.013
0.034	21.931	0.007	20.685	0.014	21.196	0.008	19.578	0.01	23.177	1	21.875
0.102	26.593	0.0282	23.38	0.041	24.646	0.032	23.702	0.025	28.147	3	21.704
0.204	31.522	0.0493	26.063	0.082	29.396	0.073	25.486	0.03275	36.5	5	24.464
0.306	30.541	0.1126	30.102	0.109	30.657	0.121	28.336	0.05	46.519	7	23.571
0.408	35.235	0.1971	32.272	0.136	31.687	0.145	26.738			10	34.303
0.999	36.04	0.2816	32.665	0.163	34.209	0.169	27.157			15	40.048
		0.2957	32.665	0.19	46.323					20	47.018
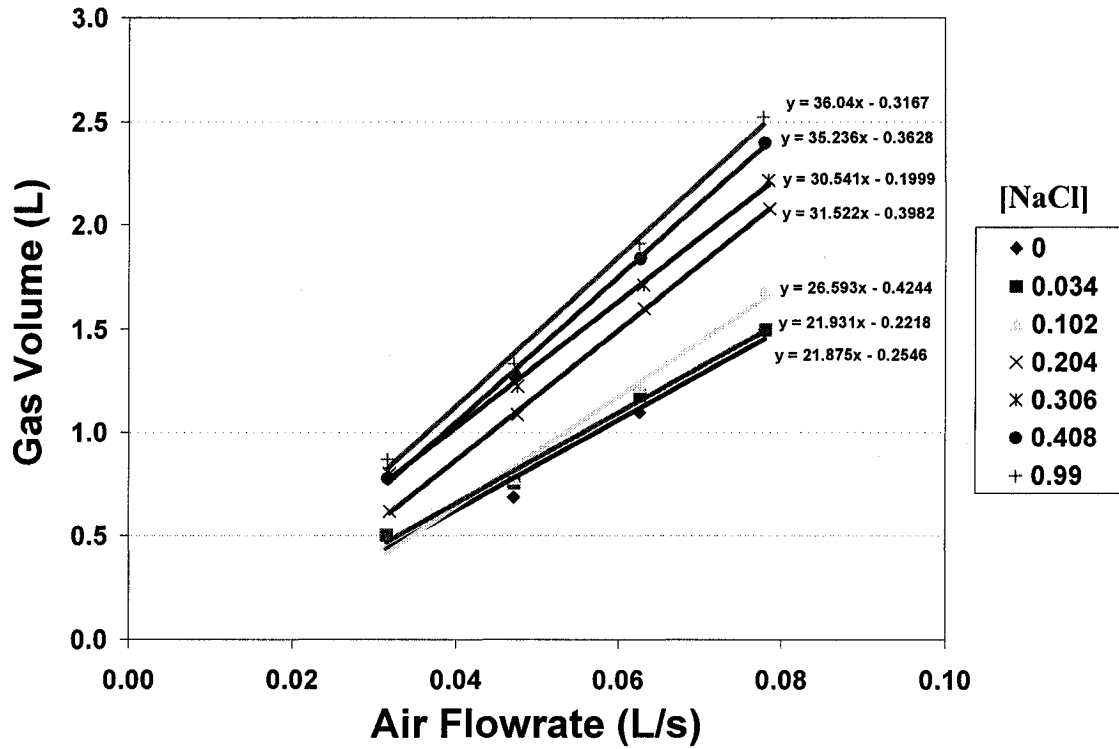
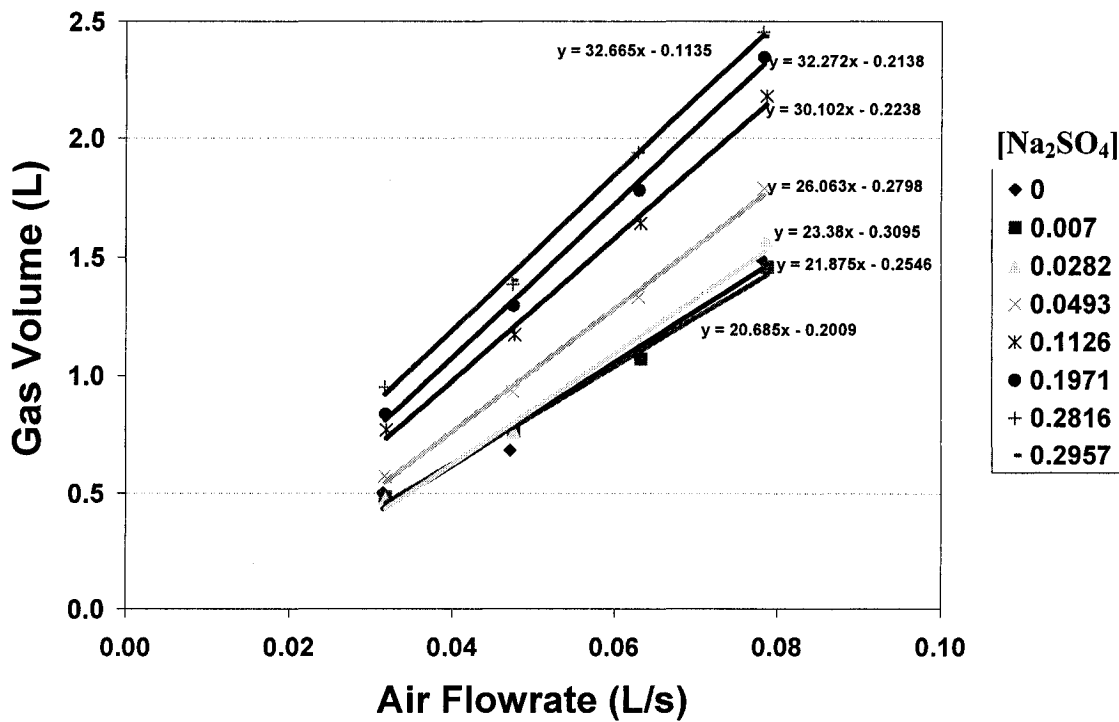Figure A1 – rt calculations for NaCl tests
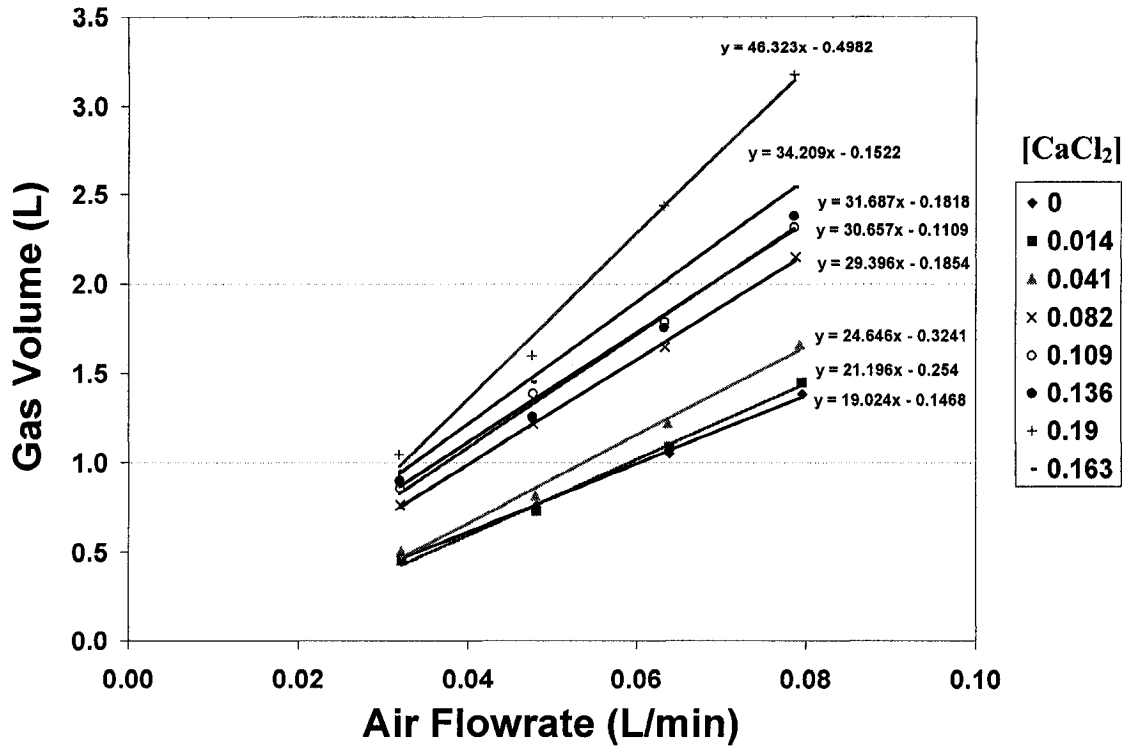

Figure A2 – rt calculations for Na$_2$SO$_4$ tests
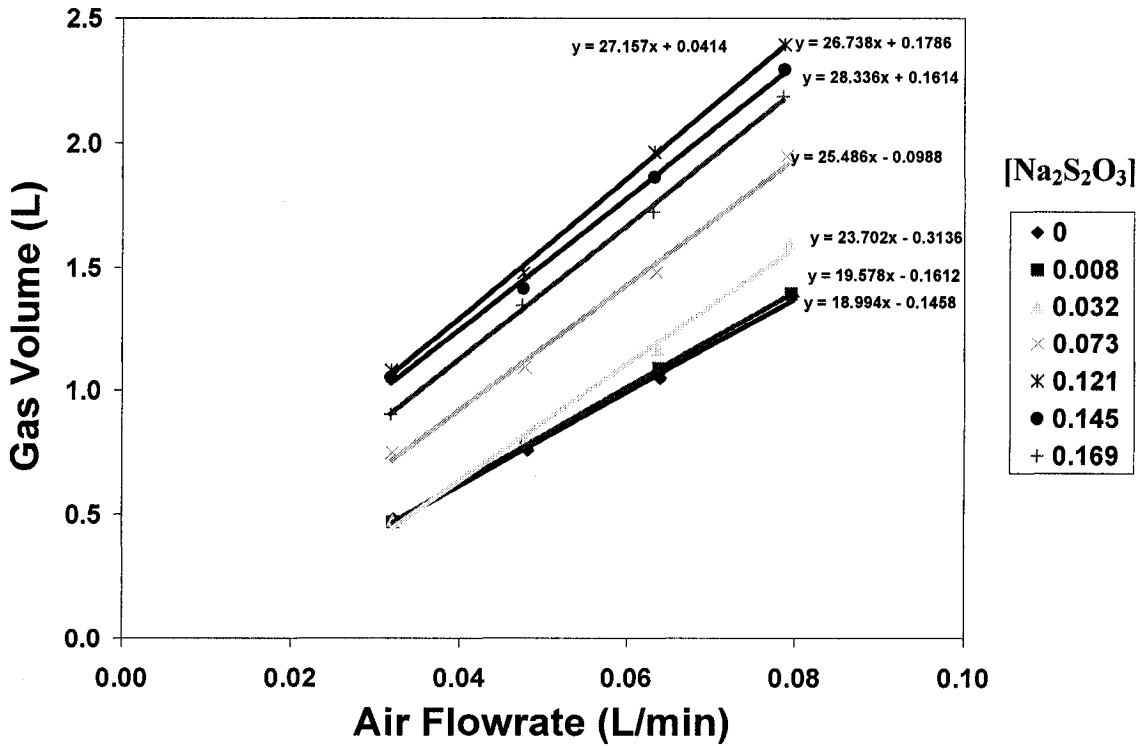
Figure A3 – rt calculations for CaCl₂ tests

Figure A4 – rt calculations for Na₂S₂O₃ tests

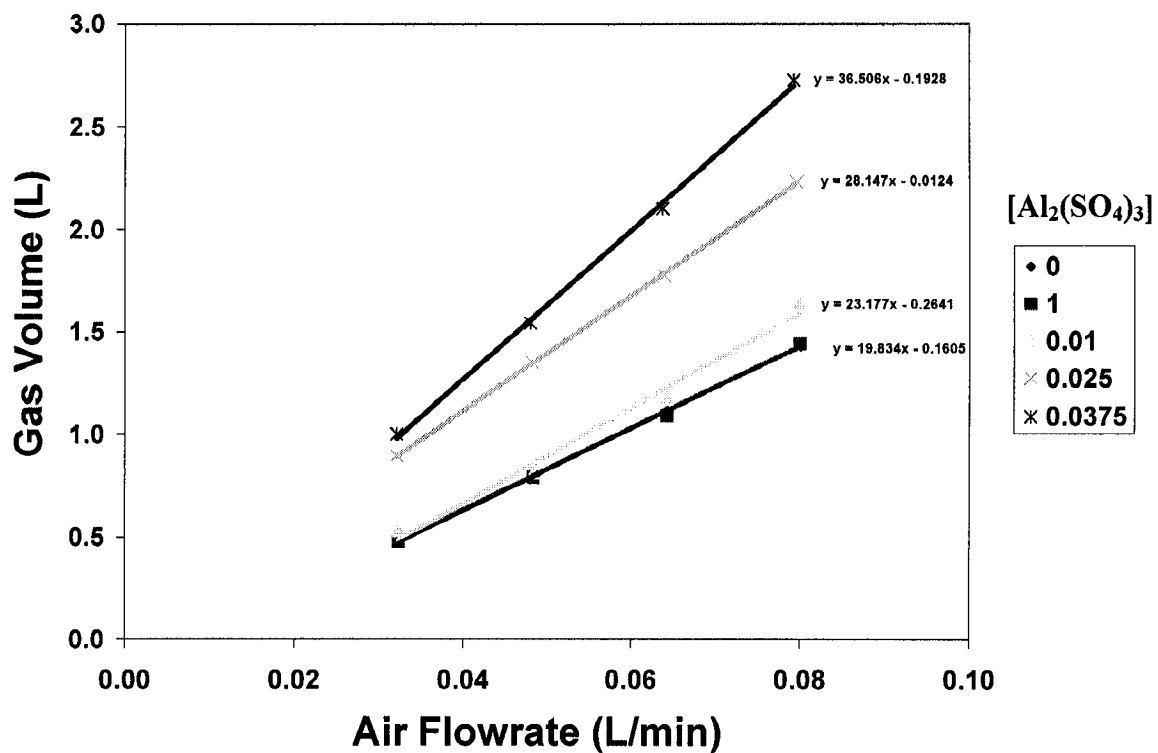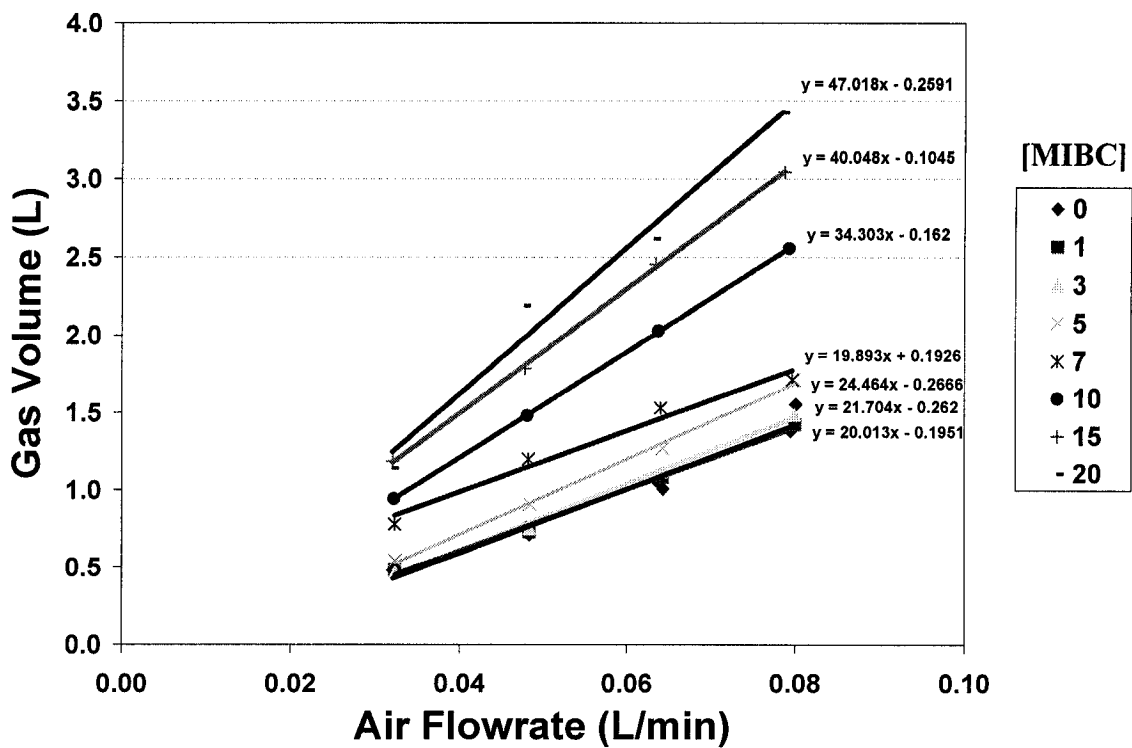Figure A5 – rt calculations for Al$_2$(SO$_4$)$_3$ tests

[Al$_2$(SO$_4$)$_3$]

♦ 0
■ 1
  0.01
✕ 0.025
✳ 0.0375

y = 36.506x - 0.1928
y = 28.147x - 0.0124
y = 23.177x - 0.2641
y = 19.834x - 0.1605

Figure A6 – rt calculations for MIBC tests

[MIBC]

♦ 0
■ 1
  3
✕ 5
✳ 7
● 10
+ 15
- 20

y = 47.018x - 0.2591
y = 40.048x - 0.1045
y = 34.303x - 0.162
y = 19.893x + 0.1926
y = 24.464x - 0.2666
y = 21.704x - 0.262
y = 20.013x - 0.1951

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3-Phase Tests with Talc

Reproducibility

Repeat tests were conducted in 0.1M NaCl and 0.2M NaCl (3 repeats each) at J_g=1.4cm/s. The tables below show the data sets, mean and standard deviation (stdev). The pooled standard deviation for this data is shown in Table A12.

Table A11 – 3-phase with talc repeat 0.1M and 0.2M NaCl tests

Sol'n	Jg (cm/s)	O/F Rate (g/min)			O/F %w/w solids	Recovery (%)	
		Tot.	Solids	sol'n		Solids	liq
0.1M	1.4	105.5	28.5	77.0	27.0	60.3	7.9
0.1M	1.4	122.9	22.7	100.2	18.5	48.6	10.3
0.1M	1.4	116.6	19.3	97.3	19.6	41.4	10.0
	mean	115.0	23.5	91.5	21.7	50.1	9.4
	stdev	8.8	4.7	12.6	4.6	9.6	1.3

Sol'n	Jg (cm/s)	O/F Rate (g/min)			O/F %w/w solids	Recovery (%)	
		Tot.	Solids	sol'n		Solids	liq
0.2M	1.4	135.9	27.7	108.2	20.4	60.2	11.0
0.2M	1.4	122.3	29.8	92.5	24.4	64.3	9.4
0.2M	1.4	143.1	34.0	109.0	23.8	73.5	9.4
	mean	133.7	30.5	103.2	22.8	66.0	10.0
	stdev	10.6	3.3	9.3	2.2	6.8	0.9

Table A12 – 3-phase with talc pooled standard deviations

	O/F Rate (g/min)			O/F %w/w solids	Recovery (%)	
	Tot.	Solids	sol'n		Solids	liq
pooled stdev	9.7	4.0	11.1	3.6	8.3	1.1

3-Phase Overflow Tests
1%w/w talc, NaCl

NaCl (M)	Jg (cm/s)	O/F Rate (g/min)			%w/w solids	Recovery (%)	
		Tot. (S+L)	Solids (S)	Liquid (L)		Solids	liquid
0	0.38	0	0	0	0	0	0
0	0.95	0	0	0	0	0	0
0	1.43	0	0	0	0	0	0
0	1.91	0	0	0	0	0	0
0.1	0.38	20.6	7.0	13.6	34.1	14.79	1.39
0.1	0.95	44.6	12.7	31.9	28.5	26.88	3.27
0.1	1.43	116.6	19.3	97.3	19.6	41.4	10.0
0.1	1.91	157.7	23.8	133.9	15.1	51.21	13.72
0.2	0.38	73.0	27.3	45.7	37.3	57.92	4.66
0.2	0.95	120.8	35.0	85.9	28.9	74.92	8.75
0.2	1.43	143.1	34.0	109.0	23.8	73.5	9.44
0.2	1.91	222.4	42.5	179.9	19.1	92.88	18.33
0.4	0.38	138.9	37.1	101.8	26.7	79.71	10.37
0.4	0.95	173.0	42.7	130.3	24.7	92.08	13.28
0.4	1.43	188.1	39.9	148.2	21.2	86.58	15.10
0.4	1.91	281.9	43.5	238.4	15.4	96.33	24.29

Table A14 – 3-phase tests (talc) MIBC

3-Phase Overflow Tests
1%w/w talc, MIBC

MIBC (ppm)	Jg (cm/s)	O/F Rate (g/min)			%w/w solids	Recovery (%)	
		Tot. (S+L)	Solids (S)	Liquid (L)		Solids	liquid
0	0.38	0	0	0	0	0	0
0	0.95	0	0	0	0	0	0
0	1.43	0	0	0	0	0	0
0	1.91	0	0	0	0	0	0
5	0.38	67.9	19.3	48.5	28.5	40.25	5.00
5	0.95	95.1	29.6	65.5	31.1	61.67	6.75
5	1.43	101.8	28.8	73.0	28.3	60.00	7.53
5	1.91	121.0	27.4	93.6	22.7	57.13	9.65
10	0.38	75.6	29.0	46.6	38.3	60.33	4.81
10	0.95	125.9	43.9	82.0	34.8	91.42	8.46
10	1.43	156.2	39.6	116.6	25.3	82.42	12.02
10	1.91	205.6	40.8	164.8	19.9	85.04	16.99
15	0.38	73.1	27.9	45.2	38.2	58.21	4.66
15	0.95	159.1	40.4	118.7	25.4	84.17	12.23
15	1.43	195.3	44.3	151.0	22.7	92.33	15.56
15	1.91	218.3	45.5	172.7	20.9	94.88	17.80
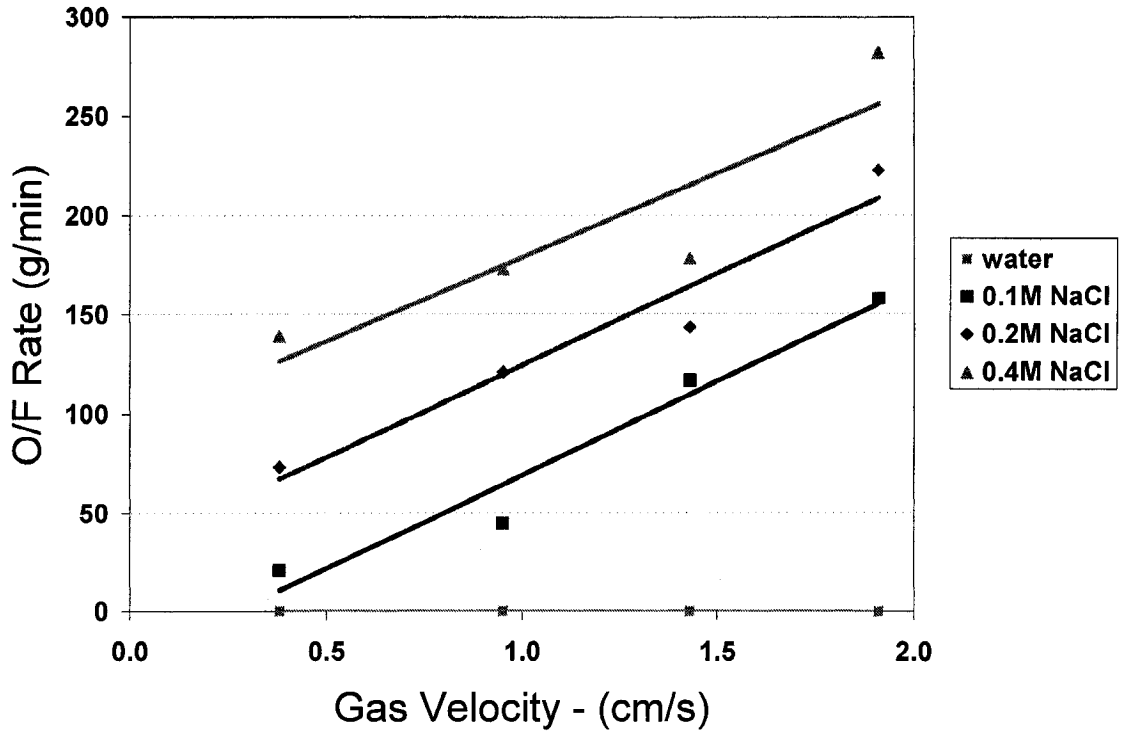
Figure A7 - Effect of NaCl concentration and gas velocity on overflow rate (solids + liquid)
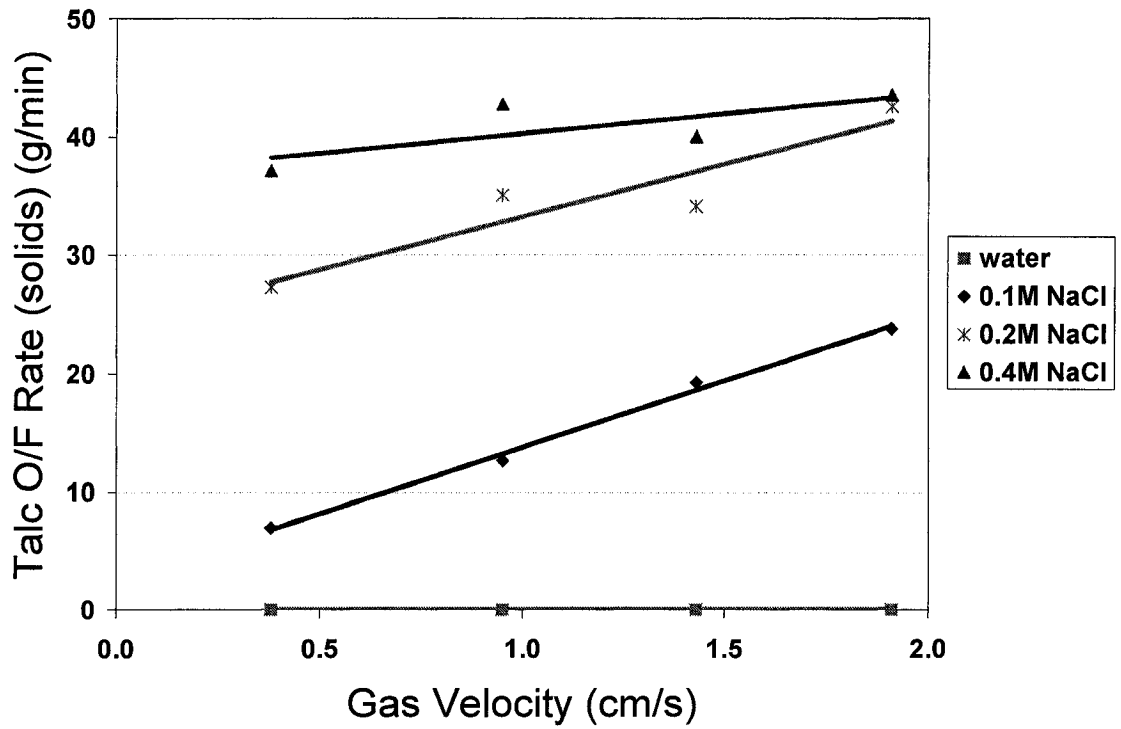
Figure A8 - Effect of NaCl concentration and gas velocity on overflow rate of solids (talc)
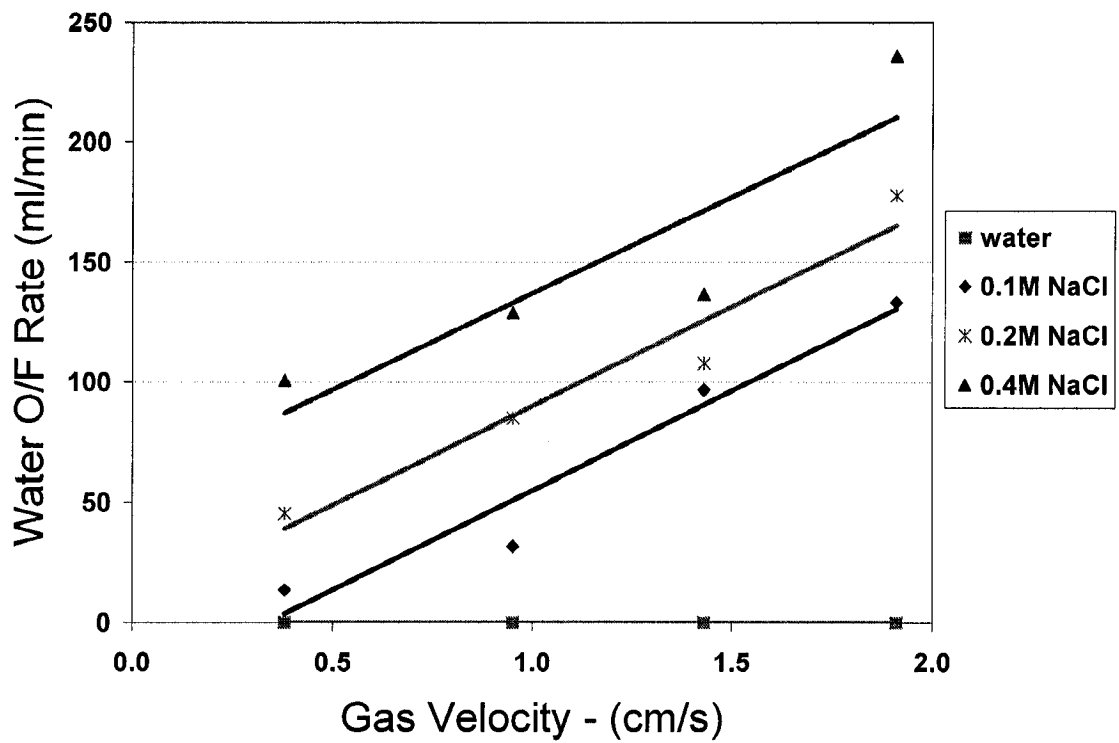
88

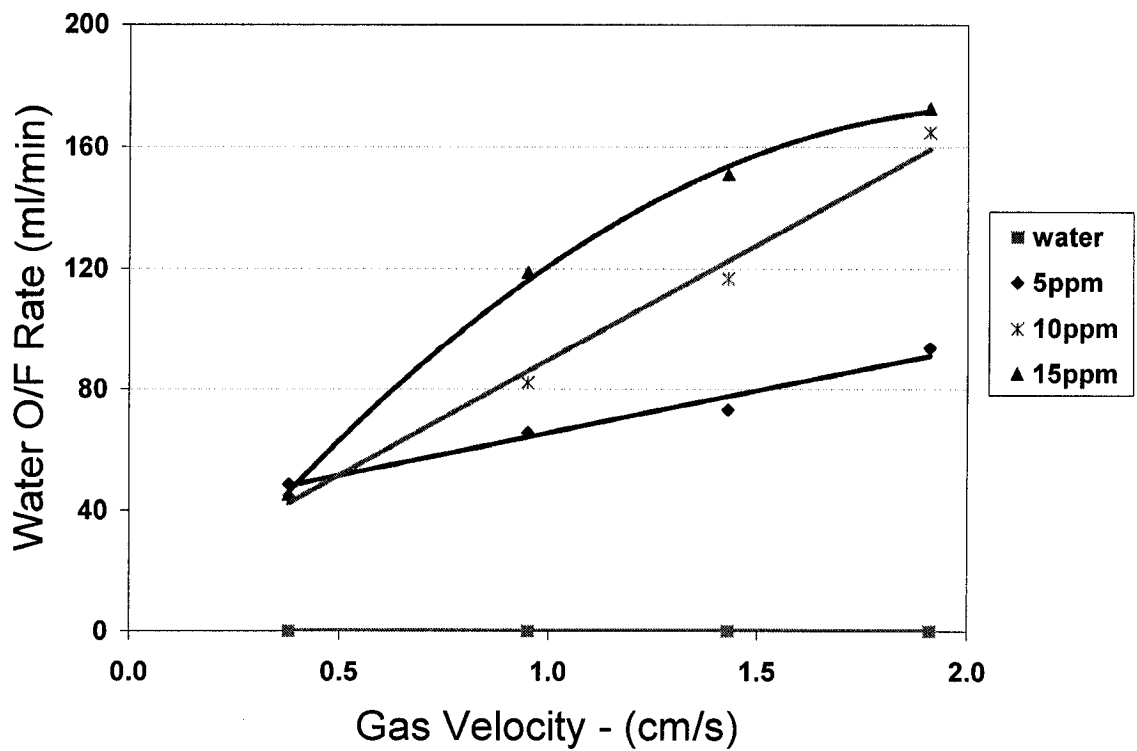Figure A9 - Effect of NaCl concentration and gas velocity on water overflow rate

Figure A10 - Effect of MIBC concentration and gas velocity on overflow rate (solids and liquid)
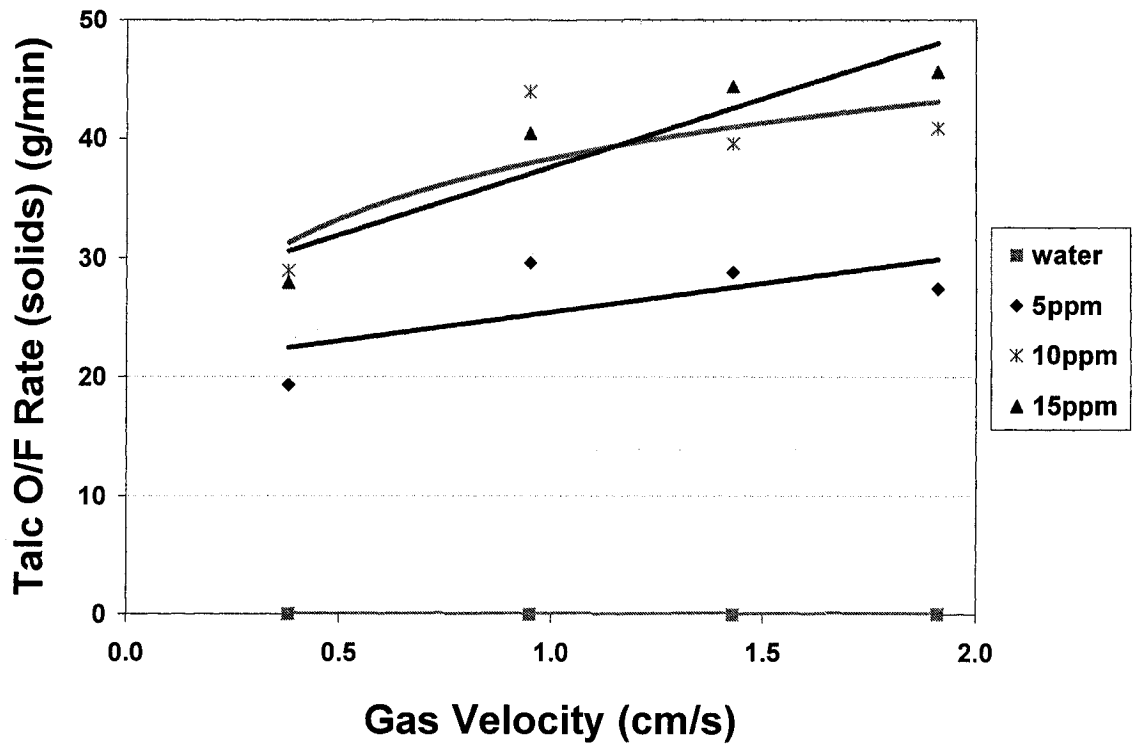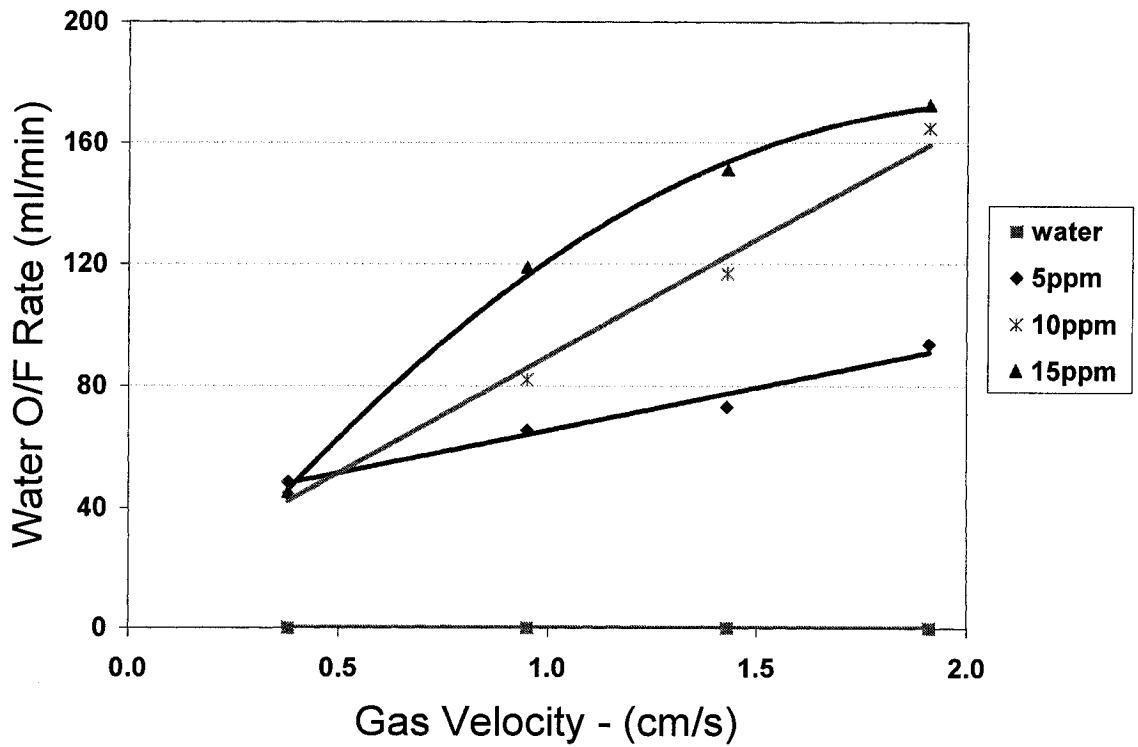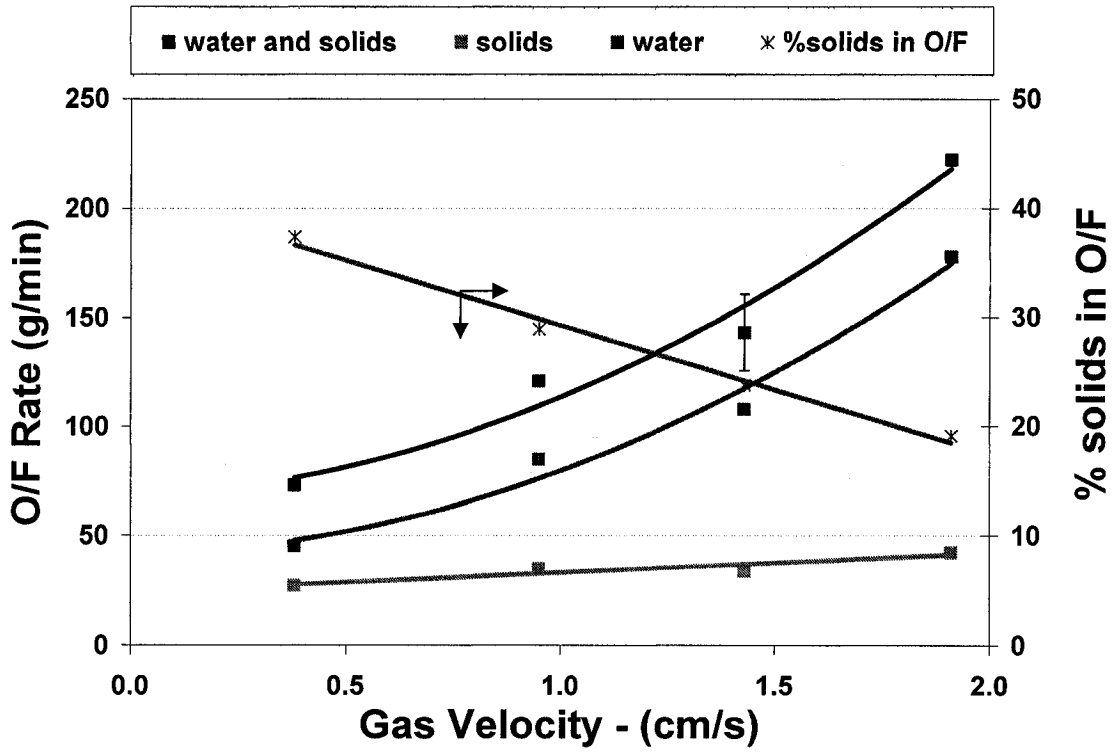
Figure A11- Effect of MIBC concentration and gas velocity on overflow rate of solids (talc)

Figure A12 - Effect of MIBC concentration and gas velocity on water overflow rate

Figure A13 - Overflow rates and percent solids for 0.2M NaCl system
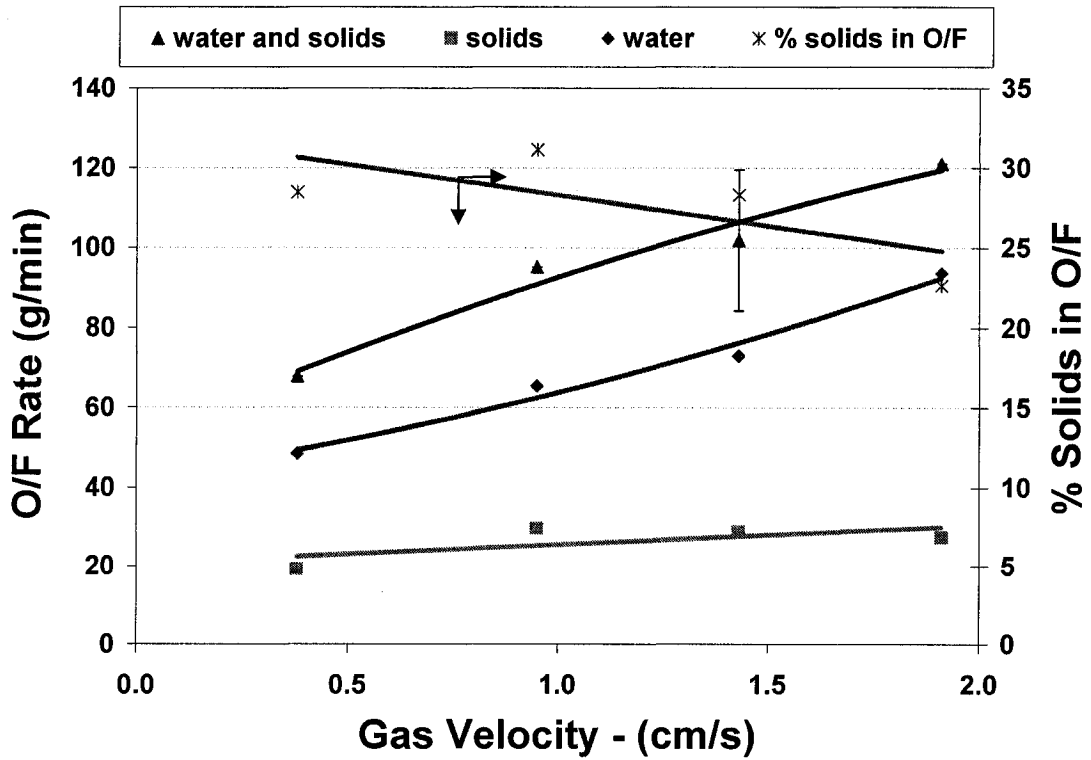
Figure A14 - Overflow rates and percent solids for 5ppm MIBC system
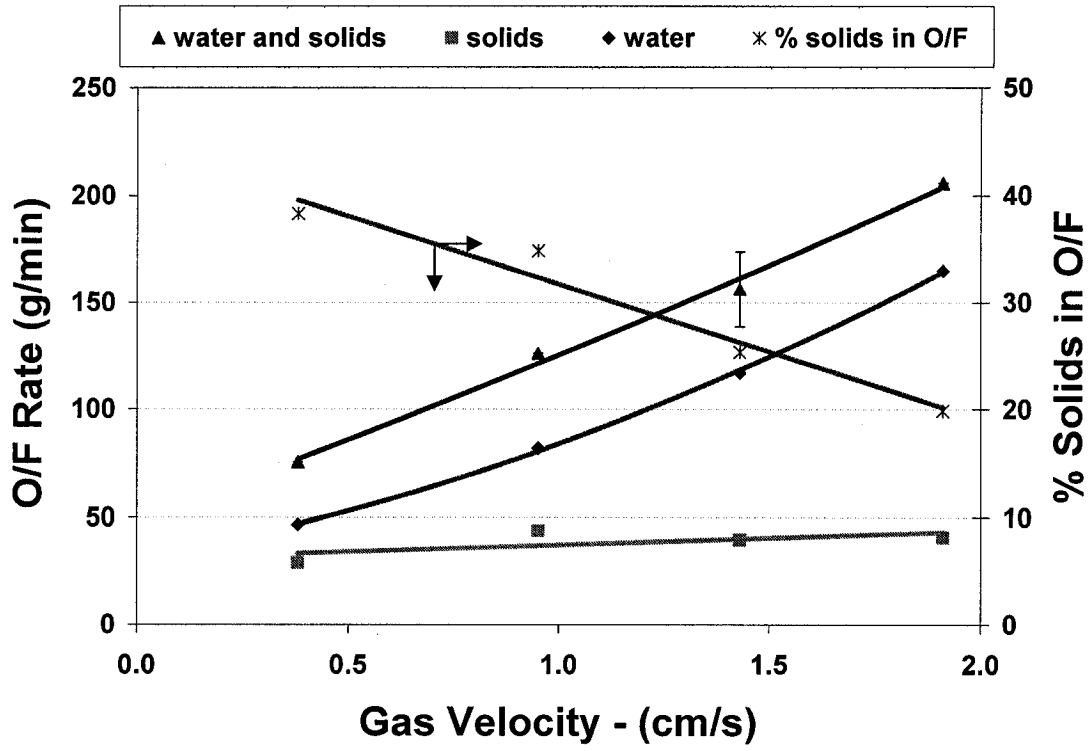
Figure A15 - Overflow rates and percent solids for 10ppm MIBC system

Three-Phase Tests with Ore
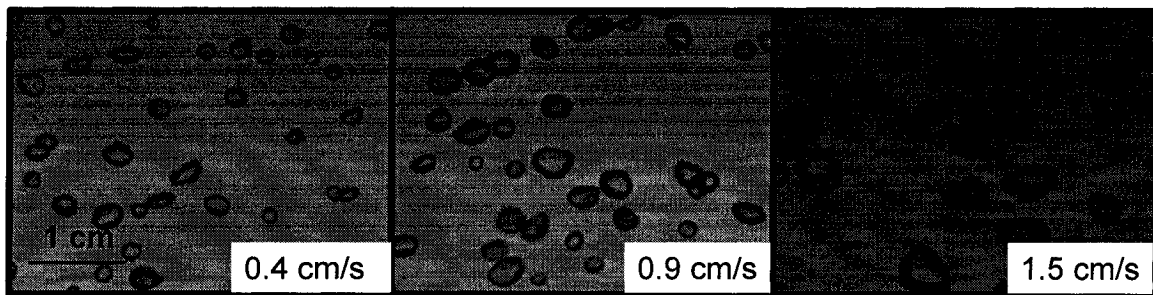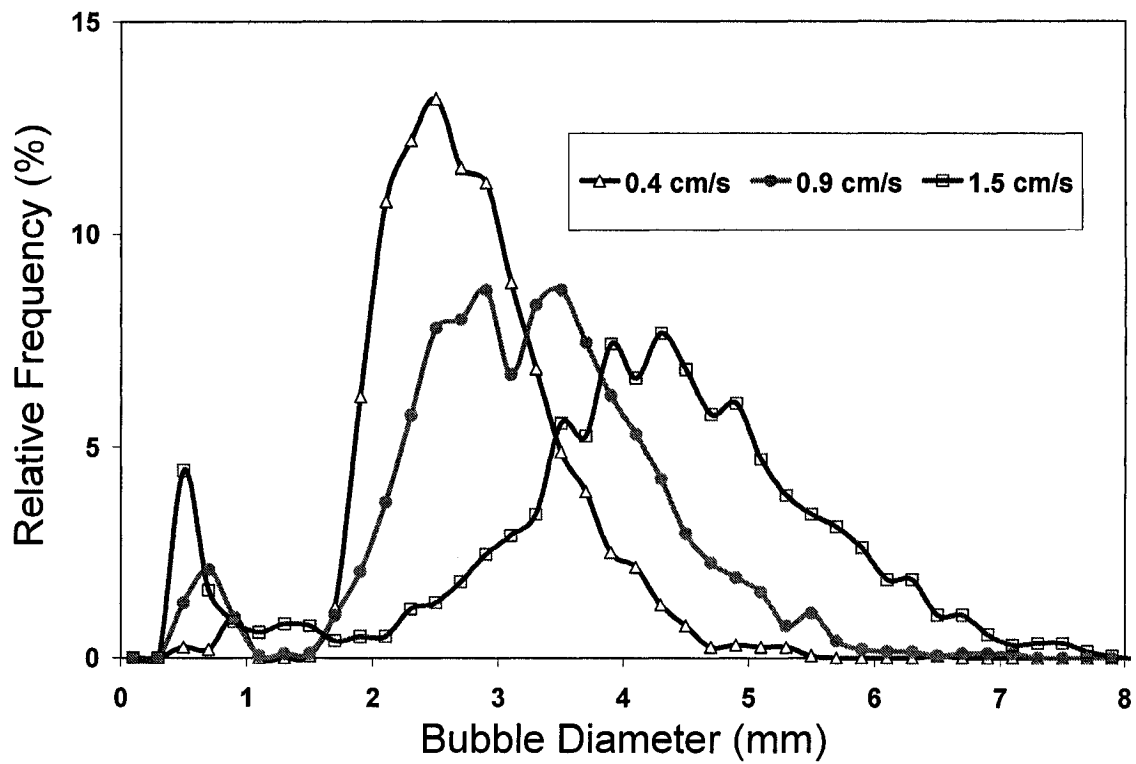
Figure A16 a) Effect of superficial gas velocity on bubble size distribution in 0.1M NaCl solution

b) Example images
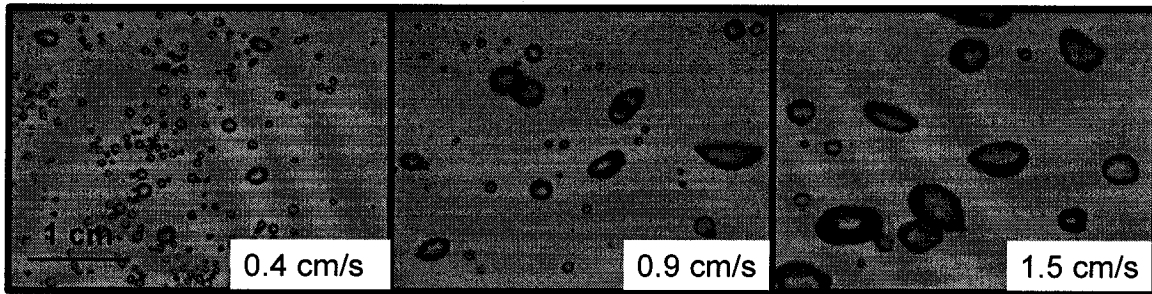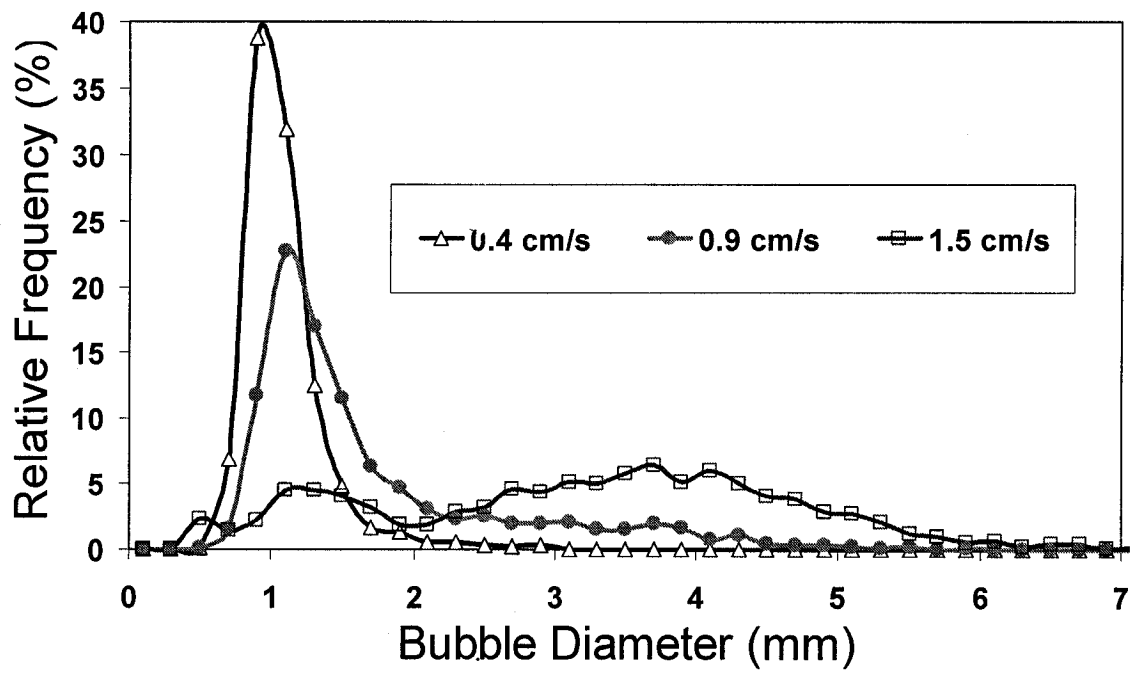
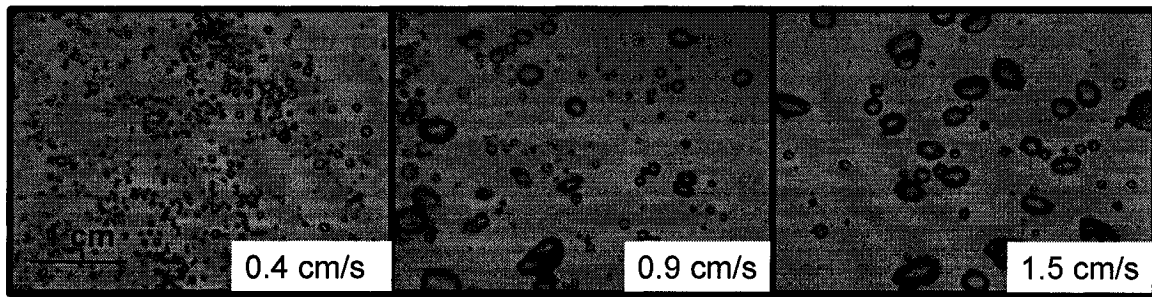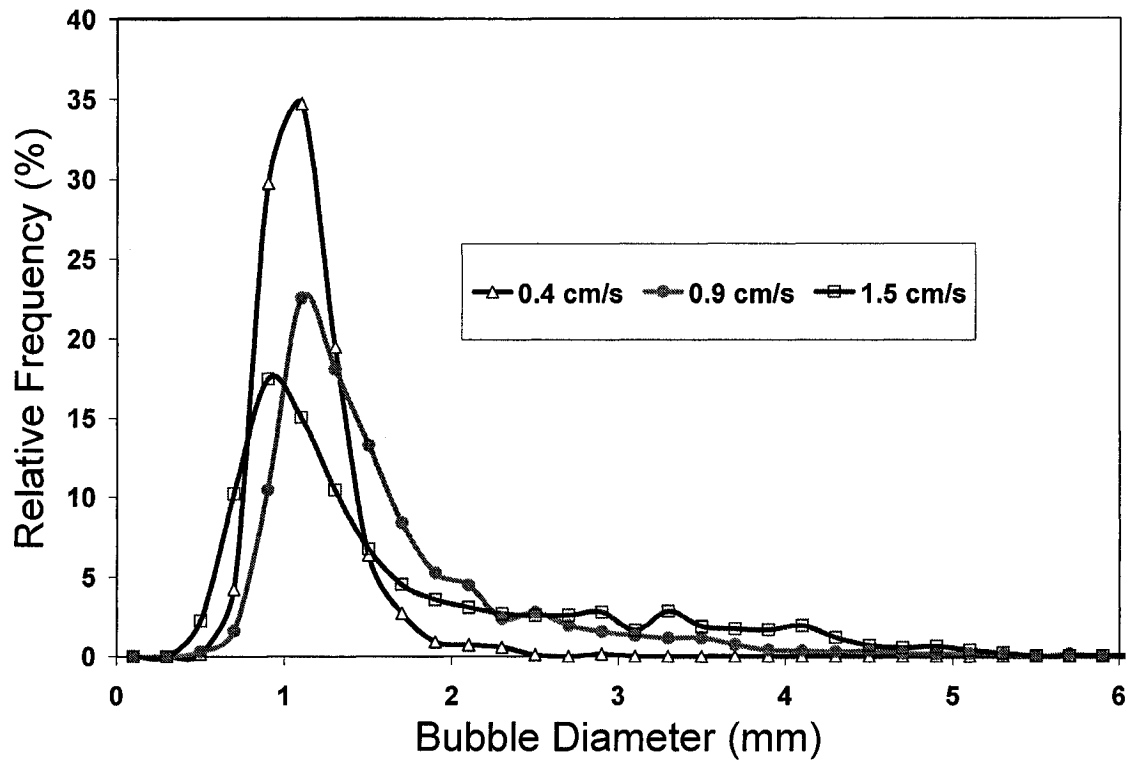Figure A17 a) Effect of superficial gas velocity on bubble size distribution in 0.2M NaCl solution
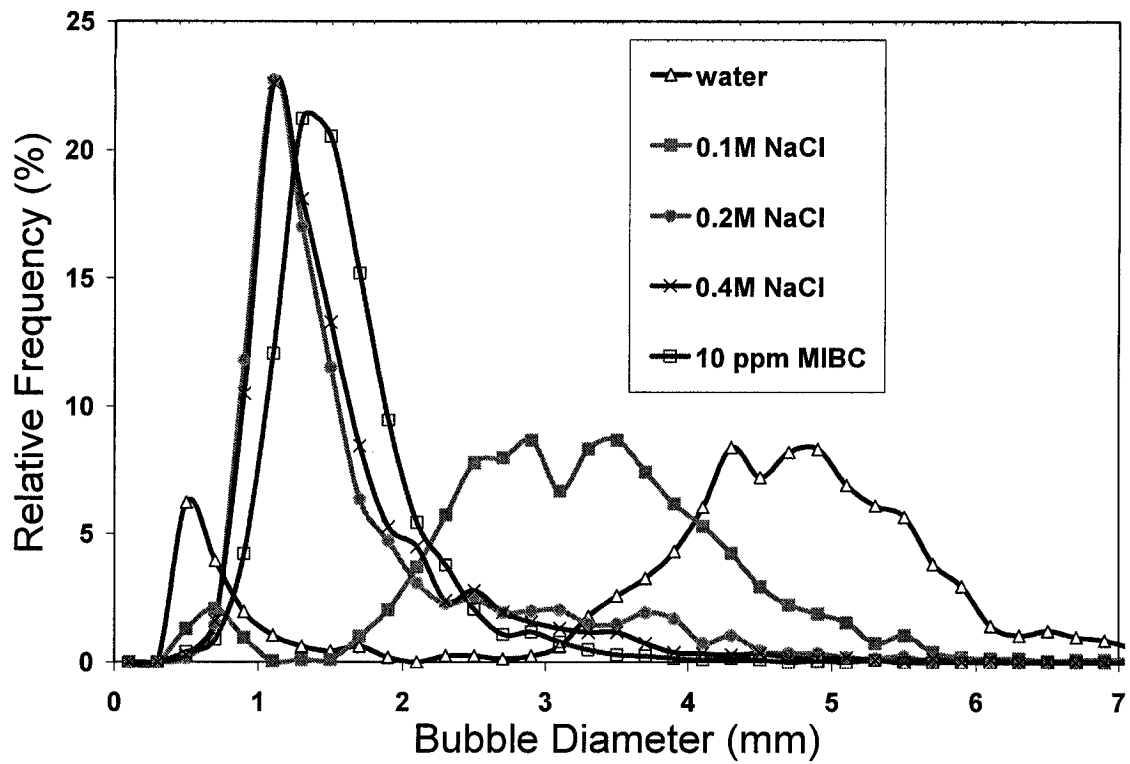
b) Example images

Figure A18 a) Effect of superficial gas velocity on bubble size distribution in 0.4M NaCl solution

b) Example images

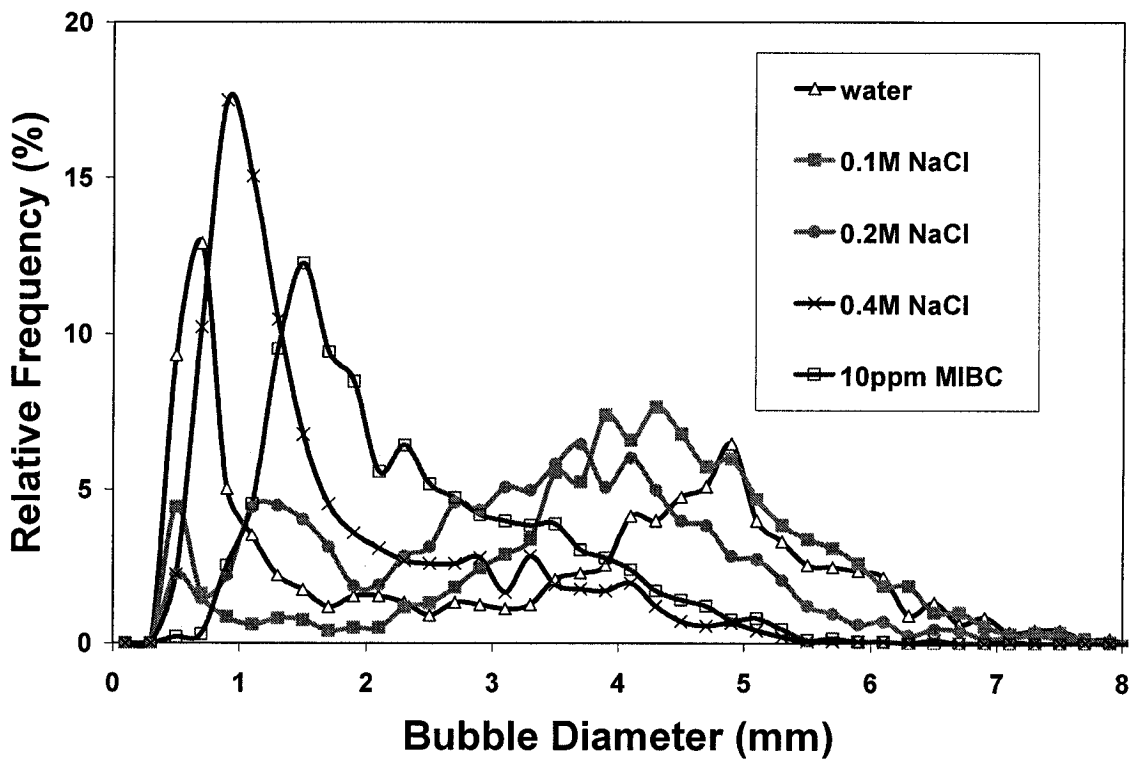Figure A19 – Comparison of bubble size distributions in NaCl and MIBC solutions (Jg = 0.9cm/s)

Figure A20 – Comparison of bubble size distributions in NaCl and MIBC solutions (Jg = 1.5cm/s)