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Hydrodynamic characterization of frother in tap and sea water

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ABSTRACT

Frothers are added in flotation to control bubble size by reducing bubble coalescence and to promote froth build-up by increasing the amount of water associated with the adsorbed frother molecules on the surface of bubbles. Mineral processing operations around the world use in their flotation circuits process water with a high inorganic salt content. It has been demonstrated that dissolved salts significantly reduce bubble coalescence, but the effect on water carrying rate is not known.

In this work, two-phase (water-air) tests were undertaken in a laboratory flotation column to quantify and compare the effect of inorganic ions present in the water on frother performance. The frother characterization approach focused on gas dispersion by collecting measurements of collection zone and froth zone parameters simultaneously. Thus, establish the effect of seawater on the ability of frothers to control bubble coalescence (first role), and the froth buildup (second role), allowing interactions between zones.

A test program run in a lab flotation column was designed to establish the effect of salts on the ability of frothers to reduce bubble coalescence (by measuring bubble size), and to increase water carrying rate which stabilizes the froth (by measuring water overflow rate for a constant froth depth). The column was instrumented to control gas flowrate and to measure gas holdup, and included equipment to manually measure bubble size and water overflow rate. These variables were measured for every frother, on fresh and synthetic sea water solutions at seven frother concentrations (0, 2, 5, 10, 15, 30, 60, 100 ppm), at a superficial gas velocity of 1 cm/s and a manually controlled froth depth of 5 cm. The frothers selected for the study were analytical grade samples of glycols (DF250, PPG425) and alcohols (MIBC and 1-hexanol), and one of a commercial frother blend (F140).

The measurements of bubble size, gas holdup and water carrying rate as a function of frother concentration were reliable and reproducible. The result of repeat tests indicated that relative errors for the three parameters were less than 5% for a 95% C.I. The results demonstrated that bubble coalescence was completely eliminated for a synthetic sea water solution as no effect of frother concentration on bubble size was observed. A linear relationship between water overflow rate and gas holdup was obtained with similar slopes in fresh and synthetic sea water solution for frother concentrations below 30 ppm. Higher water overflow rates were obtained in synthetic sea water solutions for the same gas holdup. A relationship was established between the water overflow rate and frother concentration, in the case of the glycols (DF250 and PPG425) and the commercial frother (F140) samples, but not for alcohols (MIBC and 1-hexanol).

RÉSUMÉ

Les moussants sont introduits en flottation pour contrôler la taille des bulles, en empêchant la coalescence des bulles et favorisant la formation de mousse, tout en augmentent la quantité d'eau associée avec les molécules de moussant adsorbés sur la surface des bulles. Les opérations de traitement de minerai utilisent fréquemment de l'eau de procédé riche en sel inorganique. Il a été démontré que ces sels dissous réduisent considérablement la coalescence de bulles, mais leur effet sur l'entrainement d'eau n'est pas connu.

Le travail actuel a consisté en plusieurs essais de deux phases (eau et air) effectués dans une colonne de flottation en laboratoire, pour quantifier et comparer l'effet des ions inorganiques sur le comportement des moussants. La caractérisation des moussants a été concentrée sur la dispersion de gaz, en prenant des mesures simultanés dans la zone de collection et dans la zone de mousse. Ainsi, le travail a établis l'effet de l'eau de mer sur la capacité des moussants pour contrôler la coalescence des bulles (premier rôle) et l'accumulation de mousse (deuxième rôle), en considérant l'interaction entre les deux zones.

Le programme d'essai a été conçu pour établir l'effet des sels sur la capacité des moussants pour réduire la coalescence des bulles (en mesurant la taille des bulles), et en augmentant l'entrainement d'eau qui stabilise la mousse (en mesurant le taux d'entrainement d'eau pour une profondeur fixe). La colonne était équipée pour contrôler le taux d'injection de gaz et mesurer la rétention de gaz. Ces variables ont été mesurées pour chaque moussant, en solution avec de l'eau douce et de l'eau de mer synthétisée, à sept concentrations (0, 2, 5, 10, 15, 30, 60, 100 ppm), avec une vélocité de gaz de 1 cm/s, et à une profondeur contrôlée de 5 cm. Les moussants choisies pour l'étude étaient des échantillons de qualité analytique de glycols (DF250, PPG425) et d'alcools (MIBC et 1-hexanol), et d'un mélange commercial (F140).

Les mesures de la taille des bulles, de la rétention de gaz et de l'entrainement d'eau, en fonction de moussant étaient fiables et reproductibles. Les résultats des essais répétés indiquent que les erreurs relatives pour les trois quantités ont été en bas de 5% pour un intervalle de confiance de 95%. Les résultats démontrent ainsi l'élimination complète de la coalescence de bulles pour l'eau de mer synthétisée, donc aucun effet de concentration de moussant sur la taille des bulles. Pourtant, des relations linéaires pour l'entrainement d'eau et pour la rétention de gaz ont été obtenues, ayant des pentes similaires pour l'eau douce et l'eau de mer, pour des concentrations de moussant inférieures à 30 ppm. Des valeurs d'entrainement eau plus élevées ont été observées avec l'eau de mer, pour la même rétention d'eau. Une relation a été établie entre le taux d'entrainement d'eau et la concentration de moussant, pour les essais de glycols (DF250 et PPG425) et de moussant commercial (F140), mais pas pour les alcools (MIBC et 1-hexanol).

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Chapter 1: INTRODUCTION

Mineral processing comprises two principal steps: size reduction to liberate the grains of valuable mineral from gangue minerals, and physical separation of the particles of valuable minerals from the gangue, to produce an enriched portion, or concentrate, containing most of the valuable minerals, and a discard, or tailing, containing predominantly the gangue minerals.

Flotation is a mineral separation process that exploits natural and induced differences in surface properties of minerals, i.e. whether the surface is readily wetted by water (hydrophilic), or repels water (hydrophobic). If the mineral is hydrophobic, it is possible to attach particles to air bubbles, which float and term a mineralized froth. The system is complex, involving three phases (solids, water, and air) and the interaction of chemical and physical variables (Wills and Finch, 2016).

Figure 1.1 illustrates the principle of true flotation in a mechanical flotation cell. The agitator provides enough turbulence in the pulp phase to promote collision of particles and bubbles, which results in the attachment of hydrophobic particles to bubbles and their transport into the froth phase for recovery.

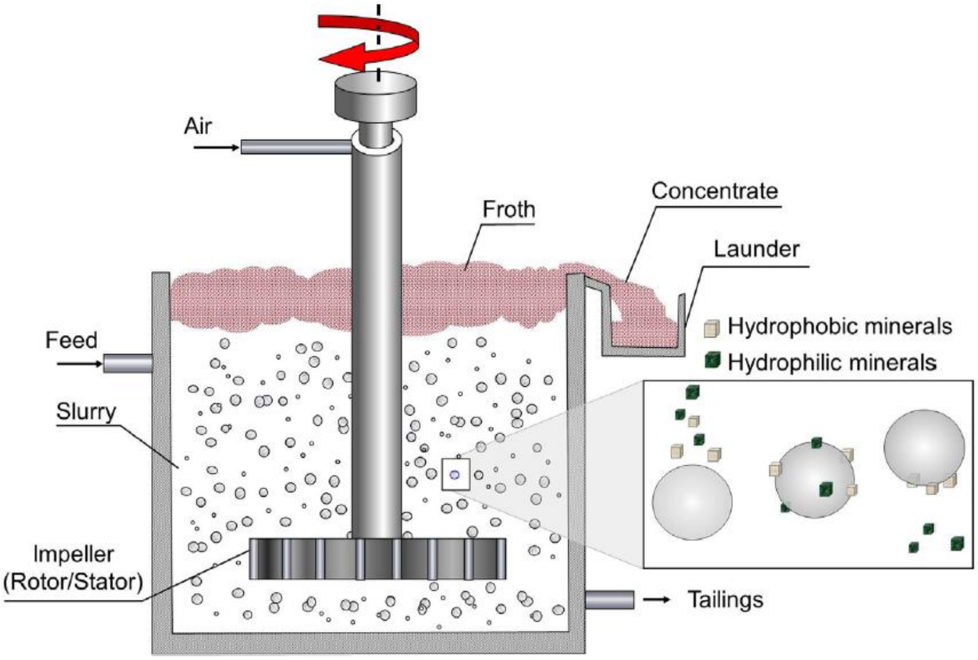

Figure 1.1: Principle of froth flotation (Wills and Finch, 2016)

Commonly used flotation reagents include collectors, depressant, pH modifiers, and frothers. Thus, reagents and flotation are inseparables in mineral processing. It is widely acknowledged that separating valuable mineral particles from gangue particles by flotation is dependent on a wide range of complex factors. One of which is the hydrodynamic conditions (gas dispersion characteristics) within flotation cells, which is known to directly influence the flotation efficiency (Gorain *et al*, 1995).

New technology has been developed in different research centers, to measure gas dispersion characteristics in industrial flotation cells. It is also widely acknowledged that the main measurements that define the hydrodynamic performance include bubble size, gas hold-up and superficial gas velocity.

Gorain et al. (1997) showed that the derived parameter "bubble surface area flux" (Sb), the total surface area of bubbles exiting the cell per unit cross-sectional area of the cell per unit of time, is a key driver of flotation recovery through the k-Sb relationship, where k represents the rate constant in the pulp phase. Since Sb is inversely proportional to bubble size D_{32}, it is seen that the rate of flotation, and hence recovery, is inversely linked to bubble size and directly proportional to the volumetric flow rate of gas. Studies of flotation performance thus requires precise measurements of these key parameters which were made possible by the breakthrough developments in sensor technology and process measurement of McGill University (Dobby and Finch, 1986; Finch and Dobby, 1990) and the Julius Kruttschnitt Mineral Research Centre (JKMRC) (Gorain et al, 1997, 1999).

Many large mineral deposits are located in the areas with limited resources of fresh water. In such cases flotation in seawater becomes an increasingly important issue. However, the use of seawater could become a sustainable solution only if it can deliver metal recoveries and concentrate grades comparable to those obtained when using freshwater.

Understanding the impact of saline water on the hydrodynamics (*i.e*. gas dispersion parameters) must be understood if operations have to run efficiently. The aim of this research is, therefore, the measurements of bubble size, gas holdup, and water overflow rate, using a flotation column and to determine the dependence of hydrodynamic variables on frothers in tap and sea water. Studying how seawater influences the foam stability is a second objective, which has not been systematically studied previously.

The study is restricted to the 2-phase air-water system. Understanding the 2-phase behavior prior to tackling the inclusion of solids avoids the logistical problems of handling solids on this scale in a laboratory.

1.1: Research Objectives

The general objective is to characterize the effect of frothers on bubble size and water carrying rate of tap and synthetic sea water using a gas-water (*i.e.* 2-phase) system in laboratory flotation column. To accomplish this, the following specific objectives were set:

1. Measurements of bubble size, gas holdup, water overflow rate and froth height, using a flotation column and then determine the dependence of hydrodynamic variables on pure frother concentrations with tap water:
    a. Determining Sauter mean bubble diameter versus concentration;
    b. Quantifying overflow rate and comparing this to gas holdup in the collection zone;
2. Measurements of bubble size, gas holdup, water overflow rate and froth height, using a flotation column and then to determine the dependence of hydrodynamic variables on pure frother concentrations with saline and synthetic sea water:
    a. Determining Sauter mean bubble diameter versus concentration;
    b. Quantifying Overflow rate and compare with gas holdup in the collection zone;
3. Determine and interpret the effect of single and blended frothers on control of hydrodynamic properties compared to same frothers but in saline and synthetic sea water.

In summary, the objectives for this research were to establish the effect of seawater on the ability of frothers to control bubble size (first role), and the foam stability (second role) by measurements of bubble size, gas holdup, and water overflow rate, using a flotation column. In addition, frothers were characterized by measuring collection and froth zones parameters simultaneously.

1.2: Research Scope

Frothers play several roles in flotation, therefore relating this understanding by selecting conditions leading to stable operation and maximum metallurgical performance is fundamental to what this work aims to provide. Previous work characterizing frothers has been conducted with only one role in mind, and the conditions were different to those in industrial flotation machines. As a starting point, this work focused on using the frother characterization technique to test frothers by gathering measurements of collection and froth zone parameters simultaneously in a pilot flotation column. This approach allows the effect of interactions between flotation zones to be considered. Further tests were designed to measure the effect of frother type and concentration on three parameters: two related to gas dispersion in the pulp (bubble size and gas holdup); and one related to the froth (water overflow rate).

Frothers were then classified using three parameters: the critical coalescence concentration (CCC) determined from bubble size vs frother concentration, the minimum gas holdup to allow an overflow for a selected froth depth; and the slope of the increase of overflow rate with gas holdup. Water solutions with synthetic sea water and fresh tap water were tested.

The choice to use the 2-phase system is not considered to be a deficiency; rather it was used to obtain initial understandings of gas-liquid behavior before introducing solids. The variables selected for study are those considered to be the main variables (gas rate, frother concentration, superficial gas velocity or gas rate Jg). Thus, the ranges selected for all the variables can be considered representative of industrial practice, with some extension above and below typical operating range for frother concentration, and typical for gas rate.

1.3: References

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Chapter 2: LITERATURE REVIEW

2.1: FROTHERS

Frothers are heteropolar surface-active compounds containing a polar group (OH, COOH, C=O, OSO_2 and SO_2OH) and a hydrocarbon radical, capable of adsorbing in the water–air interface. The frother molecules are arranged at the air–water interface such that the hydrophilic or polar groups are oriented into the water phase, and the hydrophobic or nonpolar hydrocarbon chain in the air phase. The frother concentrates at the interface of water and air bubbles, forming an envelope around the bubbles, which prevents them from colliding or touching (Bulatovic, 2007).

Frothers aid in the process of producing small bubbles, typically in the range of 0.5 to 2.5 mm (Gorain *et al.*, 1995). A high population of small bubbles in the presence of frother also helps stabilize the froth that forms as the bubbles accumulate on the pulp surface.

2.1.1: FROTHER CLASSIFICATION

In the literature, there are several different classifications of frothers depending on their properties and behaviors in solution and pulp. Four classification methods commonly used are based on pH-sensitivity, solubility, frothing/collecting ability, and selectivity/frothing-power relationship. The other classifications are tentative because some of the compounds used as frother have been or still are proprietary products and their structures are seldom disclosed (Khoshdast and Sam, 2011).

Bulatovic (Bulatovic, 2007) revised frothers classifying these as acidic, neutral and basic, with neutral frothers being the most important group of frothers used in the flotation of base-metal ores, oxide minerals and industrial minerals. They are functional in both acidic and alkaline pulps, and are divided into six sub-groups, with wide differences in chemical composition: Aliphatic alcohols, Cyclic alcohol (alpha terpineols), Alkoxy paraffins, Polyglycol ethers, Polypropylene glycol ethers, and Polyglycol glycerol ethers.

Leja (Leja, 1982) considers three main groups of frothers distinguished by chemical structure. These are alcohols, alkoxy-substituted paraffins, and polyglycol-type frothers (polyglycols and polyglycol ethers). Some representative members are listed in Table 2.1.

2.1.1.1: Alcohols

There are 3 subgroups in the alcohol class: linear aliphatic, cyclic and aromatic. As commercial products they may also contain a variety of other compounds formed during their manufacture. The linear aliphatic include both linear and branched forms that have a chain length of 5 to 8 carbon atoms. Cyclic and aromatic alcohols are much less soluble in water than linear alcohols and are less sensitive to pH. The alcohol frothers tend to produce a froth which is relatively shallow, carries little water (*i.e.*, is dry), entrains less slimes (*i.e.*, is selective), and is less stable and persistent.

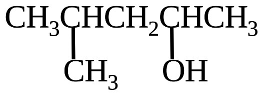
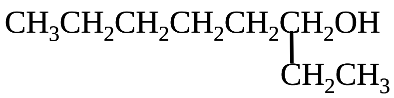
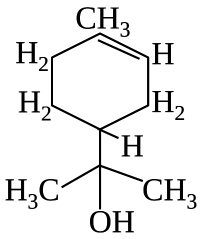
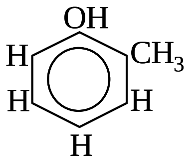
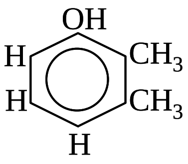
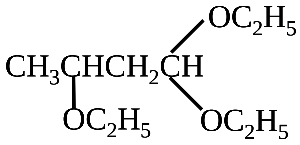
2.1.1.2: Polyglycols

Polyglycols can be divided into two groups: polypropylene or polyethylene glycols and their ethers. They are readily soluble in water. Besides their particular structure, molecular weight plays a significant role in their performance. The glycol frothers tend to produce a froth which is comparatively thick, carries more water (*i.e.*, is wet), entrains more slimes (*i.e.*, is less selective) and is relatively stable and persistent with, again, low sensitivity to pH changes. This character of polyglycols is considered an advantage when recovering coarse particles. (Azgomi, 2006).

2.1.1.3: Alkoxy-type frothers

1,1,3-Triethoxybutane (TEB) is the common frother in this group, developed and widely used in South Africa. (Klimpel and Hansen, 1988, Crozier and Klimpel, 1989) cited by Moyo (2005). It is a refinement of the alcohol group and overall has similar characteristics.

Table 2.1: Classification of flotation frothers (extracted from Azgomi F., 2006)

Frother Name	**Formula**	**Solubility in Water**
Aliphatic Alcohols	R[*]OH	
Methyl isobutyl carbinol (MIBC)	 $CH_3\underset{CH_3}{C}HCH_2\underset{OH}{C}HCH_3$	Low
2-Ethyl hexanol	 $CH_3CH_2CH_2CH_2CH_2\underset{CH_2CH_3}{C}H_2OH$	Low
Cyclic Alcohols		
α-Terpineol ($C_{10}H_{17}OH$)		Low
Aromatic Alcohols		
Cresylic acid (mixture of cresols and xylenols)	 o-Cresol  2,3-Xylenol	Low
Alkoxy paraffins		
1,1,3-Triethoxybutane	 $CH_3\underset{OC_2H_5}{C}HCH_2CH(OC_2H_5)_2$	Low
Polyglycol-type	R′[†] (X)[‡]$_n$OH	
Dowfroth 250	$CH_3(PO)$[§]$_4$OH	Total
Dowfroth 1012	$CH_3(PO)_{6.3}OH$	Total
Aerofroth 65 (Dowfroth 400)	$CH_3(PO)_{6.5}OH$	Total

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[*] R= C_nH_{2n+1}

[†] R′=H or C_nH_{2n+1}

[‡] X=EO, PO or BO

[§] EO= C_2H_4O, PO=C_3H_6O and BO= C_4H_8O

2.1.2: FROTHER CHARACTERIZATION

It is well accepted that flotation frothers reduce the bubble size and increase foam stability. These two measurements should then be employed to characterize fundamental flotation related properties of these agents.

Laskowski (Laskowski, 2004) characterized frothers by their ability to reduce bubble size in a flotation cell and to increase foam stability. He developed a frother classification system based on Dynamic foamability Index DFI and Critical coalescence concentration CCC values, which did distinguish the frothers known as being selective from those which are known to be strong. By using this methodology, a diagram in which the DFI values are plotted versus CCC values was used to classify frothers as shown in Figure 2.1. Frothers which are situated in the upper-left corner of the diagram are very strong, while those situated in the bottom-right corner are selective.

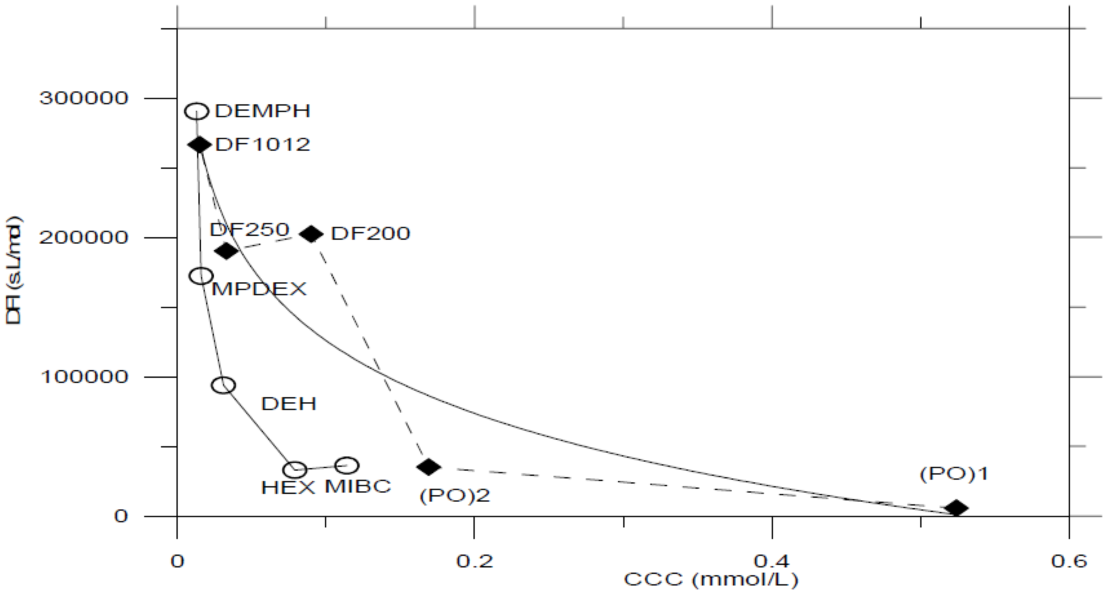

Figure 2.1: Relationship between DFI and CCC values for the some tested frothers (Laskowsky, 2004)

Cappuccitti and Finch (2008) improved the technique used by Laskowski by using gas hold-up to substitute for bubble size, and froth height (without overflow) as the froth stability metric. The gas hold-up/froth height relationship was then referred to as hydrodynamic characterization.

Other frother characterization works were focused on determining either the effect of frothers on bubble formation and coalescence, and water drainage during formation or collapsing of a froth layer. Previous studies have also shown that frother not only controlls bubble size, but also impacts the collection zone gas holdup through affecting bubble rise velocity, and on water overflow rate by affecting the froth structure and its ability to drain water. Thus, previous research did demonstrate that measurements of these variables in a lab column could be used to characterize and classify frothers (Moyo, Gomez and Finch, 2007; Azgomi, Gomez and Finch, 2007).

Moyo *et al.* (2007) found that a minimum gas holdup exists which supported a defined froth layer for water to overflow the column. Once this minimum gas holdup was reached, the overflow rate showed a linear increase with gas holdup. Thereby, water overflow rate correlated with gas holdup in the collection zone.

Later, Gomez *et al.* (2011) characterized frothers while studying a potential method of studying zone interactions. Characterizing frother roles in the pulp or froth zones separately does not allow for these interactions. In this work, gas holdup showed a continuous increase with frother concentration, and the correlation with water overflow rate strongly suggested a potential role as a variable to account for interactions between the pulp and froth zones in flotation machines. This characterization technique was conducted using three parameters: the CCC determined from the bubble size vs frother concentration; the minimum gas holdup to have overflow; and the slope of the increase of overflow rate with gas holdup.

2.1.3: FROTHER ROLES

Laskowski was among the first to try to capture the two frother roles by characterizing frothers in order to provide a basis for frother selection for a given duty, as well as to explore the link between function and frother chemistry. The two most important roles in flotation are bubble size reduction by preserving bubble formation size, and froth stabilization by defining water carrying rate into the froth and water drainage as a concentrate is collected (Gomez, Finch and Muñoz, 2011). The frother roles in the defined flotation zones will be then reviewed in more detail in sections 2.2 and 2.3.

2.2: HYDRODYNAMIC PROPERTIES: GAS DISPERSION

Gas dispersion is defined as the dispersion of air into bubbles. The gas dispersion properties (*e.g.* bubble size distribution) in the flotation process have a direct influence on flotation performance (Schwarz and Alexander, 2006). This is due to large amount of gas-liquid interfacial area affecting particle collection kinetics.

Sauter mean bubble diameter (D_{32}) and gas holdup (ε_g) are the measured hydrodynamic properties when frothers are characterized.

2.2.1: BUBBLE SIZE

Bubble size distribution is a factor determining metallurgical response. Because of the mechanics of particle collision and attachment, bubbles must not be excessively large or small. When bubbles are too small, particles could not have sufficient contact time to attachment, or if this happens, the bubble buoyancy may be too low for practical recovery. On the other hand, as the bubble size becomes larger the collision between particles and bubbles are more difficult.

The Sauter mean diameter (D_{32}) is commonly considered to be the mean size of bubbles relevant to flotation. Coalescence is one mechanism that reduces the air dispersion efficiency of a flotation system. The bubble size distribution depends on the balance between coalescence and breakup. The mean bubble size is influenced principally by gas rate, the presence of frother, the bubble generation device and operating pressure (Azgomi, 2006).

2.2.1.1: Effect of Frothers on Bubble Size

Coalescence is inhibited at frother concentrations exceeding the critical coalescence concentration as shown in Figure 2.2. The mechanism by which frothers retard coalescence is still debated. The action of frother is commonly attributed to control of coalescence; decreasing coalescence with increasing frother concentration causes the decrease in bubble size. After a certain concentration termed the “Critical Coalescence Concentration” (CCC), the argument is that coalescence is fully inhibited and bubble size is constant. Different frothers have individual CCC values. (Cho and Laskowski, 2001, 2002)

Gélinas *et al.* (2005) characterized MIBC and DF-250 frothers bubble thin films by composition and thickness determinations. They used FT-IR spectroscopy and UV–visible spectrophotometry, and concluded that the role of frother molecules in creating bubble thin films is based on their effectiveness in inducing H-bonding reorganization of the surrounding free water molecules into a coherent network. Thus, they suggested that the method would be hydrogen bonding, making it more difficult for the water to drain between approaching bubbles.

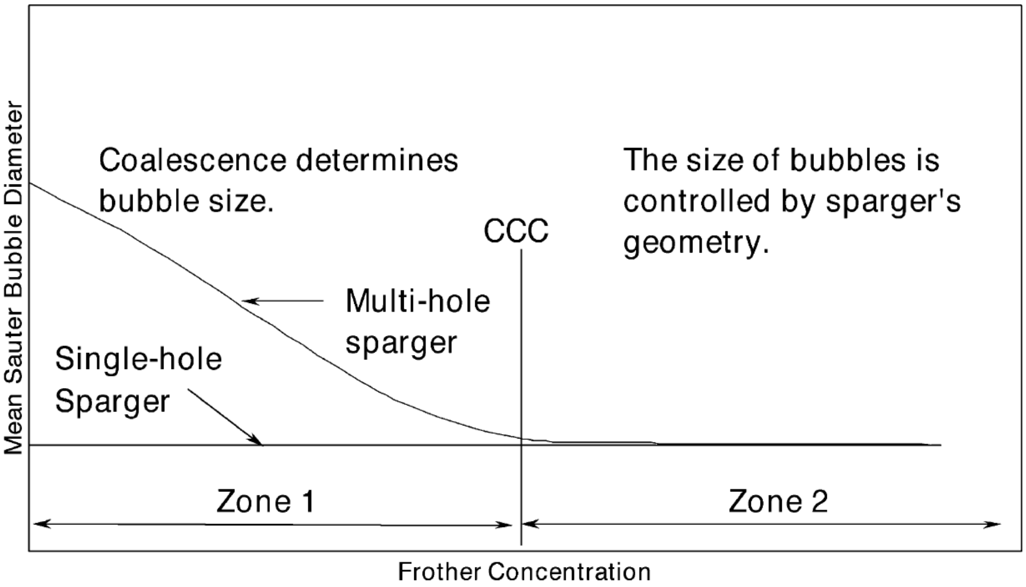

Figure 2.2: Effect of frother concentration on bubble size (schematic) – Reproduced from Cho and Laskowski, 2001.

Wang and Yoon (2008) determined the surface forces in foam films stabilized with flotation frothers using the thin film pressure balance (TFPB) technique. They found that foam stabilities are controlled by both film elasticity and disjoining pressure, the relative contributions from each changes with frother type and concentration. At relatively low concentrations, frother dampens the hydrophobic force, an attractive component of the disjoining pressure that destabilizes foams. At higher concentrations, elasticity plays a more important role in stabilizing foams. These results indicate that foam stability is determined by both elasticity and disjoining pressure.

Cho and Laskowski studied the effect of flotation frothers on bubble size and its implications for foam stability. They performed their experiments using a flotation cell with single and multi-hole spargers. The experiments indicated that the frothers control bubble size in flotation systems by controlling bubble coalescence, and that the size of bubbles strongly depends on frother concentration only when multi-hole spargers are utilized. At frother concentrations that exceed CCC, the bubble size is no longer determined by coalescence and will then strongly depend on sparger's geometry and hydrodynamic conditions. At low frother concentrations (C<CCC), the bubble size was much larger, indicating coalescence as a main mechanism determining the size. (Cho and Laskowski, 2002).

2.2.1.2: CCC Determination

The work of Cho and Laskowski (2002), suggested that bubble coalescence is completely prevented at a certain frother concentration. At frother concentrations below the CCC the bubble size is a strong function of concentration, while at concentrations exceeding the CCC, coalescence is restrained and bubble size is determined by the initial air mass break-up process. The CCC concept remains very useful although the values are difficult to establish using the geometric method of Laskowski *et al*. (2003, 2004), where CCC is the point of intersection of straight lines approximating the decreasing average size of air bubbles and the increasing frother concentration, projected down to the X axis.

Nesset *et al.* (2007, 2011) fitted bubble size (D_{32}) versus concentration using a three-parameter exponential model and introduced the CCC95, the frother concentration for which 95% of the ultimate decrease in D_{32} has been achieved, which is readily calculated from the model. The three-parameter model is:

$$D_{32} = D_0 + a \, Exp(-b*C) \tag{2.1}$$

Where C is frother concentration and D_0 refers to the limiting bubble size while a and b are fitted constants. This equation can be then subsequently modified as,

$$D_{32} = D_0 + a \, Exp(-b*C/CCC_{95}) \tag{2.2}$$

to provide a general model.

Castillo *et al.* (2014) used an analytical method to calculate the critical coalescence concentration (CCC), and identified two control bubble size zones: one controlled by bubble coalescence and other controlled by surface tension. Thus, a first curve was linearized by applying the natural logarithm to low and high concentrations, and then, by applying an exponential function, it calculates the effects of surface tension and coalescence separately. The CCC is then determined by searching the concentration at which the difference between the contributions by coalescence and surface tension corresponds to an equal or greater value than the error associated with the bubble size measurement.

2.2.2: GAS HOLDUP

Gas holdup is the volume fraction occupied by gas at any point in a flotation machine and it is the simplest gas dispersion parameter to measure that combines the influences of bubble size and gas rate.

It is a function of a number of interactive variables involving chemical (frother type and concentration), operational (gas rate) and machine (bubble generation system) factors. The gas holdup is related to bubble size (a function of frother characteristics and concentration, sparger type, solids coverage, and air flowrate), slurry flowrate, solids content, and mixing patterns in the collection zone. Gas holdup defines the bubble-flow density (bubble surface-area flux), which is related to flotation kinetics (Gorain, 1997; Comley *et al.*, 2007). Thus, knowledge of the gas holdup is useful when diagnosing and controlling the operation of a flotation column.

Gas holdup (or voidage) is a dimensionless parameter defined as the volume fraction of gas phase at any point in a cell. The average gas holdup ε_g in a total volume V_t is,

$$\varepsilon_g = \frac{V_g}{V_t}, \ \% \qquad 2.3$$

where V_g is the volume of gas. Likewise, it is possible to characterize the liquid and solid phase by their respective holdup values. The gas holdup is one of the most important parameters used to characterize the hydrodynamic state of bubble column reactors. It is a simple parameter to measure and useful as it combines the influence of both bubble size and gas rate. Gas holdup is dependent on several factors, including: gas rate; liquid properties (*e.g.*, frother type and concentration); cell dimensions; operating temperature and pressure; gas distributor design; and solid phase properties and concentration. (Azgomi, 2006).

2.2.3: SUPERFICIAL GAS VELOCITY

The superficial gas velocity, or more simply gas rate (J_g, cm/s), is the volumetric flowrate (Q_g, cm^3/s) of air per cross sectional area (A, cm^2) of the cell,

$$J_g = \frac{Q_g}{A} \qquad 2.4$$

Typically, the superficial gas velocity in flotation systems is 0.5 - 2.5 cm/s depending on factors such as bubble size and slurry rheology.

2.2.4: BUBBLE SURFACE AREA FLUX

The bubble surface area flux (S_b), a derived gas dispersion parameter, is now commonly used in flotation to link the flotation rate with the hydrodynamic variables. The flotation rate constant (*k*) has been correlated with surface area flux, and is usually expressed as (for the pulp zone):

$$k = PS_b \tag{2.5}$$

Where *P* is the "floatability factor", which encompasses the contribution of particle size and hydrophobicity. Gas holdup can be correlated with the rate constant via the following relationship with S_b proposed by Finch (Finch *et al,* 2000).

$$S_b = \frac{6 \cdot J_g}{d_b} = 5.5 \cdot \varepsilon_g \tag{2.6}$$

with S_b in s^{-1} and ε_g in *%*.

2.3: FROTH PROPERTY: WATER TRANSPORT

2.3.1: Flotation and water carrying rate

Despite the primary task of bubbles being to collect particles, they also transport water. The transport of water governs the recovery of hydrophilic particles by entrainment which plays a large role in decreasing grade, so the understanding of water recovery is vital for predicting and controlling flotation performance. The amount of water reporting to the concentrate is closely related to the recovery of gangue particles by entrainment, which is detrimental to the concentrate grade. Water is transported both as a film on the bubble surface and as a tailing wake, Figure 2.3. Bubble size, gas rate, froth depth and frother type influence the amount of water that reports to the overflow.

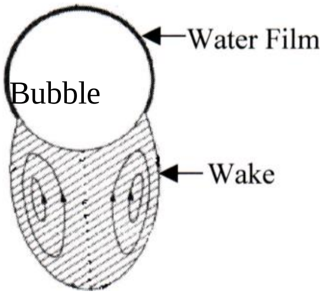

Figure 2.3: Schematic of bubble carrying water (Azgomi, 2006)

Moyo (2005) also studied a method of characterizing frothers based on water carrying rate by using gas holdup as the measured variable, which combines bubble size and gas rate effects on water transport. It was found that the common frothers could be grouped into four classes or families based on the gas holdup (ε_g) - water carrying rate (J_{wo}) relationship, as shown in Figure 2.4.

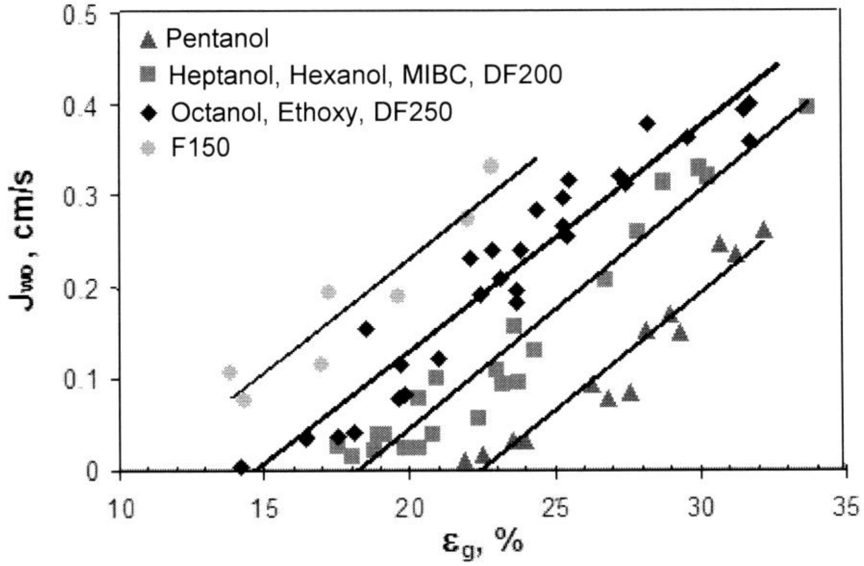

Figure 2.4: Classification of frothers based on water carrying rate (Moyo, 2005)

2.3.2: Effect of gas rate on water overflow

A linear relationship is expected if the increase in gas rate has little effect on bubble size distribution or the effective boundary layer thickness. Neethling *et al.* (2003) presented theoretical relationships for the prediction of water recovery for a flowing foam. In foams that have less than half the bubbles bursting at the top surface, the rate was proportional to the gas rate squared and inversely proportional to the bubble diameter squared. This indicates that for a constant bubble size, the relationship between water rate and gas rate should be a power law with an exponent of 2. The data is shown in Fig. 2.5 on log–log axes.

High gas rates are associated with more mixing and higher water content in the froth, which enable particles (especially coarse ones) to drain more freely. Generally, however, the overall net water recovery and particle entrainment increase with gas rate and decrease concentrate grade as was observed at Noranda's Brunswick mine concentrator (Cooper *et al.*, 2004). They investigated the role of gas (air) distribution to the cells in the final Zn cleaning stage.

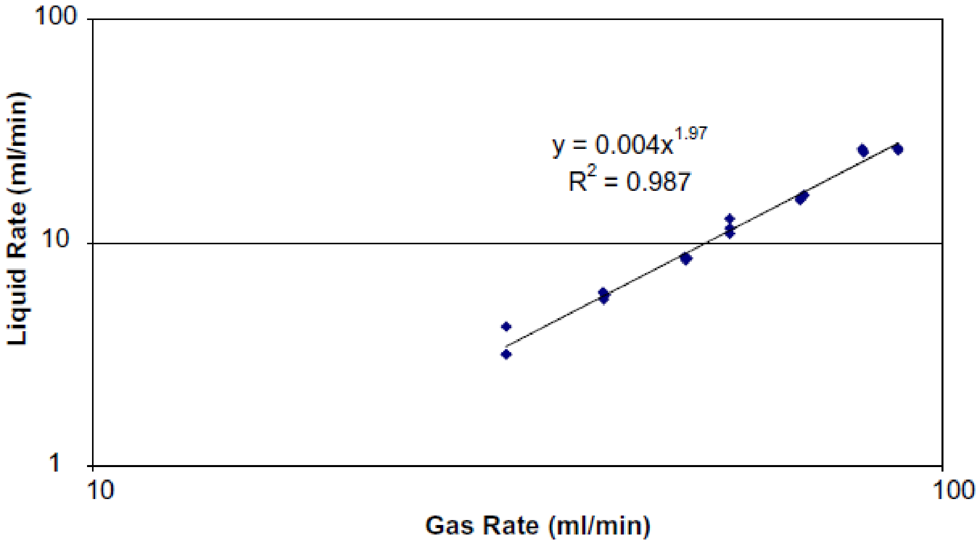

Figure 2.5: Experimental relationship between the gas flow into the column and the water recovery plotted on a log–log axis (Neethling *et al.*, 2003).

In line with other findings, Moyo (Moyo, 2005) found that the water carrying rate, J_{wo}, as a function of gas rate Jg has a linear relationship for n-hexanol at three concentrations as shown in Figure 2.6.

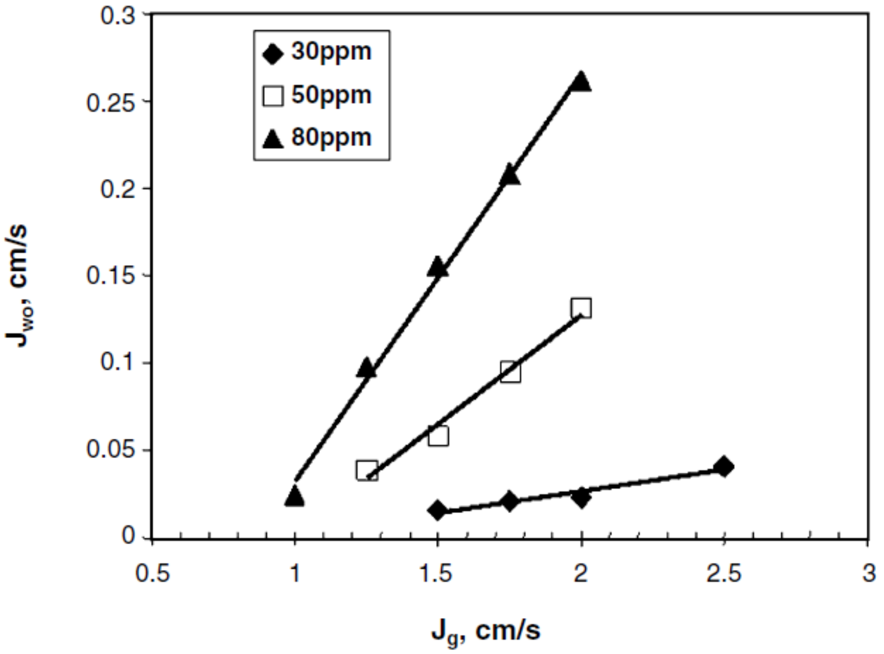

Figure 2.6: Water carrying rate as a function of gas rate for three concentrations of n-hexanol (Moyo, 2005)

2.3.3: Effect of frothers on water overflow rate

Water transport is influenced by the bubble size, or the bubble surface area flux, and possibly the nature of the frother itself (Melo and Laskowski, 2006; Nguyen *et al*., 2003). To determine the role of frother chemistry in water transport, it must be dissociated from other factors such as the frother effect on bubble size, and the role of solid particles.

Melo and Laskowski (2006) demonstrated that two alcohol frothers (Diacetone and MIBC) gave lower water recoveries in two-phase (air-water) tests than polyglycol frothers but higher water recovery in the presence of coal particles. This most likely reflects different levels of frother interaction with coal (*i.e*. adsorption of frother).

Hydrophobic solids particles can change the stress state at the air-water interface and hydrophilic particles can modify the rheology of the interstitial fluid within the froth. “The presence of hydrophobic particles is likely to make the Plateau border walls more rigid. However, the presence of hydrophilic particles in the liquid phase in a froth may cause the liquid to behave like a slurry with non-Newtonian rheology” (Stevenson *et al*., 2003). This leads to two phase systems remaining a necessary precurser in understanding the frother effect on water overflow rate.

2.3.4: Overflow rate vs. gas holdup

The work developed by Moyo (Moyo, 2005) related these variables as hydrodynamic characterization of frothers, consisting of measuring bubble size and gas hold-up as a function of concentration at set gas velocity and sparger porosity. The result, shown in Figure 2.7 for all the frothers tested, was that frothers could be grouped in ‘families’ according to the dependence of overflow rate on gas holdup. From the perspective of characterization, key conclusions were identified from this work by Cappuccitti and Finch (2008): In order of increasing overflow rate (for a given gas holdup) the ranking corresponds to the qualitative understanding that the glycols give more watery froths than the alcohols; and increasing chain length for alcohols and number of propylene oxide groups for glycols increases overflow rate. For alcohols, overflow rate depends on chain length independent of branching.

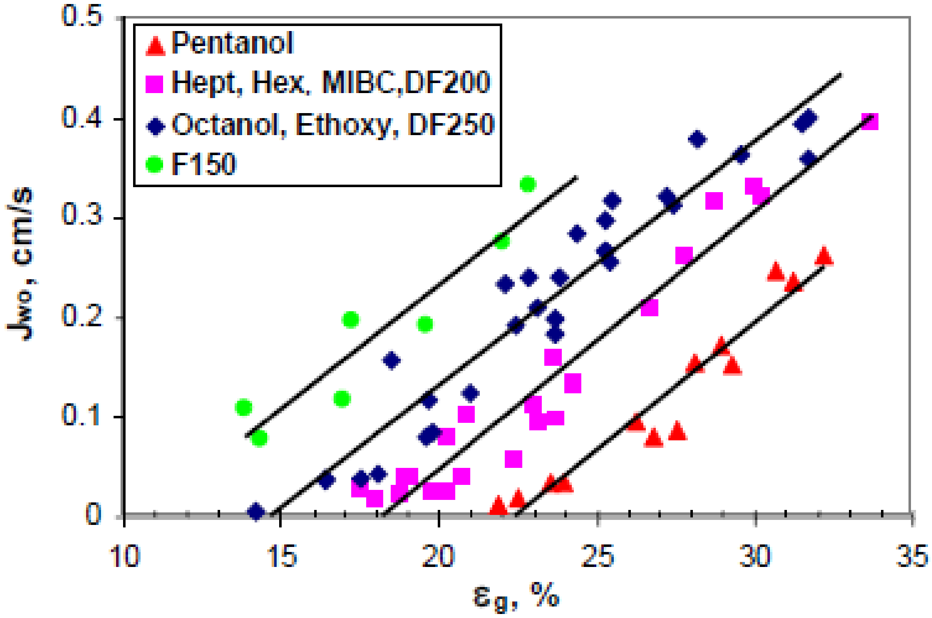

Figure 2.7: Jwo-εg relationship: results for and classification of all frothers tested. Conditions: Hf =7cm (Moyo, 2005)

2.4: THE EFFECT OF SALINE WATER

Many large mineral deposits are located in the areas with limited resources of fresh water. The Atacama Desert, where a major portion of Chilean Copper Industry is situated, illustrates this problem (Laskowski *et al*., 2013). In such cases flotation in seawater becomes an increasingly important issue. However, the use of seawater could become a sustainable solution only if it could deliver the metal recoveries and concentrate grades comparable to those that can be obtained when using freshwater.

Flotation requires a froth layer that is, to some extent, stable. It is known that foams are stabilized not only by surface-active compounds such as frothers, but also by surface-inactive compounds (inorganic ions) (Quinn *et al*., 2007; Castro *et al*., 2010).

Zanin *et al.* (2009) derived models relating the froth stability and bubble size of the top of the froth to the amount of hydrophobic material present in the froth. In this work the variables affecting froth stability are extended to electrolyte concentration and ionic composition, particularly to seawater.

Replacement of fresh water with seawater in flotation brings about other factors. Foaming characteristics of MIBC and DF-250 frothers in NaCl solutions and in seawater have been studied by Castro *et al.* (2013). The two-phase foaming was characterized through measurements of the dynamic foamability index (DFI) for both frothers at various NaCl concentrations, and in seawater. Foamability of both, MIBC and DF-250 frothers, were much stronger in seawater than in distilled water.

2.4.1: Effect of saline water on bubble properties

Marrucci and Nicodemo (1967) measured the average bubble size in a bubble column in the presence of a number of different electrolytes, KCl, KOH, KNO, KI, K_2SO4, CuSO4, K_3PO4, $AlCl_3$ and $Co(NO_3)_2$, at specified superficial gas velocities. Their conclusions detailed that electrolytes increased the electrical repulsive forces at the bubble surface, inhibiting coalescence between bubbles.

Marrucci (1969), cited by Wang and Peng (2014) found that salts can inhibit bubble coalescence by retarding the thinning of the intervening liquid film between bubble pairs. At sufficiently high salts concentration, surface tension gradient which results from the thinning process immobilize the gas–liquid interface between coalescing bubbles. When it occurs, the time required for coalescence dramatically increases.

Lessard and Zieminski (1971) investigated the effects of inorganic electrolytes including NaCl, on bubble coalescence and interfacial gas transfer in aqueous solution. The coalescence experiments consisted of contacting a number of pairs of bubbles and evaluating the coalescence percentage as a function of solute concentration. They found the existence of a sharp transition concentration which enabled a comparison of the effectiveness of the salts. The concentration resulting in 50% coalescence was defined as the transition concentration, at which coalescence was sharply reduced.

Castro *et al.* (2013) studied the interaction of MIBC with NaCl and seawater. They aimed at studying bubble coalescence in the presence of common flotation frothers in electrolyte solutions and in seawater. The values of CCC for electrolytes were considerably higher than those for frothers MIBC and DF-250. The effect of MIBC concentration on bubble coalescence at varying sodium chloride concentrations is showed in Figure. 2.8. The bubble size slightly tended to increase, but then it was stabilized and decreased again.

Seawater contains around 0.55–0.60 M NaCl, and some secondary ions, such as Mg, Ca, sulfate, etc. Thus, they found that seawater, similar to inorganic electrolytes, is by itself able to prevent bubble coalescence. These results also suggested that secondary ions play a significant role and the blend of frothers and seawater clearly stabilizes bubbles against coalescence.

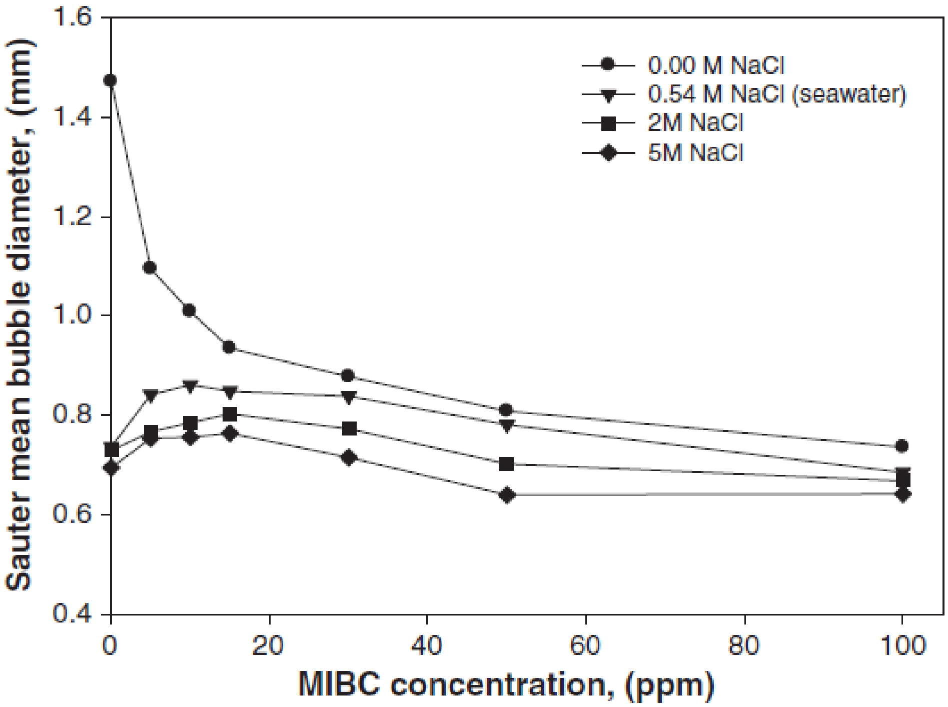

Figure 2.8: Sauter bubble diameter as a function of MIBC concentration, for 0; 0.54; 2; and 5 M NaCl solutions (Castro *et al.*, 2013)

2.4.2: Effect of saline water on gas holdup

Alexander *et al*. (2012) demonstrated that in the presence of coalescence inhibiting salts, gas dispersion appears to play a significant role in dictating flotation performance. They investigated two-phase batch gas holdup tests in a laboratory bubble column with inorganic salts (KCl, NaCl, Na_2SO_4, $MgCl_2$, $CaCl_2$, $MgSO_4$). Electrolytes grouped according to the gas holdup: salts containing divalent ions (1-2, 2-1 and 2-2 cation-anion pair) increased gas holdup at lower molar concentrations than salts containing monovalent ions (1-1 salts) and a dependence on ionic strength was demonstrated.

2.4.3: Effect of saline water on froth stability - Froth zone

Froth structure and froth stability are known to play a significant role in determining the mineral grade and recovery achieved from flotation. Froth stability is mainly dependent on frother (type and concentration) and amount and nature of the suspended particles, in particular, particle hydrophobicity and size (Schwarz and Grano, 2005). However, there are other parameters such as quality of process water, gas dispersion and particle contact angle that can affect froth stability.

Quinn *et al.* (2007) investigated why the Raglan concentrator (Xstrata Nickel) did not employ frother (MIBC) compared to a typical frother system and focused on gas dispersion and froth overflow rate. In two-phase tests, the results revealed that bubble size was reduced, gas holdup (which correlated with ionic strength) increased and froth formation was limited in salt solutions. Figure 2.9 from this study shows the overflow rate increases for the three phase tests with salt concentration and becomes similar to that achieved by 10 ppm MIBC between 0.2 and 0.4 M NaCl. However, without the small bubbles provided by frother or salts the overflow rate is limited. The combination of gas dispersion and froth overflow results in both the two- and three-phase systems provided the evidence that salts present in the Raglan water can substitute for frother.

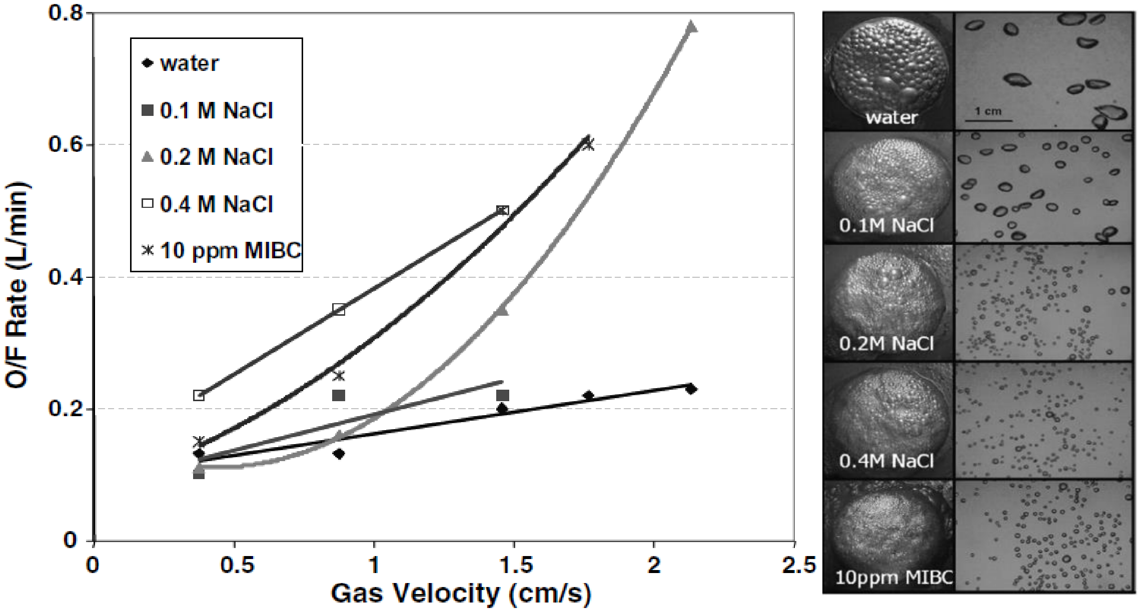

Figure 2.9: Overflow rates as a function of superficial gas velocity and salt concentration compared to 10 ppm MIBC (corresponding to pictures right - Top views of froth and corresponding image of bubbles below the froth for flotation of sample of Brunswick Mine ore, water, Quebec City tap) (Quinn *et al.* (2007))

Inorganic salts generally tend to increase surface tension while frothers reduce it; and inorganic ions are usually not able to form froth (foam) in two-phase (water–gas) systems. Lekki and Laskowski (1975), cited by Wang and Peng (2014) observed that only in the presence of hydrophobic particles would salt solutions form a stable froth, so inorganic electrolytes would fall into the category of surface inactive agents while frothers are surface active.

Kurniawan *et al.* (2011) investigated flotation of coal particles in $MgCl_2$, NaCl, and $NaClO_3$ solutions in the absence and presence of Dowfroth 250 frother. The results of the experiments showed that the presence of electrolytes in the system clearly enhanced the flotation recovery depending on its type and concentration. During the experiments, $MgCl_2$ and $NaClO_3$ solutions showed the highest and the lowest flotation performance improvements, respectively. The froth stability tests indicated that there is a correlation between the flotation recovery and the stability profile of the froth. The most stable froth was obtained with $MgCl_2$ and the lowest froth stability was obtained with $NaClO_3$.

Corin *et al*. (2011) conducted flotation tests under varying degrees of ionic strength of synthetic plant water. An increase in the ionic strength of the system resulted in an increase in froth stability, leading to increased mass pulls and water recoveries. The affect appeared to be directly related to the 2-phase frothing property of the frother rather than changes in the hydrophobicity of the particles entering the froth.

Farrokhpay and Zanin (2012), studied the effect of water quality, including pH, and type and concentration of salts ($CaCl_2$, $AlCl_3$ and NaCl) on froth stability and its relationship with mineral particles zeta potential and slurry viscosity. They found that the froth stability is higher in the presence of multivalent metal ions. Addition of $CaCl_2$ and $AlCl_3$ considerably increased both froth stability and pulp viscosity.

2.5: METHODS AND PROCEDURES

2.5.1: Measurements - Bubble Size

Bubble size has a direct effect on flotation efficiency. Bubble size measurement has been investigated for decades using a wide variety of techniques and approaches (Chen *et al.,* 2001). Only a limited number of techniques are available which can operate at any scale from laboratory to plant.

Chen *et al.* (2001) mention some methods for the size range typically found in flotation (0.5 to 1.5 mm) including: measuring bubble frequency and total bubble volume collected in a graduated burette; using conductivity probes, or fiber optics to measure bubble velocity and intercepted chord; or methods based on measuring the length of the equivalent volume cylinder formed; and methods by analysis of images collected using photographic. However, the devices developed by the University of Cape Town (UCT) and McGill University (capillary and imaging, respectively) are two that have been tested both under plant and laboratory conditions (Hernandez-Aguilar *et al*, 2004).

Randall *et al.* (1989) developed a method for measuring the sizes of bubbles in two- and three-phase systems. The length and velocity of each bubble is measured by a pair of optical detectors in a brass block surrounding a capillary tube through which bubbles are drawn, with this data is stored in memory by a microprocessor system. The values were similar to those obtained using other techniques but are considered more accurate since a direct measurement of a significantly large number of bubbles is made (Figure 2.10).

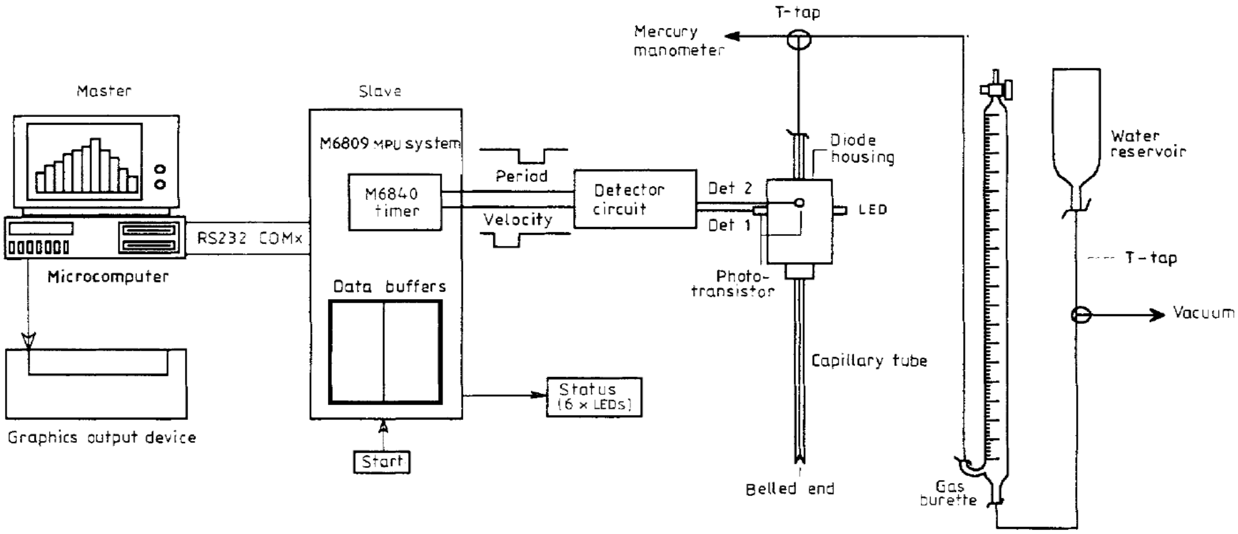

Figure 2.10: Schematic diagram of bubble-sizing apparatus (Randall *et al,* 1989)

2.5.2: The McGill University technique

The working principle of the McGill University technique is based on directing a sample of bubbles into a viewing chamber where they are exposed and photographed with a digital camera (Figure 2.11). An automated image analysis procedure is used to size the collected bubbles. The system comprises a sampling tube attached to the bottom of the sealed viewing chamber. Bubbles from the dispersion travel in the sampling tube under noniso-kinetic conditions.

The viewing chamber is made of plastic (PVC) with two facing glass windows. In order to enhance image contrast, a light diffuser is attached to the back window. The chamber is sloped (angle 15 °) to spread the bubbles into a single layer to limit overlap and provide an unambiguous plane of focus. (Hernandez-Aguilar *et al,* 2004).

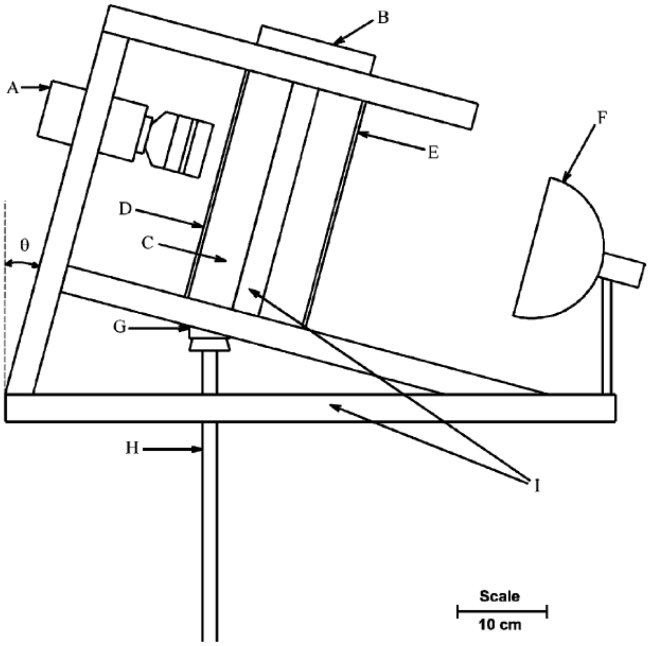

Figure 2.11: Scaled diagram of the McGill University bubble size measurement device. A: digital camera, B: filling cap, C: viewing chamber (bubble viewer), D: front window, E: back window, F: lamp, G: bubble viewer inlet, H: sampling tube, I: aluminum square bars (for support) and h: angle of the inclined window (15°). (Hernandez-Aguilar *et al.,* 2004)

Azgomi (2006) described the mechanism of operation: The sampling tube is initially closed and the assembly filled with water of similar temperature and chemistry (*e.g.,* the same frother and concentration) as the bulk (to preserve the bubble environment and prevent bubble coalescence). The sample tube is the immersed to the desired location below the froth and is opened. Bubbles rise into the sampling tube by buoyancy, and enter the viewing chamber where they spread into a single plane after contact with the inclined window. Due to diffuse backlighting, bubbles cast shadows, which are digitally imaged as the bubbles slide up the window.

Bubble size distributions are generated as a number distribution and represented by two means, the number mean (d_{10}) and Sauter mean (d_{32}), calculated as follows:

$$d_{10} = \frac{\sum_{i=1}^{i=n} d_i}{\sum_{i=1}^{i=n} n_i} \qquad 2.7$$

$$d_{32} = \frac{\sum_{i=1}^{i=n} d_i^3}{\sum_{i=1}^{i=n} d_i^2} \qquad 2.8$$

where, d_i is equivalent spherical bubble diameter, and n is total number of bubbles. For each bubble, the maximum and minimum axes are computed by software and d_i is obtained from:

$$d_b = \sqrt[3]{d_{\max}{}^2 d_{\min}} \qquad 2.9$$

where d_{max} and d_{min} are the maximum and minimum diameters, respectively.

2.5.3: Measurements – Gas Holdup

Gas hold-up (ε_g) in the two-phase system (air–water) is normally measured by pressure difference over a section of length, L in cm in the collection zone just below the froth. Pressure is sensed by water-filled manometers and the fractional gas hold-up is determined by:

$$\varepsilon_g = \Delta H/L \qquad 2.10$$

where ΔH (cm) is the difference in the manometer readings or pressure taps.

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Chapter 3: EXPERIMENTAL PROCEDURES

This chapter describes the equipment assembled and procedures used to accomplish the objectives of this work. A bubble column was built and instrumented to measure variables such as superficial gas velocity (J_g) and gas holdup (ε_g). A technique developed at McGill for industrial installations was used to measure bubble size (D_b). A description of the column is given along with the instrumentation and measurement techniques.

The experimental procedure was designed to allow for establishing the effect of salts on the ability of frothers to reduce bubble coalescence (by measuring bubble size), and to increase water carrying rate to stabilize the froth (by measuring water overflow rate for a constant froth depth). The equipment was instrumented to control gas flowrate and to measure gas holdup, and included equipment to manually measure bubble size and water overflow rate. These variables were measured for every frother, on fresh and sea water solutions of several concentration (0, 2, 5, 10, 15, 30, 60, 100 ppm), at a superficial velocity of 1 cm/s (and other velocities for specific tests) and a manually controlled froth depth of 5 cm. The frothers selected for the study were analytical grade glycols (DF250, PPG425), alcohols (MIBC and 1-hexanol) and commercial frothers blends (F140).

3.1: Reagents used

Measurements of variables were tested for every frother both on fresh and sea water solutions using several concentrations (0, 2, 5, 10, 15, 30, 60, 100 ppm). Between each test, the column was emptied and carefully cleaned.

3.1.1: Frothers

The frothers selected for the study were analytical grade glycols (DF250, PPG425), alcohols (MIBC and 1-hexanol), and commercial frothers blends (F140). Table 3.1 gives a summary of the frothers examined. Solutions were made using Montreal tap water.

3.1.2: Salt

The Instant Ocean sea salt used for marine aquarium is a formulated sea salt supplied by Instant Ocean Spectrum Brands. It is used exclusively by many of the leading large-scale aquariums and research facilities.

This commercially available, synthetic sea salt mixes were prepared as 1.5 lb. salt/5 gallons of water as indicated by the supplier, and then analyzed for some elements and chemical parameters using ICP equipment . The results is shown in Table 3.2.

Table 3.1: Summary of the frother properties

Frother	Structure	Molecular weight	Densisty	Solubility	Supplier
		g/g.mol	gr/cm3	in water	
MIBC	Aliphatic alcohol	102.18	0.802	Low	Sigma Aldrich
1Hexanol	Aliphatic alcohol	102.18	0.814	Low	Sigma Aldrich
PPG425	Polyglycol	116.20	0.822	Slightly low	Sigma Aldrich
DF250	Polyglycol ether	264.35	0.980	Very good	The Down Chemical company
F-140	Mixed alcohols, heavy aldehydes, esters	425.00	1.010	Low	Flottec

Table 3.2: ICP test results of the sea water solution

	Compound (ppm)			
Sea salt solution	**Na**	**Mg**	**K**	**Ca**
Sample 1	9,009.9	1,370.8	366.5	332.3
Sample 2	8,875.9	1,312.8	354.4	305.5
Sample 3	8,828.9	1,337.8	320.7	318.5
Average	8,904.9	1,340.5	347.2	318.8

3.2: Flotation Column

3.2.1: Setup of the equipment

The bubble column was commissioned to measure variables such as superficial bubble size (D_b), gas holdup (ε_g) and superficial gas velocity (J_g). The technique developed at McGill for industrial installations was used to measure bubble size (D_b) (Gomez and Finch, 2007). The laboratory flotation column used to perform the testing was set up with five cylindrical sections with a total length of 4.6 m and a 10.2 cm diameter (Figure 3.1). Details of dimensions can be seen in the Appendix.

A porous cylindrical steel sparger mounted vertically at the bottom of the column (nominal porosity diameter 10 um) dispersed the air into bubbles at a set gas (superficial) velocity (J_g) maintained at specified velocities (0.5, 1.0, 1.5, 2.0, and 2.5 cm/s) at the sparger. The setup was operated in closed loop with the overflow and underflow going to the mixing tank and returned to the feeding point of the column. The feed was introduced into the column using a peristaltic pump at a flow rate such that a froth layer of 5 cm was formed and maintained during all experiments.

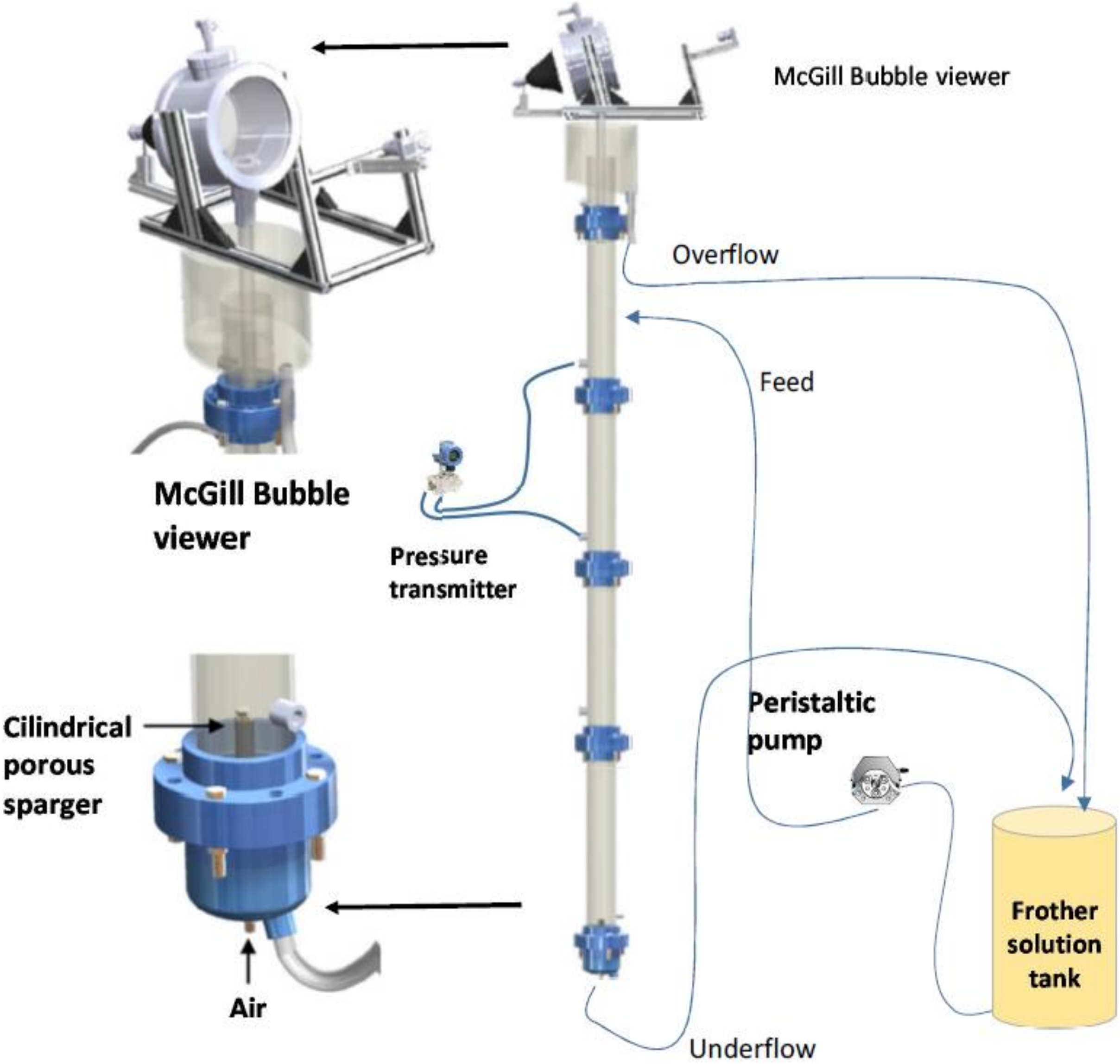

Figure 3.1: Experimental set-up: Column and accessories

The column was operated continuously; addition of frother (addition method) or dilution water was conducted with the system running with the air flow turned off intermittently to allow adequate mixing as judged by steady gas holdup readings. The dilution experiments for each frother were performed with 7 different concentrations (2.0, 5.0, 10.0, 15.0, 30.0, 60, and 100 ppm). Montreal tap water and synthetic sea water were used. The temperature ranged between 12 and 18 °C. Summary of parameters is shown in Table 3.3.

Table 3.3: Summary of fixed and measured parameters in the column

Fixed parameters					Measured parameters				
Sparger	Jg cm/s	Q air liter/min	Froth Depth cm	Water	Gas Holdup (%)	Bubble size (mm)	Water carrying rate (cm/s)	Pressure	Temperature
1	1	4.87	5	Tap	-	-	-	-	-
1	1	4.87	5	Salty	-	-	-	-	-

A differential pressure transducer connected at pressure taps separated 71 cm, was used to continuously measure a differential pressure to calculate gas holdup (ε_g). The column length defined by these pressure taps was considered as the test section for measuring the three gas dispersion variables.

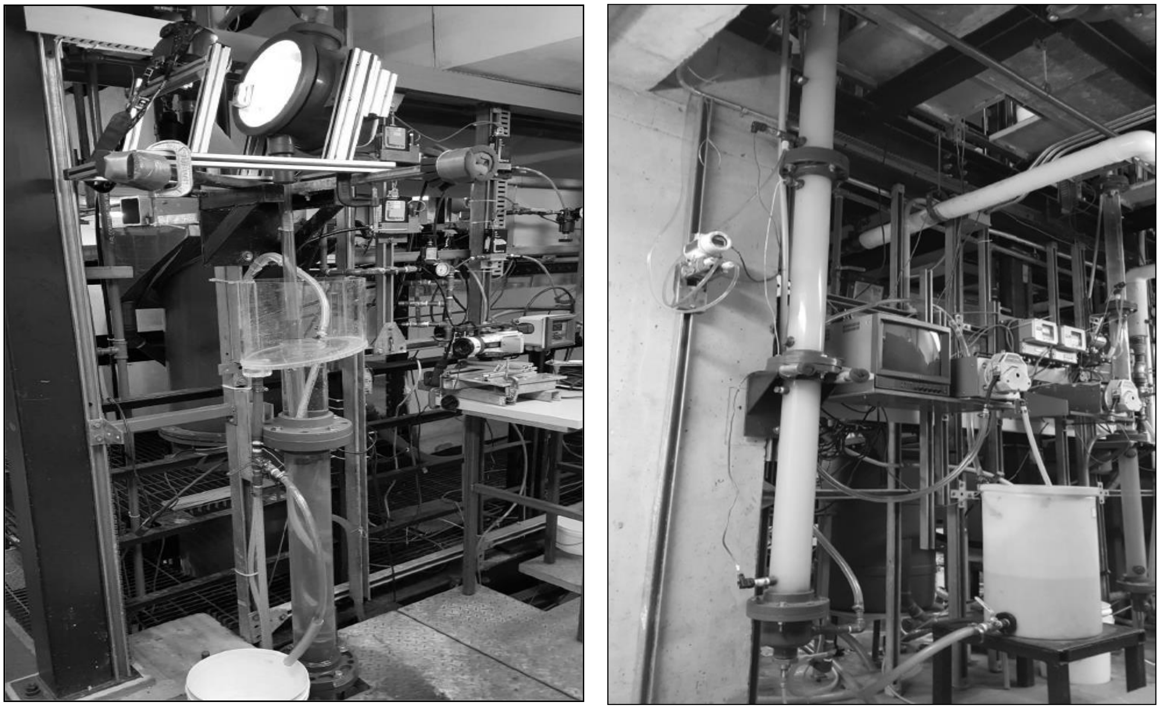

Figure 3.2: Experimental set-up: Column and accessories

All instruments were connected to a 16-channel signal conditioning interface (Transduction, model OPTO 22). Operational data was continuously monitored and registered once every second using iFIX installed in a dedicated computer. Data was selected and retrieved from the iFIX historical database using an in-house Excel application. The computerized system monitors and registers signals from the installed instrumentation. The control of the froth depth during operation at specified gas velocity was manually by adjusting the flow of the feed pump to the column.

Fifty litres of Montreal tap water were used to prepare solutions of the frothers tested; this volume was required to fill the column and the equipment to measure bubble size. The water overflow (J_{wo}) generated during the experiments was measured by collection and weighing of timed samples.

3.2.2: McGill Bubble Size Analyzer

The McGill Bubble Size Analyzer (MBSA) was used to measure the size of bubble distributions. It was placed at the top of the flotation column. The tube of the bubble viewer (BV) was located in the collection zone, at the middle point of the test section, were bubbles then captured and incorporated to the viewer chamber.

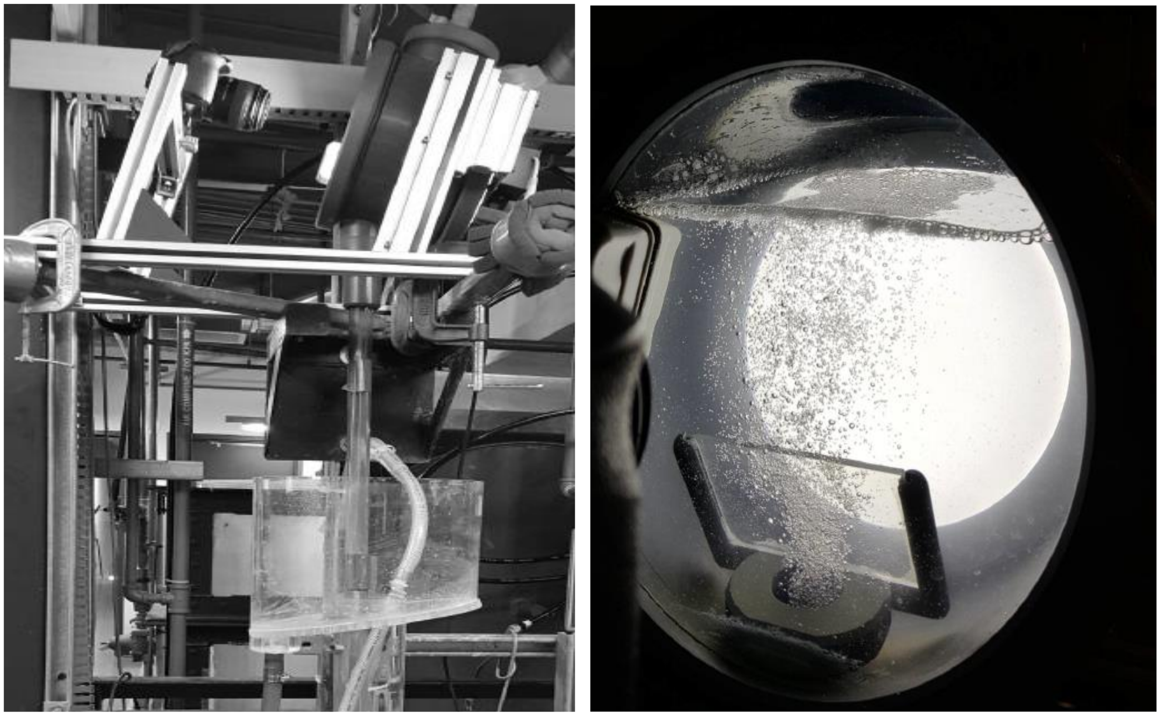

Figure 3.3: McGill Bubble size analyzer

Bubble size measurement were conducted using the McGill Bubble size analyzer, image processing and data analysis (Gomez and Finch, 2007). The technique uses a viewing chamber, made of plastic (PVC) with two facing tempered glass windows, a digital camera, installed at the front window, and a light source installed at the back. From the literature and experience, it can be seen that this combination of features and the use of a high magnification render high-quality images which facilitate automatic image processing. These three components are mounted on an aluminum frame in order to facilitate transportation, operation and installation. As shown in Figures 3.1, 3.2 and 3.3, the unit was installed at the top of the column and bubbles were collected by means of a vertical sampling tube which reached the center of the test section (a length of 41 cm from the top of the column).

3.3: Measurements

3.3.1: Bubble Size

The bubble viewer consisted of a sampling tube attached to a viewing chamber with a window inclined 15° from the vertical. The viewing chamber (31.7 × 22.1 × 13.0 cm) is made of PVC with two facing glass windows. To operate, the sampling tube was closed and the assembly filled with water of similar temperature and chemistry (*e.g.*, the same frother and concentration) as present in the bulk (to preserve the bubble environment and prevent bubble coalescence). The sample tube was immersed to the desired location below the froth and then opened. Bubbles rise into the sampling tube by buoyancy, and enter the viewing chamber where they spread into a single plane after contact with the inclined window. Due to diffuse backlighting, bubbles cast shadows, which are digitally imaged as the bubbles slide up the window.

Data were collected using a digital CCD (charge-coupled device) camera Model Canon EOS 60D, and the PVC plastic sampling tube used had an inner diameter of 2.54 cm and length of 78 cm, with a globe valve. Typically 3000 bubbles were processed for any given experiment. Images were captured and analyzed using Empix Northern Eclipse v6.0 and in-house Empix BSD (bubble size distribution) processor software.

Bubble size distributions, as presented in this thesis, are generated as a number distribution and represented by two means, the number mean (D_{10}) and Sauter mean (D_{32}), calculated from Equations 2.7 and 2.8.

3.3.2: Gas Holdup

When the system contains no solids (as here), gas holdup can be accurately estimated from the pressure difference, using the Equation 2.10.

3.3.3: Water overflow rate

Once pressure signals reach a steady state (between 5–10 min), readings of water carrying rate J_{wo} were recorded maintaining a defined froth depth (5cm) using a monitor that allows to see the froth depth in the top of the column as can be shown in Figure 3.4. Water carrying rate (l/min) was determined manually by collecting overflow in a graduated cylinder over given time intervals.

The water carrying rate was measured as the water overflow rate (J_{wo}), the volumetric flowrate of water to the overflow (Q_{wo}, cm^3/s) per column cross sectional area (A, cm^2) *i.e.*, $J_{wo} = Q_{wo}/A$. The Q_{wo} was measured at a constant foam height over a period of time after steady state had been reached.

The methodology used measures the collection and froth zone parameters simultaneously in a pilot flotation machine, allow us to be considered the effect of interactions between collection and froth zones.

Figure 3.4: Experimental set-up: Monitor

3.4: Sea water solution

Solutions with salt concentrations similar to sea water were prepared dissolving 1.5 lb of a mixture of salts (Instant Ocean sea water) in 5 gallons of water, as indicated by the supplier. The resulting concentration of the solution was 35.95 gr/L or 35,950 ppm which is relatively close to sea water composition.

Sovechles and Waters, 2015, found that to mimic industrial flotation process waters, a synthetic sea salt solution is a robust alternative. It was found that when the multicomponent sea salt solution was broken down into its constituent parts, the addition of the ionic strength of each ion correlated well with the overall ionic strength curve of all the salts tested.

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Chapter 4: RESULTS – COLLECTION ZONE AND CRITICAL COALESCENCE CONCENTRATION

In this chapter, bubble size and critical coalescence concentration are investigated as a function of frother concentration for five frothers in tap and synthetic sea water solutions. The sizes of bubbles, which are determined by bubble coalescence, play a very important role in the flotation process. Bubble coalescence is a particularly complex phenomenon especially when it takes place in saline water or seawater, since both surface active compound (frother) and surface-inactive compound (inorganic salt) are able to stabilize bubbles against coalescence and thus reduce bubble size. The coalescence of bubbles can be completely prevented at frother concentrations exceeding the critical coalescence concentration (Castro *et al.,* 2013).

Figures 4.1 to 4.5 show the effect of increasing frother concentration on the Sauter mean diameter (D_{32}) for the five frothers in Table 3.1. For all frothers in tap water solution, the bubble size decreases with increasing frother concentration until a certain concentration is reached (*i.e.*, CCC), in accord with the literature. Blue squares show the bubble size versus frother concentration curves of the frothers illustrating the bubble coalescence phenomena in tap water solution, and the critical coalescence concentration. The results demonstrate that frothers in salt water solution are more effective in preventing bubble coalescence than frothers in tap water solution. This behavior would be in agreement with their surface activity.

4.1: Critical coalescence concentration

The red squares show the effect of frothers concentration on bubble coalescence at salty water solutions. In all cases, the first top curve in blue shows the effect of the frother on bubble size at increasing frother concentrations in tap water. The same effect is shown at different frothers solution. At low concentrations of MIBC for instance, in sea water solutions the bubble size slightly tends to increase, but then it is stabilized and decreases again. The bubble size in sea water solutions, for all concentrations of most of frothers, were smaller than in tap water.

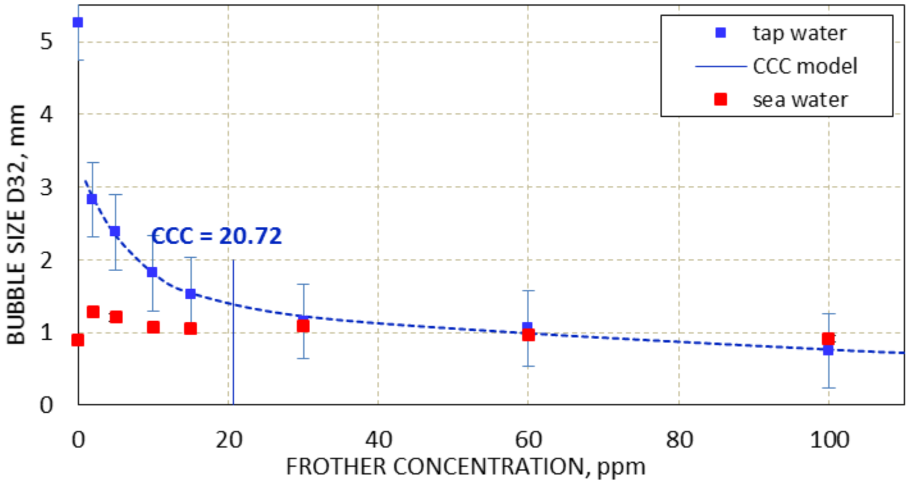

Figure 4.1 Sauter bubble diameter as a function of frother concentration – Tap and synthetic sea water solutions. DF 250

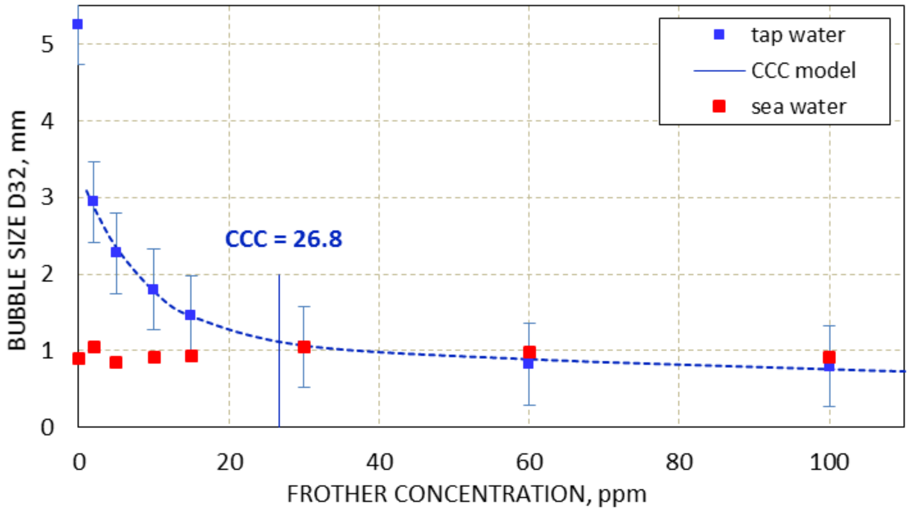

Figure 4.2 Sauter bubble diameter as a function of frother concentration – Tap and synthetic sea water solutions. PPG 425

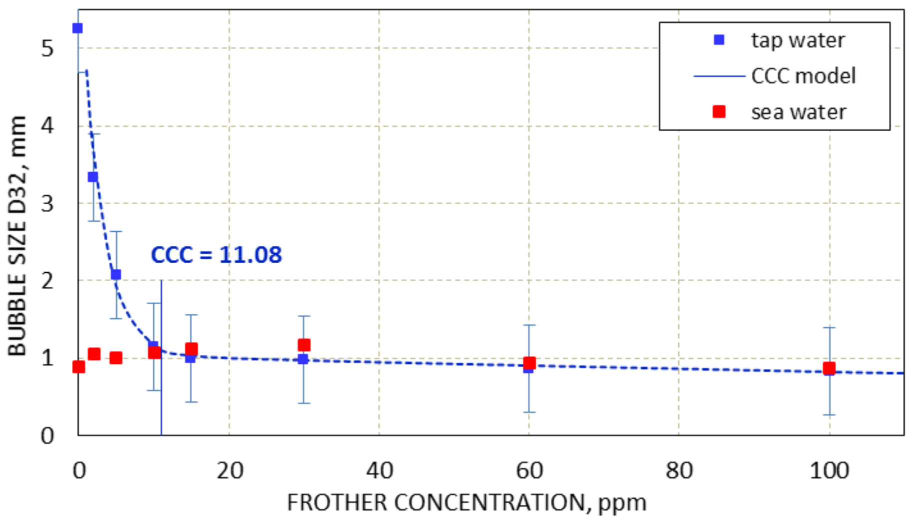

Figure 4.3 Sauter bubble diameter as a function of frother concentration – Tap and synthetic sea water solutions. MIBC

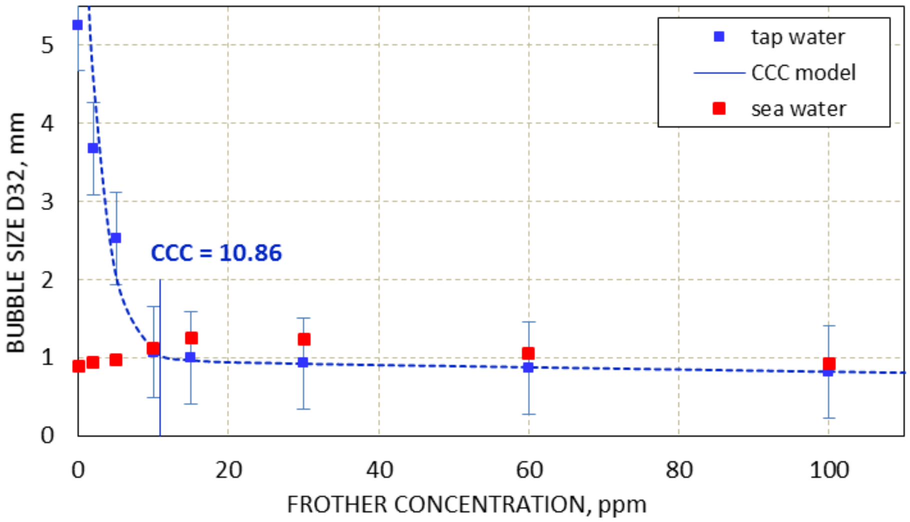

Figure 4.4 Sauter bubble diameter as a function of frother concentration – Tap and synthetic sea water solutions. 1 Hexanol

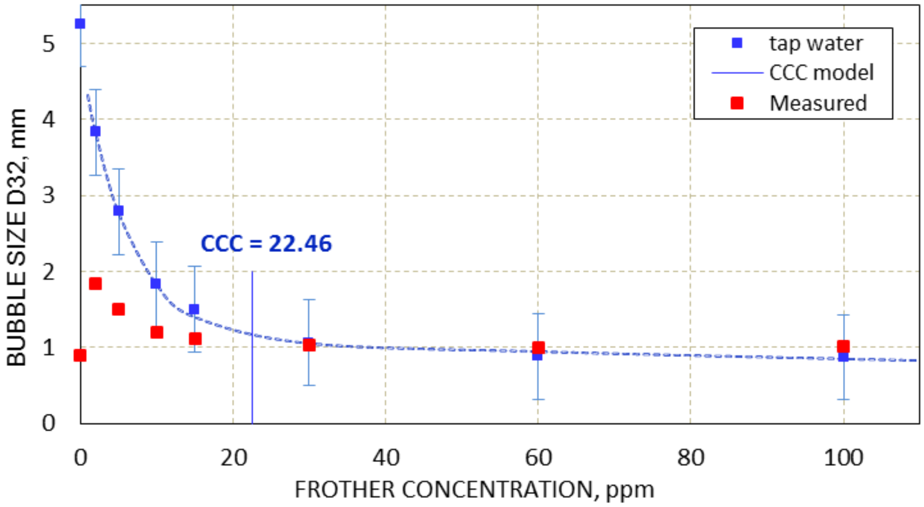

Figure 4.5 Sauter bubble diameter as a function of frother concentration – Tap and synthetic sea water solutions. F 140

4.2: Reproducibility

One important characteristic of any test is its reliability. The reproducibility of the measurements proposed to characterize frother was determined by running three repeat tests run at conditions selected differently for the MIBC, PPG-425 and 1-hexanol. The repeated tests included preparation of the frother solution.

The results showed good reproducibility as illustrated in Tables 4.1, 4.2 and 4.3. All of them for both solutions in tap and sea water. Results for the three repeats do not show much difference, this thus must lead to similar CCC values.

Plots of repeated tests can be seen in the Appendix.

Table 4.1: Repetition tests for MIBC

FROTHER	Water solution	Frother conc (ppm)	D32 (mm)				
			Test			AVG	SD
			1	2	3		
MIBC	TAP	2	3.50	3.56	3.34	3.47	0.114
		5	2.20	1.94	2.08	2.07	0.130
		10	1.06	1.02	1.15	1.07	0.066
		15	1.07	1.11	0.99	1.05	0.061
		30	0.95	1.01	0.98	0.98	0.030
		60	0.86	0.90	0.87	0.88	0.018
		100	0.81	0.83	0.83	0.82	0.011
	SALTY	2	1.02	0.97	1.05	1.01	0.038
		5	1.13	1.02	1.00	1.05	0.070
		10	1.01	1.14	1.07	1.07	0.064
		15	1.12	1.13	1.12	1.12	0.001
		30	1.16	1.21	1.17	1.18	0.025
		60	0.93	0.91	0.94	0.93	0.015
		100	0.91	0.87	0.86	0.88	0.022

Table 4.2: Repetition tests for PPG 425

FROTHER	Water solution	Frother conc (ppm)	D32 (mm)				
			Test			AVG	SD
			1	2	3		
PPG 425	TAP	2	2.94	2.96	2.99	2.96	0.023
		5	2.28	2.27	2.28	2.28	0.005
		10	1.80	1.78	1.81	1.80	0.013
		15	1.45	1.43	1.48	1.45	0.023
		30	1.05	1.06	1.07	1.06	0.008
		60	0.82	1.02	0.92	0.92	0.101
		100	0.79	1.06	0.93	0.93	0.136
	SALTY	2	1.05	1.07	1.00	1.04	0.036
		5	0.85	0.87	0.82	0.85	0.027
		10	0.92	0.96	0.88	0.92	0.040
		15	0.92	1.00	0.92	0.95	0.042
		30	1.05	1.06	1.07	1.06	0.008
		60	0.97	0.95	0.99	0.97	0.020
		100	0.91	0.98	0.95	0.95	0.034

Table 4.3: Repetition tests for 1 Hexanol

FROTHER	**Water solution**	**Frother conc (ppm)**	**D32 (mm)**				
			Test			**AVG**	**SD**
			1	**2**	**3**		
1 Hexanol	SALTY	2	0.92	0.93	0.96	0.93	0.020
		5	1.05	1.12	1.21	1.13	0.081
		10	1.17	1.12	1.15	1.14	0.022
		15	1.21	1.25	1.24	1.23	0.020
		30	1.23	1.23	1.23	1.23	0.002
		60	1.06	1.12	1.17	1.12	0.057
		100	0.87	0.92	0.89	0.89	0.024

4.2.1: Reproducibility 1

This considers repeat tests conducted for frothers in tap water solution. Figure 4.6 show repetitions tests performed for Sauter bubble diameter as a function of frother concentration for MIBC in Tap water solution.

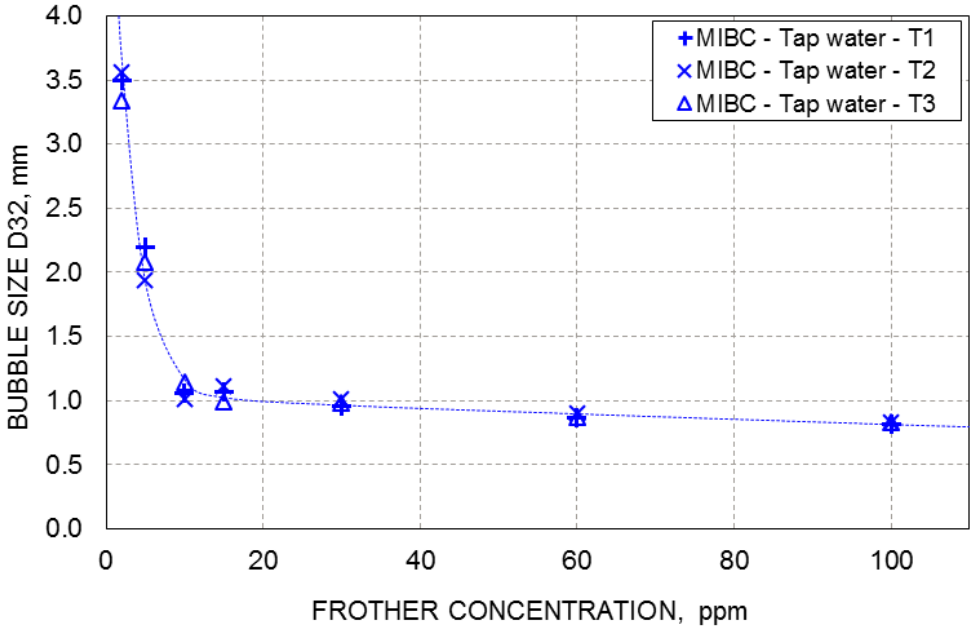

Figure 4.6 Sauter bubble diameter as a function of frother concentration – Tap water solution. MIBC

4.2.2: Reproducibility 2

This considers repeat tests conducted for frothers in sea water solution.

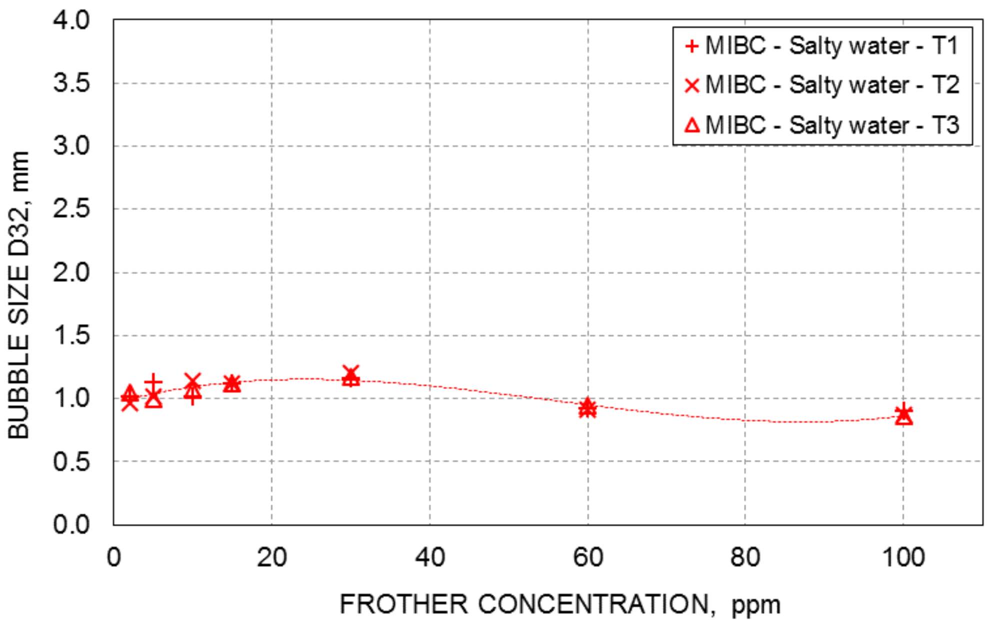

Figure 4.7 Sauter bubble diameter as a function of frother concentration – synthetic sea water solution. MIBC .

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Chapter 5: RESULTS – FROTH ZONE AND WATER CARRYING RATE

This chapter outlines the behavior in the froth zone with gas holdup and frother concentration as the independent variables and then used to compare the effect on water carrying rate, in tap and sea water solutions. Five frothers were used for these comparisons.

5.1: Water carrying rate and Gas holdup

Figures 5.1 to 5.5 show the plots of water carrying rate, J_{wo}, against gas holdup, ε_g. The trends are approximately linear for the tested frothers except some alcohols such as 1 Hexanol in salty water solution. As gas holdup increases, the water carrying rate increases both in tap and synthetic sea water solutions. Figures show the results of combining and plotting J_{wo} as a function of ε_g. Some plots show an intercept with initial low gas holdup of around 7% with tap water, and 12% with salty water (case of F140) which means that the foam could not reach the required 5 cm at gas holdups below these points.

A comparison of different frothers in tap and salty waters solution of water carrying rate Jwo against concentration are also shown in Figure 5.11 to 5.15. A higher water carrying rate with frothers in salty water solutions is observed except with alcohol frothers.

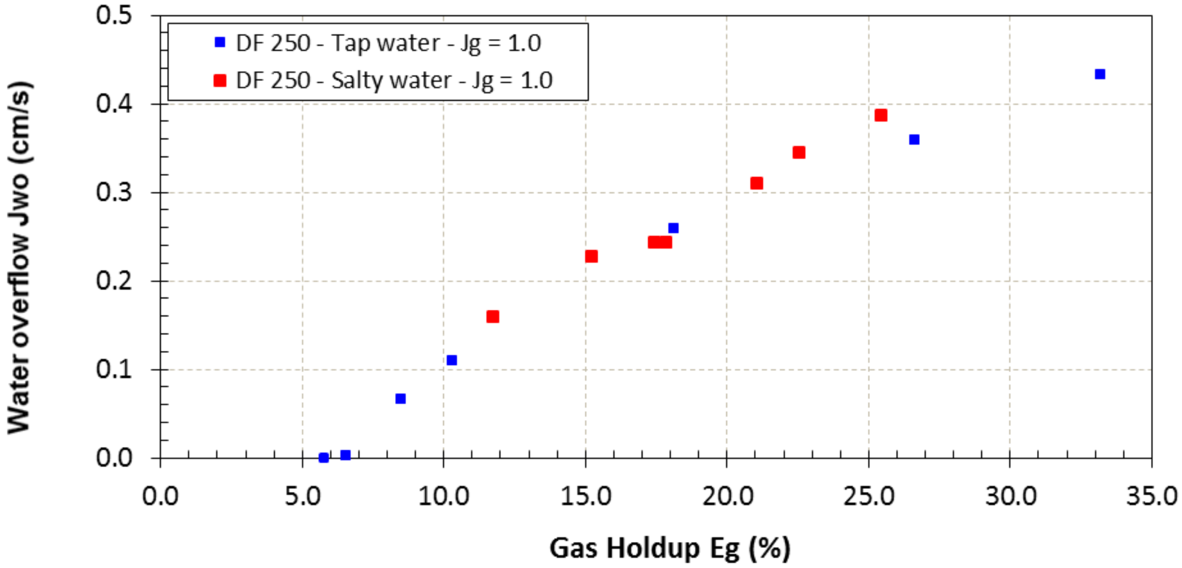

Figure 5.1 J_{wo} - ε_g relationship: Effect of tap and synthetic sea water. Conditions: DF 250, foam height (Hf) = 5 cm

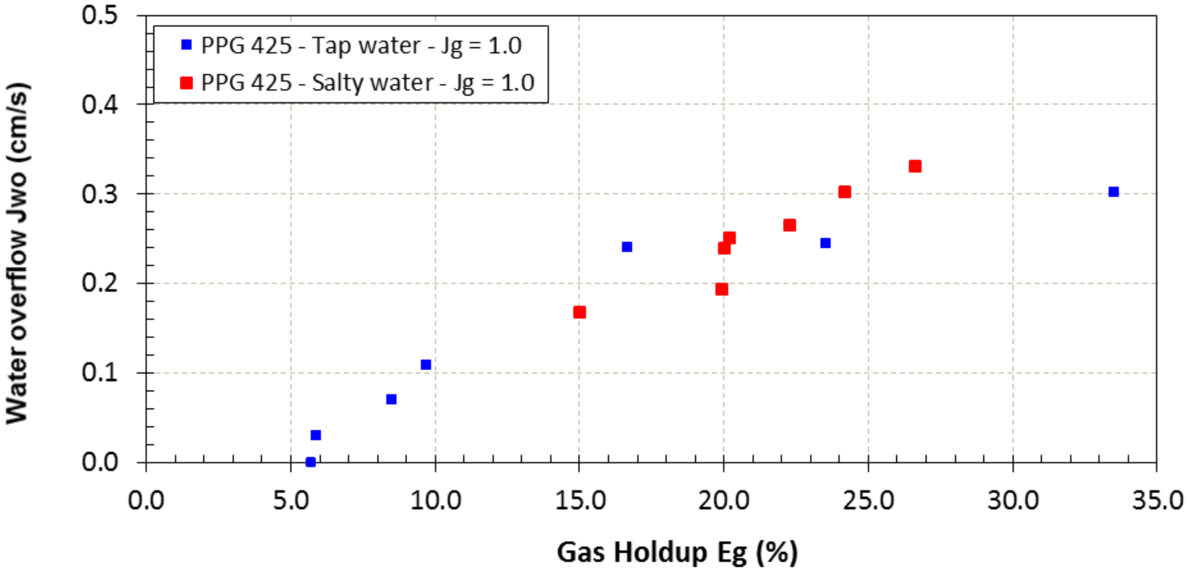

Figure 5.2 J_{wo} - ε_g relationship: Effect of tap and synthetic sea water. Conditions: PPG 425, foam height (Hf) = 5 cm

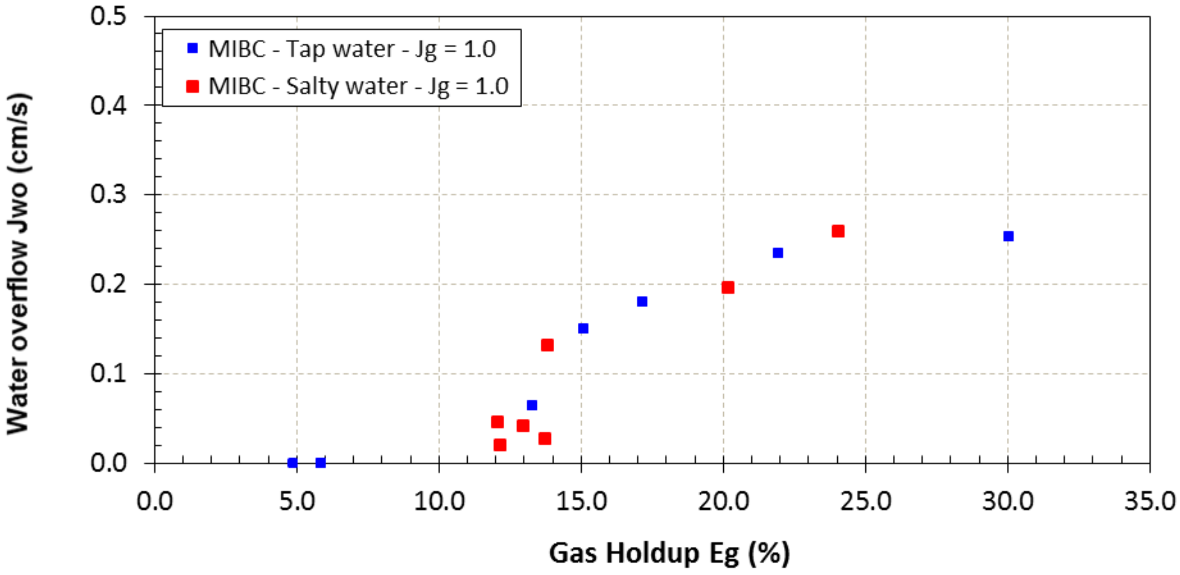

Figure 5.3 J_{wo} - ε_g relationship: Effect of tap and synthetic sea water. Conditions: MIBC, foam height (Hf) = 5 cm

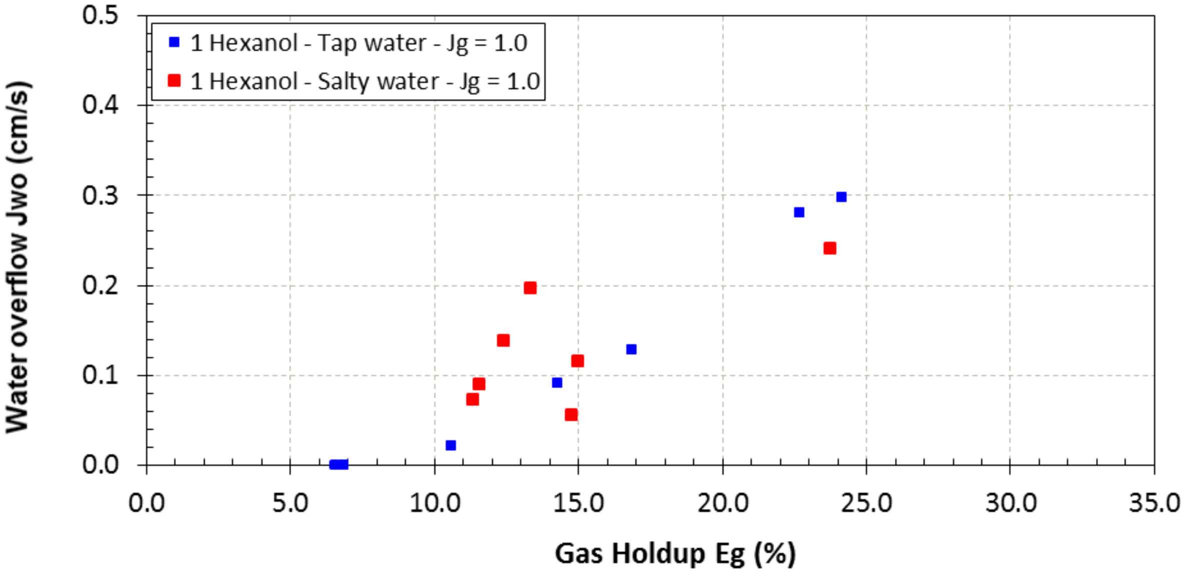

Figure 5.4 J_{wo} - ε_g relationship: Effect of tap and synthetic sea water. Conditions: 1 Hexanol, foam height (Hf) = 5 cm

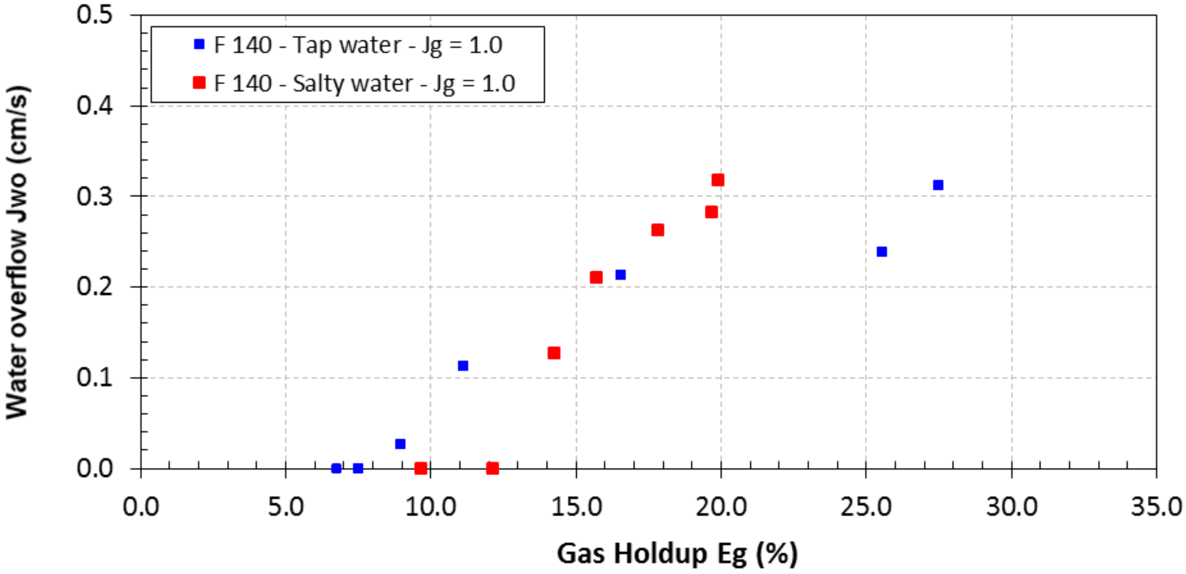

Figure 5.5 J_{wo} - ε_g relationship: Effect of tap and synthetic sea water. Conditions: F 140, foam height (Hf) = 5 cm

5.2: Gas holdup and frother concentration

Figures 5.6 to 5.10 show the plots of gas holdup against frother concentration for different frothers in tap and synthetic sea water solutions. The trends in bubble size is mirrored by the gas holdup measurements, and gas holdup increases with increasing frother concentration, which corresponds to the decrease in bubble size.

The relative position of each frother, gas holdup of frother in salty water solution over gas holdup in tap water solution in initial concentrations, is the same for most of the frothers. The notably lower gas holdup for specific frother concentrations, is because frother in tap water solutions has markedly less effect on slowing bubble rise compared to same frother in synthetic sea water solution (Acuna and Finch, 2008).

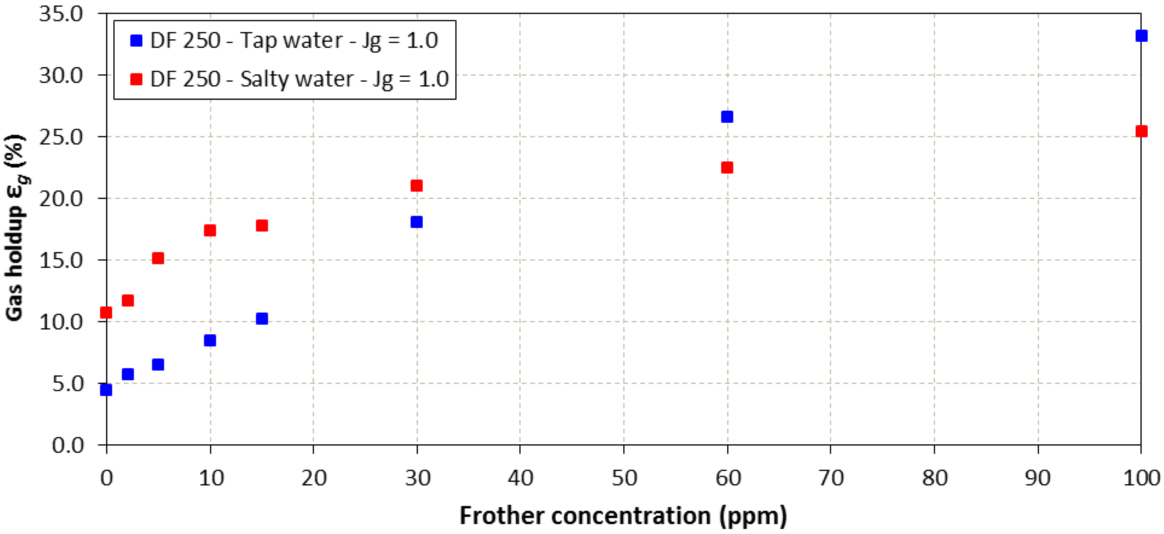

Figure 5.6 Gas holdup - frother concentration relationship: Effect of tap and synthetic sea water. Conditions: DF 250, foam height (Hf) = 5 cm

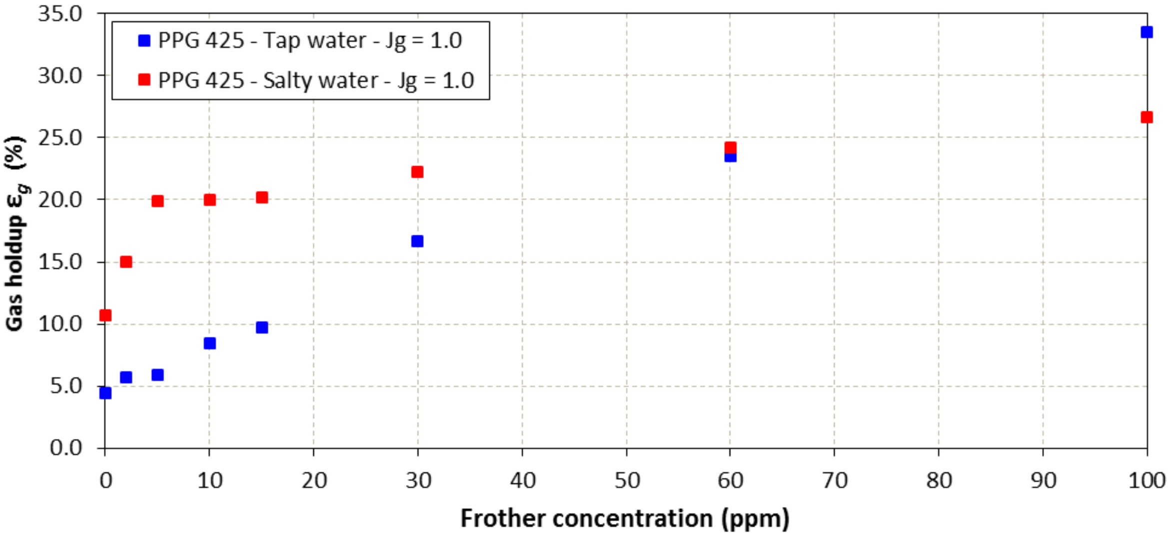

Figure 5.7 Gas holdup - frother concentration relationship: Effect of tap and synthetic sea water. Conditions: PPG 425, foam height (Hf) = 5 cm

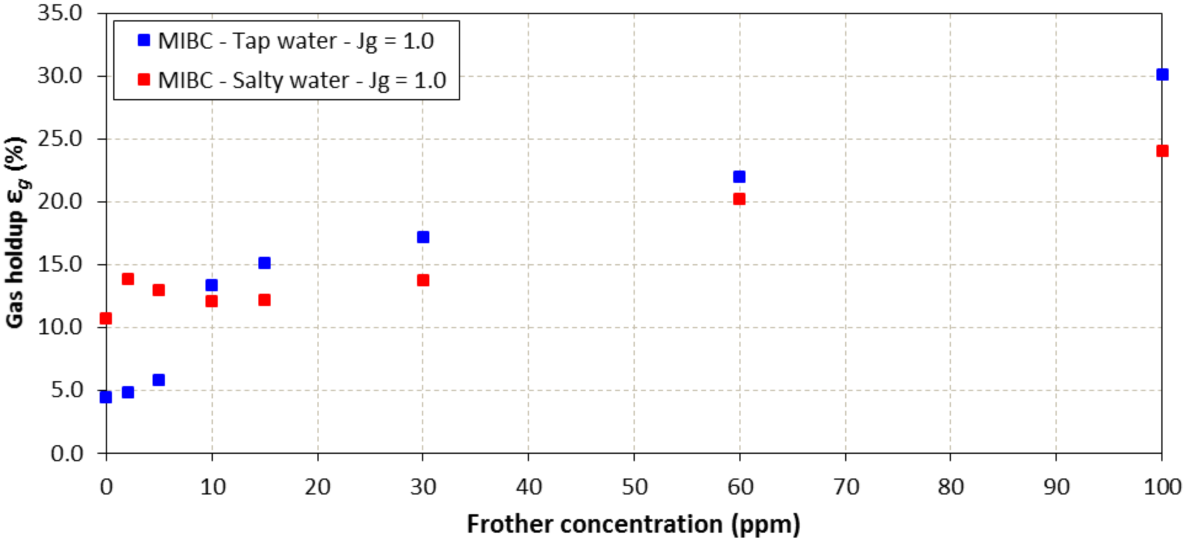

Figure 5.8 Gas holdup - frother concentration relationship: Effect of tap and synthetic sea water. Conditions: MIBC, foam height (Hf) = 5 cm

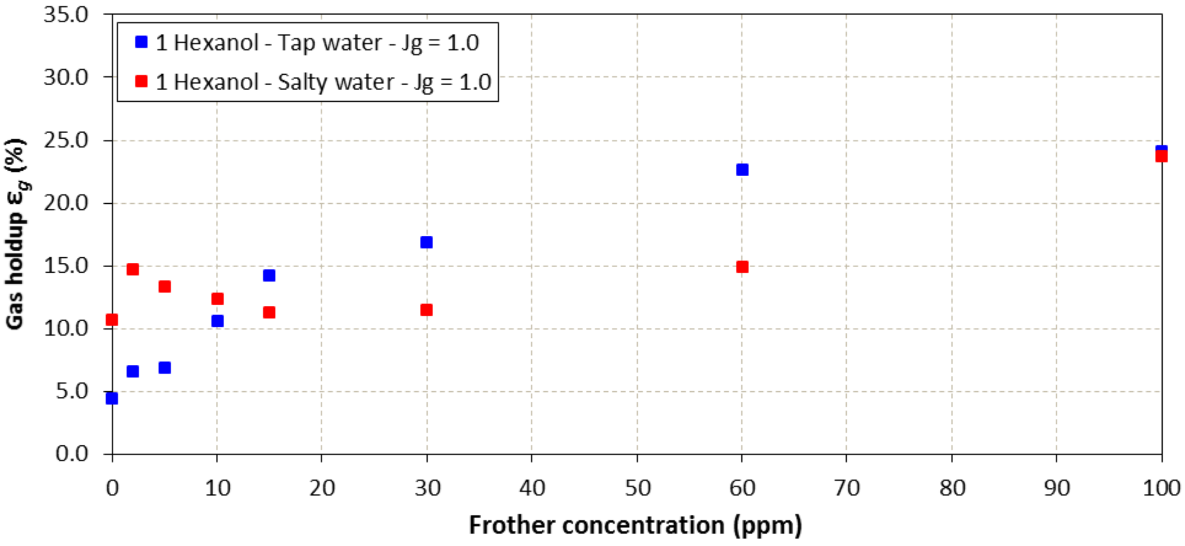

Figure 5.9 Gas holdup - frother concentration relationship: Effect of tap and synthetic sea water. Conditions: 1 Hexanol, foam height (Hf) = 5 cm

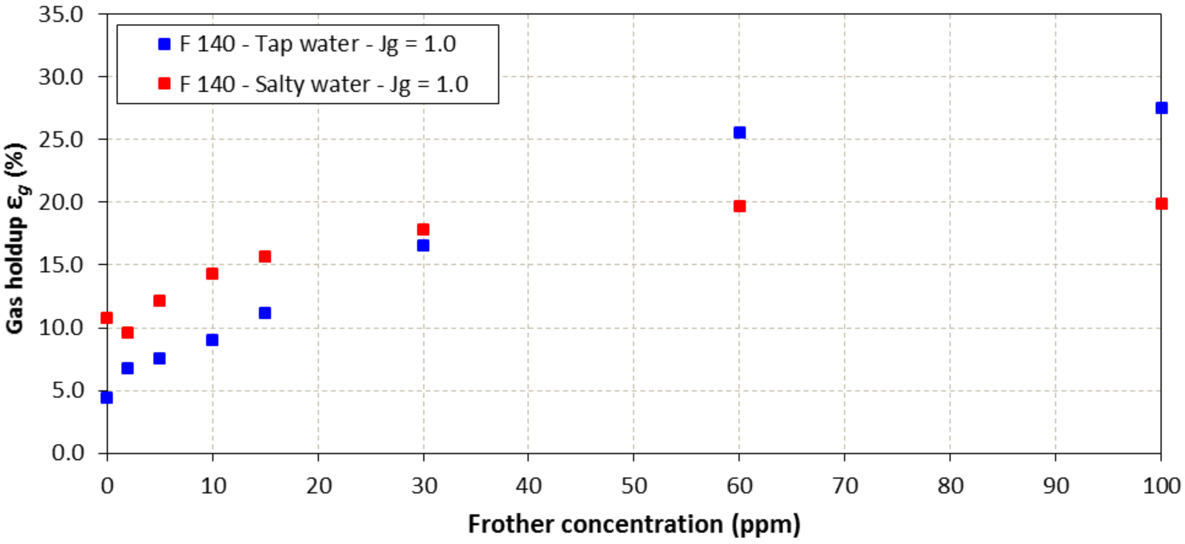

Figure 5.10 Gas holdup - frother concentration relationship: Effect of tap and synthetic sea water. Conditions: F 140, foam height (Hf) = 5 cm

5.3: Water carrying rate and frother concentration

Figures 5.11 to 5.15 show the plots of water carrying rate against frother concentration for different frothers in tap and sea water solutions. Figures show water overflow rate for DF 250, PPG 425, and F140 with similar behavior, the relative position of each water overflow rate of frother in synthetic sea water solution over those in tap water solution. The frothers in the synthetic sea water solution always exceeded the overflow rate for frothers in tap water solution. Different behavior instead is observed for alcohols MIBC and 1 hexanol (Figures 5.13 and 5.14). This result implies that family of frothers would impact the effect of the frother role in this flotation zone (froth).

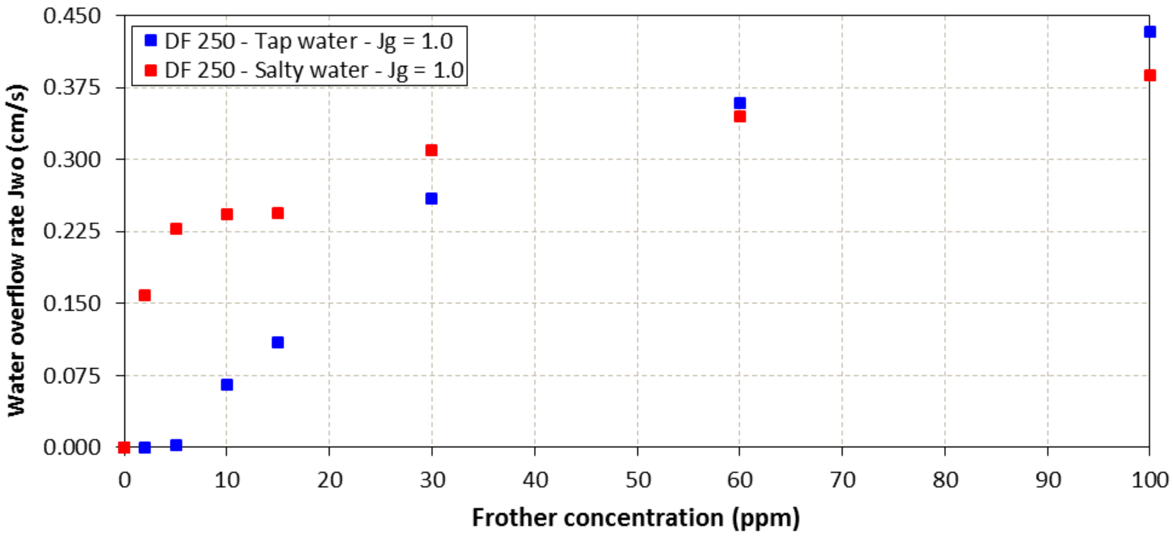

Figure 5.11 Water carrying rate - frother concentration relationship: Effect of tap and synthetic sea water. Conditions: DF 250, foam height (Hf) = 5 cm

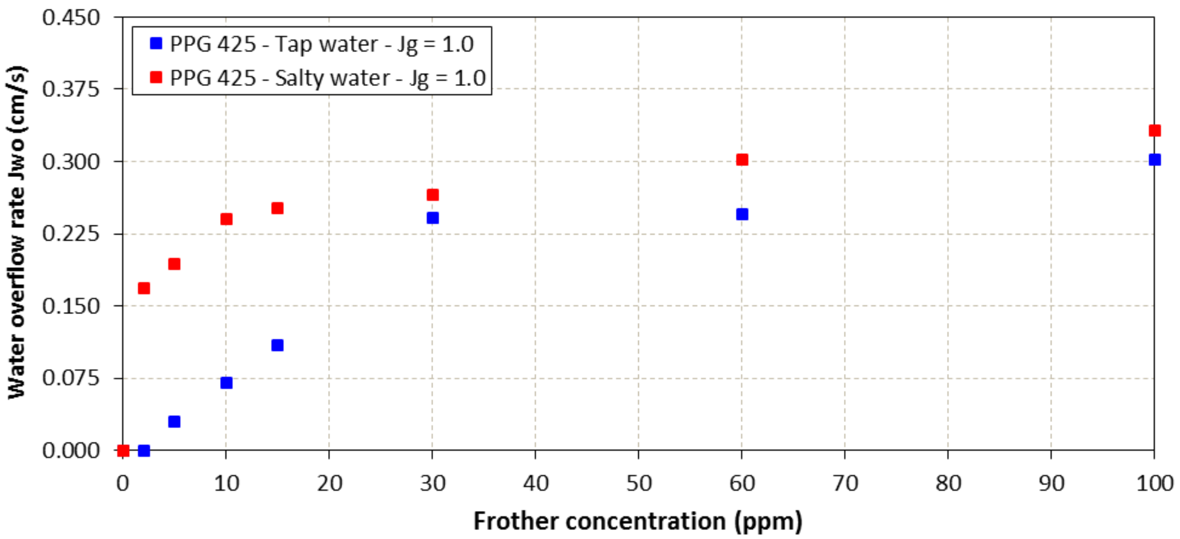

Figure 5.12 Water carrying rate - frother concentration relationship: Effect of tap and synthetic sea water. Conditions: PPG 425, foam height (Hf) = 5 cm

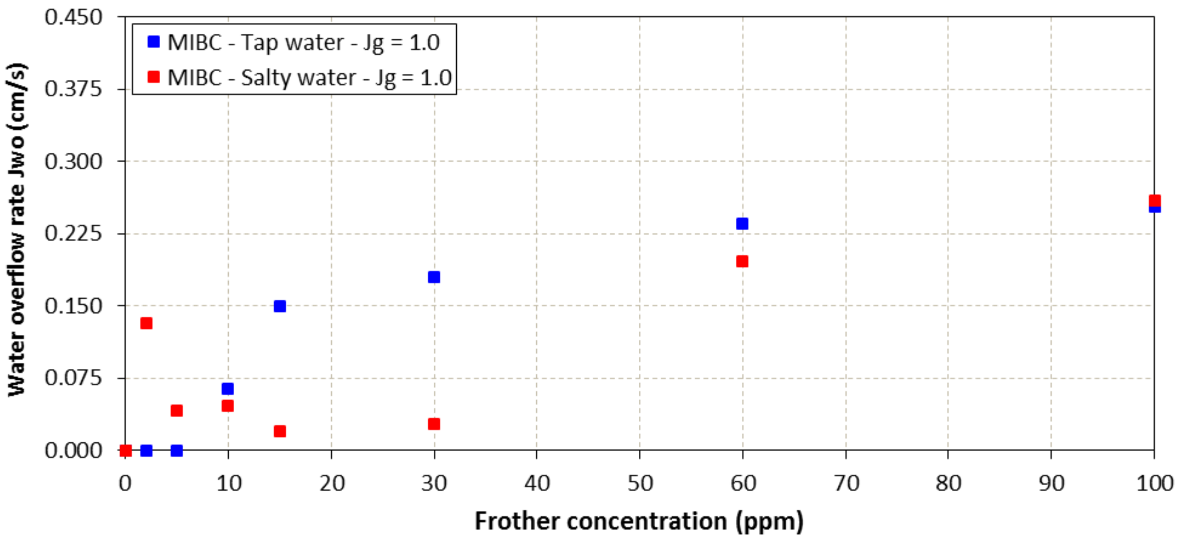

Figure 5.13 Water carrying rate - frother concentration relationship: Effect of tap and synthetic sea water. Conditions: MIBC, foam height (Hf) = 5 cm

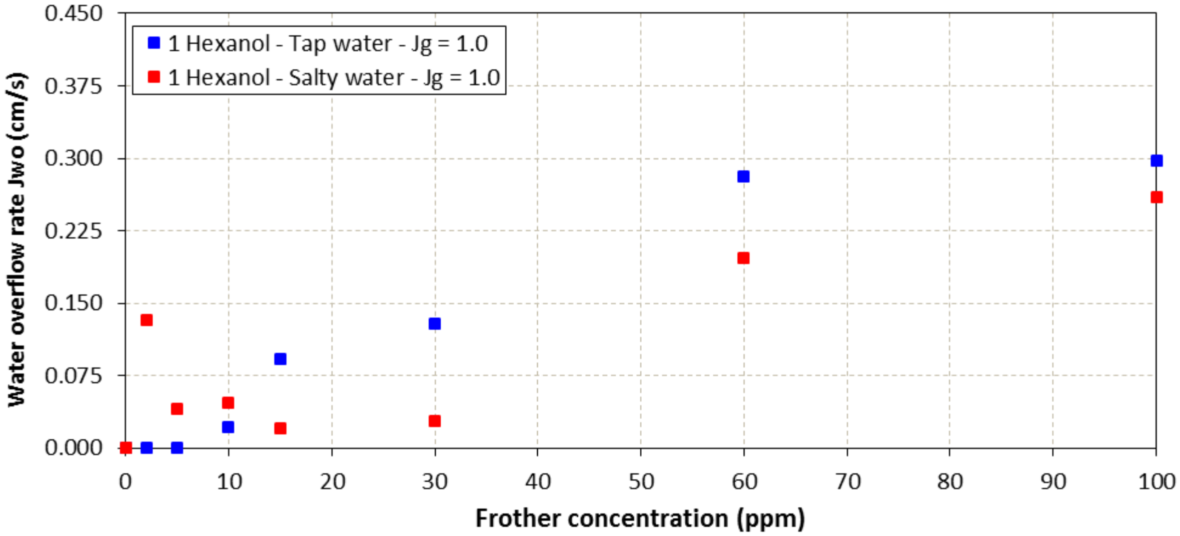

Figure 5.14 Water carrying rate - frother concentration relationship: Effect of tap and synthetic sea water. Conditions: 1 Hexanol, foam height (Hf) = 5 cm

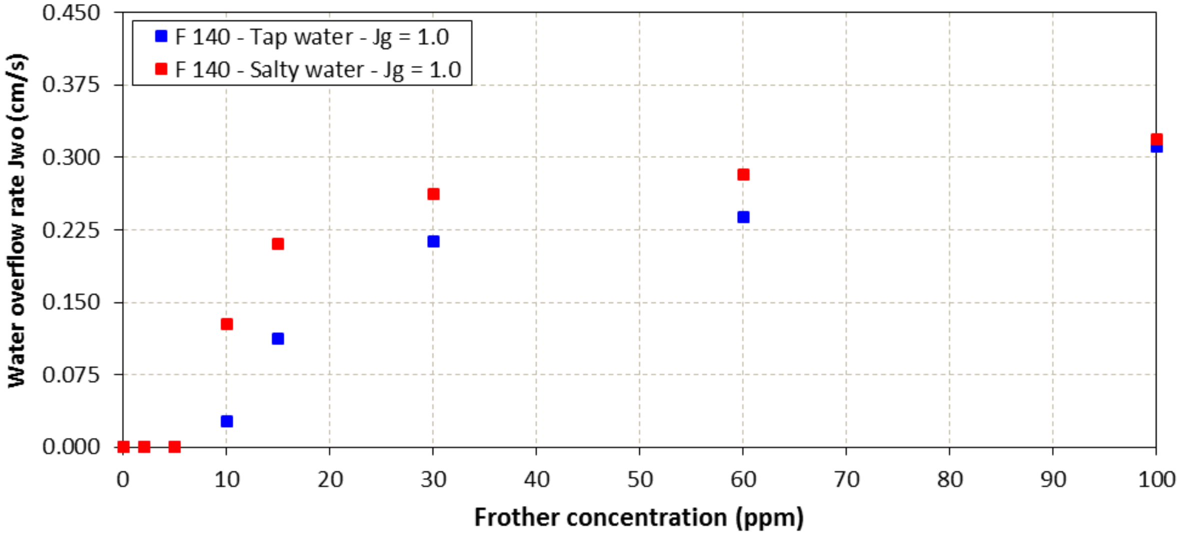

Figure 5.15 Water carrying rate - frother concentration relationship: Effect of tap and synthetic sea water. Conditions: F 140, foam height (Hf) = 5 cm

5.4: The effect of superficial gas velocity Jg

The gas holdup and water carrying rate as a function of superficial gas velocity, J_g, for DF 250 and 1 Hexanol at some specific conditions were explored and are shown in Figures 5.16 to 5.24.

Gas holdup was measured as a function of gas rate and frother type and concentration. Figures 5.16 and 5.17 show the typical relationship for some concentrations: a general increase in gas holdup with gas rate and frother concentration is observed. The water overflow rate (water carrying rate, J_{wo}) as a function of J_g corresponding to the data are shown in Figure 5.18 onward.

Gas holdup is an indirect measure of bubble size, increasing as bubble size decreases (for a given air flow rate). This reflects the fact that smaller bubbles rise at lower velocities and thus gas residence time (holdup) in the column increases. Bubble size is dictated by sparger characteristics, airflow rate and the system chemistry. Figures show the expected near linear response in gas holdup with superficial gas velocity (Finch and Dobby, 1990). Linear trends as expected were found which depend on frother concentration and J_{wo} is clearly not related to J_g alone.

5.4.1: Superficial gas velocity and Gas holdup

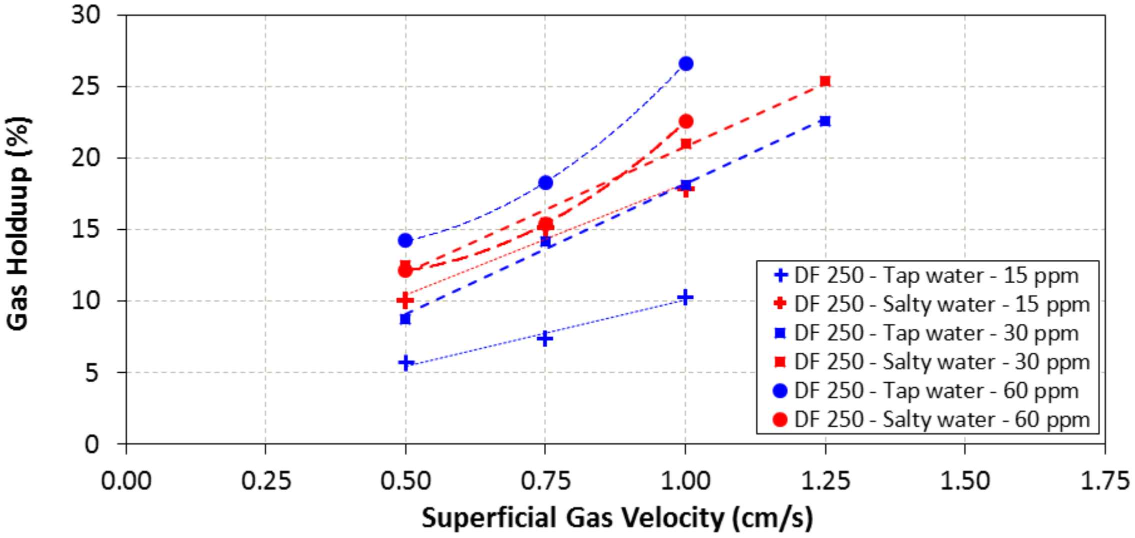

Figure 5.16 Gas holdup and superficial gas velocity for DF 250 with different concentrations

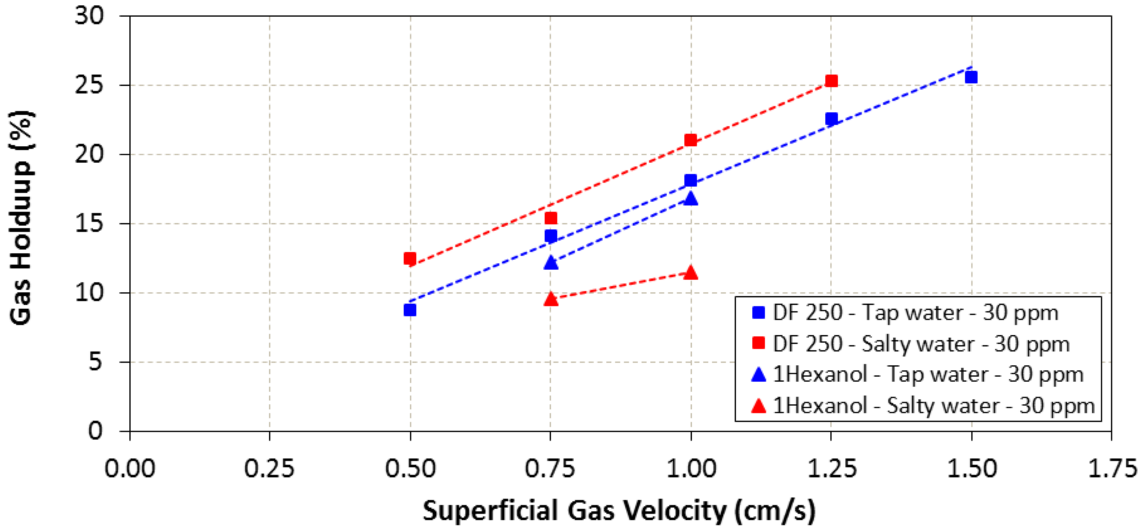

Figure 5.17 Gas holdup and superficial gas velocity for two frothers - 30 ppm

5.4.2: The effect of superficial gas velocity Jg at different frother concentrations – DF 250

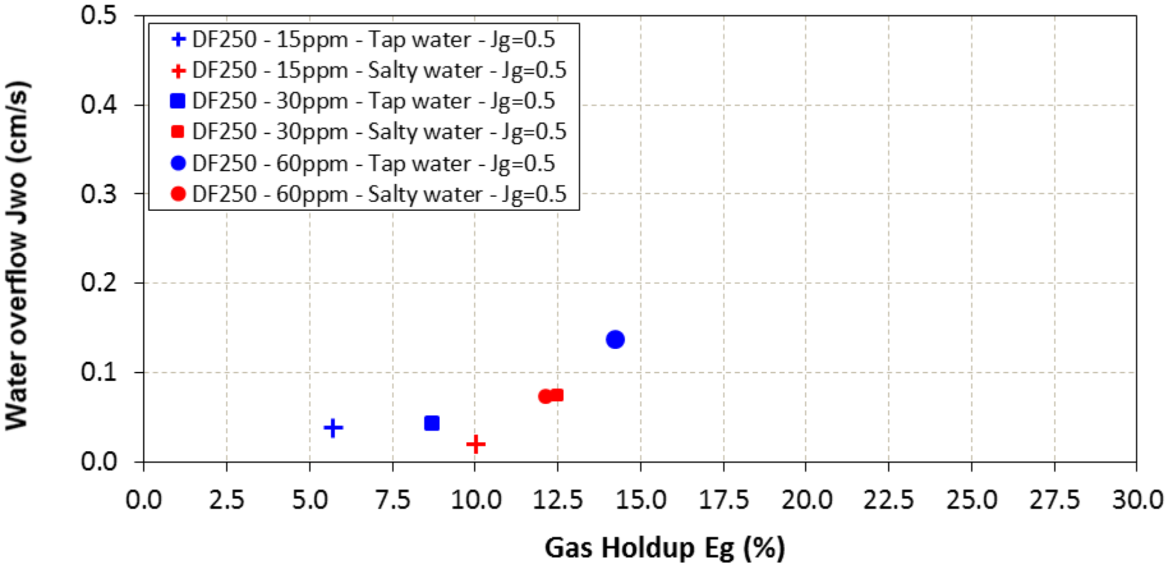

Figure 5.18 Jwo - εg relationship: Effect on DF 250 tap and synthetic sea water solution. Conditions: DF 250, Jg = 0.5 cm/s

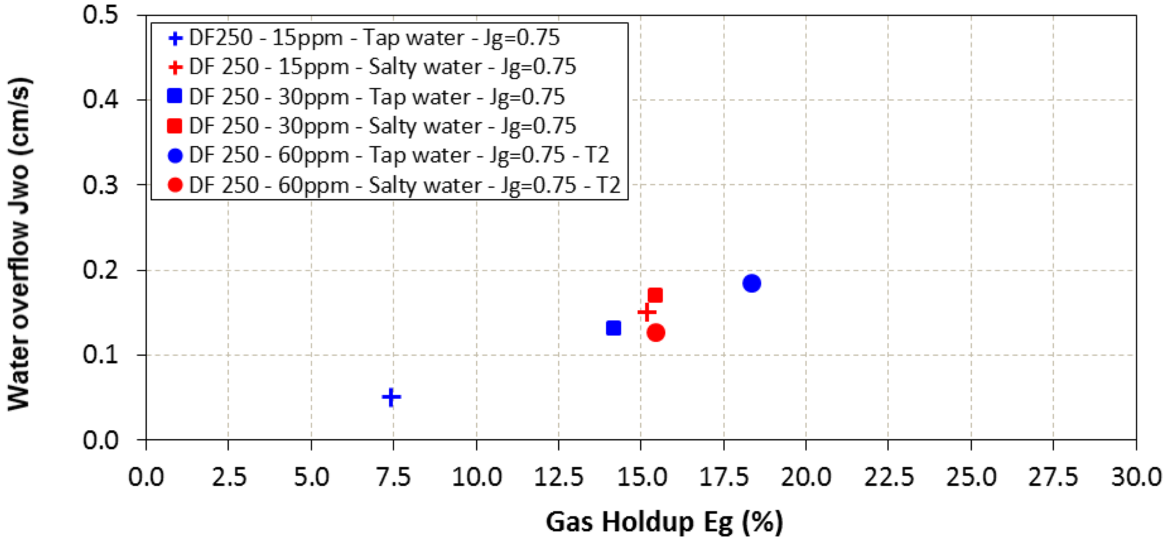

Figure 5.19 Jwo - εg relationship: Effect on DF 250 tap and synthetic sea water solution. Conditions: DF 250, Jg = 0.75 cm/s

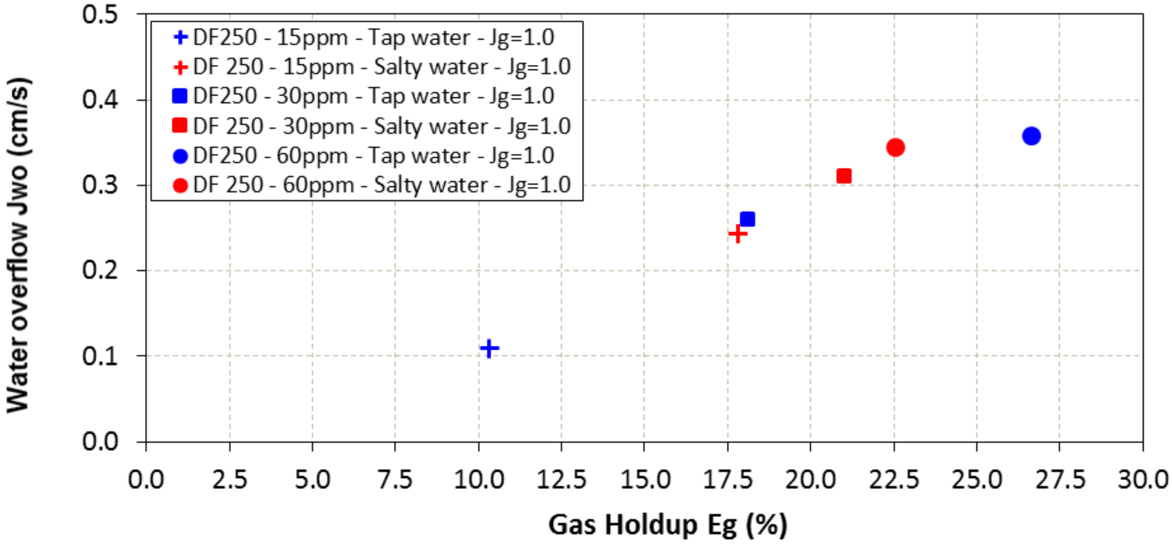

Figure 5.20 Jwo - εg relationship: Effect on DF 250 tap and synthetic sea water solution. Conditions: DF 250, Jg = 1.0 cm/s

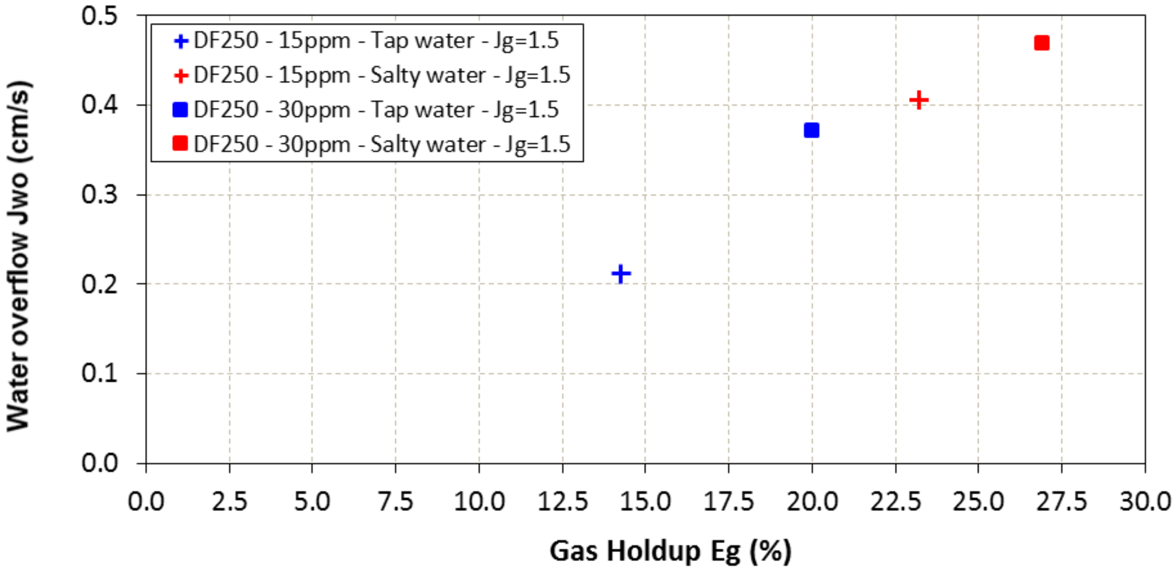

Figure 5.21 Jwo - εg relationship: Effect on DF 250 tap and synthetic sea water solution. Conditions: DF 250, Jg = 1.5 cm/s

5.4.3: The effect of different Jg at 30 ppm frother concentration - DF 250

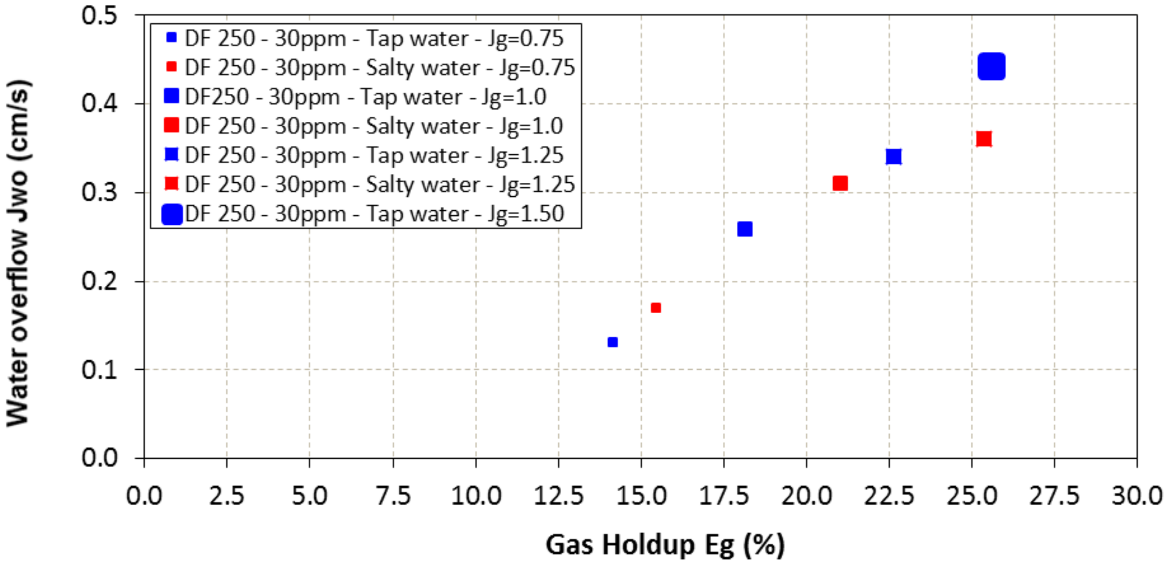

Figure 5.22 Jwo - εg relationship: Effect on DF 250 tap and synthetic sea water solution. Conditions: DF 250, Jg = 0.5 cm/s

5.4.4: The effect of superficial gas velocity Jg at different frother concentrations – 1 Hexanol

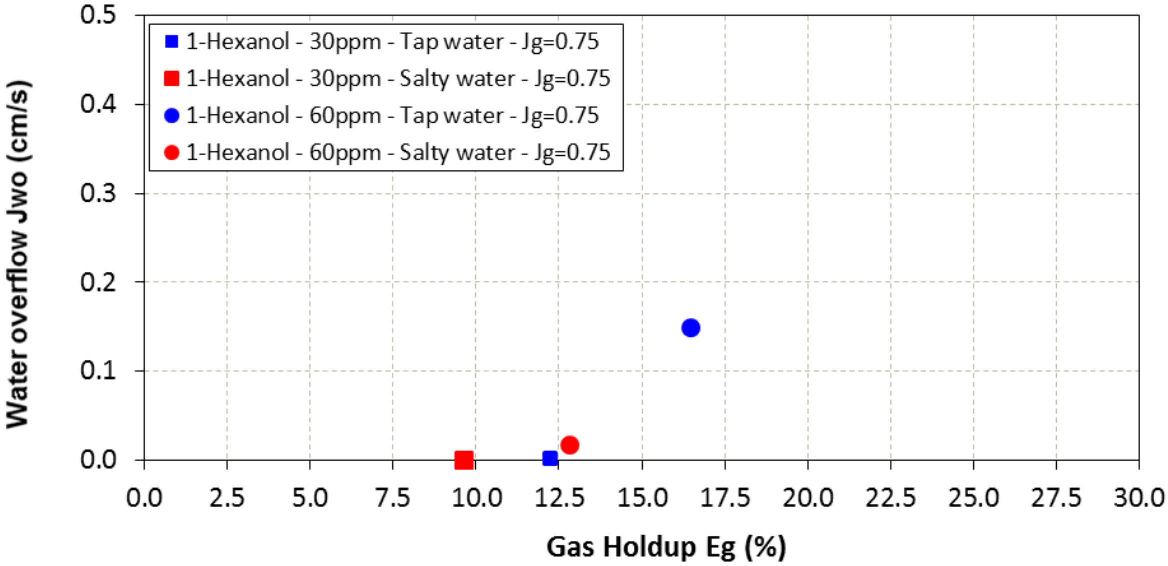

Figure 5.23 Jwo - εg relationship: Effect on 1 Hexanol tap and synthetic sea water solution. Conditions: 1 hexanol, Jg = 0.75 cm/s

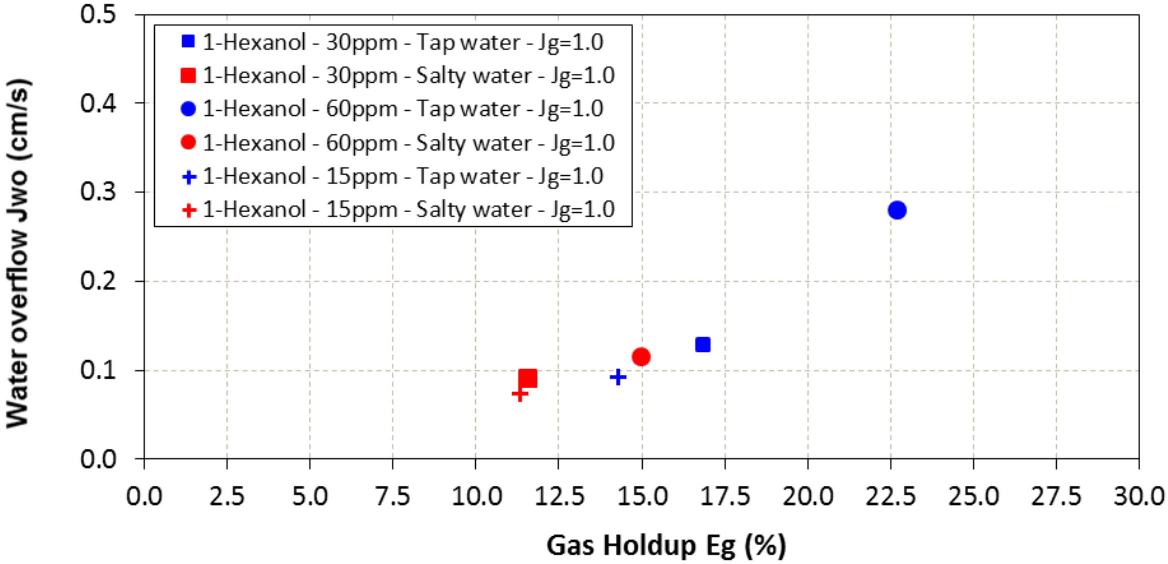

Figure 5.24 Jwo - εg relationship: Effect on 1 Hexanol tap and synthetic sea water solution. Conditions: 1 Hexanol, Jg = 1.0 cm/s

5.5: The ocean sea salt equivalence to frothers

Figures 5.25 to 5.29 compare gas holdup as a function of the concentration of salt and five used frothers (right axis). While it is evident that frothers are capable of greater increases in gas holdup the results for the synthetic sea water cover a similar range. The trend-lines are polynomial fits and are used purely for illustrating purposes.

From the curves, it can be estimated that used sea water salt has the same effect, with respect to increased gas holdup, as roughly 16 ppm DF 250 for instance which is a typical average concentration in plant operations.

Similar estimations can be done for the other frothers tested.

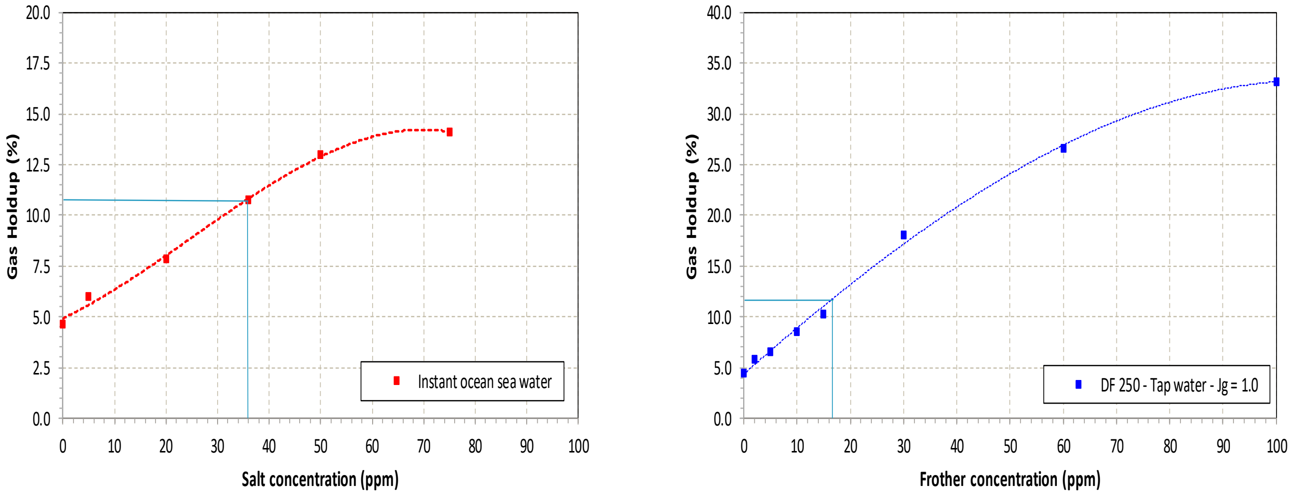

Figure 5.25 Comparison of Gas holdup for used ocean sea salt and frother concentration: Conditions: DF250, Jg = 1.0 cm/s.

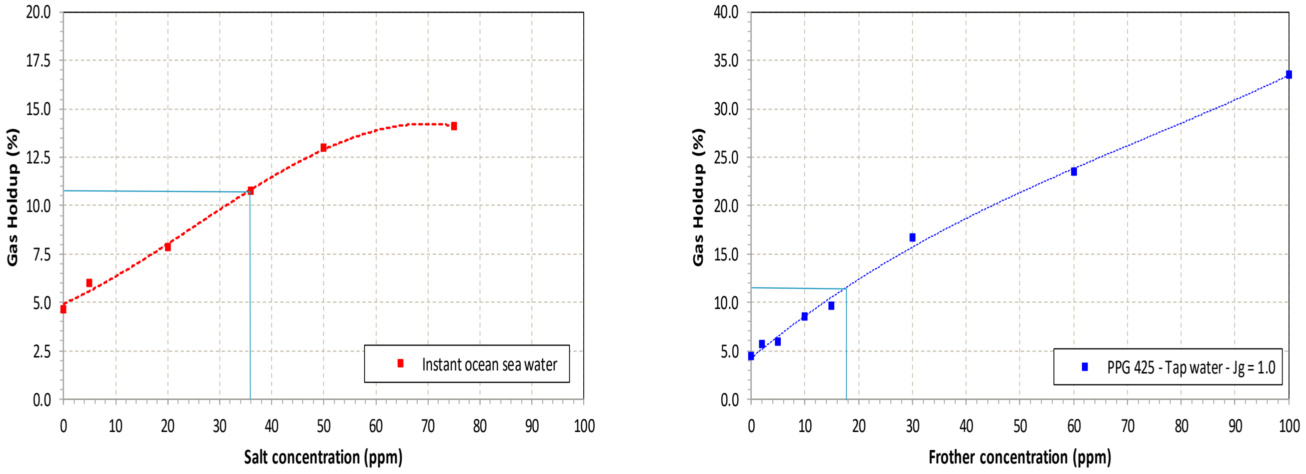

Figure 5.26 Comparison of Gas holdup for used ocean sea salt and frother concentration: Conditions: PPG 425, Jg = 1.0 cm/s.

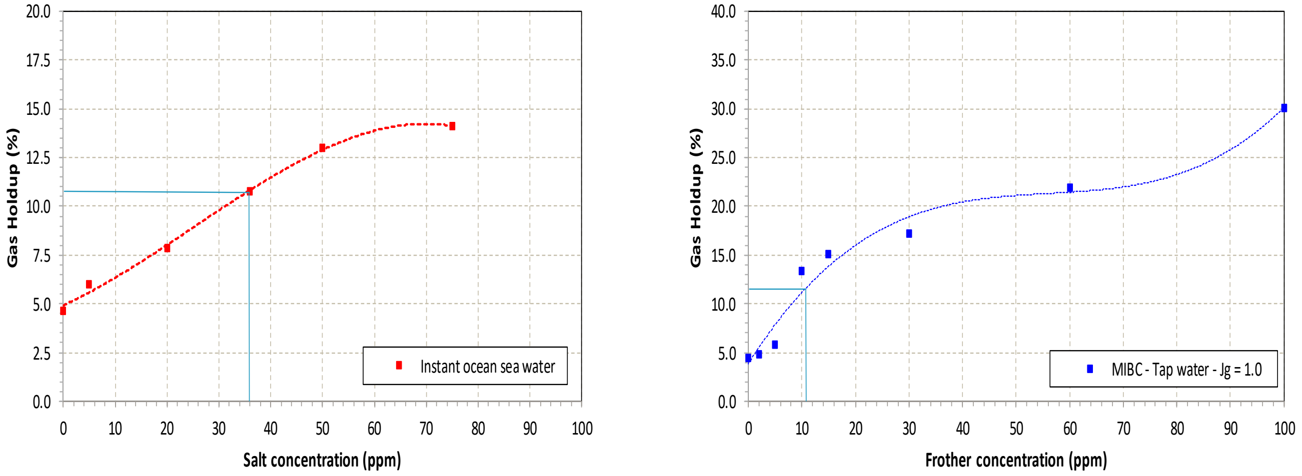

Figure 5.27 Comparison of Gas holdup for used ocean sea salt and frother concentration: Conditions: MIBC, Jg = 1.0 cm/s.

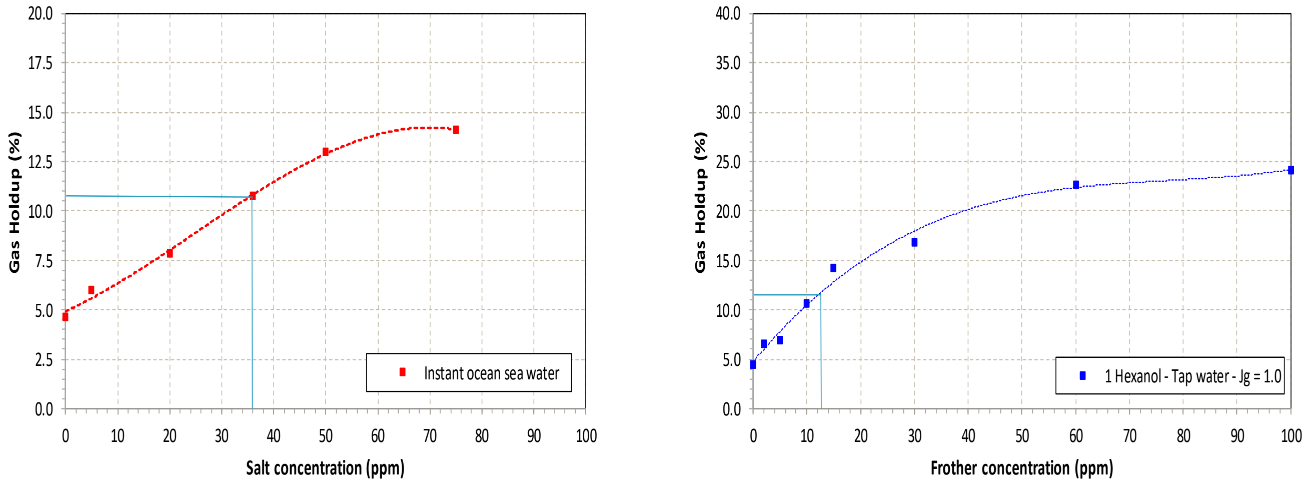

Figure 5.28 Comparison of Gas holdup for used ocean sea salt and frother concentration: Conditions: 1 Hexanol, Jg = 1.0 cm/s.

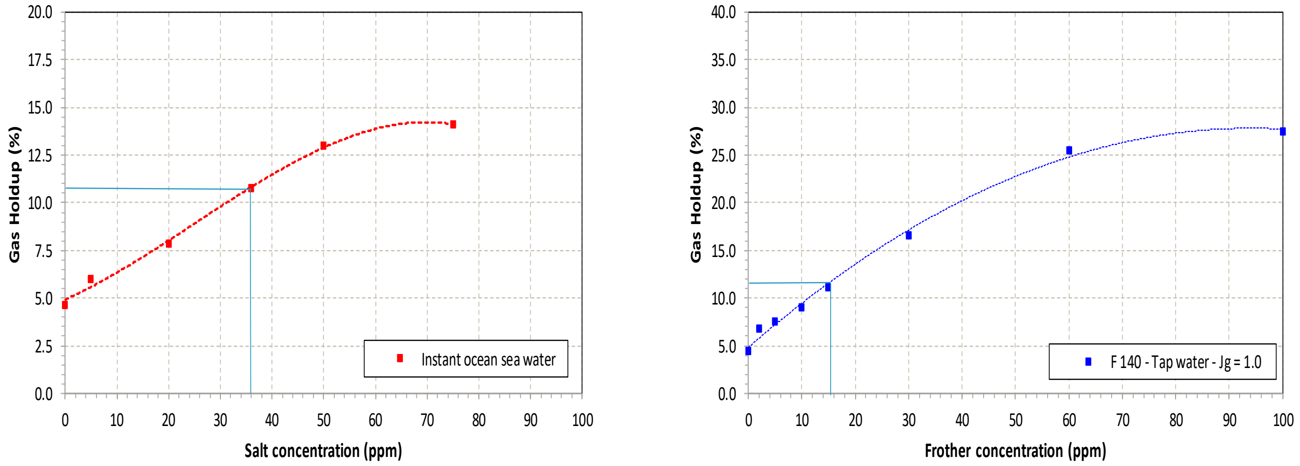

Figure 5.29 Comparison of Gas holdup for used ocean sea salt and frother concentration: Conditions: F 140, Jg = 1.0 cm/s.

5.6: Relevant Results

5.6.1: <u>Water carrying rate – DF 250 and PPG 425 Glycols</u>:

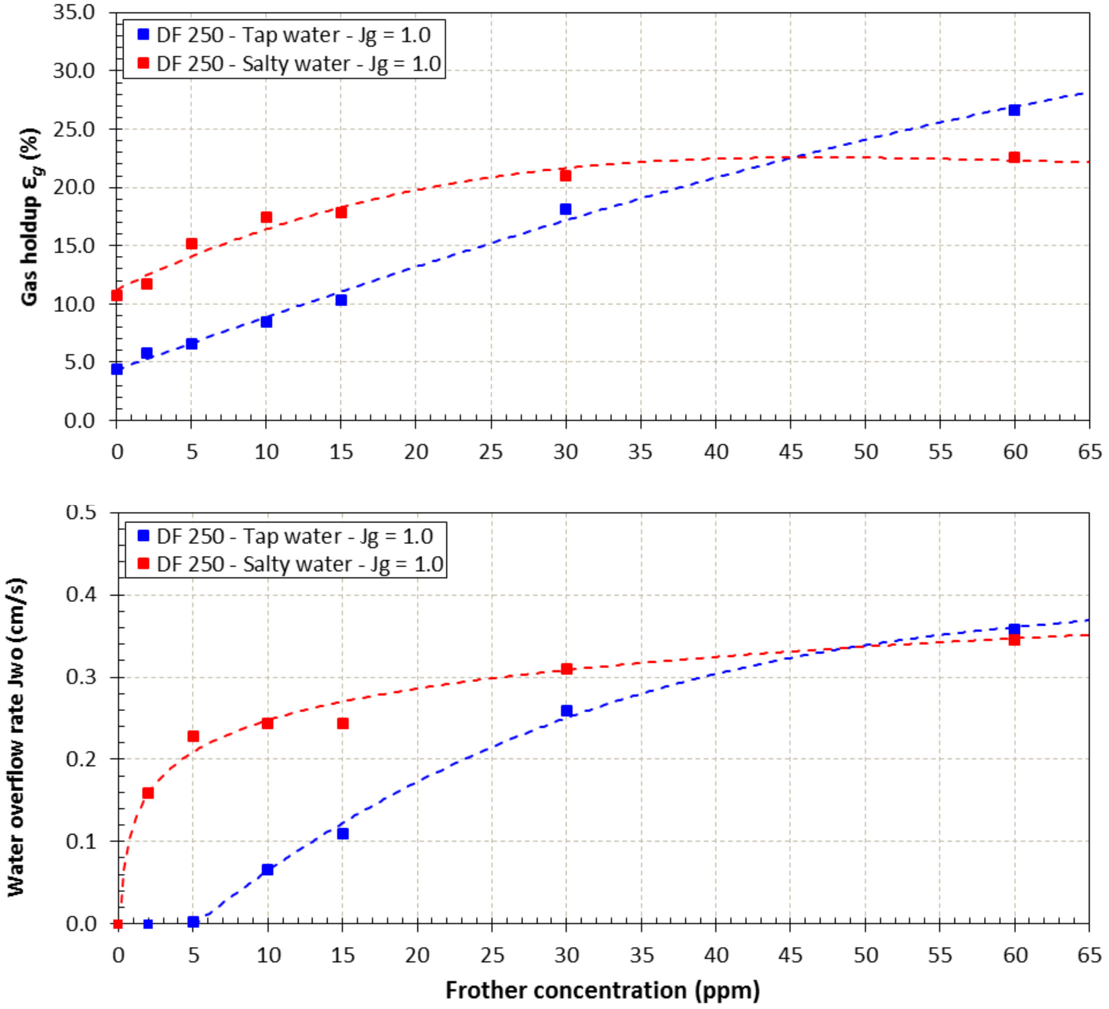

Figure 5.30 Gas holdup and Water overflow rate as a function of frother concentration for DF250 in both tap and synthetic sea water solution

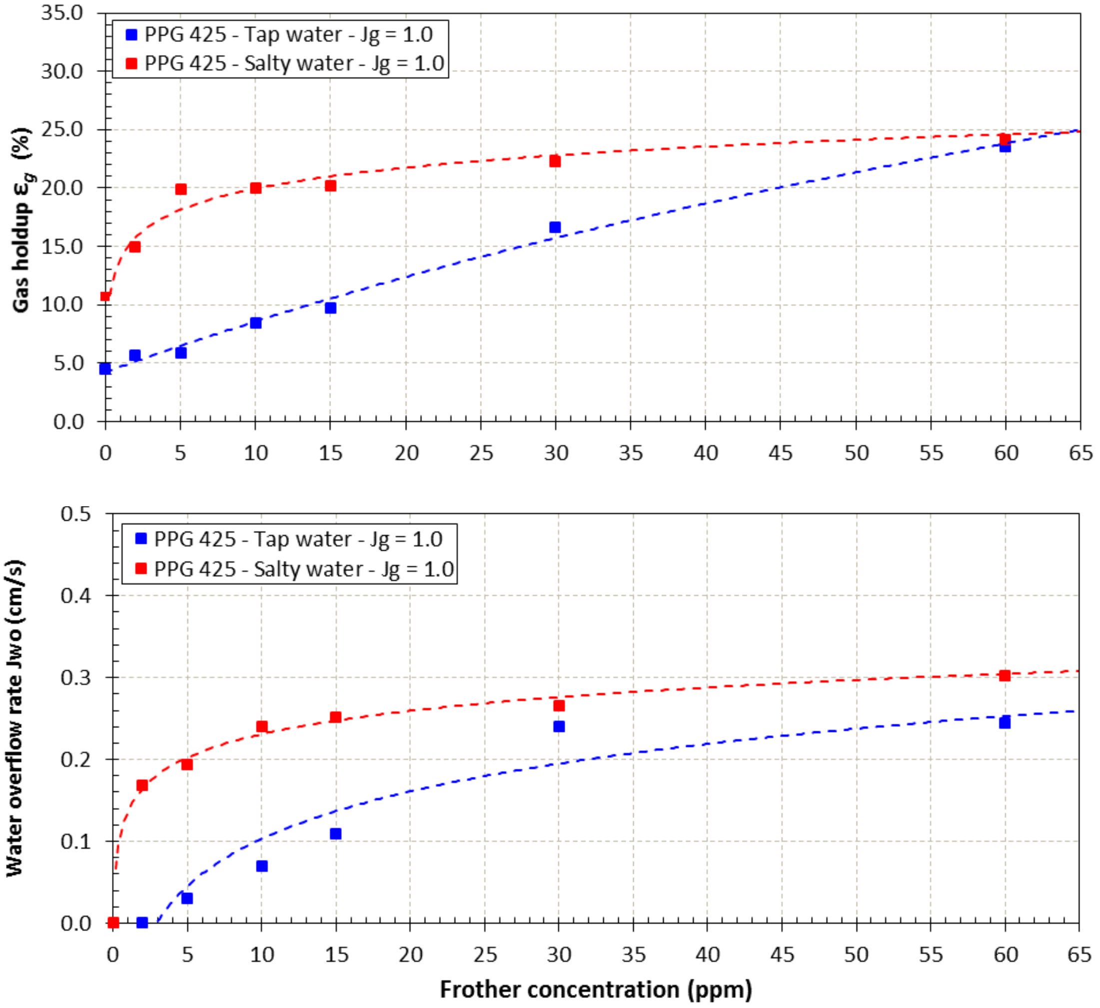

Figure 5.31 Gas Holdup and Water overflow rate as a function of frother concentration for PPG425 in both tap and synthetic sea water solution

5.6.2: Water carrying rate – MIBC and 1-hexanol Alcohols:

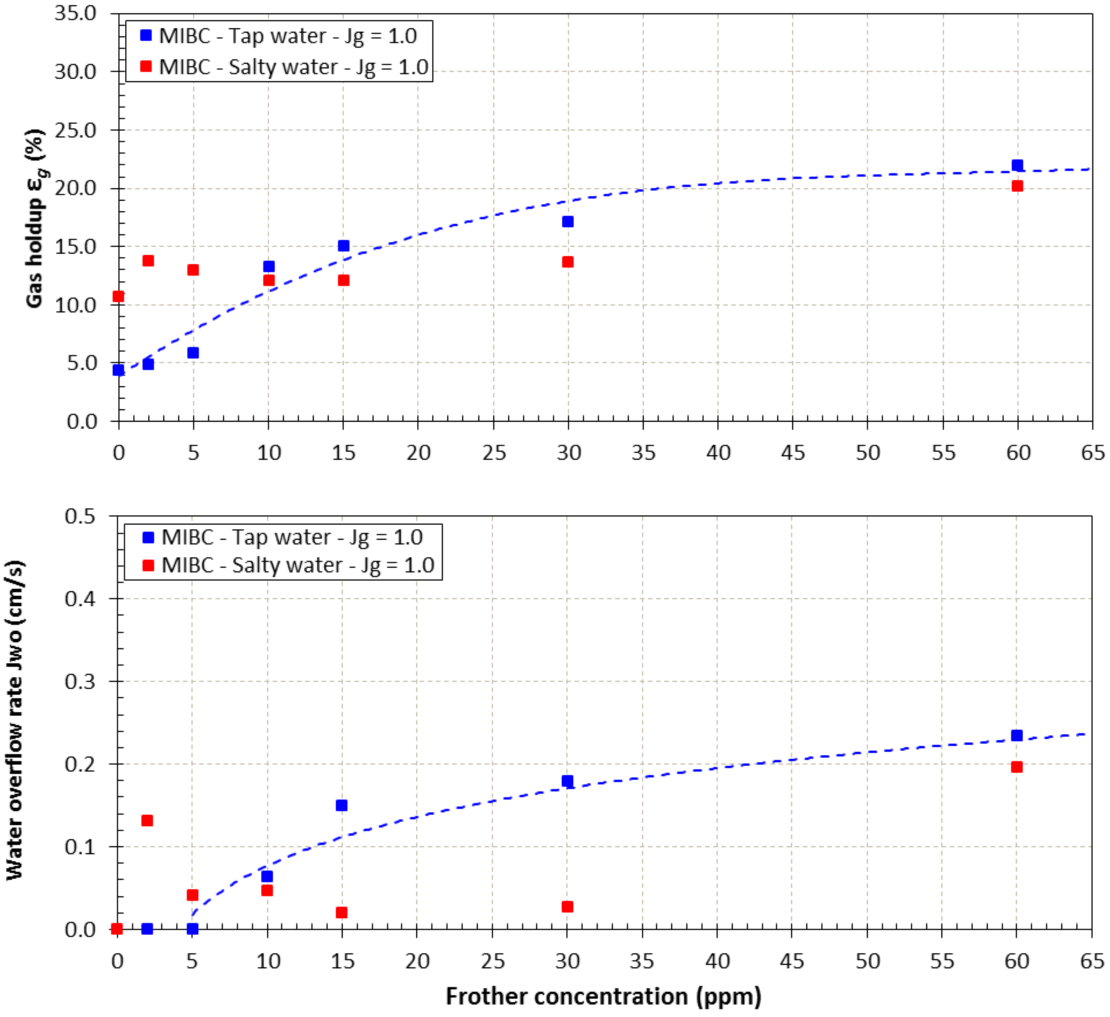

Figure 5.32 Gas holdup and Water overflow rate as a function of frother concentration for MIBC in both tap and synthetic sea water solution

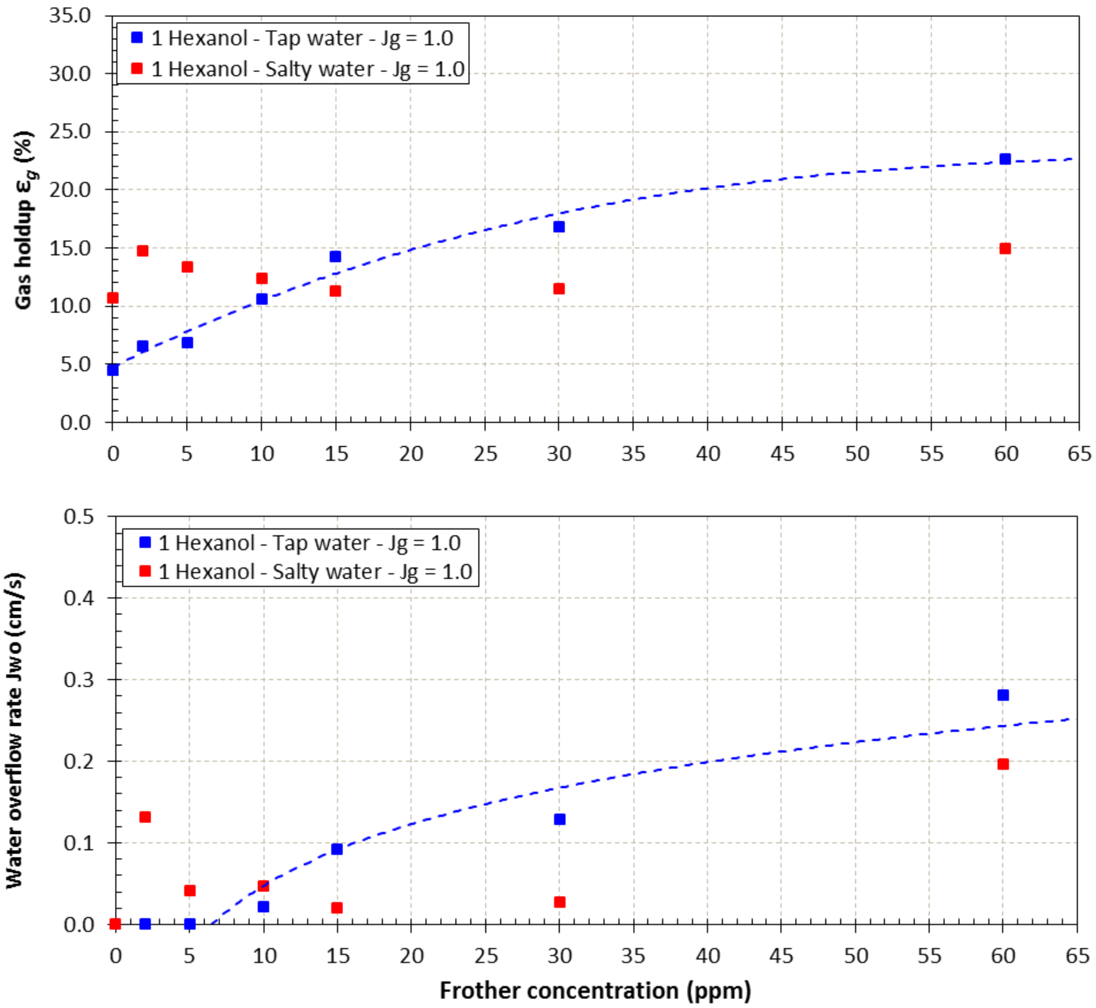

Figure 5.33 Gas holdup and Water overflow rate as a function of frother concentration for 1 Hexanol in both tap and synthetic sea water solution

5.6.3: Water carrying rate – F 140 commercial frother:

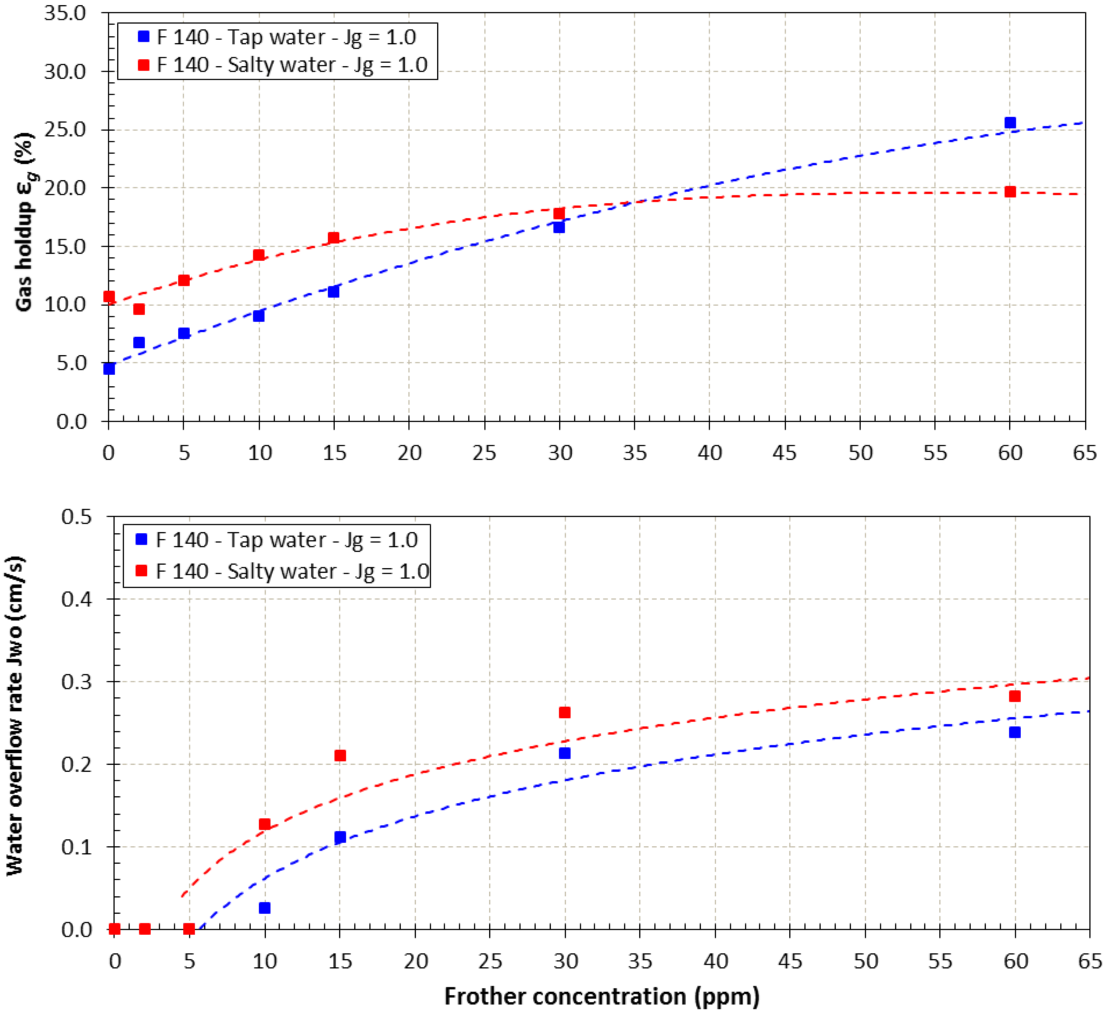

Figure 5.34 Gas Holdup and Water overflow rate as a function of frother concentration for F 140 in both tap and synthetic sea water solution

5.7: Reproducibility

One important characteristic of any test is its reliability. The repeated tests included preparation of the frother solution. Three repeats were completed for each condition of four frothers both in tap and sea water solution as shown in Tables 5.1 and 5.2 where summarize the reproducibility for all the conditions used showing values of the standard deviation.

The results showed good reproducibility which can be also illustrated in Figures 5.35 and 5.36.

Table 5.1: Repetition tests - Jwo - ε_g relationship – Tap water

FROTHER -Test	Water solution	Conc frother (ppm)	Jg (cm/s)	ε_g (%)	Jwo cm/s	AVG		SD	
						Eg	Jwo	Eg	Jwo
DF 250 - tap - 60ppm - Jg:0.75 - T1	Tap	60	0.75	18.1	0.182	18.3	0.186	0.114	0.004
DF 250 - tap - 60ppm - Jg:0.75 - T2	Tap	60	0.75	18.3	0.185				
DF 250 - tap - 60ppm - Jg:0.75 - T3	Tap	60	0.75	18.4	0.189				
DF 250 - tap - 30ppm - Jg:1.0 - T1	Tap	30	1.0	18.0	0.258	18.1	0.258	0.084	0.003
DF 250 - tap - 30ppm - Jg:1.0 - T2	Tap	30	1.0	18.2	0.260				
DF 250 - tap - 30ppm - Jg:1.0 - T3	Tap	30	1.0	18.1	0.254				
MIBC - tap 30ppm - Jg:1.0 - T1	Tap	30	1.0	17.2	0.1795	17.2	0.180	0.755	0.001
MIBC - tap 30ppm - Jg:1.0 - T2	Tap	30	1.0	16.4	0.1804				
MIBC - tap 30ppm - Jg:1.0 - T3	Tap	30	1.0	17.9	0.1787				
1 Hexanol - tap 30ppm - Jg:1.0 - T1	Tap	30	1.0	16.9	0.129	16.9	0.124	0.420	0.004
1 Hexanol - tap 30ppm - Jg:1.0 - T2	Tap	30	1.0	16.5	0.120				
1 Hexanol - tap 30ppm - Jg:1.0 - T3	Tap	30	1.0	17.4	0.124				

Table 5.2 Repetition tests - Jwo - εg relationship – Synthetic sea water

FROTHER	Water solution	Conc frother (ppm)	Jg (cm/s)	ε_g (%)	Jwo cm/s	AVG		SD	
						Eg	Jwo	Eg	Jwo
DF 250 - salty - 60ppm - Jg:0.75 - T1	Sea water	60	0.75	15.2	0.128	15.3	0.128	0.117	0.002
DF 250 - salty - 60ppm - Jg:0.75 - T2	Sea water	60	0.75	15.4	0.126				
DF 250 - salty - 60ppm - Jg:0.75 - T3	Sea water	60	0.75	15.3	0.130				
DF 250 - salty - 30ppm - Jg:1.00 - T1	Sea water	30	1.0	20.9	0.305	21.0	0.310	0.187	0.004
DF 250 - salty - 30ppm - Jg:1.00 - T2	Sea water	30	1.0	21.0	0.314				
DF 250 - salty - 30ppm - Jg:1.00 - T3	Sea water	30	1.0	21.2	0.311				
MIBC - salty - 60ppm - Jg:1.0 - T1	Sea water	60	1.0	20.2	0.1966	19.1	0.197	1.046	0.001
MIBC - salty - 60ppm - Jg:1.0 - T2	Sea water	60	1.0	18.1	0.1958				
MIBC - salty - 60ppm - Jg:1.0 - T3	Sea water	60	1.0	19.1	0.1974				
PPG 425 - salty - 15ppm - Jg:1.0 - T1	Sea water	15	1.0	20.195	0.251	19.9	0.259	0.513	0.010
PPG 425 - salty - 15ppm - Jg:1.0 - T2	Sea water	15	1.0	19.307	0.255				
PPG 425 - salty - 15ppm - Jg:1.0 - T3	Sea water	15	1.0	20.195	0.270				

5.7.1: Repetition plots

The reproducibility of the measurements performed to characterize DF250 was determined by running three repeat tests at conditions selected differently (Figures 5.35 and 5.36). Tables can be also seen in the Appendix section.

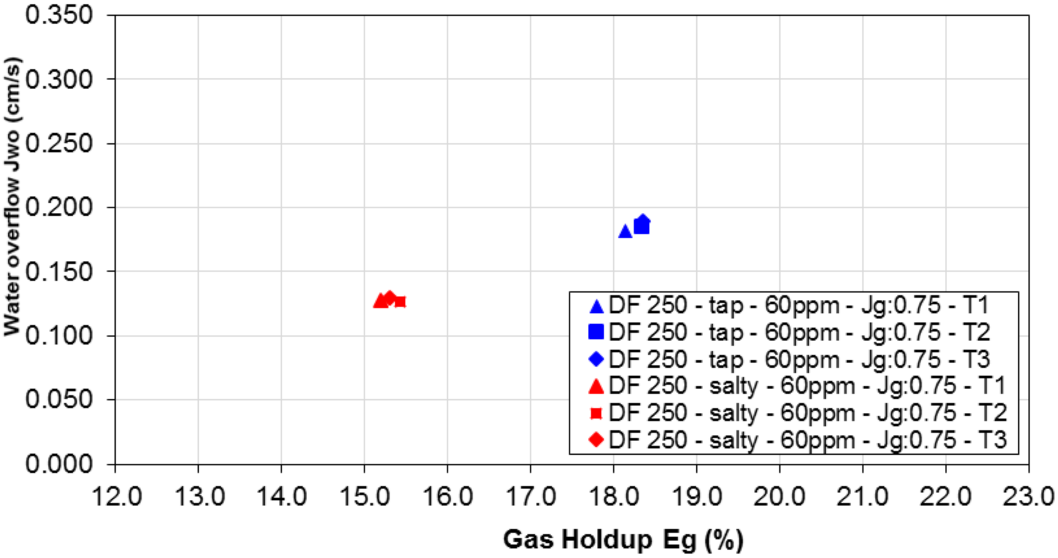

Figure 5.35 Jwo - εg relationship: Repetition tests on DF 250 in tap and synthetic sea water solution. Conditions: DF 250 at 60 ppm, Jg = 0.75 cm/s

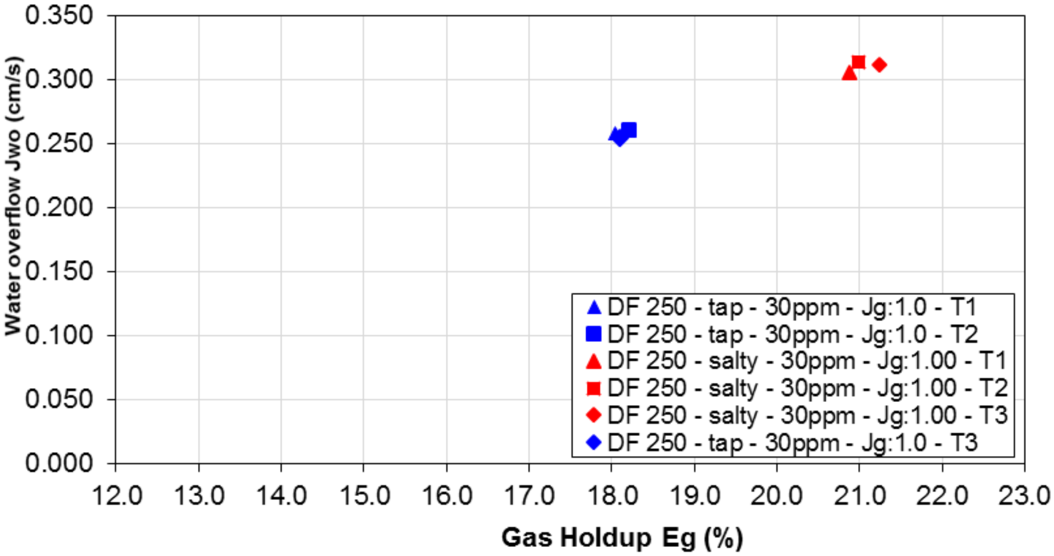

Figure 5.36 Jwo - εg relationship: Repetition tests on DF 250 in tap and synthetic sea water solution. Conditions: DF 250 at 30 ppm, Jg = 1.0 cm/s

5.7.2: Statistical test

In the repetition tests performed, it was intended to statistically test whether the central tendencies (mean or median) of 2 groups of tests (Gas holdup and water carrying rate) were different from each other on the basis of repetitions. Student's t -test for unequal variances was used to make this comparison. Tables 5.3 and 5.4 shown the Student's t-tests for DF250 in tap and salty water solution. The Appendix section includes detailed data of all tests for the group of repetitions of Tables 5.1 and 5.2.

Table 5.3: Student's t -test for Repetition tests - 1

DF 250 - tap - 60ppm - Jg:0.75

t-Test: Two-Sample Assuming Unequal Variances

	Variable 1	*Variable 2*
Mean	18.3	0.186
Variance	0.013041	0.000013
Observations	3	3
Hypothesized Mean Difference	0	
df	2	
t Stat	274.3	
P(T<=t) one-tail	0.0000066	
t Critical one-tail	2.9199856	
P(T<=t) two-tail	0.0000133	
t Critical two-tail	4.3026527	

DF 250 - salty - 60ppm - Jg:0.75

t-Test: Two-Sample Assuming Unequal Variances

	Variable 1	*Variable 2*
Mean	15.3	0.128
Variance	0.0137955	0.0000031
Observations	3	3
Hypothesized Mean Difference	0	
df	2	
t Stat	223.8	
P(T<=t) one-tail	0.0000100	
t Critical one-tail	2.9199856	
P(T<=t) two-tail	0.0000200	
t Critical two-tail	4.3026527	

Table 5.4: Student's t -test for Repetition tests - 2

DF 250 - tap - 30ppm - Jg:1.0

t-Test: Two-Sample Assuming Unequal Variances

	Variable 1	*Variable 2*
Mean	18.1	0.258
Variance	0.007118	0.000011
Observations	3	3
Hypothesized Mean Difference	0	
df	2	
t Stat	366.3	
P(T<=t) one-tail	0.0000037	
t Critical one-tail	2.9199856	
P(T<=t) two-tail	0.0000075	
t Critical two-tail	4.3026527	

DF 250 - salty - 30ppm - Jg:1.00

t-Test: Two-Sample Assuming Unequal Variances

	Variable 1	*Variable 2*
Mean	21.0	0.310
Variance	0.0351361	0.0000195
Observations	3	3
Hypothesized Mean Difference	0	
df	2	
t Stat	191.5	
P(T<=t) one-tail	0.0000136	
t Critical one-tail	2.9199856	
P(T<=t) two-tail	0.0000273	
t Critical two-tail	4.3026527	

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Chapter 6: DISCUSSION OF RESULTS

This chapter explores the possible explanations of the trends observed in Chapters 4 and 5. The points to be discussed include: Effect on bubble coalescence, and Effect on water carrying rate.

6.1: Effect on bubble coalescence

The concept of critical coalescence concentration (CCC) proposed by Cho and Laskowski (2002) is an accepted metric to characterize frothers. From the measured bubble size distribution, the Sauter mean diameter is calculated and plotted as a function of frother concentration. The D_{32}-C curve is characterized by a sharp initial decrease in D_{32} which levels off to reach a minimum which defines the critical coalescence concentration CCC.

Frothers are added in flotation to control bubble size by controlling bubble coalescence. It has been demonstrated that dissolved salts significantly reduce bubble coalescence. The frothers tested to evaluate the CCC values with both tap and synthetic sea water solutions included MIBC, 1-Hexanol, DF250, and PPG425 being the most well characterized of the frothers.

Figures 4.1 to 4.5 show the bubble size versus frother concentration curves of five frothers (DF250, PPG425, MIBC, 1Hexanol and F140) illustrating the bubble coalescence phenomena in both Montreal tap water and synthetic sea water, and the critical coalescence concentration. The results demonstrate that frothers in salty water solutions are more effective in preventing bubble coalescence than in tap water solutions.

Inorganic salts present in the synthetic sea water solution inhibit bubble coalescence as shown in the Figures 4.1 to 4.5. The shape of the curves of frothers in sea water solution were somehow different from those obtained with frothers in tap water solution, where the CCC is usually determined by the graphical interpretation as an intersection of two straight lines. It is also noted that the bubbles generated in synthetic sea water solutions are finer than in tap water solutions.

The figures also show the effect of different frothers concentration on bubble. In all cases, the first top curve shows the effect of the frother on bubble size at increasing concentrations in tap water. In this observation, an interesting effect is shown with synthetic sea water solutions, at low concentrations of frother in synthetic sea water solutions the bubble size slightly tends to increase, but then it is stabilized and decreases again. Thus, the bubble size in synthetic sea water solutions, for other concentrations (30, 60, 100 ppm) of frothers, were similar to those in tap water. These results imply that the size of the primary bubbles generated by a sparging mechanism depends on electrolyte inside of the solution, with similar behaviors for all tested frothers.

Seawater contains 0.55–0.60 M NaCl, and a number of secondary ions, including magnesium, calcium, and sulfate. Sea water is made up of inorganic electrolytes, and is by itself able to prevent bubble coalescence. The blend of frothers and seawater clearly stabilizes bubbles against coalescence (Castro *et al.*, 2010).

It is clear that when the frother concentration is greater than critical coalescence concentration both in tap and sea water solutions, bubbles do not coalesce as the CCC values reported for frothers are in the range of a few ppm, for instance 11 ppm for MIBC which is 0.1 mole/L (Laskowski *et al*., 2003), for sea water solutions CCC values are in the range of 0.78 mole/L (Castro *et al*., 2012a).

In seawater, bubbles are quite stable and frother is not required to stabilize them further. In both cases what is stabilizing bubbles are water molecules bound to the bubbles. In the case of frothers, which molecules adsorb at the gas/liquid interface, some water is bound to the bubbles by hydrogen bonding to the adsorbed frother molecules. In the case of electrolytes, the water layer is formed around bubbles since inorganic ions are surface inactive, they increase water surface tension because they are expelled from the surface layer. Thus, in both cases the difference is the mechanism by which water molecules accumulate around the bubbles (Laskowski *et al.,* 2013)

6.2: Effect on water carrying rate

6.2.1: Water carrying rate and gas holdup

The results confirmed reductions in bubble size and increasing gas holdup, when fresh water was replaced by sea water, as previously reported in the literature (Castro *et al*., 2013). The water overflow rate, associated with stabilizing effects of the froth layer, was higher when frother was added to synthetic sea than to fresh water solutions of glycols and F140. However, in the case of alcohols, the higher overflow rates in sea water was obtained at the lower concentrations, but it was reversed when the concentration was increased.

Figures 5.1 to 5.5 show the comparative behavior of water carrying rate of different frothers in both tap and salty water solutions, so the case the DF 250 probably better represents the comparative behavior, which was fitted and broken down as shown in Figures 6.1 and 6.2. The Figures show that for each frother, water carrying rate is uniquely related to gas holdup; as gas holdup increases water carrying rate increases linearly in both tap and sea water solutions. The increase in gas holdup is due to an increase in frother concentration, which concurrently results in an increase in water carrying rate. The extent to which water carrying rate increases with gas holdup is, however, dependent on frother type.

The J_{wo} - ε_g relationship was treated as linear and showed essentially the same slope for each frother in salty and fresh water solution. The amplitudes of the lines for frother in salty water solution were lower than lines for frother in fresh water solution, this is especially clear with glycols DF250 and PPG425 as can be shown in Figure 6.1.

Likewise, it can be seen in Figure 6.2 that water carrying rate for DF 250 in salty water solution are higher than same frother in fresh water solution for most of concentrations. There is an concentration generating an gas holdup where the water carrying rate in fresh waters solution switch, and overpass to those in salty water solution.

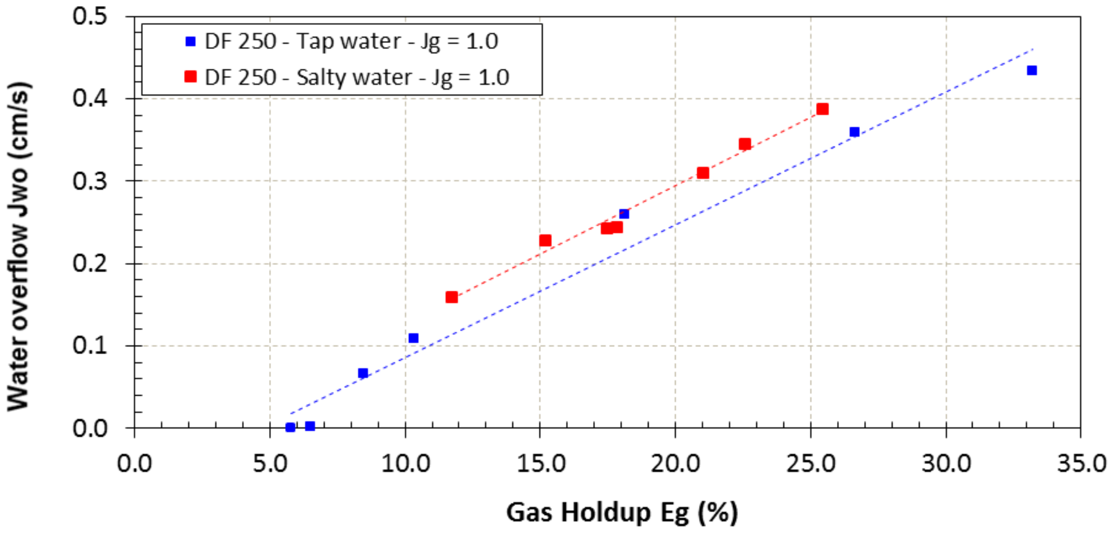

Figure 6.1 Water carrying rate as a function of gas holdup for DF250 in both tap and synthetic sea water solution

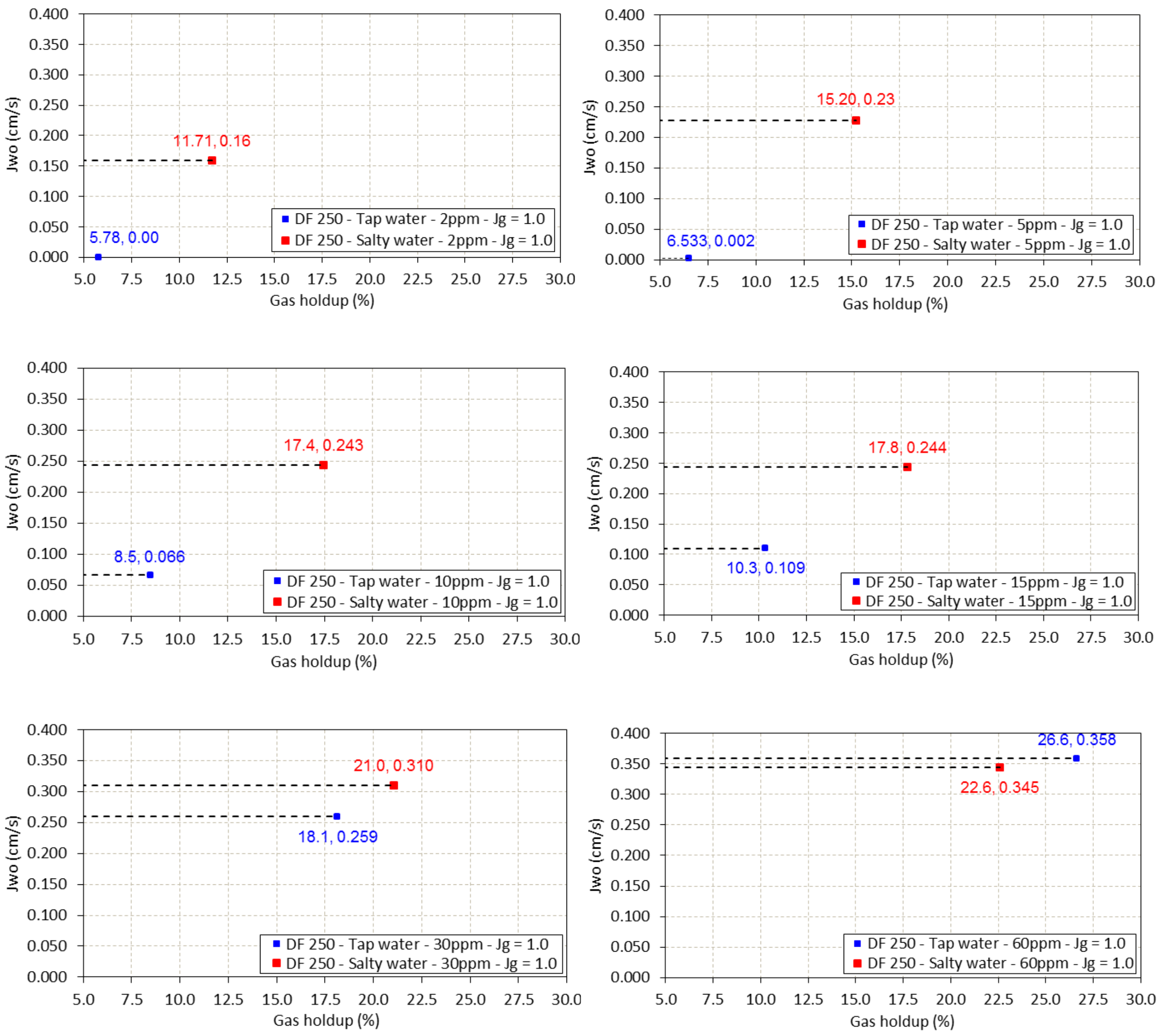

Figure 6.2 J_{wo} vs ε_g - Comparison for points of Figure 6.1

The frothers tested (pure glycols, alcohols and a commercial blend) showed that even in fresh and sea water solutions, they behave as per their chemical families: glycols, alcohols, and mixed alcohols-heavy aldehydes-esters. The behavior fits the qualitative assessment that alcohols transport less water than glycols. The DF250 and PPG425 behave similar showing the impact of salt on the water carrying rate. In the case of DF250, this behavior is observed until the frother concentration reaches greater than 50 ppm.

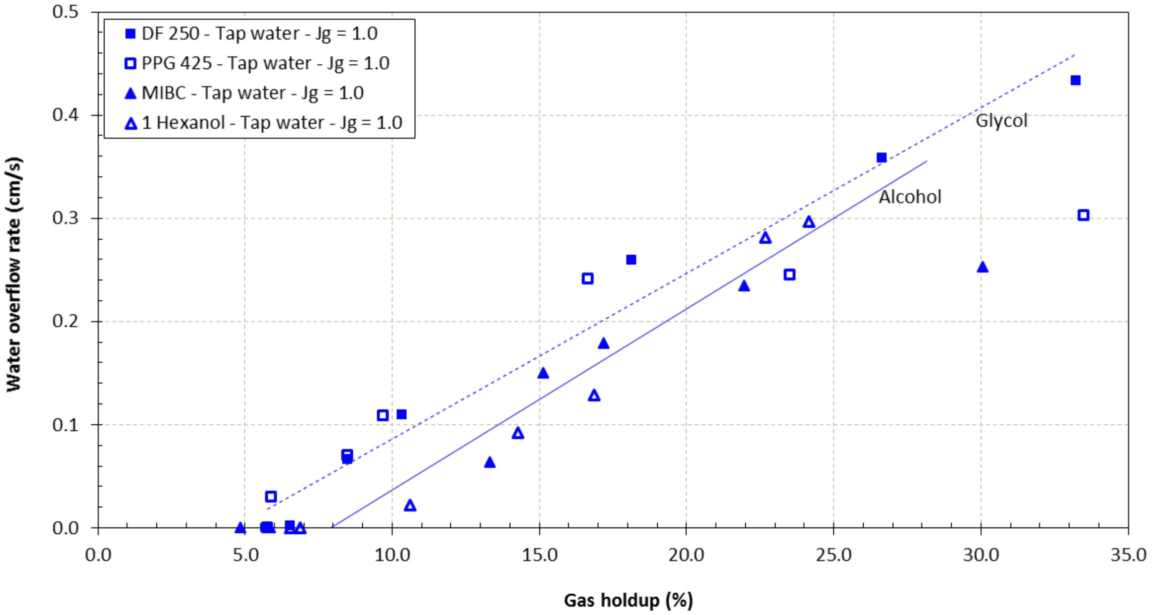

Figure 6.3 Water carrying rate as a function of gas holdup for tested alcohol and glycol frothers in fresh water solution

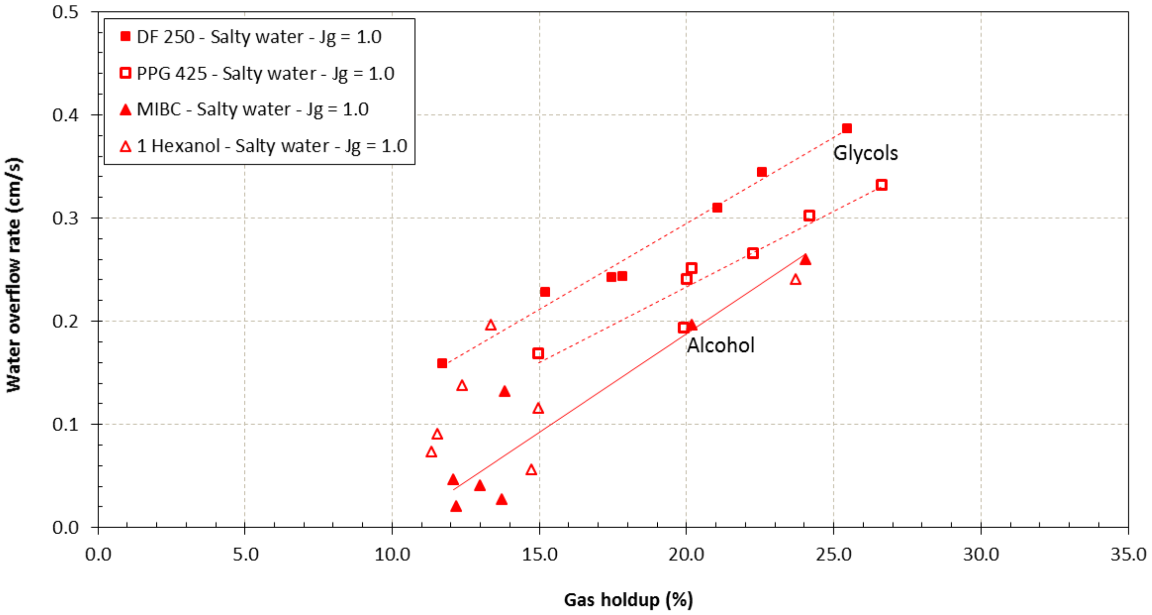

Figure 6.4 Water carrying rate as a function of gas holdup for tested alcohol and glycol frothers in synthetic sea water solution

According to Figures 5.30 to 5.34, which show the gas holdup as a function of frother concentration for the different tested frothers in both fresh and tap water solution, gas holdup increases with frother concentration for all frothers in tap water solution, a similar characteristic can be seen for frohers in synthetic water solution (glycols and F140) and showed different behavior and significant differences in case of alcohol frothers (MIBC and 1 hexanol). In general, the gas holdup was higher for frothers in synthetic sea water solutions compared to measured ε_g for frothers in tap water solutions, for most of the frother concentrations. The gas holdup variations for frothers in tap water solutions were steady and followed the expected trend. This was not the case for MIBC and 1 hexanol in salty water solutions which showed unexpected decreases at frother concentrations over 2 ppm, respectively.

Among the tested alcohols, both the MIBC and 1-hexanol, gave a similar response. The MIBC and 1 hexanol behave similar, showing that effect of salt improve the water carrying rate only at low concentrations (2 and 5 ppm). For the other concentrations, alcohols in fresh water solution have higher water overflow rate. This suggests that as far as the water carrying rate is concerned, the number of carbons in the structure is important but not whether the chain is branched (Moyo *et al.,* 2007)

From Figure 6.1, the amplitude range of the red lines (frothers in synthetic sea water solution) is diminished respect of blue lines (frothers in tap water solution) as frother concentration is increased. For instance, at low frother concentrations and up to 45 ppm, the water carrying rate of DF250 in synthetic sea water solutions is higher than same frother in tap water solution. This indicates us that at a constant superficial gas velocity, the frother concentration is critical to defining water carrying rate in synthetic sea water solutions.

The relationship between water overflow rate and gas holdup was considered as linear; for every frother, lines with the same slope were obtained in fresh and salty water solution, with the later above the former. Therefore, lower concentration of frother were necessary for the same water overflow rate for synthetic sea water solutions. Also, it can be seen that water carrying rate in synthetic salty water solution are higher than in fresh water solution for most of concentrations. There is an concentration generating an gas holdup where the water carrying rate in fresh waters solution switch, and overpass to those in salty water solution.

From Figure 6.5, it can be seen that there is a range of frother concentration where water overflow rate is higher for synthetic sea water solution than for tap water solution (2 -30 ppm in case of glycols DF250 and PP425, and 15 ppm in case of commercial F140). A correlation between water carrying rate and frothers concentration for alcohols MIBC and 1 hexanol could not be established.

The water overflow rate is higher when glycols (PPG425, and DF250) and F140 are added to sea than to fresh water solutions. In the case of alcohols (MIBC, and 1-hexanol), the higher overflow rates in sea water was obtained at low concentrations, but it was reversed when the concentration was increased.

Finally, several practical interpretations can be determined from the Figure 6.5. The type of frother and concentration are important parameters to consider when sea water is used in a flotation system. Volume of water carried to the froth zone, which is related to stability, depends on the unit flotation stage (i.e., rougher or cleaner). Frother selection is a critical component in the strategy to operate cells and circuits.

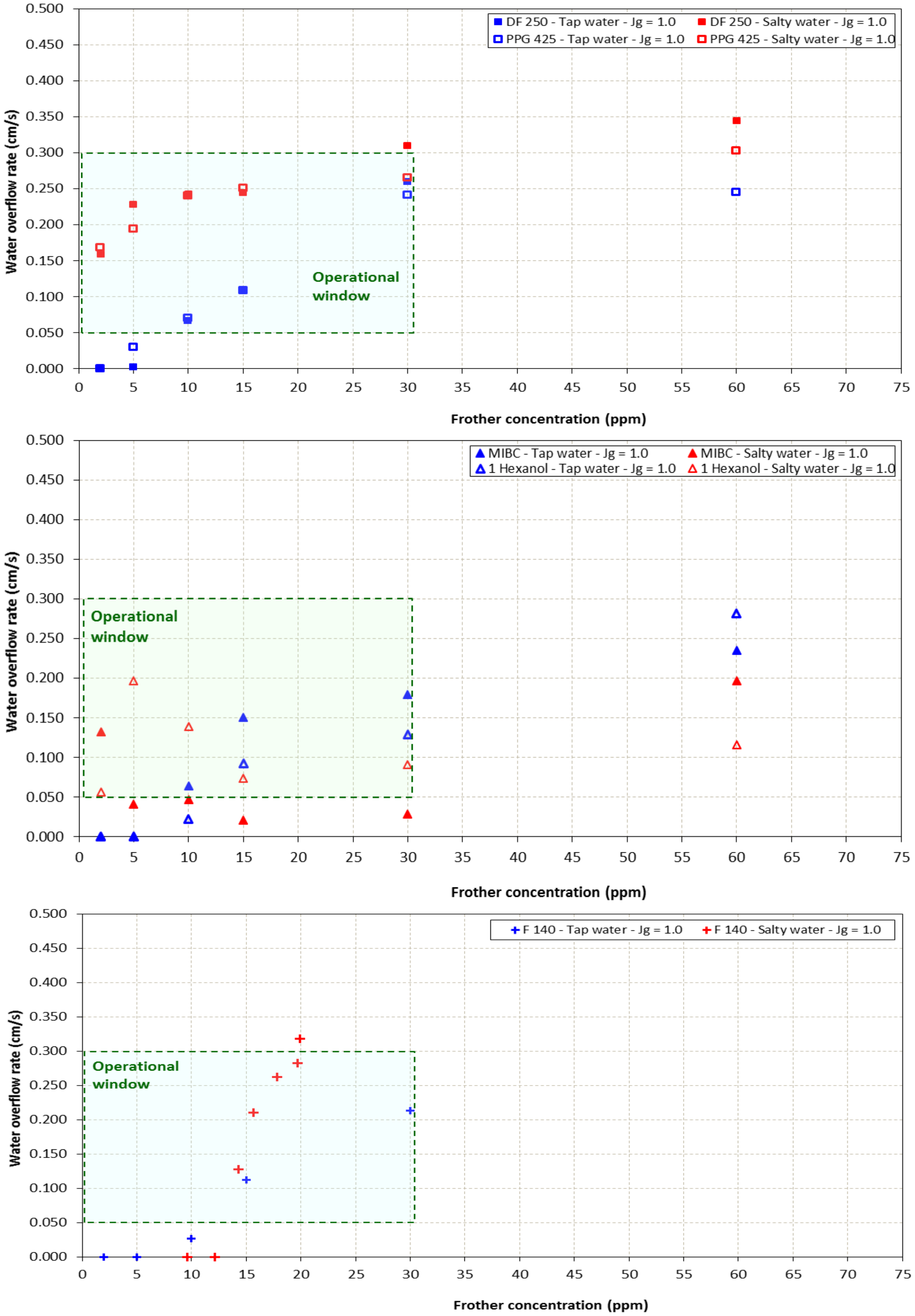

Figure 6.5 Water carrying rate as a function of frother concentration (by families)

6.3: References

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Chapter 7: CONCLUSIONS AND RECOMMENDATIONS

7.1: Conclusions

The following conclusions can be drawn from the results obtained in continuous tests using a laboratory flotation column operated with frother solutions prepared in fresh and synthetic sea waters:

1. The measurement of bubble size, gas holdup and water carrying rate as a function of frother concentration was reliable and reproducible. The result of repeat tests indicated that relative errors for the three parameters were less than 5% for a 95% C.I., with averages of 2.5% and 2.0% for gas holdup and water overflow rate, respectively. The central tendencies (mean or median), of the gas holdup and water carrying rate repetitions, were not different from each other.

2. The results demonstrated that bubble coalescence was completely eliminated for a synthetic sea water solution with no frother added. CCC curves (bubble size vs. frother concentration) showed that the typical exponential decrease at increasing low concentrations was not obtained for synthetic water solutions. No effect of frother concentration on bubble size was observed in the case of synthetic sea water solutions.

3. The relationship between water overflow rate and gas holdup, considered as linear, showed similar slopes in fresh and synthetic sea water solution for frother concentrations below 30 ppm. Higher water overflow rates were obtained, for the same gas holdup, for synthetic sea water solutions. As the frother concentration increases, the water overflow rates in fresh and synthetic sea water solutions become about the same.

4. It was shown that there is a clear relationship between the water overflow rate and frother concentration, in the case of the glycols (DF250 and PPG425) and the commercial frother (F140) samples. This relationship could not be established for alcohols (MIBC and 1-hexanol).

5. The type of frother and concentration in a circuit are important parameters to consider when sea water is used. Frother selection becomes a critical component in the strategy to operate cells and circuits, as different rates of water carried to the

froth zone are necessary, depending on the location of the cell in the circuit (high for rougher and low for cleaner cells, respectively).

7.2: Future Work

To further understand the influence of sea water on the frother roles, the following recommendations are made:

1. It would be very interesting in seeing the difference in the water carrying rate between salt water with no frother but with a CCC at minimum and what happens with water carrying rate as frother dosage is increased but maintaining the bubble size the same. This is the key between seeing the difference in bubble reduction uses ions and bubble reduction using frothers.
2. The effect of solids must be investigated. This includes:

   Fine hydrophilic material – entrainment

   Size distribution of hydrophobic material to analyze froth stability.

   The synergy between frothers and collectors should be investigated further
3. Test quality of water. It will be interesting to further investigate how the quality of water influences the water carrying rate of frother, e.g., the role of dissolved salts, as in concentrator recycled water compared to the tap water.
4. It is suggested to conduct a study to investigate effect of solids on frother properties, to identify solid types that alter gas holdup and / or bubble size.

Appendix A:

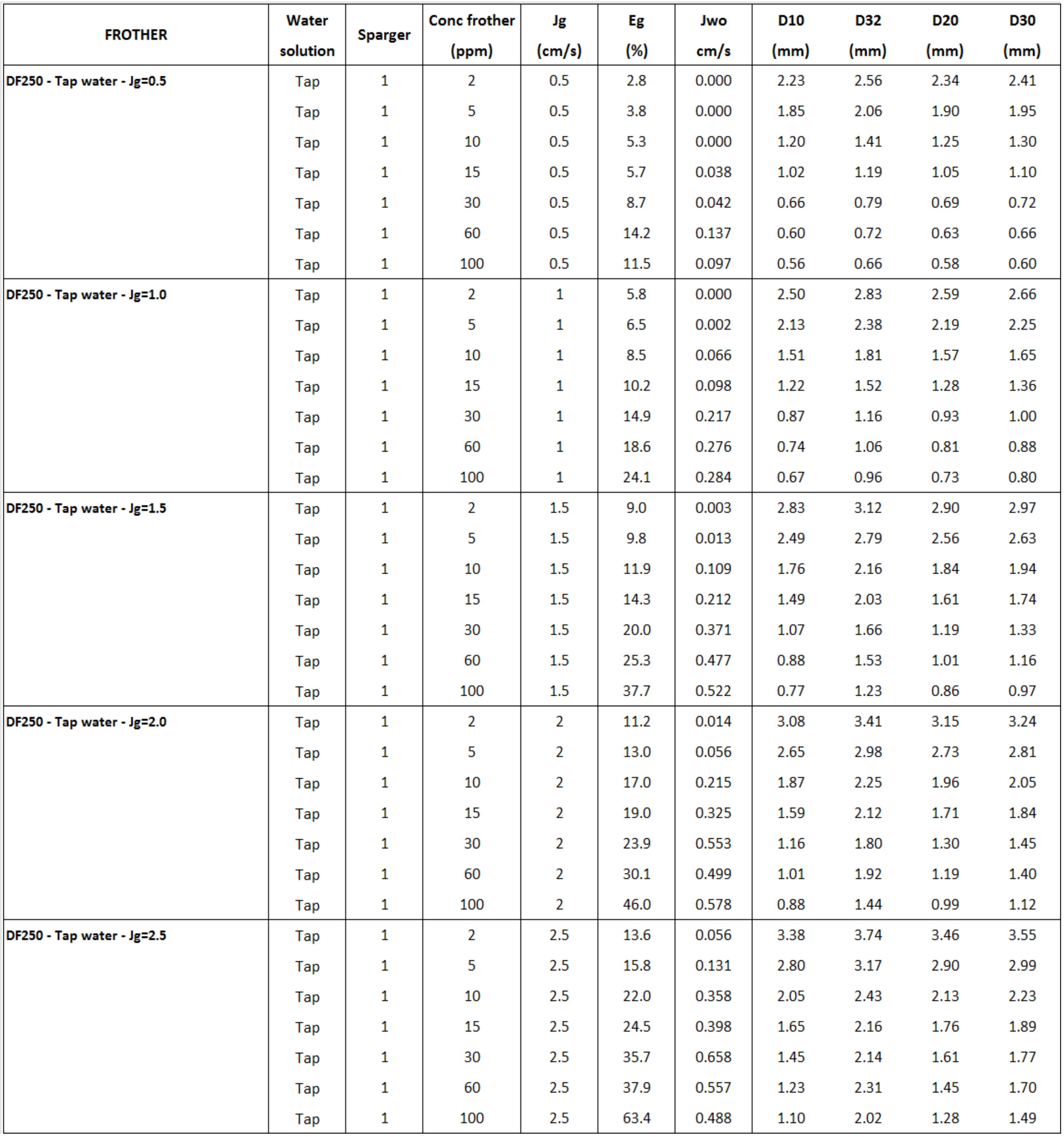
A.1: ALL FROTHER RAW DATA AT Jg:1.0 cm/s – TAP WATER

FROTHER	Water solution	Sparger	Conc frother (ppm)	Jg (cm/s)	Q (L/M)	Eg (%)	W (L/M)	Jwo cm/s	D10 (mm)	D32 (mm)	D20 (mm)	D30 (mm)
DF 250 - Tap water - Jg = 1.0	Tap	1	0	1.00	4.87	4.5	0.000	0.000	3.71	5.26	4.24	4.55
	Tap	1	2	1.00	4.87	5.8	0.000	0.000	2.50	2.83	2.59	2.66
	Tap	1	5	1.00	4.87	6.5	0.011	0.002	2.13	2.38	2.19	2.25
	Tap	1	10	1.00	4.87	8.5	0.310	0.066	1.51	1.81	1.57	1.65
	Tap	1	15	1.00	4.87	10.3	0.516	0.109	1.22	1.52	1.28	1.36
	Tap	1	30	1.00	4.87	18.1	1.222	0.259	0.87	1.16	0.93	1.00
	Tap	1	60	1.00	4.87	26.6	1.689	0.358	0.74	1.06	0.81	0.88
	Tap	1	100	1.00	4.87	33.2	2.042	0.433	0.67	0.96	0.73	0.80
MIBC - Tap water - Jg = 1.0	Tap	1	0	1.0	4.87	4.5	0.000	0.000	3.71	5.26	4.24	4.55
	Tap	1	2	1.0	4.87	4.9	0.000	0.000	2.99	3.34	3.08	3.16
	Tap	1	5	1.0	4.87	5.9	0.000	0.000	1.81	2.08	1.87	1.93
	Tap	1	10	1.0	4.87	13.3	0.300	0.064	0.91	1.15	0.96	1.02
	Tap	1	15	1.0	4.87	15.1	0.706	0.150	0.82	0.99	0.86	0.90
	Tap	1	30	1.0	4.87	17.2	0.846	0.180	0.81	0.98	0.84	0.89
	Tap	1	60	1.0	4.87	21.9	1.106	0.235	0.73	0.87	0.76	0.79
	Tap	1	100	1.0	4.87	30.1	1.192	0.253	0.70	0.83	0.73	0.76
1 Hexanol - Tap water - Jg = 1.0	Tap	1	0	1.0	4.87	4.5	0.000	0.000	3.71	5.26	4.24	4.55
	Tap	1	2	1.0	4.87	6.5	0.000	0.000	3.32	3.67	3.41	3.50
	Tap	1	5	1.0	4.87	6.9	0.000	0.000	2.16	2.53	2.25	2.34
	Tap	1	10	1.0	4.87	10.6	0.102	0.022	0.86	1.03	0.90	0.94
	Tap	1	15	1.0	4.87	14.3	0.433	0.092	0.82	1.00	0.86	0.90
	Tap	1	30	1.0	4.87	16.9	0.606	0.129	0.79	0.92	0.82	0.85
	Tap	1	60	1.0	4.87	22.7	1.325	0.281	0.84	1.15	0.90	0.97
	Tap	1	100	1.0	4.87	24.2	1.400	0.297	0.68	0.82	0.71	0.74
PPG 425 - Tap water - Jg = 1.0	Tap	1	0	1.0	4.87	4.5	0.000	0.000	3.71	5.26	4.24	4.55
	Tap	1	2	1.0	4.87	5.7	0.000	0.000	2.55	2.94	2.67	2.76
	Tap	1	5	1.0	4.87	5.9	0.139	0.030	2.01	2.28	2.07	2.14
	Tap	1	10	1.0	4.87	8.5	0.331	0.070	1.45	1.80	1.52	1.60
	Tap	1	15	1.0	4.87	9.7	0.514	0.109	1.19	1.45	1.24	1.31
	Tap	1	30	1.0	4.87	16.7	1.135	0.241	0.79	1.05	0.85	0.91
	Tap	1	60	1.0	4.87	23.5	1.153	0.245	0.68	0.82	0.71	0.75
	Tap	1	100	1.0	4.87	33.5	1.425	0.302	0.66	0.79	0.69	0.72
F 140 - Tap water - Jg = 1.0	Tap	1	0	1.0	4.87	4.5	0.000	0.000	3.71	5.26	4.24	4.55
	Tap	1	2	1.0	4.87	6.8	0.000	0.000	2.64	3.83	3.04	3.28
	Tap	1	5	1.0	4.87	7.5	0.000	0.000	2.33	2.79	2.44	2.55
	Tap	1	10	1.0	4.87	9.0	0.125	0.027	1.49	1.83	1.57	1.65
	Tap	1	15	1.0	4.87	11.1	0.528	0.112	1.19	1.50	1.26	1.33
	Tap	1	30	1.0	4.87	16.6	1.006	0.214	0.82	1.06	0.87	0.93
	Tap	1	60	1.0	4.87	25.6	1.125	0.239	0.70	0.88	0.74	0.78
	Tap	1	100	1.0	4.87	27.5	1.469	0.312	0.66	0.87	0.70	0.76

A.2: ALL FROTHER RAW DATA AT Jg:1.0 cm/s – SYNTHETIC SEA WATER

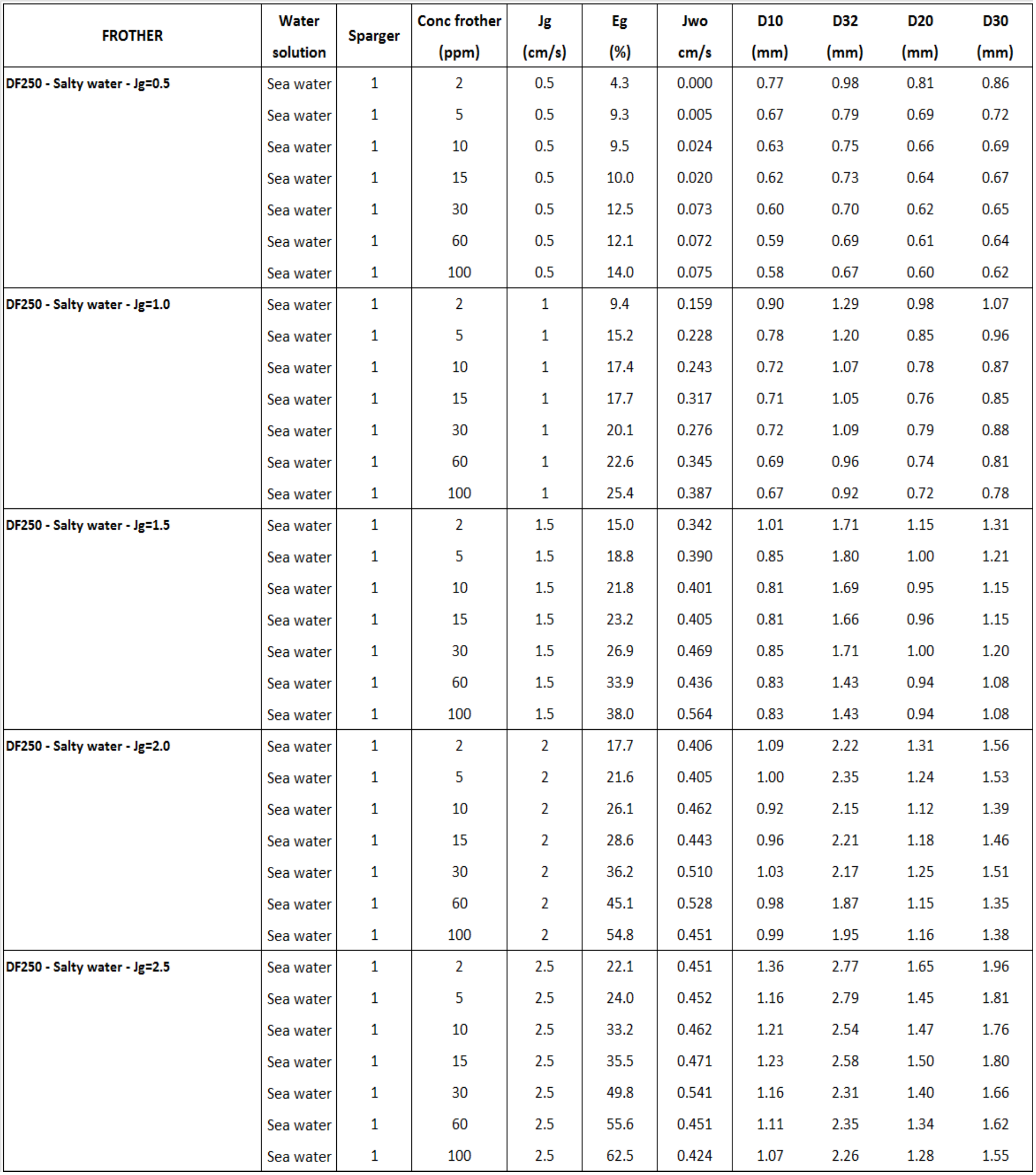
FROTHER	Water solution	Sparger	Conc frother (ppm)	Jg (cm/s)	Q (L/M)	Eg (%)	W (L/M)	Jwo cm/s	D10 (mm)	D32 (mm)	D20 (mm)	D30 (mm)
DF 250 - Salty water - Jg = 1.0	Sea water	1	0	1	4.87	10.7	0.000	0.000	0.71	0.89	0.74	0.79
	Sea water	1	2	1.00	4.87	11.7	0.750	0.159	0.90	1.29	0.98	1.07
	Sea water	1	5	1.00	4.87	15.2	1.075	0.228	0.78	1.20	0.85	0.96
	Sea water	1	10	1.00	4.87	17.4	1.145	0.243	0.72	1.07	0.78	0.87
	Sea water	1	15	1.00	4.87	17.8	1.150	0.244	0.71	1.05	0.76	0.85
	Sea water	1	30	1.00	4.87	21.0	1.461	0.310	0.72	1.09	0.79	0.88
	Sea water	1	60	1.00	4.87	22.6	1.625	0.345	0.69	0.96	0.74	0.81
	Sea water	1	100	1.00	4.87	25.4	1.825	0.387	0.67	0.92	0.72	0.78
MIBC - Salty water - Jg = 1.0	Sea water	1	0	1.0	4.87	10.7	0.000	0.000	0.71	0.89	0.74	0.79
	Sea water	1	2	1.0	4.87	13.8	0.624	0.132	0.81	1.05	0.85	0.91
	Sea water	1	5	1.0	4.87	13.0	0.194	0.041	0.82	1.00	0.85	0.90
	Sea water	1	10	1.0	4.87	12.1	0.220	0.047	0.85	1.07	0.90	0.95
	Sea water	1	15	1.0	4.87	12.2	0.096	0.020	0.91	1.12	0.97	1.03
	Sea water	1	30	1.0	4.87	13.7	0.131	0.028	0.87	1.17	0.93	1.01
	Sea water	1	60	1.0	4.87	20.2	0.926	0.197	0.77	0.94	0.80	0.85
	Sea water	1	100	1.0	4.87	24.0	1.224	0.260	0.73	0.86	0.76	0.81
1 Hexanol - Salty water - Jg = 1.0	Sea water	1	0	1.00	4.87	10.7	0.000	0.000	0.71	0.89	0.74	0.79
	Sea water	1	2	1.00	4.87	14.7	0.267	0.057	0.75	0.92	0.78	0.82
	Sea water	1	5	1.00	4.87	13.3	0.928	0.197	0.85	1.05	0.89	0.94
	Sea water	1	10	1.00	4.87	12.4	0.653	0.138	0.91	1.17	0.96	1.03
	Sea water	1	15	1.00	4.87	11.3	0.348	0.074	0.92	1.21	0.98	1.05
	Sea water	1	30	1.00	4.87	11.5	0.428	0.091	0.92	1.23	0.98	1.06
	Sea water	1	60	1.00	4.87	15.0	0.547	0.116	0.81	1.06	0.86	0.92
	Sea water	1	100	1.00	4.87	23.7	1.134	0.241	0.69	0.87	0.73	0.77
PPG 425 - Salty water - Jg = 1.0	Sea water	1	0	1.0	4.87	10.7	0.000	0.000	0.71	0.89	0.74	0.79
	Sea water	1	2	1.0	4.87	15.0	0.791	0.168	0.78	1.05	0.83	0.90
	Sea water	1	5	1.0	4.87	19.9	0.913	0.194	0.69	0.85	0.72	0.76
	Sea water	1	10	1.0	4.87	20.0	1.131	0.240	0.68	0.92	0.73	0.79
	Sea water	1	15	1.0	4.87	20.2	1.184	0.251	0.66	0.92	0.70	0.77
	Sea water	1	30	1.0	4.87	22.3	1.250	0.265	0.68	1.05	0.74	0.83
	Sea water	1	60	1.0	4.87	24.2	1.425	0.302	0.66	0.97	0.72	0.80
	Sea water	1	100	1.0	4.87	26.6	1.563	0.332	0.67	0.91	0.72	0.78
F 140 - Salty water - Jg = 1.0	Sea water	1	0	1.0	4.87	10.7	0.000	0.000	0.71	0.89	0.74	0.79
	Sea water	1	2	1.0	4.87	9.6	0.000	0.000	1.12	1.84	1.26	1.43
	Sea water	1	5	1.0	4.87	12.1	0.000	0.000	0.87	1.51	0.98	1.13
	Sea water	1	10	1.0	4.87	14.3	0.602	0.128	0.74	1.20	0.81	0.93
	Sea water	1	15	1.0	4.87	15.7	0.991	0.210	0.72	1.11	0.79	0.88
	Sea water	1	30	1.0	4.87	17.8	1.237	0.262	0.72	1.03	0.77	0.85
	Sea water	1	60	1.0	4.87	19.7	1.331	0.283	0.69	1.00	0.74	0.82
	Sea water	1	100	1.0	4.87	19.9	1.500	0.318	0.65	1.01	0.71	0.80

A.3: DF250 DATA AT DIFFERENT Jg – TAP WATER



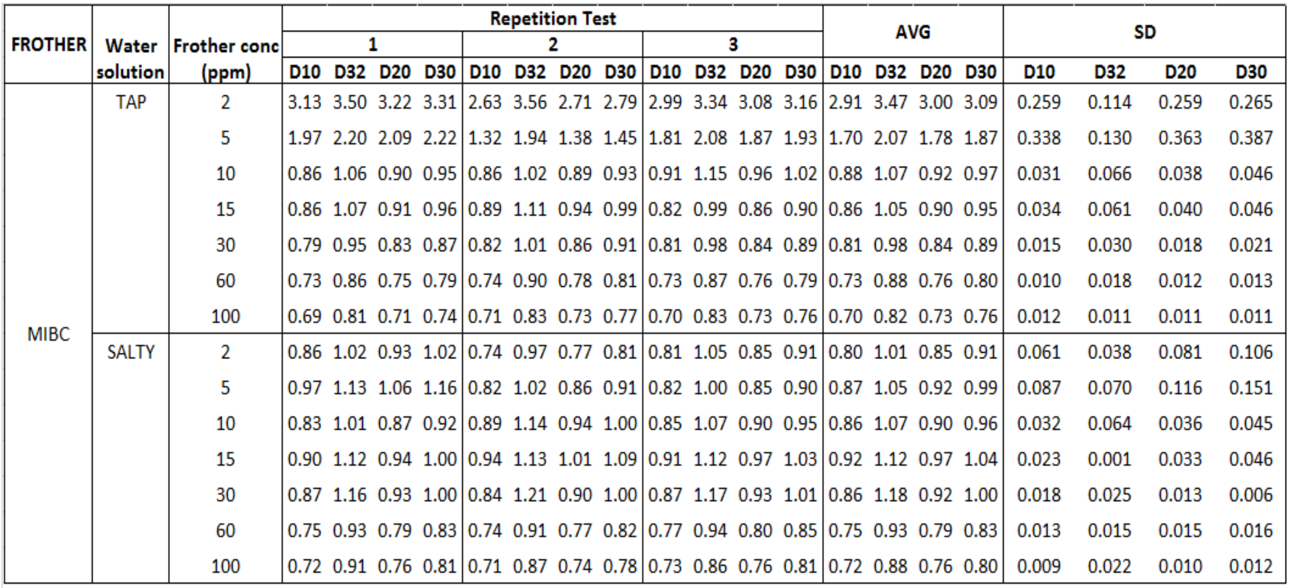
FROTHER	Water solution	Sparger	Conc frother (ppm)	Jg (cm/s)	Eg (%)	Jwo cm/s	D10 (mm)	D32 (mm)	D20 (mm)	D30 (mm)
DF250 - Tap water - Jg=0.5	Tap	1	2	0.5	2.8	0.000	2.23	2.56	2.34	2.41
	Tap	1	5	0.5	3.8	0.000	1.85	2.06	1.90	1.95
	Tap	1	10	0.5	5.3	0.000	1.20	1.41	1.25	1.30
	Tap	1	15	0.5	5.7	0.038	1.02	1.19	1.05	1.10
	Tap	1	30	0.5	8.7	0.042	0.66	0.79	0.69	0.72
	Tap	1	60	0.5	14.2	0.137	0.60	0.72	0.63	0.66
	Tap	1	100	0.5	11.5	0.097	0.56	0.66	0.58	0.60
DF250 - Tap water - Jg=1.0	Tap	1	2	1	5.8	0.000	2.50	2.83	2.59	2.66
	Tap	1	5	1	6.5	0.002	2.13	2.38	2.19	2.25
	Tap	1	10	1	8.5	0.066	1.51	1.81	1.57	1.65
	Tap	1	15	1	10.2	0.098	1.22	1.52	1.28	1.36
	Tap	1	30	1	14.9	0.217	0.87	1.16	0.93	1.00
	Tap	1	60	1	18.6	0.276	0.74	1.06	0.81	0.88
	Tap	1	100	1	24.1	0.284	0.67	0.96	0.73	0.80
DF250 - Tap water - Jg=1.5	Tap	1	2	1.5	9.0	0.003	2.83	3.12	2.90	2.97
	Tap	1	5	1.5	9.8	0.013	2.49	2.79	2.56	2.63
	Tap	1	10	1.5	11.9	0.109	1.76	2.16	1.84	1.94
	Tap	1	15	1.5	14.3	0.212	1.49	2.03	1.61	1.74
	Tap	1	30	1.5	20.0	0.371	1.07	1.66	1.19	1.33
	Tap	1	60	1.5	25.3	0.477	0.88	1.53	1.01	1.16
	Tap	1	100	1.5	37.7	0.522	0.77	1.23	0.86	0.97
DF250 - Tap water - Jg=2.0	Tap	1	2	2	11.2	0.014	3.08	3.41	3.15	3.24
	Tap	1	5	2	13.0	0.056	2.65	2.98	2.73	2.81
	Tap	1	10	2	17.0	0.215	1.87	2.25	1.96	2.05
	Tap	1	15	2	19.0	0.325	1.59	2.12	1.71	1.84
	Tap	1	30	2	23.9	0.553	1.16	1.80	1.30	1.45
	Tap	1	60	2	30.1	0.499	1.01	1.92	1.19	1.40
	Tap	1	100	2	46.0	0.578	0.88	1.44	0.99	1.12
DF250 - Tap water - Jg=2.5	Tap	1	2	2.5	13.6	0.056	3.38	3.74	3.46	3.55
	Tap	1	5	2.5	15.8	0.131	2.80	3.17	2.90	2.99
	Tap	1	10	2.5	22.0	0.358	2.05	2.43	2.13	2.23
	Tap	1	15	2.5	24.5	0.398	1.65	2.16	1.76	1.89
	Tap	1	30	2.5	35.7	0.658	1.45	2.14	1.61	1.77
	Tap	1	60	2.5	37.9	0.557	1.23	2.31	1.45	1.70
	Tap	1	100	2.5	63.4	0.488	1.10	2.02	1.28	1.49

A.4: DF250 DATA AT DIFFERENT Jg - SYNTHETIC SEA WATER

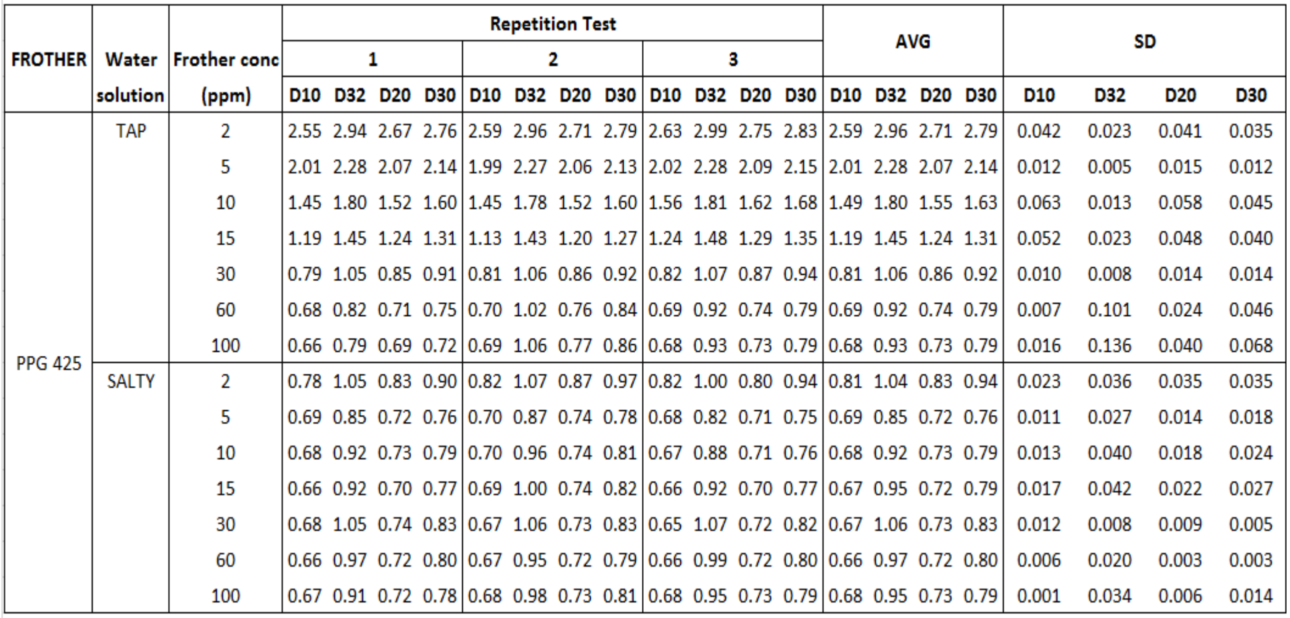


FROTHER	Water solution	Sparger	Conc frother (ppm)	Jg (cm/s)	Eg (%)	Jwo cm/s	D10 (mm)	D32 (mm)	D20 (mm)	D30 (mm)
DF250 - Salty water - Jg=0.5	Sea water	1	2	0.5	4.3	0.000	0.77	0.98	0.81	0.86
	Sea water	1	5	0.5	9.3	0.005	0.67	0.79	0.69	0.72
	Sea water	1	10	0.5	9.5	0.024	0.63	0.75	0.66	0.69
	Sea water	1	15	0.5	10.0	0.020	0.62	0.73	0.64	0.67
	Sea water	1	30	0.5	12.5	0.073	0.60	0.70	0.62	0.65
	Sea water	1	60	0.5	12.1	0.072	0.59	0.69	0.61	0.64
	Sea water	1	100	0.5	14.0	0.075	0.58	0.67	0.60	0.62
DF250 - Salty water - Jg=1.0	Sea water	1	2	1	9.4	0.159	0.90	1.29	0.98	1.07
	Sea water	1	5	1	15.2	0.228	0.78	1.20	0.85	0.96
	Sea water	1	10	1	17.4	0.243	0.72	1.07	0.78	0.87
	Sea water	1	15	1	17.7	0.317	0.71	1.05	0.76	0.85
	Sea water	1	30	1	20.1	0.276	0.72	1.09	0.79	0.88
	Sea water	1	60	1	22.6	0.345	0.69	0.96	0.74	0.81
	Sea water	1	100	1	25.4	0.387	0.67	0.92	0.72	0.78
DF250 - Salty water - Jg=1.5	Sea water	1	2	1.5	15.0	0.342	1.01	1.71	1.15	1.31
	Sea water	1	5	1.5	18.8	0.390	0.85	1.80	1.00	1.21
	Sea water	1	10	1.5	21.8	0.401	0.81	1.69	0.95	1.15
	Sea water	1	15	1.5	23.2	0.405	0.81	1.66	0.96	1.15
	Sea water	1	30	1.5	26.9	0.469	0.85	1.71	1.00	1.20
	Sea water	1	60	1.5	33.9	0.436	0.83	1.43	0.94	1.08
	Sea water	1	100	1.5	38.0	0.564	0.83	1.43	0.94	1.08
DF250 - Salty water - Jg=2.0	Sea water	1	2	2	17.7	0.406	1.09	2.22	1.31	1.56
	Sea water	1	5	2	21.6	0.405	1.00	2.35	1.24	1.53
	Sea water	1	10	2	26.1	0.462	0.92	2.15	1.12	1.39
	Sea water	1	15	2	28.6	0.443	0.96	2.21	1.18	1.46
	Sea water	1	30	2	36.2	0.510	1.03	2.17	1.25	1.51
	Sea water	1	60	2	45.1	0.528	0.98	1.87	1.15	1.35
	Sea water	1	100	2	54.8	0.451	0.99	1.95	1.16	1.38
DF250 - Salty water - Jg=2.5	Sea water	1	2	2.5	22.1	0.451	1.36	2.77	1.65	1.96
	Sea water	1	5	2.5	24.0	0.452	1.16	2.79	1.45	1.81
	Sea water	1	10	2.5	33.2	0.462	1.21	2.54	1.47	1.76
	Sea water	1	15	2.5	35.5	0.471	1.23	2.58	1.50	1.80
	Sea water	1	30	2.5	49.8	0.541	1.16	2.31	1.40	1.66
	Sea water	1	60	2.5	55.6	0.451	1.11	2.35	1.34	1.62
	Sea water	1	100	2.5	62.5	0.424	1.07	2.26	1.28	1.55

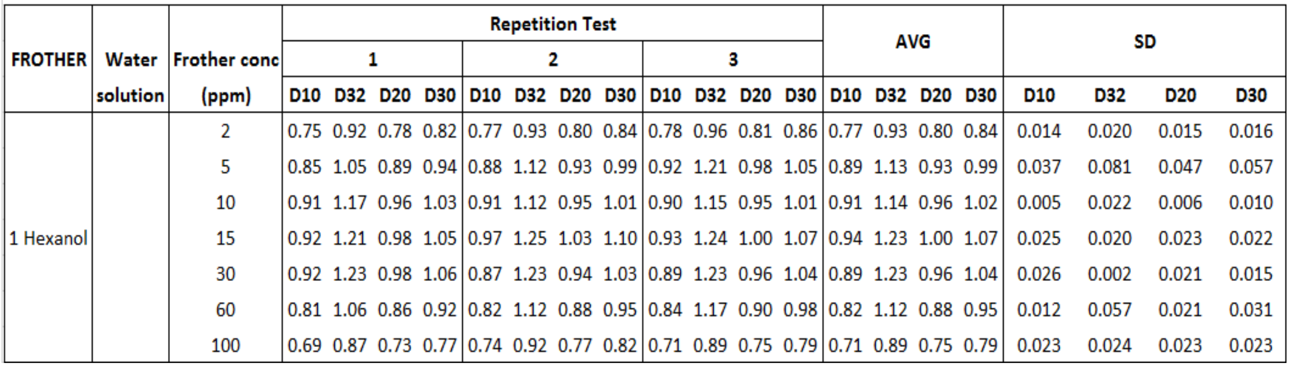
A.5: REPETITION TESTS FOR BUBBLE SIZE DETERMINATION



FROTHER	Water solution	Frother conc (ppm)	Repetition Test												AVG				SD			
			1				2				3											
			D10	D32	D20	D30	D10	D32	D20	D30	D10	D32	D20	D30	D10	D32	D20	D30	D10	D32	D20	D30
MIBC	TAP	2	3.13	3.50	3.22	3.31	2.63	3.56	2.71	2.79	2.99	3.34	3.08	3.16	2.91	3.47	3.00	3.09	0.259	0.114	0.259	0.265
		5	1.97	2.20	2.09	2.22	1.32	1.94	1.38	1.45	1.81	2.08	1.87	1.93	1.70	2.07	1.78	1.87	0.338	0.130	0.363	0.387
		10	0.86	1.06	0.90	0.95	0.86	1.02	0.89	0.93	0.91	1.15	0.96	1.02	0.88	1.07	0.92	0.97	0.031	0.066	0.038	0.046
		15	0.86	1.07	0.91	0.96	0.89	1.11	0.94	0.99	0.82	0.99	0.86	0.90	0.86	1.05	0.90	0.95	0.034	0.061	0.040	0.046
		30	0.79	0.95	0.83	0.87	0.82	1.01	0.86	0.91	0.81	0.98	0.84	0.89	0.81	0.98	0.84	0.89	0.015	0.030	0.018	0.021
		60	0.73	0.86	0.75	0.79	0.74	0.90	0.78	0.81	0.73	0.87	0.76	0.79	0.73	0.88	0.76	0.80	0.010	0.018	0.012	0.013
		100	0.69	0.81	0.71	0.74	0.71	0.83	0.73	0.77	0.70	0.83	0.73	0.76	0.70	0.82	0.73	0.76	0.012	0.011	0.011	0.011
	SALTY	2	0.86	1.02	0.93	1.02	0.74	0.97	0.77	0.81	0.81	1.05	0.85	0.91	0.80	1.01	0.85	0.91	0.061	0.038	0.081	0.106
		5	0.97	1.13	1.06	1.16	0.82	1.02	0.86	0.91	0.82	1.00	0.85	0.90	0.87	1.05	0.92	0.99	0.087	0.070	0.116	0.151
		10	0.83	1.01	0.87	0.92	0.89	1.14	0.94	1.00	0.85	1.07	0.90	0.95	0.86	1.07	0.90	0.96	0.032	0.064	0.036	0.045
		15	0.90	1.12	0.94	1.00	0.94	1.13	1.01	1.09	0.91	1.12	0.97	1.03	0.92	1.12	0.97	1.04	0.023	0.001	0.033	0.046
		30	0.87	1.16	0.93	1.00	0.84	1.21	0.90	1.00	0.87	1.17	0.93	1.01	0.86	1.18	0.92	1.00	0.018	0.025	0.013	0.006
		60	0.75	0.93	0.79	0.83	0.74	0.91	0.77	0.82	0.77	0.94	0.80	0.85	0.75	0.93	0.79	0.83	0.013	0.015	0.015	0.016
		100	0.72	0.91	0.76	0.81	0.71	0.87	0.74	0.78	0.73	0.86	0.76	0.81	0.72	0.88	0.76	0.80	0.009	0.022	0.010	0.012

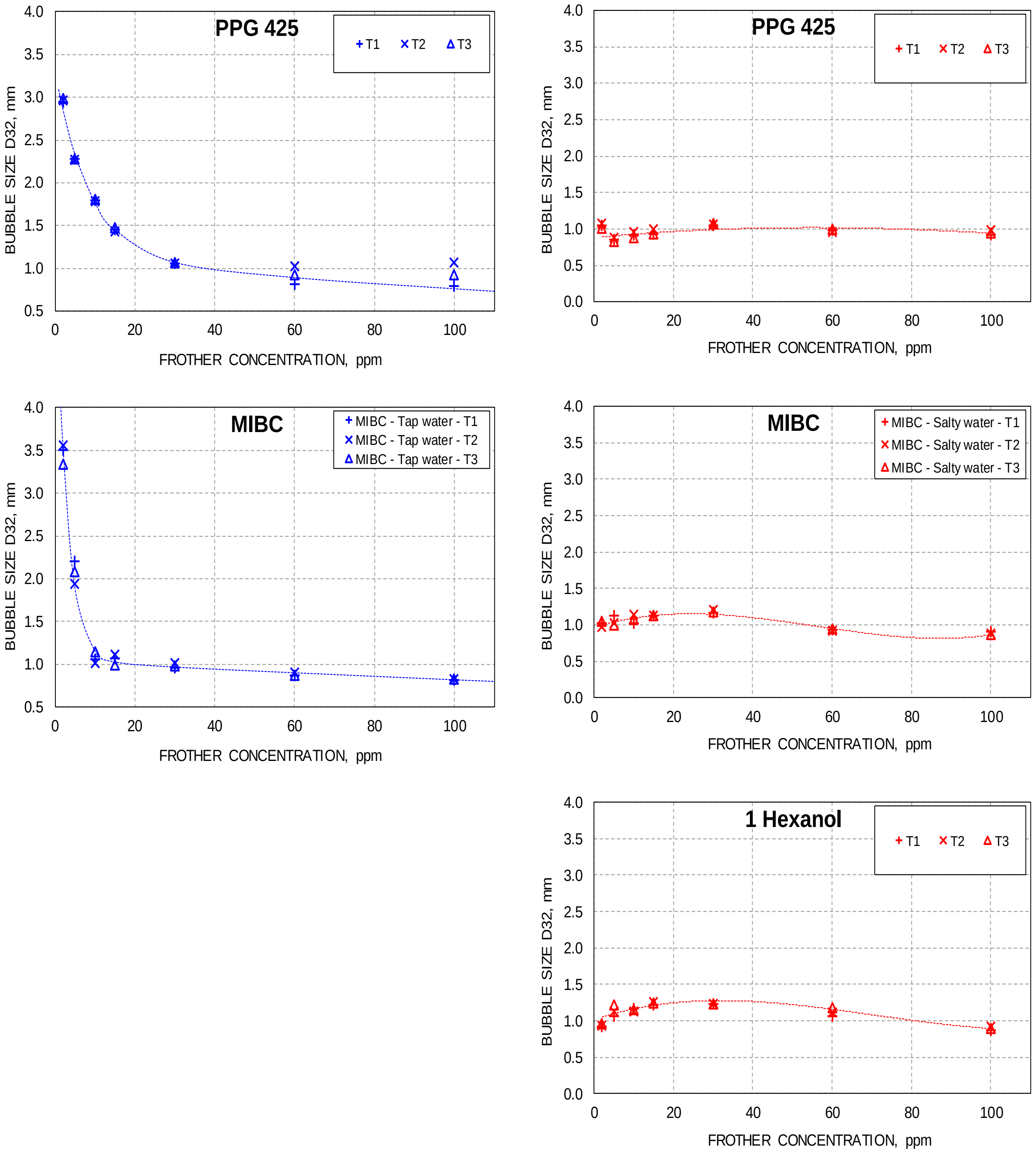


FROTHER	Water solution	Frother conc (ppm)	Repetition Test												AVG				SD			
			1				2				3											
			D10	D32	D20	D30	D10	D32	D20	D30	D10	D32	D20	D30	D10	D32	D20	D30	D10	D32	D20	D30
PPG 425	TAP	2	2.55	2.94	2.67	2.76	2.59	2.96	2.71	2.79	2.63	2.99	2.75	2.83	2.59	2.96	2.71	2.79	0.042	0.023	0.041	0.035
		5	2.01	2.28	2.07	2.14	1.99	2.27	2.06	2.13	2.02	2.28	2.09	2.15	2.01	2.28	2.07	2.14	0.012	0.005	0.015	0.012
		10	1.45	1.80	1.52	1.60	1.45	1.78	1.52	1.60	1.56	1.81	1.62	1.68	1.49	1.80	1.55	1.63	0.063	0.013	0.058	0.045
		15	1.19	1.45	1.24	1.31	1.13	1.43	1.20	1.27	1.24	1.48	1.29	1.35	1.19	1.45	1.24	1.31	0.052	0.023	0.048	0.040
		30	0.79	1.05	0.85	0.91	0.81	1.06	0.86	0.92	0.82	1.07	0.87	0.94	0.81	1.06	0.86	0.92	0.010	0.008	0.014	0.014
		60	0.68	0.82	0.71	0.75	0.70	1.02	0.76	0.84	0.69	0.92	0.74	0.79	0.69	0.92	0.74	0.79	0.007	0.101	0.024	0.046
		100	0.66	0.79	0.69	0.72	0.69	1.06	0.77	0.86	0.68	0.93	0.73	0.79	0.68	0.93	0.73	0.79	0.016	0.136	0.040	0.068
	SALTY	2	0.78	1.05	0.83	0.90	0.82	1.07	0.87	0.97	0.82	1.00	0.80	0.94	0.81	1.04	0.83	0.94	0.023	0.036	0.035	0.035
		5	0.69	0.85	0.72	0.76	0.70	0.87	0.74	0.78	0.68	0.82	0.71	0.75	0.69	0.85	0.72	0.76	0.011	0.027	0.014	0.018
		10	0.68	0.92	0.73	0.79	0.70	0.96	0.74	0.81	0.67	0.88	0.71	0.76	0.68	0.92	0.73	0.79	0.013	0.040	0.018	0.024
		15	0.66	0.92	0.70	0.77	0.69	1.00	0.74	0.82	0.66	0.92	0.70	0.77	0.67	0.95	0.72	0.79	0.017	0.042	0.022	0.027
		30	0.68	1.05	0.74	0.83	0.67	1.06	0.73	0.83	0.65	1.07	0.72	0.82	0.67	1.06	0.73	0.83	0.012	0.008	0.009	0.005
		60	0.66	0.97	0.72	0.80	0.67	0.95	0.72	0.79	0.66	0.99	0.72	0.80	0.66	0.97	0.72	0.80	0.006	0.020	0.003	0.003
		100	0.67	0.91	0.72	0.78	0.68	0.98	0.73	0.81	0.68	0.95	0.73	0.79	0.68	0.95	0.73	0.79	0.001	0.034	0.006	0.014

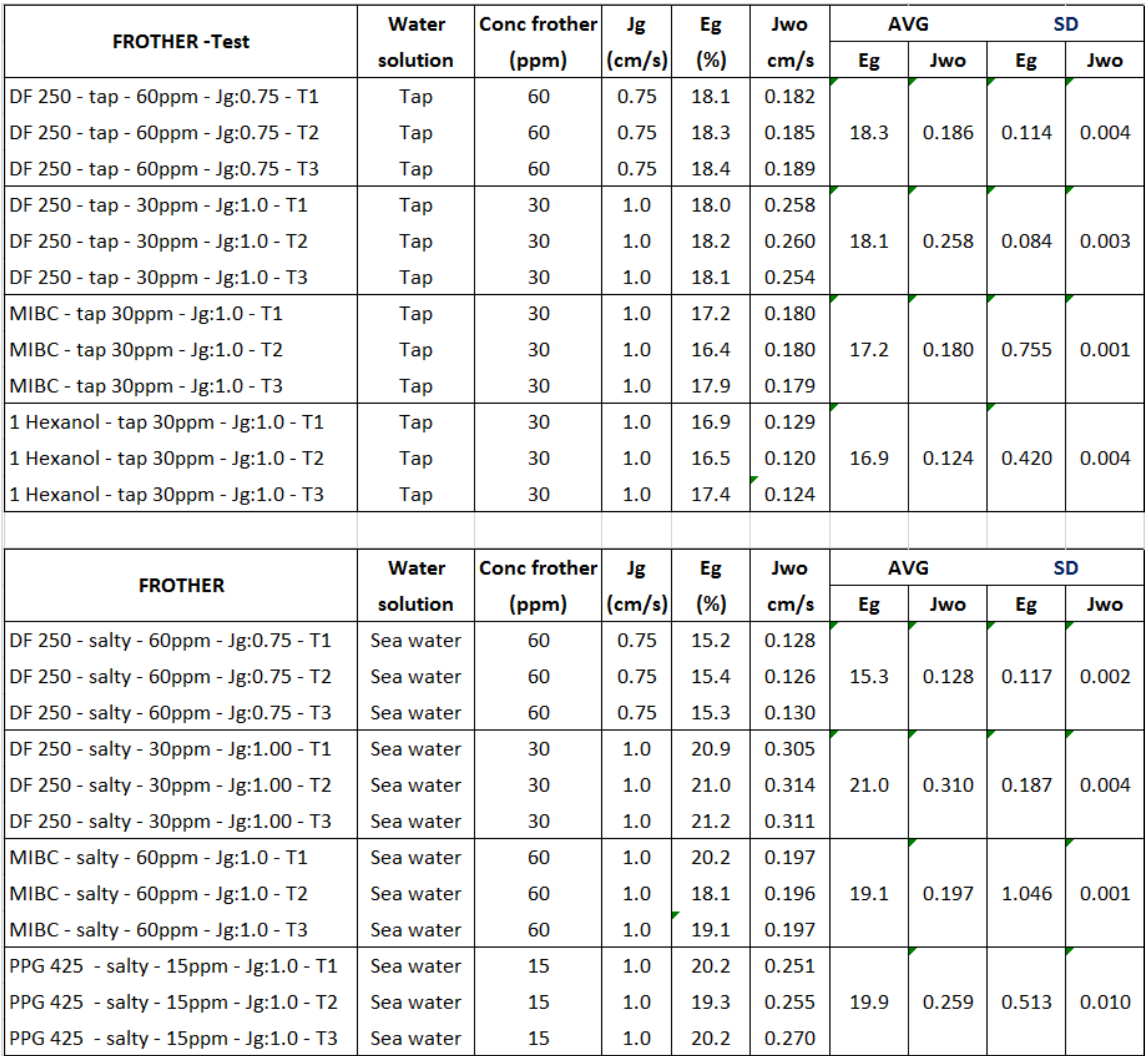


FROTHER	Water solution	Frother conc (ppm)	Repetition Test												AVG				SD			
			1				2				3											
			D10	D32	D20	D30	D10	D32	D20	D30	D10	D32	D20	D30	D10	D32	D20	D30	D10	D32	D20	D30
1 Hexanol		2	0.75	0.92	0.78	0.82	0.77	0.93	0.80	0.84	0.78	0.96	0.81	0.86	0.77	0.93	0.80	0.84	0.014	0.020	0.015	0.016
		5	0.85	1.05	0.89	0.94	0.88	1.12	0.93	0.99	0.92	1.21	0.98	1.05	0.89	1.13	0.93	0.99	0.037	0.081	0.047	0.057
		10	0.91	1.17	0.96	1.03	0.91	1.12	0.95	1.01	0.90	1.15	0.95	1.01	0.91	1.14	0.96	1.02	0.005	0.022	0.006	0.010
		15	0.92	1.21	0.98	1.05	0.97	1.25	1.03	1.10	0.93	1.24	1.00	1.07	0.94	1.23	1.00	1.07	0.025	0.020	0.023	0.022
		30	0.92	1.23	0.98	1.06	0.87	1.23	0.94	1.03	0.89	1.23	0.96	1.04	0.89	1.23	0.96	1.04	0.026	0.002	0.021	0.015
		60	0.81	1.06	0.86	0.92	0.82	1.12	0.88	0.95	0.84	1.17	0.90	0.98	0.82	1.12	0.88	0.95	0.012	0.057	0.021	0.031
		100	0.69	0.87	0.73	0.77	0.74	0.92	0.77	0.82	0.71	0.89	0.75	0.79	0.71	0.89	0.75	0.79	0.023	0.024	0.023	0.023

A.6: Repetitions of Sauter bubble diameter as a function of frother concentration for Tap and synthetic sea water solutions.



A.7: REPETITION TESTS FOR GAS HOLDUP AND WATER CARRYING RATE



FROTHER -Test	Water solution	Conc frother (ppm)	Jg (cm/s)	Eg (%)	Jwo cm/s	AVG		SD	
						Eg	Jwo	Eg	Jwo
DF 250 - tap - 60ppm - Jg:0.75 - T1	Tap	60	0.75	18.1	0.182	18.3	0.186	0.114	0.004
DF 250 - tap - 60ppm - Jg:0.75 - T2	Tap	60	0.75	18.3	0.185				
DF 250 - tap - 60ppm - Jg:0.75 - T3	Tap	60	0.75	18.4	0.189				
DF 250 - tap - 30ppm - Jg:1.0 - T1	Tap	30	1.0	18.0	0.258	18.1	0.258	0.084	0.003
DF 250 - tap - 30ppm - Jg:1.0 - T2	Tap	30	1.0	18.2	0.260				
DF 250 - tap - 30ppm - Jg:1.0 - T3	Tap	30	1.0	18.1	0.254				
MIBC - tap 30ppm - Jg:1.0 - T1	Tap	30	1.0	17.2	0.180	17.2	0.180	0.755	0.001
MIBC - tap 30ppm - Jg:1.0 - T2	Tap	30	1.0	16.4	0.180				
MIBC - tap 30ppm - Jg:1.0 - T3	Tap	30	1.0	17.9	0.179				
1 Hexanol - tap 30ppm - Jg:1.0 - T1	Tap	30	1.0	16.9	0.129	16.9	0.124	0.420	0.004
1 Hexanol - tap 30ppm - Jg:1.0 - T2	Tap	30	1.0	16.5	0.120				
1 Hexanol - tap 30ppm - Jg:1.0 - T3	Tap	30	1.0	17.4	0.124				

FROTHER	Water solution	Conc frother (ppm)	Jg (cm/s)	Eg (%)	Jwo cm/s	AVG		SD	
						Eg	Jwo	Eg	Jwo
DF 250 - salty - 60ppm - Jg:0.75 - T1	Sea water	60	0.75	15.2	0.128	15.3	0.128	0.117	0.002
DF 250 - salty - 60ppm - Jg:0.75 - T2	Sea water	60	0.75	15.4	0.126				
DF 250 - salty - 60ppm - Jg:0.75 - T3	Sea water	60	0.75	15.3	0.130				
DF 250 - salty - 30ppm - Jg:1.00 - T1	Sea water	30	1.0	20.9	0.305	21.0	0.310	0.187	0.004
DF 250 - salty - 30ppm - Jg:1.00 - T2	Sea water	30	1.0	21.0	0.314				
DF 250 - salty - 30ppm - Jg:1.00 - T3	Sea water	30	1.0	21.2	0.311				
MIBC - salty - 60ppm - Jg:1.0 - T1	Sea water	60	1.0	20.2	0.197	19.1	0.197	1.046	0.001
MIBC - salty - 60ppm - Jg:1.0 - T2	Sea water	60	1.0	18.1	0.196				
MIBC - salty - 60ppm - Jg:1.0 - T3	Sea water	60	1.0	19.1	0.197				
PPG 425 - salty - 15ppm - Jg:1.0 - T1	Sea water	15	1.0	20.2	0.251	19.9	0.259	0.513	0.010
PPG 425 - salty - 15ppm - Jg:1.0 - T2	Sea water	15	1.0	19.3	0.255				
PPG 425 - salty - 15ppm - Jg:1.0 - T3	Sea water	15	1.0	20.2	0.270				

A.8: Student's t -test for Repetition tests

REPETITION TESTS IN TAP WATER SOLUTION

DF 250 - tap - 60ppm - Jg:0.75

t-Test: Two-Sample Assuming Unequal Variances

	Variable 1	*Variable 2*
Mean	18.3	0.186
Variance	0.013041	0.000013
Observations	3	3
Hypothesized Mean Difference	0	
df	2	
t Stat	274.3	
P(T<=t) one-tail	0.0000066	
t Critical one-tail	2.9199856	
P(T<=t) two-tail	0.0000133	
t Critical two-tail	4.3026527	

DF 250 - tap - 30ppm - Jg:1.0

t-Test: Two-Sample Assuming Unequal Variances

	Variable 1	*Variable 2*
Mean	18.1	0.258
Variance	0.007118	0.000011
Observations	3	3
Hypothesized Mean Difference	0	
df	2	
t Stat	366.3	
P(T<=t) one-tail	0.0000037	
t Critical one-tail	2.9199856	
P(T<=t) two-tail	0.0000075	
t Critical two-tail	4.3026527	

MIBC - tap 30ppm - Jg:1.0

t-Test: Two-Sample Assuming Unequal Variances

	Variable 1	*Variable 2*
Mean	17.2	0.180
Variance	0.570769	0.000001
Observations	3	3
Hypothesized Mean Difference	0	
df	2	
t Stat	39.0	
P(T<=t) one-tail	0.0003287	
t Critical one-tail	2.9199856	
P(T<=t) two-tail	0.0006574	
t Critical two-tail	4.3026527	

1 Hexanol - tap 30ppm - Jg:1.0

t-Test: Two-Sample Assuming Unequal Variances

	Variable 1	*Variable 2*
Mean	16.9	0.124
Variance	0.176395	0.000019
Observations	3	3
Hypothesized Mean Difference	0	
df	2	
t Stat	69.2	
P(T<=t) one-tail	0.0001042	
t Critical one-tail	2.9199856	
P(T<=t) two-tail	0.0002085	
t Critical two-tail	4.3026527	

REPETITION TESTS IN SEA WATER SOLUTION

DF 250 - salty - 60ppm - Jg:0.75

t-Test: Two-Sample Assuming Unequal Variances

	Variable 1	*Variable 2*
Mean	15.3	0.128
Variance	0.0137955	0.0000031
Observations	3	3
Hypothesized Mean Difference	0	
df	2	
t Stat	223.8	
P(T<=t) one-tail	0.0000100	
t Critical one-tail	2.9199856	
P(T<=t) two-tail	0.0000200	
t Critical two-tail	4.3026527	

DF 250 - salty - 30ppm - Jg:1.00

t-Test: Two-Sample Assuming Unequal Variances

	Variable 1	*Variable 2*
Mean	21.0	0.310
Variance	0.0351361	0.0000195
Observations	3	3
Hypothesized Mean Difference	0	
df	2	
t Stat	191.5	
P(T<=t) one-tail	0.0000136	
t Critical one-tail	2.9199856	
P(T<=t) two-tail	0.0000273	
t Critical two-tail	4.3026527	

MIBC - salty - 60ppm - Jg:1.0

t-Test: Two-Sample Assuming Unequal Variances

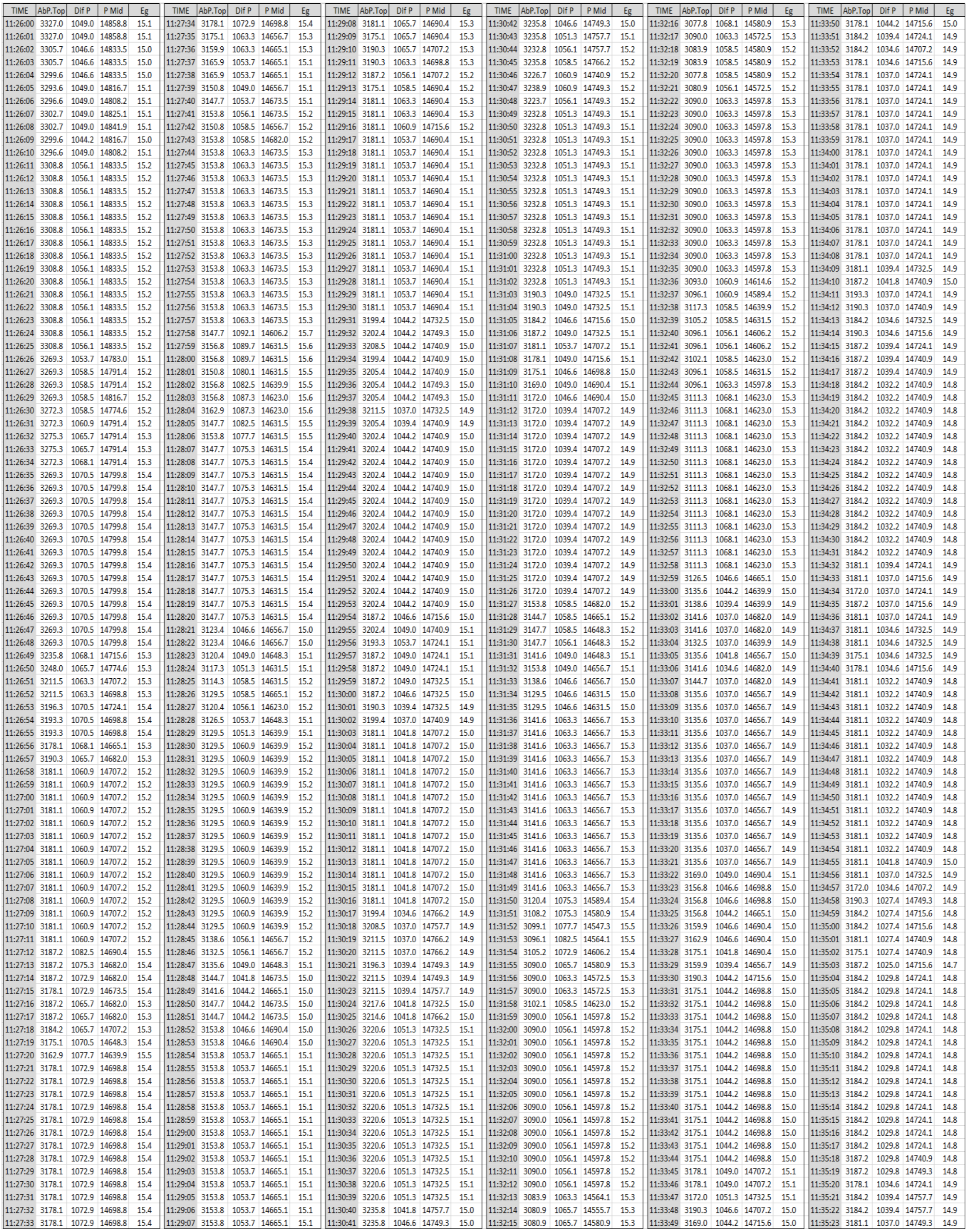
	Variable 1	*Variable 2*
Mean	19.1	0.197
Variance	1.0951487	0.0000006
Observations	3	3
Hypothesized Mean Difference	0	
df	2	
t Stat	31.3	
P(T<=t) one-tail	0.0005084	
t Critical one-tail	2.9199856	
P(T<=t) two-tail	0.0010167	
t Critical two-tail	4.3026527	

PPG 425 - salty - 15ppm - Jg:1.0

t-Test: Two-Sample Assuming Unequal Variances

	Variable 1	*Variable 2*
Mean	19.9	0.259
Variance	0.2629220	0.0000963
Observations	3	3
Hypothesized Mean Difference	0	
df	2	
t Stat	66.3	
P(T<=t) one-tail	0.0001136	
t Critical one-tail	2.9199856	
P(T<=t) two-tail	0.0002272	
t Critical two-tail	4.3026527	

A.9: Example of Extracted Ifix Data – PPG425 – 2ppm – Synthetic sea water



TIME	AbP.Top	Dif P	P Mid	Eg
11:26:00	3327.0	1049.0	14858.8	15.1
11:26:01	3327.0	1049.0	14858.8	15.1
11:26:02	3305.7	1046.6	14833.5	15.0
11:26:03	3305.7	1046.6	14833.5	15.0
11:26:04	3299.6	1046.6	14833.5	15.0
11:26:05	3293.6	1049.0	14816.7	15.1
11:26:06	3296.6	1049.0	14808.2	15.1
11:26:07	3302.7	1049.0	14825.1	15.1
11:26:08	3302.7	1049.0	14841.9	15.1
11:26:09	3299.6	1044.2	14816.7	15.0
11:26:10	3296.6	1049.0	14808.2	15.1
11:26:11	3308.8	1056.1	14833.5	15.2
11:26:12	3308.8	1056.1	14833.5	15.2
11:26:13	3308.8	1056.1	14833.5	15.2
11:26:14	3308.8	1056.1	14833.5	15.2
11:26:15	3308.8	1056.1	14833.5	15.2
11:26:16	3308.8	1056.1	14833.5	15.2
11:26:17	3308.8	1056.1	14833.5	15.2
11:26:18	3308.8	1056.1	14833.5	15.2
11:26:19	3308.8	1056.1	14833.5	15.2
11:26:20	3308.8	1056.1	14833.5	15.2
11:26:21	3308.8	1056.1	14833.5	15.2
11:26:22	3308.8	1056.1	14833.5	15.2
11:26:23	3308.8	1056.1	14833.5	15.2
11:26:24	3308.8	1056.1	14833.5	15.2
11:26:25	3308.8	1056.1	14833.5	15.2
11:26:26	3269.3	1053.7	14783.0	15.1
11:26:27	3269.3	1058.5	14791.4	15.2
11:26:28	3269.3	1058.5	14791.4	15.2
11:26:29	3269.3	1058.5	14816.7	15.2
11:26:30	3272.3	1058.5	14774.6	15.2
11:26:31	3272.3	1060.9	14791.4	15.2
11:26:32	3275.3	1065.7	14791.4	15.3
11:26:33	3275.3	1065.7	14791.4	15.3
11:26:34	3272.3	1068.1	14791.4	15.3
11:26:35	3269.3	1070.5	14799.8	15.4
11:26:36	3269.3	1070.5	14799.8	15.4
11:26:37	3269.3	1070.5	14799.8	15.4
11:26:38	3269.3	1070.5	14799.8	15.4
11:26:39	3269.3	1070.5	14799.8	15.4
11:26:40	3269.3	1070.5	14799.8	15.4
11:26:41	3269.3	1070.5	14799.8	15.4
11:26:42	3269.3	1070.5	14799.8	15.4
11:26:43	3269.3	1070.5	14799.8	15.4
11:26:44	3269.3	1070.5	14799.8	15.4
11:26:45	3269.3	1070.5	14799.8	15.4
11:26:46	3269.3	1070.5	14799.8	15.4
11:26:47	3269.3	1070.5	14799.8	15.4
11:26:48	3269.3	1070.5	14799.8	15.4
11:26:49	3235.8	1068.1	14715.6	15.3
11:26:50	3248.0	1065.7	14774.6	15.3
11:26:51	3211.5	1063.3	14707.2	15.3
11:26:52	3211.5	1063.3	14698.8	15.3
11:26:53	3196.3	1070.5	14724.1	15.4
11:26:54	3193.3	1070.5	14698.8	15.4
11:26:55	3193.3	1070.5	14698.8	15.4
11:26:56	3178.1	1068.1	14665.1	15.3
11:26:57	3190.3	1065.7	14682.0	15.3
11:26:58	3181.1	1060.9	14707.2	15.2
11:26:59	3181.1	1060.9	14707.2	15.2
11:27:00	3181.1	1060.9	14707.2	15.2
11:27:01	3181.1	1060.9	14707.2	15.2
11:27:02	3181.1	1060.9	14707.2	15.2
11:27:03	3181.1	1060.9	14707.2	15.2
11:27:04	3181.1	1060.9	14707.2	15.2
11:27:05	3181.1	1060.9	14707.2	15.2
11:27:06	3181.1	1060.9	14707.2	15.2
11:27:07	3181.1	1060.9	14707.2	15.2
11:27:08	3181.1	1060.9	14707.2	15.2
11:27:09	3181.1	1060.9	14707.2	15.2
11:27:10	3181.1	1060.9	14707.2	15.2
11:27:11	3181.1	1060.9	14707.2	15.2
11:27:12	3187.2	1082.5	14690.4	15.5
11:27:13	3187.2	1075.3	14682.0	15.4
11:27:14	3187.2	1072.9	14682.0	15.4
11:27:15	3178.1	1072.9	14673.5	15.4
11:27:16	3187.2	1065.7	14682.0	15.3
11:27:17	3187.2	1065.7	14682.0	15.3
11:27:18	3184.2	1065.7	14707.2	15.3
11:27:19	3175.1	1070.5	14648.3	15.4
11:27:20	3162.9	1077.7	14639.9	15.5
11:27:21	3178.1	1072.9	14698.8	15.4
11:27:22	3178.1	1072.9	14698.8	15.4
11:27:23	3178.1	1072.9	14698.8	15.4
11:27:24	3178.1	1072.9	14698.8	15.4
11:27:25	3178.1	1072.9	14698.8	15.4
11:27:26	3178.1	1072.9	14698.8	15.4
11:27:27	3178.1	1072.9	14698.8	15.4
11:27:28	3178.1	1072.9	14698.8	15.4
11:27:29	3178.1	1072.9	14698.8	15.4
11:27:30	3178.1	1072.9	14698.8	15.4
11:27:31	3178.1	1072.9	14698.8	15.4
11:27:32	3178.1	1072.9	14698.8	15.4
11:27:33	3178.1	1072.9	14698.8	15.4
11:27:34	3178.1	1072.9	14698.8	15.4
11:27:35	3175.1	1063.3	14656.7	15.3
11:27:36	3159.9	1063.3	14665.1	15.3
11:27:37	3165.9	1053.7	14665.1	15.1
11:27:38	3165.9	1053.7	14665.1	15.1
11:27:39	3150.8	1049.0	14656.7	15.1
11:27:40	3147.7	1053.7	14673.5	15.1
11:27:41	3153.8	1056.1	14673.5	15.2
11:27:42	3150.8	1058.5	14656.7	15.2
11:27:43	3153.8	1058.5	14682.0	15.2
11:27:44	3153.8	1063.3	14673.5	15.3
11:27:45	3153.8	1063.3	14673.5	15.3
11:27:46	3153.8	1063.3	14673.5	15.3
11:27:47	3153.8	1063.3	14673.5	15.3
11:27:48	3153.8	1063.3	14673.5	15.3
11:27:49	3153.8	1063.3	14673.5	15.3
11:27:50	3153.8	1063.3	14673.5	15.3
11:27:51	3153.8	1063.3	14673.5	15.3
11:27:52	3153.8	1063.3	14673.5	15.3
11:27:53	3153.8	1063.3	14673.5	15.3
11:27:54	3153.8	1063.3	14673.5	15.3
11:27:55	3153.8	1063.3	14673.5	15.3
11:27:56	3153.8	1063.3	14673.5	15.3
11:27:57	3153.8	1063.3	14673.5	15.3
11:27:58	3147.7	1092.1	14606.2	15.7
11:27:59	3156.8	1089.7	14631.5	15.6
11:28:00	3156.8	1089.7	14631.5	15.6
11:28:01	3150.8	1080.1	14631.5	15.5
11:28:02	3156.8	1082.5	14639.9	15.5
11:28:03	3156.8	1087.3	14623.0	15.6
11:28:04	3162.9	1087.3	14623.0	15.6
11:28:05	3147.7	1082.5	14631.5	15.5
11:28:06	3153.8	1077.7	14631.5	15.5
11:28:07	3147.7	1075.3	14631.5	15.4
11:28:08	3147.7	1075.3	14631.5	15.4
11:28:09	3147.7	1075.3	14631.5	15.4
11:28:10	3147.7	1075.3	14631.5	15.4
11:28:11	3147.7	1075.3	14631.5	15.4
11:28:12	3147.7	1075.3	14631.5	15.4
11:28:13	3147.7	1075.3	14631.5	15.4
11:28:14	3147.7	1075.3	14631.5	15.4
11:28:15	3147.7	1075.3	14631.5	15.4
11:28:16	3147.7	1075.3	14631.5	15.4
11:28:17	3147.7	1075.3	14631.5	15.4
11:28:18	3147.7	1075.3	14631.5	15.4
11:28:19	3147.7	1075.3	14631.5	15.4
11:28:20	3147.7	1075.3	14631.5	15.4
11:28:21	3123.4	1046.6	14656.7	15.0
11:28:22	3123.4	1046.6	14656.7	15.0
11:28:23	3120.4	1049.0	14648.3	15.1
11:28:24	3117.3	1051.3	14631.5	15.1
11:28:25	3114.3	1058.5	14631.5	15.2
11:28:26	3129.5	1058.5	14665.1	15.2
11:28:27	3120.4	1056.1	14623.0	15.2
11:28:28	3126.5	1053.7	14648.3	15.1
11:28:29	3129.5	1051.3	14639.9	15.1
11:28:30	3129.5	1060.9	14639.9	15.2
11:28:31	3129.5	1060.9	14639.9	15.2
11:28:32	3129.5	1060.9	14639.9	15.2
11:28:33	3129.5	1060.9	14639.9	15.2
11:28:34	3129.5	1060.9	14639.9	15.2
11:28:35	3129.5	1060.9	14639.9	15.2
11:28:36	3129.5	1060.9	14639.9	15.2
11:28:37	3129.5	1060.9	14639.9	15.2
11:28:38	3129.5	1060.9	14639.9	15.2
11:28:39	3129.5	1060.9	14639.9	15.2
11:28:40	3129.5	1060.9	14639.9	15.2
11:28:41	3129.5	1060.9	14639.9	15.2
11:28:42	3129.5	1060.9	14639.9	15.2
11:28:43	3129.5	1060.9	14639.9	15.2
11:28:44	3129.5	1060.9	14639.9	15.2
11:28:45	3138.6	1056.1	14656.7	15.2
11:28:46	3132.5	1056.1	14656.7	15.2
11:28:47	3135.6	1049.0	14648.3	15.1
11:28:48	3144.7	1041.8	14673.5	15.0
11:28:49	3141.6	1044.2	14665.1	15.0
11:28:50	3147.7	1044.2	14673.5	15.0
11:28:51	3144.7	1044.2	14673.5	15.0
11:28:52	3153.8	1046.6	14690.4	15.0
11:28:53	3153.8	1046.6	14690.4	15.0
11:28:54	3153.8	1053.7	14665.1	15.1
11:28:55	3153.8	1053.7	14665.1	15.1
11:28:56	3153.8	1053.7	14665.1	15.1
11:28:57	3153.8	1053.7	14665.1	15.1
11:28:58	3153.8	1053.7	14665.1	15.1
11:28:59	3153.8	1053.7	14665.1	15.1
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11:29:05	3153.8	1053.7	14665.1	15.1
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11:29:07	3153.8	1053.7	14665.1	15.1
11:29:08	3181.1	1065.7	14690.4	15.3
11:29:09	3175.1	1065.7	14690.4	15.3
11:29:10	3190.3	1065.7	14707.2	15.3
11:29:11	3190.3	1063.3	14698.8	15.3
11:29:12	3187.2	1056.1	14707.2	15.2
11:29:13	3175.1	1058.5	14690.4	15.2
11:29:14	3181.1	1063.3	14690.4	15.3
11:29:15	3181.1	1063.3	14690.4	15.3
11:29:16	3181.1	1060.9	14715.6	15.2
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11:29:19	3181.1	1053.7	14690.4	15.1
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11:29:26	3181.1	1053.7	14690.4	15.1
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11:29:33	3208.5	1044.2	14740.9	15.0
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11:29:40	3202.4	1044.2	14740.9	15.0
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11:30:02	3199.4	1037.0	14740.9	14.9
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11:33:45	3178.1	1049.0	14707.2	15.1
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11:33:47	3172.0	1051.3	14732.5	15.1
11:33:48	3190.3	1046.6	14707.2	15.0
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11:33:50	3178.1	1044.2	14715.6	15.0
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11:33:52	3184.2	1034.6	14707.2	14.9
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11:34:01	3178.1	1037.0	14724.1	14.9
11:34:02	3178.1	1037.0	14724.1	14.9
11:34:03	3178.1	1037.0	14724.1	14.9
11:34:04	3178.1	1037.0	14724.1	14.9
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11:34:08	3178.1	1037.0	14724.1	14.9
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Cont.

TIME	AbP.Top	Dif P	P Mid	Eg
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11:38:04	3193.3	1034.6	14774.6	14.9
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11:39:07	3184.2	1032.2	14757.7	14.8
11:39:08	3184.2	1032.2	14757.7	14.8
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11:39:14	3181.1	1013.0	14783.0	14.5
11:39:15	3159.9	1015.4	14757.7	14.6
11:39:16	3175.1	1015.4	14757.7	14.6
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11:39:32	3162.9	1017.8	14757.7	14.6
11:39:33	3178.1	1005.8	14766.2	14.4
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11:39:35	3181.1	1001.1	14808.2	14.4
11:39:36	3169.0	991.5	14799.8	14.2
11:39:37	3165.9	989.1	14799.8	14.2
11:39:38	3172.0	993.9	14783.0	14.3
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11:39:40	3169.0	1001.1	14766.2	14.4
11:39:41	3184.2	1003.5	14799.8	14.4
11:39:42	3178.1	1003.5	14816.7	14.4
11:39:43	3178.1	1003.5	14816.7	14.4
11:39:44	3178.1	1003.5	14816.7	14.4
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11:39:46	3178.1	1003.5	14816.7	14.4
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11:39:48	3178.1	1003.5	14816.7	14.4
11:39:49	3178.1	1003.5	14816.7	14.4
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11:39:51	3178.1	1003.5	14816.7	14.4
11:39:52	3178.1	1003.5	14816.7	14.4
11:39:53	3178.1	1003.5	14816.7	14.4
11:39:54	3178.1	1003.5	14816.7	14.4
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11:39:56	3196.3	998.7	14825.1	14.3
11:39:57	3184.2	1001.1	14825.1	14.4
11:39:58	3184.2	1001.1	14833.5	14.4
11:39:59	3193.3	998.7	14816.7	14.3
11:40:00	3199.4	998.7	14816.7	14.3
11:40:01	3199.4	1001.1	14808.2	14.4
11:40:02	3199.4	1001.1	14808.2	14.4
11:40:03	3205.4	1005.8	14841.9	14.4
11:40:04	3199.4	1005.8	14833.5	14.4
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11:40:07	3190.3	1003.5	14816.7	14.4
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11:40:21	3220.6	1008.2	14850.3	14.5
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11:40:24	3232.8	1005.8	14867.2	14.4
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11:40:26	3223.7	1015.4	14833.5	14.6
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11:40:28	3235.8	1003.5	14816.7	14.4
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11:40:43	3257.1	1010.6	14825.1	14.5
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11:40:45	3254.1	1015.4	14858.8	14.6
11:40:46	3238.9	1013.0	14833.5	14.5
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11:40:55	3238.9	996.3	14858.8	14.3
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11:41:02	3238.9	996.3	14858.8	14.3
11:41:03	3238.9	996.3	14858.8	14.3
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11:41:05	3223.7	1005.8	14841.9	14.4
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11:41:11	3226.7	1003.5	14858.8	14.4
11:41:12	3223.7	1005.8	14833.5	14.4
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11:41:14	3235.8	1005.8	14841.9	14.4
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11:41:55	3244.9	996.3	14867.2	14.3
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11:41:59	3238.9	986.7	14875.6	14.2
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11:42:01	3241.9	984.3	14875.6	14.1
11:42:02	3241.9	984.3	14875.6	14.1
11:42:03	3241.9	984.3	14875.6	14.1
11:42:04	3241.9	984.3	14875.6	14.1
11:42:05	3241.9	984.3	14875.6	14.1
11:42:06	3241.9	984.3	14875.6	14.1
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11:42:08	3241.9	984.3	14875.6	14.1
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11:42:11	3241.9	984.3	14875.6	14.1
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11:42:13	3241.9	984.3	14875.6	14.1
11:42:14	3241.9	984.3	14875.6	14.1
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11:42:16	3248.0	998.7	14884.0	14.3
11:42:17	3263.2	998.7	14917.7	14.3
11:42:18	3251.0	993.9	14875.6	14.3
11:42:19	3248.0	991.5	14884.0	14.2
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11:42:21	3248.0	989.1	14875.6	14.2
11:42:22	3244.9	991.5	14858.8	14.2
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11:42:27	3257.1	1003.5	14875.6	14.4
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11:42:46	3272.3	998.7	14892.4	14.3
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11:43:07	3281.4	1015.4	14875.6	14.6
11:43:08	3284.4	1010.6	14892.4	14.5
11:43:09	3284.4	1010.6	14892.4	14.5
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11:43:12	3287.5	1017.8	14892.4	14.6
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11:43:15	3287.5	1017.8	14892.4	14.6
11:43:16	3287.5	1017.8	14892.4	14.6
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11:43:18	3287.5	1017.8	14892.4	14.6
11:43:19	3287.5	1017.8	14892.4	14.6
11:43:20	3287.5	1017.8	14892.4	14.6
11:43:21	3287.5	1017.8	14892.4	14.6
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11:43:26	3281.4	1020.2	14867.2	14.6
11:43:27	3269.3	1020.2	14875.6	14.6
11:43:28	3281.4	1020.2	14875.6	14.6
11:43:29	3278.4	1020.2	14875.6	14.6
11:43:30	3275.3	1010.6	14858.8	14.5
11:43:31	3272.3	1008.2	14867.2	14.5
11:43:32	3260.1	1008.2	14867.2	14.5
11:43:33	3266.2	1015.4	14884.0	14.6
11:43:34	3266.2	1015.4	14884.0	14.6
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11:43:36	3266.2	1015.4	14884.0	14.6
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11:43:39	3266.2	1015.4	14884.0	14.6
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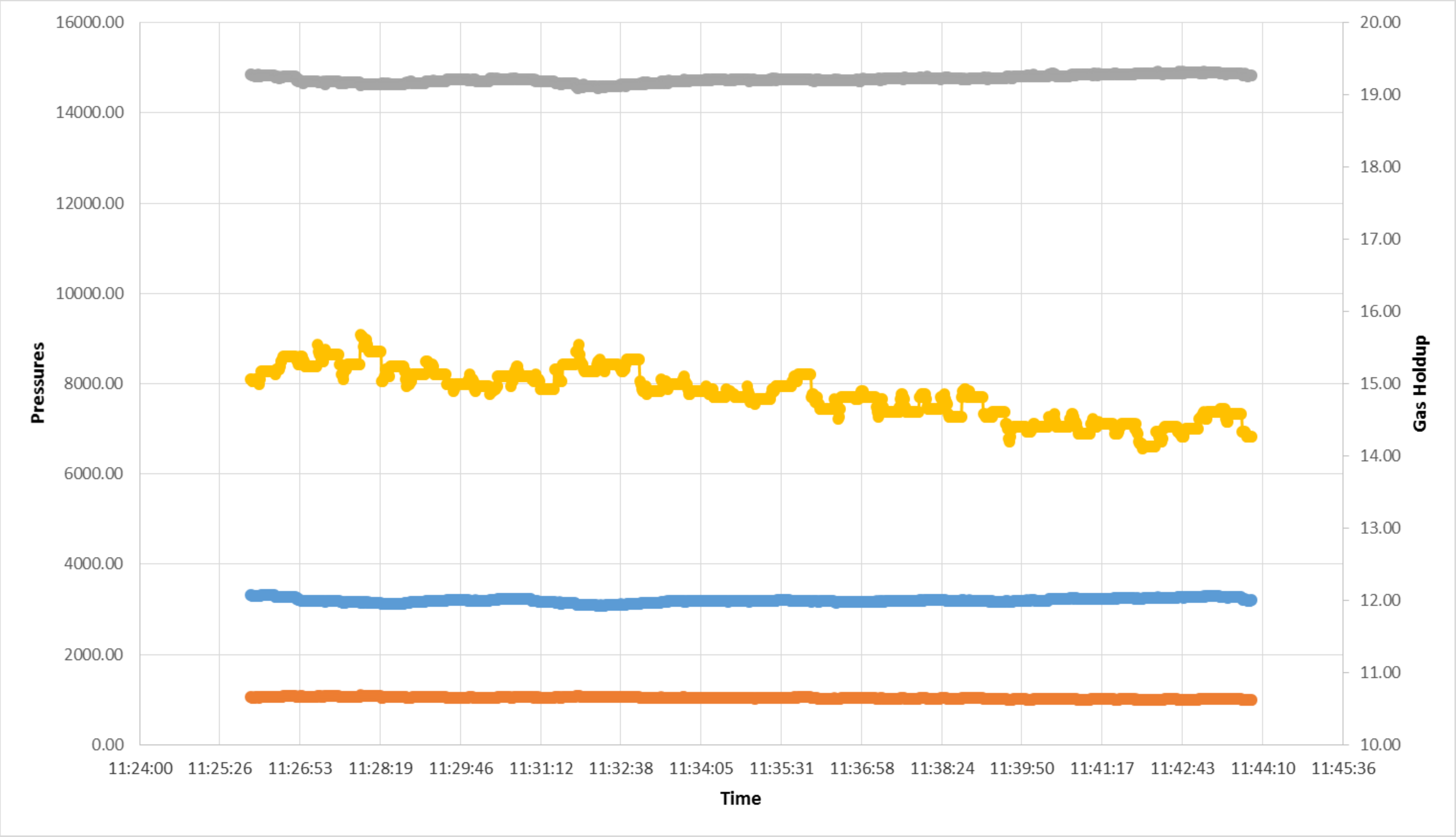
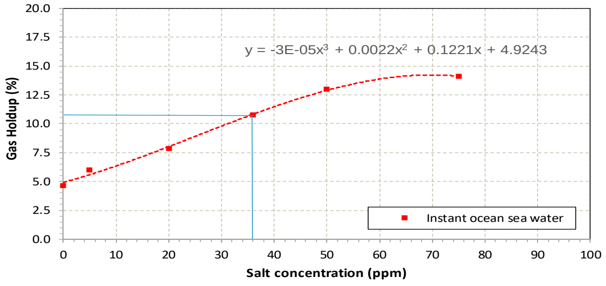
11:43:42	3266.2	1015.4	14884.0	14.6
11:43:43	3266.2	1015.4	14884.0	14.6
11:43:44	3266.2	1015.4	14884.0	14.6
11:43:45	3266.2	1015.4	14884.0	14.6
11:43:46	3266.2	1015.4	14884.0	14.6
11:43:47	3266.2	1015.4	14884.0	14.6
11:43:48	3232.8	998.7	14841.9	14.3
11:43:49	3214.6	998.7	14833.5	14.3
11:43:50	3220.6	998.7	14841.9	14.3
11:43:51	3223.7	998.7	14867.2	14.3
11:43:52	3208.5	996.3	14833.5	14.3
11:43:53	3202.4	993.9	14833.5	14.3
11:43:54	3190.3	993.9	14808.2	14.3
11:43:55	3193.3	993.9	14833.5	14.3
11:43:56	3193.3	993.9	14833.5	14.3
11:43:57	3199.4	993.9	14825.1	14.3
11:43:58	3199.4	993.9	14825.1	14.3

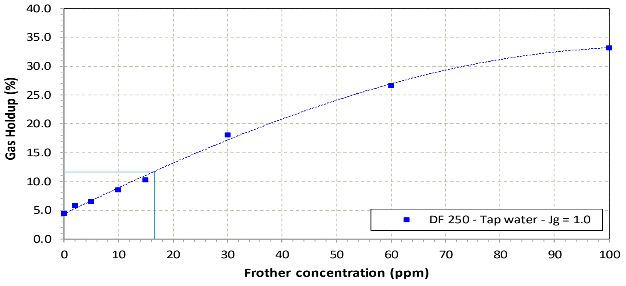
A.10: Tendencies of A6

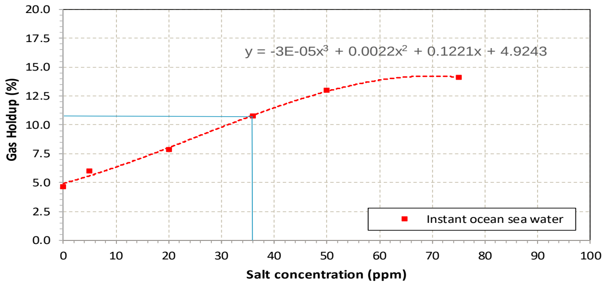


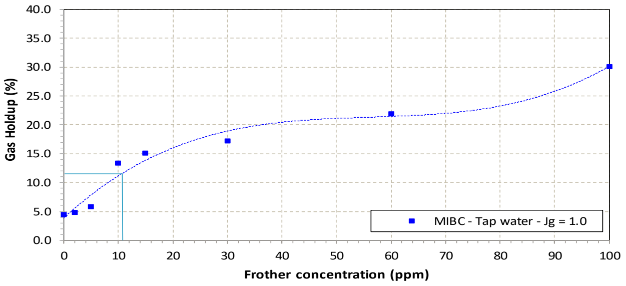
Appendix B:

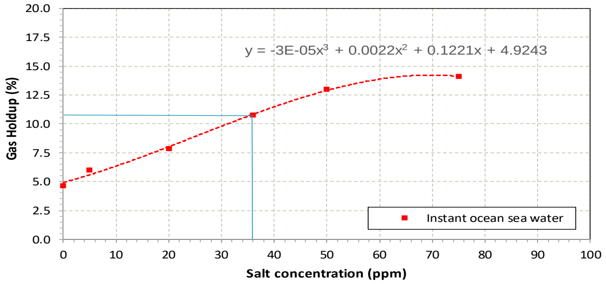
B.1: Comparison of Gas holdup for used ocean sea salt and frother concentration

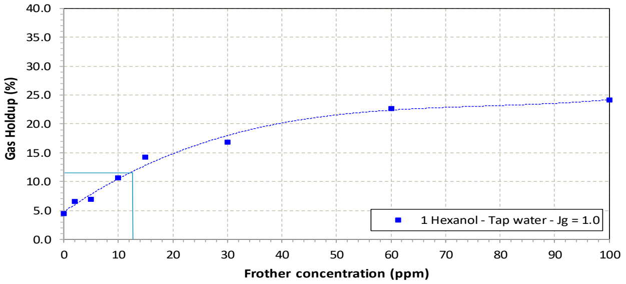


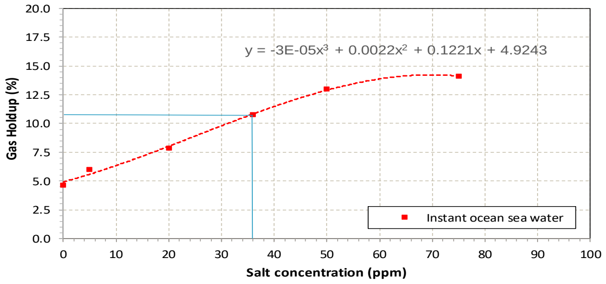


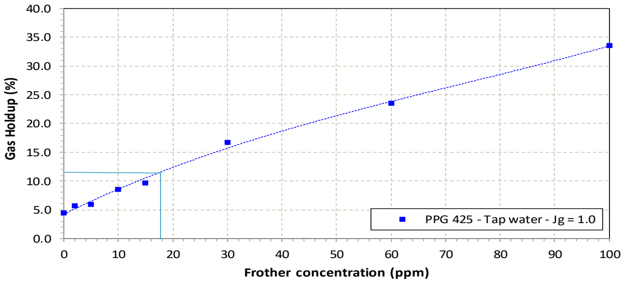


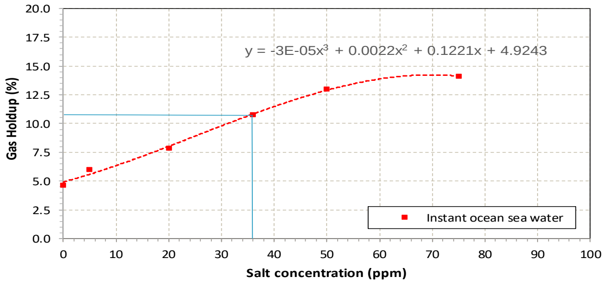


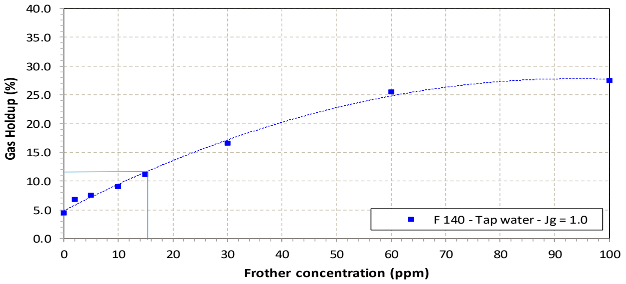












B.2: Bubble Column - Dimensions