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Observations on bubble size and bubble coalescence in two self-designed aeration systems.

Stuart Monteith
Master of Science in Aquaculture

Institution: Norges miljø - og biovitenskapelige universitet

Norges miljø - og biovitenskapelige universitet,

Universitetstunet 3,

1430 Ås, Norge

Abstract

The aeration of water, using either normal air or pure oxygen, is a critical process of Recirculating Aquaculture Systems. Carrying capacity in recirculating systems is typically governed by levels of dissolved oxygen in the water, and in order to allow the metabolic functions of fish to occur unencumbered, additional oxygen must be added. Maximising gas-liquid surface area, by generating small bubbles, will increase the transfer of gases into the water. Reducing bubble coalescence will maintain these smaller bubbles and will enable the effective transfer of gasses into the water with minimal losses in efficiency. In this study, two separately self-designed aeration systems were assembled in order to evaluate bubble size and bubble coalescence, of normal air, as a result of different variables in fresh and saltwater. The first system used a transparent acrylic cylinder (total ø: 150mm, inner ø: 142mm and height: 1m). Webcams were attached to the cylinder at different points to observe bubble diameter and bubble coalescence. Air was injected by a needle, connected to a syringe, which was inserted through the bottom of the cylinder in order to evaluate the effect of water height on bubble diameter. In the next setup, a needle 'bracelet', which allowed the distance between two separate needles to be increased from 1cm up to 5cm was used to observe differences in bubble coalescence at these distances. Furthermore, the needle bracelet was also used to alter the angle between two needles, from 0° to 20°, in order to observe the effect of needle angle on bubble coalescence. Rulers attached to the interior of the tank were used for measurements of bubble diameter, whilst bubble coalescence was characterised by observing number of bubbles and bubbles ≥5mm in diameter.

The results showed that initial bubble diameter generated at the bottom of the cylinder was the same in fresh and saltwater. Bubbles near the top of the cylinder were larger in diameter in freshwater than in saltwater. Increasing the distance between the two needles had no overall effect on bubble coalescence. Increasing the angle between the two needles reduced bubble coalescence. Overall, bubble coalescence occurred more frequently in freshwater than in saltwater.

The second system was assembled using transparent PVC pipes (total ø: 32mm & internal ø: 27.2mm) to form a rough 'U' shape, with two vertical sections (0.7m in length), and one elongated horizontal section (2m in length). This aeration system used four observation points in order to observe differences in bubble diameter and bubble coalescence at separate sections within the system. A self-designed venturi, using a transparent PVC pipe (total ø: 25mm & internal ø: 22mm) with a single needle inserted into the pipe, was installed at the first vertical section of the system. Increasing water velocities; 0.92 m/s, 0.98 m/s, 1.04 m/s, 1.12 m/s, 1.18 m/s, 1.25 m/s and 1.29m/s were generated in order to observe effects on bubble diameter and bubble coalescence at the different observation points.

The results showed that when increasing the water velocity, bubble diameter and bubble coalescence decreased. Bubble diameter was observed to be smallest after the bends in the piping. Whilst bubble diameter was largest at the end of the 2m horizontal pipe, due to increases in bubble coalescence. Overall, both bubble diameter and the frequency of bubble coalescence were smallest in saltwater than in freshwater.

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Notations

Dissolved Oxygen: DO

Downflow Bubble Contact Aerators: DBCA

Polypropylene: PP

Polyvinyl chloride: PVC

Practical Salinity Units: psu

Standard two-film theory: STFT

Suspended Solids: SS

Total Suspended Solids: TSS

Volatile Suspended Solids: VSS

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1. Introduction

As one of the world's fastest growing agri-food sectors, the aquaculture industry represents significant opportunities for continued growth in terms of supplying a growing world population with a source of high quality protein, as well as doing so in an environmentally friendly and sustainable matter. Due to the past and continuing focus on optimising efficiency whilst either maintaining or maximising sustainability, production technologies such as Recirculating Aquaculture Systems (RAS) have become increasingly popular since their initial incorporation into the aquaculture sector (Bregnballe, 2010). As such, recirculation aquaculture continues to grow in multiple areas of the fish farming industry due to the environmental and costs advantages that the technology affords (Helfrich & Libey, 1991; Tal *et al*, 2009). One such method for increasing costs effectiveness is to hold a larger standing stock on the farm, and in doing so invest in either aeration or oxygenation technology that ensure that the increased oxygen demands from the fish can be met (Kowsari, 2008). As aeration plays such a vital role in increasing the production capacity of aquaculture systems, the evaluation of these technologies in terms of their efficiency in delivering the required oxygen demands, whilst minimising the loss oxygen to the atmosphere, is of increasing concern (Kumar *et al*, 2014).

Evaluation of these technologies is usually conducted in terms of their aeration efficiency, represented as the mass of oxygen transferred per unit power input, which is itself directly correlated to the process of mass-transfer (Farmer & Arndt, 1995). Mass-transfer is dependent on numerous factors such as bubble size, bubble mixing, partial pressure, and mole fraction of a desired gas (usually oxygen). Optimisation of these factors will lead to higher rates of gas transfer, as well as increased transfer efficiency (Lekang, 2008). Bubble size, in particular, has been identified as having a large influence on aeration efficiency, as this directly presides over the total gas-liquid surface area that is available for aeration to occur, where an increased surface area as a result of smaller bubbles allows more gas transfer to occur (Chen, 1991; Chen *et al*, 1992). Another factor directly linked to bubble size that can influence the gas-liquid surface area is the phenomenon of bubble coalescence. The occurrence of bubble coalescence in gas-liquid systems leads to substantial decreases in surface area and thus inhibits rates of mass transfer (Drogaris & Weiland, 1983). Therefore, understanding how bubble coalescence and bubble size can be influenced and controlled by factors present in aquaculture are of vital importance in ensuring efficient aeration practices as well as the continued sustainability of large scale production.

1.1. Objectives of the Study

The general objectives of this study were to investigate the influence of factors such as pressure, water velocity, and system design on bubble size as well as the prevalence of bubble coalescence using normal air. Whilst comparisons would also be drawn between the effects that salinity had on these factors by testing all factors in both fresh and saltwater. In order to achieve this, two separate self-designed testing systems would be designed and constructed to enable testing for these factors. The systematic objectives of this study are as follows:

1) To investigate changes in bubble size, characterised as bubble diameter, as a result of changes in depth and therefore, the resulting pressure change.
2) To record the bubble rising velocity difference between fresh and saltwater.
3) To investigate whether changing the distance between two separate air sources, within a testing tank, would alter the frequency of bubble coalescence occurring.
4) To investigate whether altering the angles of two separate air sources relative to each other, instead of the distance between them, would influence the frequency of bubble coalescence occurring.
5) To investigate the influence of water velocity on the frequency of bubble coalescence.
6) To investigate the prevalence of bubble coalescence at different observation points within a test aerator.
7) To run and compare all of the above factors between both fresh and saltwater.

A secondary objective of the study will be the evaluation of the self-designed testing systems themselves, with respect to factors critical to aeration efficiency. Should the experiment produce un-anticipated results, a second order analysis of the laboratory equipment itself will be conducted. There will be two aims for the secondary analysis: first, to understand if the equipment itself was the reason for the un-expected results; and secondly, to make recommendations, where applicable, as to suggested equipment design modifications, with the intention of informing future research.

2. Literature review

2.1. Principles of Recirculating Aquaculture Systems Designs and Operation

Recirculating Aquaculture Systems, in their most simplified form, are closed systems that allow for the production of fish, as well as other aquatic organisms, within a system where water already used in the production process is re-used, reducing water exchange (Ebeling & Michael, 2002). The re-use of water is based on the utilisation of several water treatment technologies in order effectively and continuously clean and remove waste products excreted by the cultured organism, as well as ensuring the addition of required compounds and materials back into the water re-entering the production tanks to achieve optimal quality for the cultured species (Bregnballe, 2010). The basic components that are required to make up an effective recirculating system are shown (figure 1), whilst individual components of the system will be discussed below in greater detail.

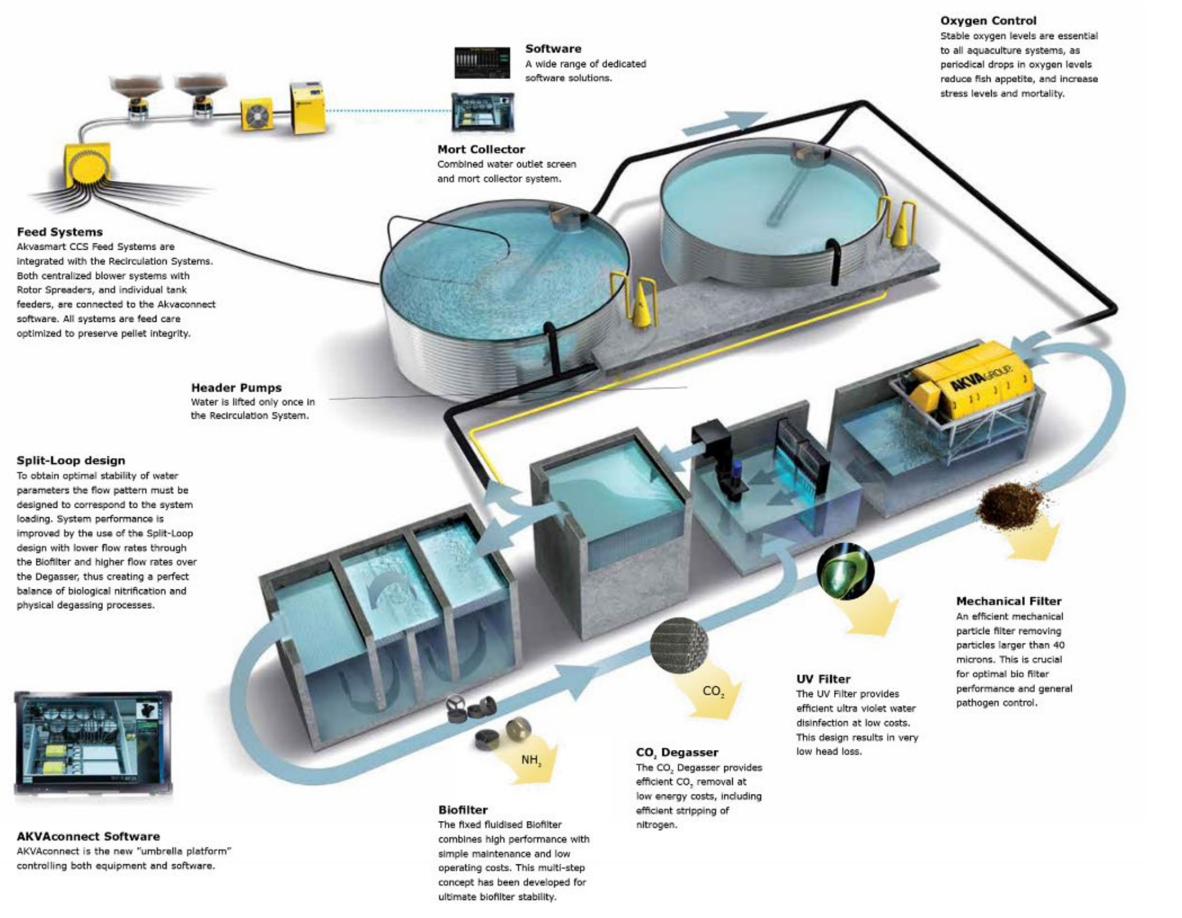

Figure 1. A standard layout of a Recirulating Aquaculture System (RAS). Source: AKVAgroup.

2.1.1. Water quality

The water in these production tanks must be of optimal quality as the tanks stand as single enclosed units so suboptimal conditions can lead to highly undesirable scenarios regarding disease and fungi, and thus mortality and/or loss of growth. Within the tank the feed is eaten and digested and feeding regimes may vary based on eith er species or life stage of the fish. As a result of metabolic processes, waste products such as carbon dioxide and ammonia are excreted from the gills of the fish. In addition to this, faeces are also excreted (typically termed suspended solids – SS) (Losordo *et al*, 2000). It is desirable therefore to minimise potential negative impacts that these waste products can pose as much as possible. This can be done through husbandry methods, for example: by having high feed utilisation rates, and selection of the most optimal tank designs, and water treatment methods (Bregnballe, 2010).

2.1.2. Production tanks

The design of the tank itself, specifically its hydrodynamic properties, is very important for addressing issue regarding water quality, particularly that of mixing qualities and solids removal. Proper mixing is important when considering dissolved oxygen within the water, and a correctly designed tank can help facilitate the even distribution of added oxygen throughout the tank rather than concentrating it at the inlet. Additional factors such as self-cleaning ability and solids removal are also heavily influenced by the tank's hydrodynamics and must also be considered when evaluating tank designs (Bregnballe, 2010; Malone, 2013). Currently three main tank designs dominate recirculation aquaculture: circular tanks, rectangular tanks, and raceway tanks (figure 2).

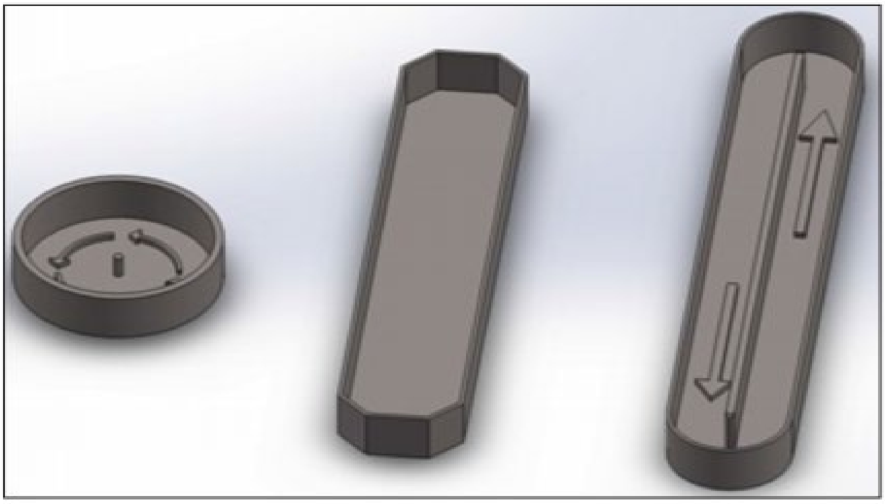

Figure 2. Showing the three dominant tank designs; circular (left), rectangular (centre), and raceway (right) (Malone, 2013).

Circular tanks currently dominate broodstock and fingerling production farms due to the significant hydrodynamic advantage that they offer as well as their ease to maintain the range of available operational rotational water velocities (Timmons *et al*, 1998). This hydrodynamic advantage is due to the movement of the water column around the centre of the tank, leading to relatively short residence times for organic particles as well as producing a self-cleaning effect within the tank. Optimal diameter-depth ratios for achieving efficient self-cleaning typically vary within the range of 3:1 - 5:1 (Larmoyeux *et al*, 1973). The lower radial velocity of water near the centre of the tank also allows for the relatively easy removal of SS due to solids accumulation near the centre, whilst the addition of a central drain further enhances the natural accumulation of solids that can also be readily removed from the system (Malone, 2013). The circular design means that water pressure is evenly distributed across the walls of the tanks, allowing for relatively straightforward construction out of materials such as thin polyethylene plastic or sturdier fiberglass materials. Water injection is typically tangential to the tank wall. This is of importance as in circular tanks this type of water inlet creates a primary initial water flow around the centre of the tank, whilst the no-slip conditions that exist between the primary flow and the tanks side walls and bottom leads to the creation of a secondary flow between the tanks bottom and side walls. This in turn leads to very good mixing properties and can create near perfect uniform water conditions within the tank (Goldsmith & Wang, 1993; Timmons *et al*, 1998). This is important for water parameters such as dissolved oxygen, which, due to constant mixing, can be kept uniform whilst also being easily and accurately measured using an oxygen probe (Bregnballe, 2010).

Rectangular tanks, while lacking the efficiency in solids removal when compared to circular tanks, offer more effective utilisation of floor space and ease of harvesting. Accumulation of solids can occur in the corners of the tanks where either drainage or removal can be difficult and this, combined with heavy stocking of the tank, can potentially lead to re-suspension of these solids. These tanks have a significant drawback in that they are not self-cleaning due to poor hydrodynamics and thus are typically designed with a 45° bevel on corners in order to provide at least some rounding to aid with hydrodynamics. Dissolved oxygen however tends to be higher nearer the inlet due to the poor mixing qualities and this can lead to undesirable oxygen gradients within the tank (Bregnballe, 2010). The bevel on the corners can also represent structural concerns due to increased water pressure placed on the corner of the tanks. Construction of rectangular tanks is therefore typically done utilising studier materials, such as fibreglass or concrete (Malone, 2013).

Raceway tanks are also able to effectively utilise available floor space whilst also combining some of the mixing qualities expected from a circular tank. Oxygen gradients can occur in these tanks however, so some aeration units can be fitted throughout the raceway although this is not ideal (Malone, 2013). A third inner wall can be added to aid in the controlled circulation of water whilst also providing natural accumulation points for solids; again, this is not an ideal solution as it can add extra labour requirements and also interfere with grading or harvest work (figure 2). Of the three dominant tank designs raceways are the utilised least frequently (Bregnballe, 2010).

2.1.3. Mechanical filtration

Up to half the quantity of consumed feed can be excreted as waste solids, and depending on the retention time within the water column, can further degrade into finer particles. The sum of these solids within the water column is termed Total Suspended Solids (TSS) of which a large fraction is comprised of organic matter (usually faeces) which is itself termed Volatile Suspended Solids (VSS) (Masser *et al*, 2000; Malone, 2013). Removal of these solids is extremely important as these solids promote the growth of bacteria and are usually extremely small (>20 microns- µm) providing greater surface area for bacterial growth (Chen *et al*, 1993). Almost all mechanical filtration units are placed to directly filter the outlet water from the tank so that organic load on the biofilter is reduced whilst improving nitrification conditions. A mechanical filtration unit itself will typically depend on the size of the particulate matter targeted (Bregnballe, 2010).

The simplest form of mechanical filtration is done by utilising gravity in the form of settling basins. These are mostly present in the tank itself and must be paired with a retention time of roughly 15-30 minutes for maximum efficiency. Solids will sink and accumulate in the tank before being siphoned off by drain or removed by either hand net or another instrument. Settling basins however are ineffective at removing fine particles which can remain closer to the surface and accumulate (Malone, 2013).

A rotating microscreen filter (also known as a drum filter) utilises a microscreen mesh fastened to a rotating structure within a drum shaped casing. A typical mesh filter size employed on a recirculation farm would be between 30-60 microns (µm) resulting in the majority of solids being removed from the water. One potential drawback to these drum filters however, is their inefficiency in removing very fine suspended particles (<30 microns) - (Malone, 2013). Nevertheless, drum filters require relatively little maintenance and floor space and can utilise the difference in water level inside/outside as a driving force for rotating the screens, saving further costs on electricity (Ali, 2013). Over time the mesh can accumulate filtered material and can itself be cleaned by spraying water from rinsing nozzles placed within the drum and outside the filter mesh. Organic material separated from the mesh by the nozzles is then washed into a sludge tray (Bregnballe, 2010). Below a typical design and layout of a drum filter is shown (figure 3).

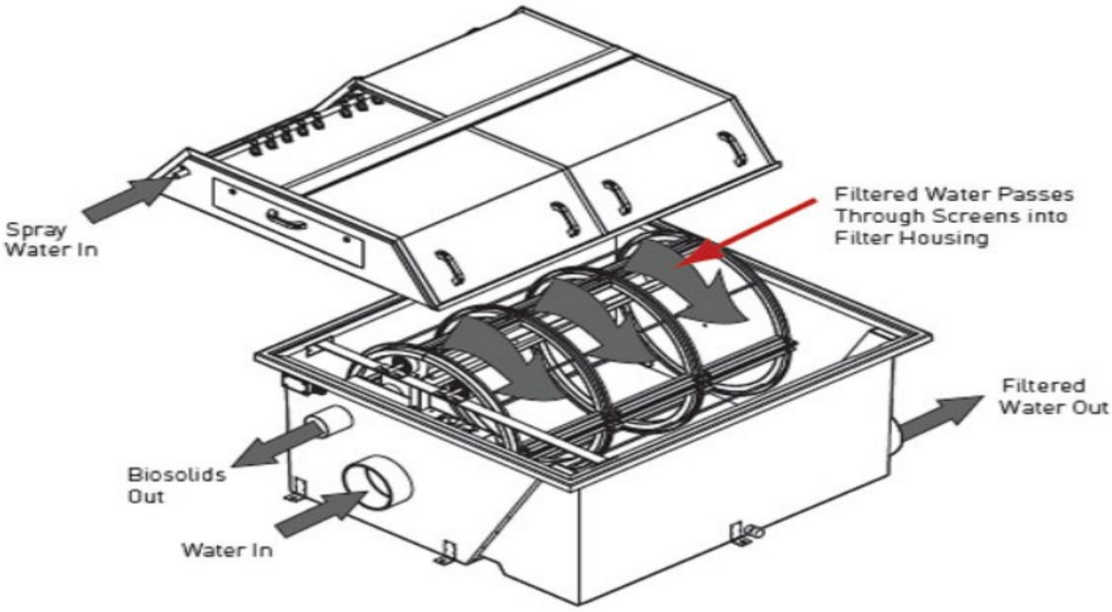

Figure 3. Showing a schematic of a common drum filter. Source: Pentairaes.

Floating bead filters (FBFs) are another mechanical filtration option available for recirculating systems (figure 4). FBFs typically have a removal system similar to that of a sand filter, whilst also promoting the growth of bacteria that are able to further remove waste products through biofiltration (Malone & Beecher, 2000). Water is passed through roughly 30-90 cm of granular plastic bead media which are able to 'catch' solids by multiple processes such as: straining, settling, interception, and adsorption. Particles down to roughly 30 microns can be caught in a single cycle of the water and almost all solid particles after multiple passes (Malone, 2013). The system is cleaned via backwashing, and captured solids are then allowed to settle and are removed as a sludge. One drawback of backwashing however is the loss of water from the system (Losordo *et al*, 2000). FBFs differ based on the method of backwashing which can be either hydraulic and air washed units (categorised as 'gently washed') or propeller/paddle driven backwashing (categorised as 'aggressively washed') - (Malone & Beecher, 2000). Newer FBFs are able to backwash internally, drastically reducing water losses (Malone, 2013).

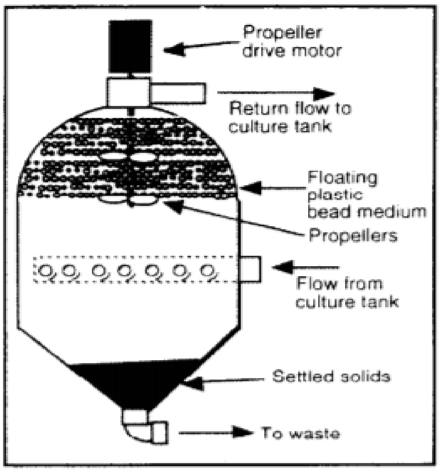

Figure 4. Showing a schematic of a propeller driven floating bead filter (Losordo et al*, 2000).*

2.1.4. Biological filtration

Typically mechanical filtration will not achieve 100% removal efficiency of organic material, and dissolved compounds such as nitrogen and phosphorus will be present in the water after mechanical filtration. Great importance is placed on the prevalence of nitrogen within the system, as in the water it is able to form both ionised ammonia (NH_4^+) and free ammonia (NH_3). This occurs as a result of heterotrophic bacteria oxidising remaining organic matter, with ammonia and carbon dioxide (CO_2) as co-products of this reaction (Bregnballe, 2010). Free ammonia in particular is highly toxic, and so must be removed by the biofilter via the nitrification process, where ammonia is converted to nitrate (NO_3-) – (Helfrich & Libey, 1991). This is a biological process that is carried out by nitrifying bacteria attached to suitable biofilter media (sand or plastic beads) that forms a biofilm on the media within the biofilter. Initially, ammonia is converted into nitrite (NO_2-) via oxidation by *Nitrosomonas*, followed by the conversion of nitrite into nitrate via oxidation by *Nitrobacter* (Ward, 1996; Kuhn *et al*, 2010). Efficiency of the biofilter is primarily dependent on oxygen availability as well as both water temperature and pH within the system, of which pH is itself influenced by CO_2 production levels as a result of the metabolic process of the farm's stock (Malone, 2013). Correct management of the several biofilter systems available is critical in order to produce water of optimal quality that can be re-used whilst posing no threat to the farms stock.

Biofilters are typically categorised as either fixed bed or moving bed filters (figure 5). Both filter types are configured based on the principle of water flow over either free moving or fixed submerged media (Bregnballe, 2010). Fluidised Bed Reactors (FBRs) and Moving Bed Reactors (MBRs) are the most common types of moving bed biofilters. These are essentially reactors filled with a bed of media (usually in the form of sand and plastic or glass beads) that is kept constantly suspended in the water column by either an upwelling current of water in the case of FBRs or aeration in the case of MBRs (Helfrich & Libey, 1991; Malone, 2013). These reactors provide a large suitable surface area for the growth of nitrifying bacteria and these reactors are capable of very high volumetric conversion rates in terms of amount of ammonia converted per unit of media – though typically efficiency of MBRs is roughly ¼ - ½ when compared to FBRs (Malone, 2013). As mentioned under mechanical filtration, bead filters are also able to act as biofilters as well as filtering out larger particles of organic matter. These reactors utilise either plastic or polyethylene beads kept in a floating bed within the reactor. They can be further sub-divided into 1) floating bead biofilters: typically characterised by the need to back wash the system by either air-injection or propeller to remove solids attached to the beads and 2) dynamic floating bead biofilters: where the beads are kept in constant motion due to hydraulic or air-induced circulation in order to achieve high rates of nitrification (Malone, 2013).

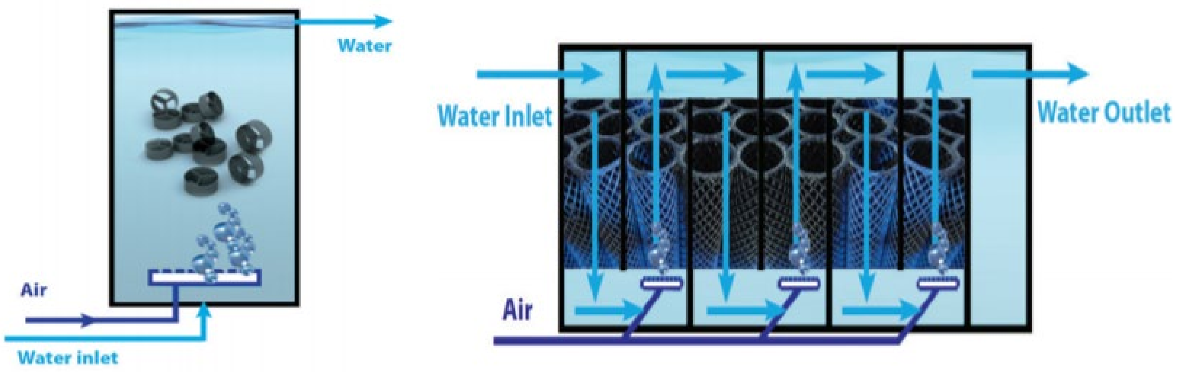

Figure 5. Simple examples of the setup and functioning of a moving bed reactor (left) and a floating bead biofilter (right). Source: (Bregnballe, 2010).

In fixed bed reactors the media supporting bacterial growth are fixed, with a water flow running laminar to achieve maximum contact with the biofilm. Typically, nitrification rates of these types of bioreactors are not as high as that of moving bed filters, likely due to the reduction of contact surface area and the lack of additional swirling hydraulic action (Bregnballe, 2010).

2.1.5. Disinfection

Recirculating systems are susceptible to rapid outbreak and replication of diseases due to the high densities of fish within the system. Whilst chemicals can be used to control such outbreaks, there are usually negative repercussive effects on the nitrifying bacteria within the bioreactors (Losordo *et al*, 2000). Subsequently, other methods of disinfection dominate RAS culture, UV and ozone disinfection (Malone, 2013).

Figure 6. Examples of a 'closed' UV disinfection unit (top) and 'open' unit (below). Source: LIT Ultraviolet Technology.

UV disinfection is more common than ozone due to the relative ease of installation and operation that the system offers, and the most common designs of UV units utilise a submerged UV source within either a 'closed' or 'open' UV channel systems (figure 6). The principle behind UV disinfection is applying UV light at specific wavelengths that specifically target and destroy, via denaturing, the DNA of pathogenic biological organisms within the water (Summerfelt, 2003; Bregnballe, 2010). Disinfection rates are reliant on several factors such as: organism size, UV intensity, flow rate, and penetration of the UV light into the water column (Spotte, 1970; Losordo *et al*, 2000). To achieve maximum disinfection efficiency microorganisms within the water should be in close proximity (≈0.5cm) to the UV bulbs with minimal water turbidity and a contact time of ≈10-30 seconds with the light. The UV dosage levels should be size and species specific: ≈ 2000 to 10000 µWs/cm² for removing bacteria, 10000 to 100000 µWs/cm² for removing fungi, and 50000 to 200000 µWs/cm² for small parasites (White, 1992; Bregnballe, 2010).

The other commonly available disinfection method is ozone. ozone (O_3), a powerful oxidant which operates similarly to chlorine in its disinfection action, is efficient in removing unwanted organisms by heavy oxidation of organic matter (Bregnballe, 2010). The ozone is generated typically via a corona discharge design, where the ozone generation and performance is controlled based on the levels of enriched oxygen fed into the system (Summerfelt, 2003). Once generated the ozone can be dosed into the water via either a packed column or, more commonly, a venturi system where energy generated from the pumps can itself be used to 'suck' the ozone into the water (Malone, 2013). Ozone systems can however have drawbacks: ozone can pose extreme hazards to both the stock on the farm as well as employees if dosages are incorrect or sufficient operation training is not completed; and high installations costs can be a discouragement for farmers (Losordo *et al*, 2000; Bregnballe, 2010).

2.1.6. Degassing and Aeration

Gasses, in particular CO_2 and N_2 which will have accumulated in the water due to the metabolic process of the stock and heterotrophic bacteria, must be removed prior to the water returning to the culture tanks. Build-up of CO_2 and N_2 can cause harm to the stock as well as significantly reducing welfare and growth rates and, combined with poor management, can cause a reduction in water pH, leading to a reduction in nitrifying bacteria activity. Dissolved CO_2 therefore should ideally be kept under roughly 25 mg/L^{-1} (Losordo *et al*, 2000; Bregnballe, 2010). The process of degassing is typically carried out by aeration of the water, either by blown air into the water or packed trickling columns (Malone, 2013).

In blown air systems low pressure air can be added to the water via a diffuser located near or at the bottom of the tank. The turbulence caused by the air bubbles is able to remove the build-up of undesirable gasses due to gas gradients between the water and the air (Losordo *et al*, 2000). Whilst relatively simple, this system is not as efficient for gas removal as the trickling columns system. In packed trickling columns, water is pumped to the top of the filter and held in a holed sump tank and, via gravity, the water runs down the filter packed with, usually, plastic media. In this case it is the physical contact with the media that degasses the water of CO_2 (Malone, 2013). These types of systems can be relatively economical to run, as the principle cost is pumping the water to the top of the filter. Possible additional costs can be incurred if air is also blown into the column to further increase exchange efficiency, by maximising the gas/liquid ratios (Losordo *et al*, 2000). It is also worth noting that whilst undesirable gasses are removed, CO_2 for example, adequate oxygenation for efficient fish production does not usually occur using the two system described above. Below an example of the interior design of a packed trickling column is shown, with emphasis on maximising contact surface area between the water and media (figure 7).

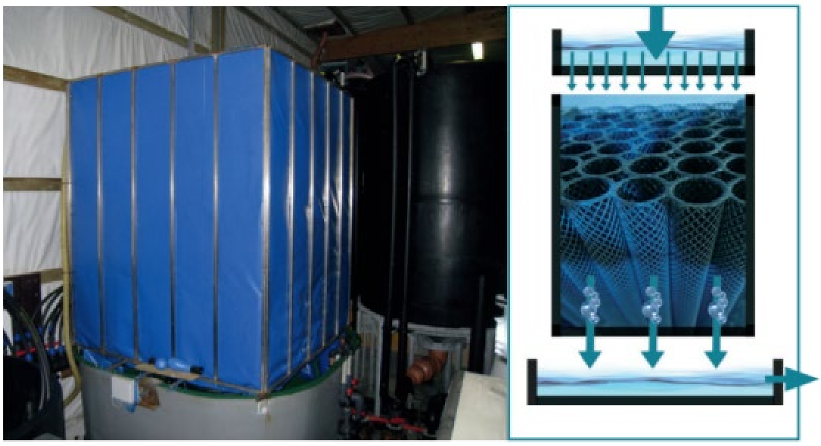

Figure 7. Showing a simple but effective packed trickling column for degassing, and schematic indicating water flow over the packed media (Bregnballe, 2010).

2.1.7. Other treatments

pH regulation: A by-product of the nitrifying process in the biofilter is that of acid and in order to maintain pH levels within safe parameters for the fish, a base must be added to the water. Several system exist for this purpose such as: 1) automatic dosing system that uses sodium hydroxide (NaOH) with a feedback regulation to a dosage pump, and 2) lime mixing station, where limewater is slowly fed into the system (Bregnballe, 2010).

Temperature regulation: Running the system with the optimal water temperature is important for factors such as growth. The regulation of temperature can be achieved in several ways. One of the most common ways is the addition of cooler 'intake' water to the system. This acts by cooling the water that has already been warmed by metabolic process of the fish and bacterial activity occurring within the system. Another method is to the use of a heat pump, where energy usually lost from discharged water is then used for cooling the circulating water. Heating of the water may also be required, in which case the water can be heated. The addition of a heat exchanger can also aid in further reducing costs for heating (Bregnballe, 2010).

2.1.8. Oxygenation

Due to its importance and the parallels between the delivery of pure oxygen and the aims of this study using normal air, oxygenation techniques and methods for maximising efficiency will be reviewed separately in section 2.4.

2.2. Gas Transfer Theory

The exchange of gases between both the aqueous and gaseous phases is a pivotal function of numerous environmental processes. In addition, gas transfer is utilized in a range of different industries and functions including: wastewater treatment, the removal of volatile chemicals from water, and aquaculture (Zander *et al*, 1989). When dissolving gases into water, at least at normal atmospheric pressures and at a given temperature, water which has taken up its maximum quantity of dissolved gas is referred to as either fully saturated (100%) or in equilibrium. Additionally, water containing less gas than can be taken up at the same given conditions is referred to as less than saturated (<100%), whilst water that has taken up gases exceeding its normal saturation is referred to as super saturated (>100%) (Lekang, 2008).

The quantity and rate at which gases are both transferred in and out of water is primarily dependent on two important conditions:

1) The **equilibrium conditions** of the water/gas mixture, additionally referred to as the saturation concentration.
2) **Mass transfer** that occurs within the system.

2.2.1. Equilibrium Conditions

If there is ample time within which environmental conditions are held constant then the net transfer of gases between both the gaseous and liquid phase will cease. Whilst transfer of gas molecules may continue via transport though the liquids surface, the quantity of transfer in will equal the transfer out of the liquid. Continued addition of gas to a liquid that has achieved supersaturation will however result in the gas remaining as bubbles within the liquid (Lekang, 2008). However, the equilibrium conditions can in fact be altered by manipulation of several factors. But first the equilibrium conditions must be quantified, and this can be done by using Henry's law:

$$P_g = H \cdot X_g$$

Henry's law expresses that the quantity of gas that can be dissolved in a liquid is directly proportional to the partial pressure, where P_g represents the partial pressure of the solute (atm), X_g the concentration of the solute within the water (mol/m^3), and H represents Henry's constant (atm/mol) (Lincoff & Gossett, 1984). The proportionality factor within the equation is Henry's constant, and is additionally dependent on factors such as temperature and gas species, where increasing temperature will cause the value for Henry's constant to increase (Tchobanoglous *et al*, 2002; Lekang, 2008).

Partial pressure can additionally be manipulated. This represents the quantity of a given gas in the atmosphere above the liquid, where the partial pressure of each gas is directly proportional to the mole fraction of that gas (Ebeling & Michael, 2002). This pressure that is exerted upon the liquids surface is what forces the gas into the liquid as the partial pressures of both the atmosphere and liquid will always try to be in equilibrium. By increasing the quantity of a given gas within the atmosphere, eg: increasing oxygen content from 20% (normal atmospheric air) to 100% (pure oxygen), this will increase the P_g value from 0.2 to 1, and can therefore alter the equilibrium conditions (Lekang, 2008). Additionally, increasing the total gas pressure to that above normal atmospheric conditions can also lead to new equilibrium conditions, and these can be expressed by Dalton's law:

$$P_g = p_{tg} \cdot y$$

In Dalton's law, P_g represents the partial pressure of the solute (atm), p_{tg} the total pressure of a gas mixture (atm), and y the mole fraction of the solute (mol gas g/mol total gases) (Silberberg *et al*, 1996). Dalton's law can additionally be combined with Henry's law to give the Henry-Dalton law:

$$p_{tg} \cdot y = H \cdot X_g$$

This equation clearly demonstrates that by increasing either the total gas pressure (p_{tg}) or the mole fraction of the solute (y), a subsequent increase in the partial pressure (P_g) will occur. And by increasing the partial pressure, the concentration of the solute within the water (X_g), will therefore also increase, meaning that the solute quantity, in this case gas, within the water will be higher (Ebeling & Michael, 2002; Lekang, 2008).

2.2.2. Mass Transfer

Mass transfer is a non-equilibrium process and refers to the mechanisms by which gas transfer occurs. Mass transfer can occur across numerous different interfaces; liquid/liquid, gas/liquid, and liquid/solid. However the transfer across the gas/liquid phase is of particular interest to this study. To describe the transfer mechanism between these two phases, the simple and common 'standard two-film theory' (STFT), has been put forward (Lekang, 2008). The STFT is a diffusion based mechanism that states that the interface between the gas and liquid phases can be split into two separate films; one gas film, and one liquid film, with laminar flow between the two (figure 8) (Lewis & Whitman, 1924). This theory assumes that resistance to mass transfer across these phases is due to these films attached to each phase (Wang *et al*, 2018). Additionally, the resistance of transfer is constrained by the thickness of the films, where efficient transport is increased with a decrease in film thickness. Film thickness itself can be manipulated by factors such as air and water turbulence, where increasing the turbulence of either state will reduce the film thickness, aiding in transport (Lekang, 2008). Application of the STFT also requires several assumptions: 1) that steady state concentrations of species exist at all locations and will not alter with time, 2) the laminar flow exists at the interface of both the gas and liquid phases, and 3) that at the interface equilibrium is reached almost instantaneously, leading to negligible resistance from the interface (Wang *et al*, 2018).

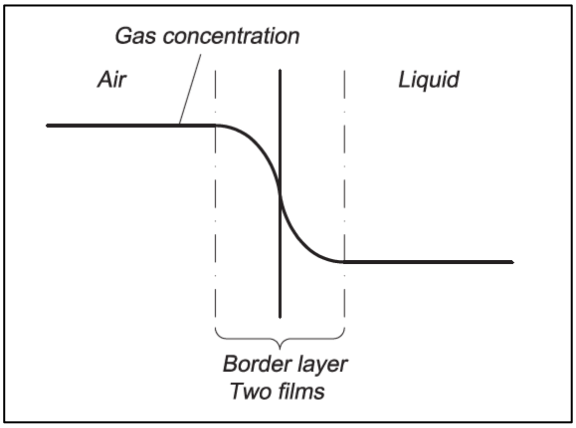

Figure 8. Simple representation of the two-film theory (Lekang, 2008)

The mechanism itself, at least when gas is transported into water from air, begins at the gas phase where gas enters the gas film via the process of convection and diffusion. Subsequently the gas will pass through the gas-liquid film interface, which is diffusion driven, before finally the gas is passed through the liquid film into the liquid by convection (Lekang, 2008; Wang *et al*, 2018). The rate of gas transfer can itself be modelled as a result of the driving force of concentration gradients between both the equilibrium and actual concentration (Gas Transfer, n.d.). Combining this with a gas transfer coefficient based on surface area and gas species results in a differential equation, where the gas transfer rate per unit time can be calculated:

$$\frac{dc}{dt} = K_I * \left(\frac{A}{V}\right) * (C^* - C_0)$$

In this equation *dc/dt* represents the change in concentration per unit time (mg/L per h), K_l the coefficient for gas transfer (cm/h), *A/V* the contact area of the gas-liquid phases (cm^2) over total liquid volume (cm^3), *C** the saturation concentration of the gas in the liquid (mg/L), and C_0 the initial concentration of the gas in the liquid (mg/L^{-1}) (Lekang, 2008).

In general, when describing aeration practices, a single mass transfer coefficient is usually utilised for its simplicity in modelling gas transfer between both gas and liquid phases (Chen *et al*, 1992). This gas transfer coefficient (K_l) is related to the rate of diffusion through the surface film and is inversely proportional to the film thickness thus, further showing the benefits of thinner film thicknesses caused by factors such as increased water turbulence and velocity (Lekang, 2008). Like with equilibrium conditions, K_l can also be manipulated as this coefficient considers all effects of gas-liquid properties (Hackney & Colt, 1982). Factors such as temperature, gas-liquid ratios, surface contact area, and species of gas and liquid used will all influence K_l. Temperature, which increases diffusion velocity, will cause K_l to increase, as will increasing interface surface area (*A/V*) between the two phases as a result of producing smaller bubbles during aeration or oxygenation, whilst increasing reactor volume will cause K_l to decrease (Eddy, 1979; Chen, 1991; Chen *et al*, 1992). Thus calculating K_l is both difficult and system specific, as each system will have its own specific associated coefficient value, whilst this value can further shift based on different experimental conditions (Watten & Beck, 1985; Weber & DiGiano, 1996; Lekang, 2008).

With a given K_l value and time, the gas concentration in a system can be calculated by integration of the following equation:

$$Ln\left(\frac{(C - C^*)}{(C_0 - C^*)}\right) = K_l t$$

This equation shows that, when rearranged, the concentration within the system (*C*) after a specific time (*t*) is dependent on the initial concentration of gas in the liquid (C_0), the saturation concentration of the gas in the liquid (*C**) and of course the coefficient value (K_l) according to the following equation (Lekang, 2008):

$$C = C^* + (C_0 - C^*) \cdot e^{K_l t}$$

The rate of gas transfer follows a pattern similar to that of logarithmic growth, where a liquid body devoid of a gas species present in the atmosphere will experience an initial rapid increase in the gas content transported into the liquid body. The rate of transfer will then decrease as the saturation concentration approaches 100%. $(C - C^*) / (C_0 - C^*)$ is referred to as the gas deficit, and when plotting the natural logarithm of this deficit against time, the logarithmic growth pattern is observed (figure 9).

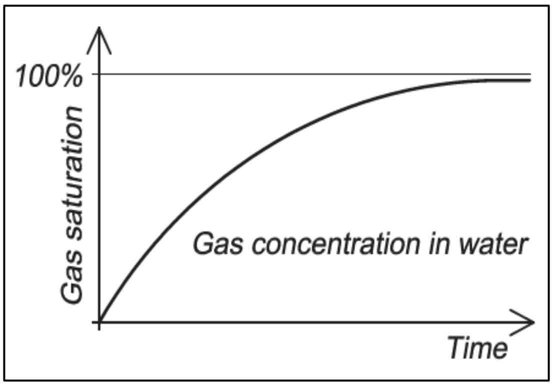

Figure 9. Showing the changing gas concentration in water over time when plotted against gas saturation (%) (Lekang, 2008).

Plotting these values has the additional function of finding the value of K_l based on the slope of the curve, which can be beneficial when evaluating and estimating the efficiencies of aeration systems (lekang, 2008).

2.3. Bubble formation and coalescence

As previously mentioned above, maximising factors beneficial to mass transfer, such as increasing surface area will lead to an increase in the gas transfer rate. In an industry such as aquaculture, efficient gas transfer is highly desirable and thus the performance of aerators with regards to the bubbles they produce and, in particular the behaviour of these bubbles, is of great importance. Maximising the surface area between the liquid and gas phases is the primary aim of most aerators, and this is done by producing small bubbles. As well as this, numerous other factors are also involved in the process of gas transfer, including bubble coalescence and the initial size of the bubbles generated. These factors, as well as methods of achieving minimal bubble size, will be further analysed below, as well as the vast effect that saltwater can have on these factors.

2.3.1. Bubble size

Gas bubbles can be generated in a number of different ways including: dissolved air, induced (dispersed), directly injected, electrolyte, and vacuum, where generally bubble formation is caused by passing air through an orifice (Motion of bubbles and bubble characteristics, n.d.). The bubble size generated will vary across different methods and systems of bubble generation however, it is not only the method of generation which will affect the resulting bubble size (Lekang, 2008). Factors such as gas flow rate has been shown in numerous articles to have a profound effect on bubble size, where increasing the flow rate will subsequently lead to the generation of larger bubbles (Alkhalidi & Amano, 2011; Alkhalidi & Amano, 2015). Additionally, the diameter of the orifice through which air is injected has also been shown to heavily influence bubble size, where a larger orifice will lead to the creation of larger bubbles (Alkhalidi & Amano, 2011; Motion of bubbles and bubble characteristics, n.d.). An important method for achieving optimal bubble size is the creation of pressure within either aeration or particle removal systems (Han *et al*, 2002). In this instance, bubble size is affected by the pressure difference across both the system of injection and nozzle type, where increasing the pressure within a system leads to the creation of smaller bubbles up until a threshold of ≈5 atmospheres, after which bubble size does not decrease further (De Rijk & Blanken, 1994; Letterman & American Water Works Association, 1999). Other factors include the type of gas used, for example; CO_2 will create bubbles larger than that of normal air in identical conditions, whilst ozone will produce smaller bubbles (Lekang, 2008).

Of particular interest to this study is the effect that salinity has on bubble size. Salinity influences bubble size as a result of altering the ionic strength of a solution and the air-water interface surface tension (Anguelova & Huq, 2017(a)). The addition of salts can have a range of effects on surface tension, and is heavily dependent on the purity of the water to which it is added, where addition to pure water can result in an increase in surface tension, and addition to water containing either organics or surfactants will result in a decrease in surface tension (Anguelova & Huq, 2017(b)). Decreasing the surface tension is more favourable, as this creates a positive surface film pressure, which in turn aids in the formation of bubbles, as well as enhancing the stabilisation of bubbles against bursting. The effect of increasing salinity also influences the bubble size spectrum, by narrowing the spectrum towards smaller bubble sizes (figure 10) (Scott, 1975; Monahan, 2001; De Leeuw *et al*, 2011). This is additionally supported by findings from a study conducted by Anguelova & Huq (2017(a)) who found that a constant volume of entrained air was found to produce increasingly small bubbles as salinity was increased. Whilst other factors such as air flow may influence bubble size in a magnitude greater than that of salinity, the function of salinity in bubble generation must be considered, as this can have additional effects on a phenomenon known as coalescence.

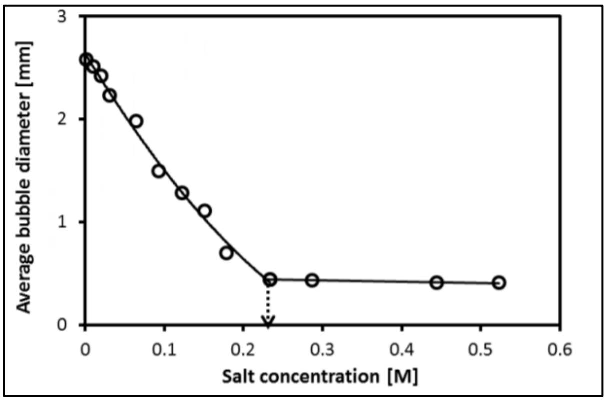

Figure 10. Illustration of the effect of salt concentration on average bubble diameter (Firouzi et al, 2015)

2.3.2. Coalescence

Coalescence refers to the merging of bubbles to form larger ones. The primary driver of bubble coalescence is due to the difference in pressure across different bubbles, where a smaller bubble with a higher pressure will try to coalesce with a larger bubble of less pressure (Lekang, 2008). The process itself can be divided into 4 separate stages: 1) bubble approachment, 2) hydrodynamic interaction between these approaching bubbles leading to the creation of a 'dimple', c) formation of a plane-parallel film leading to the disappearance of the dimple, and d) the coalescence of the bubbles, providing the attractive pressures outweigh the negative pressures along the surface of the film (figure 11) (Firouzi *et al*, 2015). In gas-liquid reactors, knowing the frequency of coalescence occurrence is important (Orvalho *et al*, 2015). The performance of gas-liquid reactors is usually dependent on the rate of gas-liquid mass transfer, and is directly correlated to bubble size and therefore surface area available for diffusion (Chaudhari & Hofmann, 1994). The frequency of bubble coalescence occurring within the system will directly influence the gas-liquid interphase surface area and, when the frequency is often, this can reduce the transport or reaction process efficiency occurring within the system (Chesters, 1991).

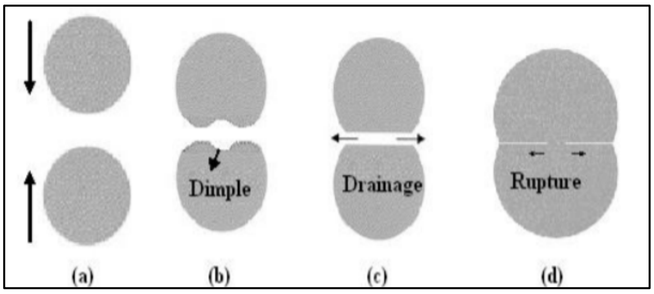

Figure 11. Visualisation of the 4 stages of bubble coalescence (Firouzi et al, 2015).

There are numerous factors that can affect bubble coalescence such as: temperature, bubble geometrical arrangement, and phase properties such as: density, viscosity, and surface tension (Orvalho *et al*, 2015). In addition, a large number of studies have shown that bubble coalescence can be diminished by the addition of surfactants or salts to a system (Lessard & Zieminski, 1971; Cartmill & Su, 1993; Lekang, 2008). For example, in pure water, gas bubbles brought into contact with one another will coalesce almost instantly. When adding either salts or surfactants to the water however, the frequency of coalescence decrease with rising salt concentrations, where inhibition of coalescence will dramatically

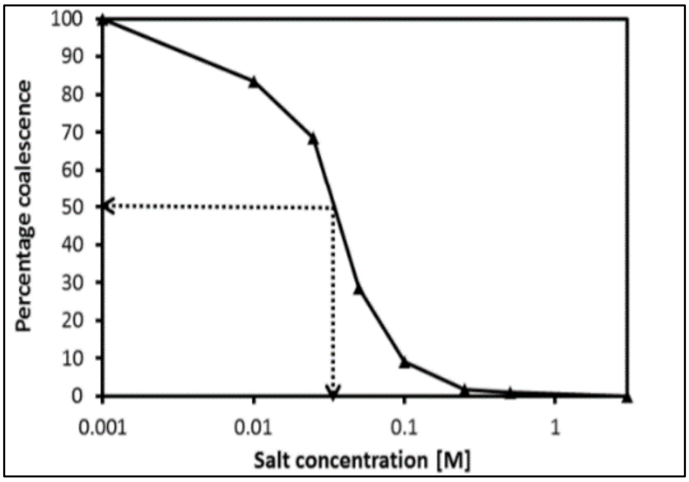

Figure 12. Illustration of the effect of salt concentration on percentage of bubble coalescence (Firouzi et al, 2015)

increase after a critical salt concentration, also known as the transition concentration, is reached (figure 12) (Nguyen, 2017). The introduction of salts or surfactants into a system, using water again as an example, will increase the liquids ion content, which interacts with bubble coalescence by altering the intermolecular forces and surface rheology of the thin liquid films between bubbles (Firouzi *et al*, 2015). Increasing the salt concentration within the liquid will lead to increasingly frequent creations of liquid films between bubbles, therefore significantly inhibiting the occurrence of coalescence (Foulk & Miller, 1931; Firouzi *et al*, 2015). It is also worth noting that the inhibition of bubble coalescence is ion specific, where different cations and anions will all have different effect on coalescence, whilst the liquid itself is also able to influence the effects of adding salts (Christenson *et al*, 2008; Nguyen, 2017; Anguelova & Huq, 2017(a)). Bubble size has been shown to influence coalescence by producing bubbles with varying pressure, recognising that bubble coalescence has also been shown to able to govern the size distribution of bubbles, further highlighting the importance of controlling bubble size and coalescence in order to maximise factors beneficial to gas-transfer (Jo & Revankar, 2010; Nguyen, 2017).

2.4. Oxygenation on RAS farms

Carrying capacity in recirculating systems is typically dependent on levels of dissolved oxygen (DO) within the water (Speece, 1981; Summerfelt *et al*, 2000). Depleted levels of DO within either an ecosystem or closed system, such as a RAS farm, can have extremely adverse effects on organisms within these systems. In order to maintain aerobic conditions within the water, and allow the metabolic functions of the fish to occur unencumbered, additional oxygen must be added to the system (Kowsari, 2008; Davis & Masten, 2009).

As previously mentioned (section 2.2.), equilibrium conditions, as well as mass transfer of gas into water, can be manipulated in order to achieve higher transfer rates and better transfer efficiencies. Thus aeration and oxygenation units are designed in order to maximise factors such as partial pressure, fraction of oxygen within the atmosphere, and surface area interface (*A/V*), whilst reducing negative factors such as film thickness between the gas-liquid interface (Lekang, 2008). Since roughly the 1970s, changing the mole fraction of gas has been done by adding pure oxygen gas, sourced from either compressed oxygen cylinders or liquid oxygen, in order to create supersaturated water, and so intensifying fish production (Speece, 1981; Losordo *et al*, 2000). Though oxygen can also be added directly from the atmosphere by using aerators and packed trickling columns, in some cases, when considering water with heavily depleted levels of DO or farms with densities of fish requiring supersaturated water, the use of pure oxygen for aeration is preferred in aquaculture. Based on gas theory (section 2.2.), saturation concentrations post oxygenation can be roughly five times that of standard air aeration, and the addition of pure oxygen gas at a pressure of 1 atm and 15°C can increase the solubility of DO from roughly 10.1 to 48.1 mg/l^{-1} and up to 97.0 mg/l^{-1} at 2 atm (Colt, 1984; Colt & Watten, 1988; Barber, 2014). Additional factors such as retention time of bubbles in the water, a result of bubble size and tank depth, can also affect oxygen absorption, with short retention times producing efficiencies as low as 3-7% with direct gas diffusion into the culture tanks (Summerfelt *et al*, 2000). Aeration using pure oxygen also has the added advantage of stripping nitrogen from the water, as nitrogen in supersaturated concentrations can lead to gas bubble disease in the fish. As with oxygen, the stripping efficiency of an oxygenation unit also relies on retention time (Colt & Watten, 1988). Therefore recirculation systems are applying oxygenation technologies using pure oxygen and designated oxygenation units in order to increase fish production, however the drawback with employing these techniques is that they are energy intensive and in some cases can account for up to 60% of the overall energy costs put into the system (Severson *et al*, 1986; Barber, 2014). Below the main oxygenation systems commonly utilised on RAS farms will be summarised.

2.4.1. Down flow Bubble Contact Aerator (DBCA)/Speece Cone

Down flow Bubble Contact Aerators (DBCA), or Speece Cones, are a popular choice of farmers for a pressurized oxygen delivery system. Pressure is achieved via pumps and these cones typically operate at pressures of around 1.4 bar, however this consumes large quantities of electricity (Bregnballe, 2010). These units are shaped like upside-down cones, with an oxygen input at either the middle or near top of the cone, and a water inlet at the top (see figure 13). The velocity of the water entering the cone is greater than the velocity of the rising bubbles from the oxygen input, and due to the conical design, the increasing surface area down the length of the cone slows the velocity of the water, where eventually water exiting the chamber is slower than that of the rising bubbles (Speece, 1971 & Malone, 2013). This leads to the trapping of bubbles within the chamber and results in extended contact time between both gas and water, and this, combined with the additional effects of the turbulence created by the bubbles, improves the transfer of oxygen and therefore the overall efficiency where ≈90% of

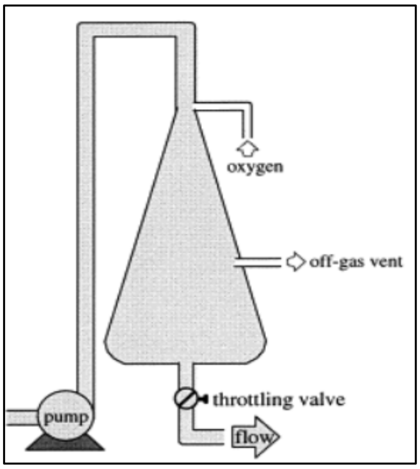

Figure 13. Simple example of a downflow bubble contact aerator (Summerfelt et al, 2000).

the oxygen injected into the system can be diffused, with water leaving the system containing oxygen concentrations of 25mg/L^{-1} (Losordo *et al*, 2000; Kowsari, 2008).

2.4.2. U-tube Diffusers

U-tube diffuser systems consist of a vertical shaft ≈10-45m deep, usually buried, and below tank level to both save space and energy requirements due to the reduction of required hydrostatic pressure (Losordo et al, 2000). This shaft is either segregated into two sections or consists of two concentric pipes (see figure 14). Oxygen is injected and mixed with the water at the inlet pipe to the U-tube itself, and the gas-liquid mixture flows down to the bottom of the tube through the contact loop where the transfer of oxygen occurs (Colt & Watten, 1988). Oxygen transfer efficiency is greater nearer the bottom of the U-tube due to increases in pressure that can reach up to 2 bar (Helfrich & Libey, 1991). Oxygen transfer efficiencies for this type of system are typically either around or below 70% (≈15-20mg/L^{-1}), however the efficiency can be increased by recycling the oxygen rich 'off-gas' back into the system (Watten & Beck, 1985; Losordo et al, 2000).

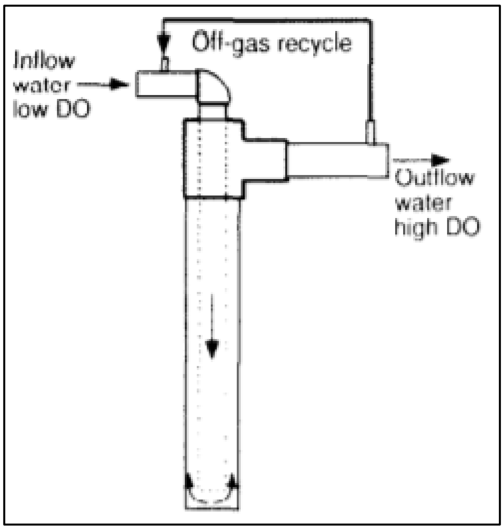

Figure 14. Showing a U-tube diffuser (Losordo et al*, 2000).*

2.4.3. Low Head Oxygenators

These systems are typically more common in raceway systems, due to the small differences in elevation between adjacent tanks, and so differ from the first two systems described due to the lower pressures that they operate at (≈0.1 bar) (Bregnballe, 2010). Low head oxygenators consist of horizontal distribution plates as well as vertical contact chambers positioned adjacent to the distribution plates. Water is distributed via the plates and trickles down through the unit whilst pure oxygen is added from the side of the system to one end of the chamber (figure 15). Oxygenated water exits the system into the tank/pool below whilst effluent gasses exit via holes through the adjacent chambers (Davenport *et al*, 2001; Vilbergsson *et al*, 2016). These systems are highly

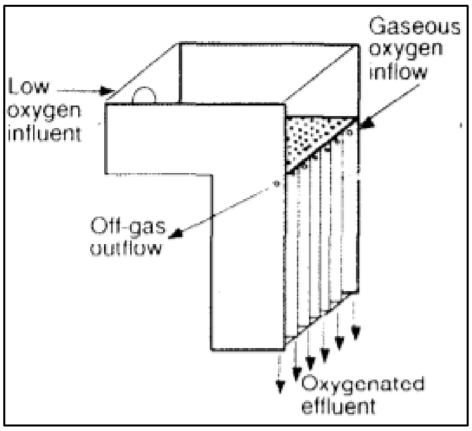

Figure 15. Showing a simple schematic of a low head oxygenator (Losordo, 1997).

dependent on numerous factors that determine effluent DO concentrations such as: flow rates of both gas and water, number of chambers, and contact time in the system (Timmons, 1994).

2.4.4. Pressurized Packed Column

Pressurized packed columns are designed as enclosed pressurized chambers, within which sit high surface area specific media. This design is almost identical to that of packed trickling filters used for stripping and aeration, but instead pure oxygen is blown into the bottom of the column and under pressure (Lekang, 2008). Oxygen transfer occurs as water entering the top of the column cascades down through the media counter current to rising oxygen. These systems can achieve oxygen transfer efficiencies of ≈50-90% leading to effluent DO concentrations of >100mg/L[1] (Losordo et al, 2000). Though levels of effluent DO can be very high, the system has several drawbacks, mainly in the form of build-up of biological growth on the media (bio-fouling) and the high energy requirements needed to maintain pressure within the column (Losordo et al, 2000; Malone, 2013).

2.4.5. Pressurized Spray Column

This is an alternate, yet still similar, design to that of pressurized packed columns. The systems differ due to the absence of media within the spray column, as well as the presence of a bio-fouling resistant pressurized nozzle at the top of the unit that distributes water droplets throughout the column, with oxygen rising throughout the column (Malone, 2013).

2.4.6. Non-pressurized Spray/Packed Column

Both packed and spray columns can also be designed to operate without pressure. Whilst oxygen absorption efficiencies are not as high when compared to the pressurized systems (≈40-55% vs 50-100%), the required power input for these system is in fact less. It is also worth noting that these systems can also act as efficient nitrogen strippers (Hackney & Colt, 1982).

2.4.7. Oxygen Injection

This oxygenation method mainly refers to venturi systems. These systems consist of a pressure pump leading directly into a tube with a segment of reduced cross-sectional area which increases water velocity whilst decreasing pressure (figure 16) (Colt & Watten, 1988). Oxygen is injected into the pipe either directly before the venturi or at the point where water velocity is at its highest. This is done as turbulence created by the high velocity leads to excellent mixing qualities and thus injected oxygen is dispersed throughout the water as fine bubbles, increasing the surface area for diffusion. In order to achieve desired absorption efficiency these systems need to be run under high pressures (≈4-6 bar). Whilst transfer rate is maximised by utilising the system in saltwater rather than freshwater, due to the reduced bubble size (Collins *et al*, 1984; Kils, 1977). Oxygen transfer efficiencies for venturi designs can vary greatly, with various sources claiming various figures between 15-95%, though higher efficiencies (≈80-95%) are currently expected of venturi designs (Colt & Watten, 1988; Aeration and gas stripping: Water Treatment, n.d.).

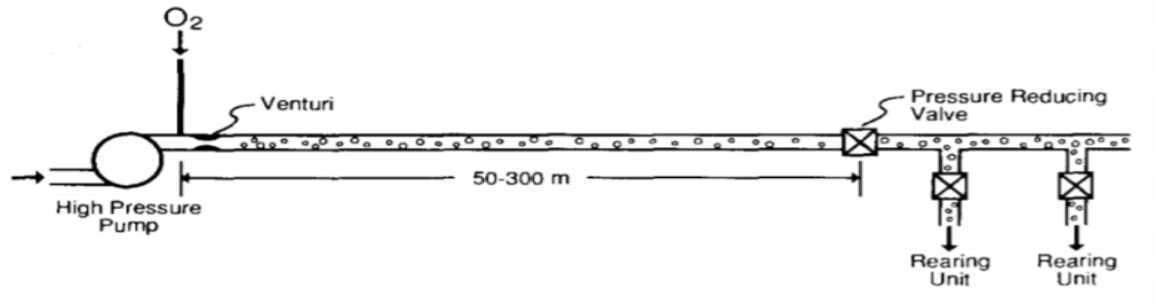

Figure 16. Showing simple schematic of a venturi oxygen injector aerator (Colt & Watten, 1988).

2.4.8. Diffused Aeration

This system is again very similar to that of blown air systems for diffusion of air. A diffuser is placed at or near the bottom of the tank and pure oxygen is diffused into the water column. These aerators have low absorption efficiencies, and in many cases are reserved for emergency use (Colt & Watten, 1988).

3. Materials and Methods

The experiments were carried out between 24/09/2018 – 01/11/2018 at the science and technology building run by the faculty for science and technology; based on the NMBU main campus in Ås. In total two experiments (with experiment 1 containing 3 separate procedures) were performed.

3.1. Experiment 1

3.1.1. Experiment Conditions

Testing Tank

The first testing tank set up for investigating bubble diameter, rising velocity and coalescence had a standard height of 1m, total ø of 150mm, an inner ø of 142mm, and a volume of 16L (figure 17). This tank was made of acrylic and was completely open at the top, and sealed at the bottom by a Polyvinyl chloride (PVC) panel (total ø: 170mm & height: 15mm) with countersunk screw threading. This panel was screwed onto the bottom of the tank, giving the tank a total height of 1.015m. The PVC panel had a small hole (ø: 15mm) drilled through the centre, giving access to the tank from below (figure 18). Through this hole, silicon tubing (total ø: 8mm & internal ø: 6mm) serving as an airline was fed into the tank, whilst any gaps were sealed with silicon sealant. The end of the tubing protruding into the tank was fitted with a needle (ø: 0.6mm & length: 25mm) to act as an aerator (figure 18 & 19). The opposite end of the tubing could be fixed to either a 10ml or 60ml syringe which was used to provide normal air into the tank (figure 19). Additionally, separate 10cm segments of a clear acrylic ruler could be fixed, using either sealant or tape, depending on the procedure, to the interior of the tank at observation points A, B, C and D (figure 19). Observation point C was 5cm above the tip of the needle, with point A 5cm below the 15L mark on the side of the tube. Finally point B was positioned at the 9L mark, and point D at the 4L mark (figure 17). The tank was modified for procedures 2 and 3 of experiment 1, where the airline fed through the bottom of the tank would be removed, and the subsequent hole refilled with sealant so that the tank could only be accessed from the top.

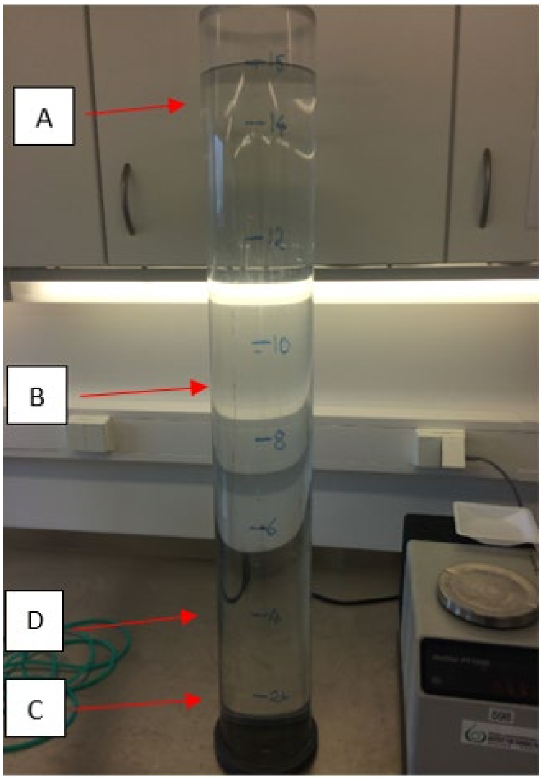

Figure 17. The testing tank used and the observations points during experiment 1.

Figure 18. Hole through the PVC panel at the bottom of the tank (left), silicon tubing sealed and fed through the underside of the panel (centre), & needle extruding from the silicon tubing and sealant through the top side of the panel (right).

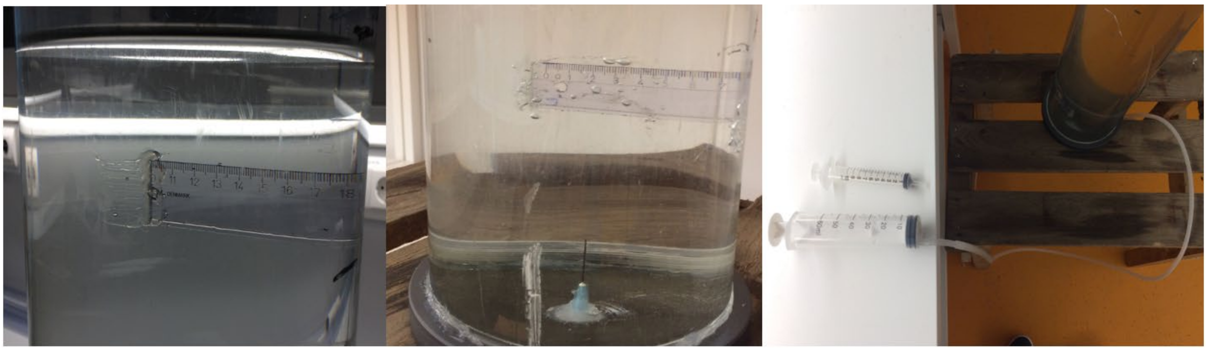

Figure 19. Ruler fixed to the inside of the tube 5cm below the level of the water (left) and 5cm above the needle tip (centre), & the two syringes used for blowing air into the tank through the silicon tubing.

Other Equipment

Webcams: These webcams were 8mm USB webcams that could be connected to a computer. They were positioned directly facing observation points within the testing tank, at a distance of 10cm from the perimeter of the tank (figure 20).

Webcam 'holders': In order to secure the webcams at the desired positions, two 3D printed 'holders' were designed (figure 20). These devices could be snapped into place outside the perimeter of the tank, whilst the webcams could be fixed to the vertical cylindrical section of the device.

Airline splitter: PVC tubing device (total ø: 6mm & internal ø: 4mm), that split the main silicon airline into two airlines when testing more than one needle (figure 20).

Needle 'bracelet': The needle bracelet was a heavy PVC tube (total ø: 130mm, inner ø: 110mm, height: 130mm). Two rulers were fixed to this tube in order to act as a base to which the needles could be fixed and also to act as a measuring device so the distance of the needles could be measured (figure 21). The addition of a second needle, and thus a second airline required the bracelet to be lowered into the testing tank from the open top. Thus the airlines were strapped, using tape, through the bottom of the grey PVC tube so that the whole device could be lifted and lowered into the tank (figure 21).

Figure 20. The webcam bracelet (left), airline splitter (centre) and webcam attached to the webcam bracelet (right).

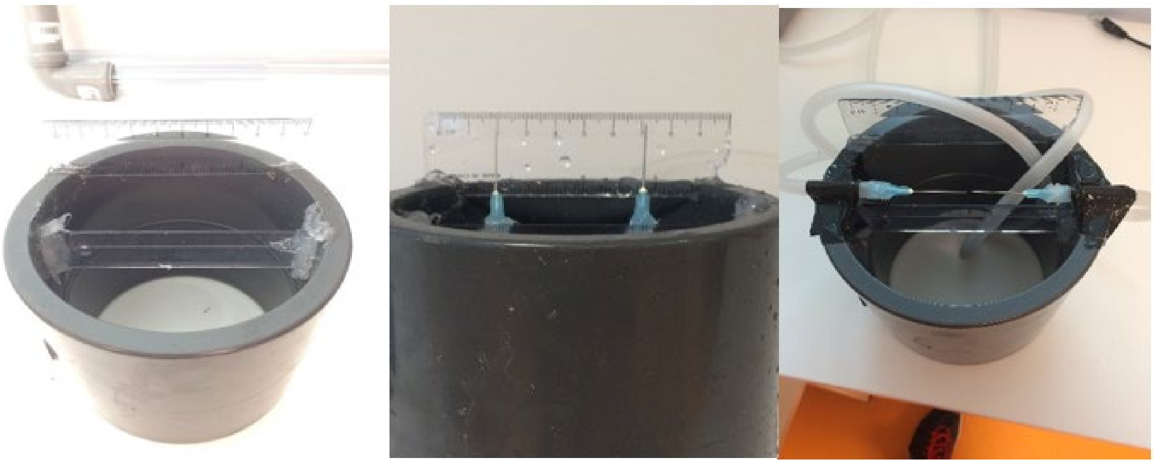

Figure 21. The needle bracelet for testing multiple needles (left), with needles added for testing procedures 2 (centre) and 3 (right).

3.1.2. Experimental Design

Procedure 1 – bubble diameter

Hypothesis:

1) Bubble size at observation point A (top) will be significantly larger than bubble size at observation point C (bottom) in freshwater.
2) Bubble size at observation point A (top) will be significantly larger than bubble size at observation point C (bottom) in saltwater.
3) Bubble size at both observation points in saltwater will be significantly smaller than bubble size at both observation points in freshwater.

Design:

The testing tank was filled with 15L of fresh tap water. Using the 10ml syringe to blow normal air, 10 bubbles in slow succession were blown from the needle protruding from the bottom of the tank. Using the webcams, these 10 bubbles were photographed as they passed observation points C and A. For recording bubble velocity, a further 10 bubbles were blown from the needle and the time taken to reach the surface from the moment of release from the needle was recorded. Upon completion of these tasks, the freshwater was replaced with saltwater. Saltwater was created by mixing salt with freshwater (35g salt per litre of freshwater), thus in total 525g of salt was required to make up the saltwater. The procedure of blowing and photographing bubbles was then repeated in the saltwater.

Observation:

Photographs taken were visually analysed on a computer. The bubble size (diameter) was read from the photographs using the mm scale from the rulers at observation points C and A. Approximations were made to the nearest mm.

Procedure 2 – bubble coalescence; needle distance

Hypothesis:

1) The overall frequency of bubble coalescence occurrence at all needle distances (1-5cm) tested will be significantly higher in freshwater than in saltwater.
2) The frequency of bubble coalescence occurrence will decrease as the distance between the needles is increased in both fresh and saltwater.

Design:

The tank was drained, washed, and then refilled with 15L of fresh tap water. The needle protruding through the bottom of the tank was removed and the hole was sealed. Using the 'needle bracelet', two needles were positioned facing vertically at a distance of 5cm between the tips of the needles. The bracelet was then lowered into the tank using the airlines. The rulers were then fixed to observation points B and A. Clusters of roughly 10-15 bubbles of normal air were blown from each of the two needles simultaneously, this time using the 60ml syringe. As the bubbles passed observation points B and A, they were video recorded using the webcams. Five video recordings were made at the 5cm distance, after which the needles were repositioned 1cm closer to each other. Five recordings were made for all the remaining distances. As with procedure 1, after completion of recording, the tank was drained and was refilled with saltwater of the same concentration, and the procedure was repeated, again for distances of 5-1cm.

Observation:

The video recordings were replayed on a computer. During these videos, moments where bubbles passed the observation points were paused, and images were taken. These images were then visually analysed and the total number of bubbles that could be clearly identified were counted from the image. In order to determine if bubble coalescence had occurred, the total number of bubbles counted at observation point B would be compared with the total number of bubbles counted at observation point A, where less bubbles counted at point A would indicate that coalescence had occurred.

Procedure 3 – bubble coalescence; needle angle

Hypothesis:

1) Frequency of bubble coalescence occurrence at both needle angles tested will be significantly higher in freshwater than in saltwater.
2) Frequency of bubble coalescence occurrence will decrease when increasing the needle angle in both fresh and saltwater.

Design:

The tank was drained, washed, and then refilled with 15L of fresh tap water. Using the 'needle bracelet', needles were fixed to the ruler facing each other, with both needles at a 20° angle. As with procedure 2, the rulers within the tank were removed, and the 'needle bracelet' was lowered into the tank, however this time only one observation point (point D) would be used when reattaching the rulers. Clusters of bubbles of normal air were blown from both needles, and similar to procedure 2, the bubbles were video recorded using the webcam as they passed point D. Five recordings of the bubble clusters were made. The 'needle bracelet' was then withdrawn and the needles were then repositioned to face each other horizontally at 0°, and the procedure of blowing and recording 5 bubble bursts was repeated. Upon completion of this, the tank was drained and refilled with the same saltwater concentrations that had been used before, and the procedure was repeated.

Observation:

The video recordings were replayed on a computer. During these videos, moments where bubbles passed observation point D were paused, and images were taken. These images were then visually analysed and any bubbles ≥5mm in diameter that were observed from the image were assumed to be coalesced bubbles.

3.1.3. Observation Analysis

Procedure 1

The bubble diameters were entered into an excel spreadsheet and values such as the mean, standard deviation, and size increase were calculated for observation points C and A in both fresh and salt water. In order to determine if there was any significance between bubble size at observation points C and A in freshwater and then again in saltwater, an independent two-samples T-test (considering $P<0.05$ as significant) using SPSS (version 25.0) was conducted (IBM Corp, 2017). Additionally the independent two-samples T-test was also used for determining any significant difference in bubble size between observation point C of fresh and saltwater, and also for observation point A of fresh and saltwater.

Procedure 2

The number of bubbles counted for each of the five recordings at each different distance was entered into an excel spreadsheet, and the total number of bubbles at observation points B and A was calculated for each needle distance tested. The difference between the total bubbles observed at points B and A was then calculated, where positive values would indicate more bubble observed at the top observation point (A) than the bottom (B). In order to determine the effect of fresh vs. salt water, and needle distance on bubble number observations and therefore bubble coalescence, a 2-way ANOVA test (considering $P<0.05$ as significant) using SPSS (version 25.0) was conducted using the bubble difference between the two observation points instead of the absolute numbers recorded at each point (IBM Corp, 2017).

Procedure 3

The number of bubbles ≥5mm counted for each of the five recordings was entered into an excel spreadsheet, and the total number for each angle tested was calculated. No statistical test would be carried out (reasons stated in the discussion).

3.2. Experiment 2

3.2.1. Experiment Conditions

Test Aerator Design

A test aerator was constructed using several different units of transparent PVC piping, as well as extension fittings and bend units. The fitted pipe units would form the 'aeration unit', whilst this would additionally be combined with two water 'recycling tanks' and a single 'holding tank'. The general principle of the system is described below with accompanying schematics and figures. Certain units of interest within the system will also be described in greater detail below.

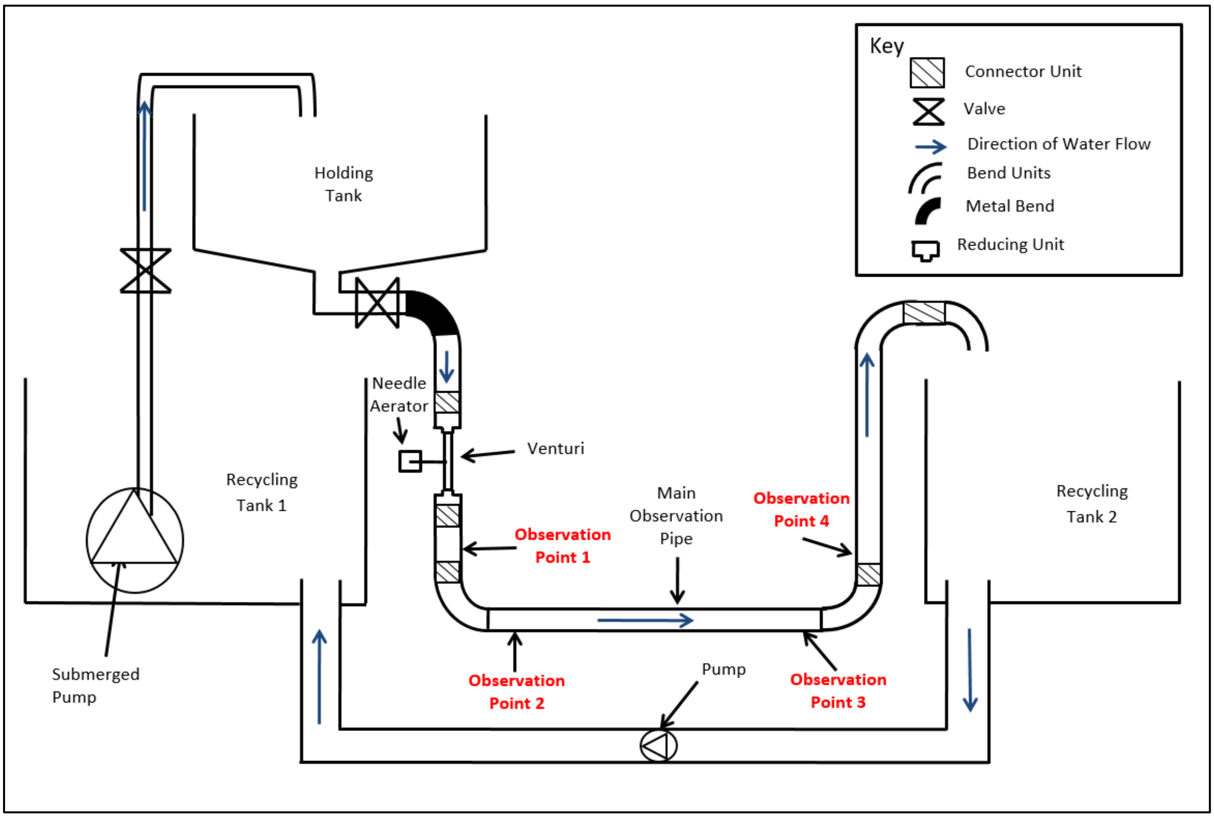

Figure 22. A simple illustrated schematic view of the system from the side. Heights at which different units are placed is not considered in this sketch, whilst the sketch itself is at a rough, not exact scale.

The entire system was designed so that water could be recycled. The system started with recycling tank 1, within which the majority of the water would be held. From recycling tank 1, a submerged pump fed water up into the holding tank. The holding tank was used so that a constant desired volume of water could be kept above the aeration unit in order to generate different water flows that could additionally be kept constant when experimenting. The bottom of the holding tank also had a valve to allow quicker filling of the tank. From the valve the water was fed into the aeration unit via a metal-plastic connector unit, where the water would then flow through the first PVC pipe above the venturi, before then flowing into the venturi itself and then into the PVC pipe below. The water then enters the first bend unit within the system, and is fed into the main horizontal observation pipe before then entering the second bend unit. The water then runs up the final PVC pipe before then entering the outlet. From the outlet, the water is emptied into recycling tank 2. This recycling tank had an outlet at the side of the tank near the bottom, and from this outlet water was pumped back into recycling tank 1, completing the cycle. The system had four 'observation points': 1, 2, 3 and 4, from which video recordings of bubble size could be made through the transparent pipe sections. Point 1 was situated in the centre of the PVC pipe directly below the venturi. Points 2 and 3 were both located along the main observation pipe, with one directly after the first bend unit, and the other just before the second bend unit. The final observation point 4 was located directly after the second bend unit (figure 22).

Equipment

Main observation pipe: This was a 2m long transparent PVC pipe (total ø: 32mm & internal ø: 28.4mm) (GPA Flowsystem AS).

Pipe above the venturi: The pipe used was identical to the main observation pipe, however this section of pipe had been cut to 20cm length.

Pipe below the venturi: The pipe used was identical to the main observation pipe, however this section of pipe had been cut to 50cm length.

Venturi: The venturi was designed to have a reduced cross sectional area. This was achieved by using several PVC 'reducing' units (total ø: 32mm & internal ø: 25mm), between which was a transparent PVC pipe (total ø: 25mm & internal ø: 22mm) (GPA Flowsystem AS). A small hole (1mm) was drilled through one side of the PVC pipe so that a needle (ø: 0.6mm & length: 25mm) could be inserted to act as an aerator. The needle was sealed into the hole using silicon sealant as in experiment 1. Air was fed through the needle using the same silicon tubing that had been used in experiment 1, whilst instead a 60ml syringe would be used in order to provide more air into the system.

Observation points: In order to make up these points, 10cm sections of rulers were attached to the outside of the PVC pipes using tape. These rulers were positioned so that the mm scale was slightly to the side of where observations would be made. Observations were carried out using the 'slow motion' video capture on a mobile phone.

Bends: Bends used on the system were drainage bend units. Made of polypropylene (PP) and at an angle of 87°, these units had an internal ø of 32mm on the 'inlet' section of the bend with a rubber O-ring, whilst the 'outlet' section of the bend had an internal ø of 28mm. In order to be connected to subsequent pipes from the 'outlet' section, a connector unit had to be fitted between the bend unit and adjacent pipe.

Connectors: Connectors were necessary to secure piping together whilst removing the possibility of leakage. These were PP 'expansion sleeve' units sourced from Bauhaus (internal ø: 32mm). Both ends of the connector units were fitted with O-rings.

Holding tank: The holding tank was a large, non-transparent PVC cylindrical tank (volume: 200L) with a conical shaped funnel at the bottom. This tank additionally stood on a metal frame (not shown in figure 22) and had a small opening at the top to allow the insertion of the pipe from the submerged pump. At the bottom of this tank was the outlet which was screwed into the bottom of the funnel. The outlet itself comprised of a large section of metal piping which had an open/closed valve attached to it. This metal section additionally had a metal-plastic connector unit attached after the valve so that a watertight seal could be achieved with the PVC pipes.

Other Equipment

'Camera': The webcams used in experiment 1 were not suitable for this experiment due to the fact that PVC is not as transparent as acrylic. Instead an Iphone was used to function as a video recorder due to the enhance image campture.

Pumps: Two pumps were used to aid in maintaining the system. The first was a submerged centrifugal pump, whilst the second was dry-placed centrifugal pump.

3.2.2. Experimental Design

Procedure

Experiment 2 investigated the effect of water velocity on the frequency of bubble coalescence, as well as observing the frequency of bubble coalescence at different observation points within the test aerator.

Hypothesis:

1) Bubble size at all observation points and system flows will be significantly larger in freshwater than those in saltwater.
2) Bubble size will decrease as water velocity increases in both fresh and saltwater.
3) Bubble size will be largest at observation point 3 (the end of the horizontal observation pipe).
4) Frequency of bubble coalescence occurrence at all observation points and system flows will be significantly higher in freshwater than in saltwater.

5) Frequency of bubble coalescence occurrence will increase as water velocity is increased in both fresh and saltwater.

Design:

The system was filled with approximately 400L of fresh tap water, and the valve at the bottom of the holding tank was opened so the system could run for a couple of minutes to eliminate all air pockets and bubbles from within the aeration unit. The system was initially set at 80L in the holding tank. Once equilibrium at 80L was achieved, the flow rate of the system was measured. This was done by measuring how long it took the outlet water of the 'aeration unit' to fill a container to 10L. After the flow rate had been measured, a slow stream of air was blown from the aeration needle into the system using the 60ml syringe. As the air was added, the bubble size was recorded using the cameras slow motion video capture at each of the four observation points. The camera was positioned so that each of the rulers attached to the PVC pipes was kept in the same field of view of the camera. Each observation point was recorded twice, thus in total of eight air injections were made from the syringe. Upon completion of the required eight recordings, the flow rate of the submerged pump was increased and the system was rebalanced to 100L in the holding tank, and the air injecting and recording procedure was repeated. Eight video recordings were made at system flows of 80, 100, 120, 140, 160, 180 & 200L.

Once all necessary recordings had been made, salt was then added to the system. The addition of salt, as with experiment 1, was based on 35 grams of salt per litre of water, and thus a total of 14kg was added to the system. The system was then allowed to run without interference to the flow rate for roughly 1 hour in order to allow all the salt to dissolve. Once the salt was observed to have dissolved, the procedure of the setting the system to 80L and taking eight recordings at the 4 observation points was repeated. As with freshwater the procedure was repeated for 100, 120, 140, 160, 180 & 200L.

Observation:

The video recordings were replayed on a computer. During these videos, moments where bubbles passed the observation points were paused, and images were taken. Ten images were taken for each observation point at each system flow, where in total 560 images were taken. Bubble size was recorded in the same way to that in procedure 1 of experiment 1, where the photographs was visually analysed on a computer and the bubble diameter was read from the mm scale of the rulers at the observation points. As with procedure 3 of experiment 1, any bubble observed that had a diameter ≥5mm was classed as a coalesced bubble.

3.2.3. Observation Analysis

The results were summarised in an excel spreadsheet and both the mean and standard deviation for bubble diameter at each observation point and each flow velocity were calculated, whilst the occurrence of bubble coalescence at each observation point and each flow velocity was additionally calculated. At each observation point at each system flow, a minimum of ten observations would be entered, whilst a maximum of twenty was allowed. This was due to the fact that some images contained only one bubble, whilst others contained many. Separate methods of analysis were employed for bubble size and bubble coalescence.

Bubble diameter: For investigating the difference in bubble diameter as a result of the three variables; water condition, system flow, and observation point, a 2-way ANOVA test was run on SPSS (version 25.0) (IBM Corp, 2017). This method was chosen due to the mean values in size that were calculated from all the observations made.

Bubble coalescence: Total number of coalesced bubbles observed per observation point at each system flow was converted to the percentage of coalesced bubbles observed. Unlike with analysing bubble size, no statistical tests was used to analyse bubble coalescence, as the data was presented as a single percentage value for each observation point at each system flow. Instead the data was represented in tables, showing the total number of coalesced bubbles in both fresh and saltwater, as well as the mean percentage values observed for each system flow, and each of the four observation points in fresh and saltwater.

4. Results

4.1. Experiment 1

4.1.1. Procedure 1 – Bubble diameter at two different water depths

Analysis of the data showed that there was not a significant difference (t-test: considering $P<0.05$ as significant) in the bubble diameter between the bottom point (C) (M=4.16±0.57mm) and the top point (A) (M=4.55±0.51mm) in freshwater, conditions; $t(28)=-1.939$, $p=0.063$. The same phenomenon was observed in saltwater as there was no significant difference (t-test: considering $P<0.05$ as significant) in the bubble diameter between points C (M=4.08±0.51mm) and A (M=4.10±0.57mm) in saltwater, conditions; $t(20)=-0.072$, $p=0.943$ (figure 23).

When comparing the same observation points it was found that there was no significant difference (t-test: considering $P<0.05$ as significant) in the bubble diameter at point C in fresh (M=4.16±0.57mm) and saltwater (M=4.08±0.51mm), conditions; $t(22)=0.373$, $p=0.713$. However the same result was not concluded for observation point A, where it was found that there was a significant difference (t-test: considering $P<0.05$ as significant) in the bubble diameter in fresh (M=4.55±0.51mm) and saltwater (M=4.10±0.57mm), conditions; $t(26)=2.173$, $p=0.039$ (figure 23).

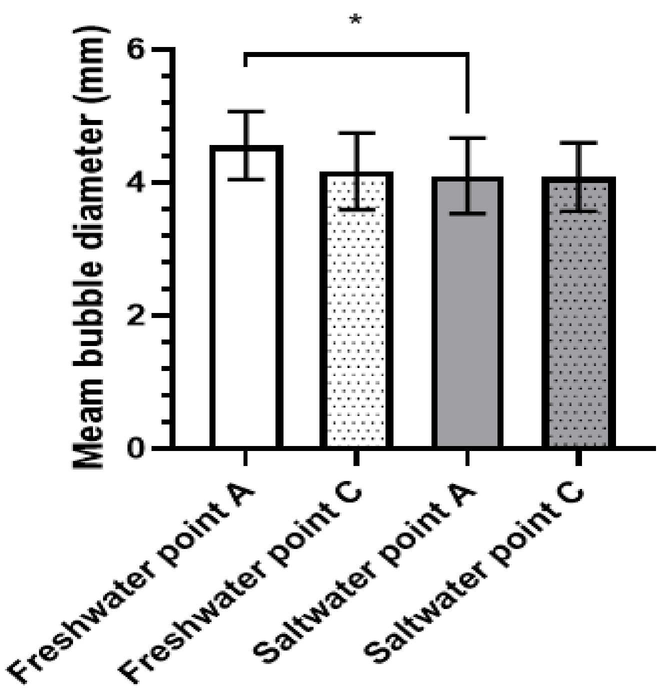

Figure 23. Mean bubble diameter and standard deviations observed at point C (bottom) and point A (top) in fresh and saltwater, with significant differences between point A of fresh and saltwater indicated (indicates a P value <0.05).*

Bubbles observed in freshwater at the top observation point (A) were marginally larger than those observed at the bottom point (C), and showed an increase in diameter of 0.38mm from 4.16mm to 4.55mm. The observations in saltwater showed almost no increase in bubble diameter, where mean bubble diameter at point C was observed to be 4.08mm, and increased by 0.02mm to 4.10mm. Standard deviations calculated were between 0.51mm – 0.57mm for all of the separate mean values. Bubbles recorded at the top observation point for fresh water were 0.55mm larger in diameter than those recorded at the same observation point in saltwater, whilst bubbles recorded at the bottom observation point in freshwater were 0.08mm larger than those of the same observation point in saltwater (figure 23). A sample image is provided in order to illustrate the observations on bubble size (figure 24).

Figure 24. One of the images taken in order to observe bubble size. The bubble can be observed between the 14cm and 15cm marks of the ruler and sitting just above.

Bubble rising velocity was almost identical between the two water conditions tested, with bubbles in saltwater (0.34m/s) rising marginally faster than those in freshwater (0.33m/s) (appendix 2).

4.1.2. Procedure 2 – Bubble coalescence at different needle distances

Results of the 2-way ANOVA test (considering $P<0.05$ as significant) on the effect of water condition on bubble coalescence yielded an F value of $F(1,40) = 5.597$, $p=0.023$, indicating that there was a significant difference between freshwater (M=0.76±4.94) and saltwater (M=3.80±4.69). The effect of needle distance on bubble coalescence produced an F value of $F(4,40) = 2.508$, $p=0.570$, meaning that there was no overall significant difference between 1cm (M=-1.30±6.13), 2cm (M=2.00±3.06), 3cm (M=3.20±4.83), 4cm (M=2.60±4.20), and 5cm (M=4.90±5.09). The interaction effect of water condition*needle distance was also found to not be statistically different $F(4,40) = 0.992$, $p=0.420$ (tables 1 & 2, figure 25 & 26).

Although there was no overall significant difference between the needle distances, pairwise comparisons from the ANOVA test showed that there was a significant difference in the frequency of bubble coalescence between 1cm and both 3cm (p=0.033), and 5cm (p=0.004), whilst there was no significance between 1cm and 2cm (p=0.112) and 4cm (p=0.062) (tables 1 & 2, figure 25 & 26).

Freshwater:

The mean number of bubbles observed at both the top and bottom observation points was highest at 1cm, with slightly fewer bubbles observed at the top observation point. Mean numbers of bubbles were observed to decrease for both 2cm and 3cm, however at these needle distances, more bubbles were observed at the top observation point. Observations at 4cm and 5cm produced mean bubble numbers that also consecutively increased in relation to 3cm. At both of these observation points, more bubbles were observed at the top observation point than at the bottom. Deviations within the observations themselves varied, with high standard deviations calculated for observations at 1cm and 5cm, whilst smaller deviations were calculated for 3cm and the top observation point at 4cm (table 1 and figure 25).

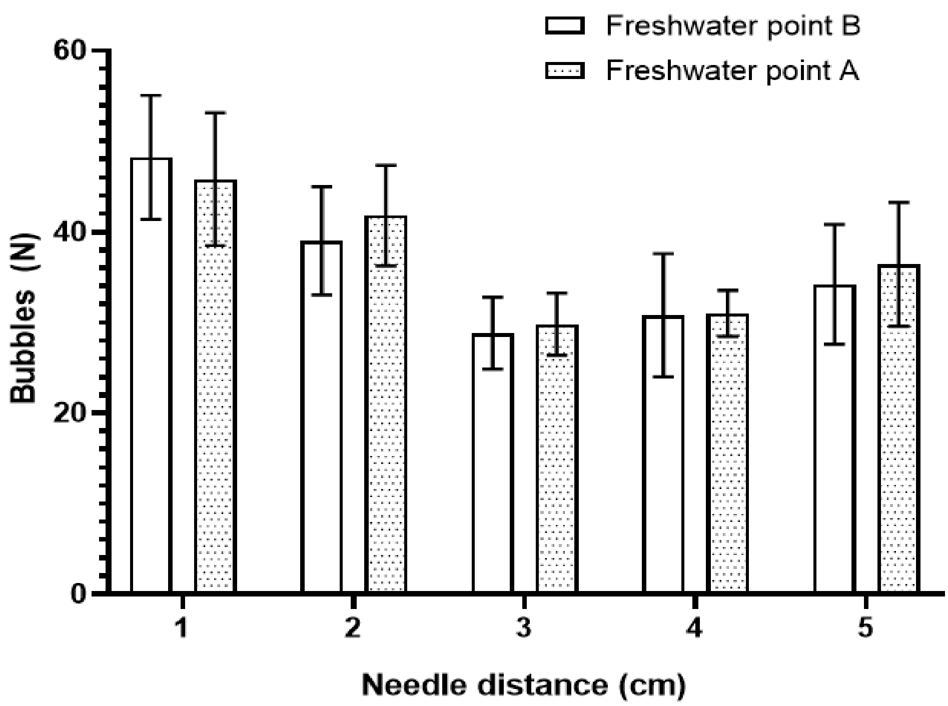

Figure 25. Number of bubbles observed at both the top (A) and bottom (B) observation points at the different needle distances tested in freshwater, as well as the standard deviations calculated for each set of observations.

Table 1. The number of bubbles at observation point A (top) and observation point B (bottom) for each recording at each needle distance in freshwater, as well as the mean and standard deviation values.

Needle distance (cm)	1		2		3		4		5	
Point	**Bottom (B)**	**Top (A)**	**Bottom (B)**	**Top (A)**	**Bottom (B)**	**Top (A)**	**Bottom (B)**	**Top (A)**	**Bottom (B)**	**Top (A)**
Recording 1	46	57	35	38	34	28	25	30	24	28
Recording 2	59	48	34	37	29	31	31	33	39	34
Recording 3	50	45	39	41	28	31	37	32	33	34
Recording 4	41	38	38	42	30	34	38	33	34	41
Recording 5	45	41	49	51	23	25	23	27	41	46
Mean	48.2	45.8	39.0	41.8	28.8	29.8	30.8	31.0	34.2	36.4
Std. dev.	6.83	7.33	5.96	5.54	3.96	3.42	6.80	2.55	6.61	6.84

Saltwater:

Unlike in freshwater, observations at 1cm in saltwater produced the lowest mean number of bubbles observed. Needle distances of 2cm, 3cm, and 4cm were shown to produce similar mean values for bubble numbers observed at the top observation point, whilst there was slightly more deviation between the observations made at the bottom point. The number of bubbles observed was the highest at both the bottom and top observation point at 5cm. Far more variance was observed between the standard deviations calculated in saltwater, where the highest values of deviation were observed at 2cm, whilst the lowest values were observed at 3cm and the bottom observation point at 5cm (table 2 and figure 26).

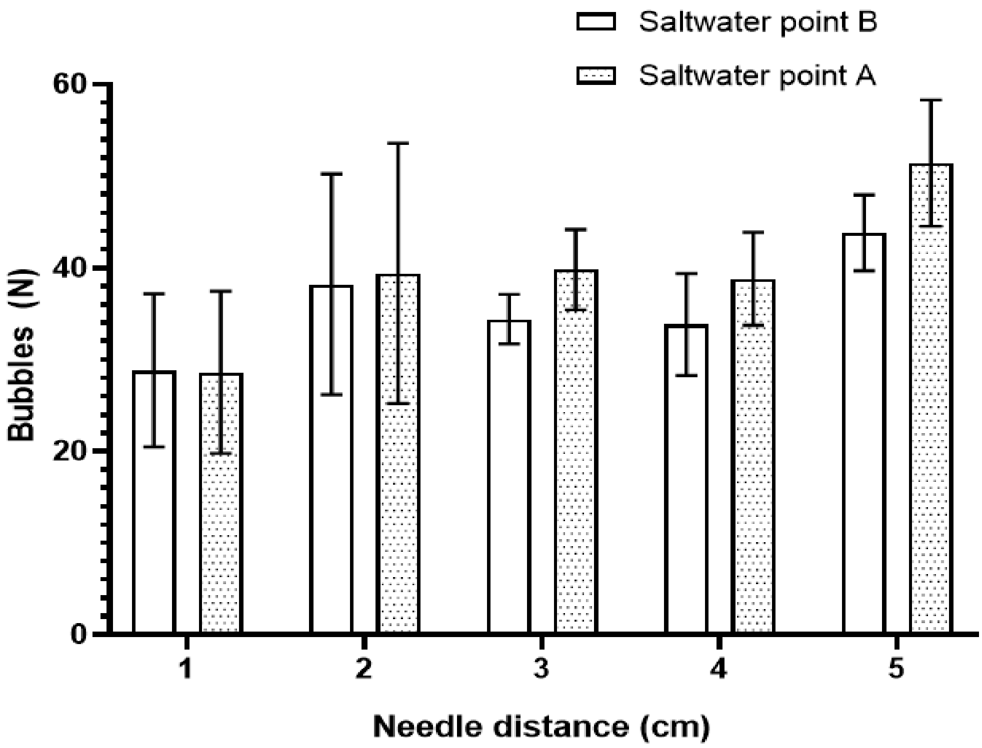

Figure 26. Number of bubbles observed at both the top (A) and bottom (B) observation points at the different needle distances tested in saltwater, as well as the standard deviations calculated for each set of observations.

Table 2. The number of bubbles at observation point A (top) and observation point B (bottom) for each recording at each needle distance in freshwater, as well as the mean and standard deviation values.

Needle distance (cm)	1		2		3		4		5	
Point	**Bottom (B)**	**Top (A)**	**Bottom (B)**	**Top (A)**	**Bottom (B)**	**Top (A)**	**Bottom (B)**	**Top (A)**	**Bottom (B)**	**Top (A)**
Recording 1	25	22	41	43	31	41	34	39	38	46
Recording 2	16	17	25	26	36	33	37	41	42	45
Recording 3	32	38	32	36	34	41	27	34	44	56
Recording 4	36	35	36	30	38	45	41	46	49	61
Recording 5	35	31	57	62	33	39	30	34	46	49
Mean	28.8	28.6	38.2	39.4	34.4	39.8	33.8	38.8	43.8	51.4
Std. dev.	8.35	8.85	12.03	14.17	2.70	4.38	5.54	5.07	4.15	6.88

4.1.3. Procedure 3 - Bubble coalescence at different needle angles

Procedure 3 showed a marked difference in the occurrence of bubbles ≥5mm in fresh and saltwater. In freshwater, needle angle was observed to reduce bubble coalescence as two fewer coalesced bubble were observed at 20°. Additionally, in freshwater, observations at 0° showed a higher standard deviation than that observed at 20°. In saltwater, increasing the needle angle had a larger effect on reducing coalescence than in freshwater, whilst the standard deviation was also observed to decline. Far fewer of these coalesced bubbles were observed overall in saltwater than in freshwater, where fewer coalesced bubbles were observed at both needles angles in salt than in freshwater (table 3 and figure 27).

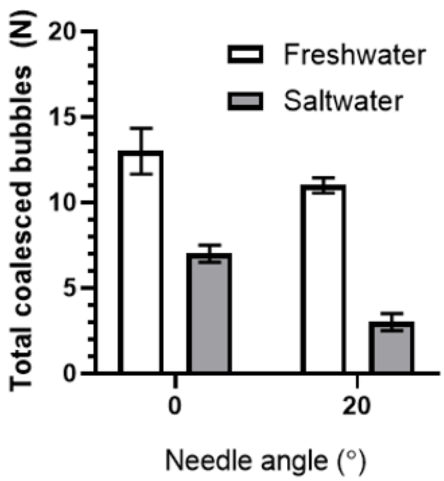

Figure 27. Total number of bubbles ≥5mm observed in fresh and salt water at different needle angles, as well as the standard deviations calculated for each set of observations.

Table 3. Number of bubbles ≥5mm observed at each recording at 0° and 20°, as well as the mean and standard deviations for each angle in both freshwater and saltwater.

	Freshwater		**Saltwater**	
Needle Angle	**0°**	**20°**	**0°**	**20°**
Recording 1	4	3	1	0
Recording 2	1	2	1	1
Recording 3	4	2	2	0
Recording 4	2	2	2	1
Recording 5	2	2	1	1
Total	**13**	**11**	**7**	**3**
Mean	**2.6**	**2.2**	**1.4**	**0.6**
Standard Deviation	**1.34**	**0.45**	**0.55**	**0.55**

4.2. Experiment 2

4.2.1. Bubble size

Water Condition:

The effect of water condition on bubble size produced an F value of $F(1,1011) = 455.77$, $p=<0.001$, indicating that there was a significant difference between the mean bubble sizes observed at all flows and observations points between fresh (M=5.08±3.12mm) and saltwater (M=3.38±1.73mm), agreeing with the hypothesis (figure 28). A sample image is provided in order to illustrate the differences in bubble diameter between fresh and saltwater (figure 29).

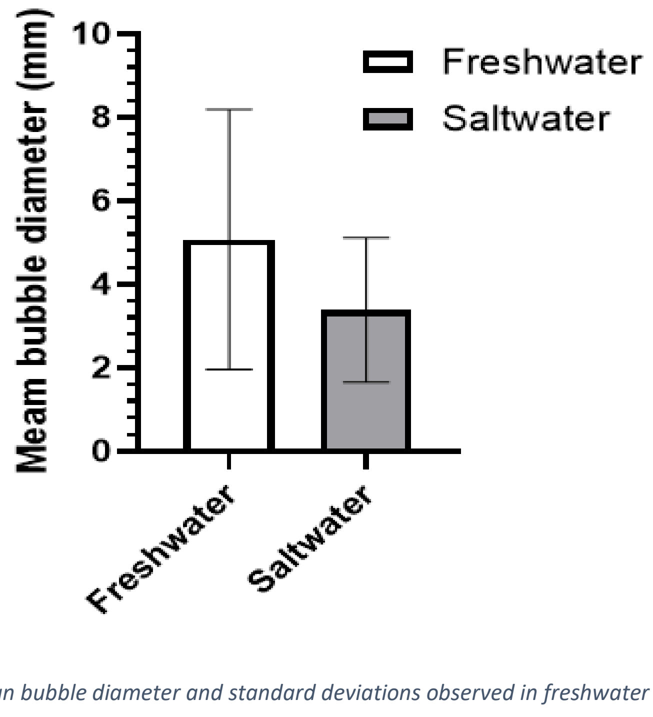

Figure 28. Overall mean bubble diameter and standard deviations observed in freshwater and in saltwater.

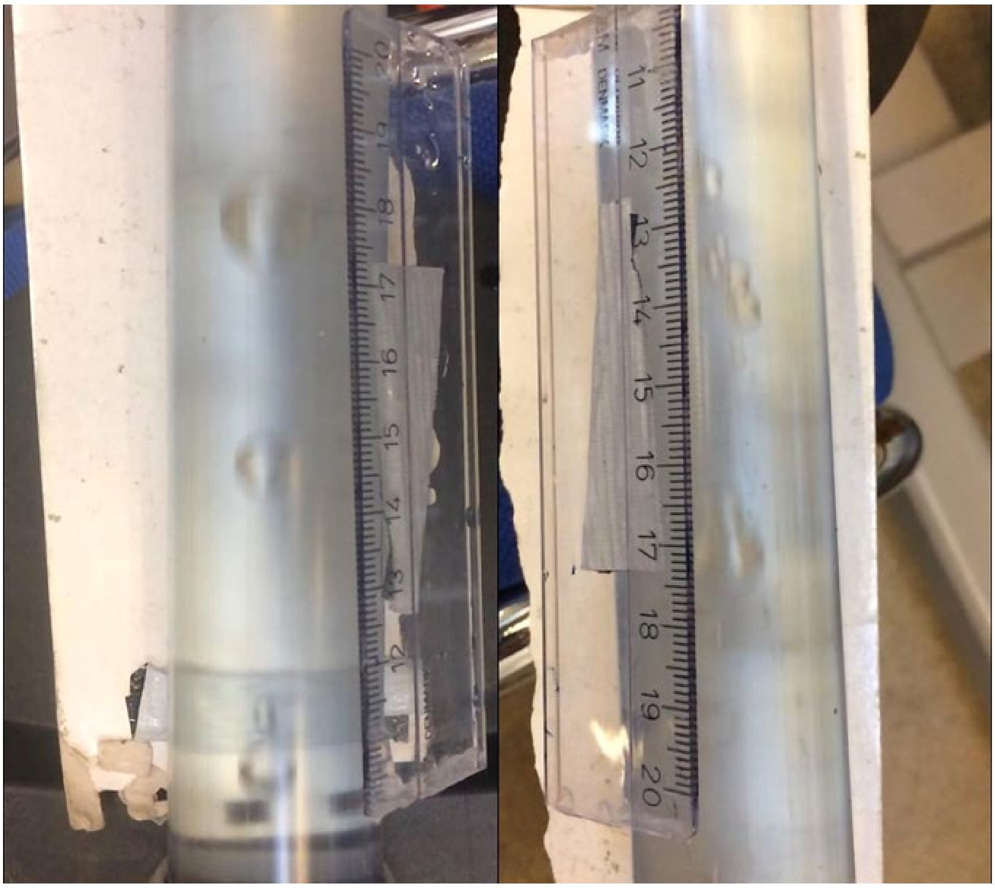

Figure 29. Comparison of bubble diameter between freshwater (left) and saltwater (right). Images are taken from observation point 3 at a system flow of 80L.

System Flow:

The effect of system flow on bubble size yielded an F value of $F(6,1011) = 25.08$, $p=<0.001$, indicating that there was an overall significant difference in bubble size between 80 (M=5.24±2.74mm), 100 (M=4.81±2.50mm), 120 (M=4.83±3.07mm), 140 (M=4.47±2.61mm), 160 (M=3.94±2.57mm), 180 (M=3.83±2.42mm), and 200 (M=3.55±2.29mm) litres. However, pairwise comparisons from the 2-way ANOVA test additionally showed that there were significant differences between 80 and 140 (p=<0.001), 160 (p=<0.001), 180 (p=<0.001) and 200L (p=<0.001), whilst no significant differences were observed between 80 and 100 (p=0.419) and 120L (p=0.515). Overall mean bubble diameter decreased as the system flow was increased (table 4). A sample image is provided in order to illustrate the differences in bubble diameter between system flows (figure 30).

Table 4. Mean bubble diameter observed at each observation point, in both fresh and saltwater combined, at the different system flows tested, as well as the standard deviation.

System flow (L)	80	100	120	140	160	180	200
Water velocity (m/s) [a]	0.92	0.98	1.04	1.12	1.18	1.25	1.29
Observation Point 1 mean (mm)	3.78	4.08	3.45	3.38	3.08	3.08	2.88
Observation Point 2 mean (mm)	2.95	2.58	2.55	2.48	2.28	2.13	1.98
Observation Point 3 mean (mm)	8.63	7.44	8.10	7.21	6.15	5.98	5.25
Observation Point 4 mean (mm)	5.59	5.16	5.22	4.69	4.28	4.13	4.10
Overall mean (mm)	5.24	4.81	4.83	4.44	3.94	3.83	3.55
Std. dev	2.74	2.50	3.07	2.61	2.57	2.42	2.29

[a] Calculations for water velocities taken from appendix 3.

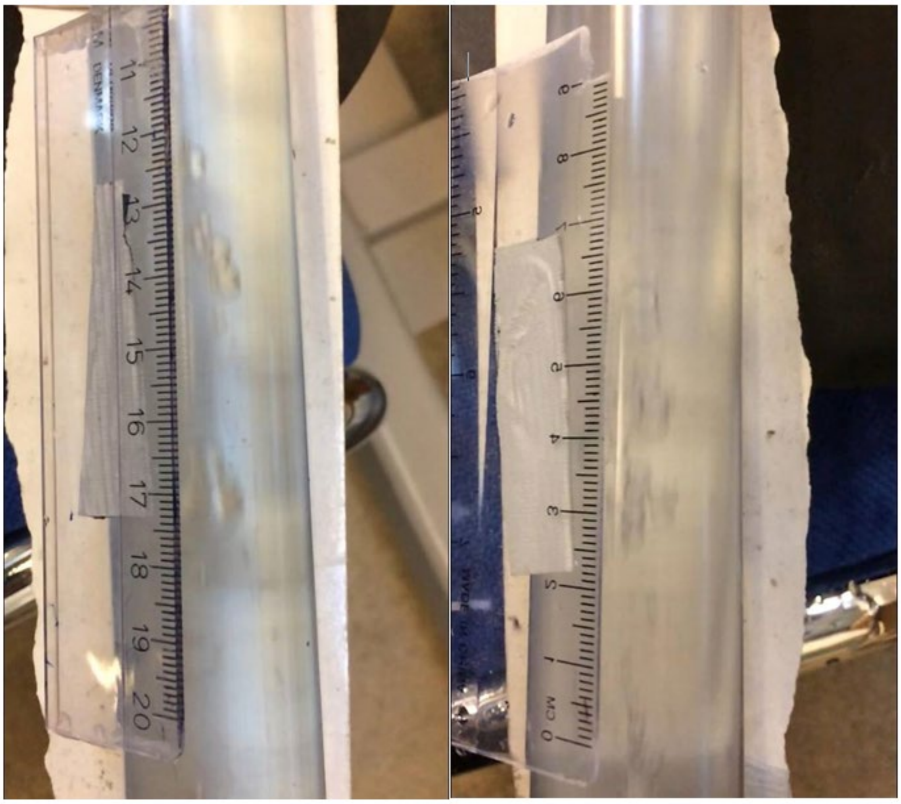

Figure 30. Comparison of bubble diameter between system flows of 80L (left) and 200L (right). Both images are taken from saltwater at observation point 3.

The interaction of water condition and system flow was however found to not be significant, producing an F value of $F(6,1011) = 0.698$, $p=0.651$, indicating that the size difference in bubbles observed at the different system flows were not statistically different between fresh and saltwater. Overall, the mean bubble diameter decreased as the system flow was increased in both fresh and saltwater. There is a clear difference in the mean bubble sizes observed between the two water conditions, with observations in saltwater showing a bubble size ≈1mm smaller than that of freshwater throughout the system flows tested (table 5).

Table 5. Overall mean bubble diameter observed at the different system flows tested in freshwater and saltwater, as well as the standard deviations of these observations.

System Flow (L)	80	100	120	140	160	180	200
Water velocity (m/s)	0.92	0.98	1.04	1.12	1.18	1.25	1.29
Mean in freshwater (mm)	6.26	5.83	6.00	5.46	4.90	4.8	4.38
Std. dev	3.26	2.92	3.72	3.16	3.04	2.90	2.76
Mean in saltwater (mm)	4.21	3.79	3.66	3.41	2.99	2.85	2.73
Std. dev	2.07	1.77	1.99	1.69	1.47	1.20	1.25

The interaction of system flow*observation point was however found to be significant, producing an F value of $F(18,1011) = 3.076$, $p=<0.001$, indicating that the size difference in bubbles observed at the different system flows were statistically different between the separate observation points. Results of this test have additionally been separated by the water condition so that additional comparisons can be made between the different mean bubble sizes observed at each observation point and each system flow (figures 31 & 32).

Mean bubble diameter was observed to be largest at all system flows for observation point 3 and, except for 120L, all system flows gradually reduced the mean bubble diameter. Bubble diameter was second largest at point 4 for all system flows except 100L. As with point 3, observations at point 4 and 120L also led to an increase in bubble diameter, contrary to the overall trend. This was also observed at 180L for point 4. Bubble diameter was on average smallest at observation points 1 and 2, with point 2 clearly yielding the smallest average diameters. Observations at 100L for point 1 also showed an increase in bubble diameter, contrary to the general trend of the all the observations (figure 31).

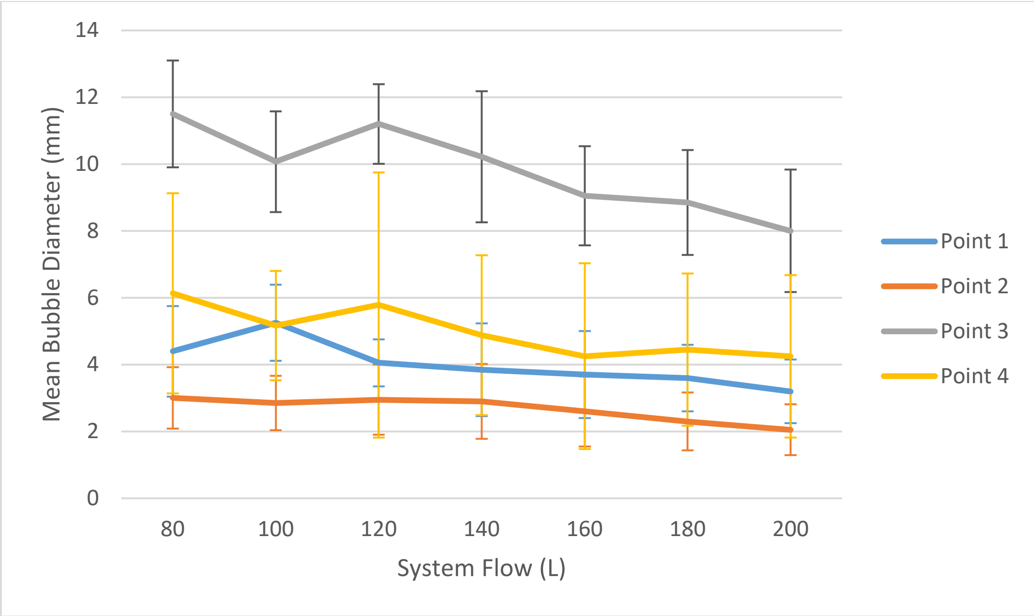

Figure 31. Mean bubble diameter at the different observation points across the system flows tested in freshwater, as well as the standard deviations calculated for each set of observations.

The same overall trend was also observed for saltwater, where mean bubble diameter tended to decrease as the system flow was increased. In saltwater, point 4 was shown to have the largest average bubble diameter at all system flows except 80L and 120L. Again, contrary to the overall trend observed, bubble diameter increased at 100L and 200L for point 4, 140L and 180L for point 1, and 120L for point 3. Similarly to freshwater, observation points 1 and 2 yielded the smallest average bubble diameters (figure 32).

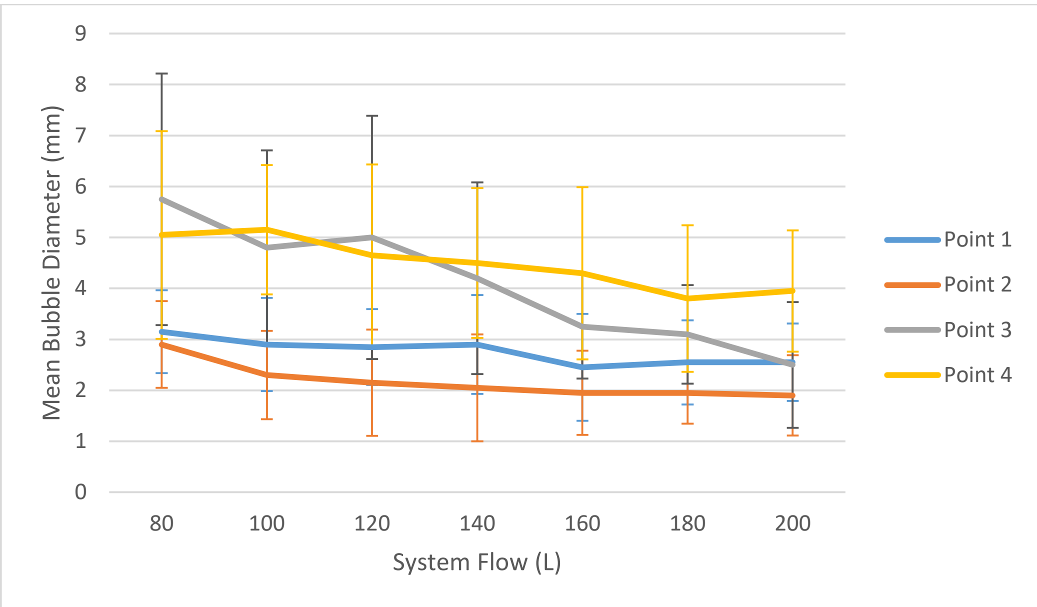

Figure 32. Mean bubble diameter at the different observation points across the system flows tested in saltwater, as well as the standard deviations calculated for each set of observations.

Observation Point:

Analysis of the data for the effect of the observation point in the system on bubble size gave an F value of $F(3,1011) = 434.26$, $p=<0.001$, indicating there was a significant difference in bubble size between observation points 1 (M=3.33±1.22mm), 2 (M=2.42±0.98mm), 3 (M=6.55±3.68mm), and 4 (M=4.68±1.67mm) (figure 30). Pairwise comparisons for the overall effect of observation point on bubble size showed that there were significant differences between point 1 and all other observation points; 2 ($p=<0.001$), 3 ($p=<0.001$), and 4 ($p=<0.001$) (figure 33). A sample image is provided in order to illustrate the differences in bubble diameter between observation points (figure 34).

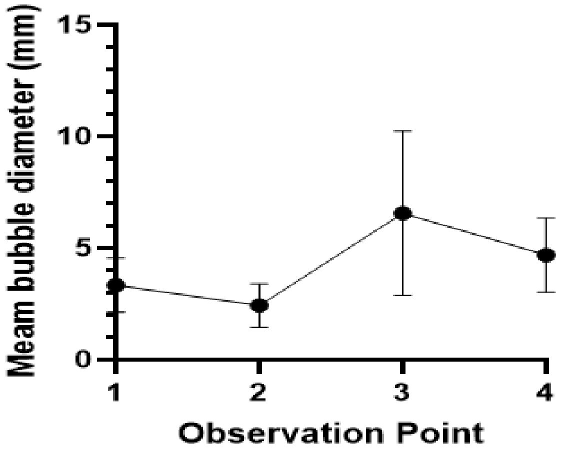

Figure 33. Overall mean bubble diameter at the different observation points for fresh and saltwater combined, as well as the standard deviations calculated for each set of observations.

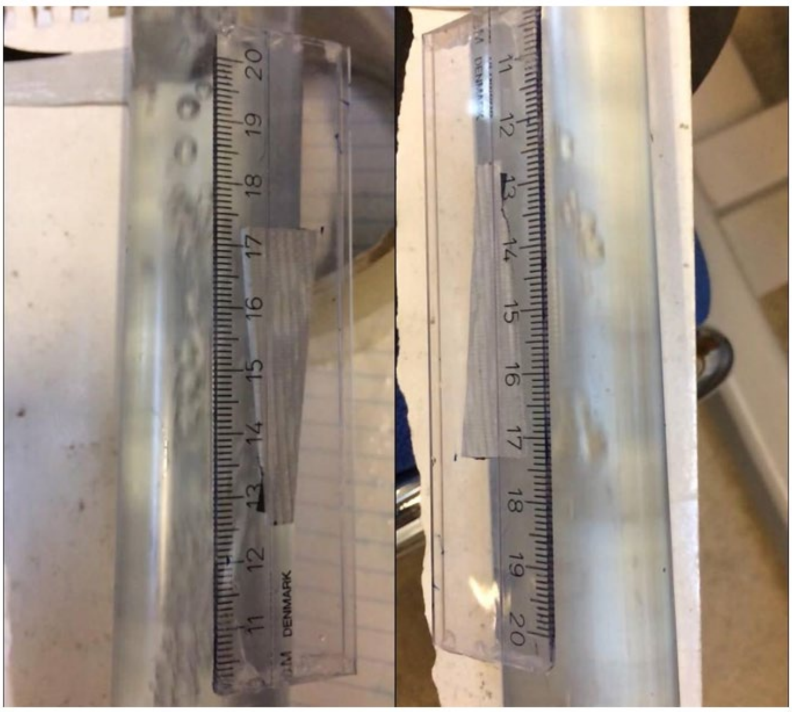

Figure 34. Comparison of bubble diameter at observation point 2 (left) and observation point 3 (right). Images are taken from saltwater at a system flow of 80L.

The results from the ANOVA also indicated that interaction of water condition*observation point was significant. This test yielded an F value of $F(3,1011) = 173.886$, $p=<0.001$, indicating that the size difference in bubbles observed at the different observation points was statistically different between fresh and saltwater.

Both similarities and discrepancies are seen between the observation made on bubble diameter between fresh and saltwater. Both fresh and saltwater showed a decrease in bubble diameter from observation point 1 to point 2. However from point 2 to point 3, freshwater showed a far larger increase in bubble diameter (≈6.5-7mm) than that of saltwater (≈2mm). Differences in bubble diameter alteration were also observed between the two water conditions from point 3 to point 4, where freshwater showed a large decrease in bubble diameter, whilst saltwater actually showed a slight increase in bubble diameter. Also demonstrated is a continuous difference in the overall bubble diameter between the two water conditions, with bubbles observed at each of the separate four observation points in saltwater being smaller than the corresponding bubbles observed in freshwater (figure 35).

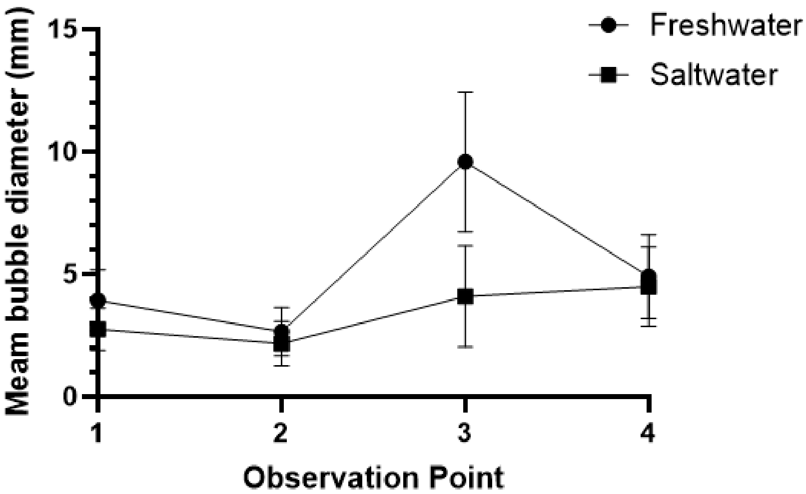

Figure 35. Mean bubble diameter at the different observation points between fresh and saltwater, as well as the standard deviations calculated for each set of observations.

4.2.2. Bubble Coalescence

Water Condition:

The total number of coalesced bubbles observed were far greater in freshwater than in saltwater, as were the mean values calculated. The standard deviation was also a good deal greater in freshwater than in saltwater, indicating that fewer coalesced bubbles were more consistently observed in the saltwater trials (table 6).

Table 6. Total number of bubbles ≥5mm (coalesced) observed at all system flows and observation points in fresh and saltwater, as well as the mean and standard deviation of coalesced bubbles observed.

	Freshwater	**Saltwater**
Total Number	168	70
Mean	6.0	2.5
Standard Deviation	6.12	3.55

System Flow:

Observations of coalesced bubbles in freshwater showed a clear overall trend. Generally, as the system flow was increased, the mean percentage of bubbles ≥5mm observed was seen to decrease. This trend was observed at all system flows tested except for observations made at 100L, where the frequency of coalesced bubbles increased. Variance was also observed between the standard deviations calculated, with the highest standard deviation in coalescence occurrence observed at 120L, and the lowest observed at 200L (table 7).

Table 7. The mean percentages of bubble coalescence occurrence and standard deviations at the different system flows, and subsequent water velocities, tested (for all observation points) in freshwater.

System Flow (L)	**80**	**100**	**120**	**140**	**160**	**180**	**200**
Water velocity (m/s)	0.92	0.98	1.04	1.12	1.18	1.25	1.29
Mean Percentage (%)	45.0	47.2	39.3	36.6	33.8	31.3	26.3
Std. dev.	44.35	41.20	48.62	44.18	39.45	42.50	37.72

The same overall trend observed in freshwater was also observed in saltwater, where the mean percentage of bubble coalescence occurrence was shown to decrease as the system flow was increased. Unlike with freshwater however, all the observations made agreed with the overall trend observed. Variance between the standard deviations calculated was far greater than in freshwater, where the highest observed value at 80L was ≈11 times that of the lowest observed value at 200L. Also shown is the large differences in the mean percentage of bubble coalescence between fresh and saltwater, where far fewer bubbles ≥5mm were observed at each system flow relative the same observation made in freshwater (table 8).

Table 8. The mean percentages of bubble coalescence occurrence and standard deviations at the different system flows, and subsequent water velocities, tested (for all observation points) in saltwater.

System Flow (L)	**80**	**100**	**120**	**140**	**160**	**180**	**200**
Water velocity (m/s)	0.92	0.98	1.04	1.12	1.18	1.25	1.29
Mean Percentage (%)	25.0	18.8	15.0	15.0	10.0	2.5	1.3
Std. dev.	29.15	21.75	17.32	17.80	16.83	5.00	2.50

Observation Point:

Large differences in the mean percentage of bubble coalescence frequency are observed between the four observation points. The initial occurrence of 12.5% at observation point 1 was rather low, however this decreased even further at point 2, where no bubbles ≥5mm were observed during the whole experiment. In contrast to this decrease, a large increase in the number of bubbles ≥5mm was observed at point 3, where 82.5% of bubbles observed were assumed to have coalesced. This was followed by another decrease to 34.7% at observation point 4. Large degrees of variance in the standard deviations were also observed between the observation points, where the highest deviation was observed at point 1, and the lowest at point 4 (table 9).

Table 9. The mean percentage of bubble coalescence occurrence and standard deviations at the different observation points (at all system flows) in freshwater.

Observation Point	**1**	**2**	**3**	**4**
Mean Percentage (%)	12.5	0	82.5	34.7
Std. dev.	17.90	0	7.87	13.67

No bubbles ≥5mm were observed at observation points 1 and 2. As with freshwater, the number of coalesced bubbles observed increased at point 3, where 23.6% of the bubbles observed were ≥5mm. Unlike in freshwater however, the mean percentage of bubble coalescence increased at observation point 4. The standard deviation calculated at observation point 3 was greater than that calculated at point 4. Overall, excluding observation point 2, the mean percentage of bubbles ≥5mm observed was lower in saltwater than in freshwater, particularly at observation point 3, where ≈3.5 times as many coalesced bubbles were observed in freshwater than in saltwater (table 10).

Table 10. The mean percentage of bubble coalescence occurrence and standard deviations at the different observation points (at all system flows) in saltwater.

Observation Point	1	2	3	4
Mean Percentage (%)	0	0	23.6	26.4
Std. dev.	0	0	21.93	14.35

5. Discussion

Experiments 1 and 2 will be discussed separately, as will procedures 1-3 within experiment 1. Suggested improvements to the designs and conditions of the two experiments will be discussed separately, noting that potential improvements for procedure 1-3, within experiment 1, will be collated.

5.1. Experiment 1

5.1.1. Procedure 1

This study found that bubble diameter at observation point A (top) was not significantly larger than at observation point C (bottom) in both fresh and seawater. This suggests that in both water conditions the minimal pressure change experienced by the bubbles, approximately 0.1 bar in our testing tank, was not able to negatively influence factors important for efficient aeration, principally that of surface area. When considering the efficiency of either aeration or oxygenation in a freshwater system, whilst the occurrence of bubble expansion will enlarge the surface area available for gas transfer, it will additionally lead to faster rising velocities as the bubble expands, thus reducing the retention time within the system for gas transfer to occur. Whilst increasing the surface area for aeration is positive, many smaller bubbles are more preferable to one larger bubble. The findings of this study are therefore encouraging, as the failure of the bubble to expand has positive ramifications for aeration efficiency.

It is important to note however, that whilst it has long been established that increases in pressure produce smaller bubbles, studies investigating the effects of pressure on bubble size often observe pressures where bubble size is likely to be heavily influenced (2-6 atmospheres) (Han *et al*, 2002). In addition, numerous studies also use an additional variable when investigating bubble size distributions, such as air flow or water flow. The principle purpose of procedure 1 was to gain insight into how bubble diameter would be affected by pressure, if at all, in the absence of any other variable. Even though the pressure change within the tank was very small, other studies have shown that bubble volume can be influenced by such shallow depths. One such study found that there was a volume increase of roughly 10% for a bubble released at a depth of 1m, and whilst the values obtained for the increase in bubble diameter of this study fall short of that 10%, marginally short in the case of freshwater, the increase in size is not enough to be statistically different (Cihan & Corapcioglu, 2008).

In contrast to the hypothesis, the second finding of procedure 1 was that there was no difference in the diameter of bubbles generated at the bottom observation point (C) between fresh and saltwater, whilst there was a difference in the diameter of bubble generated at the top observation point (A) between fresh and saltwater. The findings suggest that the presence of salinity within the testing tank had no influence on the initial bubble diameter generated, but did prevent the bubble expanding as it rose, to a degree where it was significantly different than that of freshwater. The observations made at the bottom observation point are in stark contrast to the literature, where numerous studies have concluded that increasing salinity causes the bubble diameter to shift towards smaller sizes (Slauenwhite & Johnson, 1999; Nye *et al*, 2014; Anguelova & Huq, 2017(a)). An increase in salinity can lead to, in some cases, the creation of smaller bubbles due to 'premature detachment', where the reduced surface tension causes the bubble to detach (Lekang, 2008). Another interesting observation with regards to initial bubble diameter generated was the diameter of the bubble itself regardless of the salinity. The mean bubble diameter generated was 4.16mm in freshwater and 4.10mm in saltwater, however, other studies investigating bubble size in saline waters have produced smaller bubbles, even when using larger needles. For example, Navisa *et al* (2014), produced bubble diameters of 2.67, 1.83, and 1.45mm using needles with a diameter of 1.27, 0.9, and 0.7mm respectively. Whilst this was achieved using a more accurate and consistent method of air injection, a fixed gas flow of 8m/sec, the difference in diameter between the bubbles in salt water from this experiment and Navisa *et al* (2014) suggest that our observations of 4.1-4.16mm are too large, and that reasons for this may rest with the experimental design.

Observations on bubble diameter made at the top observation point between fresh and saltwater are more difficult to explain. Surprisingly little research has been found on the different influences that salinity, and the resulting changes in surface tension, have on the expansion of bubbles. Anguelova & Huq, (2017(b)) state that the increased ionic strength of a solution when adding salts results in positive film pressures acting on the bubble, which in turn stabilises the bubbles against bursting. By stabilising the bubble, one would assume that the bubble would be less perceptible to the effects of reducing the pressure, leading to expansion. This was seen in our experiment, where the bubbles in saltwater were significantly smaller than those in freshwater. Another study, conducted by Andonova & Sekhar (2016), aimed to investigate the effects of surface tension on bubble rise velocity, as a function of bubble expansion factor. They found that surface tension heavily influenced the expansion of smaller bubbles (1µm), and an increase of 10 to 15% expansion was calculated when reducing the surface tension of a liquid. Additionally, the study also observed that larger bubbles (0.1mm) were not affected by the change in surface tension. Relating the findings of Andonova & Sekhar (2016) to our own however, must be done with caution, as the bubbles generated in this study were roughly 4mm in size, and doing so would suggest that there should have been no difference in the sizes of the bubbles observed at the top observation point between fresh and saltwater.

Other studies investigating the effects of salinity on bubble size have conducted experiments based on bubble clouds and not single bubbles, where the conclusion was also that the 'size spectrum' or size distribution tends to shift towards the smaller sizes with increasing salinity, as a result of the lack of instantaneous coalescence that is seen in freshwater (De Leeuw *et al*, 2011; Anguelova & Huq, 2017(a)). The absence of a bubble cloud for procedure 1 of this research therefore eliminates coalescence as the main function by which bubble diameter is diminished in saltwater and can therefore possibly explain the findings of our study (Experiments on Salinity Influence, n.d.). In addition to this, a study investigating the effects of salinity on the surface lifetime of large bubbles conducted by Anguelova, & Huq, (2017(b)) concluded that salinity did not reduce the diameter of individual bubbles (figure 36). They were able to illustrate that when increasing the salinity, the respective changes to the ratio between surface tension and air-water density difference would only lead to a 7.6% reduction in bubble size over a salinity range of 0-40 psu. It is also important to note other possible factors that may additionally be influencing the bubble diameter within the testing tank. The result of competing factors such as the influence of pressure, mass-transfer, and possible heat transfer, may provide alternative explanations as to the consistency of the bubble diameters when comparing the observations points between fresh and saltwater.

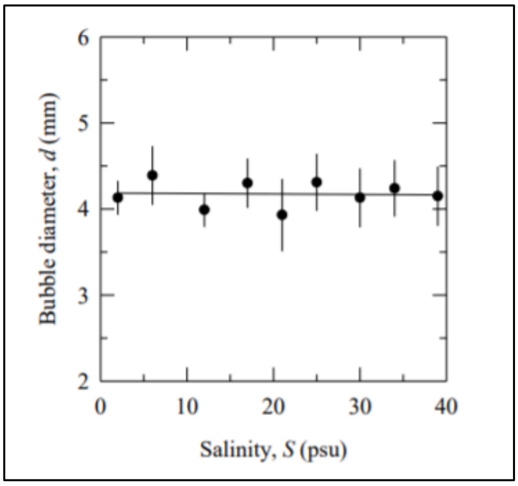

Figure 36. Bubble diameter for single bubbles in varying salinity (Anguelova & Huq, 2017(b)).

5.1.2. Procedure 2

Procedure 2 demonstrated that there was a significant difference in the occurrence of bubble coalescence between fresh and saltwater, where coalescence occurred more frequently in freshwater. As stated in the literature review, the phenomenon of coalescence has important ramifications for gas transfer, where increasing the occurrence of coalescence will reduce the overall gas-liquid interface surface area that is available for transfer (Chen, 1991; Chen *et al*, 1992). This study also demonstrated that the significant difference found between coalescence in fresh and saltwater occurred within a bubble rising distance of roughly 75cm. When considering tank design, circular tanks are constructed with a diameter-depth ratio of 3:1 – 5:1, with many farms now employing tanks with diameters greater than 8m and thus a subsequent depth of >2m (Larmoyeux *et al*, 1973). Therefore, the occurrence of coalescence will be even more prevalent in these deeper freshwater tanks and this, combined with the findings from procedure 1, will further reduce the efficiency of gas transfer within the system. The findings also have implications for aerators that utilise numerous holes or pores for air injection, such as aeration stones or bar aerators. The results would indicate that the use of such an aerator, while perhaps not optimal, would be acceptable in a saltwater system, where the occurrence of coalescence is inhibited sufficiently when compared to freshwater. In freshwater though, the use of such aerators could be very much suboptimal, where coalescence would frequently occur, reducing the surface area available for aeration and thus reducing the effectiveness of the aerator. These findings, regarding the frequency of coalescence in fresh and saltwater, are in accordance with both the literature and the hypothesis for this procedure.

Furthermore, in agreement with the findings of this study, most studies conclude that when adding either salts or surfactants to water, the occurrence of bubble coalescence decreases (Cartmill & Su, 1993; Lekang, 2008; Firouzi *et al*, 2015). Christenson *et al* (2008) was additionally able to show the same phenomenon occurring for bubble pairs instead of bubble clouds. This was done by forcing two individually blown bubbles, from two separate nozzles, into each other at different salinities, where bubbles in pure water were observed to coalesce almost instantly, whilst the bubbles blown in a high salt concentration did not coalesce. These studies suggest that the observations of this study, with regards to significantly higher numbers of bubbles recorded at the top observation point in saltwater, and thus decreased coalescence, are in line with the hypothesis and can be accepted with a reasonable degree of certainty. Additionally, Slauenwhite & Johnson (1999) found that bubbles which coalesce in freshwater do not produce what is known as 'satellite' bubbles, whilst these satellite bubbles are produced on the few occasions that bubbles in saltwater do coalesce. This can therefore offer an additional explanation for the higher numbers of bubbles observed at the top observation point in saltwater.

This procedure however, when critically analysed, is mainly reliant on observations of the number of bubbles at the top observation point (A). The design of this procedure assumed that less bubbles observed at the top of the testing tank would indicate that coalescence had occurred. However, differences in the number of bubbles between the observation points in both fresh and saltwater may have resulted due to other reasons rather than the occurrence of coalescence as was assumed. The first explanation that may account for the higher numbers of bubbles observed at the top observation point in saltwater is due to the likely occurrence of bubble coalescence at the moment of release from each individual needle. In this case, coalescence would occur regardless of the needle distance and, as external research has shown that coalescence occurs more frequently in freshwater, the significant differences in the overall number of bubbles observed at the top observation point between fresh and saltwater may be because of this factor and not the effect of the needle distance as hypothesised.

The second possible explanation for the differences in bubble observation may be down to the non-uniformity of the bubble sizes produced, and their subsequent influence on the experiment. Throughout this procedure, it was frequently noted that in fresh, and to a lesser extent in saltwater, different bubble sizes were produced from the two needles, as the air flow from the syringe was not fixed and was thus not consistent. This, combined with the likelihood of some coalescence occurring in the lower section of the testing tank, created large variations in the bubble sizes, and this led to large difference in rising. In freshwater, larger bubbles (assumed to be coalesced bubbles) were frequently observed to pass observation point A before smaller un-coalesced had entered the frame of the video recording. Thus, several screenshots were made from the recordings at observation point A, and in doing so this introduced the possibility of counting bubbles more than once. This same issue was also present in saltwater, although it occurred less often due to the more homogenously grouped bubble sizes. Observation uncertainty was also present at point B, where the bubble clusters were still in close proximity to each other. In this instance, the bubble clusters that were released were on many occasions not distinguishable from each other, where what appeared to be one bubble on the photograph could in fact be two or three bubbles in close proximity to each other. Although the observations between fresh and saltwater followed the predicted trends, outliers, such as the difference in bubbles recorded at 2cm, may possibly be skewed due to the aforementioned factors.

The results of procedure 2 also detailed that the occurrence of bubble coalescence was in some cases affected by the distance between two sources of air bubbles and therefore the distances between the bubbles. Additionally, the procedure also demonstrated that there was no effect from the interaction of either salt or freshwater on the occurrence of coalescence at these different distances. The hypothesis regarding these observations was devised on the premise that increasing the distance between the bubble sources, and the resulting bubbles, would decrease the interaction between these bubbles, therefore reducing the occurrence of coalescence. Several studies have also concluded that the behaviour of two bubbles, with regards to coalescence, was governed by the inter-bubble distance, where increasing this distance decreased the interactions between the bubbles and therefore reduced the possibility of coalescence (Otake *et al*, 1977; Fong *et al*, 2009; Chew *et al*, 2011). Although the overall significance of needle distance on bubble coalescence was found to not be significant, the raw data does indicate that there is a decrease in the occurrence of coalescence when increasing the needle distance from 1cm, and in this regard the findings of this study agree with the literature. However, whilst the findings of these studies suggest that increasing the needle distance from 1cm up until 5cm should have reduced the occurrence of coalescence, it must also be noted that these studies, apart from Otake *et al* (1977), deal with dimensionless distances in order to predict bubble behaviour based on mathematical models. Additional research conducted into the effects of inter-bubble distance has focused on the effects of interfacial forces, and subsequent surface forces that occur at short separation distances. This includes forces such as Van der Waals interactions and electrostatic double-layer interactions. However, as these forces act at such short distances, <10nm for Van der Waals, the application of these findings for the observations of this study must be critically considered (Hahn *et al*, 1985). In contrast to other studies, Otake *et al* (1977) was able to determine a distance, calculated to be roughly 3-4 times the diameter of the bubble, at which two bubbles will begin to exert an influence on each other, and the findings of that study are applicable to the findings of this procedure. However, whilst Otake *et al* (1977) was able to find this distance, this distance simply relates to a commencement of inter-bubble influence and not an absolute inhibition of coalescence. Regrettably, overall there is a lack of research regarding the systematic and quantitative determination of the effect of bubble distance on bubble coalescence, and therefore the determination of a 'critical distance' for preventing or diminishing coalescence is not known. Most of the research would indicate however, that a study on the effects of inter-bubble distances might be more beneficial to reduce needle distances below 1cm rather than increasing them.

5.1.3. Procedure 3

The observations of procedure 3 suggested that bubble coalescence was affected by needle angle, where increasing the needle angle led to subsequent fewer observations of bubbles assumed to have coalesced. Additionally, the findings of procedure 3 also agreed with that of procedure 2, regarding the inhibition of bubble coalescence with increased salinity, as far fewer coalesced bubbles were observed at both angles tested in saltwater. Differences in the occurrence of bubble coalescence have the same implications for the aquaculture industry as stated in the discussion for procedure 2, where the increased frequency of coalesced bubbles observed in freshwater will lead to a subsequent decline in aeration efficiency. Observations on the effect of needle angle on coalescence suggest that, in both fresh and saltwater, the use of any aeration systems where air is injected horizontally into each other is less optimal than a system where air is injected at an angle.

However, the data collated is only able to suggest and not confirm the relationship between needle angle and bubble coalescence, as no statistical tests were carried out. This was decided upon due to the methods of observation used in this procedure. The nature of these observations was qualitative rather than quantitative, as analysis of the photographs proved to be quite difficult. Bubbles that appeared as ≥5mm could in fact have been several bubbles of 2-3mm in close proximity to each other, whilst bubbles that were ≥5mm could have been initially large bubbles generated from the needles due to the inconsistency of the air flow injected by the syringe. Therefore no definitive statement can be made regarding this procedure, nevertheless, the data does show the expected trends and differences in coalescence between fresh and saltwater, whilst the effect of altering the needle angle was the same for both water conditions.

Unfortunately, there do not appear to be any studies which specifically examined the effect of changing the angle at which two bubbles are forced into each other. Whilst several studies have investigated bubbles and contact angle, these studies usually refer to the effects of bubble size on contact angle with solid surfaces, or observations of bubble contact angle on a surface during the process of bubble nucleation (Drelich, 1997; Yang *et al*, 2000). The lack of research is further compounded by the fact that studies on bubble coalescence using either needles or capillary tubes will maintain a fixed angle during the entirety of the experiment. However, comparisons may be drawn between these separate studies in order to potentially explain the differences in the observations of this study. Two such studies that will be compared are Christenson *et al* (2008) and Tse *et al* (1998). Whilst these studies were investigating separate factors regarding bubble coalescence, the method used for initiating coalescence was the same except for the angle at which the bubbles were forced into each other. Tse *et al* (1998) used nozzles directly facing each other horizontally, whilst Christenson *et al* (2008) used nozzles which were facing each other at angle. Although the exact angle is not mentioned in the latter study, figures provided in the experimental design suggest the angle is roughly 45°. Due to the different aims of the studies, the data is not comparable, however, photographs in the experimental setup and results show a difference between the bubbles generated from these nozzles. The clearest difference is the shape of the bubble as it expands and nears detachment from the nozzles. Due to the 'teardrop' shape of these bubbles as they are generated and begin to become influenced by buoyancy, as well as the interactions of tension on the capillary nozzle and bubble, contact between the two bubbles is more likely to be instigated in the two horizontal nozzles than the angled nozzles (Oguz & Prosperetti, 1993) (figure 37). Tse *et al* (1998) nozzles were set apart at a distance of 5mm and, whilst the inter-tube distance of Christenson *et al* (2008) was not stated, both studies used 2mm nozzles, so based on the scale observed between the two experiments, the nozzles of Christenson *et al* (2008) are considerably closer (figure 37). In order for bubble contact to be initiated in the study of Christenson *et al* (2008), the nozzles had to be placed very close together, and withdrawing these nozzles to the same inter-nozzle distance used by Tse *et al* (1998) would result in no interaction between the bubbles, at least at the moment of release. This may therefore, offer a potential comparison between the angle of either nozzles, capillary tubes, or needles used in the generation of small bubbles, whilst additionally providing a possible explanation as to why fewer coalesced bubbles were observed in both fresh and saltwater at 20° relative to 0° in this study.

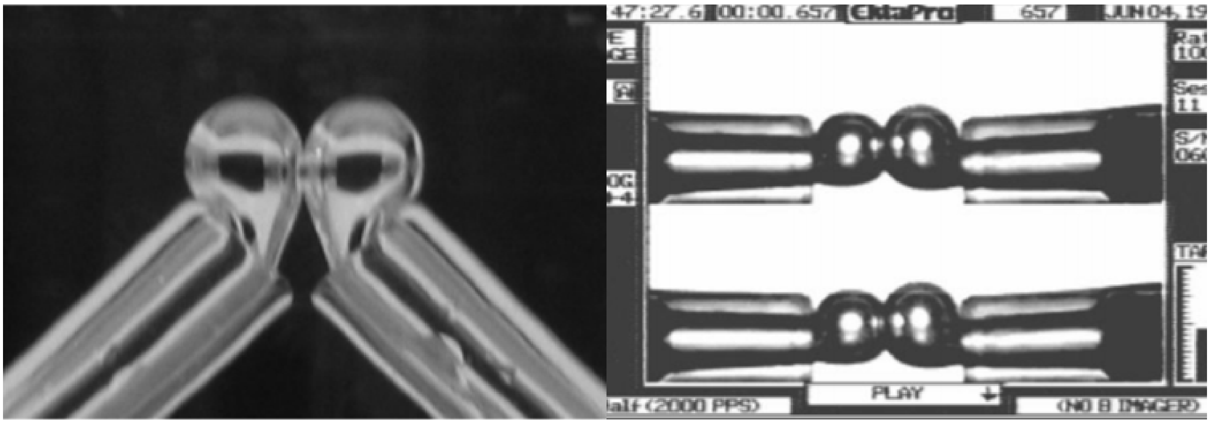

Figure 37. Contact between two bubbles generated from nozzles at an angle (left) and two bubble generated from nozzles positioned horizontally (right) - Christenson et al *(2008) and Tse* et al *(1998).*

However, whilst this comparison may hold true for systems or experiments where two single bubbles are released from two separate sources, the exact effect when releasing bubble clouds, such as in this study, cannot be predicted with a sufficient degree of certainty. Whilst increasing needle or nozzle angle may prevent coalescence at the moment of release, the bubble clouds will quickly begin to interact soon after release, as also observed in this study. Additionally, unlike the studies of Christenson *et al* (2008) and Tse *et al* (1998), this study did not utilize a fixed air flow. Thus, prediction or estimation of the exact effects of increasing the angles between two air sources is further compounded by the introduction of non-homogenous bubble sizes and therefore, further research into these effects could prove beneficial to the industry.

5.1.4. Experiment 1 – Design and Data Improvements

Materials and design:

Throughout the experiment, several methods that were used, including the equipment used to carry out these methods, began to shows signs that they might be suboptimal for this particular experiment. Were this experiment to be carried out again, these changes to both method and equipment utilised would be implemented.

One of the principle factors that could be improved upon is the method of bubble generation. This factor includes all aspects involved in the generation of a bubble from the air flow injected to the type of nozzle used to eject the gas. Regarding the type of nozzle used, several studies investigating bubble behaviour have chosen to use capillary tubes instead of needles, likely due to the fact that the straight cut edge of the capillary tube, in contrast to the angled cut of the tip of a needle, produces a more uniform bubble shape as well as more homogenous detachment properties (Christenson *et al*, 2008;

Tse *et al*, 1998). As well as introducing the use of capillary tubes, a controlled air flow would also be introduced. Numerous studies investigating bubble behaviour opt for fixed air flow, as air flow has a large, direct influence on bubble size (Alkhalidi & Amano, 2011). By controlling the air flow, using either step motors to control the pistons of the syringes or through the use of a valve, more homogenously sized bubbles of a smaller size can be produced. This has a considerable number of benefits, as when producing bubbles of uniform size, coalescence can be more easily classified by larger bubbles, whilst with single bubble experiments, large bubbles, such as 4-4.2mm that were recorded for procedure 1, will be eliminated in favour of smaller bubbles that agree with external studies on this subject.

Another improvement to both the equipment and design used in this experiment is the method of image capture. The quality of the photographs obtained by the webcam, particularly those taken from video recordings, was suboptimal and these images were extremely difficult to assess accurately, leading to high occurrences of estimation for both bubble size and bubble number. When reviewing external research, most studies opt for the use of high quality cameras with fast shutter speeds as well as an additional lighting source behind the bubbles the camera is photographing, in order to enhance the outline of the bubbles (Slauenwhite & Johnson, 1999; Firouzi *et al*, 2015). The cameras would also be positioned slightly rather back from the testing tank in order to capture a larger area of the tank with each photograph. This would be done so that the likelihood of bubbles excluded from the image would be reduced.

The testing tank itself would also be changed were the experiment to be re-run. The first change to be suggested would be a deeper tank, so that size differences between bubbles at the bottom and top of the tank could be enhanced, as well as allowing more points for cameras to be set up. The second change would be to use a rectangular tank. One factor that may influence the observations was the curvature of the tank, and this, in combination with the sub-standard webcams, can contribute to the misinterpretation of the photographs. A straight edge would aid in eliminating any distortion that may occur around the edges of the photographs as the curvature of the testing tank increases.

Procedures 2 & 3 may additionally benefit from a different method of coalescence classification that would additionally allow the use of statistical analysis in procedure 3. The current method had many qualitative rather than quantitative aspects regarding coalescence. The use of the 'needle bracelet', and the subsequent need to lower the bracelet and the airline down into the testing tank, meant that air had to be forced down through the silicon tubing airline and out of the needles. This created a burst of bubbles with very little control over the number and size of bubbles produced, where 'coalesced' bubbles might simply just be larger bubbles. Additionally, the release of bubble clouds creates the occurrence of coalescence regardless of the distance or angle between the needles. If the experiment were re-run, the airlines would be fed up through the bottom of the tube as in procedure 1, whilst the use of capillary tubes and a controlled air flow would allow for coalescence to be classified in more accurate and reliable manner.

Data:

Procedure 1: As previously mentioned, observations of roughly 4mm for bubble diameter was most likely due to flaws in the experimental design and equipment. Observation averages were closely grouped together amongst the difference observation points, whilst the standard deviation for all of these observations were fairly consistent with each other, suggesting that there was little observational error involved. An independent two samples T-test would be re-used were the experiment to be re-run.

Procedure 2: Observations for procedure 2 varied significantly between each other. Large deviations were calculated at 1cm and 2cm in both fresh and saltwater, suggesting that the closer the needles were placed together, the greater the variation in numbers of bubbles recorded (figures 25 & 26). This was likely due to the high number of bubbles overlapping each other in the images, increasing the possibility of incorrect counts. Additionally, as mentioned previously in materials and design improvements, the classification of bubble coalescence, derived from the number of bubbles, risks inaccurate observations and large variance between the separate recordings (tables 1 & 2). Nowhere is this more evident than the observations made at the bottom observation point (B), where these numbers should be consistent throughout the procedure, whilst the observations at the top observation point (A) should be the ones to change based on needle distance. Consistent measurements at the bottom observation point were not achieved and, whilst this might be a product of the design and equipment, this variation can also be due to observer error. These variations additionally have a negative impact on the statistical test carried out, skewing the data in favour of incorrect bubble number differences between the top and bottom points. The use of a 2-way ANOVA would be replicated should the experiment be re-run. In conclusion the data set gathered for this procedure was not as expected, as the expected effect of needle distances was not shown, whilst a combination of observation error and sub-optimal design contributed to a data set that was difficult to explain. Enhancement of the data could be achieved by implementation of the suggested improvements to equipment and design, whilst more replicates of the study could reduce the observation error and deviation of the results.

Procedure 3: As mentioned in the discussion, the classification of 'coalesced' bubbles was not entirely accurate due to the equipment and method used. Whilst the data most likely has qualitative rather than quantitative traits, deviations amongst the mean values were in fact rather small, and comparisons between the deviations of the water conditions and angles suggest that any error involved in observations was consistent throughout the experiment (table 3 and figure 27). Clear patterns between the interactions of needle angle and water conditions also suggest that whilst observation error was likely present, the data set as a whole is perhaps not so unreliable. Re-running the experiment with several replications, as well as introducing suggested changes to the equipment and design, would aid in eliminating qualitative aspects of the data.

5.2. Experiment 2

This study was able to show that bubble diameter was significantly smaller in saltwater than in freshwater, whilst also showing that increasing the system flow of the aerator caused subsequent decreases in bubble diameter in both fresh and salt water combined. Bubble diameter was also observed to differ statistically between the separate observation points tested, where the largest bubbles were mostly observed at observation point 3 at the end of the 2m horizontal observation pipe. The results of this study also suggest that, with regards to coalescence, bubble coalescence occurred far more frequently in freshwater than in saltwater. When considering the effect of system flow on bubble coalescence, increasing the flow was shown to decrease the occurrence of coalescence in both fresh and saltwater. Whilst, as expected based on the findings regarding bubble diameter, coalescence was observed to occur most frequently at points 3 and 4 in both fresh and saltwater.

It is important to note that no statistical tests were carried out regarding bubble coalescence, and thus exact quantified differences between the different variables and their subsequent observations are not available. It was decided that statistical test would not be used for two reasons. Firstly, due to the extremely close relationship and correlation between bubble diameter and coalescence, and secondly, due to the conversion of the raw data to coalescence percentages. Both of these factors excluded the possibility of using a 2-way ANOVA as was used for bubble diameter. Regardless of the absence of statistical confirmation, clear trends and relationships are shown in the data in correlation and agreement with observations regarding bubble diameter. Due to the relationship that these two factors share, and the fact that some studies identify bubble coalescence as the governing factor that influences the size distribution of bubbles, bubble diameter and coalescence will be discussed together (Jo & Revankar, 2010; Nguyen, 2017).

In contrast to procedure 1 of experiment 1, observations on bubble diameter showed that there was in fact, a significant difference between fresh and saltwater, with larger bubbles observed in freshwater. This is in agreement with numerous studies, where increasing salinity and thus decreasing surface tension, relative to freshwater, causes the bubble diameter to shift towards smaller sizes (Slauenwhite & Johnson, 1999; Nye *et al*, 2014; Anguelova & Huq, 2017(a)). Agreement with procedure 2 and 3 was also reached regarding the occurrence of coalesced bubbles, where observations of greater numbers of coalesced bubbles were made in freshwater. This is also observed in external literature, where numerous studies and reviews indicate that the addition of salt to a system reduces the occurrence of coalescence (Cartmill & Su, 1993; Lekang, 2008; Firouzi *et al*, 2015).

Observing both bubble diameter and coalescence to decrease when increasing the system flow, and the subsequent water velocity, agrees with both the hypothesis made for this experiment, as well as the literature. The mechanism behind this result has to do with the venturi section of the system. A pressurized fluid that is mobile within a pipe, in this case water, enters the venturi and is constricted as the cross sectional area of the pipe is reduced. This increases the velocity of the water, as a result of the differential pressure, and results in a decrease in pressure in the narrow section, or 'throat' of the venturi, creating a vacuum at the air injection point and sucking the air into the water. When exiting the venturi the velocity of the water is reduced and is reconverted into pressure energy, however at a lower pressure than at the inlet of the venturi (Baylar & Ozkan, 2006; Baylar *et al*, 2009). The bubbles generated, whilst initially larger in the throat section of the venturi, will collapse and become smaller at the diverging section of the venturi due to the recovery of pressure within the pipe and increased forces acting on the surface of the bubbles (Kawamura *et al*, 2004). Increasing the system flow also meant increasing the volume of water within the holding tank, and this in turn increased the height difference between the venturi and the water surface within the tank. By increasing this height difference, more pressure is acting on system at the point of air injection in the venturi, and it is this increase in pressure that further reduces bubble size (Han *et al*, 2002; Cihan & Corapcioglu, 2008; Satterfield, 2010). Numerous studies have additionally documented the effects of both liquid flow and velocity on bubble size. A study conducted by Kawamura *et al* (2004), found that bubble diameter distributions were in fact a result of the difference in collapsing qualities at different liquid velocities. They observed that bubbles produced at a velocity of 15.8 m/s tended to collapse suddenly upon exit of the venturi, whilst bubbles at 9.9 m/s were observed to exhibit slower changes in diameter. Another study by Alhashan *et al* (2018) that was investigating the effect of flow rate on bubble formation and collapse, observed that when increasing the flow rate, more bubbles were formed and by recording high frequency vibration signals, they were able to determine that an increase in bubble collapsing was occurring. This finding was additionally supported by Zhao *et al* (2017), who found that when increasing the liquid flow, a subsequent increase in intensity of bubble collapse would occur. From the external literature it becomes clear that bubble diameter, as a function of either flow rate or velocity, is mainly determined by the intensity of bubble collapse at the diverging section of the venturi. Bubble diameter within the system can also be influenced by the system flow post venturi, by action of the turbulence within the system. Increasing the water flow, and thus the velocity, leads to a subsequent increase in turbulence (Falkovich, 2018). Studies have shown that turbulence plays a major role in the determination of bubble diameter, where increasing the turbulence results in pressure deformation forces that act on the surface of the bubble, causing either a reduction in size, collapse, or breakup (Martinez, 1998; Martinez-Bazan *et al*, 1999). In this regard the observations made at point 3 agree with external research, and due to the close relationship shared between bubble diameter and the occurrence of coalescence, one can additionally assume that increasing the flow velocity additionally reduces the occurrence of coalescence, which was also observed in this study.

One of the more interesting observations from this study were the differences in bubble diameter at the separate observation points within the system. Overall, when collating the data from both fresh and saltwater, a large increase in bubble diameter was recorded at point 3. Observations at point 3 were made at the end of the 2m horizontal observation pipe, and these bubbles were much larger than those recorded at point 2. Whilst little literature has explored bubble behaviour in horizontal pipes, the few that have make observations similar to those which were observed in this study. Whilst not quantifiable, smaller bubbles that had yet to coalesce were observed to travel at a faster velocity through the pipe than the larger coalesced bubbles. A study conducted by Ekambara *et al* (2012) also observed the migration of bubbles towards the top of the pipe due to buoyancy. This negatively affects bubble diameter, primarily due to differences in 'wall lubrication forces' and drag forces, where the liquid flow rate is lower between the bubble and the wall, but higher between the bubble and the main flow, and thus the larger bubbles rise, coalesce more frequently, and travel slower than that of smaller bubbles still dispersed within the main flow (Ekambara *et al*, 2012). This represents a problem in terms of efficiency of aeration, where large bubbles form in such a relatively short distance, leading to a large loss of gas-liquid surface area, as well as increased drag forces due to these larger bubbles. Comparing these observations between fresh and saltwater reveals much larger bubbles at point 3 in fresh than in saltwater, suggesting that whilst a horizontal pipe might not be optimal for transportation of water containing bubbles, the detrimental effects are far more pronounced in freshwater. It was also observed that, whilst the bubbles in freshwater were large coalesced bubbles, in saltwater, a congregation of smaller bubbles had formed, giving a 'foam' like appearance. This is commonly observed in seawater and research agrees that even if bubbles come into contact, the presence of either salt or surfactants prevents the coalescing of the bubbles, but does not prevent them from remaining connected (Anguelova & Huq, 2017(a)). A greater deviation in the observations at point 3 was also calculated in freshwater, where bubbles approximately three times that of the mean diameter for saltwater were observed. Again these observations agree with most external research, where salinity has been shown to decrease bubble diameter by actively inhibiting the occurrence of coalescence (Lekang, 2008).

When considering the results regarding the effects of both system flow and observation point, mean bubble diameter was, generally speaking, observed to decrease at all observation points when increasing the system flow (figures 31 & 32). External literature also records this difference between velocities. Palsson (n.d.) stated that at low velocities bubbles were large and accumulated at the top of the pipes, whilst at higher velocities the bubbles became more 'foam like'. Ekambara *et al* (2012) additionally concluded that, in relation to observations made within the horizontal pipe, bubble diameter within a horizontal flow was determined primarily by the liquid flow turbulence, where increasing the water flow, and thus the velocity, led to a subsequent increase in turbulence (Falkovich, 2018). Furthermore, as previously noted, increasing turbulence leads to a decrease in bubble diameter (Martınez, 1998; Martınez-Bazan *et al*, 1999).

Observations regarding points 2 and 4 were also of interest to this study in terms of developing an efficient aeration system, as decreases in both bubble diameter and coalescence were observed at both points 2 and 4 relative to their preceding points in freshwater. In saltwater however, bubble diameter was observed to decrease at point 2 only, whilst no coalescence occurred at points 1 and 2 and increased at point 4 relative to point 3. When considering the design of the system, observation points 2 and 4 were positioned directly after 'bend' units, and the causation for smaller bubbles after these bends is also due to the effects of turbulence (figure 33). When fluid within a pipe enters a bend this cause the particles to change their direction of motion, creating an adverse pressure gradient that is generated from the curvature of the bend. This causes an increase in pressure, and subsequent decrease in fluid velocity at the 'inner' section of the bend, whilst the 'outer' section experiences a decrease in pressure and a subsequent increase in fluid velocity, resulting in an increase in turbulence and pressure deformation forces which in turn act on the surface of the bubble, reducing its diameter (Kalpakli, 2012; Jain, 2017). The fact that smaller bubbles were observed directly after bends shows agreement with what the literature predicts, and this is of course beneficial in maximising surface area available for aeration. However in saltwater, as previously mentioned, point 4 showed a slight increase in bubble diameter and coalescence relative to point 3, suggesting that the increased salinity is able to stabilise the bubbles against bursting or collapsing due to the pressure differentials however, further replicates or observations regarding this factor are required to quantify any relationship (Anguelova & Huq, (2017(b)). Overall bend units were observed to be very beneficial for reducing bubble size and coalescence in freshwater, whilst in saltwater bubble size was reduced in the first bend unit, but not the second, suggesting that the presence of bends within a saltwater system is not optimal.

Observations regarding the combined effect of system flow and water condition were surprising. It was assumed that the effect of increasing the system flow would be further enhanced by the addition of salt to the system, resulting in significantly smaller bubbles at all system flows tested relative to freshwater. According to the raw data this was achieved, where bubble diameter was observed to be ≈2mm larger in fresh than in saltwater at all system flows tested. The fact that this was found to not be statistically different is most likely due to the large standard deviations calculated. This has its own explanation however, as the mean bubble sizes calculated for each system flow include all of the observation points observed. As bubbles observed at point 3 were consistently the largest, roughly 10mm and 4mm in fresh and saltwater respectively, and bubbles at point 2 were consistently the smallest, roughly 3mm and 2mm in fresh and saltwater respectively, this caused large deviations in the dataset for this analysis. Regardless however, a clear trend is seen in the data, and as bubble diameter in saltwater was observed to be consistently smaller, we can conclude that although not statistically different, the observations agree with external studies regarding the size distributions of bubbles in fresh and saltwater.

As previously mentioned, the importance of bubble size is paramount, as this directly influences the gas-liquid surface area that is available for aeration. The observations regarding both the effects of system flow and observation point on bubble diameter have important implications for the industry. The effect of both of these factors on bubble diameter represents an important trade-off, where a lower system flow that is cheaper to operate will produce larger bubbles, but greater retention time within the water, allowing for a longer period of gas transfer. On the other hand, an increased system flow that is more expensive to operate will result in smaller bubbles, but a shorter retention time. The same case can additionally be made regarding the observation points, where it was clearly shown that whilst a 2m horizontal section of piping may increase the retention of bubbles in the water, the increased retention time allows for more coalescence to occur. These are important trade-offs that are relevant for the efficient and cost effective delivery of either air or oxygen to the water of an intensive aquaculture unit. However, significant differences observed between fresh and saltwater at the different observation points and overall suggest that the use of long horizontal piping post aeration in order to supply production tanks is viable in saltwater, due to the effect of salinity on bubbles diameter (figure 33 & 35). Ekambara *et al* (2012) categorised the bubble diameter as a principle variable that can characterize the internal flow structure of a horizontal pipe. When considering the larger bubbles formed in our system in freshwater, these bubbles will negatively affect the flow of the system, increasing drag and friction, and reducing the efficiency of both the aeration and pumping, whilst these factors will be less prevalent in a saltwater system. This study does suggest however, arising from the observed effect of pipe 'bends' on bubble diameter, that the use of these structures could be beneficial in freshwater aquaculture. Due to the large sizes of tanks now employed, in addition to the number of these tanks, long horizontal pipes are necessary, and the use of either bends or 'hourglass' structures (similar to a venturi but without a hole for aeration) within the pipe may represent an interesting solution for maintaining small bubble sizes whilst also increasing bubble retention time (Kawamura *et al*, 2004). Further testing would be required in order to categorise the viability of the use of these structures, as an additional trade-off is presented. Whilst introducing either bends or 'hourglass' structures may reduce bubble diameter and increase aeration efficiency, the increased turbulence caused by these structures will lead to head loss and reduction in pumping efficiency. Again however, no quantifiable conclusions can be made, and testing regarding aeration efficiency and pumping efficiency would be required.

5.2.1. Experiment 2 – Design and Data Improvements

Materials and design:

As with experiment 1, several methods were identified during experiment 2 that could be improved upon in order to enhance the accuracy and quality of measurements made. The following section will detail the identified weaknesses of this experiment as well as suggesting possible improvements that could be implemented were the experiment to be carried out again.

As in experiment 1, the method of air bubble generation could be improved upon. Were the experiment to be re-run, a fixed air flow would be utilised in order to generate homogenously sized bubbles and hopefully eliminate some of the variance that was calculated between the observations at a specific system flow and observation point. The use of an inconsistent airflow can also lead to the creation of larger bubbles, where a bubble that was assumed to have coalesced could in fact just have been a large bubble that was initially generated. The use of a needle would also be reconsidered. It was frequently observed during this experiment that the needle, which jutted out from the hole that was drilled to roughly the middle of the venturi pipe, had an effect on the turbulence and, when increasing the system flow, an enhanced disturbance of the turbulence by the needle would have ensued. Although constant across both water conditions tested, this enhanced turbulence would have influenced bubble diameter differently at different system flows. A redesign of the venturi would benefit from utilising a capillary tube attached to the hole that was drilled, with none of the tube protruding into the inner pipe of the venturi.

Again, like procedure 1, the method image capture for this experiment would be reconsidered. The use of webcams was initially rejected due to the faster movement of the bubbles relative to experiment 1, and instead the camera of a phone was used. This however proved to still be suboptimal, whilst the image quality was further reduced due to the fact that the transparent PVC pipes used at the different observation points were in fact far less transparent than the acrylic used for the testing tank in experiment 1. This led to distorted images, and bubbles that were difficult to classify. One possible improvement could be the use of higher quality cameras, as well as an additional lighting source to enhance the image and the perimeter of the bubbles. This could further be aided by the use of acrylic piping in order to reduce any 'haziness' or 'mistiness' that was observed in some of the images captured for this experiment.

Data:

Overall, the raw data collated for this experiment showed agreement with external literature, as well as what was predicted in the hypotheses. However, some sets of observations showed far more deviation than others. Standard deviations were consistently highest at observation point 3, whilst they were consistently lowest at observation point 2. Deviations amongst the data could be due to several reasons, drawn predominantly from the experiment design as well as observation error. The use of suboptimal images can especially negatively influence the observations, where large bubbles may in fact be several smaller bubbles clumped together, or a large bubbles may be a smaller bubble that has an elongated appearance due to the distortion of the image. This could possibly explain the results calculated for 120L, where the mean bubble diameter increased slightly relative to the observations at 100L. A greater number of observations were made during the saltwater testing. This is due to the fact that more bubbles were observed from the ten images at each observation point within each system flow because these bubbles had not coalesced and appeared, particularly at point 3, more 'foam' like than the large bubbles observed in freshwater. Even considering these possibilities, the data still shows the same trends across observation points, system flow and salinity, and overall high variations in the data are most likely what is actually occurring in the system due to the presence of turbulence and the subsequent pressure differentials that act across the whole cross sections of the piping. Nevertheless, further enhancement of the data could be achieved by implementation of the suggested improvements to equipment and design. More replicates of the study could reduce the observation error and deviation of the results, whilst also solidifying the trends in the observations that were made.

5.3. Recommendations

1) Further testing regarding whether a relationship exists between the effects of reducing pressure on bubble size as a bubble rises, and the presence of salinity. Observing a relationship between the two factors presents knowledge that can be applied for RAS culture, where the placement of aerators at different heights within the tank can be quantitatively proven to give benefits to aeration efficiency.
2) Although not statistically confirmed, increasing the distance from 1cm up to 5cm between the two needles reduced the occurrence of bubble coalescence. This sustains an increased surface area that is available for aeration and therefore increases the aeration efficiency within a system. More observations on the effect of altering inter-bubble distances is recommended. Moreover, in this instance, investigating the effects of altering distances >1cm may prove to be more beneficial in terms of aquaculture application, where the effects of inter-bubble distance have, in some cases, shown to be extremely small. Further investigation of these effects may produce a quantitative determination of a 'critical distance', where the occurrence of bubble coalescence is reduced.
3) As increasing the angle from 0° to 20° between the two needles produced less bubble coalescence, increasing the efficiency of an aeration system by maintaining smaller bubbles can be achieved by doing this. However, more testing, using more replicates, different equipment, and a greater number of angles to test would possibly result in a more quantified relationship.
4) The use of horizontal piping in RAS farming may not be optimal in saltwater culture due to the effects of buoyancy on the bubble within the pipe. It is however, far less recommended in freshwater culture due to the increase in bubble coalescence and the resulting effects on system efficiency. The use of certain structures within a piping system, such as 'hourglass' structures or bends may prove beneficial to the overall aeration efficiency by reducing bubble size. Further testing of this relationship, using water with low levels of DO and recording oxygen levels post aeration, whilst also factoring in the losses of pumping efficiency due to these structures, is recommended in order to provide informed knowledge to freshwater RAS facilities.
5) Running an aeration system at higher water velocities will lead to greater gas transfer due to smaller bubbles produced, but will increase costs related to maintaining the velocity. Again, further testing is required in order to evaluate the trade-off between aeration efficiency and pumping efficiency in order to determine optimal system settings.

6. Conclusion

Two self-designed aeration systems for observations of bubble diameter and bubble coalescence were assembled in order to evaluate gas-liquid surface area as a result of different variables.

Experiment 1, which comprised of three separate procedures, involved the assembly of a cylindrical testing tank. The tank was approximately 1m in height and had webcams attached to the tank in order to observe bubble size and coalescence. For procedure 1, a needle attached to a syringe was inserted through the bottom of the tank in order to evaluate the effect of water height on bubble diameter. For procedure 2 a needle 'bracelet' was used, which allowed the distance between two separate needles to be increased from 1cm up to 5cm in order to observe differences in bubble coalescence. Procedure 3 also used the needle bracelet, but instead the angle between the two needles was increased from 0° to 20° in order to observe differences in bubble coalescence. Rulers attached to the interior of the tank were used for measurements of bubble diameter (procedure 1), and bubble coalescence was characterised by observing number of bubbles (procedure 2) and bubbles ≥5mm (procedure 3). All procedure were run in both fresh and saltwater.

Experiment 2 involved the assembly of an aeration system using transparent PVC pipes (total ø: 32mm & internal ø: 27.2mm) to form a rough 'U' shape, with two vertical sections, roughly 0.8m in length, and one elongated horizontal section, roughly 2m in length. The system contained four observation points in order to observed differences in bubble size and coalescence at separate sections within the system. A self-designed venturi, using a transparent PVC pipe (total ø: 25mm & internal ø: 22mm) with a single needle inserted into the pipe to act as an aerator, was installed at the first vertical section of the system. Increasing water velocities; 0.92, 0.98, 1.04, 1.12, 1.18, 1.25 and 1.29m/s were generated in order to observe their subsequent effects on bubble size and bubble coalescence at the different observation points within the system. All velocities were run in both fresh and saltwater.

Experiment 1

- Initial bubble diameter generated at the bottom of the testing tank was the same in fresh and saltwater, whilst bubbles at the top of the testing tank, a height difference of 0.9m, were larger in diameter in freshwater than in saltwater.
- Increasing the distance between the two needles from 1cm up to 5cm, had no overall effect on bubble coalescence.
- Increasing the angle between the two needles from 0° to 20° reduced bubble coalescence.
- Overall bubble coalescence occurred more frequently in freshwater than in saltwater.

Experiment 2

- When increasing the system flow, and subsequently water velocity within the system, bubble diameter and coalescence occurrence decreased.
- Bubble diameter was smallest after the 'bend' units due to a lack of coalescence, whilst bubble diameter was largest at the end of the horizontal observation pipe due to increases in bubble coalescence.
- Overall, both bubble diameter, and the frequency of bubble coalescence, were smallest in freshwater than in saltwater.

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Appendix

Appendix 1: Raw data observed for procedure 1, showing all individual bubble diameters recorded.

Appendix 2: Recorded times and calculated mean times for bubbles to reach the surface from the moment of release from the needle, and the subsequent bubble velocity calculated for the 90cm distance the bubble had to travel.

Appendix 3: Calculated water flows and water velocities for the different system flows tested.

Appendix 4: Raw data observed for freshwater testing in experiment 2. Red blocks within the data indicate bubbles ≥5mm.

Appendix 5: Raw data observed for saltwater testing in experiment 2. Red blocks within the data indicate bubbles ≥5mm.

Appendix 1:

Freshwater		Saltwater	
Bottom Point (C) (mm)	**Top Point (A) (mm)**	**Bottom Point (C) (mm)**	**Top Point (A) (mm)**
5	5	4	4
5	5	4	4
4	4	4	5
3	5	3	5
4	5	4	4
5	5	5	4
4	4	5	4
4	5	4	3
4	4	4	4
4	4	4	4
4	4	4	
4	4	4	
	5		
	5		
	5		
	5		
	4		
	4		

Appendix 2:

Recording (s)	Freshwater	Saltwater
Recording 1	2.89	2.78
Recording 2	2.69	2.66
Recording 3	2.56	2.64
Recording 4	2.58	2.70
Recording 5	2.74	2.54
Mean (s)	2.69	2.66
Velocity (m/s)	0.33	0.34

Appendix 3:

System Flow (L)	80	100	120	140	160	180	200
Water flow (L/min)	32.02	34.09	36.42	39.16	41.05	43.42	44.82
Water Velocity (m/s)	0.92	0.98	1.04	1.12	1.18	1.25	1.29

Appendix 4:

System Flow (L)	80L				100L				120L				140L				160L				180L				200L			
Observation Point	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Bubble Diameter (mm)	3	2	15	8	6	3	12	4	3	5	14	5	3	5	15	4	3	3	12	4	5	3	10	6	3	2	12	3
	6	3	10	4	4	2	8	8	5	4	14	5	3	4	10	7	4	3	8	6	2	2	14	4	3	3	5	3
	4	3	18	7	5	4	10	5	5	2	13	6	4	3	15	6	3	3	4	6	4	2	10	3	3	3	13	4
	4	3	10	5	5	3	10	3	4	3	19	6	3	3	10	5	4	2	15	6	4	2	10	3	3	3	7	4
	5	4	12	5	3	3	10	4	4	3	10	8	2	2	9	7	4	2	12	4	3	1	7	6	3	2	7	4
	5	3	8	7	7	2	13	4	4	4	10	6	2	2	9	8	2	4	9	3	2	1	10	2	2	3	11	4
	6	3	11	5	5	4	10	5	4	3	10	6	4	3	8	3	4	5	11	3	4	3	11	6	5	2	8	6
	4	2	9	6	6	4	8	6	4	1	7	7	5	3	9	3	2	2	8	4	5	1	11	5	4	2	4	5
	3	2	10	4	4	2	10	7	3	3	8	7	7	4	12	4	4	2	8	3	3	1	7	3	5	2	8	2
	8	5	12	7	6	2	12	4	5	3	7	4	6	4	8	5	6	2	9	4	3	3	5	3	4	1	9	2
	4	1		7	6	4	10	3	4	2	10	5	4	3	10	9	3	1	3	2	3	4	5	4	4	1	8	3
	4	2		6	6	3	11	4	5	2	7	4	3	3	10	4	3	1	13	5	4	3	10	7	3	3	9	2
	2	3		5		2	10	5	4	2	19	5	3	3	7	3	4	2	7	4	5	3	7	6	2	3	7	6
	4	3		6		4	7	5	3	5	12	7	4	2	11	4	6	3	8	6	3	2	9	6	3	2	10	5
	3	4		10		3		8	4	3	8		3	2		3	2	4	8	3	2	3	10	5	2	2	9	3
	4	4				3		6	4	2			4	5		3	2	2	9	4	3	3	6	3	4	1	7	5
	4	3				2		6	5	2			5	2			5	4	10	6	4	3	10	4	3	2	10	7
	4	3				2		6	3	3			2	3			4	2	9	7	4	2	7	7	2	2	6	7
	6	3				2			4	4			4	1			6	3	10	3	5	2	8	3	4	1	5	8
	5	4				3				3			6	1			3	2	8	2	4	2	10	3	2	1	5	2
mean (mm)	4.40	3.00	11.50	6.13	5.25	2.85	10.07	5.17	4.05	2.95	11.20	5.79	3.85	2.90	10.21	4.88	3.70	2.60	9.05	4.25	3.60	2.30	8.85	4.45	3.20	2.05	8.00	4.25
variance	1.83	0.84	8.94	2.55	1.30	0.66	2.69	2.26	0.50	1.10	15.74	1.41	1.92	1.25	5.72	3.85	1.69	1.09	7.73	2.20	0.99	0.75	5.19	2.47	0.91	0.58	5.89	3.36
standard dev	1.35	0.92	2.99	1.60	1.14	0.81	1.64	1.50	0.71	1.05	3.97	1.19	1.39	1.12	2.39	1.96	1.30	1.05	2.78	1.48	0.99	0.86	2.28	1.57	0.95	0.76	2.43	1.83

Appendix 5:

System Flow (L)	80L				100L				120L				140L				160L				180L				200L			
Observation Point	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Bubble Diameter (mm)	3	2	9	5	2	3	4	5	3	2	5	8	3	4	2	5	2	3	3	6	3	2	4	4	3	2	4	3
	4	3	8	6	3	3	6	7	3	2	4	4	2	3	3	6	1	2	3	6	3	2	2	6	3	3	4	4
	3	3	3	6	3	4	5	5	3	1	7	5	2	1	3	6	2	1	3	4	2	2	2	4	4	3	5	5
	4	3	3	7	5	2	6	3	2	3	7	6	4	1	6	4	2	2	3	3	2	3	3	2	3	2	2	2
	3	4	4	2	4	2	2	4	2	1	5	7	3	3	5	3	3	2	4	2	2	1	4	4	2	2	2	3
	4	4	2	3	2	3	3	4	2	1	5	3	2	1	6	7	2	2	3	2	2	2	4	4	3	1	3	4
	2	2	3	3	3	4	5	5	3	2	4	2	4	2	2	5	2	2	6	1	2	2	5	5	2	1	1	4
	1	3	6	6	2	2	6	4	4	1	5	4	5	1	2	2	2	2	4	7	1	1	3	5	3	3	5	2
	3	2	6	6	1	2	7	6	3	2	2	2	2	4	3	3	3	1	3	6	3	2	2	5	2	1	2	3
	3	3	6	7	2	2	8	6	3	3	10	2	2	2	6	4	4	1	3	4	4	2	2	6	3	2	2	3
	3	3	7	8	3	2	4	5	2	3	3	3	3	2	6	4	4	2	3	6	1	1	3	2	2	1	2	4
	3	3	8	3	4	2	3	6	4	1	3	4	2	1	4	4	2	1	2	5	3	2	5	2	1	3	3	4
	2	3	10	5	3	3	5	5	4	3	8	5	4	2	4	5	2	2	2	3	3	3	3	5	3	3	1	7
	4	4	10	8	4	2	6	6	2	2	9	4	2	3	2	2	1	3	2	4	2	2	2	3	2	1	2	3
	4	5	5	5	3	1	1	5	3	3	3	4	2	3	7	3	2	4	4	3	2	3	3	1	2	1	1	4
	4	2	7	4	3	2	7	4	3	2	2	6	3	2	7	4	3	1	5	5	3	1	3	2	2	2	1	5
	3	3	4	2	3	1	2	8	3	1	3	7	3	1	2	5	1	3	3	6	4	2	3	3	2	2	2	4
	4	2	4	2	2	1	4	4	2	5	8	5	2	1	4	6	3	1	2	3	3	2	3	4	4	1	2	5
	3	2	7	8	3	3	5	4	2	2	3	5	4	3	3	5	5	2	3	4	3	2	4	4	2	2	3	5
	3	2	3	5	3	2	7	7	4	3	4	7	4	1	7	7	3	2	4	6	3	2	2	5	3	2	3	5
mean (mm)	3.15	2.90	5.75	5.05	2.90	2.30	4.80	5.15	2.85	2.15	5.00	4.65	2.90	2.05	4.20	4.50	2.45	1.95	3.25	4.30	2.55	1.95	3.10	3.80	2.55	1.90	2.50	3.95
variance	0.66	0.73	6.09	4.16	0.83	0.75	3.64	1.61	0.56	1.08	5.68	3.19	0.94	1.10	3.54	2.16	1.10	0.68	1.04	2.85	0.68	0.37	0.94	2.06	0.58	0.62	1.53	1.42
standard dev	0.81	0.85	2.47	2.04	0.91	0.86	1.91	1.27	0.75	1.04	2.38	1.79	0.97	1.05	1.88	1.47	1.05	0.83	1.02	1.69	0.83	0.60	0.97	1.44	0.76	0.79	1.24	1.19

Norges miljø- og biovitenskapelige universitet
Noregs miljø- og biovitskapelege universitet
Norwegian University of Life Sciences

Postboks 5003
NO-1432 Ås
Norway