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The Application of Nanobubbles in Agriculture

**This thesis is submitted in accordance with the regulations, governing the award of
the**

Degree of Master of Engineering with Honours

in

Chemical and Bio Process Engineering

Department of Chemical and Bio Process Engineering

Massey University, Manawatu, New Zealand

By

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June 2023

Abstract

Nanobubbles have an extensive range of applications across engineering and industry. Our area of interest lies in agriculture and horticulture: Irrigation, using water enriched with oxygen nanobubbles, has been shown to greatly improve crop yields when compared to irrigation with untreated water. Currently, there are no manufacturers in New Zealand producing nanobubble generators to meet the requirements of large-scale irrigation. Field trials were undertaken, to quantify the increase in plant and crop growth through irrigation with oxygen nanobubbles. The results showed a marked increase in root mass and crop growth, supporting the viability and development of a nanobubble generator.

The purpose to this thesis is to provide the research, testing and development of nanobubble tubes leading to a commercially viable, scalable nanobubble generator.

Research was carried out to provide an understanding of the science behind nanobubbles. Applying this knowledge to the iterative process of design, print, test and evaluate, allowed comparisons to be made for various tube designs and allowed one design to be selected and taken forward for commercial development. Test results show that the optimum tube design, in terms of performance, is a compromise between the dissolved oxygen readings taken from the product water and the head loss across the nanobubble tube. The results also showed that smaller multiple tube arrangements out-performed large-scale single tubes. This led to a patent application for a multi-tube design.

This thesis describes the 3-D printing of nanobubble tubes, nanobubble generators and current commercial installations under evaluation. The thesis concludes by discussing future development opportunities for the nanobubble generator.

Key Words: nanobubble, generator, agriculture, horticulture, irrigation, crops, yield

Acknowledgements

I would like to take this opportunity to thank the following:

Dr. Emilia Nowak, thesis supervisor, for her help, support and guidance.

Leon Powers and Daneel Ovtcharenko, Nanobubble Agritech, for their help and assistance.

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Terms and Abbreviations

| | |
|------------------------|--|
| Agritech | Agricultural Technology |
| Brownian motion | ‘the continuous random movement of microscopic particles, approximate size $1\mu\text{m}$, suspended in a fluid.’ ‘...the smaller the particles, the more extensive the movement’, (Oxford Science dictionary, 1997) |
| BNB | Bulk Nanobubbles |
| CMP | Centrifugal Multiphase Pump |
| DO | Dissolved Oxygen |
| H^+ | Hydrogen ion - cationic form of atomic hydrogen |
| H_2O_2 | Hydrogen Peroxide – strong oxidising agent – mild antiseptic – bleaching agent |
| IBC | Integrated Bulk Container, typically having cubic dimensions holding 1 or 2m^3 of water or aqueous solution |
| lps | Litres per second |
| lpm | Litres per minute |
| mg/l | milligrams per litre...may be expressed as mg.l^{-1} |
| mV | Millivolts |
| NaCl | Sodium Chloride – common salt |
| NB | Nanobubble |
| NBA | Nanobubble Agritech |
| NBG | Nanobubble Generator |
| NBT | Nanobubble Tube |
| OH^- | Hydroxyl ion |
| O_2 | Oxygen |
| PETG | Polyethylene Terephthalate Glycol |
| PFD | Process Flow Diagram |
| pH | Scale used to specify the acidity or basicity of an aqueous solution. |
| PSI | Pounds per Square Inch - pressure |
| skid | Frame-work upon which the nanobubble generator is mounted and secured. |

Chapter 1

Nanobubbles

1.0 Introduction

Nanobubble technology is relatively new with research and development very much in its early stages however, applications and uptake of this emerging technology are becoming more prevalent. There are few companies building nanobubble generators specifically for the agricultural industry. These generators produce both micro-bubbles and nanobubbles of oxygen in water. Irrigation, using water enriched with oxygen nanobubbles, has been shown to greatly improve crop yields. Nanobubble Agritech, (2021) verified this with data recorded from field trials, (*chapter 5*). This is also in accordance with published academic research. The potential economic benefits are significant in terms of increased yields. Furthermore, the benefit to the environment could be realised through reduced water usage leading to sustainable development and a reduced net energy consumption. Crops may not be viable in dry regions due to a lack of water. If water is used more efficiently and to better effect, then these areas where crops are considered non-viable may become viable, through the use of irrigation using water enriched with oxygen nanobubbles.

At the time of writing, (2023) there are no known companies within New Zealand building nanobubble generators. Globally, there are few companies building nanobubble generators, specifically for irrigation applications. The agricultural sector would therefore be obliged to outsource, from the limited number of international manufacturers and retrofit or modify their products to meet the requirements for large-scale irrigation. These units currently represent a significant investment for crop growers and farmers. Current prices and options place this technology beyond the reach of many. The challenge is to produce affordable units in New Zealand that can be made available to the agricultural industry, benefiting the farmer, the environment and New Zealand enterprise.

The remit for this thesis and project is to research, investigate and develop low-cost units that are accessible to most agricultural businesses, providing them with significant commercial and environmental benefits.

To improve on designs offered by the ‘market leaders’, it was necessary to procure a nanobubble tube and build a nanobubble generator for the purposes of testing and analysing the design. It became apparent, that to understand the design and seek out new ways to improve on each component, requires a detailed knowledge and understanding of engineering principles and fluid dynamics. The formation and generation of nanobubbles, and indeed the function of each component, must be fully understood to allow the design and its constituent components to be developed and improved upon.

Chapter 1 provides the research and understanding necessary, laying the foundations on which to develop the nanobubble tubes and nanobubble generators. The subsequent chapters describe the testing and development of the nanobubble tubes and nanobubble generator.

1.1 Nanobubbles

1.1.1 Definitions

The ISO, International Standards Organisation, defines ‘Ultra-fine’ bubbles, or nanobubbles as:

Ultrafine bubbles with a volume equivalent diameter of less than 1 μm . The ISO specifies the terminology and definitions to be used in the area of fine bubble technology. The Standard definitions for fine bubbles can be found in Table 1 in the appendix, section 8.1.

1.1.2 Physico-chemical characteristics of nanobubbles

i. Bubble diameter:

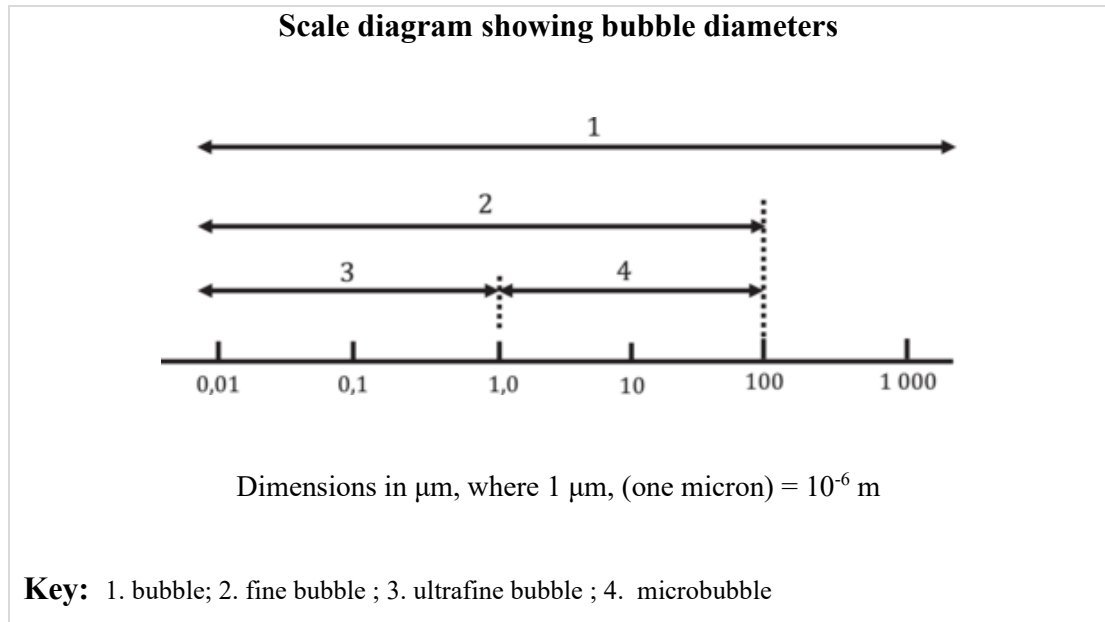


Figure 1. Bubble diameters, International Standards Organisation - ISO 20480-1:2017 : Standard definition for ‘fine bubbles’.

Measured examples of ultrafine bubbles in water, mostly range between 100 nm and 200 nm, (Standard definition for ‘fine bubbles’, ISO 20480-1, 2017).

Nanobubbles, or ultrafine bubbles, are defined as cavities of gases with a diameter < 200 nm in aqueous solutions, (Chaplin, 2017).

$$200 \text{ nm} = 200 \times 10^{-9} \text{ m}$$

Ushikubo et al. (2010), reported mean diameter of 137 nm for oxygen nanobubbles formed in de-ionised water. To put this in context; at 137 nm, the oxygen nanobubble is larger than a virus and smaller than a bacterium:

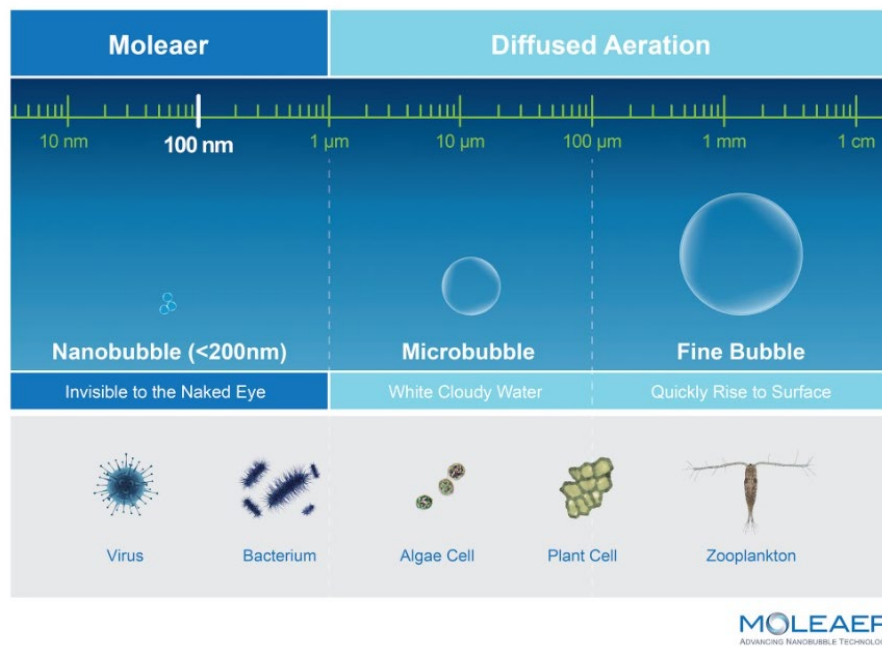


Figure 2. Graphic representation of bubble size comparison, (Moleaer.com, 2022)

ii. Surface area

One of the key characteristics of nanobubbles, is that they provide a very high specific surface area for the mass transfer of gas, (shown mathematically, in Chapter 5.0). The figures used in the calculation, provide an indication of the order of magnitude for the

increase in surface area available, for the mass transfer of oxygen. The calculation showed that when the diameter of the bubbles decreased by a factor of 1000, the total surface area available for mass transfer increased by a factor of 1000. As bubble size decreases, total mass transfer area increases for a given total volume. Total mass transfer area is therefore inversely proportional to bubble size for a given volume of gas.

iii. Buoyancy

Due to their size and mass, nanobubbles are neutrally buoyant; they do not rise or sink. They take on a random movement, (Brownian motion) within the body of the water. Brown, (1827), showed this movement in pollen particles suspended in air. This random movement further reduces the likelihood of aggregation and coalescence. The zeta potential also plays a significant part in this effect, where negative charges at the gas bubble-water interfaces will cause bubbles to repel each other due to like-charges. This too, helps promote the stability of the nanobubble. “The stability of bubbles is increased by low rising velocity, which is negligible due to Brownian motion and low buoyancy forces.” (Chaplin, 2017).

iv. Zeta Potential

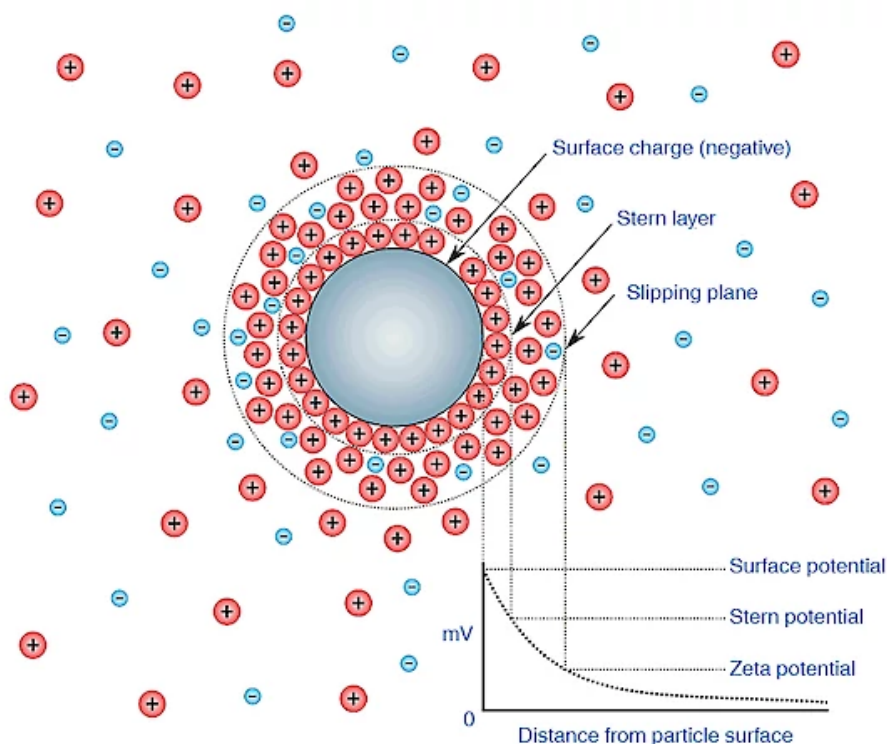


Figure 3. Graphic representation of electrical charges at the gas bubble – water interface, (Acniti.com, 2022).

Electrical double layer around an ultrafine bubble

The net electrical charge around gas bubbles in liquid, are important in understanding the interaction of nanobubbles. When a bubble is suspended in liquid, it is surrounded by oppositely charged ions. The immediate area surrounding the nanobubble comprises two regions; an inner region called the Stern layer, where the ions are strongly bound, and an outer diffuse region where the ions are less firmly attached. The outer region is cloud-like and held together by electrostatic force. It consists of ions of opposite polarities. The system, as a whole, forms an electrical double layer. The development of a net charge at the

bubble- aqueous interface, affects the distribution of ions in the neighbouring interfacial region. This results in an increased concentration of oppositely charged ions close to the surface. When the nanobubble moves through the liquid, ions within the boundary move with the bubble. Any ions beyond the boundary do not move with the bubble. This boundary is referred to as the hydrodynamic shear or the slipping plane. The potential on this surface is called the zeta potential.

High and Low Zeta potential

The Zeta potential, measured in mV, gives an indication of the magnitude of the electrostatic charge, giving rise to repulsion or attraction between particles, bubbles or droplets in dispersed phase. Zeta potential is one of the fundamental parameters to affect dispersion and subsequent nanobubble stability. Zeta potential provides a detailed insight into the causes of dispersion, aggregation and coalescence.

H⁺ and OH⁻ ions

Higher zeta potentials can be positive or negative, and give stability to nanobubbles due to repulsion between the bubbles. A lower zeta potential leads to coalescence and is less stable. A lower Zeta Potential means a value closer to zero. The charge of the solution depends on the agglomeration of positive ions, H⁺, or the agglomeration of negative ions, OH⁻. Studies have demonstrated that bubbles in distilled water are negatively charged. Meegoda et al (2018), reported a zeta potential of 22.4 mV, ± 3.4 mV for O₂ in de-ionised water at 20 °C, pH7, 0.002M NaCl and that; when measuring different bubble sizes there is no relationship between the magnitude of the zeta potential and the bubble diameter.

H⁺ ions, OH⁻ ions and pH, are factors that determine Zeta potential. When the zeta potential is negative, the gas-water interface is negatively charged with OH⁻ ions. Water has an excess of OH⁻ ions at the interface, compared to H⁺ ions. The negative value of the zeta

potential under a wide range of pH suggests that OH^- is more effectively adsorbed at the interface than H^+ . Zeta potential may be positive; this occurs under stronger acidic conditions, for example; when dissolved CO_2 concentration is high. Researchers have identified that the adsorption of OH^- onto the interface, by the difference of hydration energy between H^+ and OH^- , or by the orientation of water dipoles at the interface with hydrogen atoms pointing toward the water phase and oxygen atoms towards the gas phase, thus causing an attraction of anions to the interface.

(for full review, see acniti.com, 2023)

Meegoda et al., (2018), carried out a series of experiments to understand the behaviour of nanobubbles and showed that the size and zeta potential values of oxygen, nitrogen, air, and ozone nanobubbles were a function of the properties of the gas, specifically the gas solubility. Nitrogen, with the least solubility, had the smallest bubble diameter, while ozone with the highest gas solubility produced the largest diameter bubbles. The negative zeta potential value of nanobubbles is due to the number of OH^- ions on the bubble surface. Since all the parameters are identical except the gas, it can be concluded that the zeta potential is a function of gas diffusion rates, solubility, and would contribute to the generation of OH^- ions on the bubble surface.

v. Coalescence

The electrical charges at the liquid–gas interface creates repulsive forces that prevent bubble coalescence. This gives rise to highly dissolved gas concentrations in water. This in turn, results in smaller concentration gradients between the interface and the bulk liquid, (Ushikubo et al., 2010).

vi. Stability and Longevity

*Figure 4. Fate of macro, micro, and nanobubbles in liquids over time. * indicates that bubbles shrink & disappear, (Meegoda et al., 2018).*

Macrobubbles rise to the surface rapidly due to buoyancy forces, as shown in figure 4, and burst, while microbubbles rise at a slower rate. This increase in rise time allows for a greater transfer of gas from the bubble to the bulk liquid. This substantial loss of mass, causes the microbubble to shrink and disappear after a few hours.

Microbubbles and nanobubbles have different swelling and shrinkage properties from macrobubbles. It is reported that the critical diameter separating bubble swelling and shrinkage is 50 to 65nm, (Li et al., 2013). Bubbles larger than this critical value will swell, while smaller bubbles will shrink. Microbubbles tend to gradually decrease in size and subsequently disappear due to long stagnation and dissolution of interior gases into the surrounding water, whereas nanobubbles can remain in the solution for weeks, under the right conditions, (Takahashi, 2005).

Experimental data, from literature review, has shown that smaller bubbles with a high zeta potential, are more stable with time. Smaller bubbles tend to stay in solution longer because their motion is governed by both Brownian motion and buoyancy force. With this random motion, gas inside a bubble continuously diffuses and is supposed to decrease in size and eventually disappear. It is hypothesised that, with the loss of charges on the surface due to

diffusion, eventually, nanobubbles would shrink and disappear in a similar way to that of micro-bubbles. Figure 4 illustrates the fate of macro, micro, and nanobubbles over time. A theory is being developed to validate the above, based on diffused double layer theory and molecular dynamic simulations, Meegoda et.al., (2018).

Nanobubbles are found to exist in solution for several weeks. Azevedo et al. (2016), reported that bubbles of radii 150–200 nm were identified in solution for 2 weeks after creation. With stable existence in liquids for over several weeks, nanobubbles have an extensive range of applications across many fields of science and engineering. For an effective and functional use of these bubbles, it is important to know the reason for their long-term stability. Meegoda et.al., (2018) carried out a comprehensive laboratory investigation to determine bubble size distributions and zeta potentials of nanobubbles, first with four different gases (test series I), then with different salt concentrations, pH levels, and temperatures of the solution (test series II). Experimental results from (test series I) showed that the average bubble size depended on the gas solubility in water, and zeta potential depended on the ability of the gas to generate OH^- ions at the water/gas interface.

Experimental results from test series II showed that high pH solutions produced smaller but stable nanobubbles. Bubble diameter increased slightly, with increasing salt concentration however, bubble size did not show considerable dependence on solution temperature. Long-term tests showed that with time zeta potential of bubbles decreased while the bubble size increased. Even though bubble sizes are expected to decrease with time due to gas diffusion, results indicate increased bubble sizes. This is because of a decrease in zeta potential and bubble movement, due to Brownian motion, which causes bubble coalescence over time, forming larger bubbles.

(For full review see 'Stability of Nanobubbles', Meegoda et al., 2018).

1.1.3 Factors affecting nanobubbles

i. pH

Meegoda et.al., (2018) showed that negative zeta potential values increase when the pH value of the solution increases. This is due to the increase in OH⁻ ions. It was also observed that smaller sized bubbles were generated, using hydrodynamic cavitation, under high solution pH values. Conversely, bubbles were larger and unstable in acidic solutions. These observations also supported the hypothesis that the amount of OH⁻ ions on the surface of nanobubbles, governed stability. Higher pH levels with a high concentration of OH⁻ ions generated smaller, stable nanobubbles with higher zeta potential values. Experimental results also showed that, with increased NaCl concentrations, zeta potential values decreased, while the bubble diameter increased.

ii. Temperature

Meegoda et al., (2018), showed by way of experimental results, that zeta potential decreased as temperature increased. There was no significant change in bubble size with increased solution temperatures. The change in zeta potential value may be due to the change in OH⁻ ion concentration on the bubble surface, and with elevated temperatures and increased ion mobility it reduced the OH⁻ concentration on the bubble surface. Jia et al., (2013), reported similar data showing a decrease in negative zeta potential values with increasing temperature.

1.1.4 Free Radical Generation from Bulk Nanobubbles

Nanobubbles have been shown to have a mild disinfectant effect. They are frequently used in the treatment of wastewater and drinking water, recently developed, due to their ability to generate highly reactive free radicals, (Agarwal et al., 2011). This section provides the background to understanding the ‘mild disinfectant effect’ of water enriched with oxygen nanobubbles. Terms used include:

i. Ion

An atom, or group of atoms that has lost one or more electrons, making it positively charged (cation), or negatively charged (anion).

ii. Radical

A group of atoms either in a compound or existing alone.

iii. Free Radical

An atom, or group of atoms with an unpaired valence electron. Because of their unpaired valence electron, most free radicals are extremely reactive.

(Definitions reproduced from Oxford Concise Science Dictionary, 1997).

iv. Hydroxyl Ions, OH^- and Hydroxyl Radicals, OH^\cdot

There is a significant difference between the hydroxyl ion, and the hydroxyl radical. The hydroxyl ion acts as an antioxidant in the body. It reduces harmful radicals that destroy tissues and DNA, protecting us from premature aging and the development of degenerative diseases. Reduction is one half of a chemical process referred to as Redox, (reduction /oxidation). It is a reaction that reduces a radical’s ability to oxidize other atoms and compounds. The other half of the redox reaction is oxidation. Oxidation is the loss of electrons and Reduction is the gain of electrons.

Hydroxyl radicals cause damage, by way of oxidation to tissues and DNA. The hydroxyl ion reduces the radicals' ability to oxidize tissues and DNA. The difference between the Hydroxyl Ion and the Hydroxyl Radical is one electron. The hydroxyl radical is defined as OH (neutral) and the hydroxyl ion is defined as OH⁻ (negative). The negative character represents the negative charge for the hydroxyl ion.

An ion can be an atom or molecule that has a net charge. That charge can be positive or negative; it cannot be neutral. The hydroxyl ion has a negative charge, which means it has an excess of one electron that it can donate to a radical, or atom that lack electrons. A free radical is always looking for an electron, or electrons, to become paired again. Hydroxyl radicals are extremely damaging to living tissues.

ACniti.com, (2022), suggested that when fine bubbles are compressed at high concentrations, zeta potential will increase as the ion concentration around the nanobubbles, increases. After several minutes of compression, an excess of OH⁻ ions are formed, leading to the generation of OH radicals. It is the OH radicals that have an oxidising effect.

While the explanation offered by ACniti may not be wholly accurate, or proven, the effect of free radicals is known, however 'the how and why' OH radicals are created, is not yet fully understood. Research has been carried out to gain an understanding of the generation of free radicals, and provide scientific reason for their creation. Takahashi et.al., (2021), attempted to provide such an explanation: "Microbubbles are very fine bubbles that shrink and collapse underwater within several minutes, leading to the generation of free radicals. The drastic environmental change, caused by the collapse of the microbubbles, may trigger the generation of free radicals, by dispersion of the elevated chemical potential accumulated at the gas-water interface."

This property gives rise to many practical applications, such as wastewater treatment and semiconductor cleaning. The mechanism for the generation of free radicals, proposed by Takahashi et.al., (2021), is related to the electrical charges present when microbubbles

collapse; Takahashi et.al., used electrophoresis studies to show that the gas-water interface is negatively charged over a wide pH range.

Observations confirmed the generation of free radicals from bulk nanobubbles, through the collapsing process leading inducing cavitation. However, the existence of radical generation from bulk nanobubbles may indicate energy potential levels of bulk nanobubbles that could be useful in developing practical applications. The dispersion of physicochemical potentials may create some of these properties.”

(For full review see, Takahashi et.al., 2021).

While the research did not fully explain how and why, free radicals are generated, it did prove the presence and generation of free radicals from microbubbles and nanobubbles. The amount of hydroxyl radicals produced by NBs in solution is assumed to be very small. “The description used in the NB industry to portray the oxidation effect is that of a ‘mild’ disinfection or oxidation. For this purpose, it is used in algal mitigation of water bodies and in certain industries such as cleaning and food processing, to decrease pathogen counts,” (Meegoda, et.al.,2018).

1.2 Applications of nanobubbles

(Table 1 – Applications of nanobubbles)

| Application | Description | Reference |
|---------------------------------|--|---------------------------|
| Drinking water | Treatment of wastewater and drinking water: recently developed, due to their ability to generate highly reactive free radicals; oxygen nanobubbles have the effect of a mild disinfectant | Agarwal et al., (2011) |
| | Nanobubbles are used in sparkling water and sports drinks. With the addition of nanobubbles, the water can potentially retain gases for a longer period | Bauer Nanobubbles, (2017) |
| Waste-water treatment | Artificial flotation in water: This is accomplished by altering the ionic equilibria of dissolved ions in solutions and by changing the net charge on particle surfaces. Nanobubbles adhere to colloidal and emulsified materials promoting coagulation and facilitating separation through flotation and/or filtration. | Moleaer, (2023) |
| Decontamination of ground water | Remediation of groundwater using ozone microbubbles and nanobubbles | Hu and Xia, (2018) |
| Bio-medical engineering | Delivery of cancer drugs, where nanobubbles are placed in the body and given the ability to identify tumour cells. The bubbles are blown up when they approach tumour cells, thereby destroying the cancer | NHI, (2017) |
| | Nanobubbles have been used in emergency procedures: O ₂ nanobubbles are injected directly into the bloodstream; This can give up to 15 mins when breathing is restricted allowing additional time to reach to hospital and a greater chance of survival | Narayan, (2017) |
| Agriculture | Nanobubbles have shown the ability to create reactive O ₂ species which contribute to seed germination. This increase in reactive oxygen species has the same effect | Liu et al., (2015) |

| | | |
|---------------|---|-----------------------------|
| | as adding H ₂ O ₂ , (hydrogen peroxide), resulting in higher germination rates. | |
| | O ₂ nanobubbles have been shown to have a significant effect on plants and crops, increasing growth, yield and improving soil quality and health. (<i>Chapter5, Results, figure 27</i>) | Nanobubble Agritech, (2021) |
| Fisheries | O ₂ nanobubbles increase the DO levels in water and help reduce pathogens. This improves the health, growth rate and survival rates of farmed fish. | Moleaer, (2017) |
| Food | CO ₂ Nanobubbles help regulate pH levels in liquids; they remain in suspension for prolonged periods helping to regulate solution pH. | Moleaer, (2017) |
| Poultry farms | Ozone nanobubbles are used during the cleaning and disinfection cycles: O ₃ nanobubbles are pumped through the water lines to disinfect and clean the pipes and drinking vessels. O ₂ nanobubbles are injected into the drinking water to enhance poultry growth and health. | Acniti, (2023) |
| Paint | In the presence of nanobubbles; paint drying times are reduced; paint shows a resistance to mould and shows an increase in brightness. | Bauer, (2014) |
| Mining | The use of nanobubbles in the processing of tailings / fines, improves the separation efficiency allowing companies to comply with and meet strict environmental limits. | Chipakwe, V., (2021) |
| Separation | Nanobubble technology has been adopted in the Oil and Gas industry to enhance phase and colloidal separation; also helping to reduce the volumes of chemicals used in chemical treatment, (surface and sub-surface) and stimulants, (sub-surface). | Moleaer, (2023) |

1.3 Nanobubbles in agriculture

Nanobubbles, due to their size and numbers, provide huge surface areas for mass transfer of gas, for a given volume of gas, in solution. They have been shown to assist greatly, in the transportation and uptake of nutrients at the plant roots. A detailed knowledge of the effects of oxygenated water, as NBs, on plants and soil, provides a foundation on which to promote the NB generator. Plant life thrives on a healthy balance of water, oxygen and nutrients. Water provides the transport to deliver nutrients and oxygen to plant roots.

1.3.1 Plant Nutrients in Soil

There are 17 essential elements that act as nutrients for growth:

Carbon (C), Hydrogen (H), Oxygen (O), Nitrogen (N), Phosphorus (P), Potassium (K), Sulphur (S), Calcium (Ca), Magnesium (Mg), Boron (B), Chlorine (Cl), Copper (Cu), Iron (Fe), Manganese (Mn), Molybdenum (Mo), Nickel (Ni), and Zinc (Zn).

The three main nutrients are nitrogen (N), phosphorus (P) and potassium (K). Together they said to be, or known as **NPK**. The three macro-nutrients that plants take from water, air, or both, are; Carbon (C), Hydrogen (H) and Oxygen (O) while micro nutrients for plants include iron, manganese, copper, molybdenum, zinc, boron, chlorine and nickel.

(For full review, see <https://agritutorials.com/plant-nutrients-in-the-soil>, 2022)

1.3.2 Mass Transfer of Plant Nutrients in Soil

As the plant transpires, water, oxygen and nutrients are absorbed up into the plant. This causes a chemical imbalance between the root bowl and the surrounding soil. This, in turn, creates a concentration gradient. Water, oxygen and nutrients will migrate toward the

root bowl of the plant to reach chemical equilibrium. On reaching the plant roots, they are readily absorbed into the root structure, passing up through the plant as cells metabolise the nutrients and the plant transpires. This maintains a difference in concentration of water, oxygen and nutrients at the root bowl and the surrounding soil . This difference, or chemical imbalance, gives rise to a concentration gradient which provides the driving force, ensuring delivery and uptake of nutrients from the soil and oxygen from the water. The huge surface area and Brownian movement of the O₂ nanobubbles in water, promote the mass transfer of gas from the water to the plant roots, further promoting the chemical imbalance.

(For full review, see <https://agritutorials.com/plant-nutrients-in-the-soil>, 2022)

i. Mass transfer

Mass transfer is the movement of dissolved materials into a plant, as the plant absorbs water for transpiration. This process is responsible for the bulk transport of nitrates, sulphates, calcium and magnesium. Plant transpiration provides evaporative cooling, forming a major component of the leaf energy balance. Transpiration also provides the driving force for transport of water and nutrients from roots to shoots.

ii. Diffusion

Diffusion is the movement of nutrients, through water, to the plant roots, in response to a concentration gradient. When nutrients are found in higher concentrations in one area than another, there is a net movement to the low concentration area until chemical equilibrium is reached. Thus, a high concentration of nutrients, as chemical elements in the soil, will diffuse to an area of low concentration, specifically at the plant roots. This is particularly important for the uptake of potassium and phosphorous.

iii. Root interception

Root interception occurs when the plant root comes into contact with colloids containing nutrients, within the soil. The plant root then absorbs the nutrients. This is an important transport mechanism for calcium and magnesium and provides a minor pathway for other nutrients.

(For full review see: 'Basic Concepts of Soil Fertility', North East Region, Certified Crop Advisor, Study Resources, Cornell University, 2010.)

1.3.3 Conditions affecting the transfer of nutrients

There are a number of direct and indirect factors which affect the transfer of water, oxygen and nutrients to plant roots. Weather conditions affect the rate at which water evaporates from soil to atmosphere. This has an indirect effect on the transfer of nutrients, reducing the water available for the transport of O₂ and nutrients. Heavy clay-like soils have relatively poor porosity and permeability and directly effect the transfer of nutrients.

i. Temperature

As ambient temperature increases, soil will lose water through evaporation and without irrigation or adequate rainfall, the soil will dry out and crack to the point where the soil loses its porosity. If water cannot reach the plant root bowl, then nutrients are not transported and absorbed by the plant roots. If ambient temperature and soil temperature are too cold then there is minimal temperature differential and a significantly reduced driving force for plant respiration; this will slow or abate plant growth. Plant growth is very much dependent upon local soil conditions and species. Optimum temperatures will vary accordingly.

ii. Pressure

Atmospheric pressure is a contributing factor to the rate at which water is lost to atmosphere which in turn, will affect the transport of nutrients.

iii. Wind

Wind can be considered as a consequence of temperature and pressure differentials. Wind also directly affects the rate at which water is lost to atmosphere.

iv. Humidity

Atmospheric humidity, (the degree of water saturation in air), has a direct effect on the rate and mass at which water is lost to atmosphere.

v. Porosity

Porosity in soil can be defined as the pore space, or 'free space,' between mineral particles and solid organic matter. These spaces are filled with air or water. The greater the porosity, then the greater the capacity to hold water, air and nutrients.

In engineering terms, porosity can be calculated as Voidage where Voidage, ε , is defined as the fraction of the total volume which is free space available for the flow, or hold-up of fluids, and thus the fractional volume occupied by solid material is $(1 - \varepsilon)$.

vi. Permeability

Permeability defines how easily a fluid flows through a porous material. Soil with a high permeability will allow easy unrestricted flow of water and nutrients, whereas soil with a low permeability will resist flow.

vii. Concentration

Irrigation, using water enriched with oxygen nanobubbles, has been shown to significantly improve plant growth, (Nanobubble Agritech, 2021). It is believed that the Brownian movement of nanobubbles helps to disperse the essential nutrients in water. Dispersing the

nutrients greatly improves absorption at the plant roots. This also maintains the chemical imbalance required for the concentration gradient and resultant driving force needed. Thus, concentration of nanobubbles and nutrients has a direct effect on mass transfer.

1.4 Nanobubble Generation

There are a number of different ways in which nanobubbles can be produced. Some of these methods include electrolysis; sonication using ultrasonic sound waves; shearing by hydrodynamic cavitation and separation using membranes and diffusion.

There is an energy cost and practical aspect to each method. Hydrodynamic cavitation has been shown to require less energy input compared to other methods and has proven to be comparatively simple and more practical; the generation of NBs for commercial applications, requires large scale production. Other methods are not conducive to large-scale production. To date, (2022) cavitation is the predominant method for producing NBs in commercial generators.

Cavitation occurs when the fluid pressure, within a pipe, pump impellor, or system, falls below the gas vapour pressure. This results in gas breaking out of solution to form gas bubbles or gas filled cavities. As the localised pressure returns to its equilibrium state, the fluid pressure rises above the gas vapour pressure causing a rapid and violent collapse of said gas bubbles and cavities, giving rise to the generation of nano- and micro-bubbles. Cavitation can cause significant damage in process systems and mechanical systems. Early and experimental NBGs used ‘cavitation pumps’ designed purposefully, to induce cavitation. A limited number of manufacturers have developed the cavitation pump and use this method in their NB generator options. Cavitation can also be induced in centrifuges, although no commercially available generators, employing this method have been identified.

The use of modified or developed venturi tubes appears to be the most common method used in commercial NBGs. It is by far, the simplest and most economical method for producing nanobubbles. Essentially, it has no moving parts. Current commercial nanobubble tube designs resemble a modified venturi tube which combines the venturi and cavitation effects. Nanobubbles are produced by injecting gas into the nanobubble tube where shearing and cavitation takes effect.

“Cavitation mechanisms can be classified into four different types, (Maoming et al., 2010; Agarwal et al., 2011; Padilla-Martinez et al., 2014).

- *Hydrodynamic - variation in the pressure of liquid flux due to system geometry (Maoming et al., 2010; Agarwal et al., 2011; Oliveira et al., 2018).*
- *Acoustic - produced by applying ultrasound to liquids, (Ashokkumar and Mason, 2000; Ashokkumar, 2011).*
- *Particle - passing high intensity light photons in liquids, (Poulain et al., 2015).*
- *Optical - short-pulsed lasers focused into low absorption coefficient solutions, (Lauterborn, 1979; Martinez et al., 2014).”*

(For full review see ‘Stability of Nanobubbles’, Meegoda et al., 2018)

1.4.1 Electrolysis

This method has typically been used in laboratory experiments only, with several research articles using this method of generation, such as Kikuchi et al., (2009). However, no known large-scale applications could be found, at this time, (2022)

1.4.2 Ultrasonication

The principle of the acoustic cavitation method is based on subjecting the solution, or fluid, to periodic sound waves. These sound waves apply positive and negative pressure to the solution. Negative pressure gives rise to nucleation and expansion of bubbles. Positive pressure causes these bubbles to contract and implode when they reach their critical size. The implosion results in fragmented bubbles. Some of these bubbles continue to shrink over time, as the internal gas diffuses into the solution, and disappear, whereas others attain nanobubble size and stability.

This method has only been found in lab-based research: It is believed that this is due primarily, to the relatively low nanobubble concentrations being produced.

Bubble generation by acoustic cavitation was discovered in the mid-nineteenth century and has been studied by several researchers however, research on bubble generation using acoustic cavitation has been dominantly focused on micro/macro-sized bubbles, visible to the naked eye; furthermore, limited research has been conducted on the generation and growth of nano-sized bubbles using ultrasound. Moreover, no experimental report on the effect of dissolved gas concentration on NB generation using ultrasonication is available.

(For full review see 'Effect of Dissolved Gas Concentration on Bulk nanobubble Generation using Ultrasonication, Lee et al., 2020)

1.4.3 Cavitation

i. The Bauer Method

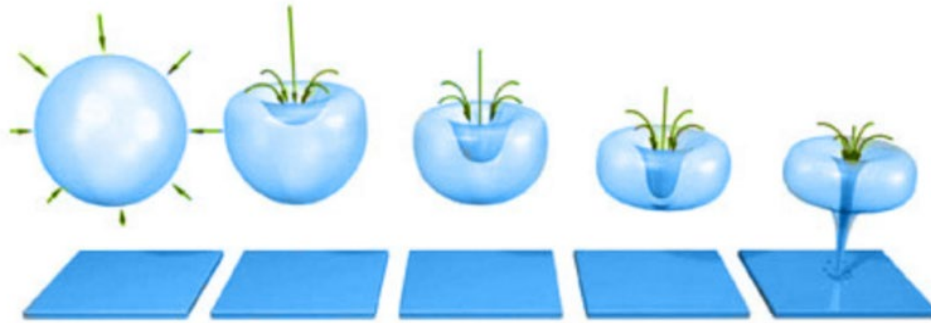


Figure 5. The Bauer method, (Nannobubbles.com., 2022)

The Bauer Nanobubble Generator comprises a number of partial plates, housed in a pipe and installed inline to a pumped water system. The plates are placed in such a way that it forces the water to expand and contract as it flows over the plates. This rapid expansion and contraction creates cavitation. Bauer claim that their NBG produces a high concentration oxygen nanobubbles, with a mean diameter between 50 -100 nm. The Bauer method and Bauer NBG are proprietary and protected under patent hence, the information on the internal design and method of generation is limited.

(For full review see nanobubbles.com.,2022)

ii. Hydrodynamic cavitation, (Venturi)



Figure 6. Example of a multiple venturi NB system, using ozone for a golf course turf application, primarily for the elimination of fungal disease, (Nano Bubble Technologies, 2020).

Hydrodynamic, (or Venturi) cavitation occurs through the depressurisation, of a gas-saturated water stream, through a flow constrictor. When the supersaturated water is forced through a needle valve, or constriction, the flow velocity rises, and the pressure falls below the vapour pressure of the liquid. Consequently, cavities (gas nuclei, or nanobubbles) form and grow into microbubbles by gas mass transfer from the liquid to the gas phase, (Azevedo et al., 2019).

Advantages of this system include; simplicity; ability to process large volumes of water and a relatively high gas transfer rate.

iii. Mechanical cavitation

High speed rotation of a pump impeller creates high pressure at the tip, or circumference of the impellor and low pressure at the eye of the impellor, (pump inlet). This results in a pressure gradient and the formation of gas cavities in the low-pressure zones.

This system does not directly inject gas; NB's are formed from gases already dissolved in water. However, this process results in lower NB concentrations per pass than other NB machines.



Figure 7. Example of mechanical cavitation NB machine, (Nanobubbles, 2020)

iv. Multiphase pumps

Etchepare et al., (2017), were commissioned to develop and research the potential for large scale nanobubble generation, using multiphase pumps: The main objective of their work was to develop a new method for generating highly-loaded nanobubbles in aqueous solutions by hydrodynamic cavitation, using a centrifugal multiphase pump (CMP), and a needle valve. Nanobubbles at 150–200 nm diameter were formed at 22 °C, with a pump

and a recycle column, at various operating pressures. Nanobubbles were found to be resistant to shearing by pump impellers throughout several bubble generation cycles. Nanobubble size remained constant and their concentration increased as a function of these cycles, reaching equilibrium after 29 cycles; this was dependent on pump pressure and the surface tension of the solution. The highest concentration, 4×10^9 nanobubbles ml^{-1} was obtained at 5 bar and 49 mN m^{-1} surface tension.

The mean diameter and concentration of these nanobubbles did not vary significantly over a period of two months, demonstrating the high stability of these concentrated nanobubbles. It is concluded that the procedure has great potential in future applications in ore flotation and wastewater treatment and reuse. Although residence times in multiphase pumps is generally lower than that using saturation vessels, the mechanism of hydrodynamic cavitation, operating in the various zones of the pump, allowed the formation of higher NB concentrations compared with the results obtained with a saturator vessel, (Azevedo et al., 2016).

Advantages for sustainable bubble generation with CMP include:

- i. Higher volumetric efficiency, providing a large mass of air per unit volume of recirculation.
- ii. Elimination of saturation chambers.

The results suggest that centrifugal multiphase pumps (CMP) have a great potential for bulk nanobubble generation at high rates, reaching a maximum concentration (4.1×10^9 nanobubbles ml^{-1} , after approximately 29 operation cycles (residence time = 2.1 min). This optimum condition was obtained at 4–5 bar and low liquid/air surface tension (49 mN m^{-1}). The bulk nanobubble dispersions were stable for over 60 days, with no decrease in nanobubbles concentration and mean size.

For full review see, (Etchepare et al., 2017).

EDUR multiphase pumps

Multiphase pumps are designed to supply integrated liquid-gas mixtures and to generate dispersions. They enable the supply of up to 30% gas proportions. EDUR-multiphase pumps are used in water and wastewater technology and varied industrial technologies. Applications include; flotation plants, ozonisation, water treatment, crude oil-water separation, fuel production and general process technology. Multiphase pumps can supply liquid-gas mixtures, enriching liquids with gases, such as air, oxygen or ozone. The multiphase pump differs, in construction and mode of operation, from conventional centrifugal pumps, allowing throttling at the pump suction inlet without cavitation arising at this point. EDUR states: The features of their multi-phase pumps include; self-priming; up to 30% by volume, gas entrainment; dynamic mixing and very high gas saturation. Multiphase pumps are sometimes referred to as Flotation pumps, Dissolved Air Flotation pumps or gas-saturation pumps. Advantages: eliminates the need for compressor systems, pressure vessels, control units, valves and associated maintenance costs. Gaseous fluids can be fed directly into the pump.

For full review see, (edur.com, 2023).



Figure 8, showing the pump impellor used in the EDUR multiphase pump, (edur.com,2023)

v. *Axial Flow - Shearing*

The water flow is rotated into several vortices, while moving along a special chamber and exiting from the discharge pipework. This rotational movement is maintained until the kinetic energy has depleted. This produces an intense shear, through respective centrifugal forces, triggering nucleation and gas bubble formation as a result of the pressure fluctuation, (Azevedo, 2019). This requires a pump for high water flows.

vi. *Diffusion through a porous membrane*

NBs are generated by flowing air, or gas through porous membranes, usually glass or ceramic, under high pressure. A key benefit of this type of machine is that a high concentration of NBs can be generated from a low energy requirement; only a low flow of water is required to pass through the NB generator, with gas pressure providing the key driving mechanism for NB production. This method is better suited to waste water treatment applications.

(For full review see 'Generation of nanobubbles by ceramic membrane filters', Ahmed et.al., 2018)

Figure 9. Graphical abstract - Generation of nanobubbles by ceramic membrane filters, (Ahmed et.al., 2018). The porous membrane forms a tube through which, the gas diffuses into the bulk liquid.

Disadvantages of this type of machine include:

- In order to achieve efficient gas transfer relative to the power required, the gas must be pre-conditioned, (filtered and pre-heated) and supplied at relatively high pressure.
- Porous membranes require a very high degree of filtration.
- Pressurising gases, such as oxygen and ozone, has inherent safety implications which must be carefully engineered and managed.
- Membranes are expensive.
- Not suited high continuous water flows

Chapter 2

Project Design for a Nanobubble Generator

2.0 Introduction

The boundaries and parameters have been set by those bodies that have contributed to the funding for project development and Nanobubble Agritech, the ‘developer’. (*The project boundaries and parameters can be found in the appendix, section 8.2, table 2*). The project has to be of environmental and commercial benefit to New Zealand.

Nanobubble generators are available from international suppliers and manufacturers offering various designs however, at present, (2023) there are no local suppliers or NBGs built in New Zealand. The units available for import, are not specific to the Agricultural industry; they would require modification to meet the needs of large scale irrigation and are thus, not suitable. These units are also relatively costly. The capital outlay plus the additional cost of modification would place them beyond the reach of many farmers. The challenge for Nanobubble Agritech is to develop and manufacture low cost nanobubble generators, specifically for high-flow irrigation applications.

Nanobubble Agritech’s vision was to develop a nanobubble generator that is ‘simple’, uses readily available low cost parts and nanobubble tubes that can be manufactured in-house. The tubes had to be designed for optimum efficiency in terms of energy losses and nanobubbles generated. The nanobubble tubes, designed and engineered by NBA, Nanobubble Agritech, are innovative in that the designs are unique.

The environmental benefit to New Zealand will be realised through the combination of a reduced energy input, potential to reduce water usage and significant increases in plant growth and yield.

The commercial benefit will be realised in terms of increased crop production and the respective income and taxation streams. Increased production may also benefit tertiary and supporting industries. Employment opportunities may arise from the manufacture, supply and installation of NBGs. Employment opportunities may also arise to meet the labour demands of increased production, in terms of growth and yield.

2.1 Design considerations

Nanobubble Agritech's market is the agricultural industry. Most, if not all of NBA's clients will come from the Agriculture sector where costs and capital investment present a significant out-lay and risk. With this in mind, NBA had to design and develop nanobubble generators that are affordable and attainable to agricultural businesses. This required a number of key factors to be considered. These include:

Safety

Safety is of paramount importance and was a prominent design consideration. The design team had to ensure that harm, injury or financial loss cannot occur as a result of human or mechanical failure, whilst operating a nanobubble generator. A full HAZOP, (Hazard and Operability study), was carried out to identify the risks and mitigations required. *(The HAZOP process is explained in the appendix, section 8.4 and a full HAZOP study can be found in the appendix, section 8.5.)*

'Fit for purpose'

In essence, 'fit for purpose' refers to the optimum capital expenditure for a required component, piece of equipment or unit that will provide adequate performance. For example: "The requirement of the Agritech nanobubble generator is to reliably supply, irrigation water, enriched with oxygen nanobubbles". The first component in the nanobubble generator is a water pump. Water pumps vary in cost and quality and the

selection criteria must be carefully considered: It is not good business practice to buy the most expensive pump available, on the assumption that it will be the most reliable, when cheaper pumps may perform adequately. Conversely, it is not necessarily good business practice to purchase the cheapest pump available; the initial cost may be cheaper however, it may prove to be more costly in terms of premature wear, breakdowns, maintenance call-outs to remote locations and the resulting inability to supply enriched irrigation water.

Simplicity

The design of the nanobubble generator has to be simple. Simple, in this context, means using the minimum number of parts which, are easily accessible and easy to maintain or replace.

Reliability and durability

The nanobubble generators will be installed in remote rural locations and subject to inclement conditions, therefore the NBGs must be robust, reliable and durable. This was an important consideration when selecting materials and equipment.

Practicality

Above all, the NBG had to be a practical solution to the design considerations. This included the feasibility and cost of manufacture.

Energy costs

The energy costs pertain to the electrical loading of the water pump, the oxygen generators' compressor and the associated charges for the electricity used. The design had to be such that energy costs can be kept to a practical minimum.

Total costs

The project team had to remain mindful of the total cost, in real terms, for the manufacture and supply of a nanobubble generator; the cost has to be viable. From the farmers' perspective, this includes initial purchase cost, reliability and running costs. From the development team's perspective, these factors had to be considered in parallel with the cost to Nanobubble Agritech in respect of manufacture, supply, installation, servicing and guarantees.

2.2 Method selected for the generation of nanobubbles

The research and study carried out in Chapter 1, provided the necessary understanding and foundations on which, to design and build an adaptable nanobubble generator to meet the needs of large scale irrigation. Different methods of generating nanobubbles and current commercially available nanobubble generators were reviewed: Their principal of operation and component parts were studied, in conjunction with the different methods by which nanobubbles can be generated, in order to identify the most suitable and effective method for large scale irrigation. The shearing of O₂ bubbles, as a result of pumping water through a nanobubble tube and injecting O₂ at close proximity to the tube inlet, was identified as the only practical and feasible method that could be used in a commercial generator, specific to irrigation. Scientific, commercial and practical research, consolidated NBA's decision to induce cavitation as a consequence axial flow shearing.

2.3 Design assessment

To provide clarity: The nanobubble generator is the name given to the skid mounted unit, in its entirety. The nanobubble tube is the single item where the oxygen nanobubbles are produced. Under advice, the patent for a nanobubble tube has been lodged as a 'nanobubble generator' with no reference to the word 'tube', within the naming. This thesis, when making reference to the nanobubble generator, refers to the entire unit.

A nanobubble tube was purchased and a nanobubble generator was fabricated, to allow Nanobubble Agritech to complete performance trials. On completion of the trials, the generator was subsequently dismantled to facilitate a critical and analytical assessment of the design and its components.

In essence, the design utilises a water pump, an oxygen generator, a nanobubble tube, associated pipework and an elementary control panel. The design also aligns with Nanobubble Agritech's vision of an adaptable design suitable for low and high water flow rates. The drawing below, depicts a simplified NBG.

Simplified process schematic for a nanobubble generator

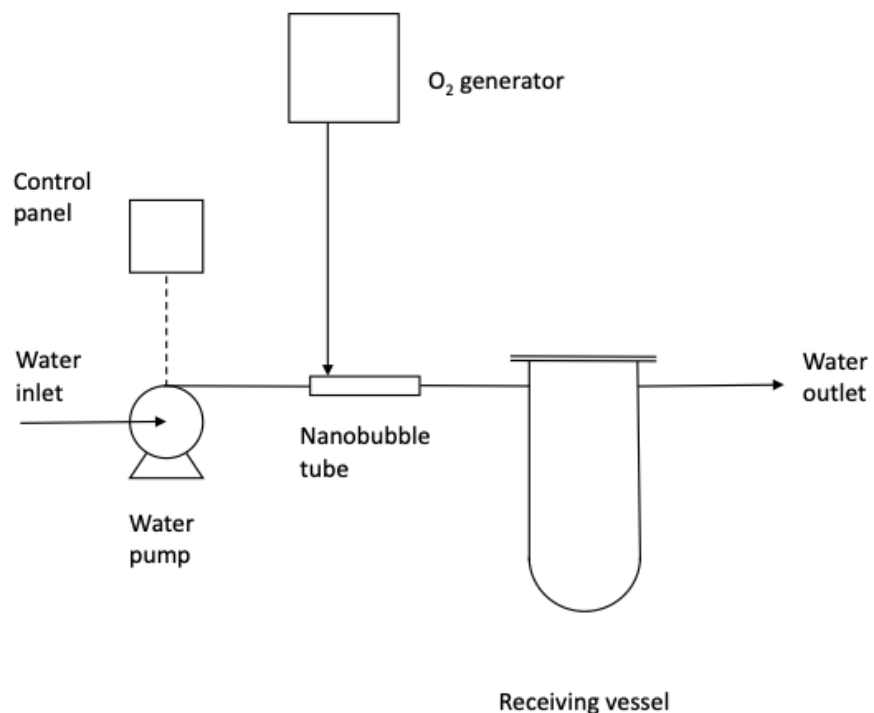


Figure 10 Process Flow Diagram for a simplified Nanobubble Generator

2.3.1 Design intent of components

The Nanobubble Generator comprises the following parts:

Water Pump

The design intent of the water pump is to supply water to the nanobubble tube at a specified flow rate and pressure.

Nanobubble tube

The intent of the NBT, is to generate nanobubbles, enriching the water with oxygen.

Receiving vessel / Dispersion Tank

The receiving vessel, or dispersion tank, provides a buffer between the nanobubble tube and the water outlet to the irrigation distribution pipe. Water enters the dispersion tank tangentially, and rotates around the circumference of the tank, where the water continues to decelerate as the momentum and kinetic energy deplete. Results from testing and evaluation, show that nanobubbles continue to be generated as the water continues to rotate. The design intent is facilitate this rotational motion and provide a degree of residence time.

Oxygen Generator

The intent of the Oxygen generator is to supply oxygen to the nanobubble tube at the required flow rate and pressure. The O₂ generator may also be replaced with an O₂ cylinder, fitted with a relief valve and a pressure regulator.

Control Panel

The control panel, or box, provides the stop / start and logic functions for the water pump and the O₂ generator.

2.3.2 Identify opportunities to develop and optimise the design

Each component was analysed to further understand its function and suitability with a view to NBA improving the design and adapting for high water flow rates, in rural locations.

Water Pump

The pump must be durable, capable of handling brackish water and not subject to rust. It must be low-cost and readily available. It should provide up to 10m lift, (*lift, or negative head, are terms used to quantify the difference in elevation between the water, at the inlet to the pump suction hose, and the pump*). Typically, the water supply will be drawn from an irrigation stream which is below the level of the nanobubble generator and the field on which it sits.

Due to the remoteness of installations, the pumps must be ‘self-priming’. ‘Self-priming’, in this context, refers to the ability to evacuate all air from the pump and pump outlet. If there is air in the system then the pump may become air locked and unable to pump. NBA will fit an auto-priming device at the pump outlet. This is a considerably cheaper option to sourcing and buying self-priming pumps.

Large irrigation schemes, found in New Zealand’s dairy farms, require flow rates ranging from 50 to 250 lps, (litres/second). The pump selected must be capable of delivering the required flow rate.

The pressure losses across the entire irrigation pipework system must be taken into account and the total figure added to the required pressure at the outlet of the irrigation system. A 10% design margin is then applied. The result is the maximum pressure required at the pump outlet. This figure will be determined after the local pipework requirements have been assessed.

For the purposes of a nanobubble generator, designed for agricultural applications, the pump selected will be rated for the specified flow rate and pressure requirements. It will be

a stainless-steel, single-stage centrifugal pump. These pumps are readily available from local farm supplies; should a pump need replacing, then one can be readily and locally sourced. NBA will source these pumps directly from the manufacturer when building nanobubble generators.

There are no development or improvement opportunities identified with respect to the water pumps. A recommendation will be made to farmers, that a readily accessible and maintainable inline water filter is installed before the NBG, to reduce the risk of blockage at the inlet to the water pump. This is particularly pertinent when brackish water is supplied to the NBG.

Nanobubble tube

A commercially available nanobubble tube was purchased to allow performance testing and assessment. A second, identical tube was also purchased which was sectioned to understand the internal profile and the potential to further develop. After initial assessment, it was determined that NBA would design, develop, patent and manufacture their own NBTs.

Receiving vessel / Dispersion tank

Further development could be undertaken to enhance the internal geometry of the vessel and the inlet nozzles, in order to optimise fluid rotation and shear at the circumference of the vessel. The development and modifications to the vessel could be extended to allow for O₂ recovery.

Oxygen Generator

Development opportunities were identified for the O₂ generator primarily around safety, efficiencies and gas re-capture.

Control Panel

NBA will use a PLC, (Programmable Logic Controller), to control the start-up and shutdown sequencing. NBA will write specific logic and algorithms for each installation.

2.3.3 Prioritise development

The nanobubble tube was identified as the primary and priority focus. NBA recognised the development potential and the opportunity to lodge a patent application for a unique and improved design.

The receiving vessel / dispersion tank was also identified as having potential for design improvements. The vessel will be further developed when resources become available.

There is scope to make improvements to the O₂ generator and the supply of oxygen. The improvements focus primarily on efficiency and gas recapture. It is recognised that O₂ generators represent the greatest cost in the manufacture and supply of NBGs however, the research and development required to improve the efficiency, through gas re-capture, represents a significant, stand-alone project requiring engineering and development. For this reason, a lower priority was placed on O₂ recapture and recovery. NBA anticipates that this will be developed after initial sales and cash flow has been established.

2.3.4 Nanobubble Agritech - Preliminary design

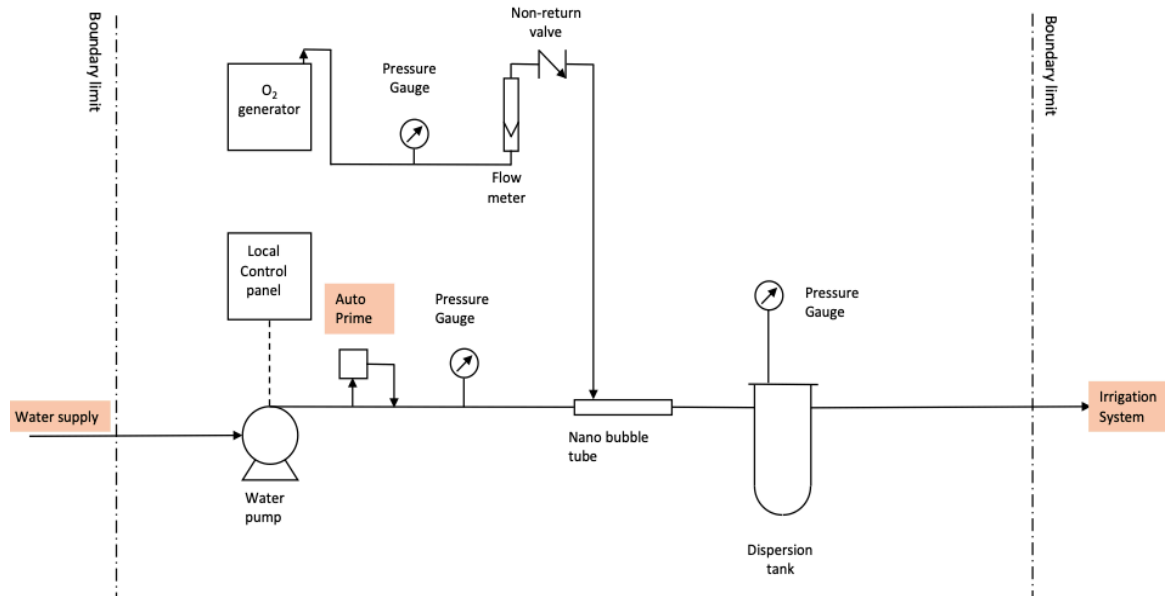


Figure 11 - Process Flow Diagram showing NBA's preliminary design

The preliminary design shown in figure 10, differs from the “Process Flow Diagram for a simplified Nanobubble Generator”, (shown in figure 9), by the addition of the following components:

Auto-Prime

The auto prime unit, fitted at close proximity to the pump discharge outlet, (described in section 2.3.2).

Pressure Gauges

Pressure gauges have been provided to allow; the O₂ supply pressure to the nanobubble tube to be monitored and the water pressure, upstream and downstream of the nanobubble

tube, to be measured in order to determine the differential pressure, (*or pressure drop*), across the tube.

Flow meter

The flow meter allows the flow of oxygen to be monitored and regulated to the nanobubble tube.

Non-return valve

The non-return valve prevents the migration of water from the nanobubble tube, into the O₂ supply line. If water migrates into the O₂ generator then the membranes would have to be replaced. This would be costly, in terms of time and capital expenditure.

Chapter 3

Testing

3.0 Testing

Purpose of testing

The purpose of testing is to gather meaningful data for evaluation: It allows the performance of the 3-D printer to be evaluated and the performance of nanobubble tubes to be compared against each other.

Desired / expected outcomes

- Set up and calibrate the 3-D printer to reliably and consistently produce robust nanobubble tubes
- Evaluate structural design and integrity of 3-D prints
- Evaluate inlet and outlet manifolds for strength and integrity
- Recommend a preferred tube design to take forward for up-scaling
- Recommend a preferred tube design to take forward for patenting
- Recommend tube profile design for commercial use

A strategy was written such that the approach to testing and evaluation, followed a structured and sequential plan:

3.1 Fabrication, Testing and Development Strategy

1. Build a nanobubble generator which allows for the nanobubble tubes to be readily and easily changed out.
2. Determine the data required for performance evaluation and comparison between tube profiles.
3. Set up the test rig
4. Write the testing method
5. Install the commercially available nanobubble tube. This will be the 'reference tube'
Run the NBG, in single pass mode and record data.
6. Using 3-D printer, replicate the commercially available nanobubble tube. Evaluate the tube for quality, structural strength and accuracy. Assess the performance of the 3-D printer.
7. Install the commercially available nanobubble tube replica, carry out testing, record data and compare against the recorded data for the commercially available nanobubble tube.
8. Use CAD imaging to develop a new profile based on test evaluation.
9. 3-D print new profile.
10. Performance test 1st tube profile and evaluate
11. Use CAD to improve / modify tube profile designs.
12. 3-D print tube profiles and test
13. Identify / select best profile to take forward
14. Scale-up - single tube 30 lps, print, test and evaluate
15. Multi-tube designs – triples; print, test and evaluate
16. Identify potential profile designs for patent.
17. Select design / designs for patenting.
18. Select a preferred tube profile design for commercial nanobubble generators.

3.1.1 Fabricate a nanobubble generator which allows for the nanobubble tubes to be readily and easily changed out.

The nanobubble generator, shown below, was constructed, based on the preliminary design and the criteria set-out in chapter 2. Figures 12 and 13, are the physical representation of figure 11, page 40, (*Process Flow Diagram showing NBA's preliminary design*).

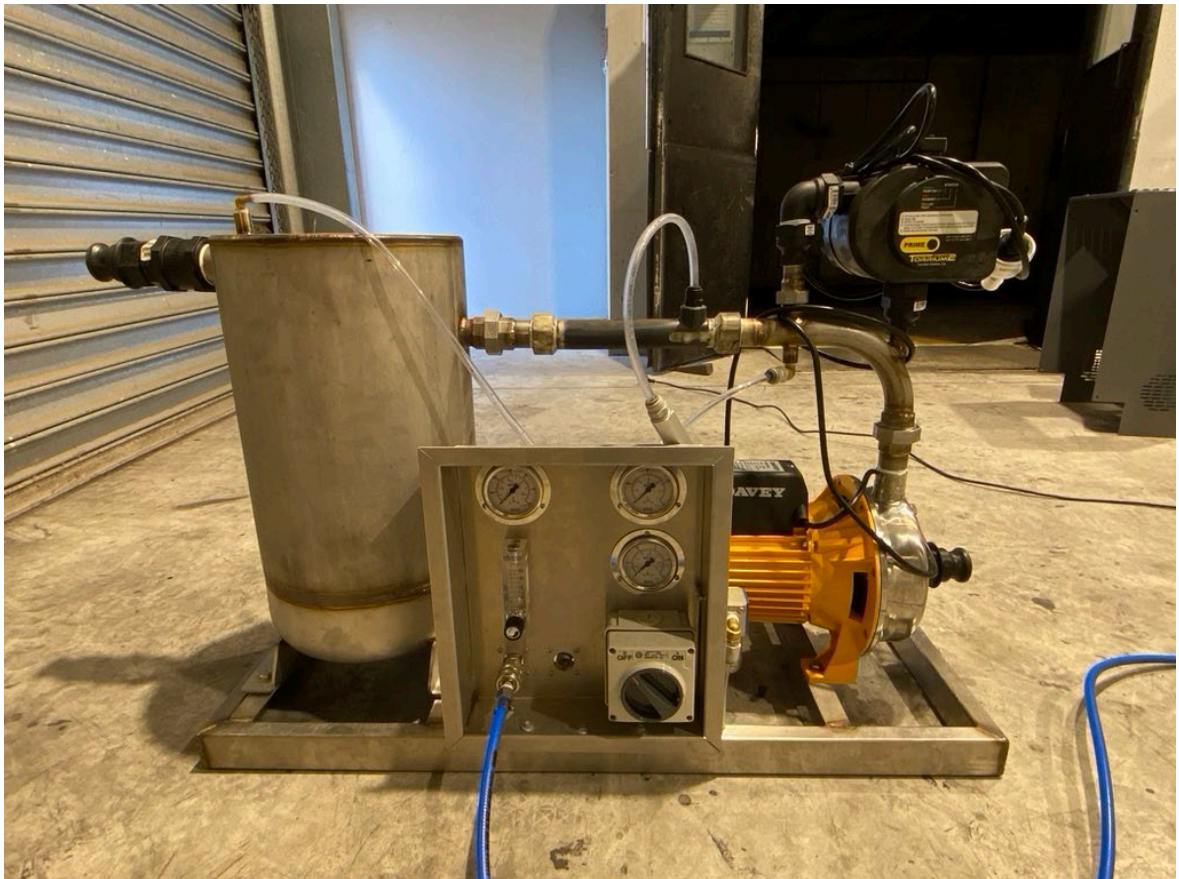


Figure 12 - The NBA Nanobubble Generator showing the commercially available NBT, (front view). The water inlet is on the right hand side and the outlet on the left



*Figure 13 - The NBA Nanobubble Generator showing the commercially available NBT, (rear view).
The water inlet is on the left hand side and the outlet on the right*

3.1.2 Determine the data required for the evaluation of performance and comparison between tube profiles.

| A | B | C | D | E | F | G | H | I | J | K | L | M | N | O | P | Q |
|----------|------------------|--------|----------|---------------------------------|--------------------------|--------------------------------|-----------------------------|-----------------------------------|--|-------------------------|-------------------------------|--------------------------------|--------------------------|---------------------------|---------------------------------|------------------|
| Test No. | Test id | Time | Date | Dissolved O ₂ in IBC | Feed Water Temp oC (IBC) | O ₂ Flow rate l/min | O ₂ pressure psi | Time to fill 200 l drum - seconds | Total volume of O ₂ used - Litres | Drum capacity - 200 lts | Pump discharge pressure - psi | pump discharge flow rate - l/s | Dispersion tank pressure | Product tank - water temp | Dissolved O ₂ - mg/l | Notes / Comments |
| 1 | Gaia UFB100 | 10:32h | 28/04/22 | 8.8 | 14.4 | 4 | 16 | 73 | 4.9 | 200 | 19 | 2.7 | Not used | 17 | 17.7 | |
| 2 | Gaia UFB replica | 10:47h | | | 14.4 | 4 | 16 | 79 | 5.3 | 200 | 19 | 2.5 | | 17.9 | 17.1 | |

Figure 14 - Extract taken from test data sheet.

Figure 14 shows an extract taken from the test data sheet. *(The data sheet can be found in Appendix 8.4, Nanobubble tube test results.)* Consideration was given to the data required, that would allow the performance of different nanobubble tubes to be evaluated. The data and reasons are explained below:

Dissolved O₂ in IBC

It is important to record the dissolved O₂ in the water supply tank. *(The supply tank is an IBC, integrated bulk container, providing 1 m³ of water).* If we know the dissolved oxygen reading before and after the NBG, then this will allow the uptake of O₂ injected and the efficiency to be determined.

Feed water temp

Temperature will affect the saturation level of dissolved O₂ in water, under ambient conditions. The water supply temperature was initially recorded for this reason.

O₂ flow rate

The O₂ flow rate was recorded to quantify the amount of O₂ injected. This information is a required factor in determining O₂ consumption, efficiency and the size of the O₂ generator required.

O₂ pressure

It is important to monitor the pressure of the O₂ supplied to the nanobubble tube to ensure that a pressure differential is maintained between O₂ supply and the water supplied to the nanobubble tube. The oxygen pressure must be greater than the water pressure to allow the O₂ to flow into the nanobubble tube. It must also be greater to prevent back-flow, (*reverse flow*), of water into the O₂ supply tubes.

Time to fill 200 litres

This information was recorded to allow the volume of oxygen injected to be determined.

The total volume is the product of time and flow rate.

The amount of O₂ injected is required to calculate efficiency and up-take of O₂.

Drum capacity

Fixed at 200 litres. This figure was a practical choice: The water discharged from the NBG is collected in a 200 litre plastic drum.

Pump discharge pressure

This gives an indication of pump discharge pressure and the back-pressure on the system, by inference; the greater the restriction to flow, within the system, then the greater the pressure observed at the pump discharge. The pump discharge pressure gauge also gives an indication of pump performance and partial restrictions or blockages at the pump suction strainer.

Pump discharge flow rate

The product of drum capacity and time, allows the water flow rate to be calculated.

This allows comparisons to be made for the different nanobubble tube profiles and their respective performance.

Dispersion tank pressure

The Dispersion Tank is a practical place to mount the down-stream pressure gauge. The pressure taken from this point was subtracted from the pump discharge pressure gauge to

give the differential pressure across the nanobubble tube. The pressure drop across the tube gives a direct indication of the restriction to flow, due to the internal profile of the tube, and is termed 'Head loss'. 'Head loss' was a criterion stipulated in the Boundaries and Parameters: "To improve and out-perform current market units, in respect of head losses across the Nanobubble Generator." Head losses are measured as the pressure drop across the nanobubble tube and the pressure drop across the nanobubble generator from inlet to outlet. The greater the head loss then the greater the pumping requirements. This will increase energy consumption, which will increase the running costs. Increased energy consumption will have also have an environmental impact hence; head losses are a criterion.

Product tank water temp

When water is pumped, the water temperature will rise, fractionally, as a result of friction. At a practical level, the amount of heat added, due to friction is negligible however, if the water is recirculated and the heat added becomes greater than the heat losses within the system, then the water temperature will rise. This is a consideration when trialling multiple passes through the nanobubble tube and recycling the product, (enriched water), back to the water supply tank. Water temperature affects the saturation level of O₂ in water, thus when trialling nanobubble tubes, the conditions under which the testing is carried out, must remain constant across trials.

Dissolved O₂ – mg/l

This reading pertains to the dissolved O₂ measured when lowering the DO meter probe into the 200 litre product drum. The product water discharges from the nanobubble generator dispersion tank, into the collection drum. After 2-minutes, the probe is lowered into the drum to a depth of 1/3 drum height, from the base of the drum. The DO reading is taken after a further 2 minutes has elapsed. This allows the fluid motion in the collection drum, and the DO meter readings to stabilise. These conditions were set to ensure consistency and expediency across trial runs.

By inference, the DO reading gives an indication of O₂ as nanobubbles: If bubbles larger than nanobubbles are produced, then these bubbles will coalesce, rise to the surface and the oxygen will be lost to atmosphere: Dissolved oxygen readings taken will initially appear high however, these readings will fall markedly in a relatively short period of time, whereas the readings taken when the water is enriched or saturated with nanobubbles will remain high and stable for extended periods.

A trial was carried to show the longevity of nanobubbles. Nanobubbles were generated using a commercially available nanobubble tube. Samples were taken and compared against control samples, from the same water supply. Dissolved oxygen readings were taken over a six week period. There was a marked difference observed between the control samples and the nanobubble-enriched water samples: The control samples varied between 9.0 and 9.8 mg.l⁻¹ The initial readings taken after the water had passed through the nanobubble generator varied between 17.0 and 17.7 mg.l⁻¹. The DO remained high and stable, showing depletion after 2-weeks. After six-weeks, the DO readings had fallen, showing values between 10 and 13 mg.l⁻¹ The DO results, and the results from field trials and commercial installations, were sufficient evidence needed to support the commercial viability of the NBG.

NBA does not have the facility to quantify NB size and distribution however, the generation of nanobubbles has been proven in two ways: by inference of high and stable DO readings taken after extended periods and the increase in plant growth, measured and recorded during crop trials at Massey University.

3.1.3 Test rig

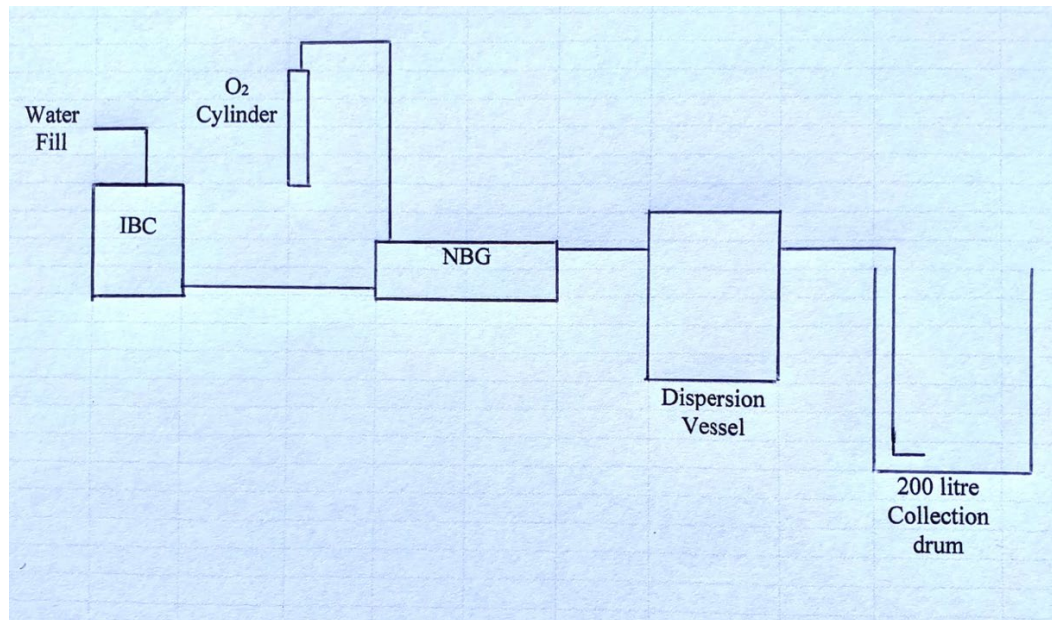


Figure 15 - Simplified schematic diagram depicting the Nanobubble Generator test rig

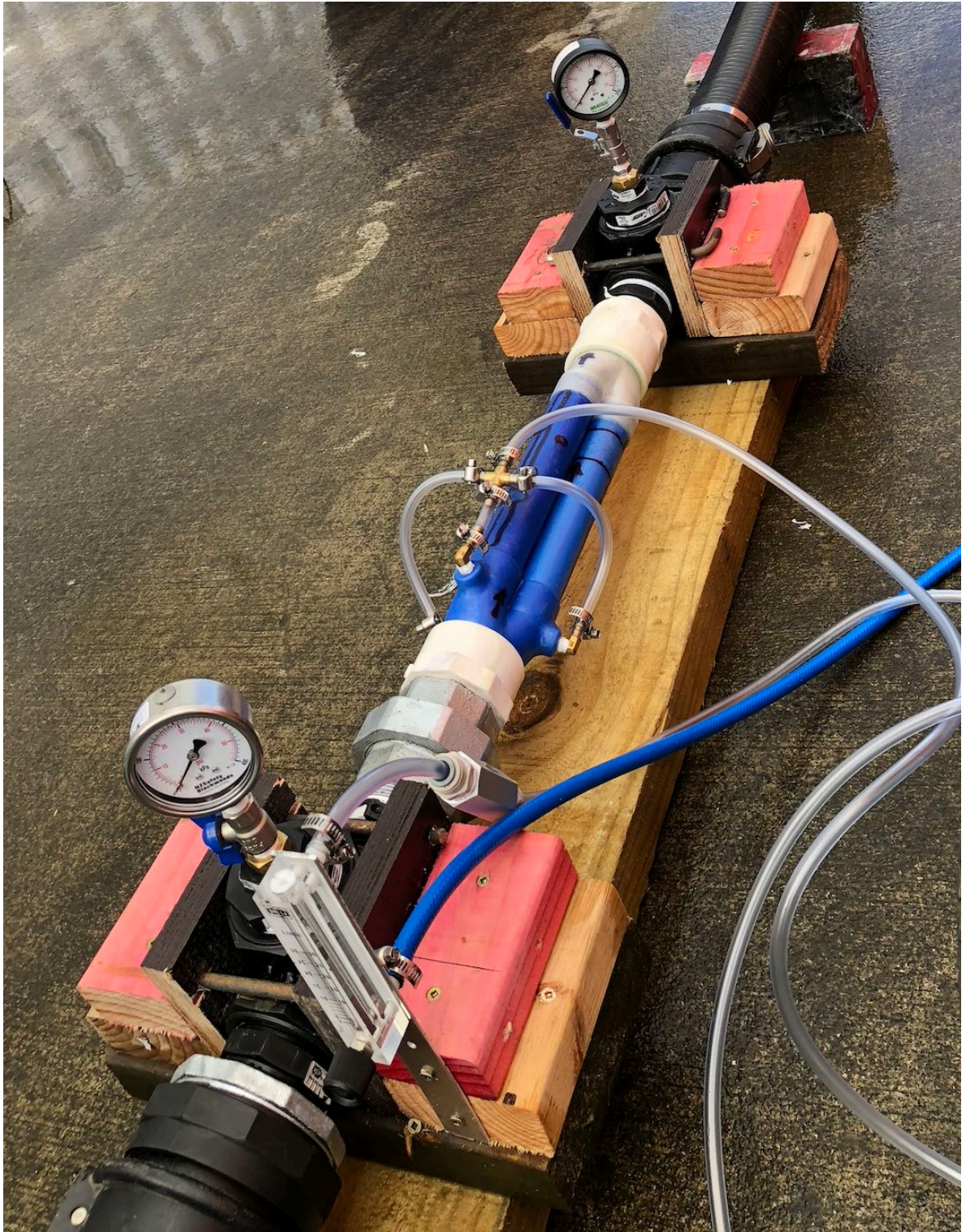


Figure 16 – Nanobubble generator triple tube design set up for test run

Figure 16 shows a triple tube design installed in the test rig and set up ready for testing. Water enters at the base of the image and exits at the top of the image. The rotameter, (variable are flow meter) seen at the base of the image allows the oxygen flow rate to be set and monitored. The blue hose supplies O₂ to the flow meter. The clear 10 mm hose from the outlet of the flow meter supplies the nanobubble tubes, teeing off to supply each individual tube with O₂. The two pressure gauges allow the upstream and downstream water pressure to be recorded and allow the differential pressure / head loss across the tube arrangement to be determined.

Describe equipment used

IBC

The integrated bulk container, is a polythene container holding 1 m³ of water and supplies the nanobubble generator. The container has a water outlet valve at its base. Water is supplied to the nanobubble generator from this point, via a connecting hose. The IBC is filled by removing the screw down lid at the top of the container and running a water hose into the IBC.

Nanobubble Generator

The Agritech nanobubble generator is shown in figures 11 and 12, (*p 44 and 45*). It includes the dispersion tank, or vessel.

RCD, (Residual Current Device), and electrical extension lead.

The RCD is an electrical protection device designed to prevent electrocution and damage to equipment. This is particularly important when water is present.

O₂ cylinder

For testing purposes, an O₂ cylinder, fitted with a pressure regulating valve and a pressure relief valve, supplies oxygen to the nanobubble tube. An O₂ generator will be supplied for commercial sales.

200 litre drum

A 200 litre polypropylene drum receives water from the nanobubble generator. This is the collection vessel for the nanobubble enriched water, (*referred to as product water*).

Dissolved oxygen meter



Figure 17 - ProSolo ODO Optical Dissolved Oxygen Meter, used to measure the dissolved oxygen in the 200 litre product water collection drum

3.1.4 Testing - Method

Pre-test run

1. Connect all pipework following the schematic diagram shown in figure 14. Note: The outlet from the nanobubble generator discharge hose should be placed on the ground to allow run-off to an open drain. The discharge hose will be placed in the 200 litre drum for the duration of a test run.
2. Confirm that the pressure regulator fitted to the O₂ cylinder, is fully wound out, (anti-clockwise). This prevents over-pressurisation of the test equipment.
3. Connect the O₂ tubing from the O₂ cylinder to the NBG oxygen regulating flow meter.
4. Connect the O₂ tubing from the flow meter to the injection point at the nanobubble tube.
5. Confirm that the regulating valve at the O₂ flow meter, (on the meter panel), is fully shut.
6. Slowly open the shut-off valve at the O₂ cylinder to approximately ¼ open.
7. Slowly wind the pressure regulator, at the O₂ cylinder, clockwise until a pressure of 50 psi is seen on the O₂ cylinder regulator gauge. The O₂ supply pressure is now set to a maximum of 50 psi.
8. Adjust the O₂ flow to the nanobubble tube by slowly opening the valve at the base of the flow meter on the meter panel. Set the flow rate to the desired value for the test; 4 litres / min for the initial low-flow tests. Note: adjustments made at the O₂ flow meter must be done very slowly so as not to damage the flow meter. Fine adjustment will be required when water flow is established.
9. Close the shut-off valve at the top of the O₂ cylinder.
10. Confirm that the On/Off switch at the flow meter panel is in the off position.
11. Connect an extension lead to the power outlet.
12. Connect an RCD, (Residual Current Device), to the extension lead. The RCD is an electrical protection device designed to prevent electrocution. Note: This is particularly important where electrical equipment may come into contact with water.
13. Take the electrical cable from the water pump and plug this into the RCD
14. Take the pre-start readings, specifically the DO and temperature for the water in the IBC.
Record time and date.

The equipment is now set up and ready for the test run.

Testing

1. Open the water outlet valve at the base of the IBC to allow water to flow to the NBG.
2. Slowly loosen the vent plug at the top of the water pump casing and bleed air from the system until water shows. Close and hand tighten vent plug. This will purge air from the system and prime the pump.
3. Open the shut-off valve, at the top of the O₂ cylinder, to the ¼ open position.
4. Confirm O₂ flow rate is 4 l/min
5. Turn the On/Off switch, at the meter panel to the On position.

Note: The pump will start at this point and the water level in the IBC will fall rapidly.

Safety note: Do not allow the pump to run dry; this will damage the pump.

6. Allow the pump to run for a few seconds to purge any remaining air from the system and to allow the water flow rate to stabilise.
7. Check the O₂ flow rate and confirm 4 litres/min. Make a fine adjustment if required.
8. Place NBG discharge hose into the 200 litre drum. As soon as water enters the drum, 2nd person starts the timer.
9. 2nd person records; pump discharge pressure, dispersion tank pressure, O₂ pressure and monitors O₂ flow rate.
10. When the water level reaches the 200 litre mark in the Product drum, stop the timer
11. Switch off the water pump at the NBG meter panel.
12. Turn off the O₂ supply at the cylinder outlet valve
13. Close the outlet valve at the base of the IBC.
14. Record the time taken for the water to reach the 200 litre mark.
15. Confirm that all the required data has been validated.

Note: The nanobubble tube may now be removed and the next tube installed in readiness for the next test.

3.1.5 Install the commercially available tube, run performance test and record results

The commercially available tube was installed in the nanobubble generator and a number of test runs were performed. This allowed familiarity with the test rig and the equipment. This

also allowed the testing method to be revised. The commissioning of the test rig and the nanobubble generator was carried out at this point, prior to the collation of test data. Primarily, we were looking for consistency and repeatability with the data. The final test with the commercially available tube provided said data, against which the 3-D replica print would be measured. The commercially available tube was considered to be the reference tube.

3.1.6 Replicate the commercially available tube

The commercially available tube was sectioned at the centre, along the vertical plane. This allowed the internal profile to be analytically and critically assessed. The tube could then be replicated using 3-D printing software, and the 3-D Printer.

3.1.7 Install and perform test run

The replica tube was installed in the NBG and testing performed. Comparing the test data recorded from the commercially available tube with the data recorded from the replica tube allowed the performance of the 3-D printer to be assessed and adjustments to be made. The performance of the replica tube was compared against the original. The results are discussed in Chapter 5.

3.1.8 Trial different designs and record data

Nanobubble tube design evolved as an iterative process by applying the knowledge gained in Chapter 1, and an understanding of fluid dynamics. This insight allowed the results from each design to be analytically and critically appraised. Each appraisal would influence or change the profile for the next iteration. The development of the nanobubble tubes and their respective profiles followed the strategy outlined in section 3.1.

Chapter 4

Nanobubble Tube Development

4.0 Analysis of a commercially available nanobubble tube

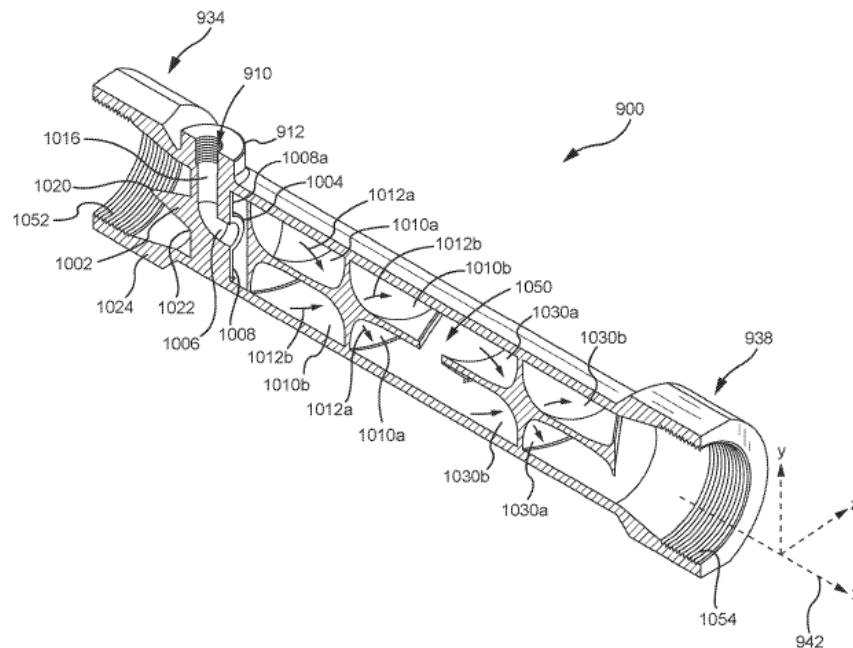


Figure 18 – Cross sectional drawing depicting a commercially available nanobubble tube, (From prior art search, carried out on behalf of Nanobubble Agritech Ltd. Patent Assigned to Gaia USA Inc.)

Principle of operation:

Water enters the nanobubble tube at the left hand side of the image and exits from the right, enriched with oxygen nanobubbles. Items 1020 / 1002 form a solid cone. The tip of the cone faces into the upstream flow. As water hits this point, it diverts around the O₂ injector

and out to the walls of the tube, (1012a, 1012b). O₂ is injected into the flow-stream via an injector and an injection port, (910, 1016, 1006). Water is forced to flow on both sides of the first helix, making one full rotation. As the water makes this rotation it is subjected to centrifugal force. The water on either side of the helix can be considered as two streams. There is a mixing region before the second helix, (1050). This region effectively provides an increase in volume. The increase in volume reduces the water pressure to a point below the vapour pressure of the O₂. This induces cavitation and promotes the generation of nanobubbles. The two streams come together in this 'mixing' region creating more turbulence. Turbulence gives rise to attrition between the O₂ bubbles and the water. Water then passes to either side of the second helix, prior to exiting the tube. Nanobubbles are generated as a consequence to the effects of centrifugal force and turbulence. Centrifugal force and turbulence give rise to attrition at the molecular level. It is hypothesised that low pressures are created when attrition occurs. The reduction in localised pressure leads to cavitation which in turn, generates nanobubbles.

Analysis

When the water diverts around the O₂ injection port, vortices will be shed giving rise to a slight increase in turbulence with additional head loss, albeit fractional. The design is such that, the O₂ can be considered to be drawn into the water flow stream as opposed to being injected into the flow stream. Mixing and dispersion of the oxygen is a consequence of the turbulence created, as the water changes direction and diverts to either side of the first helix. The two streams from either side of the helix collide as they enter the mixing zone between the two helixes. This causes more turbulence and additional head loss. The water must change direction when it enters the mixing region and change direction again, as it flows to either side of the second helix, adding to the overall head loss.

Head losses are an important design criterion and are stipulated in the parameters set out for the NBA generator. The NBA profiles must improve on existing designs and must not encroach or infringe on existing patents or copyrights. Remaining mindful of the above, the Nanobubble Agritech designs must be innovative and NBA must look for a new approach

whereby head losses can be kept to a minimum and DO readings match or better, the commercially available tube.

4.1 Tube Design

In order to produce a preliminary tube design, the fundamental principles for the generation of nanobubbles had to be considered: Nanobubbles are generated through cavitation; a consequence of ‘Shear’, which can be achieved through attrition. Attrition can be facilitated through, friction against the internal profile of the tube, acceleration, turbulence and centrifugal forces. This was taken into consideration, leading to the conclusion that tube profiles would be designed to facilitate and maximise shear, whilst optimising acceptable head losses. ‘Shear’ has to be understood and indeed, how to maximise shear:

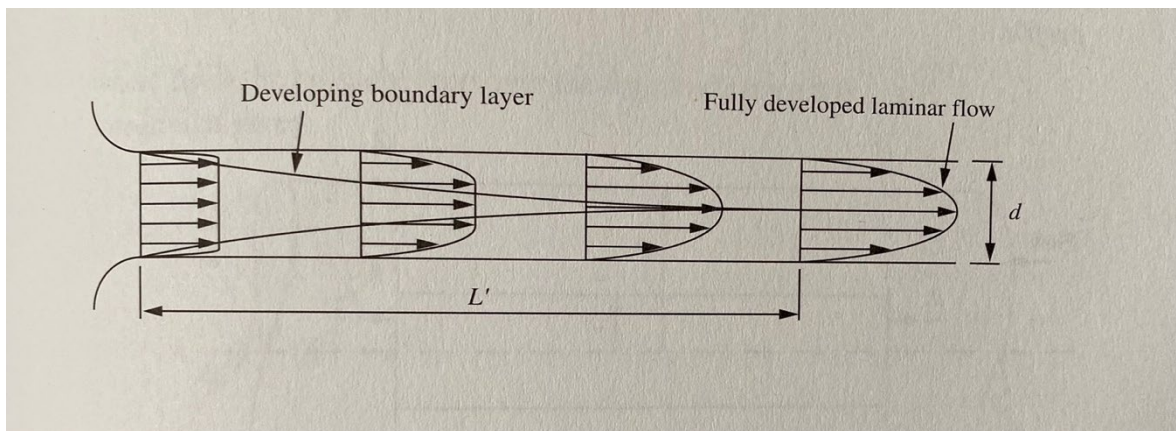


Figure 19 – Development of laminar flow, ‘Fluid Mechanics – Worked Examples for Engineers’, (Schaschke, C., 1998)

Figure 19 shows the flow profile for fluid flow within a pipe. The left hand side of the drawing shows the profile for turbulent flow with laminar flow shown on the right hand side. The fluid, (water), may be considered to flow in successive layers, in both the horizontal and vertical planes, where friction exists between each successive layer and each plane. The ‘layers’ become less defined as turbulence increases. Friction between successive layers leads to shear, promoting cavitation and the generation of nanobubbles

from the entrained, and/or, injected O₂. Water has relatively low viscosity and is discharged from a pump at high velocity thus, the flow will be turbulent however, if we can reduce or minimise the degree of turbulence throughout the nanobubble tube then this will minimise head losses and minimise the disturbance between the successive layers in the flow profile.

The intent of Nanobubble Agritech tube designs, is to maximise shear within the oxygen saturated, or enriched, water. This will be achieved by causing the water to rotate as it accelerates, in centrifugal and linear directions through the length of the tube.

4.2 Tube development

Nanobubble tubes can potentially be manufactured from a number of materials including glass, fibre glass, aluminium, stainless steel and various grades and types of plastic. The material type will have an effect on performance, (in terms of pressure drop, or head losses); this is due to the surface roughness of the material used and the respective friction factors.

Durability, robustness and reliability are also important considerations. These factors were taken into account, remaining mindful of cost, ease of manufacture and the criterion, 'fit for purpose'. The material had to be a compromise between performance and cost.

Polyethylene Terephthalate Glycol, PET or PETG, was selected: It is cheap, durable, lightweight, robust and ideal for 3-D printing. It is also commonly used in the manufacture of plastic drink bottles and containers.

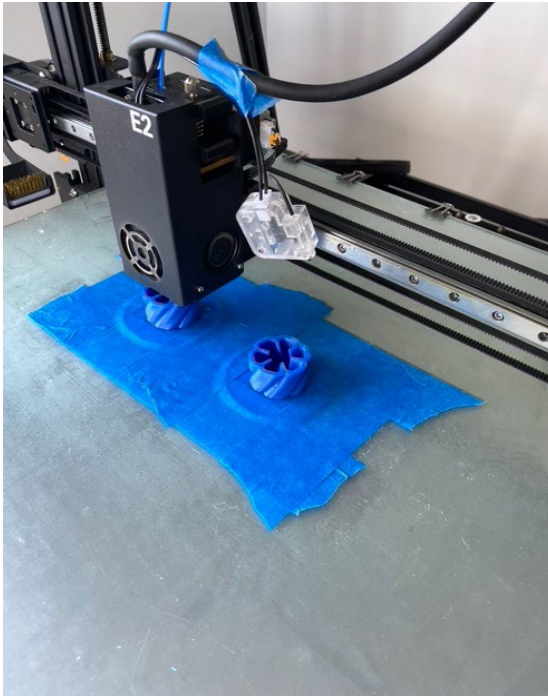


Figure 20 - Simultaneous printing of two nanobubble tubes



Figure 21 - 3-D Printer and PETG print reel cassettes

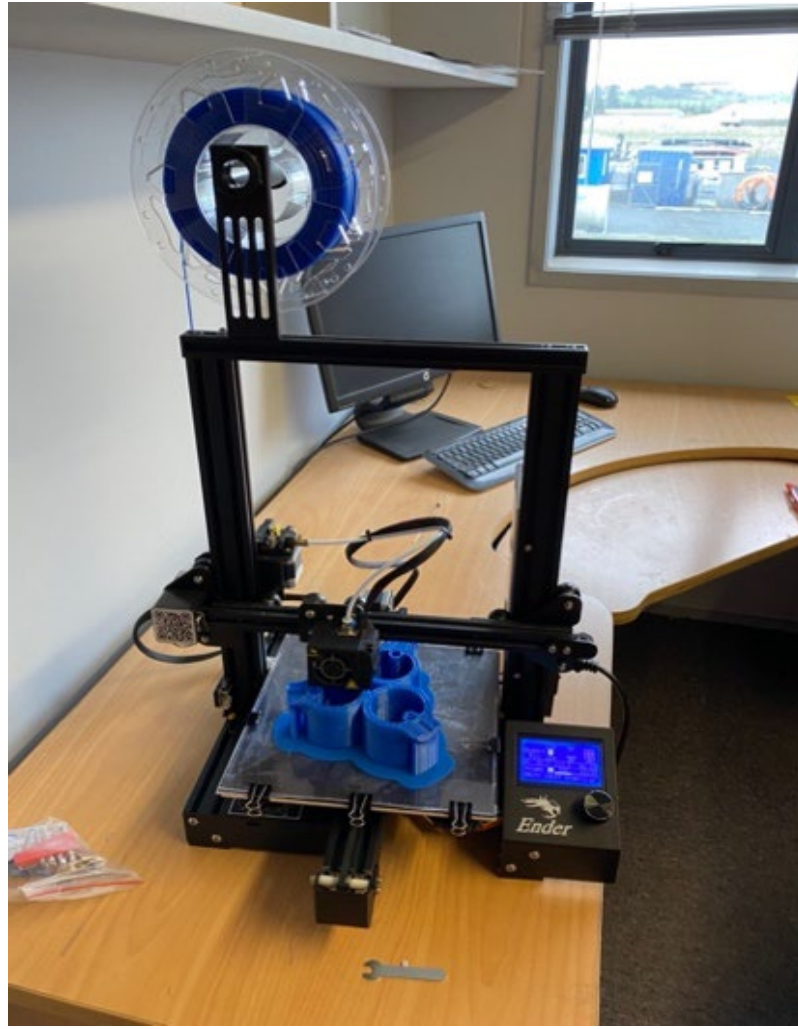


Figure 22 - Printing of a triple tube design

Figure 20 shows a 3-D print in progress. Two nanobubble tubes are being printed simultaneously. The blue polyethylene base provides an anchor and the stability required as the prints increase in length and height. Figure 21 shows the 3-D printer and the PETG cassettes, (print reels). Figure 22 shows a triple tube design. The O₂ injection ports and threads for the injectors are approximately 50% complete and can be seen at the surface of the print. The honeycomb or lattice structure of the cross-section will give strength and rigidity to the finished nanobubble tube arrangement, while saving printing time and PETG used for the print.

4.3 Profile variations

There are a number of variations that can be made to the internal profile of the nanobubble tube and these include:

4.3.1 Number of helixes

A helix can be defined as a profile having a 3-dimensional shape which rotates around a central axis. Corkscrews and spiral staircases provide examples of a helix. Fins, or flutes extend from the internal wall of the nanobubble tube toward the centre of the tube forming a helix profile. It is the geometry and dimensions of the helix which will determine the acceleration of the water, the centrifugal force imparted to the water and the pressure drop across the length of the tube, as the water passes through.



Figure 23 - Nanobubble tube showing 6 fins

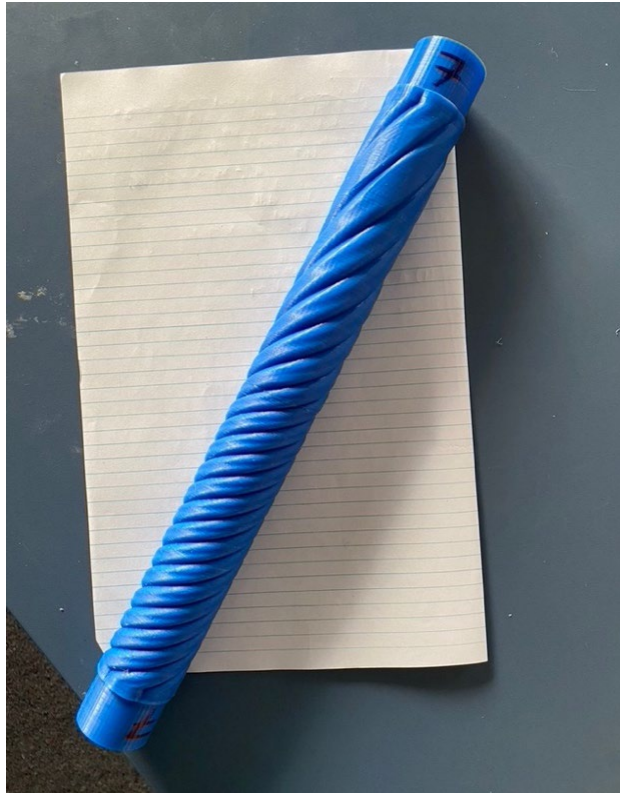


Figure 24 - Nanobubble tube showing each helix with 2 full rotations and an increasing twist rate

4.3.2 Helix twist rate – number of full rotations v length

The ‘twist rate’ can be defined as the number of full rotations for a given length.

Figure 23 shows a nanobubble tube design where each internal flute, forms a helix which makes two full rotations across the length of the tube. The entry point is at the top of the image and the exit point at the bottom. It can be seen from the profile that twist rate increases from the entry point to the exit. A combination of increasing the twist rate and varying the diameter of the internal hollow core, causes the water to accelerate and the velocity to increase, promoting shear. Water entering the tube will accelerate as it travels the length of the tube and will have rotated through 720° at the point of exit.

4.3.3 Core diameters

The core diameter refers to the hollow region extending along the length of the tube, around the centre axis. *(This region can be seen in figures 23 and 25).*

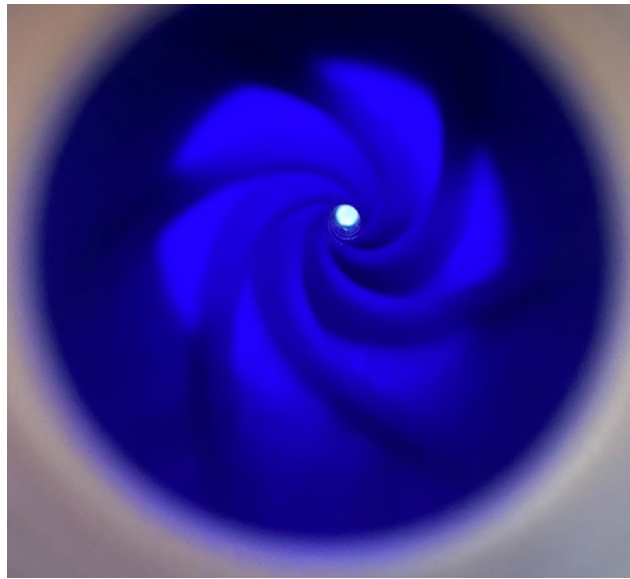


Figure 25 - Image showing internal profile of figure 23, (Nanobubble tube showing 6 fins).

Fins and flutes do not extend into this region. A percentage of the water will pass straight through the nanobubble tube, along this axis. Determining the optimum core diameter for a tube design, is an iterative process of development and testing. The optimum core diameter is compromise between the pressure drop across the length of the tube and the effectiveness in the generation of nanobubbles: A larger core diameter results in a lower pressure drop. The advantage of having a lower pressure drop, or head loss, is that the overall energy requirement is less. This suggests that a smaller pump may be selected for the nanobubble generator and the energy costs may be potentially lower. However, the pressure difference between the water at the point of entry and the water at the point of exit, provides the driving force which causes the acceleration and velocity of the water thus, a smaller core diameter favours the generation of nanobubbles.

Summarising: A larger core diameter favours energy costs, but results in a lower performance in terms of the nanobubbles generated. A smaller core diameter favours the generation of nanobubbles but does not favour the energy required and the associated costs. Thus, the optimum diameter will be a compromise between acceptable head losses and the DO reading observed at the product tank.

4.3.4 Venturi

The internal profile of the nanobubble tube can be designed as a venturi. The core diameter decreases up to the ‘throat region’. The diameter remains constant throughout the length of the throat and increases from the exit point of the throat and continues to increase up to the point of exit from the tube.

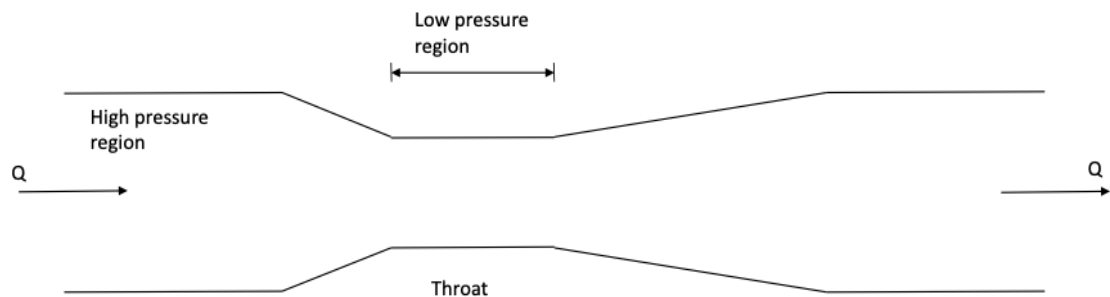


Figure 26 – Diagram representing a Venturi profile

The rationale behind this design is to create high and low pressure regions within the tube. The throat is a restriction to flow. As water approaches this restriction, the pressure increases creating a high pressure region. As water passes through the throat, and exits, a low pressure region occurs within the throat. This pressure reduction leads to cavitation within the water. Azevedo, (2019), showed this experimentally and provided an explanation for his findings: Hydrodynamic, (or Venturi) cavitation occurs as a consequence of

depressurisation of a gas-saturated water stream, flowing through a restriction. When the supersaturated water is forced through the restriction, the velocity rises, and the pressure falls below the vapour pressure of the liquid. Cavities (gas nuclei, nanobubbles and microbubbles) form as mass transfer of gas occurs from the water to the gas phase.

4.3.5 Entry Profiles

The 'lead-in' or entry profile refers to the point of entry to the nanobubble tube, prior to the flow path being made to change direction or deviate. If the flow direction deviates immediately on entry to the nanobubble tube, then the lead-in, or entry profile can be considered upstream of this point. The design intent is to minimise the disturbance to flow at the point of entry. This will reduce head loss and provide the water with a clean entry to the tube. A clean entry allows the water to enter the tube with minimal disturbance caused by physical restriction or deviation to the flow path. Flow straighteners would provide a clean entry to the nanobubble tube and have been identified as a potential improvement to the design of the NBG.

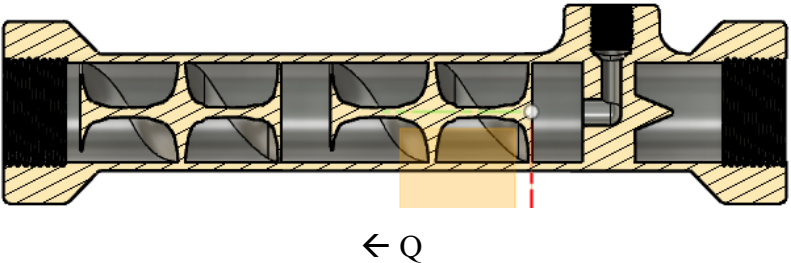
4.3.6 Exit profiles

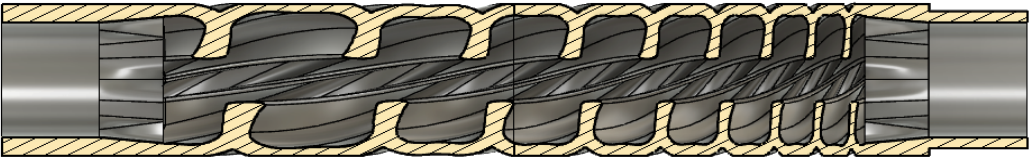
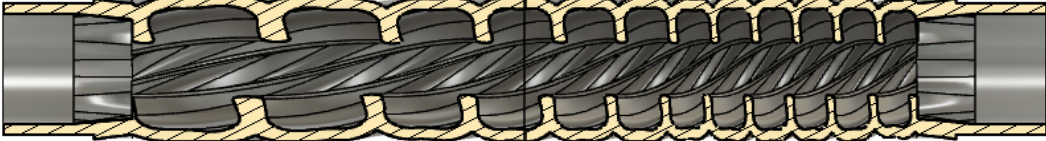
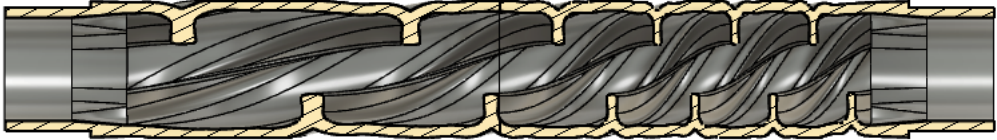

This refers to the exit point of the tube, or the manifold into which the nanobubble tube fits. It is desirable to have a clean exit profile with minimal disturbance to flow. Testing and trials have also shown that we need to maintain the rotational flow path as the water leaves the nanobubble tube and enters the dispersion tank; (nanobubbles continue to be generated as the water rotates in a centrifugal direction.)

4.4 CAD – Computer Aided Designs

By definition, CAD (computer-aided design), is the use of computer-based software to aid in the design process. Proprietary 3-D Printing software packages were purchased, specifically; (Autodesk Fusion 360 and CURA). Autodesk facilitates the 3-D print designs and CURA converts the 3-D print files to a format that the 3-D printer can recognise. This allowed tube profiles to be designed and printed. It allowed adjustments to be made to the geometry and dimensions for the internal profiles. Tubes could then be printed, tested and evaluated. The table below shows some of the early designs. The drawings were generated by the software package. The key designs are shown below and further designs can be found in appendix 8.3

Table 2, 2-D drawings generated by the CAD software package, showing tube design variations.

| <u>Variation I.D.</u> | <u>Description</u> |
|-------------------------------|--|
| Commercially available UFB100 | performance was measured and used as a reference to compare against NBA's manufactured version of the commercially available UFB 100. One helix (creating one full 360° rotation) measures 63mm in length. |
| UFB 100 replica | Reproduced by NBA. Direction of flow: right to left  |

| | |
|----|---|
| V1 | <p>10mm core diameter – flow direction: left to right</p> <p style="text-align: center;">$Q \rightarrow$</p>  |
| V2 | Same profile as V1. Core diameter 13mm |
| V3 | Same profile as V1. Core diameter 10mm, using thinner helix walls |
| V4 | Same profile as V1. Core diameter 13mm, using thinner helix walls |
| V5 | <p>6-fins. Flow follows a gradual centrifugal lead in to a single 360° helix. Core diameter 13mm.</p>  |
| V6 | <p>Same Profile as V5, except 3 fins are used</p>  |
| V7 | <p>Same Profile as V5, except that; 2 full rotations are used at the exit</p>  |

Chapter 5

Results

5.0 Field Trials

The benefits of irrigating plants and crops using oxygenated water are well documented however, this had to be quantified to determine the viability of developing a nanobubble generator specifically for this purpose. Nanobubble Agritech, in partnership with Massey University, carried out a series of field trials between 2021 and 2022:



Figure 27 - Image showing dripline irrigation trials



Figure 28 - Cropping trials



Figure 29 - Image showing 100 mm core diameter, soil samples: The samples on the left hand side of the image have been irrigated using untreated water; the samples on the right hand side of the image have been irrigated using water enriched with oxygen nanobubbles.

Grass, used for dairy pasture, was planted and watered regularly. For the ‘control’ sections, the grass was irrigated using normal untreated water. The trial sections were irrigated using water, treated with oxygen nanobubbles. Periodically, the grass was measured for height, then cut and weighed to determine mass. Figure 28 shows the control and trial sections.

Figure 29 shows the difference in root mass and soil quality after 4 months of irrigation. To help understand why there is such a marked difference in root mass, a calculation was carried out to show the effect of nanobubbles on the surface area available for mass transfer of oxygen and nutrients to the root bowl:

Mathematical calculation to show the area available, for the mass transfer of gas, relative to the bubble size, using the volume equivalent diameter:

For simplicity, using a nanobubble diameter of 100 nm;

Determine the total surface area available, for the mass transfer of gas using an NB diameter of 100 nm:

Method:

1. determine total volume of O₂ at std conditions
2. determine bubble volume
3. divide total volume by bubble volume to determine number of bubbles
4. calculate surface area of bubble
5. multiply number of bubbles by surface area for one bubble, to give total surface area

1. determine total volume of O₂ at std conditions

1 m³ O₂ weighs 1.429 kgs at standard conditions: 0 °C, 1 atm,

References used include, (www.onlineconversion.com, 2022; www.uigi.com,2022; aqua.calc.com,2022). All three references state '1 m³ O₂ weighs 1.429 kgs at standard conditions: 0 °C, 1 atm.'

Therefore, 1 kg O₂ occupies 0.6998 m³; approx. 0.7 m³

Dissolved O₂ reading for the water leaving the 'Nanobubble-Agritech generator': 30 mg/l

$$30 \text{ mg.l}^{-1} = 0.03\text{kg.m}^{-3}$$

$$\text{Total volume of O}_2 = 0.03 \times 0.7 = 0.021 \text{ m}^3$$

2. determine bubble volume:

$$\text{Volume of a sphere: } V = (4/3)\text{Pi.r}^3$$

$$D = 100\text{nm, therefore } r = 50\text{nm} = 50 \times 10^{-9}\text{m}$$

$$V_{\text{bub}} = (4/3)\text{Pi.}(50 \times 10^{-9})^3 = 5.236 \times 10^{-22}$$

3. divide total volume by bubble volume to determine number of bubbles

$$V_{\text{tot}} / V_{\text{bub}} = 0.021 / 5.236 \times 10^{-22} = 4.0107 \times 10^{19}$$

4. calculate surface area of bubble:

$$\text{Surface area of sphere: } A = 4\text{Pi. } r^2$$

$$A = 4\text{Pi}(50 \times 10^{-9})^2 \text{ m}^2 = 3.14159 \times 10^{-14} \text{ m}^2$$

5. multiply number of bubbles by surface area for one bubble, to give total surface area

$$\text{Surface area}_{\text{total}} = 4.0107 \times 10^{19} \times 3.14159 \times 10^{-14} = 1.260 \times 10^6 \text{ m}^2$$

Determine the total surface, using a micro-bubble diameter of 100 μm

$$1. \text{ Total volume of O}_2 = 0.03 \times 0.7 = 0.021 \text{ m}^3$$

2. determine bubble volume:

$$\text{Volume of a sphere: } V = (4/3)\text{Pi}.r^3$$

$$D = 100 \text{ }\mu\text{m}, \text{ therefore } r = 50 \text{ }\mu\text{m} = 50 \times 10^{-6}\text{m}$$

$$V_{\text{bub}} = (4/3)\text{Pi}.(50 \times 10^{-6})^3 = 5.236 \times 10^{-13}$$

3. divide total volume by bubble volume to determine number of bubbles

$$V_{\text{tot}} / V_{\text{bub}} = 0.021 / 5.236 \times 10^{-13} = 4.0107 \times 10^{10}$$

4. calculate surface area of bubble:

$$\text{Surface area of sphere: } A = 4\text{Pi}.r^2$$

$$A = 4\text{Pi}(50 \times 10^{-6})^2 \text{ m}^2 = 3.14159 \times 10^{-8}$$

5. multiply number of bubbles by surface area for one bubble, to give total surface area

$$\text{Surface area}_{\text{total}} = 4.0107 \times 10^{10} \times 3.14159 \times 10^{-8} = 1.260 \times 10^3 \text{ m}^2$$

Show the relationship between bubble size and total area available for mass transfer of O₂:

Surface area_{total} for a dia of 100 nm : Surface area_{total} for a dia of 100 μm

$$1.260 \times 10^6 \text{ m}^2 : 1.260 \times 10^3 \text{ m}^2 = \mathbf{1000}$$

The calculation shows that the total surface area, available for the mass transfer of oxygen from the water to the root bowl, is 1000 times greater when oxygen nanobubbles are used compared to oxygen microbubbles.

Increasing the amount of O₂ available for absorption by the plant roots has been shown to greatly improve the root mass: The subsequent growth in root mass increases the surface area of the root structure available for the uptake of nutrients, water and oxygen. Improving the root mass also benefits the health and structure of the soil. The porosity and permeability of the soil is greatly improved as a consequence. This, in turn, facilitates the transport of water and nutrients to the root bowl. Thus, the health and growth of the roots becomes self-perpetuating, providing further explanation for the results shown in figure 28, (image showing soil samples).

5.1 Nanobubble tube test results

Table 3 - Summary of Nanobubble Tube Profile test results for water flow rate of **4 lps**

| O2 injection set to 4 litres / min | | | |
|------------------------------------|------|------|--|
| Tube profile i.d. | PSI | DO | Comments |
| Commercially available tube | 19 | 17.7 | <i>Reference tube</i> |
| NBA 1 st iteration | 19 | 17.1 | <i>NBA iteration of the above profile</i> |
| V01 | 19 | 18.8 | <i>Tube profiles V01-25, are designed for a water flow rate of 4 lps – average of 2.7 lps achieved</i> |
| V02 | 14 | 18.3 | |
| V05 | 17 | 18.8 | |
| V07 | 18 | 19.4 | |
| V08 | 16 | 18.6 | |
| V09 | 17 | 18.6 | |
| V09 | 16 | 18.5 | <i>flow direction reversed</i> |
| V12 | 20 | 19.9 | |
| V20 | 17.7 | 18.6 | |
| V25 | 16.5 | 17.5 | |
| V25 | 16.5 | 18.6 | <i>flow direction reversed</i> |

Table 4 - Summary of Nanobubble Tube Profile test results for water flow rate of **10 lps**

| O2 injection set to 24 litres / min | | | |
|-------------------------------------|-----|------|---|
| Tube profile i.d. | PSI | DO | Comments |
| V32 | 13 | 23.4 | <i>Tube profile designed for an approximate water flow rate of 10 lps, 9.3 lps achieved</i> |
| V32 | 13 | 23.7 | <i>flow direction reversed</i> |

Table 5 - Summary of Nanobubble Tube Profile test results for water flow rate of 30 lps

| O2 injection set to 40 litres / min | | | | |
|-------------------------------------|------|------|------|--|
| Tube profile i.d. | PSI | DO | Q | Comments |
| | 19 | 22.9 | 29.2 | <i>Commercially available tube, upscaled for 30 lps</i> |
| | 20.5 | 24.7 | 26.2 | <i>NBA single straight tube, upscaled for 30 lps</i> |
| | 18.5 | 25.9 | 29.6 | <i>NBA multi-tube design – triple-tube, external profile: straight</i> |
| | 20 | 23.5 | 27.8 | <i>NBA multi-tube design – 5-tube, external profile: straight</i> |

PSI = differential head across the nanobubble tube, (pressure drop across the tube)

DO = Dissolved oxygen, milligrams per litre

Q = flow rate in litres per second

The commercially available tube was installed in the Nanobubble generator and a series of test runs was carried out to allow the test rig and the O₂ supply to be set-up correctly. The test runs also provided confirmation of consistency and repeatability in the results. The direct quantitative and qualitative analysis of nanobubble distribution in water is difficult to achieve therefore, dissolved oxygen readings were taken and the generation of nanobubbles was inferred through the stability and slow decline in DO readings over several days. The dissolved O₂ reading, for the water supplied to the nanobubble generator, taken at the start of the testing session, was 8.8 mg / litre water. The DO reading taken from the product collection drum was 17.7 mg / l and remained stable showing a slow decline over several days. The result inferred that the water was enriched with oxygen nanobubbles. Had the water been enriched with O₂ micro-bubbles, or larger, then the bubbles would have risen to the surface of the water, or coalesced and risen, where the O₂ would be lost to atmosphere. This would have been evident by a sharp decline in the daily DO reading.

Testing showed that NBA's first iteration did not perform as well as the commercially available tube, with specific regard to the DO reading. The test results also show that the water flow rate was slightly lower than the commercially available tube and the 200 litre drum took longer to fill. The consequence of this resulted in the O₂ injection flowing for longer and hence, more O₂ consumed. The explanation for the observations can be attributed to the quality of the internal profiles of the NBA tube and the commercially

available tube: Internal inspection shows that the profile of the commercially available tube is smooth by comparison, whereas NBA's 1st tube iteration is less smooth. Being less smooth, increases the friction factor and results in a greater restriction to flow. This reduces the velocity of the water and reduces the amount of shear between the O₂ injected and the water. This was evident by the lower DO reading observed.

Although the performance of NBA's 1st tube iteration was slightly less, (approximately 3%), than the commercially available tube, the results were still encouraging: The differences can be credited to the quality of 3-D print. NBA uses a low cost printer and the quality of the print does not match that of the commercially available tube. Comparing the data recorded for the 3-D printed tube to the commercially available tube, (17.1 v 17.7 mg/l), approximates to an efficiency of 97% which is acceptable, taking into account the accuracy of the recorded results and the following caveats:

- The pressure gauges and O₂ flow meter (Rotameter), give an accuracy of approximately 5%.
- The water pump is agricultural: The delivery pressure can fluctuate with slight fluctuations in the power supply.
- Time to fill the 200 litre drum is measured using a stopwatch. Repeat tests showed a human response timing accuracy of 1 second, or better, equating to a timing accuracy of approximately 1.5% or better
- The Dissolved Oxygen meter is accurate to 0.05 % and is therefore not a consideration when verifying results.

The initial results allowed the development to move to next stage which was the iterative process of design, print, test and evaluate. Table 3 , (*appendix 8.4*) shows the results recorded during early testing of tubes. Tables 4, 5 & 6, shows a summary of the best performing tubes. The key data required was pump discharge pressure and the Dissolved Oxygen reading.

The results show that NBA designs have matched, or improved on the performance of the commercially available tube. NBA has taken a different approach to tube design with hollow cores, multiple fins following continuous helices through the length of the tubes and the absence of mixing regions.

The V05 and V07 profiles showed the best results and were taken forward to the next stage of development: up-scaling and multi-tube configurations. Although V12 showed the highest DO reading, (for the smaller 2.7 lps, tubes), the pressure reading taken was the highest. A higher pressure indicates an increase in the restriction to flow across the tube which results in a lower flow rate, taking longer to fill the 200 litre drum. This means that the O₂ injection is flowing for longer, so the higher reading obtained for the DO will be largely due to the O₂ being injected and flowing for a longer period, increasing the total volume of O₂ injected.

V09, V25 and V32 showed some interesting observations: The tubes were installed in the nanobubble generator in the reverse flow direction; water enters the exit point and flows out from the entry point. The DO reading for V09 showed very little difference, between direct flow and reverse flow. The DO readings for V25 and V32 showed improvements. The results for V25 and V32 suggest that the exit profiles for tube design should not stop abruptly, but should facilitate a gradual decelerative path to the point of exit and should allow the water to continue to rotate up to the point of entry at the dispersion tank. These results also support the results observed in test numbers 15 and 16, (*Table 3, appendix 8.4*). The results show that nanobubbles continue to be generated as the water continues to rotate.

This emphasises the need to maintain the rotational flow path as the water leaves the nanobubble tube and enters the dispersion tank. The water enters the dispersion tank, tangentially, and continues to decelerate as it rotates around the circumference of the tank, as the momentum and kinetic energy deplete. A trial test run was carried out to quantify the effect of removing the dispersion tank and discharging the water directly from the nanobubble tube into the 200 litre collection drum, via the discharge hose. The performance of the NBG was shown to drop off markedly in terms of the Dissolved Oxygen reading: In

test number 15, the dispersion tank was removed and the product water allowed to discharge from the nanobubble tube, directly into the collection drum. The DO recorded was 17.7 mg/l. The dispersion tank was reinstated for test no.16: The recorded result for DO was 23.7 mg/l. Azevedo, (2019) also showed this, experimentally: “The water flow is rotated into several vortices, while moving along a special chamber and exiting from the discharge pipework. This rotational movement is maintained until the kinetic energy has depleted. This produces an intense shear, through respective centrifugal forces, triggering nucleation and gas bubble formation as a result of the pressure fluctuation”.

V07 would be the preferred iteration to modify the exit profile. Essentially it is the same as V05 with two full helix rotations at the exit. The results suggest merit in taking the profile of two V05 tubes, reversing the flow direction for the second tube and joining the profiles together. This would give a gradual entry and a gradual exit. This would increase the length of the tube, which would increase the overall head loss; the length of the mid-section can be shortened to reduce the head loss: Longer tube designs result in a greater pressure drop whereas shorter tubes favour smaller pressure drops thus, the advantages of adding more helix revolutions and increasing the length of the tube to accommodate, are negated to an extent, by the increase in head loss.

The next iteration of design took the profiles from V05 and 07 and used slightly modified versions for a high flow single tube, (V32). A flow rate of 9.3 lps was achieved and a DO reading of 23.4 mg/l for an O₂ injection rate of 24 lpm. The calculated O₂ requirement to match the DO reading for V05, (18.8 mg/l), is a flow rate of 13.8 lpm O₂. The actual flow rate used was 24 lpm. Factoring in these figures gave an anticipated DO result for V32, of 25.1 mg/l, which is higher than the actual result of 23.4 mg/l. Initial thoughts suggested that the figure of 23.4 mg/l, although unlikely, may represent the O₂ saturation level of the water. It was not feasible to measure the saturation level for O₂ in the product water. In order to rule out the possibility that the saturation level had been reached, the discharge hose was removed from the 200-litre collection drum and placed, submerged into the IBC, (water supply for the nanobubble generator). This provides a recycle loop or closed circuit, where the water can make multiple passes through the NBG. The test was repeated and DO

results greater than 30 mg/l were observed after multiple passes. This information showed that the earlier result of 23.4 was not due to the O₂ saturation level being reached, but due to the performance of the tube.

Designs using 3, 4 and 5 parallel tubes, were printed and tested against single tubes of greater diameter with the same length and the same overall capacity. The multi-tube configurations out-performed the 10 lps single tubes by a considerable margin in terms of the DO readings observed. This information was influential in adopting a multi-tube design for higher flow rates and led to the decision that a multi-tube design would be taken forward.

5.2 Conclusions

The results emphasise that tube development is an iterative process and that the optimum design will be a compromise between acceptable head losses and performance, in terms of the dissolved oxygen measured in the product water. The results also show that more work could be carried out on the tube entry and exit profiles however, the results achieved with the best performing tubes, shown in the summary table, have met the criteria to take forward for commercial development; which is to match or better the current market leaders in terms of performance.

Several tests and repeat tests have been completed and the testing must reach a point where the project has to move forward. Further iterations of tube development could be tested however, the law of diminishing returns becomes more prevalent. This means that the potential gains to be made through further iterations of tube development, reduces as the number of tests increases. Any tube that matches or betters the reference profile, as shown by the results, meets the criterion, 'fit for purpose', (*'fit for purpose', in this context, is discussed in section 2.1*). The V05 profile was taken forward for commercial development and a multi-tube configuration put forward for patenting.

Chapter 6

Commercial Development

6.0 Evaluation

At the time of writing, (March 2023), Nanobubble Agritech has three installations under evaluation:

- Kauri Park Nursery: Nanobubble Generator supplies 2.7 lps oxygenated water, for irrigation.
- 5-Span Pivot irrigation scheme, South Island dairy farm: 2 x nanobubble generators, in series, with a 10 lps single tube for each generator.
- Single span in a 12-span irrigation scheme on a cropping farm. Rate 2.7 lps.



Figure 30 - Image shows a 3-span pivot irrigation scheme, Lindsay.com, (2023).



Figure 31 - Image showing a 10-span pivot irrigation scheme, Lindsay.com, 2023

6.1 Kauri Park

Kauri Park, Northland is Nanobubble Agritech's first commercial installation. The Kauri Park nursery procures and supplies over a hundred plant species. The Nursery also provides large scale contract growing for regional councils and commercial businesses. The Kauri Park ethos and Nanobubble Agritech provided a good synergy for the uptake of nanobubble technology. Following discussions with Kauri Park, Nanobubble Agritech entered into an agreement to supply KP nursery with a nanobubble generator. A unit was built and duly installed on the 23rd / 24th June 2022.



Figure 32 - NBA generator prepared for shipment to Kauri Park. The stand-alone unit at the left of the image is the oxygen generator.

Prior to shipment, NBA had to be satisfied that the design and integrity can be verified and that all reasonable safety measures have been taken. The requirement for a risk assessment was apparent. Many risk assessment tools and methods exist, from which the HAZOP, Hazard and Operability Study, was selected. *(A full explanation of the HAZOP process can be found in the appendix, section 8.5).*

Kauri Park Nanobubble Generator HAZOP Summary:

The NBG would appear to be relatively innocuous, on first inspection: The unit comprises a small, low pressure water pump, a plastic nanobubble tube, a non-pressurised stainless steel vessel and an oxygen generator; in essence, it would appear to be a simple, low-risk unit however, the HAZOP study highlighted a number of salient points, some of which are

considered to be ‘high potential’ with respect to risk, specifically; the potential for a nitrogen build up, or an oxygen build up in a confined space. Nitrogen is an asphyxiant and considered highly dangerous. Oxygen promotes combustion and may give rise to a flammable atmosphere. Oxygen may also react with chemicals and compounds such as fertilisers. The HAZOP also identified the potential for electrocution and the requirement to ensure that this cannot happen. The full transcript and risk mitigations from the HAZOP study can be found in the appendix, 8.5.



Figure 33 - Nanobubble Agritech generator fully installed and online at Kauri Park

6.2 NZ Cropping Farm



Figure 34 - Nanobubble Agritech mobile drip line installation, NZ Cropping Farm.

Figure 33 shows the single span installation, in a 12-span drip-line irrigation scheme. Supplying a single span with oxygenated water, as nanobubbles, allows the farmer to make a direct comparison between irrigation with oxygen nanobubbles and conventional irrigation. Drip-lines allow water to be fed directly to the soil. This reduces the amount of water lost to atmosphere through evaporation. Dripline irrigation is favoured by many farmers for this reason.

6.3 South Island Dairy Farm



Figure 35 - Nanobubble Agritech Generator, South Island dairy farm



Figure 36 - Nanobubble Agritech Drip-line installation, South Island dairy farm

Figures 35 and 36 show a Nanobubble Agritech installation at a South Island dairy farm. The installation comprises two, single-tube nanobubble generators in series, each using a 10 lps nanobubble tube

6.4 Field Days and Agricultural Conferences

In addition to the aforementioned installations, Nanobubble Agritech has presented at field days in New Zealand and Australia. NBA presented in Adelaide and was invited, by Callaghan Innovation, to form part of a delegation to showcase New Zealand Agritech, (Agricultural Technology), at the Australian Market Immersion, Agricultural Conference in Sydney, (March 2023). Much interest was registered with several enquiries generated.

6.5 Patent

A patent application has been submitted, for multi tube designs, comprising 5 straight tubes with an inlet manifold and an outlet manifold and an alternative design with 5 twisting tubes. A summary of the patent application can be found in appendix 8.6.

Chapter 7

Future Development

Testing and evaluation identified a number of opportunities to improve and to further develop existing designs. When funds are available; the discussions supporting the following become compelling:

Flow conditioning

Flow Straighteners are predominantly used in flow measurement to condition the flow stream prior to measurement. They reduce turbulence that would cause the flow measuring element to give erroneous readings. A Flow Straightener, immediately upstream of the nanobubble tube, will pre-condition the flow, effectively streamlining the flow. This reduces turbulence and head loss at the point of entry to the nanobubble tube.

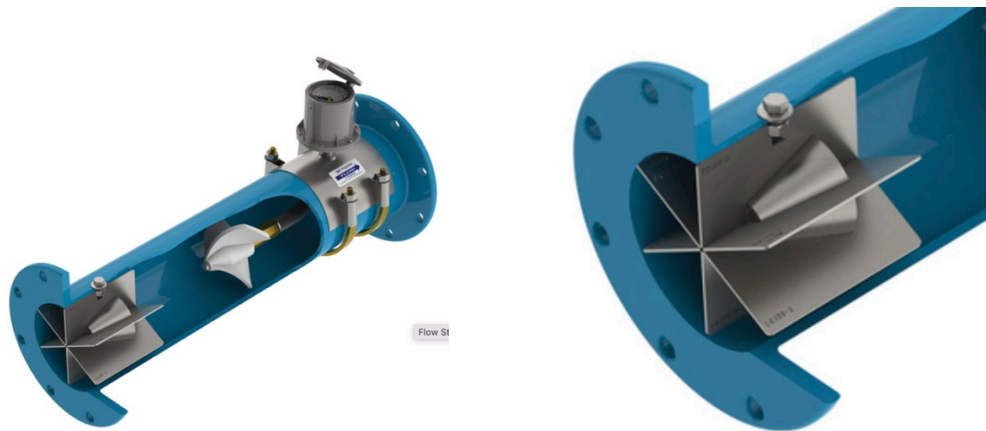


Figure 37 - Flow straightener and turbine meter, mccrometer.com, (2023)

Figure 36 shows a turbine meter designed for irrigation. The water meter is driven by the propeller or turbine at the latter part of the meter. The design at the front of the meter

houses the flow conditioning / flow straightener device. The design uses the frustum of a cone, within a standard flow straightener design. It is claimed by McCrometer Inc.,USA, (2023), that; “*The Flow Straightener provides breakthrough flow straightening technology that virtually eliminates the upstream / downstream straight pipe runs, typically required in existing or new flow meter applications.*” It would appear that the frustum, being the only point of difference within the standard flow straightener, is responsible for reducing the requirement for upstream and downstream straight pipe runs.

Applying this design for a flow straightener to the nanobubble generator would be particularly advantageous; It is not always practical to build a nanobubble generator with the necessary upstream and downstream straight pipe runs required for streamline flow. Reducing the length required for the flow straightener would be beneficial however, copyrights and patents would have to be investigated before this, or a similar design, could be adopted.

Entry profiles

The entry profile could be further developed in conjunction with a flow straightener: The geometry of the exit profile for the flow straightener would effectively ‘guide’ the water into the nanobubble tube where it will start its rotational and centrifugal path. Alternatively, the length of the nanobubble tube could be extended to include a flow straightener at the front end. There are a number of options that could be explored and evaluated through further development and testing.

Exit profiles

Exit profiles were discussed in the section 5.1: “The DO readings for V25 and V32 showed improvements. The results suggest that the exit profiles for the tubes should not stop abruptly, but should allow a gradual decelerative path to the point of exit and should allow

the water to continue to rotate up to the point of entry at the dispersion tank.” Further work could be carried out, in conjunction with the inlet configuration and geometry at the inlet to the dispersion tank.

Multi-tube exit configuration and entry configuration at dispersion tank, (entry nozzles)

The current multi-tube designs comprise an inlet manifold, a multiple tube arrangement and an outlet manifold. The individual flow streams from each tube, come together at the outlet manifold. An alternative design would prevent the flow streams from merging or colliding at this point. This would minimise unnecessary turbulence with head loss and potentially improve the production of nanobubbles.

Early testing showed that nanobubbles were still being produced in the dispersion tank and a significant drop in the dissolved oxygen reading was observed when the dispersion tank was removed, (*section 2.3.1, 'Design intent of components'*). The individual flow streams from each tube should enter the dispersion tank through dedicated inlet nozzles. The design of the inlets should allow the individual flow streams to enter the dispersion tank at different points, equidistant and offset from each other, with staggered heights of entry. The inlet nozzles should allow the flow streams to enter the tank tangentially and perpendicular to the radius of the vessel. The direction of flow for each inlet must be consistent. This will maintain the rotational motion of the water in the vessel and allow the individual streams to merge into the direction of flow. This prevents the turbulence caused when individual streams collide. It allows the water to maintain its circular motion at the wall of the vessel and to continue producing nanobubbles through shear, as the kinetic energy depletes and the velocity decreases.

O₂ injection

O₂ injection and the uptake of O₂ is most effective when there is maximum dispersion and maximum surface area for gas-water interface contact. This would suggest that further development should be afforded to the design of gas injectors and the position and number of gas injection ports. The use of fine-bubble diffusers in gas injectors should be explored and trialled with multiple injection points. The injection points should be equally spaced, forming an annular ring around the nanobubble tubes.

O₂ recapture

Early testing showed that the efficiency of O₂ uptake was 25%, with 75% of injected O₂ lost to atmosphere in a relatively short time frame. If 'free' oxygen can be recovered from the dispersion tank then this has the potential to allow a smaller and cheaper oxygen generator to be used. The O₂ generator is the most expensive item within the nanobubble generator; a smaller O₂ generator would therefore represent a significant cost saving. One company reports that their nanobubble generator achieves >85% SOTE, (Standard Oxygen Transfer Efficiency). It should be noted that this relates to the saturation level of the water and not the percentage of oxygen injected.

Commercial opportunities

The smallest and most efficient Nanobubble Agritec tube will process 2.9 lps water. This equates to 10.44 m³ water per hour. These volumes are too great for smaller agricultural businesses, such as those supplying market gardens and nurseries. A feasibility study should be carried out to investigate the viability of a smaller nanobubble generator suited to low volume requirements, making nanobubble technology available to the broader agricultural and horticultural sectors.

8.0 Appendix

Table 6 - 'Standard definition for fine bubbles - ISO 20480-1:2017', International Standards Organisation, (2017).

| |
|--|
| <p>8.1 International Standards Organisation - ISO 20480-1:2017 : Standard definition for 'fine bubbles'.</p> |
| <p>Until recently, there was no standard definition for Nanobubbles.</p> <p>In 2017, the International Organisation for Standardisation ratified the international standard for 'fine bubbles' The following is an extract from the ISO 20480-1:2017</p> |
| <p>Fine bubble technology - General principles for usage and measurement of fine bubbles.</p> |
| <p>Part 1: Terminology</p> |
| <p>Introduction</p> <p>Applications of fine bubble technologies can be found in cleaning, environmental improvement, the food and drink sector, aeration systems, medicine, water and waste water treatment, as well as agriculture and aquaculture. Developing appropriate terminology for such diverse technologies is therefore critical to business trade or product acceptance by consumers.</p> <p>Fine bubbles can be present in both liquids and solids. Fine bubbles can contain air or another gas. The bubble can be held in place by surface tension or be surrounded with a coating, e.g. a lipid. Fine bubbles generated for various applications can vary in size, gas content or bubble coating. The generation techniques used are also different.</p> <p>It should be noted that the motion of bubbles in a medium can be determined by buoyancy forces or randomly and thermally activated processes leading to Brownian motion. For this reason, larger bubbles can display buoyant behaviour (rise upwards) and smaller bubbles remain in the liquid medium displaying random motion. This document focuses on the definitions of such entities.</p> |
| <p>1 Scope</p> <p>This document specifies terminology and definitions used in the area of fine bubble technology. Terminology in this document covers general principles, measurements, and individual applications of fine bubble technology.</p> |

2 Normative references

There are no normative references in this document.

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardisation at the following addresses:

- ISO Online browsing platform: available at <http://www.iso.org/obp>
- IEC Electropedia: available at <http://www.electropedia.org/>

3.1 bubble

gas in a medium enclosed by an interface

3.2 fine bubble

bubble (3.1) with a **volume equivalent diameter** (3.8) of less than 100 µm

Note 1 to entry: 100 µm is also represented as 1×10^{-4} m.

Note 2 to entry: Annex A provides further information on the use of terms “fine bubble” or “ultrafine bubble” (3.3), instead of “nanobubble”.

3.3 ultrafine bubble

ultrafine bubble (3.2) with a **volume equivalent diameter** (3.8) of less than 1 µm

Note 1 to entry: Measured examples of ultrafine bubbles in water by particle characterisation methods, in practical application fields, mostly range between 100 nm and 200 nm. The measured results can include contaminants, as well as ultrafine bubbles.

3.4 microbubble

fine bubble (3.2) with a **volume equivalent diameter** (3.8) in the range from equal or greater than 1 µm to less than 100 µm

Note 1 to entry: Figure 1 shows the size range of **bubbles** (3.1), fine bubbles, **ultrafine bubbles** (3.3), and microbubbles.

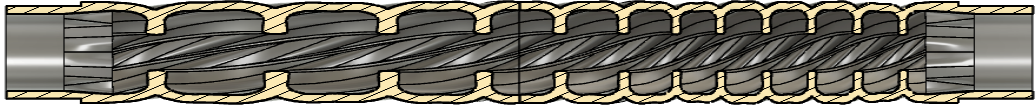

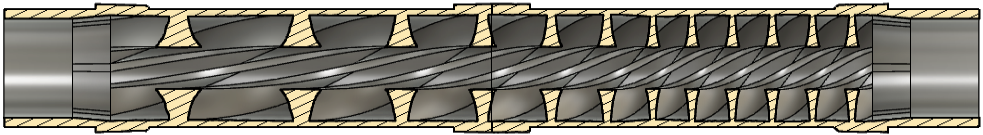
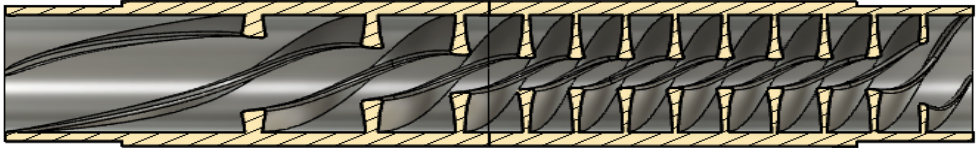
8.2 Project boundaries and parameters


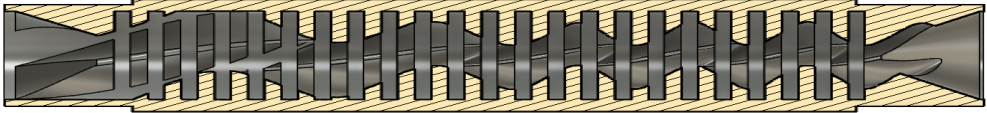
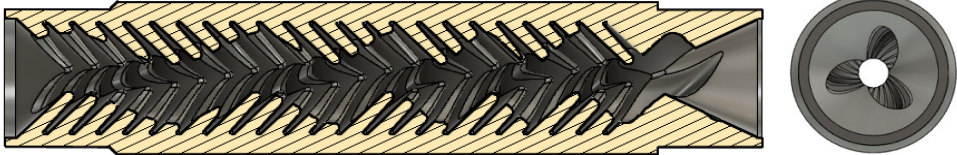

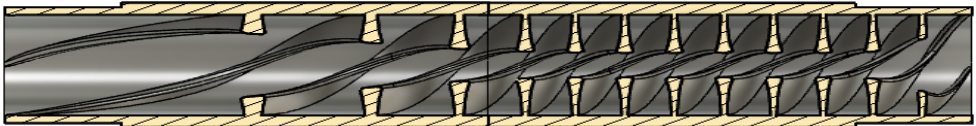
Table 7 Project boundaries and parameters

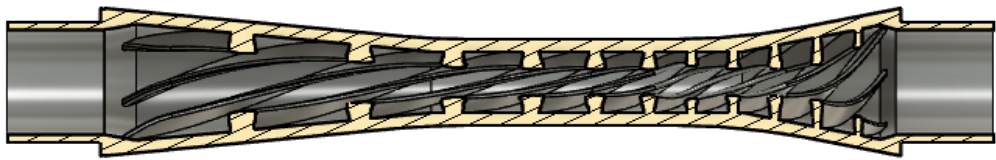
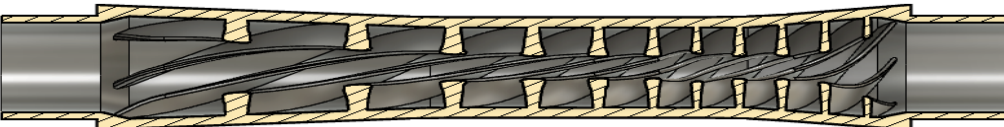

| |
|---|
| <p>○ A flow rate of 30 litres per second, of oxygen enriched water, as nanobubbles. <i>30 lps was set as a project criterion. This was decided upon, based on quoted performance, claimed by current manufacturers. NBA had to match or better, current quoted performance.</i></p> |
| <p>○ Nanobubble size must be < 200 nm in diameter. <i>Measured examples of ultrafine bubbles in water, in practical applications, mostly range between 100 nm and 200 nm. Ushikubo et al. (2010), reported a mean diameter of 137 nm for oxygen nanobubbles formed in de-ionised water.</i></p> |
| <p>○ Improve and out-perform current market units, in respect of head losses across the NBG, Nanobubble Generator. <i>Head losses are measured as the pressure drop across the nanobubble tube and the pressure drop across the nanobubble generator from inlet to outlet. As head loss increases, then energy consumption will rise.</i></p> |
| <p>○ Provide a range of NBG units, with interchangeable parts, catering for site-specific flow rates</p> |
| <p>○ NBG units to be readily and economically manufactured in-house.</p> |
| <p>○ O₂ generator to be procured and supplied by NBA</p> |
| <p>○ Skid mounted Dispersion tank to be supplied by NBA</p> |
| <p>○ Product storage and distribution pipework to be supplied by client.</p> |
| <p>○ Water supply and pipework to / from the NBG skid to be provided by client.</p> |


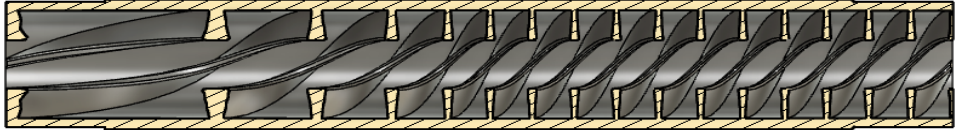
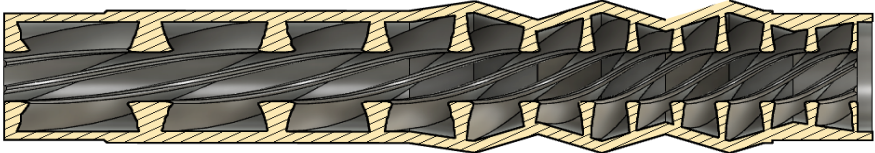


8.3 Early tube designs

Table 2 – continued: 2-D drawings generated by the CAD software package, showing tube design variations.

| | |
|-----|--|
| V8 | <p>Profile as per V5 except that; the length of one full rotation has been increased by 25%</p>  |
| V9 | <p>Profile as per V8 except that; the length of one full rotation has been decreased by 25%</p>  |
| V10 | <p>As per V5 except that, the profile geometry, (specifically angles), has been adjusted.</p>  |
| V11 | <p>3-fins, length of one full helix rotation reduced to 75% of the Gaia UFB 100: $0.75 \times 63\text{mm} = 47.25\text{mm}$. Core diameter 7mm Profile as per V5, with the above variations.</p>  |

| | |
|-----|---|
| V12 | <p>Based on the V5 profile, the core diameter closes completely in the middle of the rotation and opens-up leading toward the exit point.</p> <p>Profile at the pipe-wall has voids where the core closes-up to creating mixing zones.</p>  |
| V13 | <p>As per V5, with baffles added.</p> <p>The purpose of the baffles is to create high and low pressure regions to promote cavitation.</p>  |
| V14 | <p>As per V13; with the baffles at 45°. The rationale for this design is to reduce the pressure drop across the tube.</p>  |
| V15 | <p>As per V5; with a 7mm core diameter</p>  |
| V16 | <p>Distance per full helix rotation decreased by 25%; 4-fins; 7mm core diameter; 2 x 360* helix rotations.</p>  |

| | |
|-----|---|
| V17 | <p>Follows a Venturi profile: Core diameter 13mm at entry, reducing to 7mm at throat, with the helix and core diameter gradually expanding toward the exit point</p>  |
| V18 | <p>As per V17, with a 20mm internal throat dia.</p>  |
| V19 | <p>As per V14, with increased core diameter approx. 10mm and baffles at 45°.</p>  |

| | |
|-----|---|
| V20 | <p>As per V7, with four 360* helix rotations, 13mm core diameter, six fins</p>  |
| V21 | <p>As per V16, with three 360 helix rotations, four fins.</p>  |
| V22 | <p>As per V7, with three increasing diameter pressure drops.</p>  |
| V23 | <p>As per V7, with three 360* helix rotations.</p>  |
| V24 | <p>As per V21, with four 360* helix rotations.</p>  |

8.4 Nanobubble tube, test results

| A | B | C | D | E | F | G | H | I | J | K | L | M | N | O | P | Q |
|----------|---------------------------|--------|------------|---------------------|--------------------------|--------------------|-----------------|-----------------------------------|----------------------------------|-------------------------|-------------------------------|------------------------------|--------------------------|---------------------------|------------------------------|---|
| Test No. | Test id | Time | Date | Dissolved O2 in IBC | Feed Water Temp °C (IBC) | O2 Flow rate l/min | O2 pressure psi | Time to fill 200 l drum - seconds | Total volume of O2 used - Litres | Drum capacity - 200 lts | Pump discharge pressure - psi | pump discharge flow rate l/s | Dispersion tank pressure | Product tank - water temp | Dissolved O2 - mg/l | Notes / Comments |
| 1 | Gaia UFB100 | 10:32h | 28/04/22 | 8.8 | 14.4 | 4 | 16 | 73 | 4.9 | 200 | 19 | 2.7 | Not used | 17 | 17.7 | |
| 2 | Gaia UFB replica | | | | | 4 | | 79 | 5.3 | 200 | 19 | 2.5 | | 17.9 | 17.1 | |
| 3 | V02 | 10:47h | | | 14.5 | 4 | 14 | 68 | 4.5 | 200 | 14 | 2.9 | N/A | 17.6 | 18.3 | |
| 4 | V06 | 15:38h | | | 14.5 | 4 | 14 | 68 | 4.5 | 200 | 14 | 2.9 | N/A | 19.3 | 17.3 | |
| 5 | Gaia UFB100 | 13:50h | 03/05/22 | 9.8 | 18.5 | 4 | 16 | 78 | 5.2 | 200 | 19 | 2.6 | N/A | 17.7 | 17.7 | |
| 6 | V1 | 14:00h | | | 18.5 | 4 | 16 | 76 | 5.1 | 200 | 19 | 2.6 | N/A | 18.8 | 18.8 | |
| 7 | V3 | 14:05h | | | 18.5 | 4 | 16 | 72 | 4.8 | 200 | 19 | 2.8 | N/A | 18.4 | 18.4 | |
| 8 | V4 | 14:15h | | | 18.5 | 4 | 13 | 72 | 4.8 | 200 | 17 | 2.8 | N/A | 18.7 | 18.7 | Insert broke 3-D print had 'fill minor gaps turned off' |
| 9 | V5 | 14:33h | | | 18.5 | 4 | 14 | 70 | 4.7 | 200 | 17 | 2.9 | N/A | 18.9 | 18.8 | |
| 10 | V7 | 14:51h | | | | 4 | 15 | 74 | 4.9 | 200 | 18 | 2.7 | N/A | 18.7 | 19.4 | |
| 11 | V9 | 14:12h | 05/05/22 | 10.1 | 17.8 | 4 | 14 | 68 | 4.5 | 200 | 17 | 2.9 | N/A | 17.9 | 18.6 | |
| 12 | V8 | 14:30h | | | | 4 | 13 | 68 | 4.5 | 200 | 16 | 2.9 | N/A | 18.1 | 18.6 | |
| 13 | V10 | 14:40h | | | | 4 | 13 | 68 | 4.5 | 200 | 16 | 2.9 | N/A | 18.7 | 18.1 | |
| 14 | V9 | 14:48h | | | | 4 | 13 | 68 | 4.5 | 200 | 16 | 2.9 | N/A | 18.7 | 18.5 | Flow direction reversed |
| 15 | Gaia UFB100 | 15:13h | | | | 4 | 16 | 78 | 5.2 | 200 | 20 | 2.6 | N/A | 18.6 | 17.7 | |
| 16 | Gaia UFB100 + Disp tk | 15:00h | | | | 4 | 16 | 78 | 5.2 | 200 | 19.5 | 2.6 | 9.5 | 18.6 | 23.8 | Dispersion tank fitted |
| 17 | V7 | 15:29h | | | | 4 | 15 | 72 | 4.8 | 200 | 18 | 2.8 | 9 | 18.6 | 23.7 | |
| 18 | V5 | 15:40h | | | | 4 | 13 | 74 | 4.9 | 200 | 16 | 2.7 | 9 | 18.6 | 22.8 | |
| 19 | V1 | 15:50h | | | | 4 | 15 | 71 | 4.7 | 200 | 18 | 2.8 | 9 | 18.5 | 23 | |
| 20 | Gaia UFB100 | | | | | | 8 | | #VALUE! | 200 | N/A | #VALUE! | N/A | 18.5 | at t=0 28.3, at t=24h 25.41 | |
| 21 | V7 | | | | | | 8 | | #VALUE! | 200 | N/A | #VALUE! | N/A | 18.5 | at t=0 29.5, at t=24h 26.78 | |
| 22 | V1 | | | | | | 8 | | #VALUE! | 200 | N/A | #VALUE! | N/A | 18.5 | at t=0 29.5, at t=24h 28.31 | |
| 23 | V13 | | | | | 4 and 2 | | 193 | #VALUE! | 200 | 40 | 1.0 | | 17.9 | at t=0 34.45, at t=24h 28.51 | |
| 24 | V14 | | | | | 4 and 2 | | 145 | #VALUE! | 200 | 37 | 1.4 | | 18 | at t=0 28.61, at t=24h 23.35 | |
| 25 | Gaia UFB100 | 11:20h | 10/05/22 | | | 4 | N/A | 75 | 5.0 | 200 | 20 | 2.7 | N/A | 17.3 | 17.8 | |
| 26 | V5 | 11:25h | | | | 4 | 12 | 71 | 4.7 | 200 | 14 | 2.8 | | 17.5 | 17.9 | |
| 27 | V7 | 11:30h | | | | 4 | 15 | 74 | 4.9 | 200 | 18 | 2.7 | | 17.7 | 19 | |
| 28 | V12 | 11:37h | | | | 4 | N/A | 83 | 5.5 | 200 | 20 | 2.4 | | 17.9 | 19.9 | |
| 29 | V11 | 12:00h | | | | 4 | 14 | 73 | 4.9 | 200 | 17 | 2.7 | | 18.1 | 17.4 | |
| 30 | V15 | 12:11h | | | | 4 | 15 | 76 | 5.1 | 200 | 18 | 2.6 | | 18.2 | 17.6 | |
| 31 | V16 | 12:22h | | | | 4 | 17 | 68 | 4.5 | 200 | 19.5 | 2.9 | | 18.3 | 18.1 | |
| 32 | V17 | 12:31h | | | | 4 | 25.5 | 96 | 6.4 | 200 | 27 | 2.1 | | 18.4 | 21.2 | |
| 33 | V18 | 12:40h | | | | 4 | | 76 | 5.1 | 200 | 16.5 | 2.6 | | 18.4 | 17.3 | |
| 34 | V19 | | 13/05/2022 | | | 4 | | 81 | 5.4 | 200 | 23 | 2.5 | | 14.2 | 20.7 | |
| 35 | V20 | | 24/05/2022 | 9.47 | 17.1 | 4 | | 73 | 4.9 | 200 | 17.5 | 2.7 | | 17.0 | 18.6 | |
| 36 | V21 | | | | | 4 | | 75 | 5.0 | 200 | 21 | 2.7 | | 17.1 | 19.4 | |
| 37 | V22 | | | | | 4 | | 72 | 4.8 | 200 | 18 | 2.8 | | 17.5 | 18.3 | |
| 38 | V23 | | 24/05/2022 | | | 4 | | 72 | 4.8 | 200 | 16.5 | 2.8 | | 17.1 | 17.8 | |
| 39 | V24 | | | | | 4 | | 77 | 5.1 | 200 | 20 | 2.6 | | 17.2 | 18.8 | |
| 40 | V25 | | | | | 4 | | 73 | 4.9 | 200 | 16.5 | 2.7 | | 17.3 | 17.5 | |
| 41 | V25 | | | | | 4 | | 74 | 4.9 | 200 | 16.5 | 2.7 | | 17.3 | 18.6 | NBG reverse orientation |
| 42 | V26 | | | | | 4 | | | 0.0 | 200 | | | #DIV/0! | | | |
| 43 | V27 | | | | | 4 | | | 0.0 | 200 | | | #DIV/0! | | | |
| 44 | V28 | | | | | 4 | | | 0.0 | 200 | | | #DIV/0! | | | |
| 45 | V29 | | | | | 4 | | | 0.0 | 200 | | | #DIV/0! | | | |
| 46 | V30 | | 6/03/22 | | | 24 | | | | | 13 | 9.5 | | | 21.6 | Gaia UFB200 replica |
| 47 | V30 | | | | | 12 | | | | | 13 | 9.5 | | | 16.5 | |
| 48 | V31 | | | | | 24 | | | | | | | | | 18.6 | |
| 49 | V32 | | | | | 24 | | | | | 13 | 9.3 | | | 23.4 | |
| 50 | V32 | | | | | 24 | | | | | 13 | 8.9 | | | 23.7 | Reverse direction |
| 51 | V33 | | | | | 24 | | | | | 13 | 9.5 | | | 20.8 | 3-tube unit |
| 52 | V33 | | | | | 24 | | | | | 13 | 9.5 | | | 20.6 | above test repeated for confirmation |
| 53 | Gaia replica -10 lps | 10:00 | 6/03/22 | 9.69 | 12.6 | 12 | | | | | 12 u/s | 2 d/s | | | 16.6 | O2 diffuser reverse orientation |
| 54 | Gaia replica -10 lps | | | | | 24 | | | | | 11 u/s | 3 d/s | | | 18.5 | |
| 55 | V32 | | | | | 12 | | | | | 14 u/s, | 0 d/s | | | 16.5 | d/s pressure gauge swapped for u/s px gauge; d/s pressure still reading Opsl : issue with d/s pressure gauge tapping / port |
| 56 | V32 | | | | | 24 | | | | | 14 u/s, | 0 d/s | | | 22.1 | |
| 57 | V-35 Triple twist 10 lps | | | | | 12 | | | | | 9.5 u/s, | 0 d/s | 9.0 | | | Triple tube testing aborted: O2 flowing, preferentially through one injector; water ingress into 2nd and 3rd O2 injector tubes; Separate rotameters required for each of the 3 injectors. |
| 58 | V-36 3-leaf clover design | | | | | 12 | | | | | 13.5 u/s, | 0 d/s | 9.9 | | 17.6 | injector |
| 59 | | | | | | 24 | | | | | 13.5 u/s, | 0 d/s | | | 20.9 | injector |
| 60 | Gaia replica -10 lps | 13:30 | | | | 12 | | | | | 12 u/s | 3 d/s | | | 16.6 | O2 diffuser correct orientation |
| 61 | Gaia replica -10 lps | | | | | 24 | | | | | 14 u/s | 4 d/s | | | 18.5 | |
| 62 | | | | | | | | | | | | | | | | |
| 63 | | | | | | | | | | | | | | | | |
| 64 | | | | | | | | | | | | | | | | |
| 65 | | | | | | | | | | | | | | | | |
| 66 | | | | | | | | | | | | | | | | |

Table 8, shows the results recorded for the 3 lps tubes and the 10 lps tubes, (test numbers 46 – 59). Where cells have been left blank, the information was not required for that specific test.

8.5 Hazard and Operability Study – HAZOP

Preamble:

A ‘Hazard and Operability Study’, more commonly referred to as a HAZOP, is a very structured and systematic evaluation of a design. The process is not industry specific, although it has been widely adopted across many industries and many countries. A HAZOP is a record of the design team’s discussions, findings and recommendations. It is the only record of a detailed assessment by the design team.

Its purpose is to eliminate harm, injury and to prevent financial loss. This can only be achieved through ‘safety by design.’ The HAZOP study, or assessment, identifies any omissions, oversights or errors in the design. It identifies any deviations from the design intent. It also takes into account, the environment where the unit will be installed and used. The process was developed by ICI, Imperial Chemical Industries, in the 1960’s and has been widely adopted since the 1970’s.

A HAZOP team typically comprises:

- A HAZOP leader
- Scribe
- Independent Process Engineer
- Design Engineer
- Subject Matter Expert or Discipline Engineer - when required
- Operations Team representative
- Vendor or Specialist equipment representative – when required

The HAZOP Leader’s primary role is to chair and facilitate the HAZOP process. The Leader’s technical input is secondary; technical advice may be given to assist the Design team in their thought processes, when the HAZOP process has stalled at a particular

parameter and guide word. The HAZOP Leader should be an independent consultant, and not part of the project team. This ensures there is no financial or engineering bias toward any aspect of the design.

The Scribe is usually a graduate Design or Process Engineer who records the teams' comments and recommendations. The HAZOP Leader provides guidance and direction to the Scribe, stating what is, and what is not required to be recorded. The comments are shown on a projected spreadsheet for the team to review and provide clarity where required. The comment is summarised and verified by the team before the team moves to the next element, guideword or parameter.

The process design engineers attend the HAZOP for their design. They give definition and technical explanation for the 'Design Intent' for each node. Larger projects may also bring in an independent process engineer. A representative from the Operations team will attend and provide practical input, from an Operator's perspective and experience. Respective discipline engineers may be asked to attend to provide subject matter expertise for instrumentation, electrical and process control input. The expectation is that all team members participate, with an open mind, providing constructive input, comments and recommendations for their field of expertise.

The HAZOP Process

The HAZOP process uses P&IDs , (Piping and Instrumentation Diagrams) to represent the process design. The drawings are marked up in manageable sized, logical sections. Each section is called a 'Node'

The team works through a standard list of parameters, such as pressure, level, flow, temperature, vibration etc., and systematically applies the seven main guidewords, starting with No, More, Less etc., to the parameter and any other guidewords deemed relevant.

For example:

- The Nodes are listed in a logical sequence following the Process flow direction.
- The first Node is selected for assessment.
- The assessment starts at the inlet of the first Node, and works through to the outlet, or exit point of that Node.
- Flow is selected as the first Parameter.
- The first guideword is then applied:
- All possible causes of ‘No Flow’ to the first element in the node, are considered and assessed.
- When all credible possibilities have been exhausted, the HAZOP Leader then moves to apply the next guide-word; ‘More’, then ‘Less’ and so on...
- When all the guide-words have been applied, the team moves to the next parameter.
- This process is repeated until all Parameters have been considered and all guidewords for each parameter have been exhausted.
- The most common Parameters and Guidewords applied are shown in the table below. Other Parameters and Guidewords may be identified and applied.

| <u>Parameters</u> | <u>Guidewords</u> |
|--------------------------|----------------------------|
| Flow | No |
| Pressure | More |
| Level | Less |
| Temperature | Reverse |
| Viscosity | As well as... / Additional |
| Vibration | Part of |
| Corrosion | Other |

Ground rules:

A good HAZOP Leader sets out the ground rules for the HAZOP study. Ground rules should include the following:

- There are no right and no wrong observations or comments.
- Everybody's input is important and valued.
- No phones, email distractions or absenting ourselves during the process.
- Regular breaks are necessary.
- Action items must be closed out, before the HAZOP can be closed out.
- HAZOP should be carried out as soon as the final design is 'frozen'. There must be no further changes after the HAZOP with the exception of HAZOP action items. If a change is made, then the change will be subject to a HAZOP review.
- Open minded
- Constructive comments only

8.6 HAZOP Study - Kauri Park

HAZOP - Kauri Park NBG

Company : Nanobubble Agritech
 Facility : Kauri Park
 HAZOP date : 20.08.2022
 HAZOP leader : I. Gibbon
 Project Manager : R. Powers
 Project Engineer : D. Ochieng'oko

Node : 1

Node Description : Water inlet, pump, auto-prime, nanobubble tube, dispersion tank, water outlet

Design intent : To transfer water, from the pump inlet to the dispersion vessel outlet, leaving the dispersion vessel as water enriched with oxygen nanobubbles

| ID | Parameter | Guide Word | Cause | Consequence | Safeguards | Action | Comments | By | By when | |
|----|-----------|------------|--|--|---|--|--|----|---------|--|
| 1 | Flow | No | <ul style="list-style-type: none"> ○ Upstream or downstream valve shut ○ Inlet pipe blockage ○ Outlet pipe blockage ○ Frozen pipes | <ul style="list-style-type: none"> ○ Unit trips on no flow. ○ Pump stops. | | <ul style="list-style-type: none"> ○ Confirmation of open valves to be written into the operating instructions ○ Recommend the use of an inline water filter to the client ○ Operating instructions to include insulation / heat tracing requirements for operating environments where ambient may fall below 3°C | <ul style="list-style-type: none"> ○ Heat tracing and insulation required for operating environments where ambient temperature could fall below 3°C | | | |
| | Flow | No | <ul style="list-style-type: none"> ○ Air lock in pump discharge pipe | <ul style="list-style-type: none"> ○ Pump does not 'pump' | <ul style="list-style-type: none"> ○ Auto-prime unit fitted to pump discharge pipe | | | | | |
| | Flow | No | <ul style="list-style-type: none"> ○ Auto-prime fail | <ul style="list-style-type: none"> ○ No flow through <u>auto-prime</u>. No forward flow due to air lock ○ NBG will not start | <ul style="list-style-type: none"> ○ NBG factory tested and tested again, at site during commissioning | <ul style="list-style-type: none"> ○ Add to Factory acceptance check list: test and prove <u>Auto-prime</u>, prior to site installation | | | | |
| 2 | Flow | More | | <ul style="list-style-type: none"> ○ No consequence identified | | | | | | |
| 3 | Flow | Less | <ul style="list-style-type: none"> ○ Damaged / restricted water supply pipe ○ Turbidity – suspended solids ○ Scaling | <ul style="list-style-type: none"> ○ Pump cavitates ○ Premature wear to pump impellor ○ Reduced NBG efficiency | <ul style="list-style-type: none"> ○ Auto-prime trips pump on low / no-flow | <ul style="list-style-type: none"> ○ Add 'Trouble-shooting guide' to Operating instructions ○ Consider water filter. ○ Fit suction strainer to pump ○ Add 'scaling to trouble shooting guide' as a consideration. | <ul style="list-style-type: none"> ○ Scaling considered to be <u>low-risk</u>. To be considered for hard water applications. | | | |

HAZOP - Kauri Park NBG

Company : Namobubble Agritech
 Facility : Kauri Park
 HAZOP date : 20.06.2022
 HAZOP leader : I Gibbon
 Project Manager : L. Powers
 Project Engineer : D. Oricharenko

Node : **1**

Node Description : Water inlet, pump, auto-prime, nanobubble tube, dispersion tank, water outlet
Design intent : To transfer water, from the pump inlet to the dispersion vessel as water enriched with oxygen nanobubbles

| ID | Parameter | Guide Word | Cause | Consequence | Safeguards | Action | Comments | By | By when |
|----|-----------|------------|--|--|---|---|--|----|---------|
| 4 | Flow | Reverse | <ul style="list-style-type: none"> o Discharge pipework / irrigation scheme: Elevation > 36m above the NBG | <ul style="list-style-type: none"> o Unit stops | <ul style="list-style-type: none"> o Auto-prime unit trips pump on no forward flow | <ul style="list-style-type: none"> o Future installations to consider the design and conditions for site specific irrigation needs; specifically, the use of check valves, booster pumps and siphon breakers | <ul style="list-style-type: none"> o Difference in elevations not applicable to Kauri Park. | | |
| | Flow | Reverse | <ul style="list-style-type: none"> o Dispersion vessel or Product Storage tank at a higher elevation than the pump water supply. In stand-by / off modes. Vessel or tank drains under gravity or siphon | <ul style="list-style-type: none"> o Loss of product inventory / supply to irrigation scheme booster pump | | <ul style="list-style-type: none"> o Consider the use of check valves and siphon breakers in the client's irrigation scheme. | | | |
| 5 | Flow | Additional | <ul style="list-style-type: none"> o O₂ venting from Dispersion Vessel | <ul style="list-style-type: none"> o Hi concentration of O₂ in a confined space | | <ul style="list-style-type: none"> o Ensure NBG and O₂ generator are installed in a well-ventilated area. If this is not possible, or ventilation could be compromised, provide a vent to a safe location. Birds nest preventer to be installed at vent outlet. | <ul style="list-style-type: none"> o Site survey to determine requirements for a vent to safe location. | | |
| 6 | Pressure | No | <ul style="list-style-type: none"> o No water supply o Closed valve – upstream o Pump not running | <ul style="list-style-type: none"> o NBG will not run | | <ul style="list-style-type: none"> o Include in trouble-shooting guide | | | |

HAZOP - Kauri Park NBG

Company : Nanobubble Agritech
 Facility : Kauri Park
 HAZOP date : 20.06.2022
 HAZOP leader : I Gibbon
 Project Manager : L Powers
 Project Engineer : D. Orlanzenko

Node : 1

Node Description : Water inlet, pump, auto-piping, nanobubble tube, dispersion tank, water outlet
Design intent : To transfer water, from the pump inlet to the dispersion vessel outlet, leaving the dispersion vessel as water enriched with oxygen nanobubbles

| ID | Parameter | Guide Word | Cause | Consequence | Safeguards | Action | Comments | By | When |
|----|-----------|------------|--|---|---|---|--|----|------|
| 7 | Pressure | More | <ul style="list-style-type: none"> o Downstream valve closed | <ul style="list-style-type: none"> o Potential crack or split to nanobubble tube o O₂ pressure not great enough to overcome water pressure. No O₂ injection | <ul style="list-style-type: none"> o O₂ generator produces a greater discharge pressure than the Davney pump. | <ul style="list-style-type: none"> o Operating instructions to include pre-start checks o Test NB tubes against a closed discharge valve. | <ul style="list-style-type: none"> o Relief valve to be fitted to Dispersion Vessel ref. action item from node 2 o When upscaling future NBGs, ensure that O₂ generator is matched / sized to overcome the water pressure | | |
| | Pressure | More | <ul style="list-style-type: none"> o Downstream valve closed | <ul style="list-style-type: none"> o Increased pressure / hydraulic shock to pipework, NB tube and Dispersion vessel. | | <ul style="list-style-type: none"> o Install relief valve at Dispersion Vessel. | | | |
| | Pressure | More | <ul style="list-style-type: none"> o O₂ Generator changed out for O₂ cylinder – regulator incorrectly set | <ul style="list-style-type: none"> o Over-pressurisation of Node | | <ul style="list-style-type: none"> o Install relief valve at Dispersion Vessel | | | |
| | Pressure | More | <ul style="list-style-type: none"> o ...as above | <ul style="list-style-type: none"> o Equipment leak / failure | <ul style="list-style-type: none"> o | <ul style="list-style-type: none"> o Unit to be pressure tested up to 1.5 x maximum anticipated operating pressure o Check pressure ratings for pipework and fittings o Dispersion vessel – check requirements for certification | <ul style="list-style-type: none"> o Strength tests are carried out 1.5 x max operating pressure o Leak tests are carried out at 1.1 x max operating pressure | | |
| 8 | Pressure | Less | <ul style="list-style-type: none"> o Considered under 'Less Flow' | | | | | | |
| 9 | Pressure | Less | <ul style="list-style-type: none"> o Pump seal fails | <ul style="list-style-type: none"> o Pressurised water spray – potential damage to eyes | <ul style="list-style-type: none"> o Electric motor / pump coupling guard provides a degree of protection | <ul style="list-style-type: none"> o Operating instructions to include safety glasses under PPE | | | |

HAZOP - Kauri Park NBG

Company : Nanobubble Agritech
 Facility : Kauri Park
 HAZOP date : 20/06/2022
 HAZOP leader : I Gibson
 Project Manager : L. Poyers
 Project Engineer : D. Ovdarenko

Node : 1

Node Description : Water inlet, pump, auto-purge, nanobubble tube, dispersion tank, water outlet
Design intent : To transfer water, from the pump inlet to the dispersion vessel outlet, leaving the dispersion vessel as water enriched with oxygen nanobubbles

| ID | Parameter | Guide Word | Cause | Consequence | Safeguards | Action | Comments | By | By when |
|----|--------------|------------|--|--|---|---|--|----|---------|
| 10 | Level | | <ul style="list-style-type: none"> o | <ul style="list-style-type: none"> o | <ul style="list-style-type: none"> o | <ul style="list-style-type: none"> o | <ul style="list-style-type: none"> o Difference in elevations not applicable to Kauri Park. | | |
| 11 | Temperature | More | <ul style="list-style-type: none"> o Ambient temperature and direct sunlight | <ul style="list-style-type: none"> o Electronic sensors and controls overheat and fail. o Plastic housings fail due to UV | <ul style="list-style-type: none"> o | <ul style="list-style-type: none"> o Ensure ambient temperature swings are with the operating limits for components. o Protect from direct sunlight | | | |
| 12 | Temperature | Less | <ul style="list-style-type: none"> o Ambient temperature falls below 3° C | <ul style="list-style-type: none"> o Water freezes | <ul style="list-style-type: none"> o | <ul style="list-style-type: none"> o | | | |
| 13 | Temperature | Less | <ul style="list-style-type: none"> o | <ul style="list-style-type: none"> o | <ul style="list-style-type: none"> o | <ul style="list-style-type: none"> o | | | |
| 14 | Vibration | More | <ul style="list-style-type: none"> o Pump – mechanical issue o Local vibration | <ul style="list-style-type: none"> o Premature wear leading to equipment failure | <ul style="list-style-type: none"> o Pump mounted on rubber feet. o Unit tested prior to installation | <ul style="list-style-type: none"> o Develop maintenance schedule. o Consider vibration when installing unit at client's location. | <ul style="list-style-type: none"> o Recommend NBA maintenance programme to client | | |
| 15 | 'Other than' | | <ul style="list-style-type: none"> o Rust | <ul style="list-style-type: none"> o Fouling, Premature corrosion of cast iron pump impeller. o Reduction in pump efficiency | <ul style="list-style-type: none"> o Operating Instructions | <ul style="list-style-type: none"> o Capture the requirement to remove pump drain plug when NBG is not in use for an extended period. To be captured in the NBG operating instructions. Instructions to include reinstating the drain plug and flushing with clean water, immediately prior to returning NBG to service. | | | |

HAZOP – Kauri Park NBG

Company : Nanobubble Agritech
 Facility : Kauri Park
 HAZOP date : 20.08.2022
 HAZOP leader : I Gibbon
 Project Manager : L. Powers
 Project Engineer : D. Oviataromko

Node : **2**

Node Description : Air inlet to the Oxygen Generator, O₂ generator, O₂ lines to the injection point at the Nanobubble tube
 Design intent : To transfer high-purity oxygen to the nanobubble tube.

| ID | Parameter | Guide Word | Cause | Consequence | Safeguards | Action | Comments | Responsible |
|----|-----------|------------|---|---|---|--------|---|-------------|
| 16 | Flow | No | <ul style="list-style-type: none"> o Air inlet blocked o Nitrogen exhaust blocked o Rotameter / flow meter needle valve shut o Solenoid valve fails to open o Check valve stuck in the closed position o Compressor fails to run o O₂ generator not receiving a 'run permissive' o Rotameter / flow meter needle valve incorrectly set | <ul style="list-style-type: none"> o O₂ Generator fails to run o O₂ Generator fails to run o Nanobubbles are not produced o Start-up sequence fail: Start-up seq resets o No forward flow – no nanobubbles o Water pump does not receive a start permissive. NBG does not run o Water pump does not receive a start permissive. NBG does not run o Adjust flow to the required rate | <ul style="list-style-type: none"> o Maintenance schedule and daily checks o Maintenance schedule and daily checks o Operating instructions o Trained operators | | | |
| 17 | Flow | More | | | | | <ul style="list-style-type: none"> o Optimum flow rate from O₂ generator is achieved at a discharge pressure of 1.4 bar Rated capacity is 10 lpm @ 1.4bar, 20 psi | |

HAZOP – Kauri Park NBG

Company : Nanobubble Agritech
 Facility : Kauri Park
 HAZOP date : 20.06.2022
 HAZOP leader : I Gibbon
 Project Manager : L. Powers
 Project Engineer : D. Oviattarantko

Node : **2**

Node Description : Air inlet to the Oxygen Generator, O₂ generator, O₂ lines to the injection point at the Nanobubble tube
 Design intent : To transfer high-purity oxygen to the nanobubble tube.

| ID | Parameter | Guide Word | Cause | Consequence | Safeguards | Action | Comments | Responsible |
|----|-----------|------------|--|---|--|---|--|-------------|
| 18 | Flow | Less | <ul style="list-style-type: none"> o Air inlet filter contamination of mol sieves o Mol sieves degraded o Rotameter needle valve incorrectly set o Compressor seal leak o O₂ delivery tubes / signals to pressure sensor and pressure gauge – push-fit connections | <ul style="list-style-type: none"> o Performance drops off o O₂ efficiency drops off / unit ceases to function o Adjust flow to the required rate o O₂ discharge to atmosphere; O₂ build-up in a confined space | <ul style="list-style-type: none"> o Air filter o Clean, dry, oil-free air supply o Remove dust from Mol sieves / replace if necessary | <ul style="list-style-type: none"> o Change filter o Include in Operator Instructions, maintenance section o Ensure Unit is installed in a well-ventilated space o Fix non-removable warning sign o Include safety warnings in Ops Instructions | <ul style="list-style-type: none"> o OGSi, (O₂ generator supplier) recommends air filter be changed every 6-months o Mol sieves should last the life of the O₂ generator | |
| 19 | Flow | Reverse | <ul style="list-style-type: none"> o Water pressure greater than O₂ pressure o Air / O₂ compressor stops before water pump comes to a complete stop | <ul style="list-style-type: none"> o Water damage to Mol sieves – unit fails to work | <ul style="list-style-type: none"> o Check valve o SOV, Solenoid valve will vent the downstream line when the valve trips to the closed position. o There are two check valves, a rotameter (which acts as a check valve under reverse flow conditions and the SOV – effectively 4 barriers o Start-up sequence has to complete before the SOV will open | | | |

HAZOP – Kauri Park NBG

Company : Nanobubble Agritech
 Facility : Kauri Park
 HAZOP date : 20.06.2022
 HAZOP leader : I Gibbon
 Project Manager : L. Powers
 Project Engineer : D. Ovcharenko

Node : **2**

Node Description : Air inlet to the Oxygen Generator, O₂ generator, O₂ lines to the injection point at the Nanobubble tube
Design Intent : To transfer high-purity oxygen to the nanobubble tube.

| ID | Parameter | Guide Word | Cause | Consequence | Safeguards | Action | Comments | Responsible |
|----|-----------|------------|---|--|--|--|--|-------------|
| 20 | Flow | As well as | <ul style="list-style-type: none"> o Nitrogen exhaust | <ul style="list-style-type: none"> o N2 build-up in a confined space | | <ul style="list-style-type: none"> o Ensure Unit is installed in a well - ventilated space o Fix non-removable warning sign o Include safety warnings in Ops instructions o Physically ensure that external vent hose cannot be moved, re-positioned or blocked. | <ul style="list-style-type: none"> o "If the OG-15OG-20 unit is going to be set up in a room that is small, less than 28.3 m³, that room should be well ventilated; at least 5 air changes in the room per hour." Ref OG20 combined manual, p28, section 2. o For recommended number of air changes per hour v room volume, refer to OGS/ manual Appendix, viii | |
| 21 | Pressure | No | <ul style="list-style-type: none"> o Compressor failure o Blocked air intake o PRV stuck in the open position o Hoses disconnected o Pressure sensor malfunction | <ul style="list-style-type: none"> o O2 generator does not work o o o NBG will not run | <ul style="list-style-type: none"> o Maintenance schedule | | | |

HAZOP – Kauri Park NBG

Company : Nanobubble Agritech
 Facility : Kauri Park
 HAZOP date : 20.06.2022
 HAZOP leader : I. Gibson
 Project Manager : L. Powers
 Project Engineer : D. Ochiarenko

Node : **2**

Node Description : Air inlet to the Oxygen Generator, O₂ generator, O₂ lines to the injection point at the Nanobubble tube
 Design intent : To transfer high-purity oxygen to the nanobubble tube.

| ID | Parameter | Guide Word | Cause | Consequence | Safeguards | Action | Comments | Responsible |
|----|-------------|------------|--|---|---|--|--|-------------|
| 22 | | More | <ul style="list-style-type: none"> o Closed or restricted valve downstream o Water pressure too high o Rotameter needle valve shut | <ul style="list-style-type: none"> o Over-pressurisation causing leaks, or failure, of joints and connections. o No O₂ injection at NB tube | <ul style="list-style-type: none"> o Relief valve set to 3.8 bar | | | |
| 23 | | Less | <ul style="list-style-type: none"> o Compressor damage o Mol sieves restricted o O₂ leak in system | <ul style="list-style-type: none"> o O₂ generator does not work o Unable to achieve desired O₂ flow rate o O₂ build-up in a confined space | | | <ul style="list-style-type: none"> o Ref ID 20, 'Actions' and 'Comments' | |
| 24 | | Other | | | | | | |
| 25 | Temperature | More | <ul style="list-style-type: none"> o Ambient temperature changes | <ul style="list-style-type: none"> o Unit will under-perform or fail | | <ul style="list-style-type: none"> o Operating range: '4 to 27 oC. Ensure NBG is installed where temperatures will remain between 4 & 27 oC | <ul style="list-style-type: none"> o Ambient air supply: range 5 to 38 oC | |
| 26 | Temperature | More | <ul style="list-style-type: none"> o O₂ comes into contact with grease or oil o O₂ comes into contact with chemicals and fertilisers | <ul style="list-style-type: none"> o Fire and possible explosion | | <ul style="list-style-type: none"> o Labelling o Hazard awareness o Gas instructions to include this in the 'Safety section' | | |
| 27 | | Less | <ul style="list-style-type: none"> o Ambient temperature changes | | | <ul style="list-style-type: none"> o Operating range: '4 to 27 oC. Ensure NBG is installed where temperatures will remain between 4 & 27 oC | | |

HAZOP – Kauri Park NBG

Company : Nanobubble Agritech
 Facility : Kauri Park
 HAZOP date : 20/06/2022
 HAZOP leader : I Gibbon
 Project Manager : L. Poyers
 Project Engineer : D. O'Connell

Node : 2

Node Description : Air inlet to the Oxygen Generator, O₂ generator, O₂ lines to the injection point at the Nanobubble tube
Design Intent : To transfer high-purity oxygen to the nanobubble tube.

| ID | Parameter | Guide Word | Cause | Consequence | Safeguards | Action | Comments | Responsible |
|----|-----------|------------|--|--|--|---|----------|-------------|
| 28 | Level | | Not applicable | | | | | |
| 29 | Vibration | More | <ul style="list-style-type: none"> o Uneven surface o External vibration o Mechanical wear / damage | <ul style="list-style-type: none"> o Premature wear and failure | <ul style="list-style-type: none"> o Rubber mounted feet – factory option | <ul style="list-style-type: none"> o Confirm feet have rubber mounts o Check for local external vibration at installation site. | | |

8.7 Patent Application



<https://www.iponz.govt.nz>
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Summary of patent application

Date of summary: 27 January 2023
Application number: 795815
Case title: Nanobubble Generator
Applicant: NANOBUBBLE AGRITECH LIMITED
Flat 1, 110 Wairau Road
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New Zealand
Your reference: NAL001 / P14095NZ00
PCT number (if applicable):
Status: Filed
Traditional knowledge: No
NZ filing date: 27 January 2023
Patents Act: 2013
Convention priority details: No convention priority data or convention priority not applicable.
The specification filed with this application has been submitted to WIPO DAS.

END OF SUMMARY



New Zealand Government

“New Provisional Patent Application in New Zealand; Nanobubble Generator in the name of Nanobubble Agritech Limited. You should not claim to be the owner of a patent at this stage. Only when a patent is granted can you claim to be the owner of a patent and enforce it. (You should only refer to this application as a pending patent application, a suitable reference being: ‘NZ. Pat. Appln. No. 795815’ or ‘patent pending’.)”

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