University of Hertfordshire

School of Physics, Engineering and Computer Science

MSc by Research Project Report

Project Title:

Design and Optimisation of a Modular Industrial Air Scrubber Utilising Surfactant Absorption Technology

Submitted to the University of Hertfordshire in partial fulfilment of the requirement of the degree of MSc by Research

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1st February 2023

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DECLARATION STATEMENT

I certify that the work submitted is my own and that any material derived or quoted from the published or unpublished work of other persons has been duly acknowledged (ref. UPR AS/C/6.1, Appendix I, Section 2 – Section on cheating and plagiarism)

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ABSTRACT

A novel air scrubbing technology using a misting application and water additives has successfully demonstrated the capability of scrubbing H_2S at a water treatment plant. The air scrubber design utilises a solution of potable water and a water additive that exploits chemical surfactant technology as the scrubbing agent.

The air scrubber equipment is modular in design, so that its performance can be tailored to the application in the testing environment. The modularity aspect allows for customisation to benefit the technology in high and low pollutant concentrations and with a range of air volume flow rates. The design allows for retrofit in existing systems for air scrubbing, and can be used in series or parallel for increased flow rate and removal efficiency.

The technology of surfactant induced absorption with water is able to be studied by the ability to vary the water flow rate to a rotary atomiser, and alter the exposure time of water droplets to polluted air streams over a range of air flow rates, of 5 seconds exposure and above.

The testing site proved to be a challenging area to utilise for the research, with the fluctuating properties of the pollutant gas streams, the multiple gas species and by-products present, and changing environmental factors.

The first test results of air scrubbing was observed at an air flow rate of 1000 m^3 per hour, with 200 litres per hour of water and scrubbing additive at a concentration of 1.25%. The obtained absorption efficiency was 21.9%, where the polluted gas at the inlet had a concentration of H2S in excess of 2000 PPM.

Further tests of the air scrubber resulted in removal efficiency performances of 55% where the inlet H_2S concentration was at 500 PPM. The scrubbing additive was reduced to a 0.5% concentration into 200 litres per hour of water, and an air flow rate of 1000 m^3 per hour.

Despite the low H_2S removal efficiency calculated in the testing of the design, considerable efficiency gains can be made by optimising several features. These would include improvements in sealing joints between parts in the modular design, improving the atomisation method and reaction chamber to further prolong the water droplet lifespan increasing absorption capacity, and research and testing to the effects on surfactant additives and concentrations for increased absorption efficiency. This project has shown promising results, highlighted areas for further analysis, and testing should be performed to further validate the efficacy of the technology and the design.

ACKNOWLEDGEMENTS

This project could not have been complete without the support of my supervisors at University of Hertfordshire, staff at the company APPS UK Ltd, My family and friends. This project has demanded a lot of time and effort, and the difficulties in completing during difficult times through the COVID19 pandemic and while completing while in full time employment. The support around me has helped in the direction of the project and push my understanding of the project subject.

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GLOSSARY

OEM – Original Equipment Manufacturer

CAD – Computer Aided Design

CAE – Computer Aided Engineering

CMC – Critical Micelle Concentration

FEA – Finite Element Analysis

DFM – Design for Manufacture

DFA – Design for Assembly

FMEA – Failure Mode Effect Analysis

CHAPTER 1 - Introduction

1.1. Introduction Brief

There are many places of industry, enclosed inhabited buildings and agriculture in the world that demand clean air, although they can continually produce pollution in the form of airborne particulates, gasses, bacteria and viruses. Depending on the source of the pollution, being either organic or inorganic, some can have damaging effects to the environment, humans and living things. The pollutants can be odorous and toxic to life, which can aggravate and affect local inhabitants to the sites creating the pollution. (1-6) The risk of potential danger or public nuisance means there is a demand for air scrubbing technology, to remove these particles and gasses, before reintroducing the air into the environment or back into sites. (7-9,11)

Air Scrubbers are designed to remove microscopic particulates in the air and gasses, for the safe disposure as a waste stream. The polluting gasses in the air can be reacted with chemicals inside the air scrubber system to be neutralised and or separated for it to be removed from the atmosphere.

The design and selections of an air scrubber system can remove a virtually infinite number of different particles and gasses by using various filtration methods and technologies available. One or more air scrubbing units can be used in conjunction with several other air scrubbing units with differing technologies, to create an overall system that provides an efficiency of pollutant removal required for the application or problem. (4,8,12)

The air scrubbing technologies used in industry can often be of high expense in a number of ways, such as; for the hardware and infrastructure, the cost of operating the equipment including consumables, the maintenance and servicing, and the cost of disposing the collected waste material as trade effluent. All of these costs should be tried to be kept to a minimum as the customer aims to minimise process costs for equipment that is not going to be a revenue generating output in their manufacturing process.

This research project has been run in conjunction with APPS UK Ltd. and The University of Hertfordshire's School of Physics, Engineering and Computer Science, in a Knowledge Transfer Partnership with Innovate UK. The project has brought numerous benefits to the University and APPS UK Ltd.

1.2. Airborne Particulates

Particles that are small enough to be suspended in air are said to become airborne. The particulates that require removal come from a wide array of sources. Natural sources include dust, pollen, volcanic material, sea spray, and more. Most unnatural sources come from processes that have an anthropogenic impact on the environment which are generally particles emitted from the combustion of fossil fuels and other materials. Other unnatural sources are manmade which come from industrial processes, mining, biodegradation of materials, and more.

Particles can cause a health concern for humans and are most dangerous when the size of them are below 10 microns in size. (1-3) The main injury of particulates is in the respiratory system where, depending on particle shape and size, the immune defences are unable to reject material buried deep in the lungs and therefore causing harm. Particulate matter (PM) up to 2.5 microns (μm) in size are called fine particles, and others larger are called coarse particles.

Urban air pollution is caused mainly by the combustion of fossil fuels where the biggest current concern being the incomplete combustion and production of soot and PM2.5 produced by diesel emissions. (3,11)

The project is to utilise a chemical surfactant technology through testing which is used currently as an additive in misting systems to supress dust and odours. APPS UK Ltd. have a product that uses this technology, called Airborne 10, and it is the aim to use the technology as the scrubbing agent in the air scrubber design.

Several misting additive products are available on the market, whose ingredients consist of a blend of surfactants which clean the air through Surfactant Induced Absorption Technology (SIAT). The surfactant binds to a water molecule, a similar process to that as soap, and lowers the surface tension of water so that the absorption properties are greater than normal. (13)

The atomised water droplets are dispersed in the air and are small enough to be suspended in the air along with any dust or organic particulates. The high affinity of the droplet allows molecules to bind with it, and so becomes more concentrated. Any gasses will also be able to dissolve into the droplet, such as H_2S or CO_x or NO_x. When the droplet becomes dense enough due to the absorbed material, it drops out of suspension and falls to the ground, leaving much cleaner air behind. It is a fortunate effect for allergy and Asthma sufferers that the clean air won’t aggravate their conditions, as pollen and other particulates will also be removed.

Depending on the type of pollutant, as long as it has a low toxicity, the pollutant could be absorbed or digested by micro-bacterium in the surrounding area on the surface the mist droplet lands.

1.4. Project Overview

The research project is to design and test a new air scrubber utilising a surfactant to aid in the absorption of particulates and gases. The finished product must fulfil several aims and objectives to be considered a success, and the design process must follow a series of criteria.

1.4.1. Aims

The key aims of the project are to:

1. Design an effective air scrubber that uses Airborne 10 as the scrubbing agent while ensuring that the end design is realistic and can be manufactured.
2. Quantify the performance of the scrubber using theoretical modelling and analysis of experimental data.

1.4.2. Objectives

The objectives to complete the aims are to:

1. Research and review air scrubbing technologies for dust and odour pollution.
2. Utilise and apply a modularity design approach for the air scrubber’s component layout.
3. Use Computer Aided Design software to realise concepts and aid manufacture.
4. Utilise Computational Fluid Dynamics to test and inform on design performance.
5. Build the air scrubber prototype with in house tools and equipment available.
6. Test and record prototype performance on site.

1.5. Thesis Contents

The Introduction chapter has provided the background to the need for the research, explained the goal of the project and presented the aims and objectives. The thesis consists of 6 chapters in total. Chapter 1 – Introduction. Chapter 2 – Literature Review, and research as to what is currently out there in the world for air scrubber technology. Chapter 3 – Methodology, to understand what the requirements are for this project. Chapter 4 – Design, to look at the chosen concept air scrubber and the stages of manufacture. Chapter 5 – Testing and Results, to analyse the experimental testing and performance data. Chapter 6 – Conclusion, look to review all work carried out in the project, providing further dissection and further work to be carried out for future projects.

This project envisions a unique air scrubbing system with the potential to change and challenge future new build specifications for use in licenced industrial settings where treatment of dusts, odours and harmful pollutants is required. The technology could provide a new solution to the industry with a low energy and low cost running of equipment, with the potential for low toxicity effluent from the equipment depending on the pollutant being removed.

The final prototype will be tested and criticized for its benefits, and future works for improvements.

CHAPTER 2 – Literature Review

2.1. Literature Review Summary

The project will involve researching into all aspects of the air scrubber's operation so that each technology can be fully understood for the hope to optimise and maximise the scrubbing efficiency when in operation. This will include investigations of; the chemistry of pollutants that would be expected to be treated in everyday environments, the action of gas capture by misting droplets, the chemistry of scrubbing water enhancing additives, the technologies available in misting applications to perform the scrubbing action, and the technologies available to measure gas pollution concentrations. Although due to the infinitely complex nature of pollution and pollution abatement and capture, there are some elements that cannot be included in this review, however the main issues that will be relevant to the air scrubber are included in this chapter.

Within this chapter the selection of the best available technology will be done for the scrubbing additive to be used in the project.

2.2. Air Scrubber Technologies

There are many different types of technologies available to choose from in the air scrubbing industry, with each technology group having different methods to perform the air cleaning generation a range of efficiencies. The technologies vary from filters made of fine fibres or organic materials, biological organisms in a medium, or mixes of acid and alkali liquids reacted in vessels through polluted air flow streams. There are many benefits and disadvantages that come with each type of technology, and so the air scrubbing product should be chosen depending on what the pollutant is for each situation, and to limit and understand the negatives to the technology selected. (14)

Requirements for the selection of the best available technology should include;

- Having an optimised system to minimise the cost of consumables and operating cost of the machinery,
- Chemical selection for removing the pollutant so to avoid the need for secondary and tertiary reactions,
- The lifespan of the machinery, for prolonging the equipment life,
- The maintenance of the equipment, and service intervals,
- The machinery's efficiency of air scrubbing for the situation, to conform to gas and particulate emission regulations.

- The environmental impact from waste, power consumption, and unwanted output from running,
- The space required for the machinery and support equipment to be as minimal as possible.

When selecting and designing the infrastructure and plant equipment for abating the pollutant, a combination of technologies can also be used in series, to utilise the benefits of each and increase the overall efficiency of a system.

2.2.1. Mechanical Air Scrubbers

The dry bed air scrubber type is named as they do not require any reactants or reagents in liquid or gaseous form to remove pollutants. Primarily mechanical air separators are only used for solid pollutants, as they have low efficiency at filtering gasses. The removal and separation are generally performed by a mechanical means. Examples of mechanical air scrubbers are; electrostatic separators, gravity settlers, centrifugal separators, and filter bag separators.

Electrostatic separators operate through inducing a charge on particulates through high voltage equipment. The ionised particles are then able to be removed through magnetic attraction or repulsion, leaving a filtered air stream.

Gravity settlers are large container vessels which utilise gravity to take the entrained solid pollutant from the air stream, and the solid settles to the bottom to be collected.

Centrifugal separation is performed by forcing the polluted air through a cyclonic separator or other similar device. The airflow is made to pass at speed in a helical type pattern around a cylindrical container where the entry is tangential to the wall and exit in the container’s upper axis. The centrifugal forces on solids as they rotate around the walls of the container means that they collect and are not able to exit the outlet in the centre. The solids are then deposited at the bottom of the cyclone aided by gravity.

Filter Bag Separators are usually found as metal grids or fine meshes in the shape of a cylindrical bag. Polluted air would then be forced through these bags where solids would collect on the bag’s body, as the air gaps or holes are too small for solids to pass through. The bags will clog up and require regular maintenance for efficiency and performance.

2.2.2. Wet air scrubbers

Wet air scrubbers are so called as they use a liquid medium as a scrubbing agent, with chemical and non-chemical solutions such as strong or dilute acids and alkalis or use water with a chemical mix. The two main examples of wet air scrubbers are Packed Bed scrubbers and Venturi scrubbers. The polluted air streams will enter a reactor vessel and be forced to flow through the fluid to exit. The vessel will be continually fed with a recirculated scrubbing fluid stream to continue the process. The vessel is usually full of a packing material designed specifically for increasing turbulence for the air stream so to make smaller bubbles and maximise the surface area for scrubbing reactions to work. The scrubbing liquid can be treated through part of a recirculation cycle, so that the performance of the system is within a desired range.

Venturi air scrubbers work by forcing the polluted air through a Venturi throat along with the scrubbing liquid. The Venturi throat is shaped to increase the air flow speed and lower the pressure through the small opening. This makes the liquid mix with the air in a very turbulent fashion, breaking up the liquid into small droplets and increasing the surface area for scrubbing absorbance. The air can then be removed from the scrubbing vessel. A diagram of a Venturi and Packed Bed Scrubber can be seen in Figure 2-1.

This mixing happens quite quickly, and for the reacted air to exit it must then be separated from the liquid or dried. A packed bed separator is quite common to be used for this process and is part of the diagram for the Venturi Scrubber in Figure 2-1.

The drying of the air is important as the pollutants should be captured by the scrubbing fluid. If the fluid were to leave with the treated air, then there is a high chance for the air to be polluted again or reintroduce a new pollutant that of the scrubbing liquid.

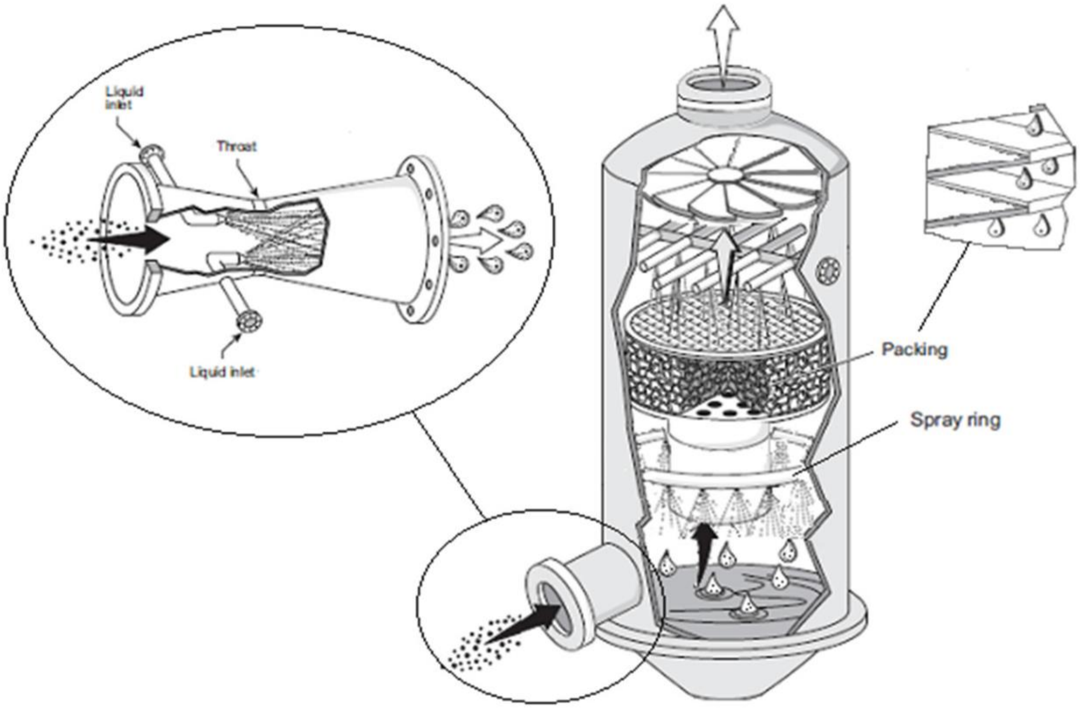


Figure 2-1 Venturi and packed bed air scrubber (11)

2.2.3. Dry Air Scrubbers

Dry air scrubbers are a technology very similar to wet air scrubbers however they are more primarily used for air streams of a higher temperature, such as metal refineries or power generation. These air scrubbers utilise bespoke chemical reagents to react with the specific pollutants in the air stream, which can be solid particles or gaseous.

2.2.4. Biological air scrubbers

A Bio-filter can be used as an air scrubber, where a polluted air stream is made to pass through a container housing a live cultivation of appropriately selected bacteria to digest the pollutant, leaving clean unpolluted air to the atmosphere. The pollution must be of a gaseous nature as solids are not as easy to remove in this method. The bacteria in the vessel are held generally in a soil substrate where they are continually fed food via the pollutant, water, and warmth to keep the colony alive. Regular monitoring and maintenance are required as if the bacterial colony were to die, a new one would have to be introduced which would involve the replacement of the soil substrate.

Figure 2-2 shows how similar a Bio-Scrubber can compare to a wet scrubber, however the scrubbing media is a porous solid mix of media. The diagram references two types of bacteria; Heterotrophic and Autotrophic. The selection of bacteria to introduce should be done specifically to what the pollutant is and what other composition of gasses are within the air to be treated, in order to make the process as efficient as possible and for maximising the longevity of the bacteria. The Autotrophic Bacteria is a family whereby they can generate their own food from carbon and organic compounds in the air. Heterotrophic bacteria are a family whereby they digest other living bacteria.

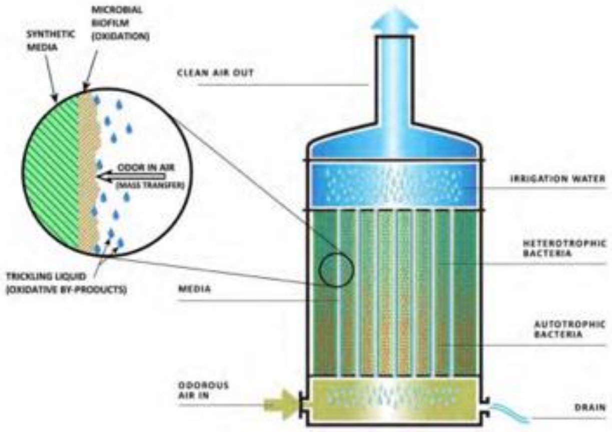


Figure 2-2 Schematic presentation of the operation of a bio-trickling filter (12)

2.2.5. Activated Carbon

The activated carbon filters are formed pellets of burnt wood resembling charcoal consistency. The common wood used is coconut shells for its resulting properties in this application. The microstructure of activated carbon has a vast number of fissures, fractures, and a very low density, which means there is a very high surface area to weight ratio with the material. The benefit of this is that very small solids are able to enter the microstructure and get trapped inside. The chemistry of the carbon with it having gone through partial combustion means that chemically it is relatively reactive, and therefore can chemically bond to organic gasses and solids that it contacts with. This means that the activated carbon acts as a very porous but efficient filter for solid matter and gasses.

These air scrubbers can be stand-alone units, or in an industrial setting, are used in series with other scrubber technologies. The activated carbon granules to be effective are packed tightly a container so that air must be forced to go through it. These containers are commonly seen as a removable cartridge design, or either a packed bed column for a more continuous flow situation.

The problem of these filters, biological agents and chemical mixes is that they carry a high expense, require regular replacement, and can have a damaging effect on the environment or carry a high cost for disposal of waste. An example of which is a packed bed scrubber where the packing material will require regular replacement after removing contaminants.

The difference to other air scrubbers for this project, is that the surfactant water solution mix is the scrubbing agent and so no filters or bio-matter will be required in the process. The mix of particulates and gasses trapped in the water droplets will be collected and sent for treatment. Depending on what is the contaminant being removed from dirty air is, the waste can be sent for disposal on; green belt lands, fields, sewage treatment plants, or chemical disposal.

2.3. Misting Technology

Misting Technology can be used as a highly effective, versatile, low-cost method for dust and odour abatement, along with being good for humidification and cooling applications. (15,16) The technology used in air scrubbing can be categorised as a type of wet scrubber due to a liquid being involved to clean a volume of air. Some air pollution abatement companies have built products using water based misting systems as suppressive instruments tailored to serve in multi-purpose portable situations. There are several suppliers in the UK and many more internationally providing products with misting as the method of abating dust and odour. Each company also supply their own water additives to improve the effectiveness of the product.

Mists are created by using atomisation equipment, either through mechanical or high pressure driven methods to break a volume of liquid down into a very high number of droplets, resulting in an extreme increase in surface area of the liquid. The benefit to this is that the greater the surface area is the more the liquid is in contact with the surrounding air which allows for increased scrubbing potential.

For example; a 1 ml sphere of water has a surface area of 4.836 x 10^{-4} m^2, whereas if the same volume was atomised into 40-micron diameter droplets the resulting surface area of all droplets would be 0.150 m^2, an increase of 31000 %. In total, the 1ml volume of water would produce 29 million 40-micron droplets, allowing a very large coverage in a volume of space.

The Figure 2-3 shows how by breaking a volume of liquid into smaller droplets creates an increase in total surface area. The two relationships show an exponential distribution as the smaller the droplet diameter the more droplets are created, and overall surface area increases. The graph is referenced from a volume of 1 ml.

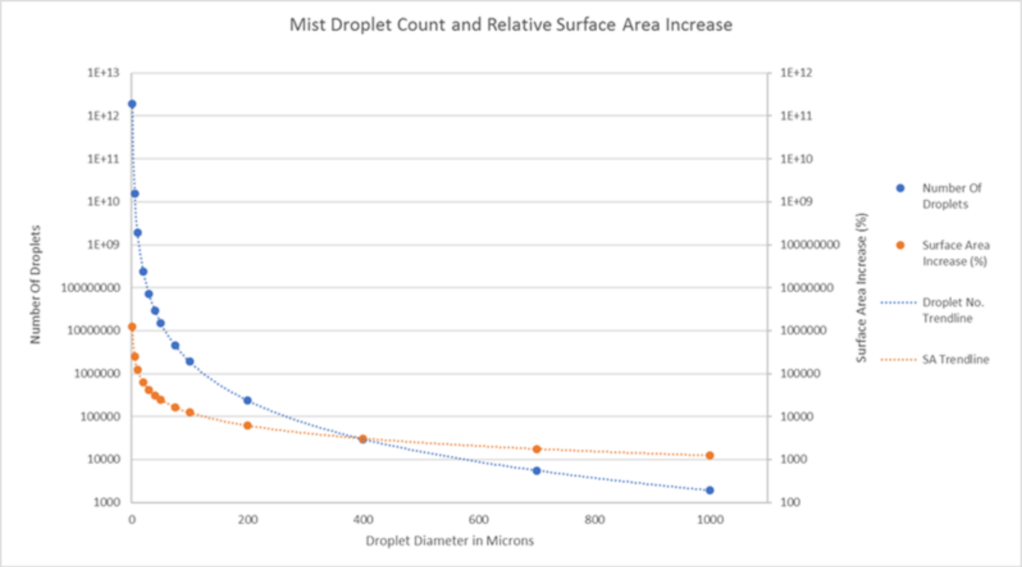


Figure 2-3 Mist droplet count and relative surface area increase

Misting technology is used similarly to how other wet scrubbers work such as spray towers or Venturi scrubbers, however the way the technology differs brings several other advantages and disadvantages due to how small the diameter the mist droplet is.

As shown previously by having smaller more numerous droplets a liquid is greater spread out in a volume of space which should increase the likelihood that a pollutant can be contacted by a mist droplet, and therefore you should have a more efficient pollution removal system.

An adverse effect to having a large surface area is that the mist droplets have an increased contact with the air and depending on the humidity and temperature of the surroundings, this will influence the lifetime of the droplet leading to a short life due to evaporation. Evaporation of droplets will be of severe detriment to air scrubbing as then a captured pollutant could be re-released to the air.

A disadvantage to using wet scrubbing is that mist eliminators or entrainment separators are often used to remove the additional moisture from the outlet air flows. Misting technology uses a much finer droplet size and therefore an increased entrainment of mist is to be expected and therefore more advanced mist eliminators should be incorporated, adding on more disadvantages such as increased pressure drop and power usage.

Some air pollution abatement companies are offering products that utilise misting technology to provide solutions for air scrubbing of gas and dust pollution. The technology allows for the design of products that are portable and versatile for situations where fixed units are not possible or not suitable.

The application for these misting products are to remove gas and dust pollution in wide uncontained areas such as outside or an open warehouse, where a negative pressure system is not feasible to trap and treat the pollutants. The application is to project a mist into suspension into the polluted air stream where the mist will over time contact the pollutant and remove it from the air, leaving unpolluted air with mist droplets carrying the pollutant. The mist droplets can coalesce given time and fall out of suspension bringing the pollutant to the ground.

The main applications that misting products are being used are in sewage treatment works and waste transfer sites, where a considerable amount of pollution is released in the form of volatile gasses and particulates. These places are often situated nearby populated areas and so companies must ensure that pollution consent levels and public complaints are kept as low as possible to avoid fines and criminal prosecution.

2.4. Pollutants

Odour and dust control companies serve the air cleaning market when an induction air scrubber, or an air scrubber where air is mechanically drawn through a cleaning system, cannot be used effectively to remove air pollutants. Examples of these situations are generally in areas of open spaces such as warehouses, uncovered collection chambers and open roads.

The most common treated pollutants by suppression technologies are;

- Dusts consisting of silica, biological detritus, inorganic solids, etc.
- Toxic and volatile gasses with species having odorous and non-odorous properties.

The pollutants can be split into two categories for discussion, dust and gasses, as there is a difference as to the mechanism of removal through misting technology.

Dusts are generally minute particles broken from a larger solid that can be suspended in air for extended periods of time through having a density close to that of air. Dusts are more commonly found to be silica particulates, biological detritus, or inorganic solids, although the compositions can be infinitely complex depending on the source.

The mechanism to capture dusts is through surface wetting, where mist droplets will accumulate onto the surface of the particle until together the solid gains enough density to come out of suspension, i.e. be heavier than air and then fall by gravity.

Pollutant gasses can be of an infinite number of forms but can be described as very generally anything that is in a higher concentration than that is usually observed in fresh air. The gas mixture in air is commonly found to be 78% Nitrogen, 21% Oxygen, and 1% other gasses (17).

Some gasses can have properties giving it an odour to humans and animals being a nuisance over time while gasses can even be harmful or toxic in certain concentrations and therefore need to be removed before it’s capable of causing damage through inhalation or contact.

Odours can be detectable in some cases in very small levels of concentration. Fowl smelling gasses can have an immediate effect in the very small concentrations over a short term or even a long term by having fowl smelling or even sweet smelling.

Gasses, similar to dusts, can only be absorbed when physically contacted with a mist droplet. The absorption of a gas molecule into water is perhaps more complex as there is an interaction between molecular charges due to the bi-polar nature of water.

A water molecule is made of one Oxygen and two Hydrogen atoms bonded through a process of electron donation called ‘Ionic Bonding’. An Ionic Bond inherently means that there is a residual charge within the molecule due to how electrons are distributed, Oxygen has a permanent negative charge and Hydrogen has a Permanent Positive charge.

Gasses with molecular charges can be seen to be quite reactive as they are more chemically unstable and interact closer than non-polar molecules, and most polluting gasses have this property. They interact with each other quite readily behaving very similarly to the way magnets do with polar properties. This is the reason that water is a very good solvent for these polar molecules as the charges quickly dissociate and dilute into the solution. Nitrogen gas and Oxygen gas molecules have neutral charge.

Figure 2-4 compares the solubility of various gasses in water. The chemical relationship of each gas species can be explained as the most solute gas has the smallest molecular size and greater interaction of charge making it easier to dissociate or mix into solution. Ammonia is one of the most solute gasses due to it comprising of one Nitrogen atom and 4 Hydrogen atoms bonding in a relatively small molecule with a polar positive charge of 4.

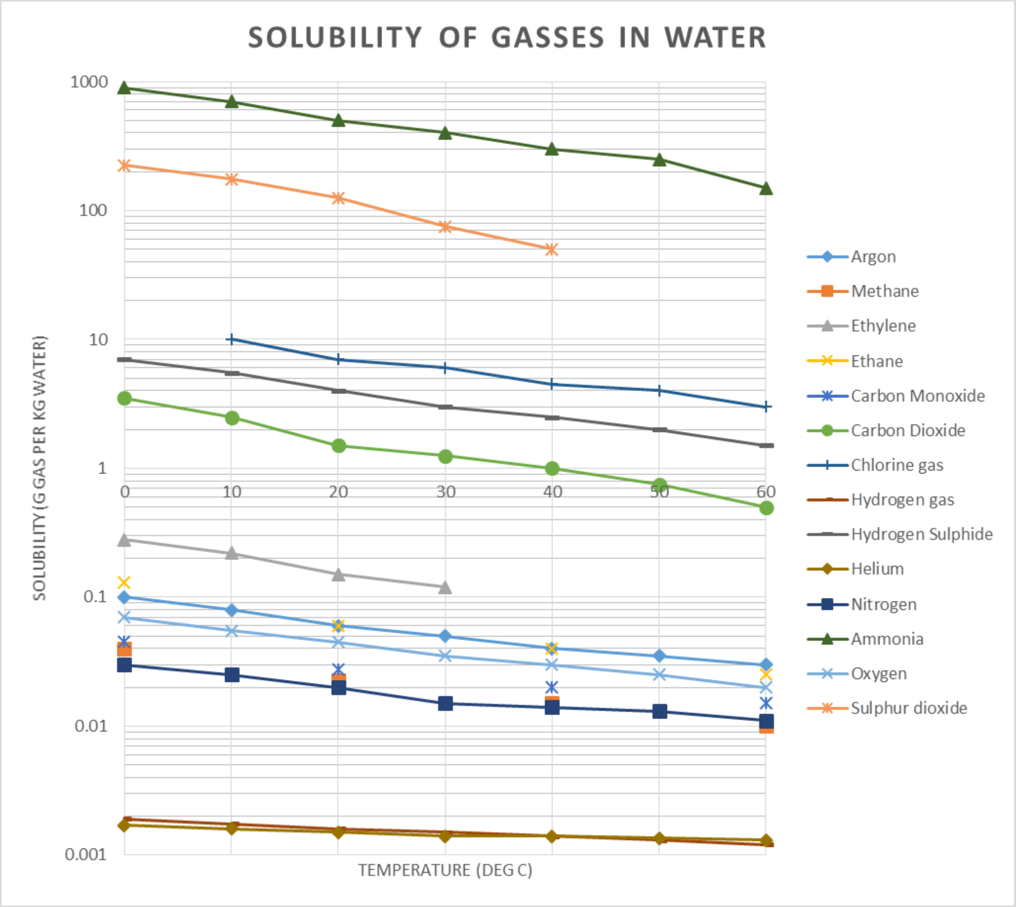


Figure 2-4 Solubility of gasses in water with temperature (18)

2.5. Enhancing Misting Technology

Air scrubbing companies are engineering and manufacturing chemical additives with the aim to maximise the air scrubbing efficiency of the misting technology by dosing the chemical into the water mist to create a more effective scrubbing liquid. Each company has branded their own bespoke chemical water additives to perform the objective. There are two distinct groups for these additives which are Surfactants and Essential Oils.

2.5.1. Surfactants

A Surfactant (Surface Active Agent) is a molecule manufactured through the process of saponification and is the main constituent of soaps. A surfactant can be one of 4 forms; Non-Ionic, Anionic, Cationic, and Amphoteric, where a representation of them can be seen in the below image respectively. Each form has a different active functional group on the hydrophilic end of the molecule which will have different benefits. Figure 2-5 shows simplified models of different surfactants.

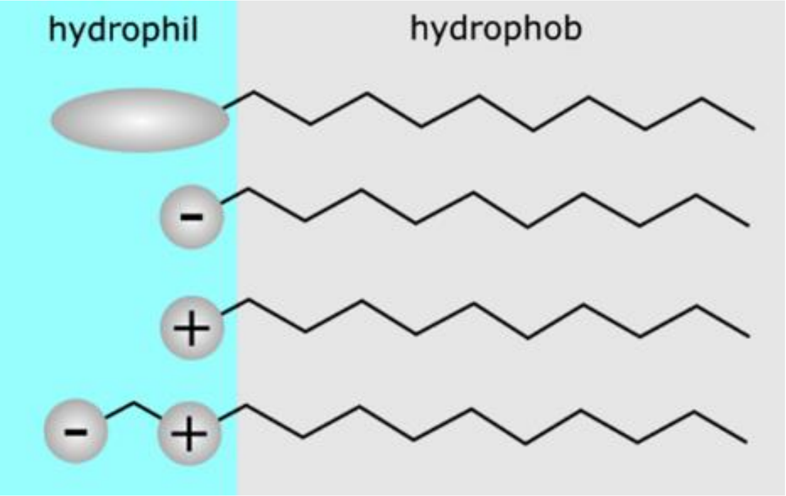


Figure 2-5 Four variations of surfactant types (19)

The hydrophobic group is usually a long chain hydrocarbon radical. This is the functional end of the surfactant that performs the greatest adsorption as the long chain has greater interaction with pollutant molecules and can bind with them through weak intermolecular forces called Van Der Waals. The group itself is not polar and therefore does not mix with water hence being called Hydrophobic (Water hating).

The hydrophilic group carries a charge through the separation of a metal atom or group usually Sodium or Potassium. This charge permits the whole molecule to interact and mix with water molecules. If the pollutant is also polar there may be some interaction with the Hydrophilic end of the surfactant and therefore this will increase the absorption probability. The chemistry of how effective each type of surfactant is not discussed in this paper however it is to be understood of the mechanism how surfactants operate to aid as a scrubbing chemical.

The correct concentration of how much surfactant to dose into water before misting is one that should be thought of carefully, as the expense for using consumables when operating equipment is the main cost throughout the product life. The most efficient proportions of water and surfactant should be used for the optimum air scrubbing efficacy in the polluted environment. It is therefore important to understand how surfactants interact with water in a solution to achieve the best efficiency using concentrations of a particular surfactant for the levels and type of pollution to be treated.

By adding surfactants to water, misting companies can improve the effectiveness of particulate absorption through increasing the wettability of water by reducing water's surface tension. This means that the mist will be able to coalesce onto particulates more easily and therefore collect a higher percentage of pollutants present.

The illustration in figure 2-6 shows the relationship and effect on water's surface tension by increasing surfactant concentration. The trend is such that as a surfactant is added to water the surfactant molecules will act on the air water boundary or surface of the water, as the hydrophobic group wishes to remain outside the water layer. The presence of the surfactant on the water's surface breaks down the surface tension and reduces it further as the surfactant concentration increases.

As the surfactant concentration increases, the surface tension reaches a minimum value called the Critical Micelle Concentration (CMC), where the surface of water has become saturated with a maximum possible density of surfactant. Micelles are then formed within the water layer which are collections of surfactant molecules joined up into balls oriented so that the ball surface has hydrophilic ends and hydrophobic ends avoid contact with water by facing the centre.

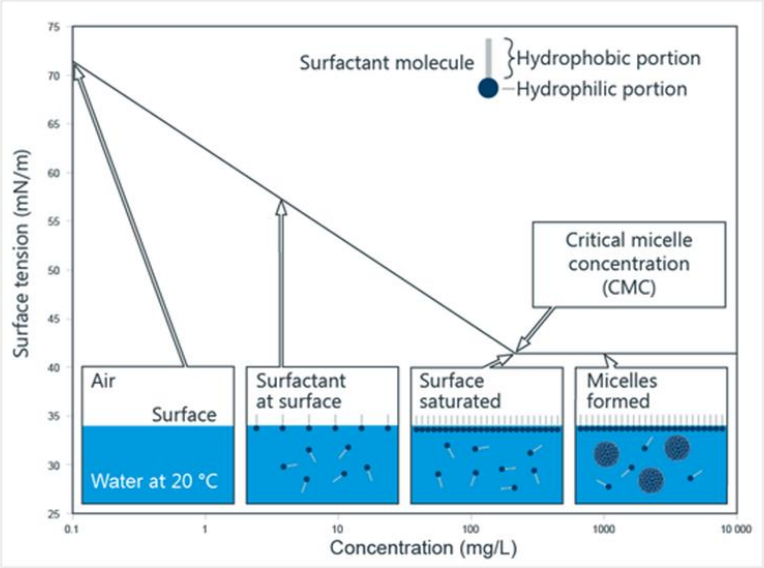


Figure 2-6 Surface tension of water with surfactant concentration (20)

For maximum effective air scrubbing using this absorption method, a good concentration should be near the CMC point, as if the concentration is any more there is no added benefit to increased absorption or lower surface tension at the boundary layer due to formations of Micelles. A higher concentration could waste money on chemical usage for then some surfactant would not be active in the absorption process. (21)

2.5.2. Essential Oils

Essential oils are a group of molecules that are artificially manufactured or extracted from plants through various methods. Essential oils consist of volatile hydrophobic molecules that dilute into the air readily through evaporation. These molecules consist of a long hydrophobic group and are formed of many different chemical arrangements. The elements within essential oils are generally Carbon, Hydrogen and Oxygen and so are of a chemical family of Organic chemistry.

The essential oil is generally a non-ionic molecule depending on internal functional groups, and therefore they are not readily miscible in water, therefore carrier oils or emulsifiers are used in a solution to permit the mixing of chemicals so that it doesn’t separate in storage.

Essential oils are generally odour carrying molecules as they give off a strong scent when detected by olfactory senses. The ability for absorption of gasses and particles in misting solutions may be limited as they function more for masking odour by overpowering the nuisance odour. However, in essential oil products other additives are used for enhancing the gas and particulate capture in misting applications, therefore these additives can be performing the main roles, generally consisting of surfactant molecules.

2.6. Pollutant Absorption in Mist

As the solid or gaseous pollutant is in suspension in the air, the mist droplets must come into contact to it for removal, similar to any other method of filtration. The method that mist droplets intercept gasses and particulates is done through several well understood means which are common to other pollution abatement technologies. In pollution abatement the pollutant must be brought into physical contact with the filter so that it is removed from air, which is the mist droplet in this case. Figure 2-7 shows several methods of capturing a particulate for filter media which is comparable for water droplets and particle collisions.

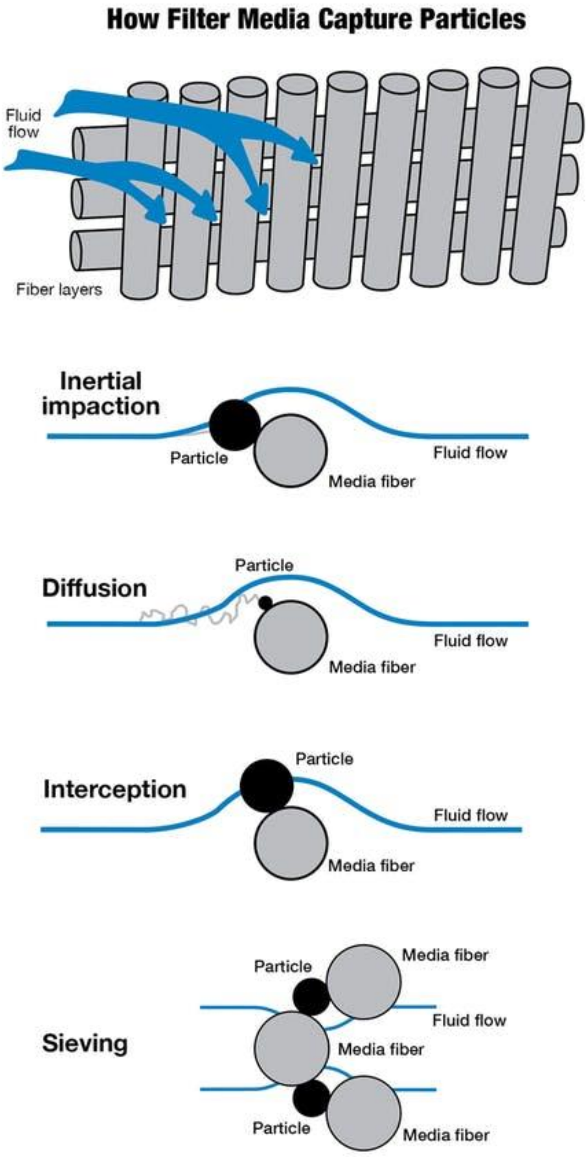


Figure 2-7 Various methods of particle capture (22)

The water droplet is the physical filter for the pollutant in a misting system which has some caveats to the technology. To maximise the pollutant removal potential the mist should be high in density and remain within the polluted air stream for as long as possible. Unfortunately the mist has a short limited life span due to environmental conditions and gravity bringing the droplet to the ground, therefore the droplets are constantly required to be recreated through atomisation equipment.

The time that the mist has in contact with a proportion of polluted air is called the ‘retention time’, and so this should be maximised as much as possible for maximum removal efficiency.

The density of the mist cloud should be analysed as if the cloud is more intense than what is required for the pollutant, then there is the potential for the excessive use of water and chemical. In contrast if there is not a dense enough mist cloud then the pollutant will have more probability to evade mist droplets and not be captured by the fore mentioned methods of capture.

Due to the size of water droplets in mist, they are also susceptible to evaporation because of the increased surface are to volume ratio. Some proportion of mist is evaporated however this is dependent on the humidity of the polluted air stream, as a dry air will mean a higher level of evaporation than that of a humid environment. (23,24)

2.7. Atomization Methods

There are many different methods and equipment available to generate a mist for air scrubbing applications, which are tailored and used to the best efficiency as possible by air pollution suppression companies.

There are two main categories for mist creation, and that is through ‘Impingement’ and ‘Mechanical’ means, both of which are in common use today.

2.7.1. Impingement

Impingement is a relatively cheap and very common method of generating a mist as it utilises the pressure of the delivery system to give the energy to break up the liquid. The application uses either the liquid’s own pressure or an additional air pressure to give the liquid a high amount of energy before being forced onto a hard, non-tangential surface. This in effect puts the liquid into a comparative high-speed impact and explosion giving the liquid enough energy to overcome its surface tension and break up into small droplets, therefore producing a mist.

Countless spray nozzle products are available on the market which vary on type and differing spray patterns. Examples of some atomisation nozzles that use liquid pressure alone are; Flat

Deflection Fan nozzles, Impingement Misting Nozzles, Hollow and Full Cone nozzles, and Straight Jet nozzles.

Nozzles that use additional air pressure to atomise liquids are called twin fluid atomising nozzles and come in a range of styles to offer the best misting pattern, similar to those that don’t use air. The benefit to using twin fluid or air assisting nozzles is that the misting pattern can be tailored more freely to create finer mists, more control of mist pattern shapes, and project the mist a further distance.

There are some potential issues with using pressure driven atomisers as if the distribution of the mist or the size of the mist is a requirement, some systems may not be able to provide the requirements through this method as the droplets may not be uniform in size.

2.7.2. Mechanical

Mechanical methods use usually an electrical supply to provide energy to break up a liquid into mist. The most common application in air pollution suppression products use rotational power from a motor, although smaller more home use applications can use ultra-sonic vibrations to generate mists.

Rotational mechanical atomisers are called Rotary Atomisers in industry, where the liquid is sent to pass through a surface that is made to spin several times per second. The action of rotation generates a centrifugal force on the liquid that forces it to pass through a small orifice. This then creates the required energy to liberate small mist droplets from the atomiser.

The benefit to this atomisation method is the size of the unit can be varied and the volume of liquid passing though can be several magnitudes higher than nozzles. The rotational method also gives the mist a greater uniformity of mist droplet size due to how regular the orifice is shaped on the surface. The units are generally relatively efficient with power usage as motor technology is at a peak of efficiency.

Air Pollution suppression companies use several of the discussed atomization technologies in their products. The decision of which one to use generally comes down to cost, level of pollution, versatility and suitability.

2.8. Gas Sensing Equipment

There are many different gas sensing technologies on the market, and selection of technology should be dependent on the application and environment of the situation, such as; if the monitoring is to be continuous or performed by hand, the gas constituents, concentration level of the gas species, and the required accuracy and precision of the measurement.

If a user wanted to measure a gas emission as a one off for experiment or on an isolated or difficult to access site far from a building, a gas sample measurement could be taken that could be taken back to a lab for further study later on. These samples could be taken in vials or bottles with some sorbent material that would keep the sample stable. Examples of these could be ‘Gresham Tubes’, ‘FlexFoils’, or ‘Tedlar Bags’, which then need further work done to achieve a sample reading through technologies such as mass spectroscopy.

Electro-chemical technologies are very popular due to how they are easily accessible due to the simple design and quick result that they give to the user, though a compact portable device. An electro-chemical cell is designed to generate an electrical potential difference when introduced to a specific gas, and the voltage is read to give a gas concentration reading. The gas sensors are designed specifically to measure one gas species due to the chemical reaction taking place within it, and so each monitoring station should be used with one or more sensors to fully analyse the constituents of the air being tested. Electro-chemical sensors are commonly found in personal protection devices, and so the main gasses sampled are ones that the user is known to be coming into contact with on the specific site and are monitored to alert in case of gas emissions becoming unsafe to the user, such as; Oxygen levels depleting in an area devoid of oxygen such as enclosed spaces, Ammonia levels on sites where there is biological activity such as composting, or Hydrogen Sulphide which can be toxic in low concentrations and is found commonly in anaerobic environments promoting septicity such as sewers.

Olfactory sense is another measurement that can be used, by using a person’s or other animal’s nose, however it can only be used for select scenarios due to the few people with the ability and skill to quantify to a high accuracy and precision for gas concentrations. The olfactory is commonly used in humans for detecting odours in food manufacture or the perfume industry. Animals such as canines can be trained to use their olfactory sense for assisting humans in situations such as; detecting controlled substances and chemicals, or in search and rescue from disaster relief.

2.9. Literature Review Conclusion

The main aspects of the air scrubber have been discussed in the literature review, for to research for the best available technology for all aspects of the air scrubber. The misting technology has been discussed for its benefits for the application. The different pollutants types that an air scrubber could encounter and be required to clean has been investigated. The methods of how chemicals can be used to enhance water's ability to be used as a scrubbing media has been discussed. The different interactions that a water droplet can have with a pollutant to make absorption successful has been researched. Different atomisation methods has been investigated to understand a best approach to generate an optimised water droplet for an application. The gas sensing technologies has been researched for to choose the best method of quantifying scrubber performance.

CHAPTER 3 - Methodology

3.1. Design Brief, Methodology & CFD Design Validation Summary

This chapter looks at the process of designing the modular air scrubber with the aim to validate the finalised design, by:

- Evaluating past designs
- Performing calculations using advanced Excel spreadsheets for sizing the chamber volumes
- Conducting Computational Fluid Dynamics simulations to inform further CAD designs

3.2. Past Prototype Design

A prototype prior to the start of the project was invented, and shown in Figure 3-1. The evaluation of the design was required in this project to understand how the application of surfactant scrubbing technology could be used effectively for use as a contained air scrubbing unit. A detailed evaluation of the design is captured within the Appendix, which includes; an overview of the constituent parts and functions, a CFD analysis of the design, and the results of the testing performed on the unit.

Figure 3-1 Air scrubber prototype

The essence of the mechanics for the unit to scrub the air is shown in Figure 3-2. The operation can be broken down into 4 main sections; at (a) the water and Airborne 10 is mixed together in a water powered dosing pump, at (b) the scrubbing container is where the scrubbing solution is atomised and introduced into the dirty air within a container, at (c) the scrubbing solution now with absorbed pollutants are removed from the treated air by a demisting element, and (d) is the impellor whose purpose is to drive the flow of air through the system.

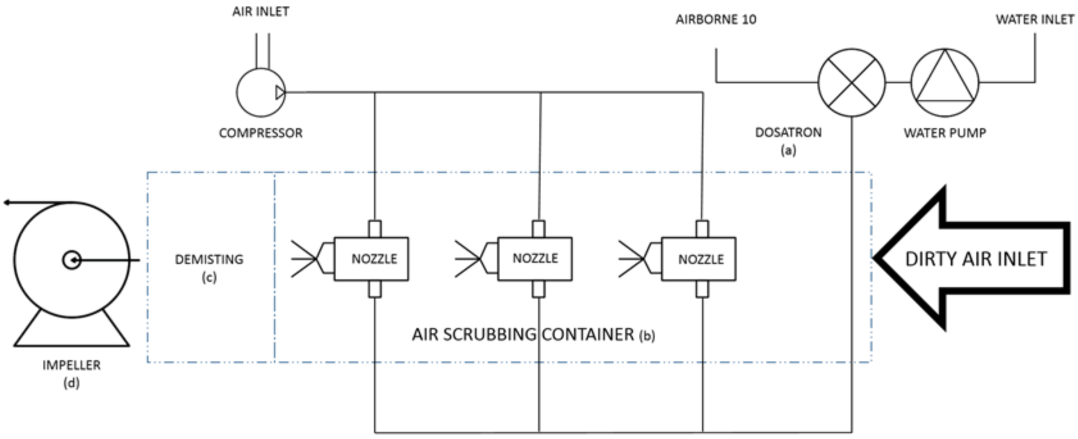


Figure 3-2 Schematic of prototype scrubber function

The modularity of this design is possible by having multiple configurations of multiple units connected in parallel, shown in Figure 3-3 (c) and (d), thereby allowing the scalability to whatever the situation requires. The design also gives the potential for recirculation of air, shown in the figure (a) and (b), if there is an environmental or financial benefit to do so, such as temperature regulation.

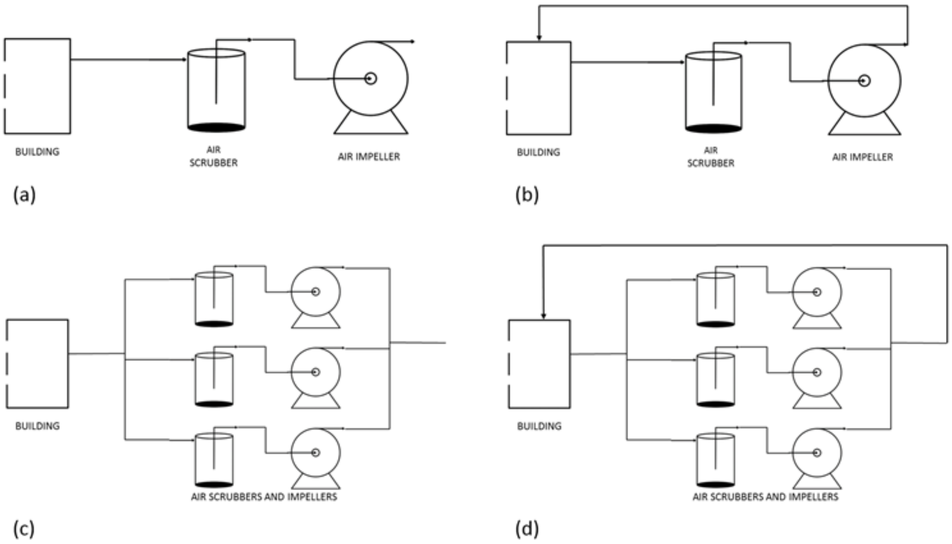


Figure 3-3 Scrubber configurations available

There was a significant amount of testing done with this prototype, and several CFD simulations were performed to analyse the design's performance. The design showed that there was a significant pressure loss through the system, which is not desired as this would mean the machinery to drive airflow through the system would have to be more powerful to get the required flow rates.

The prototype can drive a volume flow rate of either 100m^3/h or 1000m^3/h, which is a relatively low throughput compared to industrial air scrubbers on the market. The next generation air scrubber would have to be able to cope with a higher volume flow rate, closer to what systems are capable of in the project's market research.

3.3. Prototype Sizing

The main design requirement of the air scrubber is for it to be optimised to operate with misting technology within it. The limitation with misting technology is that the efficiency of air scrubbing relates to the retention time of the air in contact to the mist, and so for high volume flow rates large container volumes would be required to have a long retention time.

After design consultations with the research team, a suggested minimum retention time within the air scrubber should be 5 seconds for lightly polluted air. Data could not be provided to prove this duration of retention time as testing like this had not been performed in the past, therefore a trial and error method would have to be adopted for the future of the project.

Air volume throughputs for air scrubbers can be capable of cleaning 100,000 m^3/h of air and more, and the challenge was to determine if this volume could be pragmatically achieved. A design review was undertaken to investigate how big a unit would have to be to cope with this demand. The Table 3-1 and Table 3-2 show the result of this investigation, how big the unit should be for various throughputs of air flow rates.

The values and the contour table (Table 3-1) have been produced with conditional formatting and colour scales in Excel. Values in green indicate which chamber volumes will give a retention time of 5 seconds or more with a varying volume flow rate. The retention times have been calculated by dividing the flow rate in m^3 per second by the scrubber chamber volume in m^3. This indicates how long it would take the air to pass through a chamber of that size with the flow rate.

Table 3-1 Air retention time within various chamber volumes and flow rates

			Scrubber Chamber Volume (m^3)										
	Flow Rates m3/h	**Flow Rate m3/s**	**Retention Time (s)**										
			0.50	**0.62**	**1.00**	**2.50**	**5.00**	**10.00**	**20.00**	**50.00**	**100.00**	**200.00**	**300.00**
	50	0.01	36.00	44.64	72.00	180.00	360.00	720.00	1440.00	3600.00	7200.00	14400.00	21600.00
1st Gen Scrubber	100	0.03	18.00	22.32	36.00	90.00	180.00	360.00	720.00	1800.00	3600.00	7200.00	10800.00
	1000	0.28	1.80	2.23	3.60	9.00	18.00	36.00	72.00	180.00	360.00	720.00	1080.00
	10000	2.78	0.18	0.22	0.36	0.90	1.80	3.60	7.20	18.00	36.00	72.00	108.00
	20000	5.56	0.09	0.11	0.18	0.45	0.90	1.80	3.60	9.00	18.00	36.00	54.00
	60000	16.67	0.03	0.04	0.06	0.15	0.30	0.60	1.20	3.00	6.00	12.00	18.00
	80000	22.22	0.02	0.03	0.05	0.11	0.23	0.45	0.90	2.25	4.50	9.00	13.50
	100000	27.78	0.02	0.02	0.04	0.09	0.18	0.36	0.72	1.80	3.60	7.20	10.80
				1st Gen Scrubber									

Table 3-2 Cylindrical chamber volumes with varying diameters and heights

		Chamber Volume (m3)										
		Cylinder Diameter (m)										
		0.80	**1.00**	**1.25**	**1.50**	**2.00**	**2.50**	**3.00**	**3.50**	**4.00**	**4.50**	**5.00**
Height (m)	**1.0**	0.50	0.79	1.23	1.77	3.14	4.91	7.07	9.62	12.57	15.90	19.63
	1.5	0.75	1.18	1.84	2.65	4.71	7.36	10.60	14.43	18.85	23.86	29.45
	2.0	1.01	1.57	2.45	3.53	6.28	9.82	14.14	19.24	25.13	31.81	39.27
	2.5	1.26	1.96	3.07	4.42	7.85	12.27	17.67	24.05	31.42	39.76	49.09
	3.0	1.51	2.36	3.68	5.30	9.42	14.73	21.21	28.86	37.70	47.71	58.90
	4.0	2.01	3.14	4.91	7.07	12.57	19.63	28.27	38.48	50.26	63.62	78.54
	5.0	2.51	3.93	6.14	8.84	15.71	24.54	35.34	48.10	62.83	79.52	98.17
	7.5	3.77	5.89	9.20	13.25	23.56	36.81	53.01	72.16	94.25	119.28	147.26
	10.0	5.03	7.85	12.27	17.67	31.42	49.09	70.68	96.21	125.66	159.04	196.34

Table 3-1 shows the resulting retention time in seconds that the air would take to pass through a chamber of increasing volumes and increasing air flow rates. The parameters of the first scrubber design is highlighted in the table, where the volume of the chamber was situated low in both flow rate and volume. The table highlights how big a scrubber must be built to achieve a large enough volume to give over a 5 second retention time for high volume flow rates. For example, a scrubber to deal with a flow rate of 60,000 m^3/h would have to be 100 m^3 which is equivalent to three 20’ dry shipping containers. The scale of volumetric space required for this meant that there was going to have to be a limit on how big the air scrubber could be for the prototype build. Therefore the selection should be greater than 5 seconds but no more than the 100 seconds region of the table.

Thorough discussions with the project team took place so that the design parameters could be re-established. A number of calculations and graphs was created to help determine a volume flow rate that could be realistically achieved by manufacturing a unit to work together with misting technology, and to conform to the restrictions on physical size. This therefore was understood as a major limitation to the technology as the size of the unit would have to be limited limiting the potential market opportunities.

In keeping with the plan to scale up of the past prototype design, a new design would take on the cylindrical shape to create the volume required. Table 3-2 was drawn up to establish the relationship between the volume of a cylinder and the diameters and heights. The smallest unit as highlighted in green is of the first prototype.

To narrow down the dimensions the air scrubber should take, practical dimensions of possible diameters and heights were discussed.

The scrubber diameter brought a concern for when a completed unit may be transported by road, as if the diameter was too large costly specialist vehicles and transport restrictions may be limiting to the design. Therefore, so that the unit is not too big to move, research into transport capabilities of road vehicles such as a flat-bed lorry was done. The research showed that the width of these vehicles were around 2.5 metres, and therefore the diameter of the chamber should be below that.

The physical height of a scrubbing unit would have been a concern for the design, as if the unit was too tall it could be unstable and topple being top heavy and would be a serious concern without having an extensive supporting structure in its design. The design and material selection of the scrubber’s side walls would have to be able to withstand the weight which was also of a concern.

To realise this problem a decision was made so that the unit would not be any taller than 10 metres tall. The design of the unit would also have to be modular so to accommodate versatility and ease of transportation.

Table 3-3 was drawn to determine the relationship of the required volume a unit would have to be to take a certain volume flow rate while attaining at least a 5 second retention within the system. The feasibility for a large volume scrubber chamber would be restricted for the project, as a high volume chamber would be difficult to build, therefore this is a useful tool. The best zone to be in for the design is in the green section of Table 3-2 but close to the 5 seconds as possible.

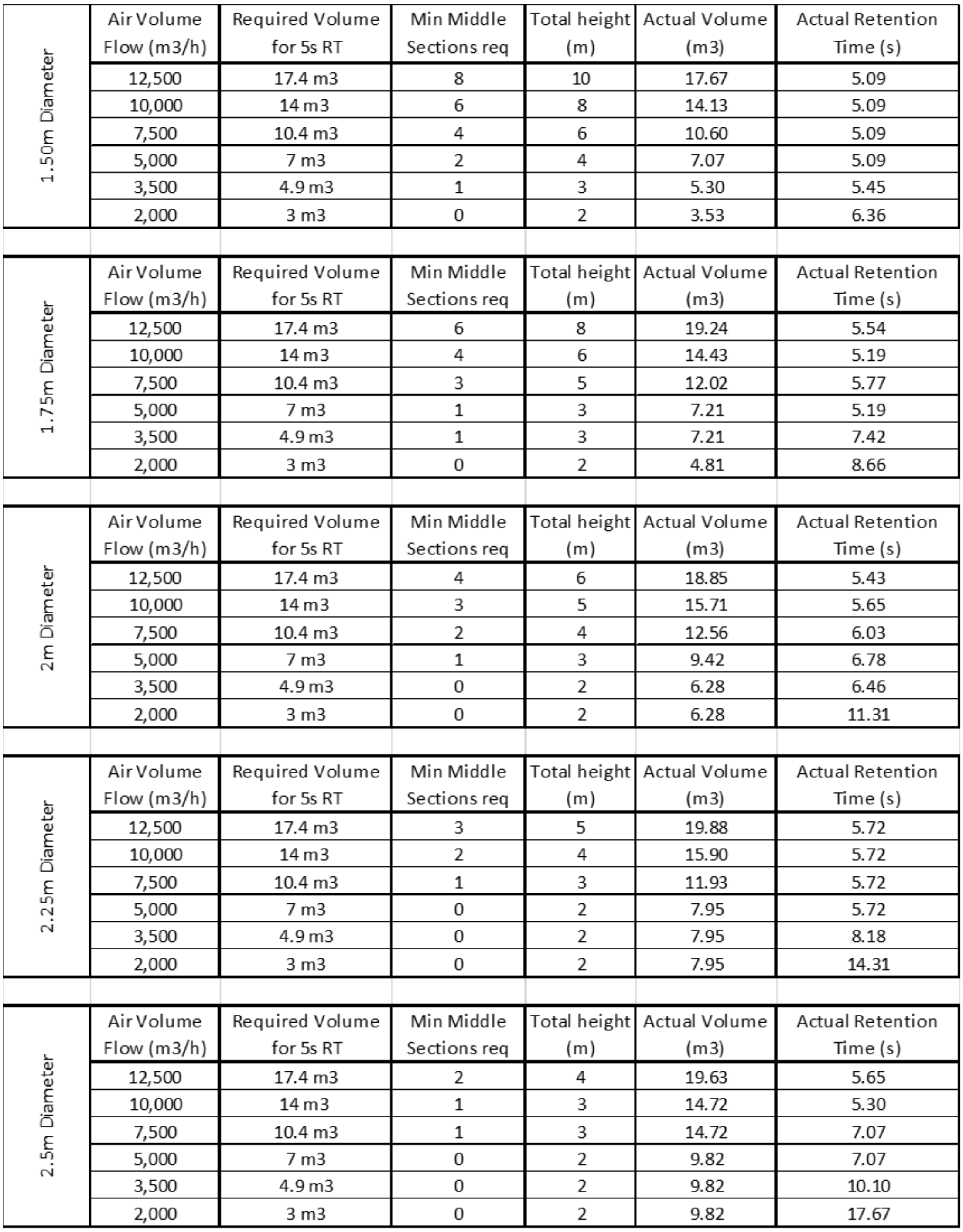
The air volume flow rates in Figure 3-3 are selected from looking at common performances from various fans available that could be used in a real system, therefore flow rates of 12,500 m^3/h, 10,000 m^3/h, 7,500 m^3/h, 5,000 m^3/h, 3,500 m^3/h, and 2,000 m^3/h are used as gradients.

The required volume for a 5 second retention time is calculated by converting the volume flow rate into per second, and multiplying by 5, to calculate the required volume that a unit volume of air needs to travel in a space 5 times its size.

The minimum middle sections required is describing in a multiple levelled tower of modules, how many extra tiers are required additionally to the upper and lower tiers, with each tier one meter in height. This is calculated by dividing the 5 second retention time volume requirement by the respective cylindrical volume using area = $\pi \times R^2$. The value is rounded to a whole number.

The resulting actual volume is a recalculation of chamber volume following from the previous rounding up of the number of sections required for the 5 second retention time. Therefore, the chamber size will never be too small and will attain greater than or equal to the 5 second retention times.

Table 3-3 Chamber sizes, volume flow rates, and retention times table



	Air Volume Flow (m3/h)	Required Volume for 5s RT	Min Middle Sections req	Total height (m)	Actual Volume (m3)	Actual Retention Time (s)
1.50m Diameter	12,500	17.4 m3	8	10	17.67	5.09
	10,000	14 m3	6	8	14.13	5.09
	7,500	10.4 m3	4	6	10.60	5.09
	5,000	7 m3	2	4	7.07	5.09
	3,500	4.9 m3	1	3	5.30	5.45
	2,000	3 m3	0	2	3.53	6.36

	Air Volume Flow (m3/h)	Required Volume for 5s RT	Min Middle Sections req	Total height (m)	Actual Volume (m3)	Actual Retention Time (s)
1.75m Diameter	12,500	17.4 m3	6	8	19.24	5.54
	10,000	14 m3	4	6	14.43	5.19
	7,500	10.4 m3	3	5	12.02	5.77
	5,000	7 m3	1	3	7.21	5.19
	3,500	4.9 m3	1	3	7.21	7.42
	2,000	3 m3	0	2	4.81	8.66

	Air Volume Flow (m3/h)	Required Volume for 5s RT	Min Middle Sections req	Total height (m)	Actual Volume (m3)	Actual Retention Time (s)
2m Diameter	12,500	17.4 m3	4	6	18.85	5.43
	10,000	14 m3	3	5	15.71	5.65
	7,500	10.4 m3	2	4	12.56	6.03
	5,000	7 m3	1	3	9.42	6.78
	3,500	4.9 m3	0	2	6.28	6.46
	2,000	3 m3	0	2	6.28	11.31

	Air Volume Flow (m3/h)	Required Volume for 5s RT	Min Middle Sections req	Total height (m)	Actual Volume (m3)	Actual Retention Time (s)
2.25m Diameter	12,500	17.4 m3	3	5	19.88	5.72
	10,000	14 m3	2	4	15.90	5.72
	7,500	10.4 m3	1	3	11.93	5.72
	5,000	7 m3	0	2	7.95	5.72
	3,500	4.9 m3	0	2	7.95	8.18
	2,000	3 m3	0	2	7.95	14.31

	Air Volume Flow (m3/h)	Required Volume for 5s RT	Min Middle Sections req	Total height (m)	Actual Volume (m3)	Actual Retention Time (s)
2.5m Diameter	12,500	17.4 m3	2	4	19.63	5.65
	10,000	14 m3	1	3	14.72	5.30
	7,500	10.4 m3	1	3	14.72	7.07
	5,000	7 m3	0	2	9.82	7.07
	3,500	4.9 m3	0	2	9.82	10.10
	2,000	3 m3	0	2	9.82	17.67

Graphs were plotted to visually compare the effect of changing the diameter of the cylinder had on retention time and the height of the required unit would have to be. This assisted in the discussions with the project team on deciding what diameter the next prototype should be.

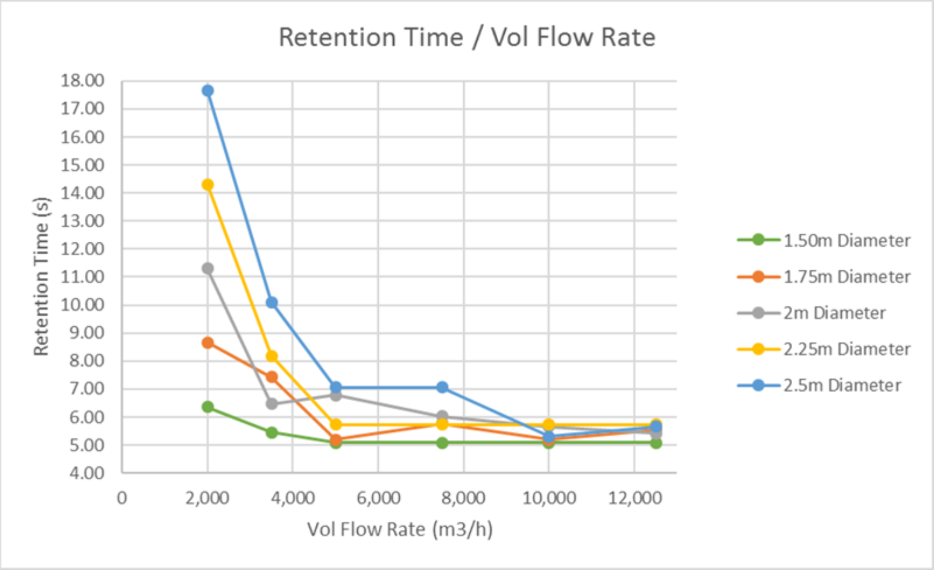


Figure 3-4 Comparison of retention time and volume flow rates

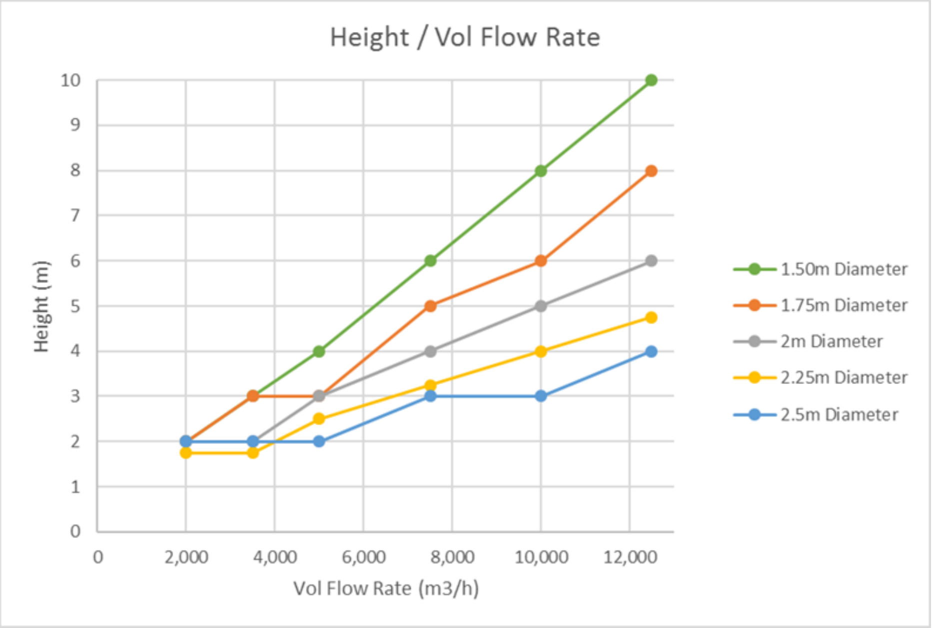


Figure 3-5 Comparison of chamber height and volume flow rates

The project team decided that the best diameter to build the air scrubber was the middle of the options due to the middle ground of advantages and disadvantages it had. Through looking at the graphs and data, the 2 metre diameter cylinder would be capable of providing a big enough volume for attaining a good retention time while not becoming overly tall or too wide in diameter for transport. This was a key decision-making stage as the diameter of the unit was set and the air scrubber was to not change for this parameter.

The air scrubber was to be built to a 2 meter diameter and be from 2 to 6 metres tall with 1 metre sections assembled in a stack.

3.4. CFD Validation of design

The scaling up of the first-generation prototype to this new size had to be validated before any CAD design or manufacturing could be started. Therefore, a fluid flow analysis is required to determine if the air flow would perform as required in a scaled-up unit.

3.4.1. CFD Set Up

Computational Fluid Dynamics software Siemens STAR-CCM+ is used to simulate the air flows around computer generated 3D model geometry of several scrubber chamber prototype models of varying dimensions and features, to be able to analyse the behaviour and character of the air flows for validation of designs. The computer 3D models are created using Computer Aided Modelling (CAD) software called Dassault Systèmes CATIA V5.

A mesh is made within the CFD package by importing a CAD model of a solid scrubber chamber and breaking the geometry into a series of polyhedrons. This is shown in Figure 3-6. A standard base size for the mesh was selected to be 0.01 meters throughout the model.

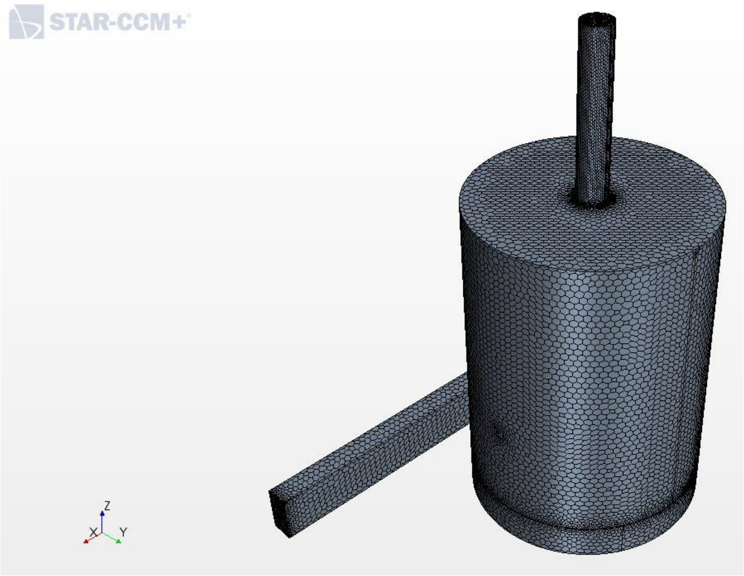


Figure 3-6 CFD mesh generation of a prototype

For each simulation set up, the airflow is to be forced through the inlet of the air chamber model, and the outlet is set to be the vertical outlet pipe. A long extension is made for the inlet and outlet, to allow the simulated air flow to settle before and after the test chamber, as seen in Figure 3-6.

The settings for air velocity is calculated depending on the cross sectional area for the model's inlet, so that each model is simulated for the required volume flow rate for the test scenario.

The flow regimes within the models are turbulent which is expected as the cyclonic movement generated has a high Reynolds Number and is not lamina. Therefore the Navier-Stokes equations are used within the CFD solver to aid in the computation, along with k-ε turbulent flow model for the solution of the Navier-Stokes equation.

3.4.2. Validation of Cyclonic Air Movement

It is important to validate that the air will rotate around the chamber for generating the cyclone, which is to ensure that the air is fully treated by the scrubbing media, and that there is sufficient time for the mist droplets to fall out and not be entrained by the outlet of the chamber. A simulation output of a model shows a section through the scrubbing chamber, and air movement displayed as a vector perpendicular to the view plane, as shown in Figure 3-7. The colour relates to the air velocity and the magnitude can be determined by the colour scale on the bottom of the Figure. Note how the analysis shows a positive velocity on one half and a negative velocity on the other half split down by the vertical axis of the outlet, proving cyclonic movement is occurring.

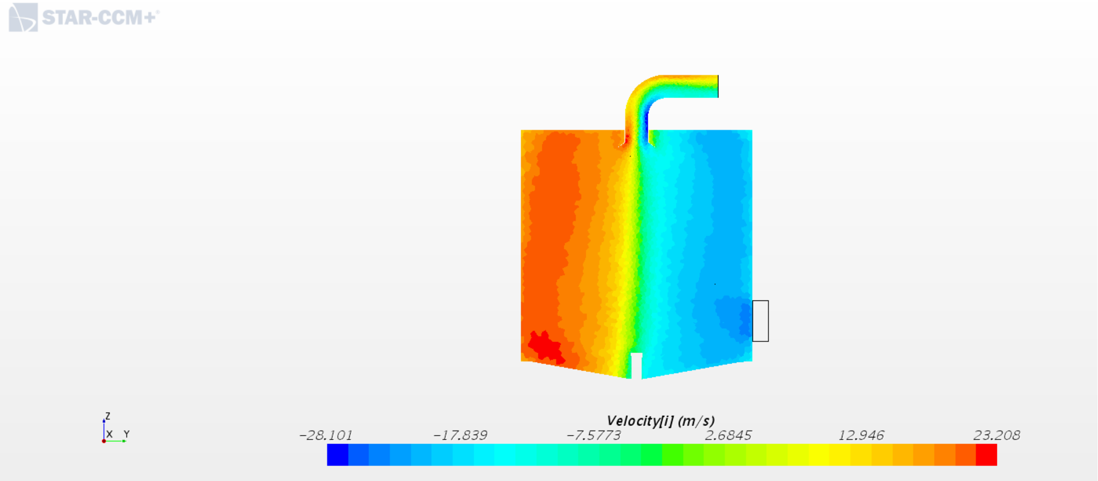


Figure 3-7 Axial velocity plot of a cyclonic chamber

3.4.3. Scrubber Chamber Scaling Up Validation

More simulations are set up to determine if a cyclonic movement is achieved by chamber sizes on the extremes of the modular scale for the prototype design. This would involve simulating the 2000 m^3/h and the 12,500 m^3/h models. A streamline output is used for displaying these models as the streamlines follow the suggested route that an air molecule would flow along through the system. The simulation for 2000 m^3/h is shown in Figure 3-8.

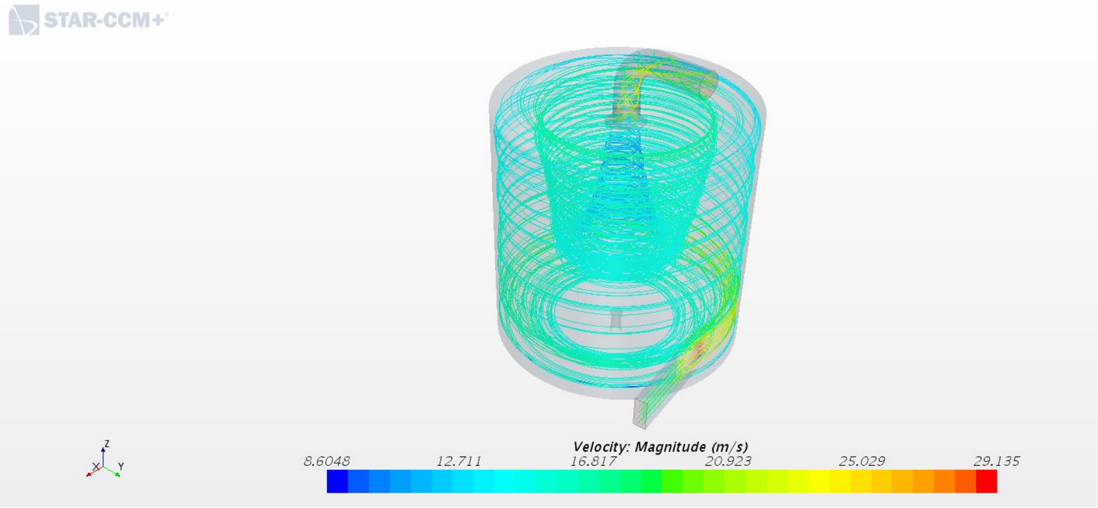


Figure 3-8 Streamline simulation result of 2000 m^3/h chamber

To display for more information as to what is occurring within the chamber, a plot for the internal air pressure is shown in Figure 3-9 of the same model. The negative pressure indicating a reduction in atmospheric pressure due to the fastest velocities in this area.

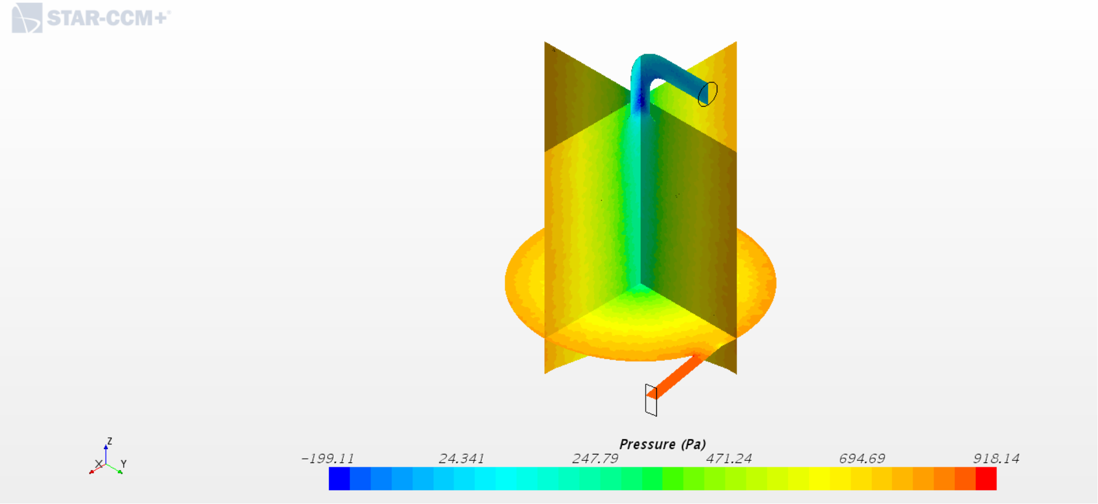


Figure 3-9 Pressure distribution result of 2000 m^3/h chamber

The other extreme of the modular design at its greatest volume, 12,500 m^3/h a streamline simulation result is shown in Figure 3-10.

To ensure that the scale up of the models are comparable to each other for inlet flow velocities as with the increases in volume flow rates, the cross sectional areas of the inlet and outlet ducts in the models were increased to compensate, and designed parametrically with the aim to keep velocity at the inlet consistent at around 20 m/s.

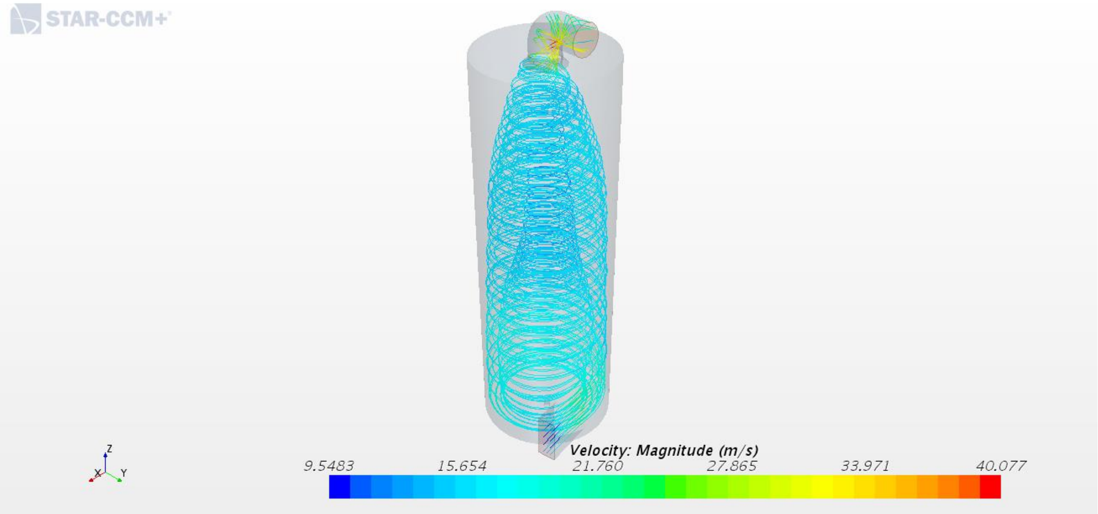


Figure 3-10 Streamline simulation result of 12,500 m^3/h chamber

The pressure distribution of this simulation is shown in Figure 3-11.

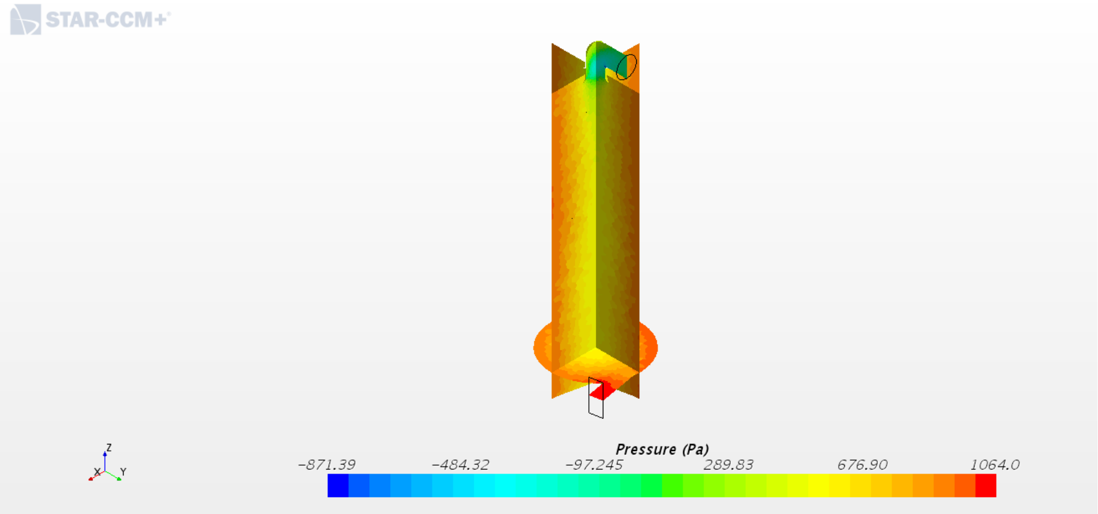


Figure 3-11 Pressure distribution result of 12,500 m^3/h chamber

The CFD simulations of the cylinders all showed that there is a well-established cyclonic airflow within each model, and therefore the scaling up of the design is viable. The streamlines display the velocity of the air along each line, and in each model the average speed of the air in the cyclone is around 15 m/s, which is perhaps unexpected. The maximum and minimum velocities observed do not show a pattern with increasing volume flow rate however this could be due to the randomness of how the lines are generated within the software. The fastest velocity observed is in the same location with each model, on the inside bend of ducting, which is as expected.

3.4.4. Experimental Design Additions

Some variations to the design were explored to investigate any potential advantage to changing design elements for the operation of the unit. As a polluted air stream was to be introduced, it was thought some changes could have the potential to bring some additional benefits.

One such thought was to introduce more than one inlet to the unit with the idea that it could increase the amount of turbulence within the unit to improve mixing of air and mist to increase absorption. The result of the experiment, which can be seen below in Figure 3-12, shows the difference in the behaviour of the air with different numbers of inlets at the base;

- 1 inlet (centre),
- 2 inlets (Top Left),
- 3 inlets (Bottom Left),
- 4 inlets (Top Right),
- 5 inlets (Bottom Right).

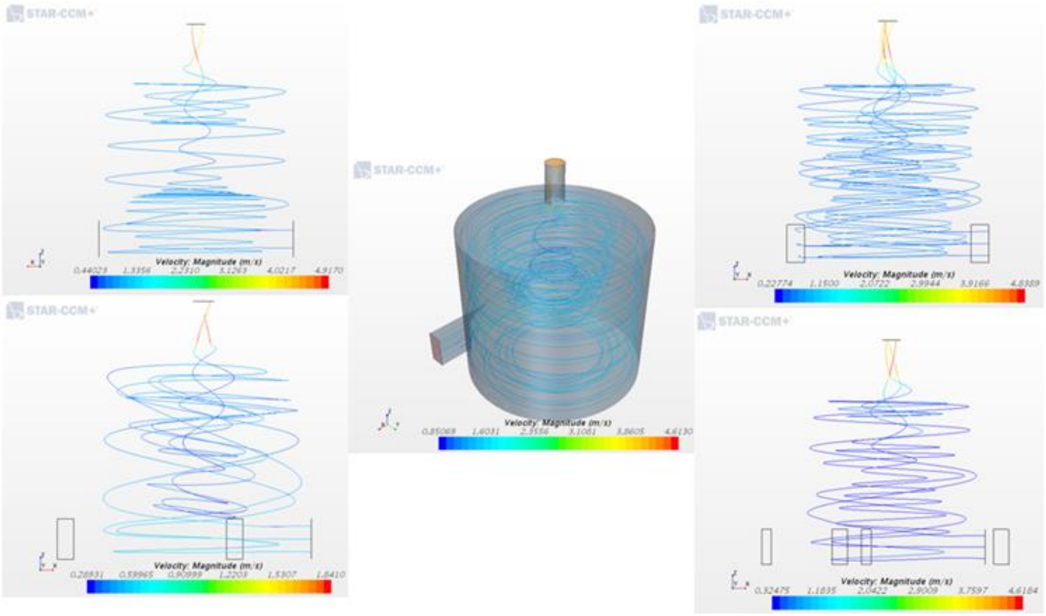


Figure 3-12 CFD of chambers with multiple inlets

To complete this test, the overall volume flow rate summed from the multiple inlets have to be equal to the volume flow rate at the outlet, otherwise the systems would be choked. Therefore similarly to the scaling up simulations, the velocity of the air through the inlets are adjusted, and the velocity relative to the single inlet, is divided by the number of inlets in each case to keep the volume flow rate consistent.

The displayers show that the cyclonic effect is still created in each one there is not real indication that there is any more turbulence within the model. There may be an added benefit in a practical sense if the airstream is arriving from different locations however if there is only one extraction point one inlet is optimised in this design.

An idea to make an inclined inlet to the chamber was investigated as it was thought that this would change the flow pattern of the air to have a possible benefit. A simulation was carried out that compared the flow between an inlet inclined at 5, 10 and 15 degrees to horizontal. The results of which can be seen in Figure 3-13. The experiment failed to see any major difference to the airflow and so the optimum being the tested horizontal position.

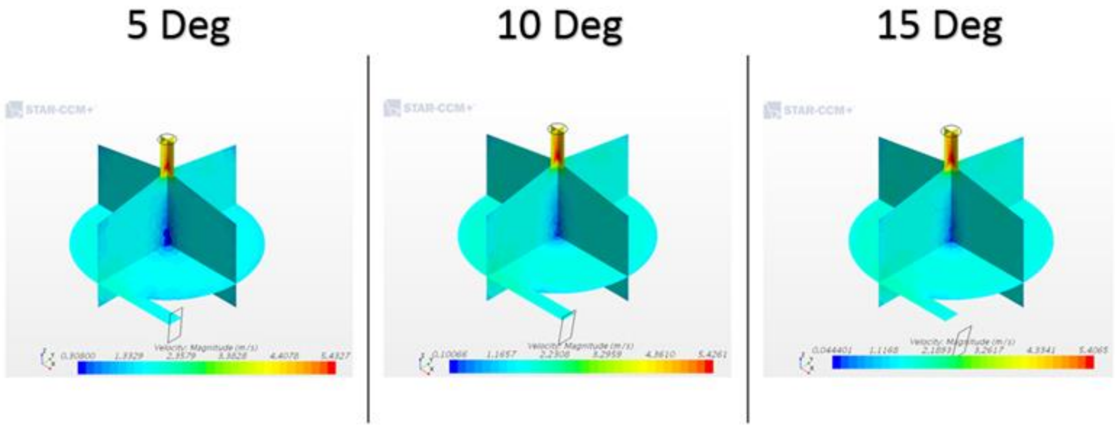


Figure 3-13 Colour scale air velocity of chambers with varying inlet angles

A suggestion shown in Figure 3-14 was made for the inlet to be positioned at the top of the chamber, similar to the design of a cyclone separator. The airflow behaviour was seen to be slightly different compared to having an inlet at the base, as there is no guarantee the air will pass through the entirety of the unit, therefore efficiency could be affected. The angling of the inlet improved slightly on the downward travel of the air although not as much as what would be required as compared to a bottom inlet. Any water atomizer equipment would have to be suspended close to the inlet as well which could mean complicating the design as it would be at height.

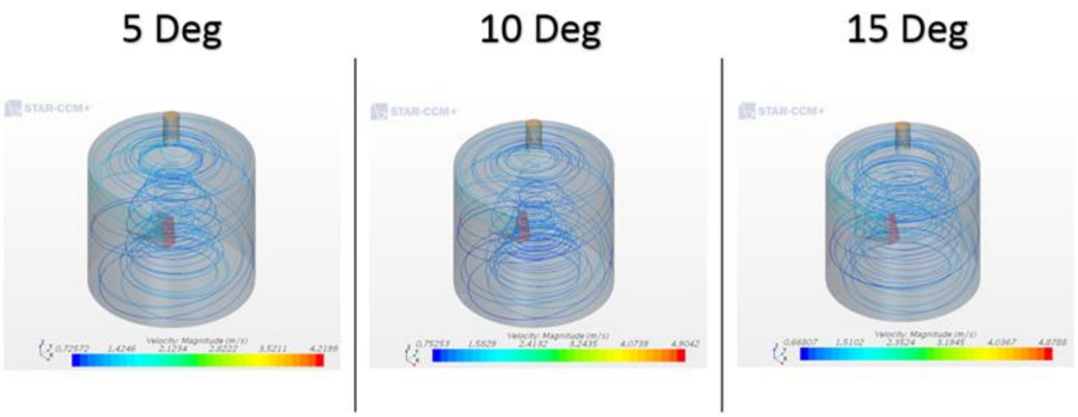


Figure 3-14 Air velocity of chambers with varying angles of inlets

Overall in the inclined inlet investigation, there seemed to be no noticeable improvement or change to the flow behaviour, and therefore this concept is not to be incorporated further, but could be utilised in further development.

3.5. CFD Result Conclusions

The results of the CFD analyses show evidence for cyclonic movement of air within the chamber, and that the air enters and exits as it is designed to do.

The cylindrical shape aids in the stability of the cyclonic movement as that the air has to continually rotate around the circular walls, and move helically to escape out the middle at the top. The inlet is positioned tangential to the wall which means that the mechanics of the air motion is ideal for starting the cyclonic movement.

The air inlet at the bottom and air outlet centre at the top, means that a cross flow can be implemented for reacting the air. The airflow will act in the direction opposite to gravity, which will help for separating the water from the outlet air, benefiting the removal efficiency for the scrubber.

Investigating the benefits for multiple inlets is useful for the future event of offsite requirements and system design finds it of value. For the prototype, one inlet is seen to be most practical. Analysis of the range of chosen angles, 5, 10 15 degrees, for the inlet slope, seems to indicate no significant effect on the cyclone. For the prototype build and for manufacturing simplicity, the inlet is to be level and tangential to the scrubber wall.

The multiple simulations performed with the varying chamber sizes over the range of volume flow rates required by the modular scrubber to achieve, have shown that the cyclonic movement is achieved irrespective of chosen chamber sizes. The velocities of the air within the chamber is comparable as well, which is desired for ideal running of the technology intended to be applied within the chamber.

The behaviour of the air and separation efficiency in practice is to be tested, as cyclone separators with high efficiency are in a different size, shape, manufacture methods and are of a different level of scale. (25) The prototype will show indicatively the performance of separation ability.

The design is shown to be satisfactory to move on to a real world prototype build.

CHAPTER 4 – Design Realisation and Build

4.1. Design and Build Introduction

This chapter evaluates what the design of a suitable air scrubber should be, and sized using calculations and graphs in the previous chapter for this study. Further study and supplementary CFD analyses have also been run to show an idealised profile or shape that a prototype should aim to recreate in real life using best available manufacturing methods and materials.

In this chapter the air scrubber prototype is designed and manufactured in readiness to be tested in a real life situation.

4.2. CAD Model Development & Scrubber Assembly

The design specification of the prototype air scrubber was realised and the basis of the design of the unit had been agreed in the project team. Through analysis of the CFD data and research into cyclonic air movement generation and sustainment, the confidence level that a cylindrical chamber with a tangential inlet and axial outlet would generate the cyclonic air movement required was high. This meant that the prototype could be designed in detail for individual modules and parts. Using Computer Aided Design software CATIA V5, and the employ of ‘Design for Manufacturing’ techniques, the prototype could be manufactured in an efficient manner for testing and design validation.

Selection of the best available fan to drive airflow through the system was done. The main requirement of the fan was to be able to draw a maximum of 2000 m^3/h air flow, as otherwise exceeding this constraint would mean the retention time would be less than the required minimum of 5 seconds.

Investigations into the methods of transporting and assembling the air scrubber early on, shown that there were limitations on the widths, heights and weights that common commercial transportation companies could facilitate. Researching into several companies found that the maximum size diameter that could be achieved of each module, without having to involve wide-load transportation, was 2 metres. Having each module assembled whole during transport is better, rather than having to assemble on site. Each module therefore had to be able to be self-supporting in an upright position during storage and transport.

The design should allow the movement of the sections on site, with precision and in a safe manner. Therefore, it was an aim to make each section weigh under or around 200 kg. It is ideal to use a crane and lifting equipment through hooks, chains, and slings to securely move the modules. Mounting points and lifting hooks therefore would have to be placed strategically on the frame to facilitate this.

4.3. Base Module Design

The base of the air scrubber is required to serve several purposes:

- to support the weight of the Air Scrubber assembly
- to be the bottom face of the scrubbing chamber to retain the cyclonic air flow
- to collect the used scrubbing liquor and remove it from the unit.

Another crucial requirement for the assembly was for an airtight and watertight seal between all the assembled components, especially considering that to be within is a water solution of potentially hazardous pollutants, and that its properties of reduced surface tension will make leaks between joints easier.

The base would also have to be designed in a way to channel the liquor out of the unit. The CAD models used in the CFD simulations had the base designed as a flat surface. This was done for simplicity of the simulation. The simulation showed that the bottom centre of the model had the lowest air flow velocities, and therefore, placing peripheral components within the design would have least impact for the desired cyclonic airflow. Therefore, the atomisation equipment was placed in the centre, where a rotary atomiser could distribute a mist radially out into the bottom of the chamber.

The base of the unit was decided to be concave shaped so that the liquor and particulates collected could travel towards the centre of the unit by gravity, and then drain through a tube at the centre out of the unit for disposal. There were some problems with this due to a limitation of manufacturing methods available to building a prototype model on a budget. The concave base bottom was to be built from stainless steel sheet which meant forming curves would not be possible. Therefore, a concave profile was created from joining 6 identical parts together, each a profiled sheet with a 10-degree incline to form a drainage solution for the liquor. The CAD model of the base is shown in Figure 4-1 below.

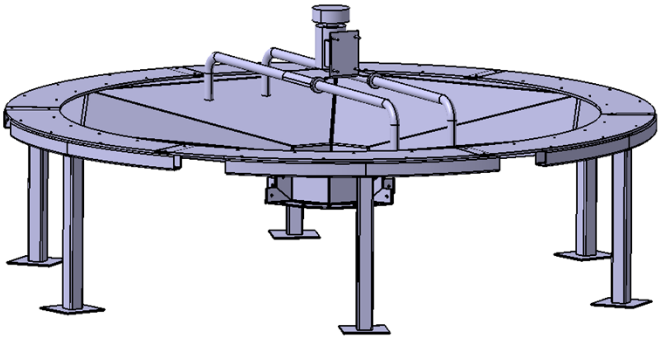


Figure 4-1 Air scrubber CAD model of base section

Figure 4-2 shows the Base Section assembled, fastened together using nuts, bolts and mating faces sealed using silicone sealant so that the assembly is watertight. The seal is made even more important as the scrubbing solution is of a low surface tension, so leaking is more susceptible.

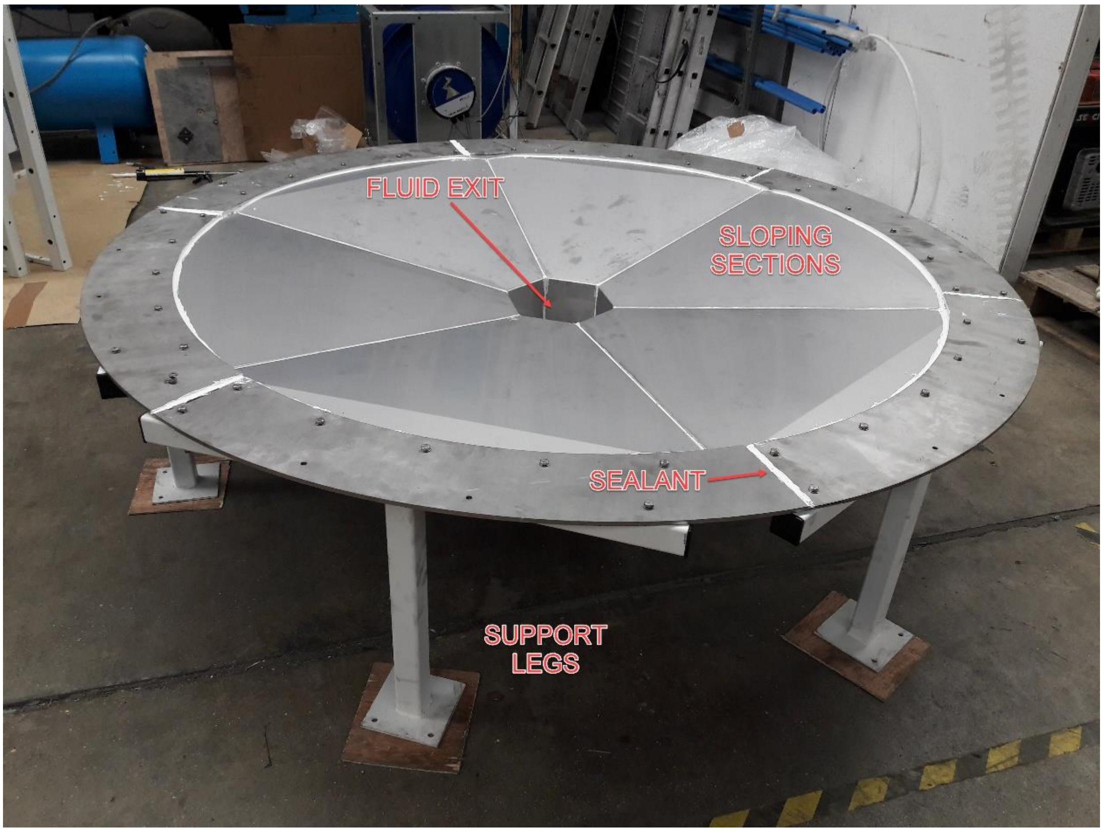


Figure 4-2 Base module assembled

4.4. Wall Module Design

The walls of the prototype would have to have an internal surface diameter of 2 metres. A requirement, bespoke for the prototype, was for the chamber walls to be transparent so that it could be seen the flow behaviour of the air and mist, therefore the walls are made from rolled clear acrylic sheets. Acrylic is selected as the wall material, as it is the best available material for manufacture and with its material properties, such as being chemically inert, it is suitable for this application, as it is expected to contact directly with pollutants being scrubbed.

The wall modules were decided to be made in sections due to manufacturing limitations for prototyping, working with what machinery was available at the time of the project. The tiered cylindrical wall modules are made from 4 quarter sections bolted together.

The sealing of the gaps between the walls was a concern and therefore tolerances had to be made tight so that parts would join well. A Sealing method was required such as rubber gaskets or some flexible sealant to be sandwiched between each wall element.

The acrylic walls are mounted on an external frame, to support and provide a sealing edge between conjoining walls. This also means the acrylic is not stressed from the weight of assembly. The frames are designed to support the load of the wall, and the weight of additional modules above it. A CAD model of a standard wall section is shown in Figure 4-3.

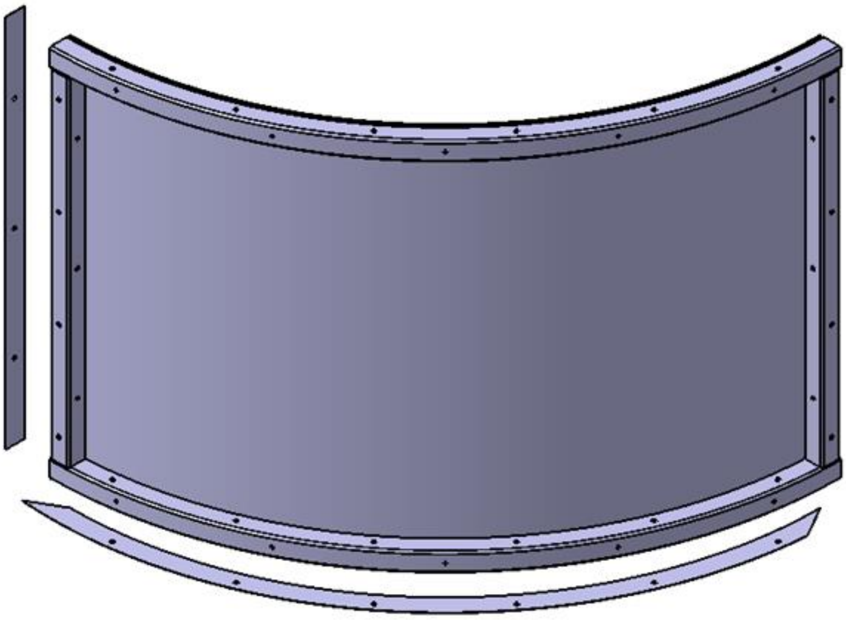


Figure 4-3 Air scrubber wall segment

Two wall sections on the bottom tier have additional elements added to them; for the air inlet to the scrubber chamber, and an access hatch to access the atomisation equipment in the centre.

In Figure 4-4 the completed wall modules are assembled and fitted on top of the base assembly. Assembled, the unit now stands over 2.5 metres tall and is of an estimated 300 kg weight.

Figure 4-4 Wall sections assembled on base section

The scrubber is required to cope for a 2,000 m^3/h and up to a 12,500 m^3/h volume flow rate. Compared to the first prototype, able to cope with 100 m^3/h, the atomiser had to be scaled up so that the mist to air ratio is maintained. Figure 4-5 shows the rotary atomiser fitted in the base section with the electrical and water connections present. Note how the cable and pipe are sealed through the wall using waterproof grommets. For access to the equipment and for cleaning, there is an access panel made in the wall.

The Rotary Atomiser was selected to deliver the scrubbing solution into the chamber, and was to be positioned in the centre of the chamber, mounted on the base section specifically so that the head of the atomiser would be at the same level as the incoming air stream. This is so to maximise the time available to scrub the air in the chamber. The rotary atomiser was chosen over air assisted nozzles, as the volume of scrubbing liquid it can deliver is 200 litres per hour, as compared to a single air assisted nozzle, which has a capacity of around 10 litres per hour. The greater amount of scrubbing liquid in the chamber should mean the more gasses and particulates can be removed effectively. The power for this and water is to be delivered from the side of the base section through a wall panel section.

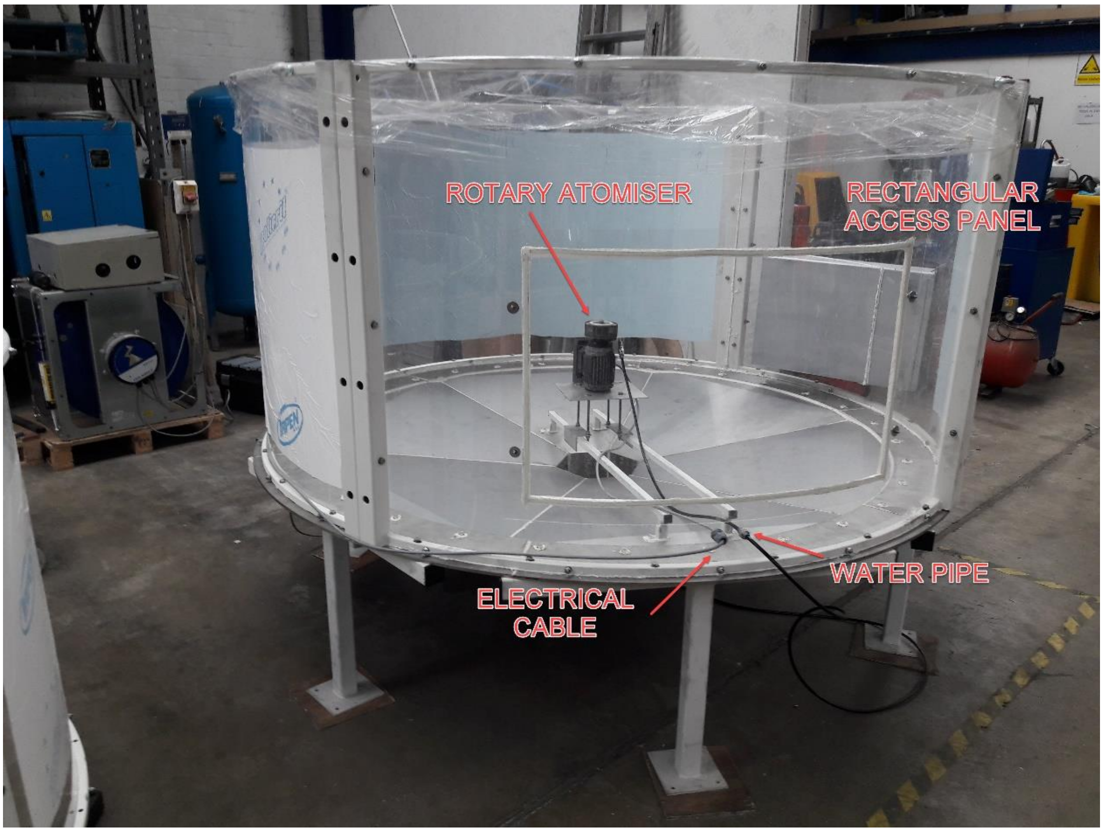


Figure 4-5 Inlet, access hatch and rotary atomiser

4.5. Outlet Module Design

The outlet module section of the air scrubber is the uppermost tier of the scrubbing chamber, serving many functions. The centre of the outlet module supports ducting and the ‘bell mouth’, where the air exits the chamber. The module also serves as the top of the scrubbing chamber and therefore must remain airtight. Furthermore, it must be able to protect the system from adverse weather, as the unit will be exposed to weather elements outside.

The components are designed to control the airflow optimally, as the diameter of the ducting is selected such to control the overall air flow speed relative to the volume flow rate. The ‘Bell Mouth’ is key in the design, aiding the creation and continuation of cyclonic air movement in the chamber, and to reduce the pressure losses in the system.

Designs looked at the possibility for mounting the fan on top of the outlet module, although through investigating the centrifugal fans available to provide the required ranges of volume flow rates for the air scrubber, it is deemed safer to have the fan contained in a ground unit or other away from the chamber. Therefore, the outlet module design routes ducting in a 180-degree bend back down the side of the chamber.

The outlet module can be seen in Figure 4-6 below, where it is ready to be mounted to the upper wall section. The bell mouth is not attached here yet as it will be proud of the top face, and not strong enough to take the weight of the module. Lifting eyes are placed strategically on the strongest parts of the frame for lifting and transporting the module.

Figure 4-6 Top section assembled

The outlet section was lifted onto the upper wall section through using a fork-lift extension tool, made especially for the prototype, along with a chain sling, as shown in Figure 4-7 at the top in red. This step was carefully thought out due to the hazards that was present. The assembly of the outlet section is shown in Figure 4-7. Once in place the assembly was bolted together and was sealed using silicone.

Figure 4-7 Fitting of top section on wall assembly

4.6. Design Considerations – Peripheral Units

The air scrubber's consumables of water, electricity and scrubbing additives need to be managed so that it is available to be supplied to the unit and be controlled. The easiest way to do this is to have a control box close to the unit for managing the respective consumables, therefore control boxes were made for managing and distributing water, scrubbing additive and electricity.

The water management unit incorporated the mixing of the scrubbing additive through using a dosing equipment, to accurately provide a concentrated mix of water and additive to the scrubbing chamber. The water control unit allowed for varying water flow rates from 0 to 200 m^3/h and concentrations of 0.15% to 1.25%. This is shown in Figure 4-8 running at maximum flow rate where the two flow rate indicators each show a flow of 100 Litres per Hour.

Figure 4-8 Water and additive control panel

The inlet of the water control box comes from the left of the water cabinet, inline to that, the blue plastic component, is the in-line dosing equipment for the scrubbing additive, powered by the action of the water pressure. The solution is then distributed to the two 100 l/h maximum flow controllers, to control the supplied scrubbing liquor to the air scrubber, which then connects to one pipe to connect to the rotary atomiser. This is shown again in Figure 4-9 from further away.

The electronics is split into two cabinets, as the centrifugal fan has a separate 3-phase power supply, and the rotary atomiser and liquor pump requires mains 240 VAC, located above the water cabinet. All elements of the control setup are shown in Figure 4-9.

Figure 4-9 Electrical power control and fan control

4.7. Inlet and Outlet Optimisation

Managing the transport of air through the scrubbing system is an essential part of its operation. The fan is key to this, as this is what drives the flow, but the inlet to the chamber is also important, as the size of it must match the diameter of the ducting to give a desired flow rate while not having the air speed too high or too low, for efficiency reasons and for maintaining the cyclonic airflow in the chamber.

The prototype scrubber is to be fitted with a fan that can deliver a volume flow rate of 12,500 m^3/h, the maximum flow rate for the scrubber if built with the maximum number of wall modules. The fan is a centrifugal type, which is found to be the best available technology for the application. It is powered by a 3-phase power supply. The fan required to be built in a bespoke frame to allow for connection to the chamber outlet, and to be able to vent the exhaust treated gas stream safely to open air.

Below in Figure 4-10, the fan is mounted in the frame, ready for the cladding to be added.

Figure 4-10 Centrifugal fan mounted in frame

The assembled fan is shown in Figure 4-11. The controls and power isolator is mounted on the side for quick access. There is a jet cowl added on the top of the unit to vent the exhaust air fast out the top and protect anyone near it from gasses emitted while in operation.

Figure 4-11 Centrifugal fan assembled

The inlet of the prototype scrubber is a complex element in the design as the inlet determines the velocity of the airflow through the scrubber chamber, which has an influence on the behaviour of the flow.

The Inlet duct parameters should be designed bespoke for the application of the site it is built for and therefore the duct size was chosen to match the requirements of potential testing sites.

From the dimensions of the air scrubber that were selected, a maximum volume flow rate is decided to satisfy the minimum 5 second retention time of airflow, and therefore sizing of the inlet duct could be made from this value. The calculation in Equation 1 shows that the Volume of the chamber, divided by the required Retention Time, gives the required volume flow rate of the system. The equation gives an answer per second, and therefore is multiplied by 3600 to give units in m^3/h

Volume Flow Rate Equation - Equation 1

Volume/RT=volume flow rate $(2 \times \pi \times (1)^2 \times 3600) / 5 = 4500 \text{ m}^3/\text{h}$

To size the dimensions of the inlet duct more calculations were made. An ideal inlet velocity is to be no more than 20 m/s as research described anything above this value raises the turbulence and system inefficiencies greatly. Noise and some instability of surface elements in turbulent wake, for example; vibrations or Von Karman vortexes, can occur within the design, which should be designed to be minimised.

A maximum volume flow rate of 4,500 m^3/h and an idealised velocity through the inlet of 20 m/s would be the best design way forward, and for any greater volume flow rates, a larger chamber would be required.

To have an inlet with velocity 20 m/s at volume flow rate 4,500 m^3/h, it is calculated in Equation 2, the resulting duct size should have a cross sectional area of 0.0625 m^2.

Cross Sectional Area of a Duct Equation - Equation 2

$$\text{CSA} = (\text{Vol flow rate})/\text{Velocity} = 4500/3600 \div 20 = 0.0625 \text{ m}^2$$

Using an aspect ratio of 0.4 for the rectangular duct, the calculation for required dimensions width and height, where width is 0.4 times the length of the height, is found in Equation 3;

Aspect Ratio Calculation - Equation 3

$$0.0625 = L \times 0.4L$$

$$0.0625 = 0.4L^2$$

$$\sqrt{(0.0625 / 0.4)} = L$$

$$L = \sqrt{(0.15625)} = 0.4 \text{ m}$$

This therefore gives a duct of size 400 mm in height, and 160 mm in width.

These dimensions were used in creating a square to round duct to direct the air as smoothly as possible into the chamber, at a tangent to the wall surface. This was to give the best chance as possible to create a strong cyclonic air movement in the chamber.

4.8. Design and Build Conclusion

The prototype has now been manufactured to be as close as possible to a designed optimised CAD model, and is ready for testing. Material selection, functionality and serviceability have been taken into account as well as transportability so that the prototype is versatile during the testing stages.

CHAPTER 5 – Testing and Results

5.1. Testing and Results Introduction

The practical testing of the prototype scrubber required the assemblies to be transported and retrofitted to an actual site to investigate the functionality of the design. In this chapter the testing, experimental set ups, and the results are discussed.

5.2. Testing and Results

The air scrubber prototype was tested in a real-world environment to analyse its performance and behaviour in scrubbing air. A live sewage treatment site was made available for this, and several tests could be performed on the prototype by evacuating air from a sewer pipe and scrubbing air coming from within it. This pipe was known for having high levels of hydrogen sulphide and other organic gasses, such as methane, due to septic conditions from the sewage being sent for treatment.

The required specification of an air scrubber was ideal for the project, as the volume flow rate needed to be generated was relatively low and the gas species is of an above normal concentration, hence easily detectable with off the shelf measuring equipment.

By utilising the table in Table 3-3, the retention time of the air within the chamber should be maximised for the theoretical best performance. Because of the lower flow rate range expected to be used, referencing the table, the smallest chamber volume can be used, therefore the chamber body selected was to have only the two mandatory tier sections; the bottom inlet section, and the upper outlet section.

A rough concept for the placement of the prototype was created so that preparations could be made to retrofit the prototype. This is shown in figure 5-1 below. Parts were acquired for; the required ducting connecting elements, designs for interfacing with the access hatch of the sewer, and gathering gas measuring and monitoring equipment.

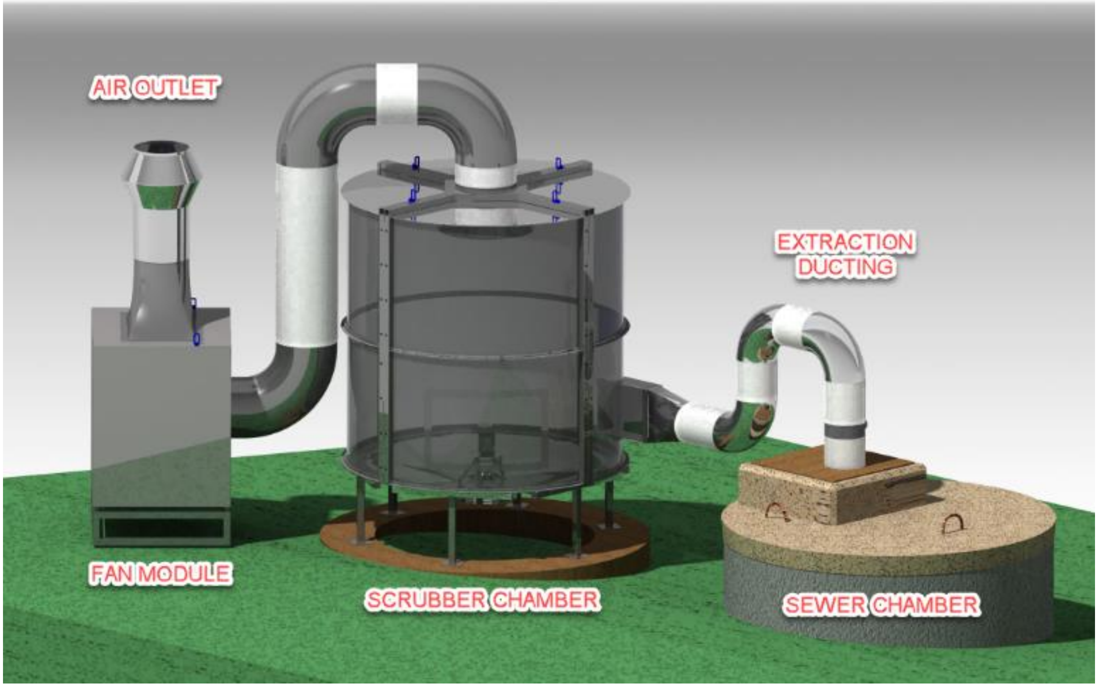


Figure 5-1 CAD image of prototype assembly

5.3. Retrofit of Prototype

The first challenge for testing the modularity of the air scrubber was to safely disassemble, transport, and reassemble on the testing site, the prototype unit, without causing any damage to the modules so that it is fully functional when reassembled.

A local transportation company was used to load and transport the modules using a boom truck, or a flatbed lorry with a mounted crane. The lifting eyes fitted to the frames of the modules were used in conjunction with chain slings. Figure 5-2 shows the prototype on the lorry now at the testing site, ready for unloading.

Figure 5-2 Transportation and lifting equipment for moving modules

5.4. Experimental Set Up

To have a metric for determining the performance of the air scrubber, gas measuring equipment was used to measure concentration levels of hydrogen sulphide present in the sewage inlet, which could be extracted and treated through the prototype. Concentrations of the gas were reported to be in the ranges of 0 to 2000 ppm and more depending on what sewage and environmental conditions are. Two hydrogen sulphide ‘OdaLog®’ sensors capable of measuring up to 2000 ppm were used for experimentation, covering the expected range.

The positioning of the gas sensors within the air scrubber ducting is crucial for achieving reliable data, to determine the performance of the machine. The sensors were positioned:

- Directly inside the inlet duct before the scrubbing chamber
- Inside the fan section.

This is so that the data collected would reflect the gas concentration before and after the scrubbing chamber, and therefore the difference should reflect the efficiency of the air scrubber of how much gas has been removed.

The gas sensor for the inlet is placed in line with the dirty air. It is suspended from a clean air inlet duct that is normally closed and to be used in an emergency shown in Figure 5-3. The sensor is exposed directly to the incoming air stream from source.

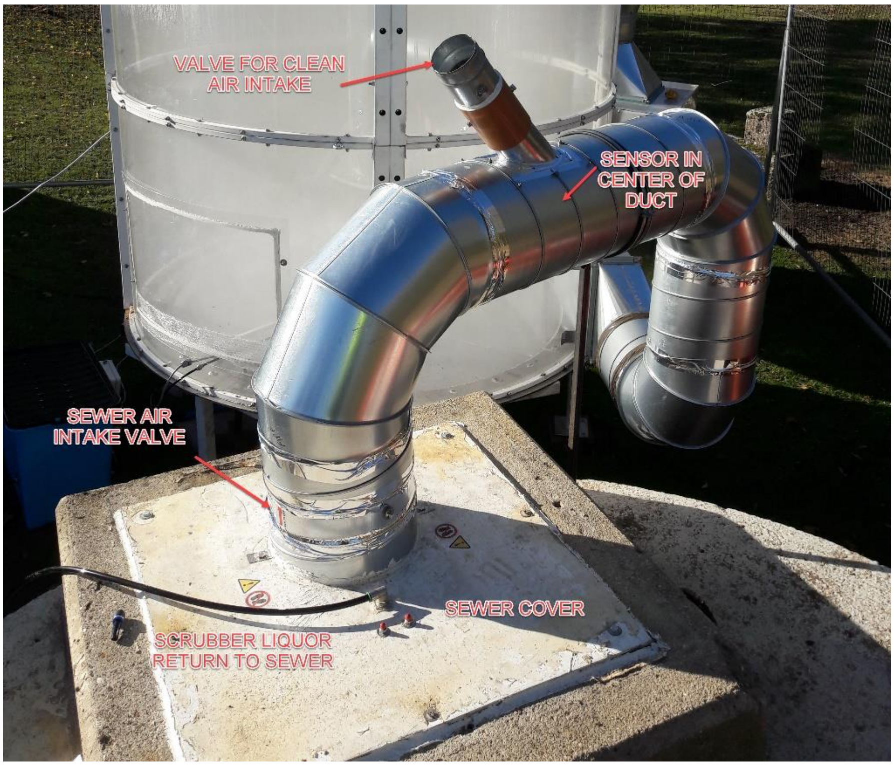


Figure 5-3 Inlet gas sensor position

The outlet gas sensor is seen inside the fan casing, visible through a detachable window, in Figure 5-4. The air exiting the air scrubber fills the container before exiting the jet cowl at the top, therefore the positioning of it is thought to be suitable and give a reliable result.

Figure 5-4 Outlet gas sensor position

5.5. Air Scrubber Tests

Three experimental tests were performed, to show the variance in performance when changing the controllable input parameters of the air scrubber system. The parameters under control are:

- The airflow rate,
- The water flow rate,
- The concentration of the scrubber additive.

The first test was to try to determine the maximum performance possible of the air scrubber, whereby we set the input parameters to the most desirable settings. In Table 5-1 the set-up conditions for Test 1 is shown.

Table 5-1 Test 1 - Experimental setup

Test 1 - Theoretical Maximum Performance		
Air Flow Rate m^3/hour	Water Flow Rate litres/hour	Additive Concentration
1000	200	1.25%

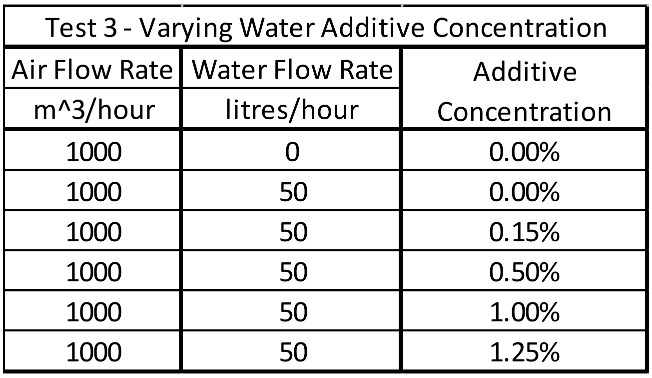
The second test was designed to show how the performance of the air scrubber will be affected, by varying the water flow rate to scrub the air. The hypothesis here is that the greater amount of water used, the greater the scrubbing efficiency due to the increased volume of affinity potential. The set-up conditions for Test 2 is shown in Table 5-2.

Table 5-2 Test 2 - Experimental setup

Test 2 - Increasing Water Flow Rates		
Air Flow Rate m^3/hour	Water Flow Rate litres/hour	Additive Concentration
1000	20	1.25%
1000	50	1.25%
1000	100	1.25%
1000	150	1.25%
1000	200	1.25%

The third test was to investigate how much the scrubbing efficiency can be affected when we use varying amounts of scrubbing additive. The hypothesis for this test is that there is an optimum concentration where the maximum scrubbing efficiency is achieved, as the additive will improve the absorbency of the water alone. The experimental set up conditions are shown in Table 5-3.

Table 5-3 Test 3 - Experimental setup



Test 3 - Varying Water Additive Concentration		
Air Flow Rate m^3/hour	Water Flow Rate litres/hour	Additive Concentration
1000	0	0.00%
1000	50	0.00%
1000	50	0.15%
1000	50	0.50%
1000	50	1.00%
1000	50	1.25%

5.5.1. Test 1 – Benchmark of Theoretical Maximum Performance

The first test was to push the air scrubber to the theoretical maximum efficiency that it could deliver, and to act as a benchmark when changing other parameters. Therefore the test had the most favourable possible parameters for operating conditions, such as; drive the minimum air flow rate of 1000 m^3/h, deliver the maximum amount of scrubbing liquid of 200 litres per hour, and have the maximum 1.25% concentration of scrubbing additive added to the water.

The test was run for 20 minutes, and the data was collected by the gas sensors. The results can be seen in Figure 5-5. A second graph displaying the perceived efficiency of the air scrubber is shown in Figure 5-6.

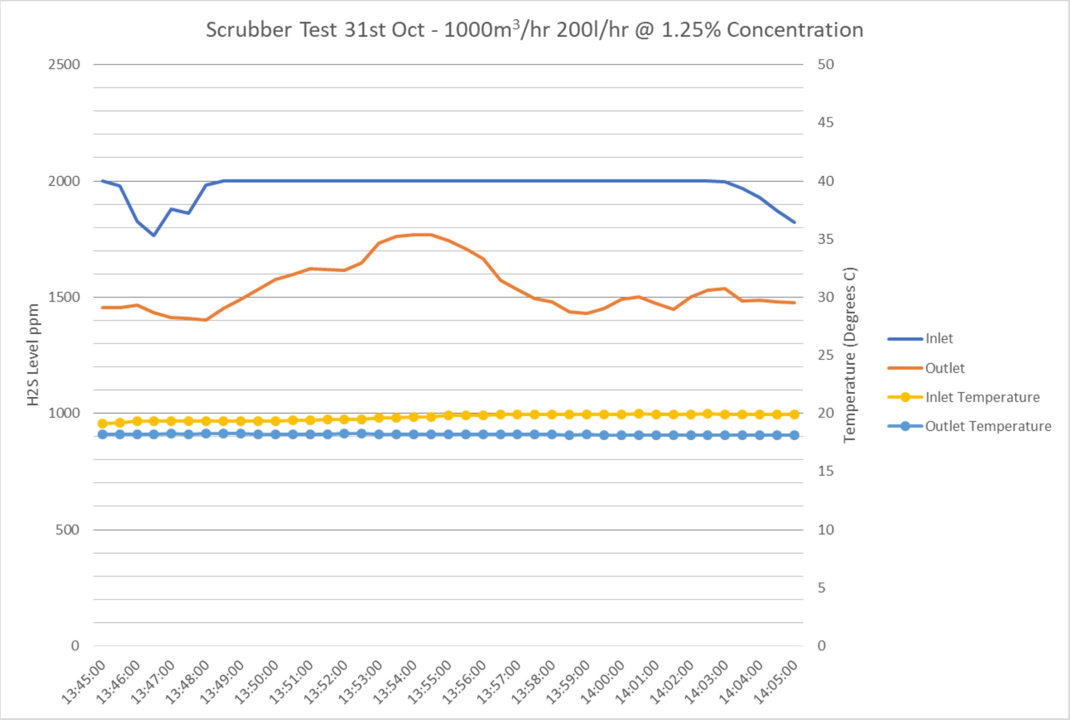


Figure 5-5 Test 1 - Theoretical maximum performance

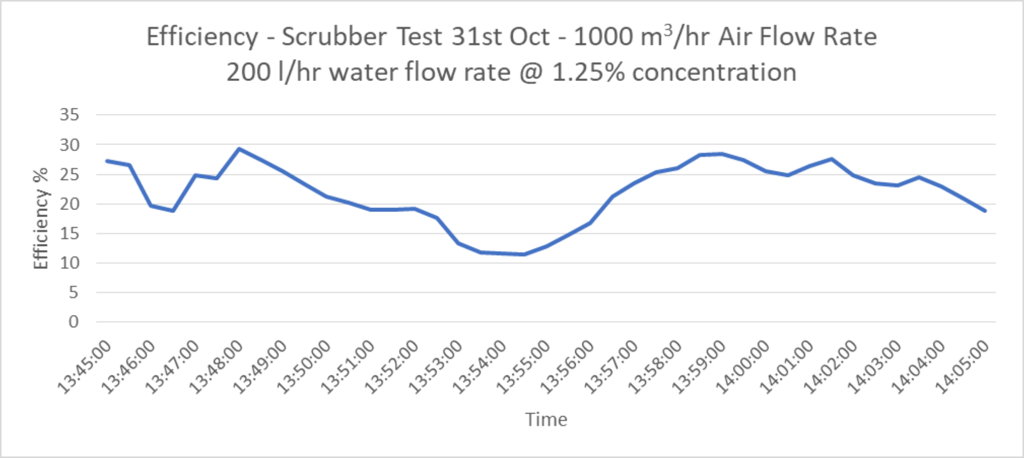


Figure 5-6 Test 1 - Scrubber efficiency from first test

The percentage efficiency of the air scrubber is calculated by the difference of the inlet to the outlet, divided by the inlet, times 100.

The data was taken over a 20 minute period and shows no clear pattern, as the gas levels both on the inlet and the outlet are not steady.

The graph has been capped at 2000 ppm at the inlet, as the hydrogen sulphide level reached the maximum of the dynamic range of the sensor. The measurements recorded was measured to be above the upper limit of the sensor, and therefore measurements above 2000 ppm cannot be considered.

The data after putting a cap of 2000 ppm on the inlet, the average concentration recorded was 1972 ppm, and at the outlet is 1540 ppm. The maximum and minimum concentration recorded at the outlet was 1770 ppm and 1401 ppm respectively. This resulted in an average removal efficiency of 21.9%.

The temperature of the inlet and outlet was also recorded, as seen in Figure 5-5. The inlet temperature did not fluctuate very much over time, nor did the Outlet, however it was interesting to see that there is a reduction through the system. This could have happened as the temperature of the septic sewage, underground, is warmer than on the surface, especially as the septic conditions with bacteria is exothermic. As the air passed through the system, it will have cooled down. An element of evaporation from the atomised water from within the chamber would have also attributed to this reduction in temperature.

5.5.2. Test 2 – Increasing Water Flow Rates

The second experimental test was to determine what effect on the scrubbing performance there would be by changing the flow rate of the scrubbing liquid in the chamber. For this test, again the minimum air flow rate of 1000 m^3/h was set, and a concentration of 0.5% scrubbing additive was used in the water. Increasing water flow rates of; 20, 50, 100, 150, and 200 litres per hour were used. Each experiment was run for a duration for 30 minutes and performed one after each other with the aim to try to have comparable inlet gas readings for all tests.

Two graphs have been created to represent the result from this test. The average gas levels in inlet and outlet for each experiment, and also the calculated average efficiency for each experiment, are shown in Figures 5-7 and 5-8 respectively.

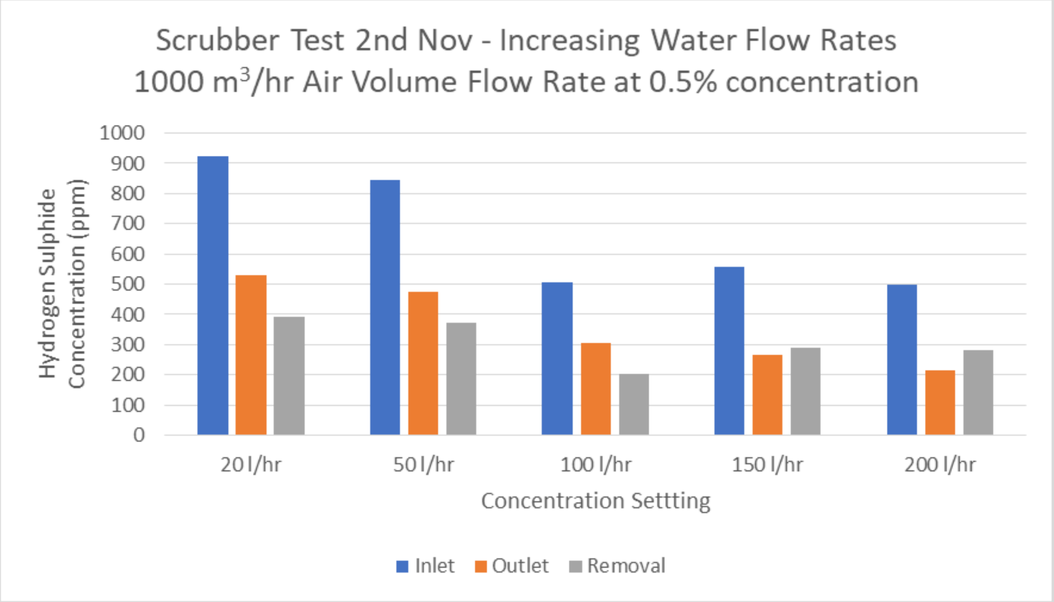


Figure 5-7 Average concentrations with increasing water flow rates

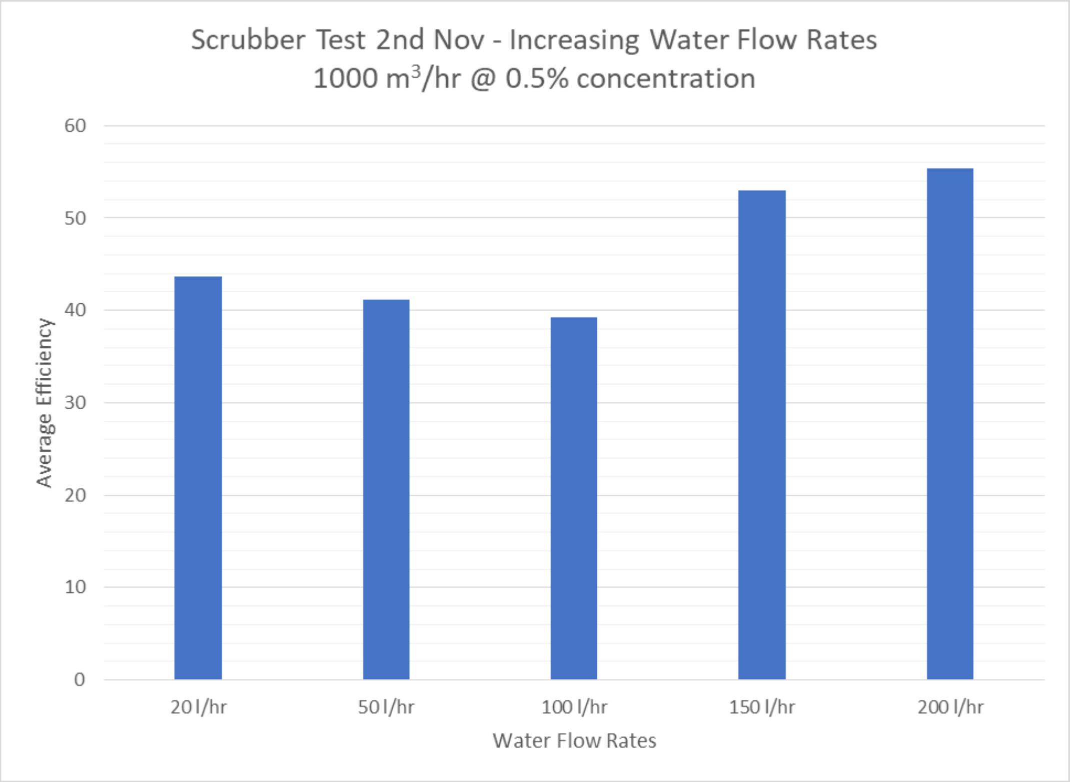


Figure 5-8 Average efficiency with increasing water flow rates

The inlet gas levels dropped from 900 ppm to 500 ppm within an hour during testing, showing the fluctuations present from the gas source we are using for the experiment. This meant that the gas seen at the outlet also reacted accordingly, as expected.

The outlet gas concentrations all showed a reduction compared to the Inlet, which shows scrubbing was occurring.

A trend can be seen in the data for average efficiency, where air scrubbing effectiveness is improved by increasing the scrubbing liquid consumed within the chamber, however with a reduction seen at 100 l/h. To maintain a high absorption rate the scrubbing water requires to be replenished and regenerated into the chamber, as the absorption capacity is reduced rapidly over time. The 42% efficiency at 20 l/h was improved to 55% for 200 l/h.

5.5.3. Test 3 – Varying Water Additive Concentrations

This experiment was to see what effect on the scrubbing performance of the air scrubber was when using different concentrations of scrubbing additive to the atomised water in the chamber. For this test, conditions were made the same for a 1000 m^3/h air flow rate, and water flow rate was set to a constant 50 litres/hr. The tests were again set up for 30 minutes each and run on the same day to try to have consistent concentrations of polluted inlet gas.

The experiment required several test scenarios of varying concentration levels of scrubbing additive to water, to show the effect on performance if any:

- No water,
- Water,
- 0.15%,
- 0.5%,
- 1.0%,
- 1.25% scrubber additive.

Two graphs were plotted for this test, shown below in Figure 5-9 for the average gas concentrations and average efficiencies for each setup.

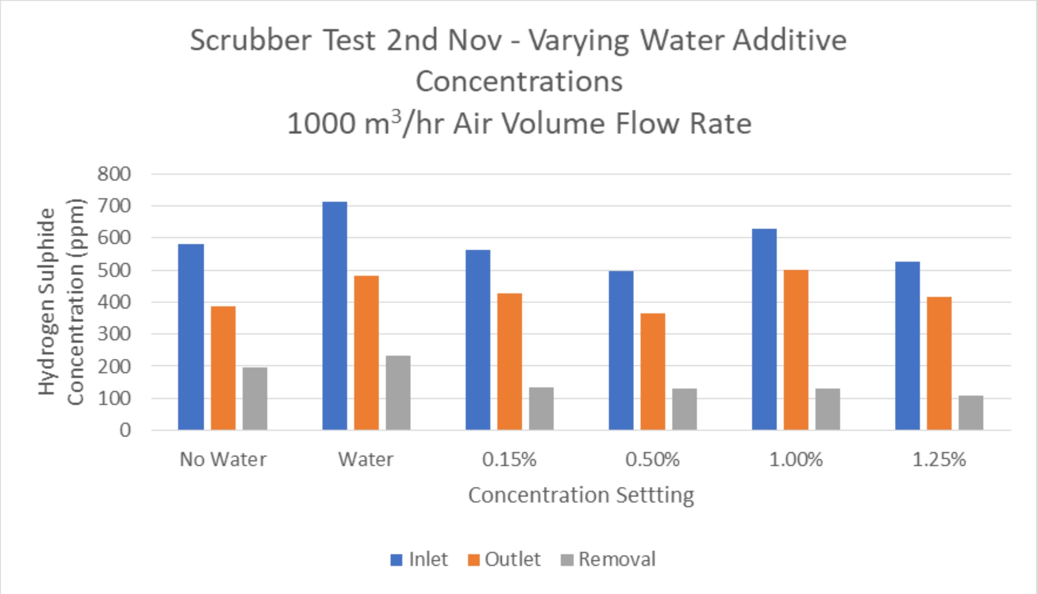


Figure 5-9 Average gas concentrations with varying additive concentrations

The average efficiency of the scrubber in this test is shown in Figure 5-10, where the hydrogen sulphide concentration difference between inlet and outlet is divided by the inlet concentration, and multiplied by 100 to get a percentage.

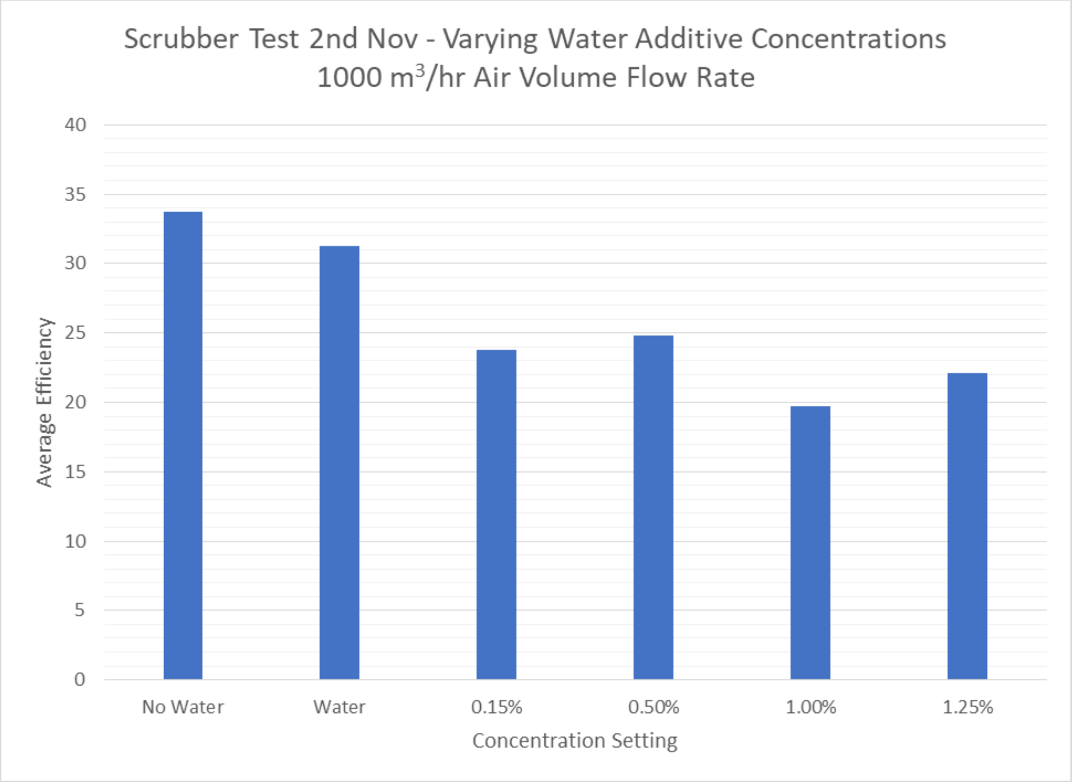


Figure 5-10 Average efficiency with varying additive concentrations

The results were conflicting, seeming to show a downward trend where an increase in scrubber additive had a negative impact on the scrubbing efficiency. The test for no water was the most surprising, as this should have theoretically showed an efficiency of zero, as there will have been no removal.

There could be a large number of uncontrollable variables changing between each of these measurements leading to erroneous or invalid data. The weather could be causing these errors, or even as the measurements were being recorded the hydrogen sulphide concentration from the source may have been inconsistent and fluctuating. If there were any leaks of clean air into the air scrubber, this would have the effect on diluting the polluted air, and give the experiment a false positive effect, showing removal whereas the gas is more spaced out.

5.6. Results Discussion

The prototype has been able to scrub an air stream from a sewage treatment works successfully, as shown in the three tests. It was seen in all tests that a reduction in H_2S concentration was made comparing the inlet to the outlet gasses through the scrubbing chamber.

The testing site provided a challenging source of polluted air, as the gasses measured were in the range of 500 ppm to over 2000 ppm, so much so it was above measuring range of the sensor in Test 1. There was a big challenge also as the testing site had ever changing conditions, and no day or hour was like another in terms of temperature, weather conditions, gas concentration, or gas consistency.

Test 1 showed that there was a definite reduction in H_2S concentration of the air after it was passed through the scrubbing chamber. The concentration of hydrogen sulphide removed was near 500 ppm, with an average efficiency of 21.9%.

Test 2 showed that there is a positive effect on the scrubbing efficiency when increased water volume in the scrubbing chamber. Increasing water flow rates from 20 to 200 litres per hour shows a relative increase in scrubbing efficiency. There is a trend that the greater the water flow rate, the greater the air scrubbing ability. A 13% improved efficiency was determined between the lowest water flow rate and highest, 42% to 55%.

Test 3 showed a conflicting result, where there was a negative trend for scrubbing performance with increased scrubber additive. This data could have been affected by a wide array of factors, from unfavourable gas compositions to the H_2S being measured, or errors in the measuring equipment. The air scrubber could also be showing signs of leaking air into the chamber which has the effect of diluting the concentration, contributing to measurement uncertainty.

As the tests were being run consecutively one after the other, an attempt to clear the chamber of pollutants was done by having a cool down by shutting off the system for a short period, as the next test was being set up. For the Zero water test result, it is undetermined that there is a potential for pollutant H_2S gas to be reacting with the scrubbing chamber and equipment, due to no water acting as a chemical barrier. For example the scrubber walls were made using Acrylic for its unreactive properties, however the ductwork is made from galvanised steel, which once the Zinc is eroded, the steel will react readily with H_2S. As well as this, any H_2S reacted with water could make diluted Sulfuric Acid, which wouldn’t have been detected. Further analysis in a future test would involve obtaining a sample of the effluent waste and analysing it using a gas chromatograph equipped with a flame photometric detector. There is potential of an unobserved aerosol in the chamber, or some chemistry that is reacting due to the air stream being taken out of its native environment, that could be altering the true results here. This could also be investigated further with multiple gas monitoring equipment. Mist if not separated effectively enough, can have mixed with the output air, the sensor may have detected some of this and affected results. Additional demisters could be implemented here to reduce this in future study. (29)

The composition of the waste air was not measured, but it can be assumed to be a mixture of different gasses due to the nature of sewers in septic conditions. Gasses including methane, ammonia, and carbon dioxide among others, is likely to have been present within the dirty air stream, and to be in high concentrations alongside the high concentration of hydrogen sulphide that was measured. More of a variety of gas detection sensors to detect other gas species would have been useful during testing. (26,27)

The waste gasses drawn from the live sewer meant that the waste gasses were not consistent in concentration, and likely composition, depending on the time of day. Weather conditions such as humidity and temperature would likely have an effect on the composition and temperature of the sewer stream and this in turn would have an effect on the water droplet for its lifespan in the chamber and the affinity to pollutants. (24,28,30)

It was intended to have a flow rate of 1000 m^3 per hour for the tests carried out, however it can be assumed that there are some areas of stagnation of flow and recirculation, where every consideration was made to limit this from the CFD study. Any undesired airflow could have reduced or increased the intended retention time within the chamber affecting the scrubbing performance.

The design of the scrubber, with its modularity in mind, means that it is well suited to and applicable to any number of sectors requiring air treatment, such as sewage treatment, material transfer sites, buildings for livestock such as hog farms or chicken sheds, developmental sites or buildings with human occupancy. (7,9,10)

CHAPTER 6 – Conclusions

6.1. Conclusions

The project has shown successfully that a modular air scrubber that utilises a surfactant as a scrubbing agent is possible. A design of an air scrubber was conceptualised and optimised for manufacture to be used at a testing site. Various designs were made on computer modelling software and designs were critiqued through discussions of performance, and aided in the use of air flow simulations.

Performance measurements were taken of the air scrubber in operation, scrubbing Hydrogen Sulphide gas, and tested to determine the effects of varying several parameters on the scrubbing performance.

The results of the testing showed that there is a positive effect by displaying a difference in Hydrogen Sulphide before and after the scrubbing action with the innovative methods.

6.2. Further Study

Future experimentation of the air scrubber should be completed, and with a secondary design with improvements made from lessons learned with this project, with the aim to improve on the achieved performance.

With the design of the modules that make up the air scrubber, certain features should be looked at for improvement. The main area should be an improvement in sealing joints between module sections, such as the use of gaskets. This would eliminate the potential for leaks in the system, i.e. harmful pollutants to escape the chamber and outside air leaking into the system.

If the maximum modular volume is utilised, the weight to be supported by the base section will be high. Further study and improvement on the design should include finite element analysis on the scrubber base and supporting legs.

More sampling should be made with the prototype in different test locations and weather conditions to fully realise its performance and optimised through further tests.

Testing the scrubber in a range of different weather conditions will be useful to understand how temperature, humidity and atmospheric pressure would affect the duration of life of the water droplet within the chamber. Temperature and humidity can affect water droplet size through agglomeration or evaporation, and hence the likelihood of absorption of the pollutant into a water droplet. A method for characterisation of water droplet sizes could be implemented, such as using optical particle sensor equipment from AlphaSense, normally used for measuring particulate matter in an air quality application. An adaptation of such could be employed to measure the size of water droplets in multiple stages of the air scrubber for monitoring.

A concept design of a mass produced air scrubber could be made benefiting from the lessons learned from this project. A conceptual design is shown in Appendix B.

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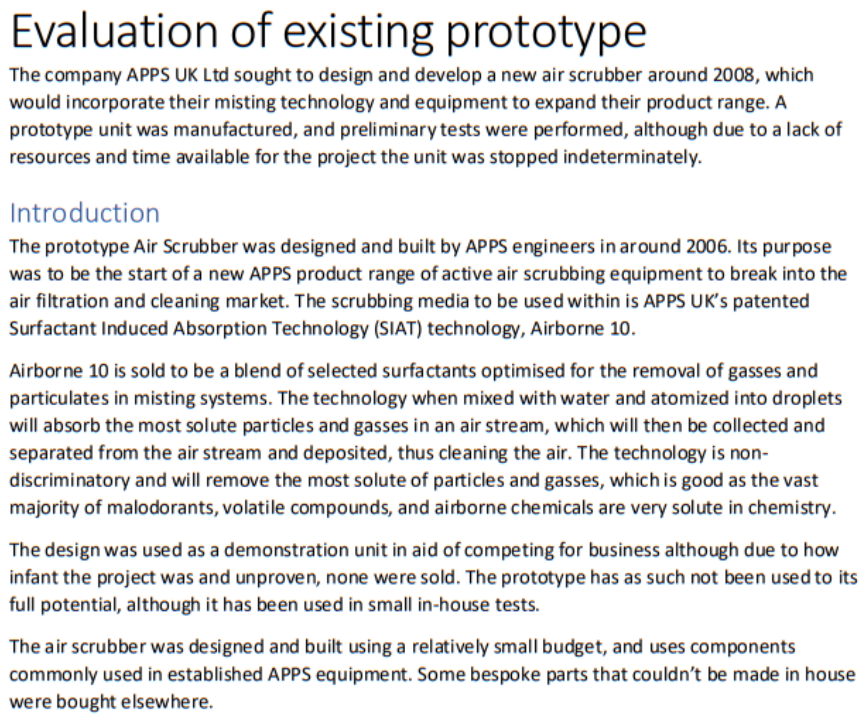
APPENDIX – TABLE OF CONTENTS

Appendix A – Evaluation of Existing Prototype



Evaluation of existing prototype

The company APPS UK Ltd sought to design and develop a new air scrubber around 2008, which would incorporate their misting technology and equipment to expand their product range. A prototype unit was manufactured, and preliminary tests were performed, although due to a lack of resources and time available for the project the unit was stopped indeterminately.

Introduction

The prototype Air Scrubber was designed and built by APPS engineers in around 2006. Its purpose was to be the start of a new APPS product range of active air scrubbing equipment to break into the air filtration and cleaning market. The scrubbing media to be used within is APPS UK's patented Surfactant Induced Absorption Technology (SIAT) technology, Airborne 10.

Airborne 10 is sold to be a blend of selected surfactants optimised for the removal of gasses and particulates in misting systems. The technology when mixed with water and atomized into droplets will absorb the most solute particles and gasses in an air stream, which will then be collected and separated from the air stream and deposited, thus cleaning the air. The technology is non-discriminatory and will remove the most solute of particles and gasses, which is good as the vast majority of malodorants, volatile compounds, and airborne chemicals are very solute in chemistry.

The design was used as a demonstration unit in aid of competing for business although due to how infant the project was and unproven, none were sold. The prototype has as such not been used to its full potential, although it has been used in small in-house tests.

The air scrubber was designed and built using a relatively small budget, and uses components commonly used in established APPS equipment. Some bespoke parts that couldn't be made in house were bought elsewhere.

Installation and Usage

The success of the air scrubber is won by its versatility in applications and ability to perform for a wide range of performance requirements and orientation scenarios. The small number of components and fixings add to the air scrubber's reliability and the operation efficiency.

The air scrubber utilises air assisted misting nozzles which are used in dispersing the Airborne 10 water mix into the air stream. Air assisted nozzles require a water and compressed air source to operate and thus both are in the system. It can be shown in Figure 1 how the air scrubber operates and what the sequence of the systems is.

Air Scrubber Operation

The Dosatron, Figure 1 (a), is used to mix a controlled amount of Airborne 10 with water. This can be varied depending on how much material needs to be removed from the air stream.

The air scrubbing container, Figure 1 (b), is a big area designed to maximise the retention or contact time with dirty air and mist to maximise the particulate and gas removal. It is shaped cylindrically to utilise a method of separation called cyclonic separation. The air stream mixed with mist droplets are intended to go round in a helical or a spiral direction. The Centrifugal forces send the heavy particles to the outer perimeter, and the clean gas moves close to the axis due to buoyancy of the high pressure generated on the outer perimeter. The clear gas stream is then allowed to exit the chamber through the axis, where all water droplets and dirt coalesce and fall to the bottom of the chamber, collected, and removed for disposal.

The scrubber requires a demister, Figure 1 (c), which is used as a failsafe to remove any water droplets that could have been re-entrained in the exiting air stream. It is necessary to rid of all water droplets as they are the scrubbing media and will have absorbed within them unwanted gasses and/or particulates. This means any escaping droplets will decrease the air scrubbing efficiency as they carry pollutant. The Demister is a fine mesh that coalesces moisture into droplets which are not allowed to pass through.

The Impeller is used to drive air through the system by providing a negative pressure system. The advantages of this is vast, but the main consideration is for leaking of the system. If there are any leaks, the gasses will travel into the air scrubber so no polluted air bypasses the system.

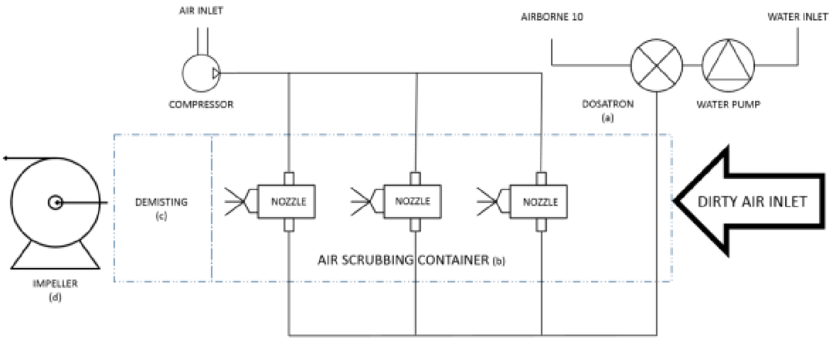


Figure 1 Basic Working of Air Scrubber

Installation Variations

The design of the air scrubber means that it can be a standalone unit or can be in parallel with more of its kind. This ability means that the air scrubber can be installed and can be made fit for purpose on any site for any performance requirement. The air scrubber can be used for an open or closed air cycle if it is desired for recirculation or not. The diagrams in Figure 2 show different ways of using the air scrubber.

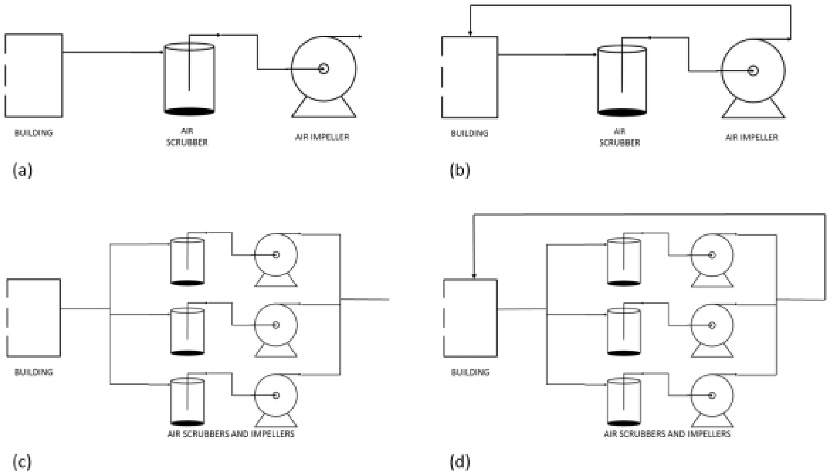


Figure 2 Air Scrubber Systems (a) Standalone open cycle to air (b) Stanalone closed cycle air recirculation (c) Paralell modules open cycle to air (d) Paralell modules closed cycle air recirculation

The most basic installation for the air scrubber is a straight in and out setup as shown in Figure 2 (a). The air is removed from the building, sent through the scrubber and exits to the atmosphere with unwanted particles and gasses removed.

The air scrubber can be used in parallel with other air scrubbers if a higher air flow is required than what is possible with one unit. The operation works the same way as (a) although in the air routing there are junctions to separate air flows. This set up allows for the ability to shut down units at a time if not required or maintenance needs to be carried out, while scrubbing still taking place.

Systems shown in (b) and (d) are for situations where air is to be replenished back in the building. This air recirculation would be useful for situations requiring air conditioning or temperature control, as useful thermal energy is not lost to the atmosphere.

Components

The air scrubber is designed with components strategically placed to optimise the contact time of the mist and dirty air as this increases the efficiency of the product. This is therefore why there are two stages within the scrubber joined by a series of pipes. The scrubber operation is shown below in Figures 3 and 4 which shows the direction of airflow.

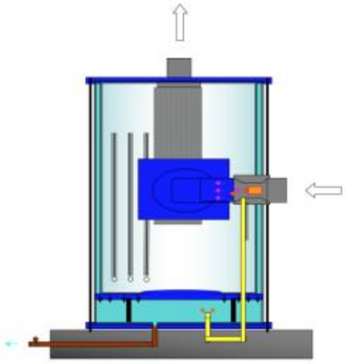


Figure 3 Side view of air scrubber

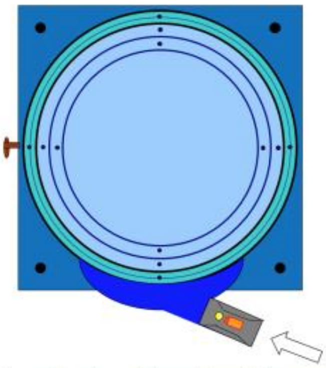


Figure 4 Plan view of air scrubber with top removed

The air inlet passes through tubing where it travels around a misting nozzle where mist is added to the airstream before entering the first stage cyclone, seen in Figure 5 below.

Figure 5 Dirty air inlet and first nozzle

The air scrubber can be seen below, in Figure 6, with its top removed showing the internal chambers and pipes. The first chamber is considerably smaller than the second one which is thought to increase the air flow speed on the first chamber increasing the separation efficiency for the first stage cyclone.

Figure 6 Air scrubber with top removed

The pipes are used to separate the two stage and move the air to the top of the second chamber to increase the efficiency of the cyclone separation. Through the first stage the vast majority of large diameter particles will have been removed. The gasses and micro-sized particles have and are being absorbed by the water droplets, which are then separated in the final chamber. More misting nozzles are added in the final chamber which increase the absorption of material.

The mist with absorbed gasses and particles require removing from the outlet air stream, as re-entrainment with the outlet would be a failure in the design of the air scrubber. Therefore the majority of the mist is separated from the air stream by the second stage cyclone as mentioned before. Some mist droplets will be entrained by the airflow and therefore a demister is used in the central axis in the path of the outlet. This can be seen in Figure 7 where the demister shroud has been removed. Note also the central nozzles can be seen on the top.

Figure 7 Demister shown without shroud

The final stage is what powers the air scrubber as to what drives the air flow through the devise, the Centrifugal Impeller. The impeller used is a dust extractor fitted to the air scrubber and has a rated volume flow rate of 1000m^3/h. The impeller can be seen below in Figure 8, where the exiting clean air is let out to the open.

Figure 8 Centrifugal Impeller

Performance

The prototype unit was turned on in a clean environment to investigate the characteristics and performance of the air scrubber. The overall efficiency of the air scrubber would be determined on difference of air quality before and after in a polluted air stream.

Addition of Airborne 10

It was thought to be important to show the effect of airborne 10 has on the water as the surface tension of water is affected, shown in Figures 9 and 10.

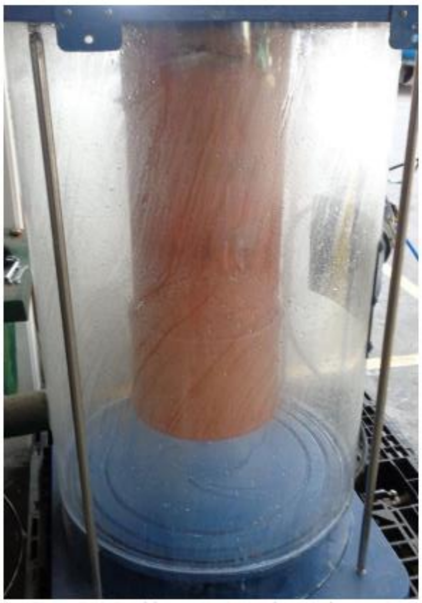


Figure 9 Air Scrubber operating without Airborne 10

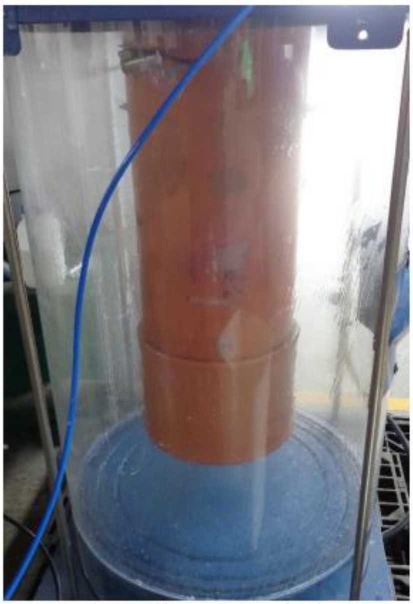


Figure 10 Air Scrubber operating with Airborne 10

With Airborne 10 in solution the water droplets coalesce far easier due to the reduced surface tension. In Figure 9 without Airborne 10 the mist forms large droplets which then fall to the base leaving tracks. This compared to Figure 10, with Airborne 10, is very different. The lower surface tension allows the droplets to run down the cyclone walls easier and wet the entire surface so the droplets form a smooth sheen as they fall, without large clumped droplets.

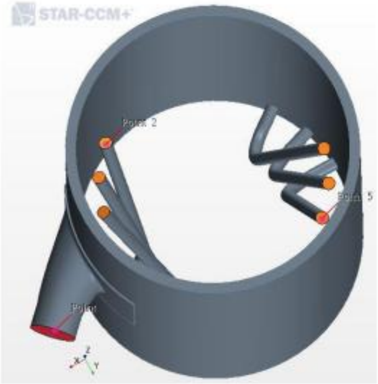
This experiment shows that there is a very positive side effect to using Airborne 10 as the air scrubber is self-cleaning internally. This will have a very positive effect as to the maintenance of any future builds of air scrubber.

CFD Analyses

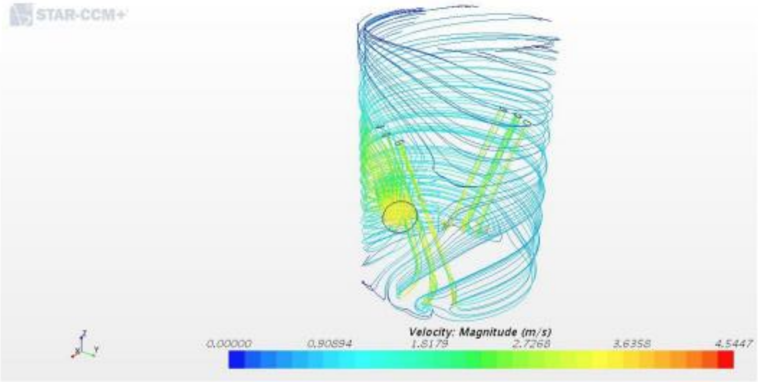
A Computational Fluid Dynamics analysis was performed to visualise the air flow inside the air scrubber, performed using CD-Adapco STAR-CCM+ computer software.

The computational analysis was set up by separating the two sections of the air scrubber; the outer and inner sections. This was done so that the displayed visuals would be clearer and to reduce the required computation time for a similar quality analysis.

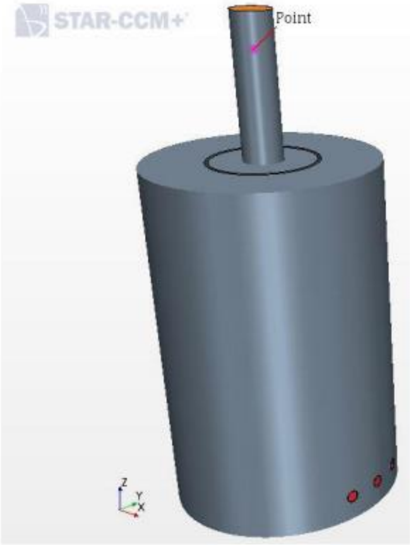
The outer section was performed first as this is what the air flow would first enter. The computer visual can be seen below in Figure xxx showing the domain of the outside section. The air enters the inlet on the left, then exiting through the 6 tubes after being made to spiral through the void.



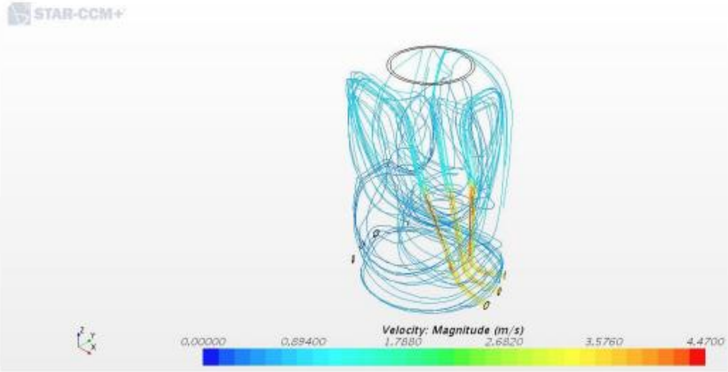
The flow is visualised in Figure xxx where an air flow speed of 3.5m/s was induced through the inlet which is the speed of the air drawn to the 100m³/h fan. It is shown that the streamlines travel in a spiral both upwards and downwards of the inlet. The air that goes downwards has a shorter retention time within the domain as it is the first to leave the volume through the pipe entrance at the bottom, whereas the air at the top remains for a longer duration almost stagnating as the lines recede at the top.



The domain of the inner section of the air scrubber is shown below where the tubes are modelled inside the body. The air enters the section at the bottom through the six tubes shown in red, which then exits through the centre tube shown in orange.



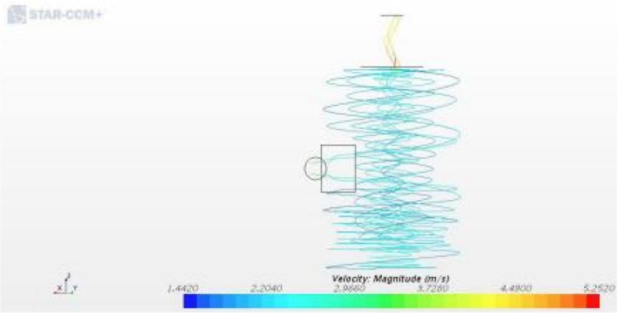
The air flow inside the inner section is visualised in the below image where three of the six tubes are shown for clarity with regards to the unit's symmetrical design. Inlet velocity is set at 3.5m3/h which is what was observed at the same point on the outer section and calculated from the volume flow rate and cross-sectional area. The streamlines of the air shows a chaotic movement emanating from each tube which doesn't resemble the intended cyclonic motion. The air swirls around after being directed towards the roof of the scrubber and then travels towards the base where it then enters the shroud of the mist eliminator and then exits the scrubber.



A second analysis was set up to investigate the flow characteristics of the scrubber with the inner wall removed so there is one region. This was done to investigate how the air would behave and see if a cyclonic movement of air could be achieved.

The following domain was created for the analysis where the air enters from the same inlet and travels up out through the shroud of the mist eliminator to exit out the orange region.

The analysis showed that a cyclonic flow within the scrubbing chamber could be achieved and is shown in the below image with streamlines for the airflow. The air is entering in the middle and is sent in a helical pattern both upwards and downwards. The air then travels to the bottom to enter the shroud of the mist eliminator and then exits upwards where it is accelerated through undergoing cyclonic movement.



Discussion

The CFD analysis has shown that the air scrubber does not have the internal flow characteristics that was intended by the designer. The designer wished to maximise the potential for the mist to absorb gasses and remove particulates through a cyclonic separation technique, although the CFD has shown there is a small region that this is actually occurring, mainly in the outer section.

There is a high proportion of the internal volume that is not being maximised, mainly in the outer section where the inlet is positioned halfway up the body. The airflow seems to be stagnating in this upper region whereas the air should be treated equally and so the inlet should be better positioned such as at the top of the body.

The tubes transferring the air from outer to inner sections seem to create a bottleneck for the airflow as it can be seen there is an increase in airflow rate. This relates to a high pressure drop which increases the work required for a fan reducing the efficiency of the unit. These bottlenecks should be reduced by making the unit have one region only or have the tubes wider or more in number.

For the unit to perform as intended with a cyclonic movement, all restrictions must be removed to allow an unrestricted flow within the unit. This was proved in the second analysis when the inner wall was removed to make one region inside.

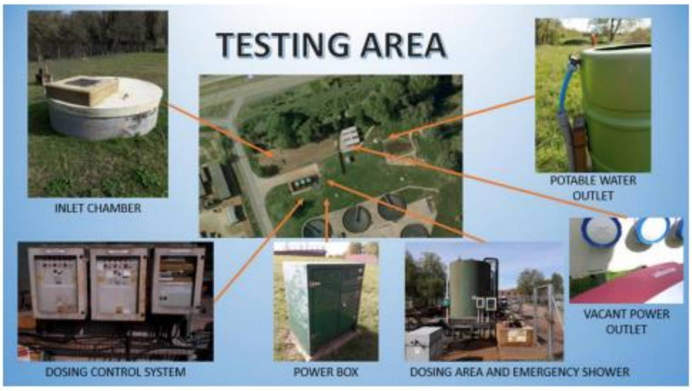
The inlet of the unit should also be placed either at the top or at the bottom of the wall at a tangent to the wall surface. This will ensure the air is distributed evenly and help to create a cyclonic movement of air.

Site Testing of Air Scrubber

Testing the performance of the air scrubber in a real world environment is paramount in investigating its capability in air scrubbing, and therefore a testing site was found with a polluting gas stream to perform this investigation.

Site Layout

A sewage Treatment Works owned and run by [redacted] in [redacted] was used as a test site for the air scrubber, the site layout is shown in Figure ###. A sewage inlet well present on the site is a source of odorous gasses and has been a problem for site officials for some time. The inlet chamber is one of the access ports on the site to the sewage incoming to the site for treatment containing waste from several industrial companies. There is, notably, a food processing company removing starch from their processes contributing to the sewage, and so the liquid has a high septicity. Past sampling tests have detected relatively high Ammonia, Methane and Hydrogen Sulphide gas concentrations in the well.



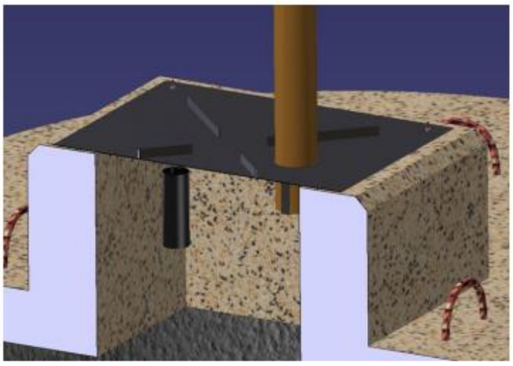
The experimental procedure is to set up the air scrubber on top of the well and extract the air from the inlet chamber through a custom-made man hole cover. There is as seen below a CAD render of the intended test layout.

Experimental Setup

It was decided to only test the scrubber's performance to remove Hydrogen Sulphide gas as it is to be the most prominent species and easiest to detect in the inlet well. H_2S levels were said to be over 1000 Parts Per Million in the past and so specialist measuring equipment was required for data collection.

The efficiency of the air scrubber is to be determined by measuring the Hydrogen Sulphide H_2S concentration on the inlet and outlet, and calculating the difference showing how much has been removed. Gas level logging equipment called an OdaLog L2 was used to measure the gas levels throughout the experiment, which is shown in the below Image.

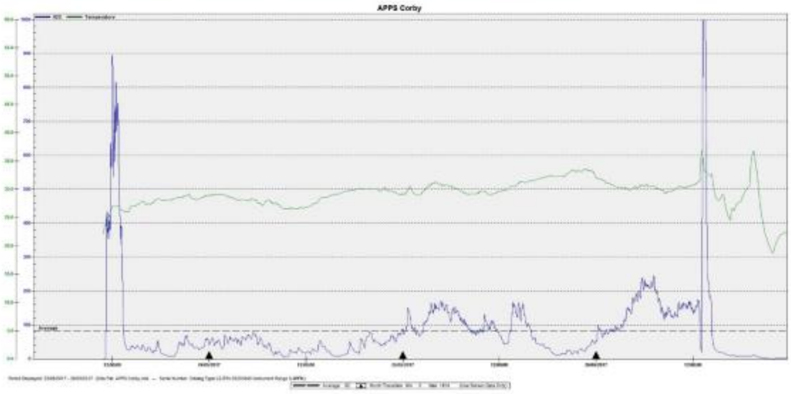
The OdaLog L2 was used initially to continuously log the gas concentration levels within the chamber over 3 days to understand any gas concentration fluctuation within the chamber. This can be seen below in the CAD render for the chamber cover, where the air is extracted from the plastic piping, and the OdaLog L2 sensor is attached on the custom-made chamber lid.



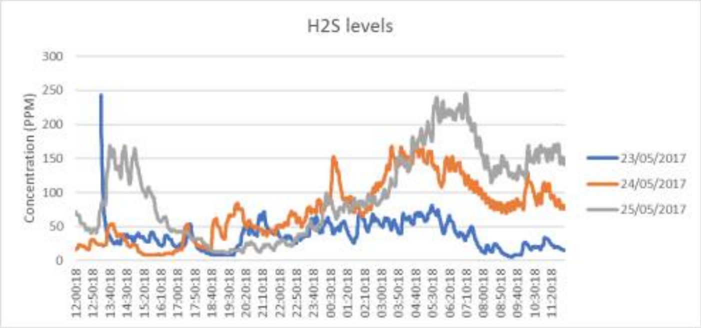
To test the performance of the air scrubber the OdaLog L2 was used at the end, where the sensor was put in the outlet of the scrubber to measure the gas levels exiting the unit. The Fan used to extract the air was set at a constant $100m^3/h$ flow rate.

Results

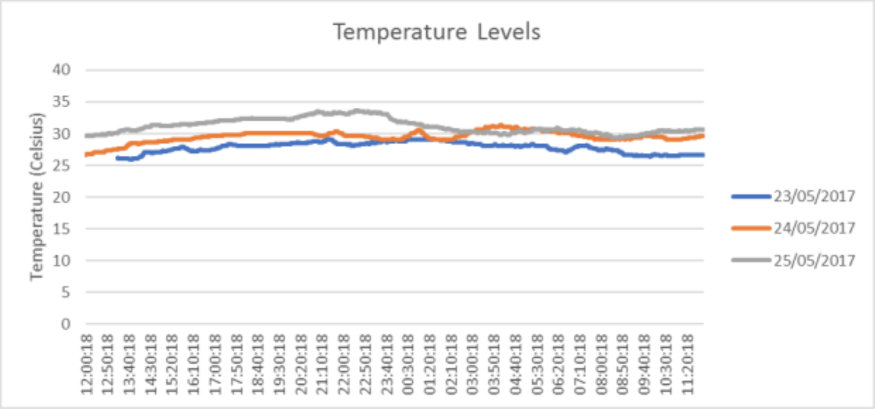
The OdaLog Logger recorded the below raw results for while it was in use over the 4-day period showing gas levels in blue and temperature in green on the below chart.



The below graph shows the H2S levels within the well during a three-day period when the scrubber was powered off. It shows that the gas levels are not constant throughout the day but vary. The levels are also considerably lower than when the scrubber was on, as a peak level of 245ppm is observed.



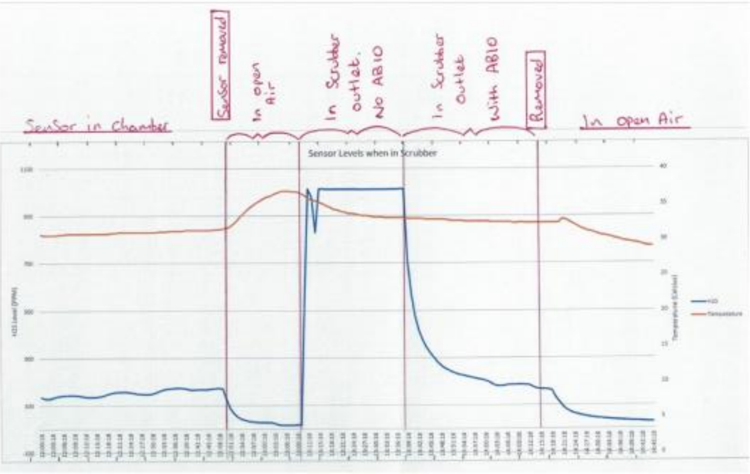
The temperature levels within the chamber were recorded and is shown below. The graph shows very little variation between the three days as it ranged between 26 and 33 Degrees.

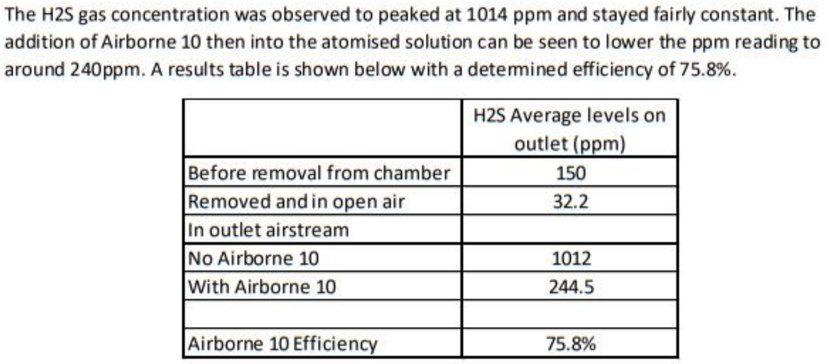


The Noon temperature outside during the three days was recorded, and are as follows;

Date	Noon temp (Deg)
23/05/2017	18
24/05/2017	21
25/05/2017	24

During the final day of testing, the OdaLog L2 sensor was placed within the outlet piping to record the vented gas concentrations. Below can be seen the results, showing the effect of Airborne 10. The air scrubber fan was powered on for 30 minutes without airborne 10 being used to determine the gas level within the air stream. After this Airborne 10 was added to the mist for a further 30 minutes to scrub the polluted air of gasses. It can be seen in the graph that the Hydrogen Sulphide level dropped dramatically therefore proving the addition of Airborne 10 was having a scrubbing effect.




The H2S gas concentration was observed to peaked at 1014 ppm and stayed fairly constant. The addition of Airborne 10 then into the atomised solution can be seen to lower the ppm reading to around 240ppm. A results table is shown below with a determined efficiency of 75.8%.

	H2S Average levels on outlet (ppm)
Before removal from chamber	150
Removed and in open air	32.2
In outlet airstream	
No Airborne 10	1012
With Airborne 10	244.5
Airborne 10 Efficiency	75.8%

Discussion

The OdaLog L2 logging unit recorded H_2S gas levels over the duration of testing on site, and the results were displayed in the graph. For the majority of the time where no air extraction occurred the gas levels fluctuated between 0 to 250 ppm. This shows that the gas levels change because of some unknown factor but could be speculated to be responding to various changes to the supply of sewage to the well or a draw to processes within the plant. Other peaks were recorded but resulted when extracting air with the air scrubber.

It can be seen also that the temperature of the gas in the well fluctuated between 25 and 35 degrees Celsius, which could be due to the type of waste being put into the sewage and the septicity of the sewage being exothermic.

When testing the air scrubber and extracting air from the well the gas levels increased dramatically compared to the air at rest. It is best explained for this to occur through comparing water and oil in a glass, as Hydrogen Sulphide is denser than air with a density of 1.36kg/m3 it sinks to the bottom of the well, whereas air is a lighter gas of approximately 1.225kg/m3. With the air being extracted the denser Hydrogen sulphide is lifted to replace it which then shows a higher reading on the sensor.

There is a problem with the OdaLog L2 as in the results during scrubber testing the reading peaked to 1014ppm and remained constant for 30 minutes. This was bad as the OdaLog L2 used was rated to measure a maximum of 1000ppm and so the gas levels were off the scale. The actual gas levels being extracted out of the well would have been far higher than 1000ppm however there is no way to determine the exact gas level without a higher power gas sensor. This therefore meant that the calculated efficiency of 75.8% should have been far greater. For future tests a gas sensor with a higher range should be used.

Prototype Reflections

The existing prototype air scrubber has had its design analysed, it has been tested and been experimented with in a real-world environment. The unit has shown to perform well as it functions as an air scrubbing unit that achieved at least a 75% efficiency during testing.

The observations, tests and experiments performed on the prototype have highlighted a wide range of good elements in its design, some design flaws, and ideas on how the unit could be improved. These have been identified from performing the in-house tests, the CFD analyses, and experimenting on an active sewage treatment works with real pollutants.

The following are some of the major design improvements that were observed which should be addressed in future designs of the air scrubber.

Through completing the in-house tests, it was observed that there were several leaks along the seals of the scrubber, which is not good as the unit should be sealed to a high quality. Leakage of scrubbing fluid is not good as there could be harmful contaminants being absorbed and so all liquids should be collected and disposed of safely. The future design of the scrubber should have a good sealing method between parts. Leaks could also mean that untreated polluted air could have the opportunity to escape.

It was observed that mist was coming out of the fan when the unit was running, meaning that the mist eliminator was not working sufficiently. The mist should not be allowed to escape as it will be carrying pollutants and therefore reduce the efficiency of the air scrubber. The mist eliminator may have expired due to its age, and therefore a future version should look to optimise with new technology a new mist eliminator, or alternatively seek a design that can eliminate the need for a mist eliminator.

The unit uses air assisted misting nozzles to create the scrubbing mist which requires the use of compressed air. That means there is an added utility required to make the system operational, whereas there are other methods to atomise water into a mist without a separate utility. Water pressure can create a mist through by using an impingement nozzle for example, or the mist can be attained through mechanical means through a rotary atomiser. These methods use a utility that is already present without adding another which could make the unit more expensive to build and run.

The inlet to the unit is not ideally situated as the airstream is not optimised for the even distribution of untreated polluted air. The air should be optimised so that it spends the longest amount of time as possible within the chamber, called retention time, so that the treatment efficiency is maximised. The air has been shown through CFD that some of the air travels through the unit much faster than the rest due to the inlet position. A future design should mount the inlet on the opposite side of the unit to the outlet to maximise retention time.

The misting nozzles are positioned within the chamber to interact as best with the polluted air as possible, however it has been seen that the longevity of the mist is quite short due to the proximity to the walls of the unit. This reduces the number of droplets mixing with the pollutants and therefore reduces the efficiency of the unit. A future model should ensure the life expectancy of the mist is maximised so that a higher percentage of pollutant is absorbed before the mist droplets agglomerate on internal surfaces.

Appendix B – Productionised Modular Air Scrubber Concept

The concept production air scrubber design shown below in AB-1. The design improves from the prototype however a product for market allows for more complex methods and tooling for manufacturing parts. As such, the concept utilises the manufacturing method of blow moulding, for making single complete module units.

The concept is made from large units which bolt together to make each module tier. As shown, one module layer is made by two units. This makes for quick assembly, and price for manufacture cheaper due to the simple design.

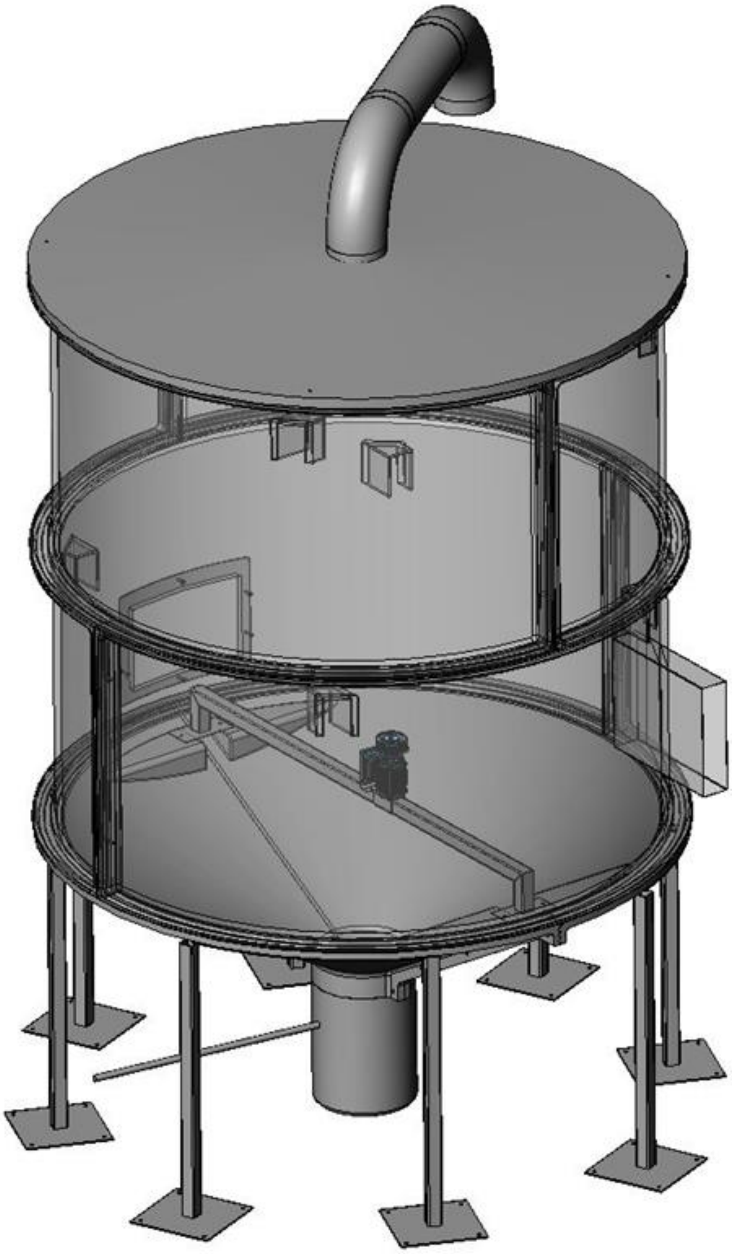


Figure AB-1 Concept of productionised air scrubber

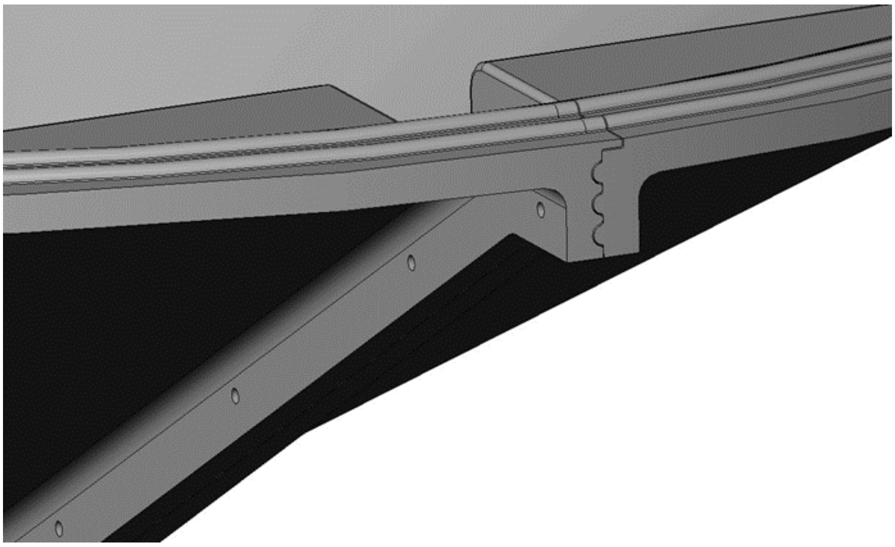


Figure AB-2 Concept of scrubbing chamber base

The scrubbing chamber has the same similar features as the prototype, where there is an inlet and outlet for the air. An access hatch is still made in a wall section for the maintenance of the atomiser equipment in the centre.

Figure AB-2 shows a benefit for a different manufacturing method allows for better performance, as this design adopts a ‘Labyrinth seal’ design between all connecting faces. As seen for the Base section joints, and for where the wall section would rest, there is a series of ridges which would have the benefit for increased sealing of the chamber. A reduction in the amount of air leaking in and out of the chamber will benefit the operation.

The benefit of using blow moulding for manufacture, would mean the surfaces inside the chamber would be more uniform, and therefore performance would increase due to less aerodynamic drag and increased efficiency of the cyclonic airflow. The weight of the scrubber could improve as well, due to plastic having a lower density than the mild steel and acrylic mix of the prototype.

The expandability of this design is not affected too, as just the same idea for additional modules can be stacked on top of each other for expanding the scrubber chamber volume.