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ShowerMagic

A Hygienic and Eco-Efficient Real Time

Greywater Reuse System for Showers

Helsinki Metropolia University of Applied Sciences

Bachelor of Engineering

Environmental Engineering

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Abstract

ShowerMagic is a water purification system designed to reduce the ecological impact of showers by filtrating, sterilizing and recirculating shower water in real time, thus significantly reducing the amount of water and energy required to enjoy a warm shower. The purification system relies on a sand and granular activated carbon filter to remove particulates, suspended solids as well as organic and inorganic compounds and to reduce turbidity. After this, an ultraviolet irradiation reactor is used to disinfect bacteria that may be present in the water to ensure clean, safe and ecological showering.

A 2^2 factorial design was conducted to model and optimize the height and width dimensions of the sand and granular activated carbon filters. Each treatment method is tested individually with a specified contaminant simulating concentrations of domestic grey water. Removal efficiency was over 98 % for particulates in the form of quartz sand, 92 % for suspended solids in the form of mineral clay in the largest filters, and a log 5 reduction was seen in *Escherichia coli* bacteria concentrations, even with turbidity values 10 greater than normal. Water quality was improved further over time with water recirculation and by combining all treatment methods. Ammonium hydroxide used to simulate inorganic compounds had conflicting results with removal efficiency around 50 %. Based on the test prototype it is proposed that a shower consuming only 10 L of water is possible which is the equivalent of 1 minute of normal showering time.

With increasing water scarcity, greenhouse gas emissions and a growing global population, the strain on resources is greater than ever before. ShowerMagic offers a viable solution for reducing our impact on the environment while still enjoying our morning rituals.

Keywords	ShowerMagic, Sustainable development, recycling water, reusing water, simple water purification system, micro water treatment system, sand filter bag, granular activated carbon bag, ultraviolet irradiation reactor, *E.coli* sterilization, grey water reuse, grey water showering, smart shower, magic shower

Abstrakti

ShowerMagic on vedenkäsittelyjärjestelmä, joka on suunniteltu parantamaan suihkujen ekologista jalanjälkeä. ShowerMagic puhdistaa ja kierrättää suihkuvettä realiajassa joka huomattavasti vähentää tarvittavan käyttöveden määrää, tämän seurauksena myös lämmitysenergian tarve laskee huomattavasti. Vedenkäsittelyjärjestelmä hyödyntää hiekka- ja aktiivihiilisuodattimia hiukkasien, kiintoaineiden sekä orgaanisien ja epäorgaanisien yhdisteitä poistamisessa ja veden sameuden alentamisessa. Ultraviolettidesinfioinnilla varmistetaan, että pesuvesi on desinfioitu, eli turvallista käyttää.

Tutkimuksessa käytettiin 2^2-analyysimallia mallintamaan ja optimoimaan suodattimien leveyttä ja pituutta. Jokaista puhdistusmenetelmää tutkittiin yksittäisesti simuloimalla suihkujen harmaanveden epäpuhtausmääriä. Kvartsihiekan hiukkasia alennettiin 98 % hiekkasuodattimella, 92 % sameutta simuloivista mineraalisavikiintoaineista poistettiin aktiivihiilisuodattimella ja *Escherichia coli* -bakteerikantoja alennettiin 5-suhdanteen logaritmiin ultravioletti desinfiointilaitteella jopa silloin, kun sameus oli 10 kertaa suurempi kuin yleensä. Veden laatu nousi, kun vedenkäsittelyjärjestelmä kierrätti veden käyttämällä kaikkia menetelmiä samanaikaisesti. Ammoniumhydroksidia (NH_4) käytettiin simuloimaan epäorgaanisia yhdisteitä. Tällöin poiston tehokkuus oli noin 50 %.

Prototyyppikokeiden tuloksista on laskettu, että on mahdollista valmistaa suihku, joka käyttää vain 10 litraa vettä ja antaa käyttäjän nauttia vedestä niin kauan kuin hän haluaa. Suihku käyttää vesi- ja energiamäärää, joka vastaa noin 1–2 minuuttia normaalista suihkuttamisajasta. Veden- ja energiankäytön vuosittainen lisääntyminen, kasvava väkiluku ja muut ympäristöhuolet rasittavat maapalloa. ShowerMagic tarjoaa ekologisen ja kannattavan vaihtoehdon peseytymiselle.

Avainsanat	ShowerMagic, kestävä kehitys, veden kierrätys, veden uusiokäyttö, yksinkertainen vedenkäsittelyjärjestelmä, mikrovedenkäsittelyjärjestelmä, hiekkasuodatin, aktiivihiilisuodatin, ultraviolettidesinfiointi, *E.coli* desinfiointi, veden desinfiointi, harmaa vesi, harmaavesisuihku.

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Nomenclature

Backwash	Reversing water flow to wash mechanical filters
CFU	Colony-forming unit; estimate of viable bacterial numbers
Dosage	See irradiance
Escherichia Coli	Gram-negative rod-shaped bacterium
E.coli	Abbreviation of *Escherichia Coli*
Fluence	The total energy delivered per unit area (J/m^2)
GAC	Granulated activated carbon
GACF	Granulated activated carbon filter
Irradiance	Total amount of radiation emitted (by the UVIR)
Irradiation zone	The 3-dimensional cylindrical midpoint of the ultraviolet reaction
Keratinocyte	Predominant cell type constituting the outer layer of skin
Log -1 [reduction]	10^{-1} or 10 % survival rate or 90 % reduction
Log -2 [reduction]	10^{-2} or 1 % survival or 99 % reduction
Microorganism	Single and multicellular microscopic organisms (including viruses)
nm	Nanometer or 10^{-9} m
NTU	Nephelometric turbidity units; a measure of turbidity
Quartz sand	Silica (silicone dioxide) sand
Quartz sleeve	A quartz glass shell which protects the ultraviolet lamp
SF	Sand filter
Solenoid valve	Electromagnetically operated valve
Suspension	Heterogeneous mixture containing solid particles that are sufficiently large for sedimentation
Turbidity	Opaqueness of water due to suspended solids and dissolved compounds

UV-C	Ultraviolet electromagnetic radiation subtype C (200-280 nm)
UVGI	Ultraviolet germicidal irradiation
UVIR	Ultraviolet irradiation reactor
UV lamp	Lamp which emits light in the UV-C spectrum
Voidage	Spaces through which a substance may pass
$\mu J/cm^2$	Micro joules / centimetre squared
$\mu W/cm^2$	Micro watts / centimetre squared
μm	Micrometer 10^{-6} m

Contents

1 Introduction

A shower really needs no introduction – most likely you took a shower the same morning. It may have taken some time for the water to get warm so you left the water it running for a while before getting in. Possibly you have a good water boiler or perhaps you live in an area with district heating, so you didn't have to wait too long for the water to get warm enough to comfortably be able to stand under the showerhead to start your morning bathing routine. This is a common scenario for hundreds of millions of people around the world. Try to remember your shower from this morning. How long did it take? How fast was the water coming out of the pipe? How much water did you use? What was the temperature of the water? How much energy would be needed to heat water to that temperature? Where does this water come from, and where does it go? Did you take a shower to get clean, warmer or cooler, or was it for some other reason? Was it ecological and were you in there for longer than you needed to be to get clean? Do you feel guilty about taking showers that are longer than they need to be?

Many people around the world experience daily problems due to the scarcity of water supplies for a wide spectrum of reasons: economic water stress (lack of available infrastructure), over drafting (excessive use), climate change and water conflicts, for instance when countries divert rivers that flow beyond political borders. It is estimated that 780 million people today lack access to clean water (Water.org, n.d.) and according to an estimation by the UN Food and Agriculture Organization the number of people living in absolute water scarcity could rise to 1.9 billion people by 2025 (Fao Water, n.d.). Population change and economic development have greatly altered the way water is used and it is predicted that they have a much greater effect on water supplies in the next 25 years than changes in the mean climate (Vörösmarty, 2000).

The authors of this thesis have invented a way of reducing the ecological footprint caused by the treating, heating, delivering and processing of potable water used for showering. The idea is simple: filter and re-circulate the water with a pump. Filtration is critical since the purpose of a shower is to get clean. In addition, bacteria that may be in safe for one area of the body can be dangerous to other areas of the body, for example if they are exposed to the eyes or ingested. The filtration system is designed, constructed and investigated throughout this thesis. The end product of the thesis is dubbed ShowerMagic, and this term is used interchangeably throughout the paper to describe both the individual filtration system as well as the shower stall.

ShowerMagic differs from traditional showers in the fact that it recycles water. During the initiation of the shower, the water comes from the plumbing network like in a regular shower. However, instead of the water exiting down the drain, the water is recycled when the pump is turned on.

Temperature control is not taken into consideration in this thesis. Soaps and oils were also not investigated in this thesis due to the limitations in resources and time. A proposed workaround is to simply use soaps and hair products at the end of showering. These two issues may require behavioural changes from the user. However, the benefits are that one is able to enjoy long, warm showers without worrying about excessive utility bills or environmental impacts.

Sand and granular activated carbon filters are utilised to clean the water. After this the water is disinfected with ultraviolet subset C radiation UV-C, which enables clean and hygienic recirculation. This filtration system allows a user to shower for as long as desired while requiring only a small amount of electrical energy to power the pump and the UIVR as well as a controlled and significantly reduced volume of water.

To address the questions regarding shower duration and energy consumption as well as usability, modern open-source microcontrollers, such as Arduino, can be used to control sensors and valves. This gives the user a feedback mechanism that can help improve their own understanding of their showering footprint. The controller is also used to inform the user of filter and UVIR maintenance.

Water is a renewable but finite resource, which must be managed intelligently for the sake of not only future generations, but our own.

2 Review of Literature

2.1 Showering Behaviour

Showering behaviour refers to the length of time one person might spend in a shower and what a person might do in the shower and in what order. It can be thought that showering is more eco-friendly than taking a bath since it uses less water. This statement can be true; however, shower duration, volumetric flow rate and temperature are all factors that affect water and thermal energy consumption in normal domestic showers. With these parameters in mind, a long shower can actually be less efficient than a bath. To prove that the concept has market potential, it has to be shown that the ShowerMagic system saves water and energy compared to regular showers and does so at a sufficiently low cost. Figure 1 below shows shower water consumption over time with different flow rates.

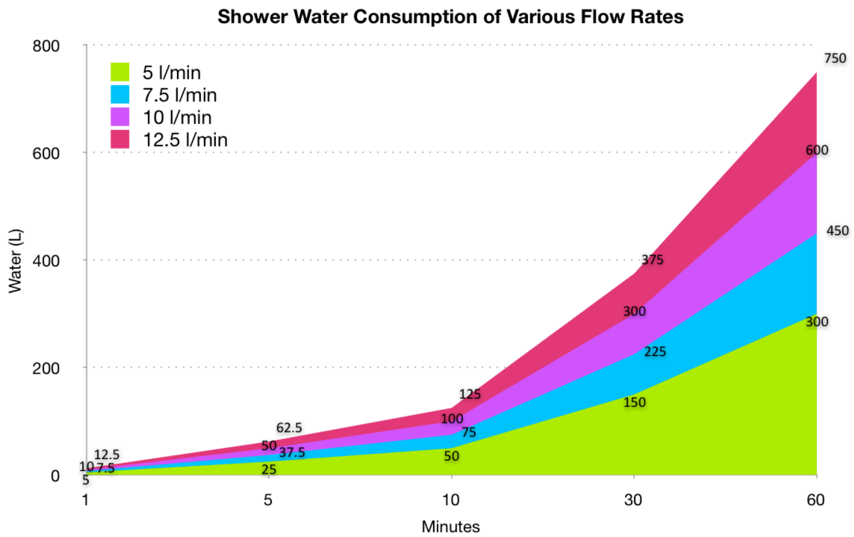


Figure 1. Litres of water consumed in a shower over time with common flow rates (l/min). Table made by the authors.

As can be seen from Figure 1, water consumption increases linearly in response to showering duration and flow rate. A showering behaviour study carried out in Australia (Stewart, 2011) showed that showering durations vary considerably; some people take showers as short as a few minutes, whereas others take showers that are over 20 minutes long. Mean showering time was 7.19 minutes. People in this study consumed on average 151 L per day and on average 33 % or 50 L was used for showering. The flow rate of the shower is set at 8 l/min.

In the same year a study carried out by Unilever in England (Kinver, 2011) showed that the average shower length is eight minutes long with an average flow rate of 7.75 l/min. In this survey, a hundred families had their showers monitored for ten days, which totalled 2,600 distinct showers. The survey was carried out by monitoring showers with digital sensors. The surveyors claim that this method provides more reliable results than questionnaires.

A survey conducted from August 2008 to December 2009 in London by a group called ecH2O (Hassell, 2010) aimed to prove that the five-minute average shower time is a myth. Data was collected from 649 people, 415 of which took showers. They determined average shower length to be closer to 13 minutes. Only 29 % of people took showers of 5 minutes or less, 30 % took showers 6 to 10 minutes long and 41 % took 11 minutes or longer. 4 % of people exceeded the 30-minute mark, as seen in Figure 2. The same study asked people how often they showered, as seen in Figure 2. 22.7 % of participants showered every other day, 64 % showered once a day and 13.5 % reported showering twice a day.

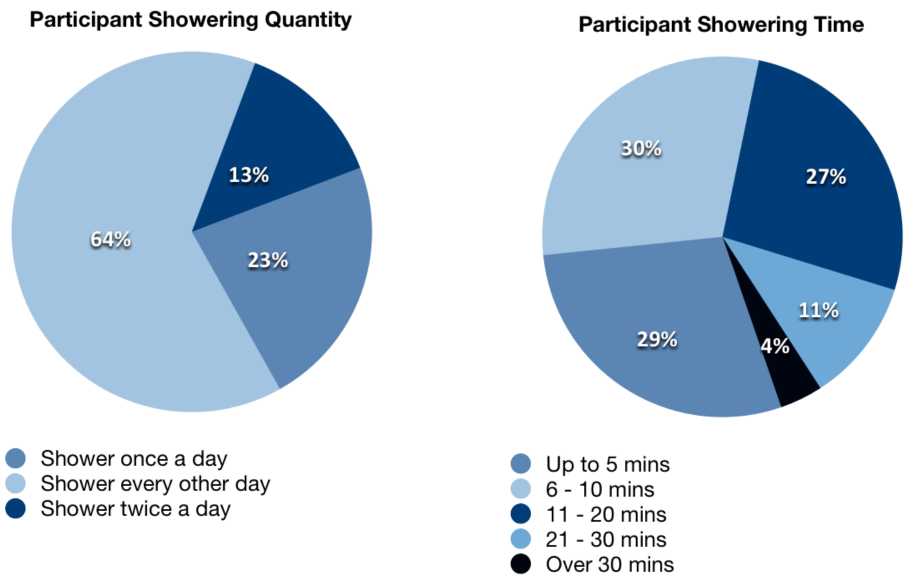


Figure 2. Daily Shower Quantity and Duration of 415 Londoners (Hassell, 2010).

2.2 Domestic Greywater Contaminants

The water in the ShowerMagic system is recycled in order to reduce the amount of energy and water consumed per individual shower. There is a set amount of water used per shower. Once the user has finished using the shower, the water is expelled. The next user then draws a fresh batch of water. During one shower, the water washes over the hair and skin of the user and is then passed through the ShowerMagic system for filtering and sterilization. After this, the water is recycled.

Design Engineering is about finding the appropriate balance between desired and needed components and the trade-offs required to achieve them. The greywater filter in question is designed to handle the most common impurities found on the body through the body's natural processes and exposure to the environment. In the case of work, where the user may be exposed to contaminants such as pesticides or various solvents, such as farming or factory labour, pre-washing without enabling ShowerMagic water recycling may be a simple solution to prevent contamination that the system may not be able to treat. Pre-washing with a reduced volume of water is recommended when the user is exceptionally dirty or in general to prolong filter lifetime.

2.2.1 Contaminates in Bathing Water

The dirt entering bathing greywater comprises of substances which come off the body, such as hair, sweat or urea, skin cells such as melanocytes and corneocytes, faeces or dust and dirt which originate from indoor and outdoor environments. The water quality is also reduced by the use of soaps. Some of these materials or pollutants will also contribute to the turbidity, colour and odour of the water depending on the amount present in the water. Water treatment for hygiene differs from fresh water or wastewater treatment due to the quantity and quality of contaminants in the water. Shower water falls between the two categories and is labelled as greywater; while contaminants are still present, greywater is often ideal for flushing toilets and irrigating gardens if bacteria concentrations can be controlled. In some cases it can even be used for washing clothes. Table 1 cites average pollutants found in bathing greywater compiled from various sources. The most significant pollutants in respect to filtration are the upper limit values of turbidity (> 100 NTU), solids (> 1g/l), as well as phosphates (> 20 mg/l) and ammonia (>2 mg/l).

Table 1. Average concentrations in mg/l of pollutants in shower or bath/shower water according to (Lehr, 2005), (Almeida, 1999), and (Eriksson, 2002). Note that Eriksson E et al. and Lehr Jay et al. both are citing (Surendran and Wheatley, 1998).

Variable	Unit	Average concentration according to Lehr.	Average concentration according to Almeida. (The range of values found in the literature is given in parenthesis).	Average concentration according to Eriksson.
Volume	l	-	42.3 (32-95)	-
BOD	mg/l	216	-	-
COD	mg/l	424	221 (-)	424
PO4-P (Phosphate as P)	mg/l	1,63	19.2 (1-2)	1,63
NH3-N (Ammonia as N)	mg/l	1,56	6.3 (0.3–0.4)	2,1.56,1.2
Turbidity	NTU	92	-	28-96
Total solids	mg/l	631	-	631
Total suspended solids	mg/l	-	200 (119–120)	120-200
pH		7,6	-	7,6
Inorganic carbon				26
Total coliforms	/100 ml		6 x 106	(70- 6x106)
Faecal coliforms				(1- 6x103)
Faecal Streptococci				(1 - 7x104)

2.2.2 Microbiological Contaminants

Bacteria are commonplace throughout the body. In fact, the human body carries 10 times more microbial cells with non-human DNA (10^{13} vs. 10^{14} cells) – it has been calculated that a human adult with a surface area close to $2m^2$ has around 10^{12} bacteria on the skin, 10^{10} in the mouth, and 10^{14} in the gastrointestinal tract (Todar, n.d.). Microbial cells are much smaller than human cells, allowing for the large volume of gut flora. The values in 0 are rough percentages of some of the bacteria found on the surface of human skin and other parts of the body. These bacteria can enter the ShowerMagic filtration system and thus come into contact with the user causing undesired negative health effects, if not properly treated.

Table 2. List of bacteria found of the surface of human skin and the percentage of carriers. 100 = nearly 100 % of humans, 25 = around 25 % of humans, 5 = less than 5 % of humans are carriers (Todar, n.d.).

Bacterium	Skin	Conjunctiva (eye)	Nose	Pharynx	Mouth	Lower gastro-intestinal tract
Staphylococcus epidermidis	100	25	100	100	100	25
*Staphylococcus aureus**	25	5	25	25	25	100
Staphylococcus mitis	0	0	0	25	100	5
Streptococcus salivarius	0	0	0	100	100	0
*Streptococcus mutans**	0	0	0	25	100	0
*Enterococcus faecalis**	0	0	0	5	25	100
*Streptococcus pneumoniae**	0	5	5	25	25	0
Streptococcus pyogenes	5	5	0	25	25	0
*Neisseria meningitidis**	0	0	25	100	25	0
*Escherichia coli**	0	5	5	5	25	100
*Pseudomonas aeruginosa**	0	0	0	5	5	25
*Haemophilus influenzae**	0	5	25	25	25	0
Bifidobacterium bifidum	0	0	0	0	0	100
Lactobacillus sp.	0	0	0	25	100	100
*Clostridium sp. **	0	0	0	0	25	100
Corynebacteria	100	25	100	25	25	25
Mycobacteria	25	0	5	5	0	25
Actinomycetes	0	0	0	25	25	0

* Indicates possible pathogen

The above-mentioned species are predominant in humans, however, peripheral species are being identified on a daily basis: a study published on November 7 2012 revealed that from the navels of a sample size of 60 persons from across the United States, 2368 separate phylotypes (species distinction based on genetic 3% genetic dissimilarity) were detected (Hulcr, 2012). The study shows that bacterial species can vary greatly from person to person and that perhaps certain body parts are neglected when bathing.

2.2.2.1 Skin as a Source of Particulate Matter

Skin protects the body by acting as a barrier against environmental damage such as heat, UV radiation, pathogens and water loss and helps to regulate body temperature. The outermost layer of human skin is the epidermis, 95% of which is comprised of keratinocytes – stem cells, which through a process of cellular differentiation turn into more specific cells. The keratinocytes migrate to the surface of the epidermis called the stratum corneum, which consists of biologically dead but active keratinocytes called corneocytes. The stratum corneum generally has 15–20 corneocyte layers, which are removed from the body via desquamation or skin peeling. (Mcgrath, 2008)

Desquamation is suggested to occur mainly through friction with clothing or bedclothes as well as bathing (Jansen, 1974). The skin surface is formed by a tessellation of irregular polygonal flakes, mostly hexagonal, derived from flattened cells. The mean projected dimensions of skin flakes is roughly 33 x 44 µm with a thickness ranging from 3 to 5 µm. With an average body surface of about 2 m^2, a complete layer of skin corresponds to about 2×10^9 cells. A complete layer of skin is replaced on average in less than 24 hours (Jansen, 1974).

2.2.3 Water Quality Standards

2.2.3.1 EU Water Quality Standards

Drinking water quality requirements are defined by (Council Directive 98/83/EC, 1998). The directive is written for water treatment plants; therefore, most items such as metal and chemical concentrations are not relevant to this research as there should be little to no inorganic or synthesized chemicals on the surface of the user's body. The parameters shown in Table 3 list are relevant to this research. Annex 1 of the directive provides the required microbiological (Part A), chemical (Part B) and indicator parameters as well as taste, odour and colour (Part C).

Table 3. Microbiological, Chemical and Indicator parameters for drinking water in the European Union (EU Council Directive 98/83/EC).

Parameter	**Parametric value**	**Annex 1: Part**
Escherichia coli (*E. coli*)	0/100 ml	A
Enterococci	0/ 100 ml	A
Ammonium	0,5 mg/l	B
Colony count 22°	No abnormal change	C
Coliform bacteria	0/100 ml	C
Conductivity*	2500 μS cm-1 at 20 °C	C
Colour	Acceptable to consumers and no abnormal change	C
Turbidity	Acceptable to consumers and no abnormal change	C
Odour	Acceptable to consumers and no abnormal change	C
Taste	Acceptable to consumers and no abnormal change	C

2.2.3.2 US EPA Water Quality Standards

The United States Environmental Protection Agency's (EPA, 2011) 2011 *edition of the Drinking Water Standards and Health Advisories* document contains limit values for different organic and inorganic chemicals that could be found in post-treatment water. The document provides information on what concentrations are acceptable in drinking water and how carcinogenic these chemicals are to humans. Many of these limit values are not applicable to the ShowerMagic system, as it is designed for use with water that already meets the current drinking water standards. The main parameters of interest are those that are added to water by the act of using the shower, see Table 4

Table 4. EPA Guidelines for Drinking Water Quality (EPA 820-R-11-002).

Parameter	**Parametric value**
Escherichia coli (E. coli)	0/100 ml
Enterococci	0/ 100 ml
Ammonium	Occurs in drinking-water at concentrations well below those at which toxic effects may occur
Colony count 22°	-
Total coliforms	No more than 5% of samples total coliform positive in a month. Every sample showing coliforms must be checked for faecal coliforms.
Heterotrophic plate count	No more than 500 bacterial colonies per millilitre
Turbidity	At no time can the turbidity go above 5 NTU (nephelometric turbidity units)
Viruses	99.99% killed or inactivated

2.3 Water Treatment Method Selection

As seen in the previous chapter, the main requirements for drinking water are clear and effectively sterile water with low concentrations of inorganic compounds. 0 superficially describes common technologies associated with water purification and rates their usefulness for ShowerMagic. Rows coloured in green highlight the best options. Sand filters are similar to fabric filters, and sand was selected for suspended solid separation due to it’s abundance and low cost.

Table 5. The various filters considered and issues related to their safety, affordability and usability. Rows coloured in green indicate the most suitable options. The table was compiled by the authors.

Filter / Considerations	Working principal	Safety considerations	Energy intensity (relative to each other)	Potential for environmental/ health risks	Low operating costs	Easy to build	Components moderately available	Real-time	Contaminates
GAC filter	Physical/ Chemical	Safe to drink in low concentration	Low	Low	☑	☑	☑	☑	☐
Sand filter	Physical		Low	Low	☑	☑	☑	☑	☐
Fabric filter	Physical		Low	Low	☑	☑	☑	☑	☐
Desalination	Physical	High pressure / temp	High	Medium - high	☐	☑	☑	☑	☐
Chlorine	Chemical	Concentrate is toxic	Low	Medium - high	☑	☑	☑	☐	☑
Bio-filter	Biological	Unknown	Low	Low - medium	☑	☑	☐	☐	☑
Flocculation	Chemical	Coagulants must be removed	Low	Low - medium	☐	☑	☑	☐	☑
Membrane filter	Physical		High	Low	Unknown	☐	☐	☑	☐
Ozone	Physical/ Chemical	Exposure is toxic	Medium	Medium	☑	☐	☑	Unknown	☑
Ultraviolet germicidal irradiation	Physical	Exposure is dangerous	Medium	Low	☑	☐	☑	☑	☐
Iodine	Chemical		Low	Low - medium	☑	☑	☑	Unknown	☑

There are many types of water treatment technologies used in domestic and industrial settings. Potable and waste water treatment plants as well as domestic aquarium filters were investigated as potential methods for water filtration. Nano membrane filtration, desalination chlorination, coagulation, flocculation and ozonation are all viable technologies but were not taken into consideration due to their technical complexity. Nano filtration and desalination were not taken into consideration due to high energy costs. Chemicals were also avoided because reaction rates are often too slow for real time filtration. The aim was to be as affordable and simple as possible so that the treatment system could be replicated without specialized manufacturing equipment or methods.

2.3.1 Sand Filter

Filtration is a method of separating solid material from a liquid medium. This is achieved by passing the liquid through a material to block the path of the solid while allowing liquid to pass through. This only works if the gaps or voids in between the filter medium (in this case sand) are smaller than the solid material that is being filtered from the liquid. Soil is a natural sand filter: rainwater infiltrates the topsoil and particulates are removed as it passes through rocks, sand and humus in the ground. Roots, fungi and other soil biota also work to purify water quality through more complex reactions.

John Gibb first used filtration as a way to treat water. In 1804 he designed a slow sand filter in Paisley, Scotland. By 1852, slow sand filtration had become a popular method of water treatment on the municipal scale (Huisman, 1974). Filters are divided into two main categories: pressure and gravity filters. The former are generally open-topped containers that utilize gravity to pull the liquid through the filter medium. One can infer that this method is generally slow. Pressure filters use pumps to pressurise the liquid before it reaches the filter in order to force the liquid through the filter medium. There are various models for describing the physical process of filtering. In slow sand filters, the medium reduces the particulate matter; turbidity, organic material and some microorganisms are caught in the sand filter. Pressure filters also remove the same compounds out of the incoming water. This thesis investigated the efficiency of pressurised sand filters (SF).

2.3.1.1 Particle Sizes

The solid materials that enter the filter medium are of different sizes. Large and hence easy to capture particles are not considered as they can be easily removed. Table 6 compares particle sizes of identifiable items. The size range of organisms and biomolecules is presented in Table 6 for a sense of scale. Visible particles are greater than 40 µm and hazes are caused by 15-20 µm particles.

Table 6. Typical sizes in µm of common solids found (Wyckomer UV Purification systems, n.d.).

Particle	**Size (µm)**
Tables salt	100
Human hair	40-70
Skin cells	33
Talcum powder	10
Fine test dust	0.5

The microorganisms that could be found in shower greywater tend to be too small for the sand filter to mechanically remove. Figure 3 illustrates the relative sizes of microorganisms.

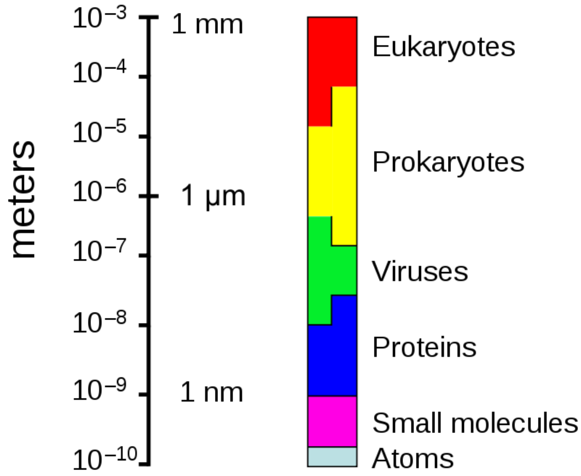


Figure 3. Scale showing typical sizes for microorganisms and biomolecules (Absolute Astronomy, n.d.).

2.3.2 Granular Activated Carbon Filter

Activated carbon (AC) has an incredibly high porosity compared to many other materials, which in turn provides it with a very large surface area in relation to its volume. Thus it has a very high capacity for removing contaminants from water by adsorption and absorption. Some of the characteristics that control the amount of adsorption are the volume of narrow pores, the surface area of the activated carbon, the ionic strength of the solutes and temperature. Adsorption relies on Van der Waals forces, which form weak electrostatic forces between the activated carbon particles and the organic compounds.

The exact mechanism of activated carbon adsorption in liquid filtering is still under debate. Some believe that the carbon acts as an ion exchange surface, while others postulate that the acidic/basic properties of the graphene layers affect adsorption. Another view is that the narrowness of the pores creates a sufficiently high adsorption potential to attract ions and retain them from the liquid (March, 2006). In this case adsorption occurs where the liquid and solid contaminants are diffused in the porous network of the AC, where that material is then caught (Layton, n.d.). Commercial AC is available in many forms and sizes, powdered activated carbon and granular activated carbon (GAC) being the most common in water treatment applications. Bacteria readily form on the surface of GAC consuming the organic material. However, studies on home water filters concluded that they do not pose a health risk (Fiore, 1977). The water quality in Fiore's study deals with pre-treated tap water, which is more pure than shower greywater. However, the following sterilization phase will deactivate any bacteria accumulating on the granulated activated carbon filter (GACF).

2.3.3 Determining SF and GACF Dimensions

When designing the filters the pressure drop against the actual filtering ability has to be considered because flow rates should coincide with standard shower flow rates. 10 L per minute has been determined as an acceptable upper-flow limit. The resistance (or pressure drop) of the sand filter (SF) and granular activated carbon filter (GACF) is described by Darcy's law:

$$U_c = K\frac{(-\Delta p)}{I} \tag{1}$$

$$U_c = B\frac{(-\Delta p)}{\mu I} \tag{2}$$

where U_c is the average velocity of the flow of the liquid, K is a constant derived from the bed and liquid, Δp is the pressure drop across the filter in Pa, l is the thickness of the filter medium in m, B is the permeability coefficient of the bed, μ is the viscosity of the fluid.

Darcy's law is used to estimate the pressure drop (kPa) of various filter sizes. Filter dimensions are chosen based on rough pipe widths and lengths, which have moderate pressure drops while still providing a relatively large coverage area for the factorial design. See Chapter 3 for more information and Appendix 7 for a table of calculations.

2.3.4 Ultraviolet Germicidal Irradiation

2.3.4.1 Working Principal

In 1877 Downes and Blunt first discovered that exposing microorganisms to direct sunlight prevented their reproduction. In 1930 Gates published the first analytical study on the bactericidal action claiming a peak effective wavelength of 265 nm (Reed, 2010) and isolated to 253.7 by Ehrismann and Noethling in 1932 (Kowalski, 2009).

Ultraviolet germicidal irradiation (UVGI) induces DNA damage in microorganisms. As a photon in the ultraviolet (UV) wavelength strikes a DNA molecule, the photon is absorbed by a double bond in pyrimidine, which opens the bond up to reactions with other molecules in close proximity to it. The most likely products are pyrimidine dimers and 6-4 photoproducts, which reduce the replication and transcription potential of the cell which has been irradiated

(Gaasbeek, 2008), i.e. the reproductive capability of microorganisms is disrupted when exposed to sufficiently high doses of UV radiation.

The UV radiation subtypes A and B are the cause of sunburns and are not dangerous when exposure is limited. UV subtype C is blocked by the ozone layer. UV-C, or short wave UV light, is on the wavelength range 100 – 280 nm, see Figure 4. Ultraviolet germicidal lamps excite mercury vapour with electricity emitting heat and UV-C light 85% of which peaks at 265 nm and 5-10% at 185 nm. Common fluorescent lamps are low-pressure gas-discharge lamps which operate on this principle. The inner surface of the lamp also has an additional layer of phosphorus which when exposed to UV light re-emits the fluorescent light in the visible light spectrum. (Zontec Ozone Generators, n.d.).

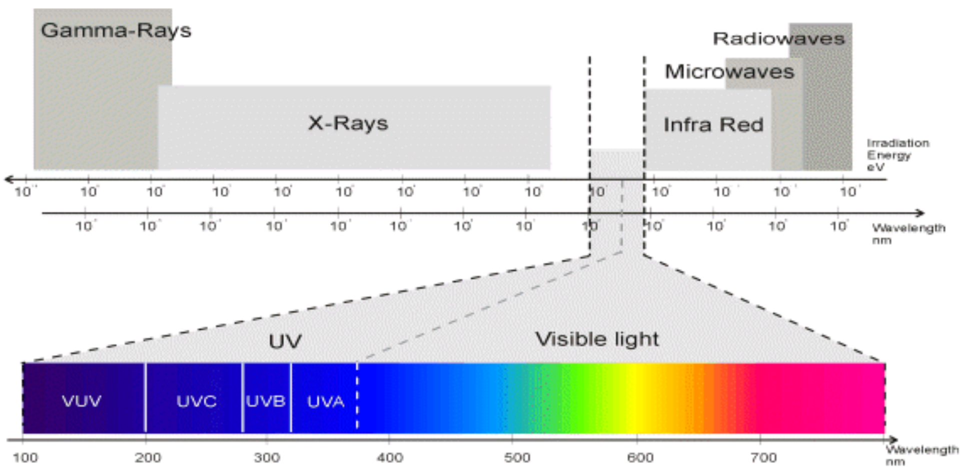


Figure 4. The electromagnetic spectrum in nm with UV and visible light spectrums emphasized. VUV is the vacuum ultra violet spectrum (Zontec Ozone Generators, n.d.).

2.3.4.2 UVC Dosage Required to Inactivate Microorganisms

Ultraviolet germicidal irradiation (UVIR) is a dose-dependent relationship between ultraviolet intensity and dose time:

$$D_{uv} = It \qquad (3)$$

Where D_{uv} is the dosage of ultraviolet radiation [μW*s/cm^2], I is fluence [μW/cm^2], t is exposure time [s].

The survival rate of microorganisms is dependent on the fact that some microorganisms require more or less irradiance than other species. It is also dependent on the dimensions of the UVIR. The survival fraction of a microbial population exposed to UVGI is an exponential function of dose (Martin, 2008):

$$S = e^{-kD_{uv}} \qquad (4)$$

Where S is the fraction of a microbial population that survives UVGI, k is a species-dependent deactivation rate constant (cm^2/μJ).

Table 7 below shows k values for common contagious microorganisms. The dosage relative to *E.coli* (the microbiological test contaminant) is shown in Figure 5.

Table 7. Table (UV): Energy dosage of ultraviolet radiation in μWs/cm^2 needed for kill factor for various bacteria and viruses (American Air & Water, 2013). The values are calculated using equation (4)

Microorganism	**UV dose in μWs/cm^2 needed for inactivation 90% (1 log reduction)**	**UV dose in μWs/cm^2 needed for inactivation 99% (2 log reduction)**
Escherichia coli (E. Coli)	3,000	6,600
Salmonela paratyphi - Enteric fever	3,200	6,100
Salmonella typhosa - Typhoid fever	2,150	4,100
Shigella dyseteriae - Dysentery	2,200	4,200
Shigella flexneri - Dysentery	1,700	3,400
Staphylococcus aureus – Skin infections	2,600	6,600
Vibrio comma - Cholera	3,375	6,500
Virus	90%	99%
Bacteriophage E. Coli	2,600	6,600
Influenza	3,400	6,600
Poliomyelitis - Poliovirus	3,150	6,600

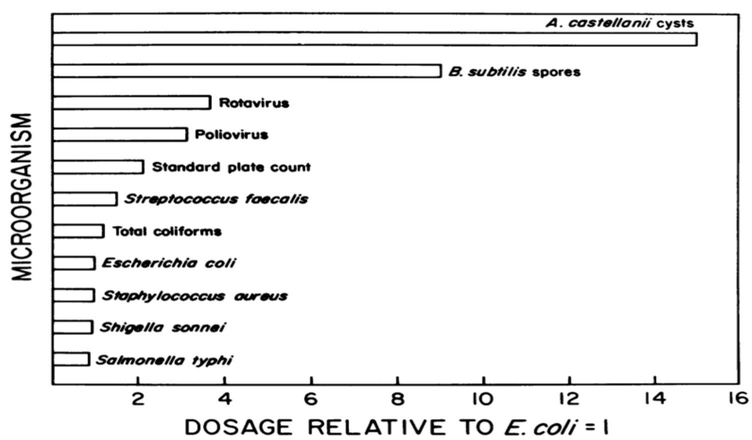


Figure 5. UVC dosage required for inactivation relative to *E.coli* (EPA, 2006).

2.3.5 Ultraviolet Irradiation Reactors

There are many configurations of Ultraviolet irradiation reactors (UVIR) for water disinfection. Units typically have one or multiple lamps, which sit above a stream of water or submerged in the stream itself. The lamps are typically protected by quartz glass which absorbs very little UVC radiation. Microorganisms receive a dose of radiation as they pass through the UVIR though they may travel through the chamber at varying distances from the UV lamp. A singular irradiation value should not be used when considering the actual dose that microbes may receive. To counteract this undesired effect the flow of the liquid can be disturbed in the chamber to allow for some mixing, which will ensure that all of the bacteria in transit will receive a more equal dose. The dose inactivation relationship is different for each species of bacteria. Most water transmitted bacteria need between 2000 and 8000 mW / scm^2 for inactivation. See Table 7 for specific dosage requirements.

2.3.5.1 Factors Affecting UVGI Dosage

Experiments involving the solar water disinfection (SODIS) method developed in Switzerland claims that at temperatures above 50°C there is a synergetic mechanism which increases the rate of disinfection by a factor of three (Wegelin, 1994). SODIS is a method of sterilization with reused PET bottles and solar UV-A. The influence of temperature may by more significant with the lower energy UV-A spectrum. Although evidence suggests that increases in temperature do decrease irradiation dosage requirements, further investigation would be required to determine the extent of the effect.

Large and small particles alike risk weakening the effectiveness of the UVGI due to the possibility of shadowing, whereby microorganisms hide inside or in the shadows of particles avoiding contact with the UV light (Osman, 2007). Ultimately organic and inorganic compounds found in shower greywater are far less hazardous to health than pathogenic bacteria and viruses. The contaminant removal efficiency of the sand and GACF is thus the primary concern in order to minimise shadowing performance of the UVGI stage.

The reactor dimensions, flow rate and distribution of microorganisms as well as temperature, turbidity and possibly multiple other factors all contribute to what is called the hurdle effect. This is when the effectiveness of UVGI is compounded based on the interaction of each factor. For instance, slower flow rates (longer exposure time) and high temperatures increase the overall UVC dosage irradiated to the microorganisms present in the water.

3 Experimental Design

3.1 Purpose

The approach chosen for the thesis is to gather data on the effect of different dimensions of the sand and activated carbon filters in order to create a mathematical model, which allows for the optimisation of the filters in the future. Optimisation means removing as much of the contaminants as possible while maintaining a practical flow rate and minimising the total water volume in the system. It must also ensure the complete sterilisation of the greywater during the UVGI stage.

3.2 Testing Concept & Hypothesis’

To simulate contaminants in a controlled manner ‘test water’ was made to represent average values of contamination concentrations as found in literature, see chapter 2.2.1. The concept for testing filter performance was to run the contaminated test water vertically through the filters once and to measure the reduction in contaminants to gauge performance. The filters were first studied separately starting with the sand filter (SF), then the granular activated carbon filter (GACF) and finally the ultraviolet irradiation reactor (UVIR). Each experimental set had different contaminants in the test water to investigate the response of the treatment method on the contaminant/s. The SF and GACF experiments were designed to investigate contaminant removal while the UVIR experiments investigated the effect of shadowing and turbidity on disinfection performance. After each individual set of tests, the best performing SF and GACF and the UVIR were combined and tested with all test water concentrations combined. The water was also circulated to investigate the performance of the filters while simulating real life conditions of the shower when in use.

3.2.1 Filter Bags

The dimensions of the filter bags, as well as the substrates within them, affect contaminant removal efficiency. Due to limitations in this research the controlled substrates were selected based on availability and best guesses. The cylindrical shape of pipes was used to reduce pressure losses. Therefore, filter bag height and width were the only variables studied.

Width is proportional to reaction time where reaction time increases with increasing width. This may be significant due to the reaction rate of chemical bonding with activated carbon. Height is considered proportional to interaction opportunities; if water is imagined to flow in a semi-straight line through a vertically positioned filter medium, the chances of colliding or being caught in voids or pores increases if there are more encounters. There is of course a chance that both variables have an effect, therefore, an experimental design was required to determine what kinds of tests should be performed for optimisation.

3.2.2 Ultraviolet Sterilisation

UVC dosage, irradiation geometry and shadowing are the main components of UV sterilisation. The flow rate is controlled, as are the dimensions of the UVIR (see Figure 13 in Chapter 4.2), therefore the only thing that could be studied was the effect of shadowing on disinfection. Test water was inoculated with cultivated bacteria and the turbidity of water was increased with each experiment. The effect of shadowing from increased turbidity could be measured by enumerating surviving cells with plate counts. See Chapter 5.4 for more information.

4.2.3 Combined SF, GACF and UVIR

The purpose of the combined experiment was to study filter performance while circulating the water through the system: the SF, GACF and UVIR, several times to simulate actual ShowerMagic showering conditions. Because the system volume (filters, UVIR and piping) could be calculated and the flow rate was controlled, the number of times the test water had been recirculated through the filters can be roughly determined (when ignoring mixing). This experiment was carried out after the best available filter bag sizes for sand and GAC were selected. UVIR was then utilised to measure optimal filtration and disinfection with the constructed components.

It was hypothesised that with each consecutive run a contaminated or dirty body of water would become less contaminated, or simply put, cleaner, as the filters perform their function. The test also provided useful data if the filters were under-dimensioned for a single cycle, i.e. the reduction in contaminants was too low to meet drinking water standards. Multiple recirculation runs might prove to be effective enough, meaning that while filtration may not be possible in real time, slower or multiple filtration cycles (with a lower water volume requirement) might enable the system to perform adequately albeit with pauses in the shower.

3.3 Experimental Design

A regression analysis provided a model, which allowed for future optimisation of the filter bag dimensions. The selected experimental design was a 2-level 2-factor or 2^2 factorial design with the variables filter height and filter width, with five centre point replicates. Factorial designs were used for the SF and GACF bag experiments. A factorial design allows for setting high and low factors for independent variables. Physical values were coded as 1’s and -1’s with centre points as 0’s so that the values of the variables could be compared. Due to standards of PVC tubing, the centre point was not immediately in the centre so the coded value is represented by values between 1 and -1. The physical high and low values were 30 and 10 cm for height and 19 and 7 cm for width. The centre point replicates were 20 cm high (coded value is -0.33) and 10 cm width (coded value is -0.5). By testing the high and low factors of one variable against the high and low factors of another (or more), the variables with the most statistically significant effect and their magnitude could be found with the use of regression analysis. Table 8 shows the coded heights and widths of non-randomised experiments.

Table 8. The coded heights and widths of non-randomised SF and GACF experiments.

Test	Height	Width
1	1	1
2	1	-1
3	-1	1
4	-1	-1
5	-0.33...	-0.5
6	-0.33...	-0.5
7	-0.33...	-0.5
8	-0.33...	-0.5
9	-0.33...	-0.5

The experiments were randomised to prevent experimental bias. Replicates were used to measure standard experimental error. Experimental error was caused by normal measurement error as well as human error. Human error could have accounted for mistakes in producing the filter bags, preparing and running the experiments as well as measurement procedures. Replicates reveal how much variation can be expected from all of the errors combined under conditions that are as controlled as possible. Five replicates were conducted for the SF and GACF tests. The number of replicates performed increased the accuracy of the model.

4 Prototype Design and Assembly

As the use and application of this technology had not been conceived in this particular way before, many of the components of the test setup needed to be designed and built to specific measurements. The working method for the design and construction of the test setup was based on rapid prototyping techniques where the availability of off-the-shelf components and available tools as well as the knowledge of the authors allowed for fast and flexible design changes.

Materials proved to be very difficult to come by, and only a few components were purchased from local hardware stores. A lot of time was spent constructing the filter parts that are rather complicated considering their simple operating principal. However, the final products turned out to be the best and most simple solutions that could be found.

Familiarity with the labs in Metropolia's Leiritie campus was a key factor to the construction and testing of the ShowerMagic prototype. Components, tools and equipment were sourced or borrowed from various educational programmes throughout the campus. Construction of the prototype components – sand and GAC filter bags, the test rig, pump, pipes and valves – was primarily performed in the Environmental Engineering Lab. More detailed components such as the filter compressors and displacers were made in the Surface Treatment Lab, which has common wood and metal working tools. The Chemical process lab was used for manufacturing test dust and performing the experiments. Analysis was conducted in the Process Lab (GAC tests), Environmental Engineering Lab (suspended solid tests), and the Microbiology Lab (bacterial enumeration).

4.1 Making SF and GACF

4.1.1 Making Filter Bags

It was decided that sand bags encased in a housing would be the most simple method of controlling filter dimensions in terms of flexibility and availability of components. The bags for both the activated carbon and the sand filters were made out of a common gardening geo-textile (purchased from Sello K-Rauta Finland), which was considered sufficient for holding in the sand. The geotextile has a pore size of 10–400 µm. The pores were initially assumed to have no influence on the test water. Rectangles were measured and marked and cut with width matching the inner circumference of the three PVC plumbing pipe sizes (70, 100 and 190 mm) and height matching the depth of the filtrate medium with the addition of several cm as sewing allowance. In total 10 different sized bags were made.

The bags were folded in half and sewed along the bottom edge (the circumference) using universal sewing string and a sewing machine (Janome 900, Japan) followed by the height of the bag (the edge opposite the folded one). A single tight width stitch was used. The bag (now sealed on all sides apart from the top) was then placed inside the appropriate housing and filled with 0.25–1 mm granular activated carbon (GAC) (Norit pk 0.2 –1, Netherlands) or Quartz sand from Nissilä (Sibelco Nordic) which was mesh screened to 250–500 µm. The correct sand and GAC depths were determined by using a tape measure on the inside of the bag. The top was then sealed as close to the correct height as possible. Excess fabric was removed with a ruler and a knife. Only one centre point bag was made for each experimental set (GAC and sand) due to time and resource constraints. See Table 9 for more details.

Table 9. Filter Bag sizes with detailed information of the experimental dimensions and the actual heights and widths achieved when filled with either Quartz sand or GAC. Note that actual height and circumference listed are ones with the bag outside of the filter housing without compression. Some bags may be more exact in size than others.

Sand bag									
length (cm)	diameter (cm)	top Area (cm^2)	circumference	one side width	ACTUAL Length/ around	ACTUAL Height	Actual circ. (cm)	Sand mass (kg)	ACTUAL VOL (L)
10.00	7.00	38.48	21.99	11.00	28.00	14.00	20.00	0.50	0.56
10.00	19.00	283.53	59.69	29.85	68.50	34.25	20.00	1.60	1.37
30.00	7.00	38.48	21.99	11.00	100.00	50.00	60.00	4.15	6.00
30.00	19.00	283.53	59.69	29.85	52.00	26.00	59.00	11.62	3.07
20.00	10.00	78.54	31.42	15.71	47.00	23.50	28.50	2.18	1.34
						TOTAL	**187.50**	**20.05**	**12.34**
GAC bag									
length (cm)	diameter (cm)	top Area (cm^2)	circumference	one side width	ACTUAL Length/ around	ACTUAL Height	Actual circ. (cm)	AC mass (kg)	ACTUAL VOL (L)
10.00	7.00	38.48	21.99	11.00	32.60	16.30	23.00	0.16	0.75
10.00	19.00	283.53	59.69	29.85	72.00	36.00	23.00	0.36	1.66
30.00	7.00	38.48	21.99	11.00	43.00	21.50	59.00	0.79	2.54
30.00	19.00	283.53	59.69	29.85	80.00	40.00	57.00	2.63	4.56
20.00	10.00	78.54	31.42	15.71	55.00	27.50	31.00	0.48	1.71
						TOTAL	**193.00**	**4.42**	**11.21**

4.1.2 Making Filter Housings

A complete list of components used for the construction of the filter housings can be seen in Table 10 (below). The filter housings consist of several parts: the outer casing, end caps, hose connectors, dispersers, compression disks and spacers. The outer pipe is made of standard PVC pipe. The 75 and 110 mm pipes were purchased from a local hardware store (Starkki, Vantaa) and the 200 mm outer diameter pipes with one enlarged end (210 mm) and 2 end hats were purchased via eBay (Mtb-sachsen, Germany). The pipes were cut to length using an automatic saw to ensure a 90-degree cut.

No affordable end caps were found for the large pipe, so the enlarged (200 mm outer diameter) end-portion of a pipe was cut and the end cap was glued with PVC glue (Tangit, Germany) so that it would fit over the narrow end of the pipe and an end plug would fit in the other end. The end caps were used to seal the pipe and allow a hose to be connected to both sides of each filter casing. The end caps (75 and 110 mm outer diameter) and ¾” hose connectors were purchased from Fluorotech. ¾” holes were cut in the centre of the end caps using a hole saw and the ¾” hose connectors were inserted. A nut was tightened on the inner side of the end caps with PVC glue to ensure a waterproof seal.

The dispersers were used to distribute the incoming water to the entire surface area of the front end of the filter in order to prevent channelling and to make sure that the entire volume of the filter would be utilised. The dispersers would also assist the compression of the filter bags. The dispersers were custom made from 4 mm acrylic and M4 nuts and bolts around 6 cm in length to provide 5 cm of space between the entrance of the pipe connector and the first compression plate.

The acrylic plates were rough-cut to each inner-pipe width using a table saw and smoothed into the right shape using a belt sander. Holes were then cut into the acrylic plates in a semi-uniform grid using clamps and a bench drill. The width of the drill bits was proportional to the width of the dispersers in order to decrease pressure drop while maintaining structural strength. Screws were cut to 50 mm + 2.5 mm x 2 (nut depth) using a metal hacksaw. Four screws were inserted into the each of the two end plates and secured in place using the nuts on both sides of the plate. The screws and nuts were then painted with epoxy resin (Inerta Primer 3 Comp A and Teknodur Hardener 0400 Comp A) to prevent them from rusting inside the housing. Stainless steel thread and nuts would be a simpler alternative.

Compression disks are similar to spacers but do not have nuts and bolts. Spacers were used to take up the free space made available when switching from the 30 cm long bag to the 10 cm long bag within the same housing. The lengths of the spacers were 10 and 20 cm x the width of the pipe. The spacers were acrylic rectangles with a central slit forming a U-shape that connects together to make a cross inside the pipe to support a compression disk on both ends (see Figure 7).

The order for assembly was as follows:

1. End cap
2. Water disperser
3. Filter bag
4. Compression disk
5. Spacer
6. Another plate with screws
7. Other end cap.

Vacuum grease (Glisseal, USA) was used to waterproof seals for the smaller filters and Teflon pipe tape (Swagelok, USA), vacuum grease and a strap ratchet was used to tighten and waterproof the wide filter as can be seen in Figure 6. The filters were essentially symmetrical so orientation was not important for the single filter experiments. Figure 7 shows the parts that were made and used to construct the sand and activated carbon filters. Figure 8 shows a completed spacing disk coated in epoxy resin to prevent rust. Figure 9 shows a cross section of the sand and activated carbon filter, the components can be seen and how they are ordered.

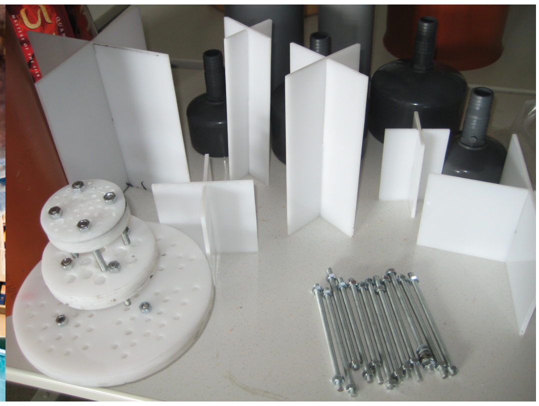
 

Figure 6. Left: Assembled wide (190mm inner diameter) filter with the custom made end cap. Keiran is pushing the Teflon tape, which moves during sealing back into the cracks to stop leakage.

Figure 7. Right: unassembled dispersers (bottom left), compression disks (bottom left), spacers, threads and bolts (bottom right), end caps and hose connectors and filter housings (back row).

Figure 8. Epoxy coated 190 mm dispersers on the test rig.

Figure 9 below shows a cross section of the sand and activated carbon filter, the water travels from the base to the top, the compression disk at the bottom allow the water to spread out and push through the filters evenly.

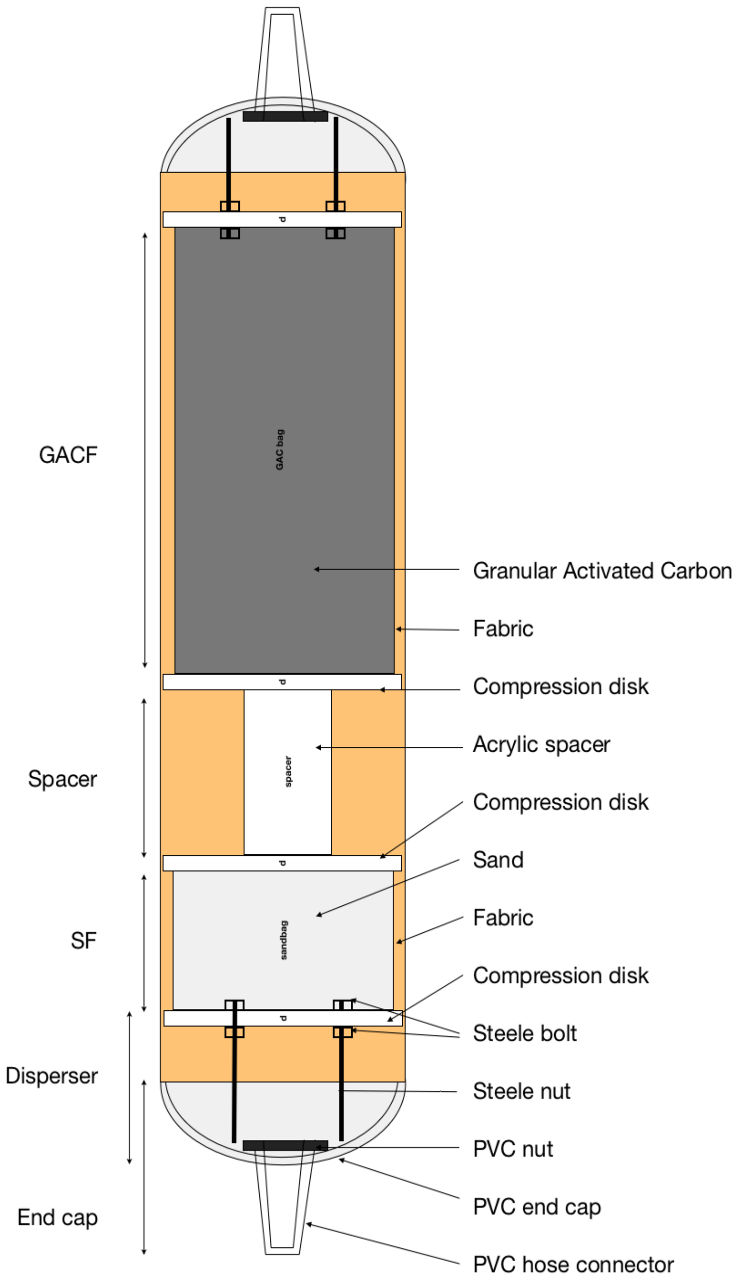


Figure 9. Unscaled assembled diagram of the water filter with sand and granular activated carbon bags and other components

Table 10 shows a list of all the components that were used in the construction of all the filters, it shows how many were made or bought and what size they are and what material it is made from. Table 11 is a short list of all the tools and equipment that was used to construct and build all parts.

Table 10. Components used for constructing the filters and UVIR. Pipe sizes are based on the outer diameter.

Test rig main category	Test rig sub category	Component	Dimensions / specs.	Quantity	Supplier
Filter	Housing	PVC pipe (standard domestic waste water pipe)	74 mm	1	Starkki
		PVC pipe (standard domestic waste water pipe)	110 mm	1	(salvaged)
		PVC pipe (standard domestic waste water pipe)	200 mm	2	E-bay
		PVC Bolt 3/4"EFV PN16	3/4"	8	Fluorotech
		PVC Hose connector 3/4"*25*27 Outer thread PN16	3/4"	6	Fluorotech
		PVC End cap PN16	110mm	2	Fluorotech
		PVC End cap PN16	75mm	2	Fluorotech
		PVC End cap	210 mm	2	E-bay
	Disperser	Acrylic	75mm x 4 mm	2	Metropolia
		Acrylic	110mm x 4 mm	2	Metropolia
		Acrylic	190 mm x 4 mm	2	Metropolia
		Nuts, bolts and washers	M6	many	Metropolia
	Compression disk	Acrylic	75mm x 4 mm	2	Metropolia
		Acrylic	110mm x 4 mm	2	Metropolia
		Acrylic	200mm x 4 mm	2	Metropolia
	Spacer	Acrylic	75 x 10 x 4 mm	2	Metropolia
		Acrylic	75 x 20 x 4 mm	2	Metropolia
		Acrylic	110 mm x 10 x 4 mm	2	Metropolia
		Acrylic	110 mm x 20 x 4 mm	2	Metropolia
		Acrylic	200 mm x 10 x 4 mm	2	Metropolia
		Acrylic	200 mm x 20 x 4 mm	2	Metropolia
	AC filter bag	Norit PK 0.25 - 1 GAC	0.25 - 1 mm (Total 12.34 L used)	9 x 2 L package	Viinimaailma Myyrmanni
		Cello geotextile	2 m2	1 package	K-rauta Pakkala
	Sand filter bag	Quartz sand / Nilsiän Qvartsi	250 µm - 500 µm (11.21 L used)	40 kg package	Sibelco Nordic
		Cello Geotextile	50 +- 200µm pores (2 m^2 used)	1 15M^2 package	K-rauta Pakkala
Sterilizer	UVIR	Purion 2500 H 90 W	80.6 x 4.7 cm	1	Purion GmbH
		PVC Hose connector 3/4"*25*27 Outer thread PN16	3/4"	2	Fluorotech

Table 11. List of tools used to build the test rig.

Power tools	Tools	Other parts
Belt sander	Socket drivers	Funnel
Electric drill	Screwdrivers	Scale
Bench drill	Spanners	Various screws
Angle grinder	Spirit level	Brushes
Automatic saw	Ruler	Cling film
Hole saw	Square ruler	Rags and towels
Mitre saw	Tape measure	Pen
Table saw	Hammers	Felts pens
Sewing machine (Janome 900, Japan)	Pliers	Crayons
	Pipe wrench	
	Hand file	
	Scissors	
	Knife	

4.1.3 Constructing and Operating the Test Rig

A complete list of components used for construction of the test rig, including the frame, piping, valves and water tanks, can be seen in Table 12 (below). The test rig is made from wood and is able to stand upright while supporting the freshwater (F_w), contaminant/clean water (C_w) tanks, the pump and the filter. The filter was clamped to the test rig between wooden blocks with three holes in a triangular arrangement, through which 1 m long 4M threaded rods were inserted and tightened with 4M washers and nuts from the top and bottom of the 'clamp'. A layer of 25 x 25 cm acrylic and chipboard plates with a hole cut in the middle was inserted at the base of the filter around the hose connector of the wide (190 mm inner diameter) filter to provide additional support. By tightening the nuts, the filter end caps were squeezed together providing compression. Good compression was determined by feeling resistance in the threaded rod.

There is space for the RZR-2102 Overhead Mixer (Heindolph, Germany) to be placed above either the F_W or C_W tanks. A spotlight was also connected to the test rig in order to increase visibility of the water level lines drawn on the Fw tank. Hoses were connected to each end of the PVC valves (Fluorotech, Finland) using ¾" to 1" hose connectors fastened by ring clamps. Teflon pipe thread was wrapped around O-rings inside the valves connections and greased to improve waterproofing. The pump 'viewport'/release valve was also greased to stop air from entering the pump. The test rig was constructed using common woodworking techniques. Most of the materials were reused from the construction of the ShowerMagic 'demonstration stall' see Figure 10.

Figure 10. Construction of the ShowerMagic ‘demonstration’ stall in the Environmental Engineering Lab. The frame was made from wood beams and polycarbonate roof sheeting. A bilge pump was used to collect and pump water to the showerhead, which was made from the same materials as the stall walls. The front door and floor are still missing.

During operating, tap water is poured into the fresh/flushing water tank (FW). The valve (V0) is capable of closing the flow from FW. The contaminant/test water tank (CW) holds the test water and has a mixer that is used for keeping the mixture homogenous. Valve (V1) is a three-way valve that can switch the flow of liquid from the freshwater tank and the test water tank. Valve (V2) is a shut-off valve located before the pump, and it is used to stop water from retreating from the filter if the pump is turned off and to throttle water flow for flushing (to reduce the initial pressure). The pump draws liquid from either FW or CW and pushes that liquid through the filter (sometimes denoted as F). Valve (V3) is able to throttle the flow from the pump. The observation port acts as a check valve, as it can be opened to release excess air from the system. This enables the pump to work at maximum efficiency since entrapped air in the system slows the pump down, contributing to uneven flow through the filter. The filter houses the sand and GAC bags. The collection tank (St1) is where the samples are taken from. This is illustrated in the P&ID diagram in Figure 11. Figure 12 shows a typical set up for an experiment: the fresh water tank is on the left, the pump is at the bottom, a filter can be seen on the right side on the experimental set up.

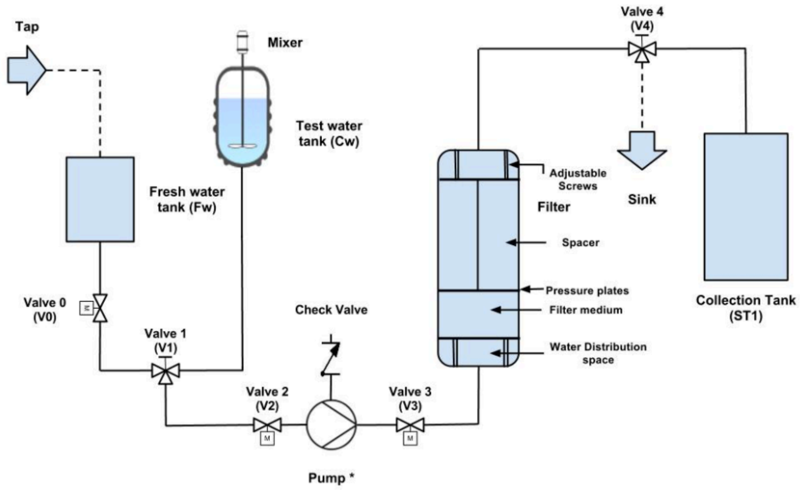


Figure 11. P&ID of the test rig for the SF experiments.

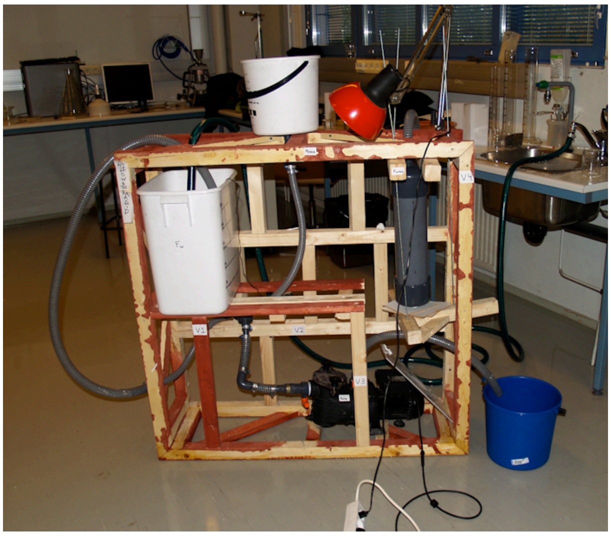


Figure 12. The test rig with C_W (top) and F_W tanks (left), the pump and centre point filter (grey PVC pipe) as well as the spot light. V_0 is inside the F_W tank; V_1 is under the F_W tank followed by V_2 (on the pump), V_3 (throttle) and V_4 are generally directed to the sink (on the right) or S_{t1} collection tank. Note that the blue bucket on the right is used to empty the filter after the experiment has been con-

ducted. S_{t1} is not visible. The mechanical mixer has also been removed prior to taking this photograph.

Table 12 shows a list of the all the components used to construct the experimental setup, which is comprised of the wood frame and all the components that made the experiment possible. Descriptions, sizes and quantities of parts are given.

Table 12. Components used to construct the test rig frame, piping, water tanks and miscellaneous parts used throughout the main categories of the test rig.

Test rig main category	Test rig sub category	Component	Dimensions / specs.	Quantity	Supplier
Frame	Body	Wood beam	2.2 x 4.7 mm	several m	Starkki
		Wood plank	4.5 mm x 4.5 mm	several m	Starkki
		Screws	3 cm cross-head	many	Metropolia
	Compression 'clamp'	Thread	100 cm M4	3	Clas Ohlson
		Nuts	M4	6	Clas Ohlson
		Washers	M4	12	Clas Ohlson
		Wood chip plates	250 mm x 250 mm x 4 mm	4	Metropolia
		Acrylic plates	250 mm x 250 mm x 4 mm	2	Metropolia
Piping	Hoses and connections	Rubber hose	3/4" (2 cm) diameter x several m	several m	Metropolia / Fluorotech
		Rubber hose	1" (2.5 cm) diameter x several m	several m	Metropolia / Fluorotech
		3/4" to 1" Hose connectors	3/4"	several	Metropolia / Fluorotech
		Rubber garden hose	3/4" (2 cm) x several m	several m	Metropolia / Fluorotech
		Tap adaptor		1	Metropolia
		Ring clamps	1" and 1 1/2"	10 +	Metropolia
	Valves	2 - way ball valve		3	Metropolia / Fluorotech
		3- way ball valve		2	Metropolia / Fluorotech
		O-rings		many	Metropolia / Etola
		Valve connectors	3/4"	5	Metropolia / Fluorotech
	Pump	Pump 180W	2.5 L volume	1	Metropolia / Future Pool
Water tanks	Cw (contaminated water) tank	Container	10 L	1	Metropolia / Orthex
		PVC Bolt 3/4"EFV PN16	3/4"	1	Fluorotech
		PVC Hose connector 3/4"*25*27 Outer thread PN16	3/4"	1	Fluorotech
	St1, storage tank	Container	65 L	2	Metropolia / Orthex
	Fw (fresh water/flushing water) tank	Container	30 L	1	Metropolia / Orthex
	Mixer	RZR-2102 Overhead mixer	1000 - 1200 rpm	1	Metropolia / Heindolph
	Weights	Ring weight	1 kg	2	Metropolia
Miscellaneous parts		Extension cord	230 V	1	Metropolia
		Zip ties		3	Metropolia
		Incandescent lamp	E 27 230 V	60 W	Metropolia
		Teflon pipe thread tape	1/2"	2 rolls	Metropolia / Swagelok
		Vacuum greese		1 60g tube	Metropolia / Glisseal
		PVC glue TANGIT 125g		1 125 g tube	Fluorotech
		Universal sewing thread red and white		2 rolls	K-city Market
		Strap ratchet	2m	1	(salvaged)
		Inerta Primer 3 Comp. A (epoxy)	Color red	1 can	Metropolia / Teknos
		Teknodur Hardener 0400 Comp. A (epoxy)		1 can	Metropolia / Teknos
			! pipe outer diameters used		

4.2 Selecting an Ultraviolet Irradiation Reactor

The Ultraviolet Irradiation Reactor or UVIR was purchased, unlike the other components of ShowerMagic, which were constructed by hand. Although preliminary designs for constructing a UV reactor were made, it became apparent that the process would likely be too time consuming for the scope of this research. Information about available liquid UVIR's was gathered from online source.

As an industry standard, dosage or fluence is expressed as joules per metre squared (J/m^2) at a set flow rate. This seems strange as no company mentions the effective surface area of their products, thus making it impossible to accurately measure the total radiation exposure that a single microbe passing through the UVIR would have. Calculations are made based on the expressed dosages and available dimensioning information in order to determine the given experimental conditions. These calculations are used to determine the most appropriate commercial UVIR to purchase. The theoretical radiation dosage that any one microbe would receive in the time it takes to travel through the UVIR is the key variable. The total irradiation is influenced by the retention time of the tube, the power output of the lamp used and the depth of the water layer and its distance from the pipe as well as the risk of shadowing mentioned in chapter 2.3.5.1.

Two viable products were found, the PURION 2500 90W from PURION, Germany and the Blue Lagoon Tech 7500 from Blue Lagoon, Holland. Because UV-C output was similar on both devices, (~30 W), the Tech 7500 was initially chosen. After some negotiations PURION was assessed to be more professional. The PURION 2500 90W is a stainless steel chamber with a 90 W PURION 90W T5L/4 HO lamp (see APPENDIX 2). The lamp has a stated UV-C output of 29 W. The useful lifetime is rated at 10000, however, the maintenance curve for the lamp shows a near 10% drop in UV-C output for every 1000 h of operation time for the first 2000 hours and then steadily drops at a slower rate to 60% total output by 9000 h. The lamp has a length of 80.6 cm and a circumference of 4.71 cm. The calculated irradiance zone has a surface area of ~ 845 cm^2 which equates to 373107 µW at 10 l/min flow rate. The UVIR was connected to the pump or filters with a ¾" hose connector and ring clamps, and supported in a slightly upward tilted horizontal position using chemistry stand clamps. The output hose connector was faced upwards to allow bubbles to flow out of the UVIR. A cross section of the UVIR can be seen in Figure 13. UV-C lamp specifications can be found in APPENDIX 2.

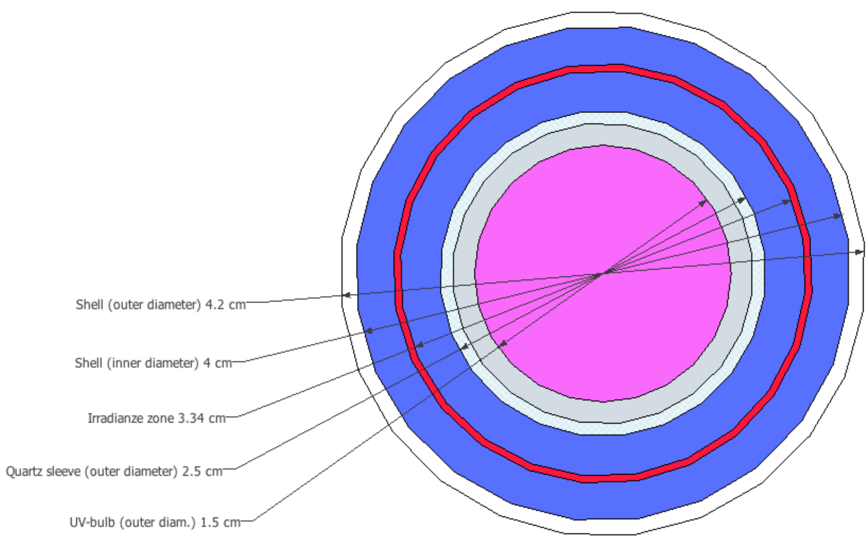


Figure 13. Shows the cross section of the UVIR with the dimensions for the Purion 2500 90W. The lamp in the centre is purple, followed by an air gap, the protective quartz tube, the water column (with irradiance zone highlighted) and finally the outer shell.

4.2.1 Determining Irradiation of the UVIR

Normally dosage is stated as J/m^2 at a given flow rate in m^3/h. This makes it difficult to calculate the exact dosage that a microbe would receive when passing through the UVIR. The authors formulated the following equations to more accurately estimate dosage. Fluence and irradiation, or dosage, are terms which can easily be confused. Fluence is defined as radioactive flux integrated over time or more simply stated the energy emitted over a given surface area over time. Irradiation and dosage is the sum of energy released and absorbed.

The total irradiance of a single lamp UVIR can be approximated with the following equation:

$$I = Fl * T_{\lambda} * t * A_{Izone} \tag{5}$$

where I is total irradiance a microbe would receive [uW], Fl is corrected fluence per cm^{2}s, T_{λ} is the transmittance of UV light passing through the quartz sleeve [%], t is exposure time [s], A_{Izone} is surface area of the irradiation zone [cm^2].

The value for fluence is extrapolated from the dosage statement of the Purion 2500 90W manual. Fluence must be adjusted to the distance between the surface of the lamp and the irradiance zone:

$$Fl = Fl_{lamp} * F_{dim} \tag{6}$$

where Fl_{lamp} is fluence of the surface area of the bulb, F_{dim} is the diminishing factor.

The corrected irradiance takes into account that the concentration of photons per cm^2 per second will be reduced by a factor relative to the expansion of the surface area of the lamp compared to the surface area of the irradiance zone. Exposure time is therefore

$$t_{exp} = {}^{V}/_{\dot{Q}} \tag{7}$$

where V is the volume of the UVIR, $\dot{Q}$ is the flow rate.

The total area of the irradiance zone is formulated to balance irradiation across the three-dimensional volume of the irradiation chamber. Microbes travelling closer to the surface of the lamp would receive a higher dose of irradiation than those travelling further away from the lamp. The equation used to calculate the total area of the irradiance zone takes a mid-point in the volume of the irradiation chamber rather than one of the diameters due to the geometry involved:

$$A_{izone} = \sqrt{\frac{\frac{\pi\left(\frac{d_{quartz}}{2}\right)^2 - \pi\left(\frac{d_{shell}}{2}\right)^2}{2} + \pi\left(\frac{d_{shell}}{2}\right)^2}{\pi}} * 2 * \pi * L_{lamp} \tag{8}$$

where d_{shell} is the inner diameter of the outer shell, d_{quartz} is the outer diameter of the quartz sleeve, L_{lamp} is the length of the lamp [cm].

The lamp is emitting UVC irradiation along the outer surface of the lamp. This is calculated with the equation

$$\boldsymbol{L_{fluence}} = \frac{\boldsymbol{P_{lamp}}}{\boldsymbol{D_{lamp}} * \boldsymbol{\pi} * \boldsymbol{L_{lamp}}} \qquad (\mathbf{9})$$

where $L_{fluence}$ is the power output per cm^2 s of the surface of the lamp [W/cm^2], P_{lamp} is the UVC output for the lamp [W], D_{lamp} is the diameter of the lamp [cm].

$$F_{dim} = \frac{\sqrt{\frac{\frac{\pi\left(\frac{d_{quartz}}{2}\right)^2 - \pi\left(\frac{d_{shell}}{2}\right)^2}{2} + \pi\left(\frac{d_{shell}}{2}\right)^2 * 2}{\pi}}}{D_{lamp}} \qquad (10)$$

where: F_{dim} is a ratio between the diameters of the irradiation zone and the lamp.

This equation gives the relationship of the power decrease of the irradiation zone, also called the diminishing factor.

The idea behind this series of equations is to determine the amount of fluence a microbe would receive with given parameters of a single lamp UVIR. See APPENDIX 3 for a table with calculated values.

5 Experimental Methods

The following chapter describes the methods used to test the SF, GACF and UVIR and a Recirculation test simulating the use of ShowerMagic in actual conditions. Step-by-step experimental procedures detailing the use of pumps to control the flow of fluid and a complete list of apparatus, reactants and reagents by experiment are listed in APPENDIX 6.

5.1 Calculating System Volume

The system volume is total amount of water within the entire experimental setup: the volume of the filters, the pump, pipes and valves. The system volume changes for each experiment due to the changes in filter sizes and changing requirements such as flushing or recirculation. See Table 13 for a table of measured values.

The total system volume was calculated with the following equation:

$$S_{tot} = (C_W \text{ } or \text{ } F_W)V_1 + V_1V_2 + V_2P + P + PV_3 + V_3F + F + FV_4 \tag{11}$$

where, S_{tot} is the total system volume (from input to output or drain to showerhead), A_xB_y is the total volume of component A to component B including connecting hose/s. (e.g. V_1V_2 is the volume of valve 1 (V_1), valve 2 (V_2) and the hoses connecting them, FV_4 is the volume of the hose connected to the filter and valve 4 (V_4) and the volume of V_4. Filter volume is mentioned separately as F), C_W is the contaminated water tank, F_W is the fresh water tank (the name does not apply for the GAC and UVIR experiments), P is the volume of the pump, F is the volume of the filter housing (without the filter bag inside to leave room for errors in measurement).

S_{tot} is calculated for all parts minus the filter in Table 13, volume is calculated by the length and thickness of all pipe lengths and the pump volume has been directly measured.

Table 13. Volume of the pump and hose connections. Some connections, e.g. F_W to V_1, were composed of two hoses with varying thickness.

Hose connections and thickness	**Component**	**length (cm)**	**thickness (cm)**	**volume (cm^3)**
Cw to V1 (Tn)		73.0	2.0	229.3
Fw to V1 (Tk section)		160.0	2.5	785.4
Fw to V1 (Tn section)		65.0	2.0	204.2
V1 to V2 (Tk section)	Cw/Fw input	48.5	2.0	152.4
V1 to V2 (Tn section)	Cw/Fw input	3.5	2.5	17.2
V2 to V3 / P	Pump			2500.0
V3 to F (Tk)	Throttle	65.0	2.5	319.1
F to V4 (Tk)	Output	100.0	2.5	490.9
			Total	4698.4
			Total (L)	**4.7**

5.2 SF Experimental Method

5.2.1 SF Experiment Setup

The system was filled with fresh tap water and run for several minutes to flush the filter bags, checked for leaks and water temperature as well as the water level was adjusted. Generally, this process took around 10 minutes once the process became familiar. The ~40 °C tap water was poured into the contaminated water tank (C_W) and contaminated with the prepared test dust. C_W has a capacity of 10 l but was only filled to 8 l. An RZR-2102 overhead mixer

(Heindolf, Germany) was used to homogenise the test water to simulate the gradual removal of dirt off the body. The test water was then drawn through the system.

All of the test water could not be drawn from the container because draining the container would introduce air into the system reducing the pumping flow rate. Therefore only half (4 l) of the water (and contaminants) was pumped through the system. The system volume was greater than the amount of water drawn, so it had to be flushed with tap water drawn from the fresh water tank (F_W). The total volume of water drawn from F_W for flushing is S_{tot}. All the water was collected into sample tank 1 (St_1) and vacuum filtered with Whatman Grade 3 filter paper (pore size 6μm). A pipette was used to rinse St_1 into the Büchner funnel used for vacuum filtration. The filter paper was dried in an oven and weighed to determine the mass of sand passing through the filter. The test rig was setup according to Figure 14 (below) and the maximum possible system volume (S_{tot}) was calculated, see Table 14.

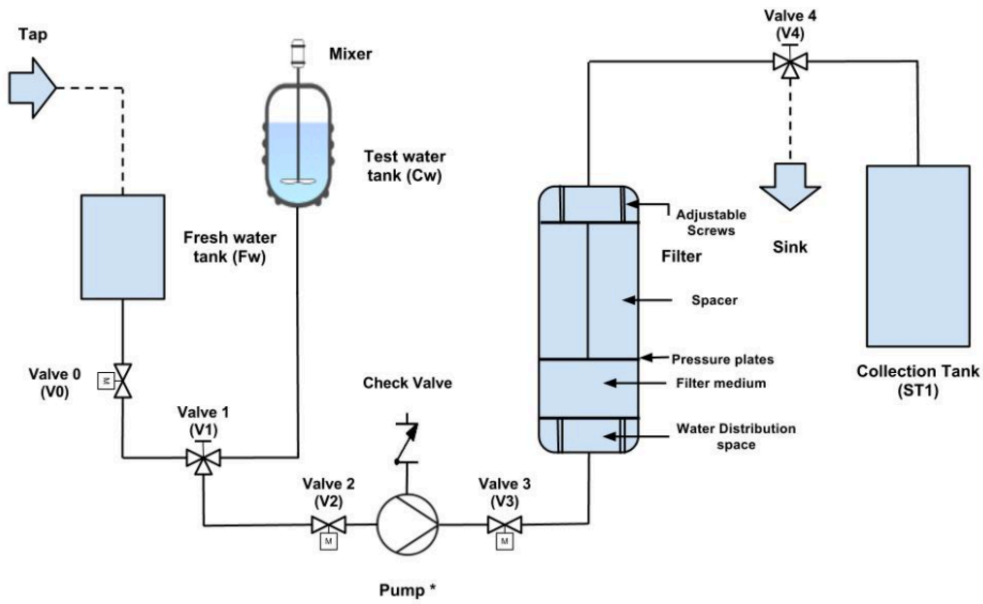


Figure 14. P&ID for SF Experiments.

Table 14. Maximum SF system volume in cm^3.

Maximum System Volume			
	Filter Sizes (no voidage)		
	Big	**Med**	**Small**
Cw-V1	229.34	229.34	229.34
V1-V2	169.55	169.55	169.55
V2-V3 / Pump	2,500.00	2,500.00	2,500.00
V3- Filter	319.07	319.07	319.07
Filter	12,570.00	3,800.00	1,770.00
Filter - V4	490.87	490.87	490.87
Total	16,278.83	7,508.83	5,478.83
Total L	16.28	7.51	5.48

5.2.2 SF Test Water

Quartz sand was used to test for suspended solid removal in the SF. The test was comprised of tap water and crushed and mesh sieved Quartz sand. 10 g of each of the five size fractions (0–56 µm, 56–75 µm, 75–106 µm, 106–150 µm and 150–212 µm) was prepared totalling 50 g of test sand per experiment.

5.3 GAC Experiment Method

5.3.1 GAC Experiment Setup

The experiment for the GACF followed a similar experimental design to the SF experiment. However, the test setup was slightly different. C_W was not required and only F_W was used. F_W was filled with tap water and mineral clay was added to increase turbidity to ~ 100 NTU. 1.5 mg/l Ammonium Hydroxide Solution (Sigma-Aldrich 25 % NH_3 Lot No. 30501) was added to simulate inorganic contaminants. F_W was then filled to 25 l with water with a temperature of around 40 degrees C. The overhead mixer was set at 1000 rpm with the mixed at the bottom of the tank to homogenise the water. The test rig was setup according to (below Figure 15) and the maximum possible system volume (S_{tot}) was calculated (see Table 15).

S_{tot} values vary because of the filter sizes. These were calculated in order to determine the system volume and the minimum saturation point (when the system had been filled with contaminated water). Samples were taken when at least 17 l had been drawn from F_W. This corresponds to the maximum system volume with the largest filter. Samples were drawn by placing a clean 100 ml plastic bottle under the 'outlet' hose, which was directed to a sink or drain. Samples were analysed with HI 88713 - ISO Turbidity meter (Hanna Instruments, USA) and DR 3900 Spectrophotometer (Hatch, USA).

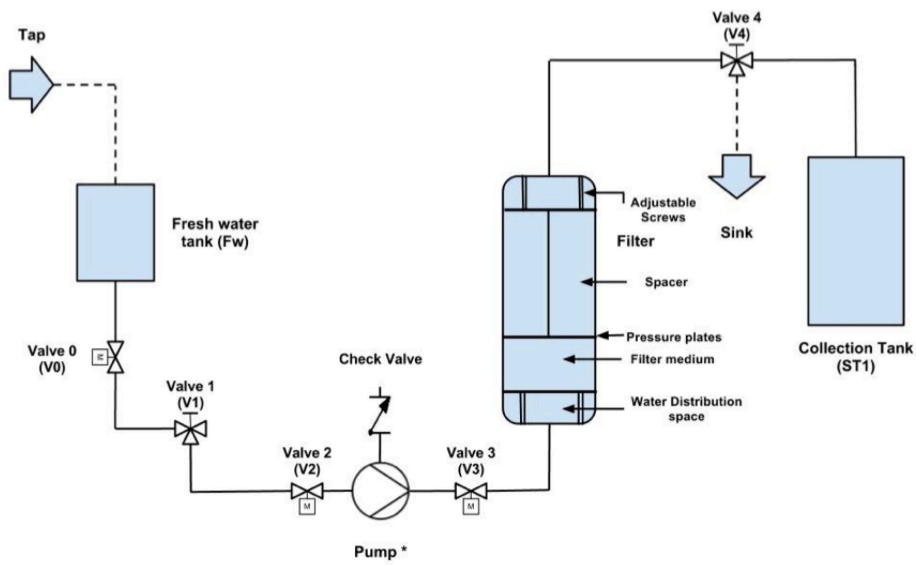


Figure 15. P&ID for GACF Experiments.

Table 15. Maximum system volume for GACF Experiments.

Maximum System Volume			
	Filter Sizes (no voidage)		
	Big	**Med**	**Small**
Fw - V1 (cm^3)	989.6	989.6	989.60
V1-V2 (cm^3)	169.55	169.55	169.55
V2-V3 / Pump (cm^3)	2500.0	2500.0	2500.0
V3- Filter (cm^3)	319.1	319.07	319.07
Filter (cm^3)	12570.0	3800.0	1770.0
Filter - V4 (cm^3)	490.9	490.87	490.87
Total (cm^3)	17039.1	8269.1	6239.1
Total (L)	17.0	8.3	6.2

5.3.2 GAC Experiment Test Water

Several attempts were made to create controlled turbid water: cinnamon was thought to be insoluble but it actually was, tea was tested but turbidity values were inconsistent when tested, store bought Terracotta (a mixture of minerals) proved to be slightly better, but ultimately mineral clay proved to be the most reliable. The mineral clay used was collected from a nearby field (Vaskipelto, Vantaa, Finland. 60.257029 N, 24.86661 W). The turbidity meter was used to detect non-ratio turbidity; the working principle of this device is similar to common photo spectrometric instruments. Turbidity measurements were taken within 20 minutes of sampling, and the samples are shaken immediately before measurements were made. 10 ml of sample water is placed in a cuvette and placed in the turbidity meter. Multiple measurements were taken within a five-minute period, and the average value was used for analysis. Figure 16 is a photo of taking mineral clay for the turbidity test of the activated carbon.

Figure 16. Taking mineral clay from a construction site in Vaskipelto, Vantaa, Finland.

5 ml of sample water was placed in a LCK 304 Ammonium sample cuvette (LANGE, USA), shaken and left to react for 15 minutes. The sample turns green in the test tube in the presence of Ammonium. Spectroscopic measurements were taken with the DR 3900 three times and an average value was used in the results table.

5.4 UVGI Experiment Method

5.4.1 UVGI Experiment Setup

The experimental setup was similar to the GAC Experimental Setup, but with a longer outlet hose and different filter volume. In this case the PURION 2500 90W UVIR was used in place of the filter. No SF or GACF were used in these experiments (see Figure 17). Outlet water was directed into the St_1 tank in case bacteria concentrations were too high to be poured down the drain and must be autoclaved. Maximum system volume was determined to be 5.4

l (see Table 16). F_W is filled to 15 l. Samples were taken before and after disinfection into sterile 100 ml plastic containers after at least 6 l had been drawn (generally after 10 l has passed through the system). The test rig and its components were rinsed and flushed with hot tap water. Lab coats and latex gloves were worn during the experiments and 70 % denatured ethanol was used for disinfecting and cleaning spills and equipment. Exposure of the ethanol with the sample water was naturally avoided.

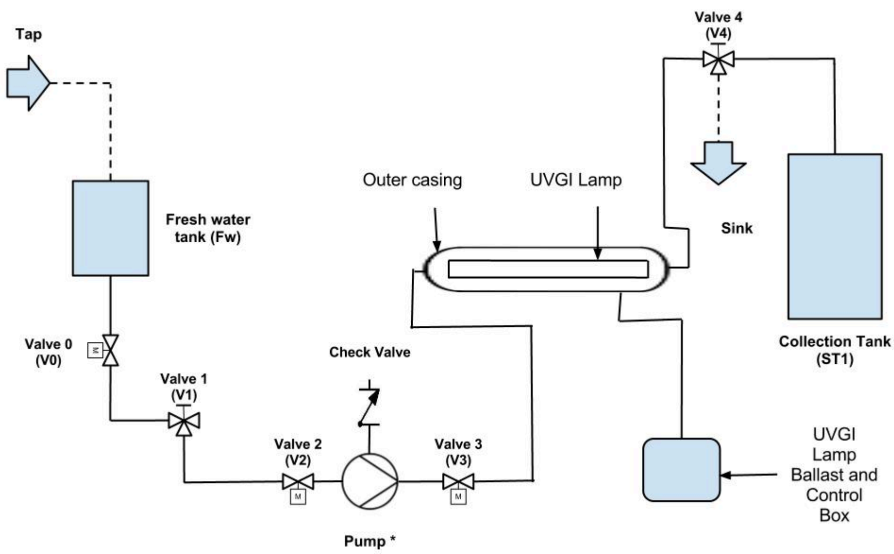


Figure 17. P&ID for UVGI Experiments.

Table 16. The system volume of UVGI Experiments.

Hose connections and thickness + P + UVIR		length (cm)	thickness (cm)	vol (cm^3)
Fw to V1 (Tk section)		160	2.5	785
Fw to V1 (Tn section)		65	2	204
V1 to V2 (Tk section)	Cw/Fw input	48.5	2	152
V1 to V2 (Tn section)	Cw/Fw input	3.5	2.5	17.2
V2 to V3 / P	Pump			2500
V3 to F (Tk)	Throttle	65	2.5	319
V3 to F (Tn)	to UV	160	2	503
F	UV			610
F to Outlet (Tn)	Output	90	2	283
			Total	5374
			Total (L)	**5.37**
*F is filter (now meaning the UV)				
V4 is outlet hose (there is no V4 valve)				

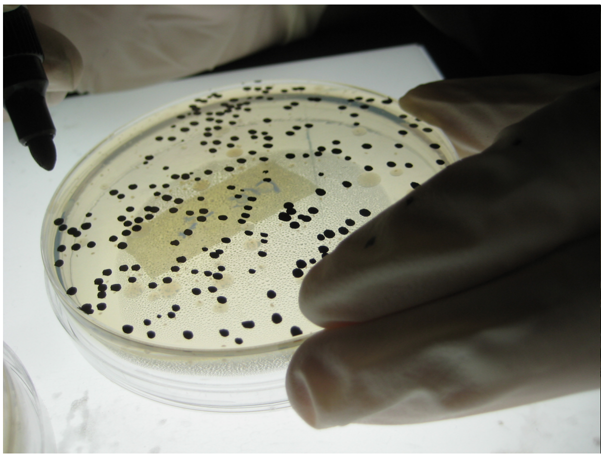
5.4.2 UVGI Experiment Test Water

1 l of nutrient broth (see APPENDIX 4) was pre-prepared. Roughly 150 ml was poured into 400 ml Erlenmeyer flasks and autoclaved. Each flask was inoculated with an inoculation loop in a laminar flow fume hood with a separate test tube containing *Escherichia coli* ATCC 8739 (LGC Standards, England) and left to incubate at 37°C for a minimum of 48 hours. Mixing was set at 100 rpm. The broth was stored in a refrigerator to halt bacterial growth until use.

The test water used in the UVGI experiments contained both 150 ml inoculated nutrient broth and mineral clay. Water turbidity values were adjusted to 0, 10, 100 and 1000 NTU to determine the effect of shadowing. The same mineral clay used in the GAC experiments (see chapter 5.3.2 GAC Experiment Test Water) was used for the UVGI experiments.

5.4.3 Enumeration of Surviving Cells of UVGI Experiments

Enumeration of surviving cells was performed by preparing pour plates in nutrient agar and comparing pre- and post-UVGI colony forming units (CFU) of *E.coli*. Pour plates were pre-pared by transferring 1 ml of sample water into sterile petri dishes with dilutions: 10^{-1}, 10^{-2}, 10^{-3} and 10^{-4} for pre-UVGI samples and 10^{-0}, 10^{-1}, 10^{-2}, 10^{-3} and 10^{-4} for post-UVGI samples. 5 ml autoclaved test tubes, caps and volumetric pipettes as well as auto pipettes were used for making dilutions. ~20 ml of nutrient agar (see APPENDIX 4) was added and left to incu-bate at 37°C for a minimum of 2 days. CFU are counted (see Figure 18) and pre- and post-UVGI samples were compared to determine bacteria reduction. Standard aseptic working methods were utilised to avoid contamination: autoclaving of the agar and equipment and using a laminar flow fume hood as can be seen in Figure 19. Zero samples, where no sample water was used, were also made in conjunction with the plate counts to determine the quality of aseptic methods.



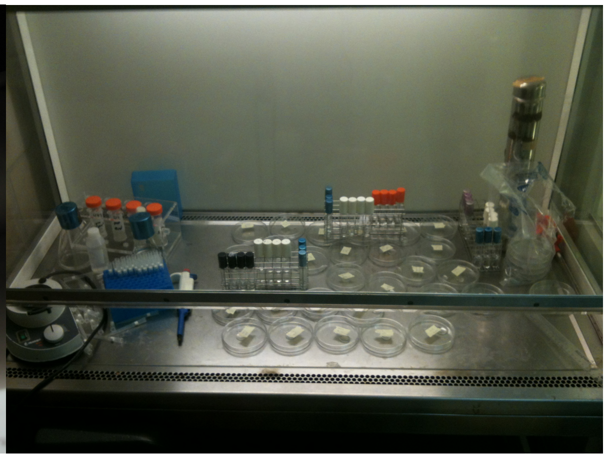


Figure 18. Left: Enumerating CFU with a marker on a light table.

Figure 19. Right: Setup used for preparing nutrient agar plate counts in a laminar fume hood.

5.5 Recirculating Water Test

All of the equipment was connected together in order to test the overall system. The test was made to reveal the interactions between the SF, GACF and UVIR and showcase how ShowerMagic would operate while in use. Sand (suspended particles), the initial concentrations of which were reduced by 50 %, mineral clay (turbidity and ammonium hydroxide) and bacteria are introduced with the same concentrations as in the previous experiments. Instead of passing through the filters only once, the system recirculated the water in F_W tank. Maximum system volume was determined to be ~17 l when accounting for voidage in the filters. F_W tank was filled to 25 l with tap water and contaminants, and the solution was homogenised with the overhead mixer (only in the beginning). The water from the outlet hose mixed with the reserve (water in F_W tank) water simulated how water would be collected in an actual shower. This action also created turbulence at the inlet water hose. The water was pumped into S_{t1} until the water level in F_W tank reached ~ 8 l and the outlet hose was directed back into F_W tank. At this point the system was fully primed with test water. Samples were taken into 100 ml sterile plastic bottles every 2 minutes for 10 minutes with each circulation taking 2.5 minutes. Each sample represented a different 'batch'. Overall six samples were taken (0,2,4,6,8,10 minutes). On the last circulation (R5 at 10 minutes), a representative sample of 2 l of test water was collected and vacuum filtered with 90 mm diameter 589[3] Whatman filter paper which had a maximum pore size of 2 μm. Figure 20 below illustrates the setup for the recycling water test.

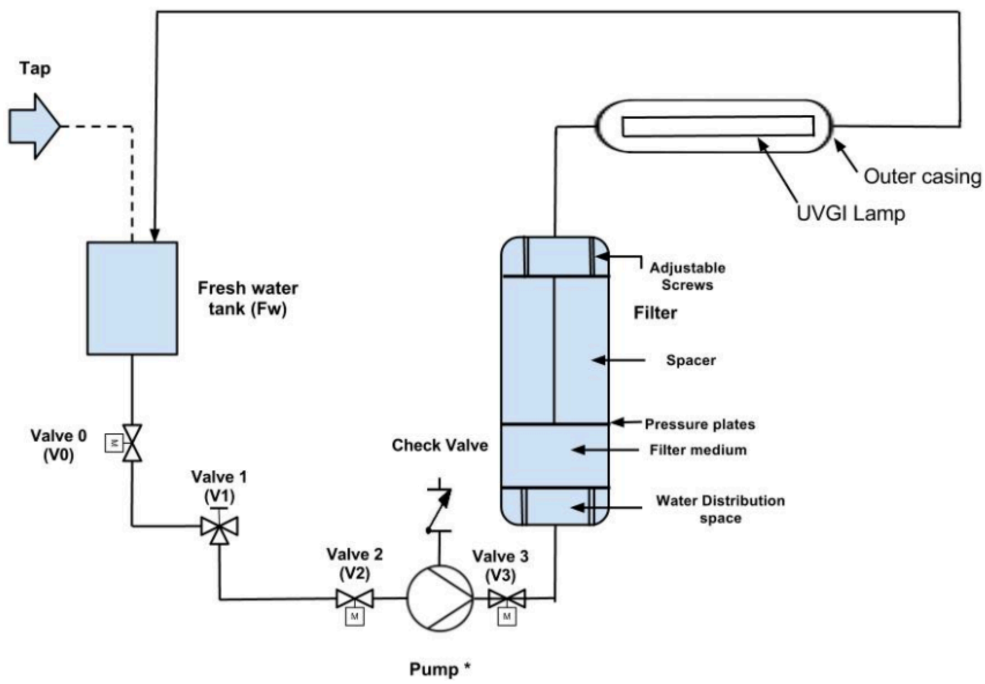


Figure 20. P&ID for UVGI Experiments.

6 Results

This chapter is composed of the results gathered from the four sets of experiments. They are divided into their own sub-chapters. The sets of experiments are performed individually to best determine the optimal filter bag dimensions for the removal of suspended solids, turbidity and ammonium hydroxide cations. The UVIR was also tested to find an upper limit for UVGI effectiveness with regards to turbidity. The final test, called 'Recirculating Water Test' was the combination of all the experiments. The test water was recycled to simulate shower-like conditions.

Table 17 and Table 18 can be used to reference general information, methods, contaminants studied and their concentrations as well as variables, controls and general conditions for each set of experiments. Table 18 is a list of what the conditions where for each test.

Table 17. The five test sets and their key points.

	SF	GACF	UVIR	Combined	Extra AC
Goal	Find optimal bag size	Find optimal bag size	Find turbidity limit	All filters combined and performance over time	Find AC response
Names	S1-S9	GAC1-GAC9	UV1-UV4	R0-R10	RR10 and RR0-RR0
Number of experiments	9	10	4	2	2
Number of experiments performed	2	10	4	2	2
Contaminant/s studied	Suspended solids	Turbidity, Ammonium hydroxide	Effect of turbidity, test UVIR	All mentioned contaminants	Turbidity, Ammonium hydroxide
Starting contaminant concentration	50 g quartz sand 0-250 µm	~100 NTU, ~ 1.15 mg/L NH4-N	0 - 1000 NTU, + 10^6 CFU/ml	25 g quartz sand, ~250 NTU, ~2.5 mg/L NH4-N, 10^6 CFU/ml	~100 NTU, ~ 1.15 mg/L NH4-N
Method of analysis	Vacuum filtration and weighing	Turbidity sensor and spectrophotometer	Pour plate CFU count	All mentioned methods	Turbidity sensor and spectrophotometer

Table 18. The five test sets as well as experimental variables, controls and conditions. Conditions refer to set conditions: for instance the SF experiments did not have contaminant concentration as a variable but were set (as can be seen in the 'Variables' row).

		SF	GACF	UVIR	Combined	Extra AC	
Names		S1-S9	GAC1-GAC9	UV1-UV4	R0-R10	GAC10	RR10 and RR0-RR0
Variables	Filter bag dimensions	☑	☑	☐			
	Contaminant concentration	☐	☐	☑			
Controls	Mixing (1000 rpm)	☑	☑	☑	☑	☑	☑
	Volumetric flow rate (10L/min)	☑	☑	☑	☑	☑	☑
	Temperature ~40°C	☑	☑	☑	☑	☑	☑
Conditions	Filter bag dimensions	☐	☐	☐	☑	☐	☐
	Contaminant concentration	☑	☑	☐	☑	☑	☑
	Flushing	☑	☐	☐	☐	☐	☐
	Recycling	☐	☐	☐	☑	☐	☑

SF Experiment

The initial experimental design called for a two-level, two-factor design with centre point replicates. However, the experiments S2–S8 (as can be seen in Table 19) are not mentioned as excessive caking on the filter bags itself made it impossible to maintain experimental conditions. The caking increased the pressure in the system, which slowed down the flow rate well below 10 l/minute. Experiments S2 and S3 were performed but final post-filter measurements were not conducted.

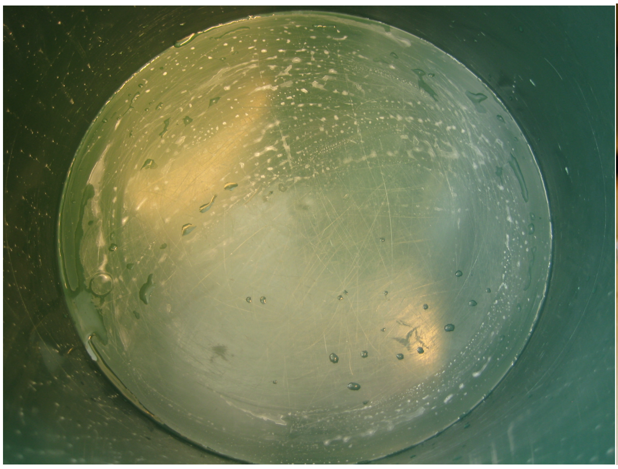
Table 19. Results of the sand filter experiments: two bag sizes were tested to measure the amount of suspended particles removed from the suspension. Both bags are 'wide' bags with varying heights.

Test number/name	Bag height (cm)	Bag width (cm)	Temperature (C)	Total test dust mass pre-filter (g)	Total test dust mass post-filter (g)	Filtration efficiency
S1	10	19	39.5	50.01	0.41	98.34
S9	30	19	38.5	50.01	0.31	98.76

Both of the wide filter bags had over 98 % reduction in suspended solids. Particles under 6 µm could not be captured with Grade 3 Whatman filter paper. Additionally some finer particles remained in the sample collection bucket (St_1) even after rinsing (see Figure 21). With normal distribution in the 0–50 µm size fraction the mass of particles under this limit would be ~ 0.6 g or slightly more than 1 % of the total mass of suspended solids in the suspension. A small amount of hair-like threads were also collected on the filter paper which were once part of the filter bag fabric.

Figure 21. Dried quartz cake inside the 190 mm filter housing. Removing the filter bag displaced the sand so it does not show its distribution within the filter.

Photographs of compression and channelling on the filters were made after each experiment and observations were noted. Figure 22 shows test dust deposits on the collection bucket (St_1) wall. Sometimes it was possible to remove the filter bag from the housing without too much distortion. Typically this indicated good compression. It should also be noted that a large amount of the test dust was captured by the filter bag fabric as seen in Figure 23, Figure 24 and Figure 25. Compression around the fastening nut and the nut itself visibly increased deposits of test dust as can be seen in Figure 24. Channelling also revealed whether the filter bag was installed and compressed sufficiently. Figure 25 depicts an example of poor compression and Figure 23 good compression.



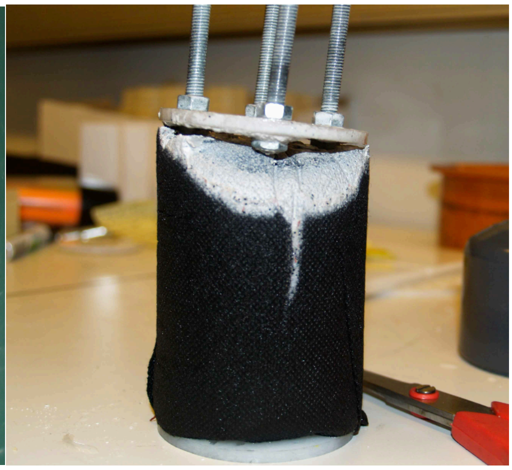


Figure 22. Left: Fine test dust particles deposited on the surface of the water collection bucket St_1 after rinsing.

Figure 23. Right: Sand filter bag with disperser (above) and compression disk (below). Clear caking is visible from test T2 (10 cm height and 7 cm width), which was aborted due to pressure losses. Compression was good, which can be seen from the shape of the bag but the circumference was slightly too wide allowing for a crease which shows caking as a visible ’tail’ (forefront).


Figure 24. Left: Compression from the fastening nut has visibly increased deposits of test dust (the two eyes and corner of the mouth). Spots reveal the placement of the holes in the displacer. The bag dimensions were not optimal as can be seen from the visible creases.

Figure 25. Right: T9 (30 cm height, 19 cm width) showing caking on the input side of the filter bag and clear channelling, which indicates poor compression. Note that the shape of the bag changed when it was removed from the filter housing.

6.1 GACF Experiment Results

Measurements were made within minutes of sampling with the turbidity meter to measure turbidity and the spectrophotometer to measure ammonium hydroxide concentrations. No odours were detected. There was visible improvement with post-filter samples, though samples with turbidity below 10 NTU appeared to be very clear and could not be distinguished by eye as can be seen in Figure 26. Turbidity and ammonium reduction (%) is calculated with equation 12.

$$Reduction_{\%} = 100 - \frac{C_{pre}}{C_{post}} * 100 \qquad (12)$$

where $Reduction_{\%}$ is the percentage reduction of concentration from the initial value, C_{pre} is the pre-treatment concentration, C_{post} is the post-treatment concentration.

As seen in Table 20, turbidity reduction ranged from 14.4 to 92.2 % with the 10 cm height and 7 cm width GACF performing the worst and the 30 cm height and 19 cm width bag performing the best. The centre point replicates ranged from 50.2 to 59.0 % reduction in turbidity values and from 12.0 to 22.0 % reduction in ammonium values. The results are visualized in experimental order from left to right in Figure 27 showing reacted sample cuvettes. The sample turns green in the presence of Ammonium when reacted with the contents of the LCK 304 Ammonium sample cuvette.

Table 20. Activate carbon filter test with the full 2^2 design with 5 centre point replicates [GAC3, GAC4, GAC6–8]. The column titled 'Tested' indicates which pre-filter samples were tested for initial Ammonium hydroxide (NH_4) concentrations (in order to test for measurement errors).

Test number /name	Height	Width	Temperature (C)	Average init. turbidity (NTU)	Average final turbidity (NTU)	NTU reduction (%)	Tested	Init. NH_4 (mg/L)	Average final NH_4 (mg/L)	NH_4 reduction (%)
GAC1	10.00	19.00		95.60	63.00	34.10	TRUE	1.16	0.73	37.03
GAC2	10.00	7.00	37.00	82.20	70.35	14.42	FALSE		1.07	7.76
GAC3	20.00	10.00	37.80	88.00	35.55	59.60	FALSE		1.01	12.93
GAC4	20.00	10.00	39.60	85.60	36.35	57.54	FALSE		1.04	10.34
GAC5	30.00	7.00	37.00	100.00	49.80	50.20	TRUE	1.16	1.04	10.34
GAC6	20.00	10.00	38.70	96.55	39.60	58.98	FALSE		1.00	14.18
GAC7	20.00	10.00	38.50	100.50	41.45	58.76	FALSE		0.91	21.77
GAC8	20.00	10.00	39.90	106.50	49.45	53.57	FALSE		0.97	16.03
GAC9	30.00	19.00	37.80	104.00	8.14	92.17	FALSE		0.32	72.41


Figure 26. Left: GAC9 sample with pre-filter water sample on the left, reacting LCK 304 Ammonium sample cuvette (LANGE, USA) in the middle and post-filter water sample on the right.

Figure 27. Right: Cuvettes with post-filter solutions tested GAC1-GAC9. GAC9 on the right side has the lowest concentration of Ammonium hydroxide.

6.2 UVGI Experiment Results

Experiments are labelled UV1–UV4. The initial concentration for UV1 was the highest as it had been incubated over a weekend for a full 70 hours which is beyond the normal 48 hour incubation period. Initial concentrations varied in general as a different Erlenmeyer flask was used for each test. The CFU counts for all experiments was reduced to 0.00001 % of the initial starting CFU counts as seen in Table 21, the equivalent of a log 5 reduction in the concentration of bacteria. Despite the increasing turbidity value of the test water in each experiment: 0, 16, 96.8, and 961 NTU, the post-UVGI CFU counts were of a similar magnitude. The post-UVGI CFU concentrations were very low which may indicate the presence of contamination from sampling rather than bacteria surviving the disinfection process. The results of UV3 should be better than results from UV4 as turbidity values (and thus shadowing) were increased by a factor of 10. Zero, or control samples were unfortunately not made at this point.

Table 21. Reduction (%) of UVGI experiments. A log 5 reduction can be seen in all cases. Initial concentrations varied as each test used a different Erlenmeyer flask which had been innoculated with *E.coli* into nutrient broth and each inoculation was made from separate culture samples.

Test number/name	Starting NTU	Temperature (C)	Flow rate (l/min)	Pre-UV concentration (CFU/ml)	Post-UV concentration (CFU/ml)	Reduction (%)
UV1	0.00	40.00	9.97	2.60E+06	0	100.0000
UV2	16.00	38.90	10.17	7.30E+05	3	99.9996
UV3	96.80	42.00	9.84	4.70E+05	0	100.0000
UV4	961.00	37.60	9.87	1.35E+06	4	+99.9997

6.3 Recirculating Water Test Experiment Results

Results are presented as reductions from the starting 'sample water' concentrations. The initial turbidity value was 261 NTU and the initial value for ammonium was 2.425 mg/l. The total or initial value for bacteria is 4 x 10^6 CFU and the total or initial sand amount is 25 g/25 l or 1 g/l.

Most of the substances that were removed from the test liquid were removed within the first 2 minutes – this corresponds to the first run through of the test water through the system. A run through can be considered as a batch or single circulation through the complete system, as can be seen from Table 22. Though some mixing occurred in F_W, as the input hose had to stay below the water level in the tank at all times to prevent air from entering the system. After the first 2 minutes both the turbidity and ammonium hydroxide concentrations continued to decrease but at a much slower rate. The bacteria concentration decreased to the minimum amount after the first run through. Several CFU were detected in the post-UVIR samples, though not with the sample taken at 8 minutes (R8). This could account for contamination in the data collection methods. Due to the collection method of the sand data it can not be known how quickly the test dust was reduced; only that it was effectively 100 % removed after 10 minutes or an equivalent of 5 cycles. If samples were taken every 2 minutes, the overall concentration of contaminants would have been reduced altering the experiment and the data collection of the other contaminants. Figure 28 is a graph of Table 22 with time in minutes on the x-axis and percentage reduction on the y-axis.

Table 22. Recycling experiments. Suspended solid, turbidity, ammonium and bacteria reductions for each cycle through the system.

Test number (sample time)	Time (minutes)	Batch run/cycles through system	Suspended solids (g)	Average NTU	Average NH4 (mg/L)	Bacteria (CFU/ml)	Particulate reduction (%)	Turbidity reduction (% NTU)	Ammonium reduction (% NH4)	Bacteria Reduction (%)
R0	0	0.00	25.00	261.00	2.43	4.07E+06	0.00	0.00	0.00	0
R2	2	0.80		17.50	1.47	0	99.00	93.06	39.59	100
R4	4	1.60		8.85	1.35	0	99.00	96.25	44.33	100
R6	6	2.40		5.31	1.33	0	99.00	97.75	45.36	100
R8	8	3.20		2.29	1.30	0	99.00	99.12	46.39	100
R10	10	4.00	0.25	1.14	1.29	0	99.00	99.55	46.80	100

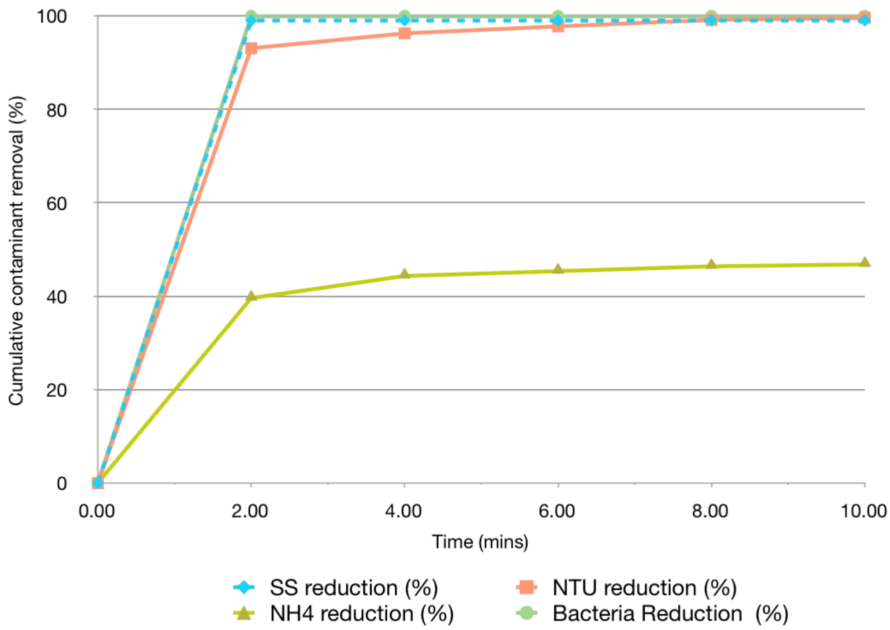


Figure 28. Cumulative contaminant removal (%) over time. Samples were taken at the beginning of the experiment and every 2 minutes afterwards corresponding to one complete cycle through the system. The initial concentration of test dust was 1g/l 261 NTU for turbidity, 2.425 mg/l for ammonium hydroxide and 4 x 10^6 CFU for bacteria.

7 Analysis of Experimental Results

7.1 Analysis of SF Experiment

Results were both better and worse than expected. The widest filters worked very well, though the fabric impeded a large amount of the quartz sand with medium to large particle sizes. This was an unexpected an unintentional effect due to the pore size of the filter fabric. It is not known how much of the contaminants were captured by the filter bag fabric and what amount of particle capture was due to the sand itself. The experiments worked well in the sense that the SS reduction was very high.

The goal was to find what size fractions get through the bag that is to say how well the different size fractions are trapped by the voidage in the sand. However, so little was captured on the filter papers that further separation of the test fractions was not possible. Caking on the filter bag was not expected to occur. The remaining sand was collected and a mesh shaker was used to see if all size fractions were present. Not all the caked test dust was collected, so although all size fractions were detected, conclusions on the SS removal efficiency of the fabric cannot be made. The result is most likely due to the caking trapping larger particles first and then trapping smaller particles in the voids between the forming cake, thus recreating similar conditions as to those inside the bag.

The geotextile was initially considered sufficient for holding in the sand, but the pores were assumed to have no influence on the test water itself. As a response to the caking, the geotextile was examined with a camera (Evolution MP, USA) attached to a microscope (Nikon, USA) and measured to have a pore size of roughly 10–400 μm (see Figure 29). Fibre distribution was not been measured but the random arrangement of fibres appeared to have normal distribution.

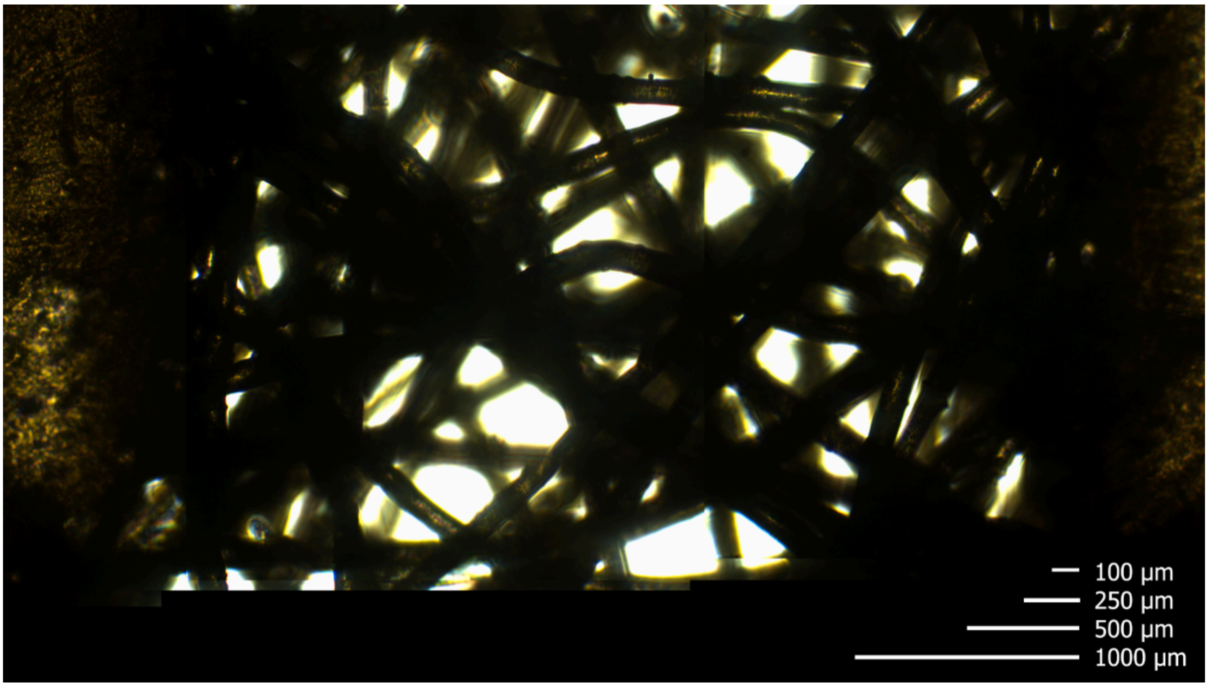


Figure 29. Microscopic view of the fabric used to construct the filters taken with Evolution MP Colour Cybernetics camera with Nikon EPLAN10/0.25 microscope at 100x magnification.

7.2 Analysis of GACF Experiment Results

7.2.1 Modelling the GAC Response Plane for Turbidity

A linear regression model was established based on the experiments. Unfortunately due to industrial standards in PVC tubing the centre-points were not directly centred and so interactions between the height and width of the variables cannot be accounted for. Multiple linear regression models provided for poor adjusted R-squared values whereby only ~70 % of the model could be explained with our variables. Multiple linear regression with a polynomial fit provided the best model, however the polynomial variables $Height^2$ and $Width^2$ were confounded resulting in the same model for both equations. The R-commands are as follows:

lm(formula = NTU ~ Width * Height + I(Width^2), data = X) and lm(formula = NTU ~ Width * Height + I(Height^2), data = X) where X is a table with the width, height and NTU reduction as a percentage. The output can be seen in Table 23.

Table 23. Output of NTU Reduction as a Percentage.

Coefficients:	**Estimate**	**Std. Error**	**t value**	**Pr(>|t|)**
(Intercept)	65.412	1.238	52.831	7.68e-07 ***
Width	15.425	1.208	12.766	0.000217 ***
Height	23.475	1.208	19.428	4.14e-05 ***
I(Height^2)	-17.688	1.730	-10.224	0.000516 ***
Width:Height	5.575	1.208	4.614	0.009926 **

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Both models produce the same output, but only one of them is correct. To discover the correct model, an additional experiment called GAC10 was carried out. The experiment followed the same procedures as described in Chapter 5.3 but with both the 10 cm and 30 cm activated carbon bags stacked on top of each other to get a data point for a 20 cm wide and 40 cm high bag. No spacers were used, but the displacers were used as normal. The results of the experiments and modelled contour plot can be seen in Figure 30.

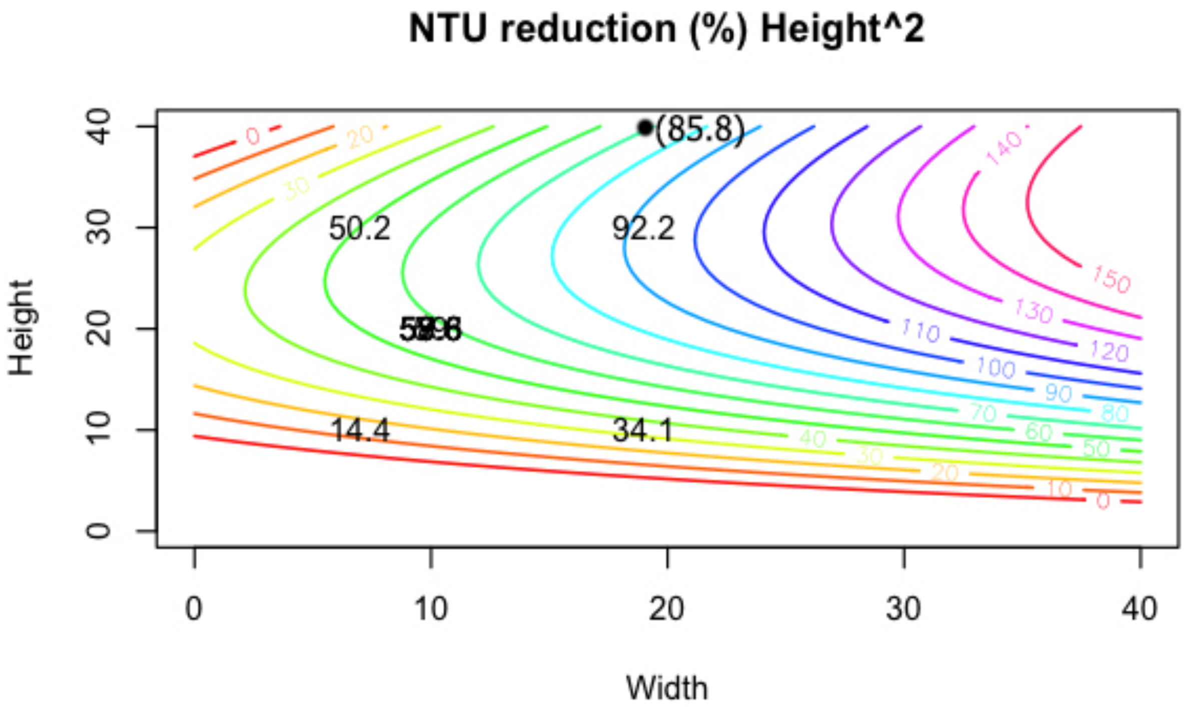


Figure 30. The contour plot of turbidity reduction based on a regression model with a polynomial-fit for height. Additional experiment results with the 20 cm wide, 40 cm long GAC filter bag within parenthesis. The centre point values are stacked on top of each other due to limitations in the R-script, the values are 59.6, 57.5, 59.0, 58.8 and 53.6.

Both width and height were statistically significant factors for turbidity reduction with a p value of 0.01. The F-statistic with 4 and 4 degrees of freedom with a probability level of 0.0005 was 76.12. Therefore, the null hypothesis was rejected with a high degree of confidence. The adjusted R-squared value described 98.6 % of the response with a p-value of 0.00013, meaning that it was statistically highly improbable that the model is based on results obtained by chance.

Optimum filter volume is determined by using Figure 31 above. The contour map is a union of two separate data sets: the thick coloured curves represent filter volumes including voidage (40 %) for GAC and the black contour lines show the modelled turbidity reduction by percentage (marked within the lines). By tracing the 100 % NTU reduction line the region of lowest filter volume can be determined based on the x and y axis. Clearly reductions greater than 100 % are not possible, but they do help describe the relationship of filter height and width

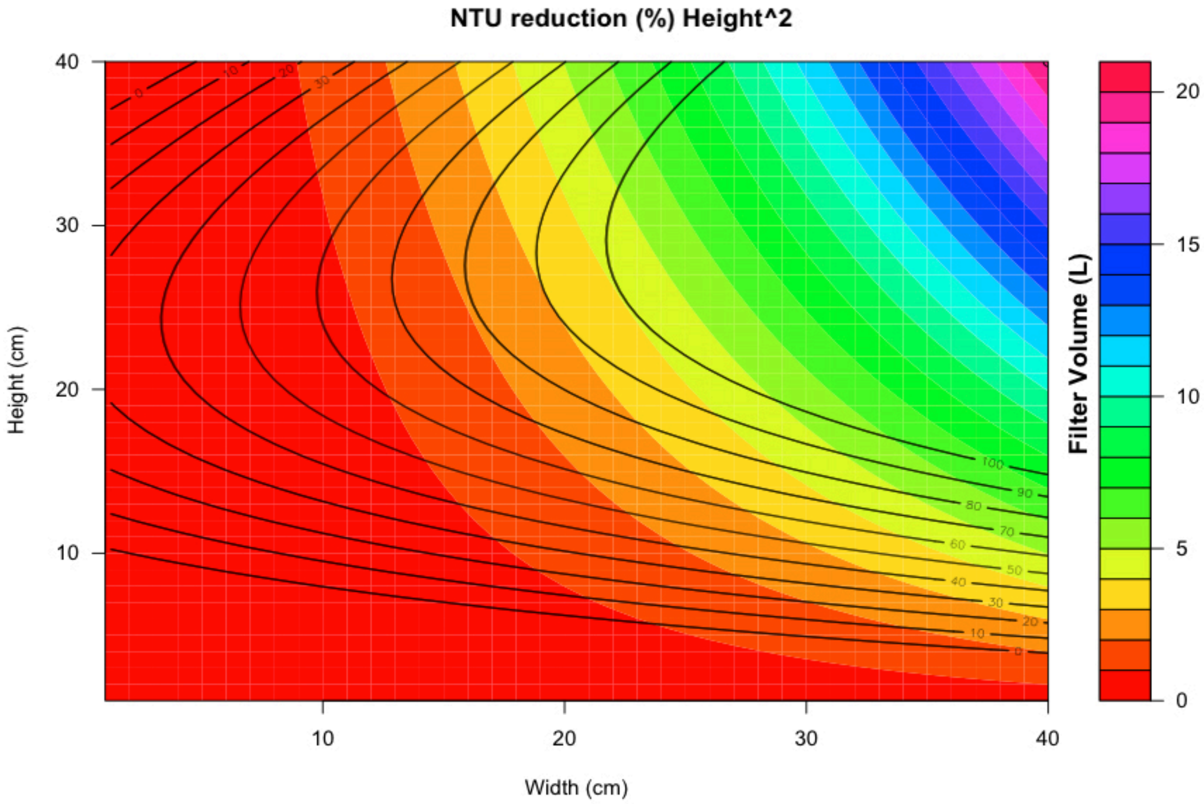


Figure 31. Two overlaid contour maps. The filled (solid) colours represent filter volume including voidage with the legend in litres to the right, the black dividing lines and values are from Figure 30, which shows the reduction of turbidity in percentages.

7.2.2 Modelling the GAC Response Plane for Ammonium Reduction

Similar to the multiple linear regression models for turbidity reduction, the models for ammonium reduction provided poor adjusted R-squared values whereby only ~ 70 % of the model could be explained with our variables. The model for multiple linear regression for ammonium with a confounded width and height and a polynomial fit gives an adjusted R-squared value of 0.959. This result was not particularly good, especially when predicting the results of the experiment AC10 where the result was 66.6 %, where the expected ammonium reduction was 90 %. Even accounting for the standard error, which was 4.31, the expected reduction was > 84.7 %. With a polynomial fit for height, the model was even worse. See chapter 7.5 for more information on the additional GAC experiments. The results can be seen in Figure 32.

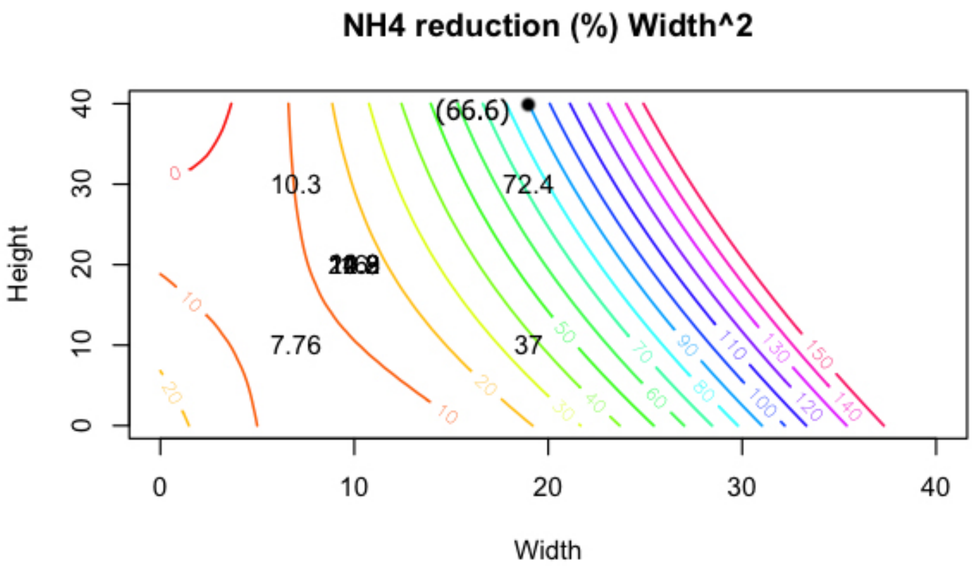


Figure 32. Contour plot of ammonium reduction with a width-based polynomial fit. Additional experiment result with the 20 cm wide, 40 cm long GAC filter bag within parenthesis; 66.6 % reduction in NH_4. The centre point values are stacked on top of each other due to limitations in the R-script, the values are 12.93, 10.34, 14.18, 21.77, 16.03.

7.3 Analysis of UVGI Experiment Results

The purpose of the UVGI experiments was to determine the upper limit for permissible turbidity in order for complete disinfection to occur. The hypothesis was that a relationship with shadowing and irradiation could be established, which would also validate the UV irradiance model created by the authors (see chapter 4.2.1). The total calculated irradiation for the PURION 2500 90W is 373107 µW or a fluence of 441.55µW*s/cm^2 in the irradiance zone with a 10 l/min flow rate. The UV dose needed for a log 1 or 90% reduction of *E.coli* is 2600 µWs/cm^2 and 6600 µWs/cm^2 for a log 2 reduction or 99 %.

It was expected that with increased turbidity, some, but not all bacteria would survive allowing for the fluence model to be validated. Without shadowing the UVIR was calculated to emit 56.5 times more UV-C radiation than required for a log 2 reduction of *E.coli*. The distance from the outside of the quartz sleeve to the inside of the UVIR shell is only 0.75 cm, which may explain why shadowing does not dramatically affect UV light transmission. While shadowing is a factor that affects overall UV-C dosage, we have no method to accurately measure it, at least within the range of the tested concentrations. *A.Castellanii Cysts,* which could, albeit rarely, cause amoebic keratitis (eye inflammation) and encephalitis (inflammation of the brain) require 15 times the equivalent dosage of *E.coli* for inactivation (see Figure 5). This value is still 3.76 times less than the mean irradiation of the PURION 2500 90W with a flow rate of 10 l/min.

7.4 Analysing Recirculating Experiment Results

Suspended particles, turbidity and bacteria concentrations all have 99 % or greater reductions in their respective contaminant concentrations within five or less cycles through the system. Water quality improvement decelerates over time. Bacteria reduction, which is the most crucial aspect of the system, was immediate. The removal of clay and suspended particles is used primarily to reduce the negative effects of shadowing, which was not detected to occur at the tested conditions. The results for ammonium hydroxide reduction were unexpected and most probably higher order reaction kinetics were taking place. See chapter 7.5 below for more analysis.

7.5 Analysing Additional GAC Experiment Results

Two additional tests were done to better understand the response experiments involving the GACF bags. The first issue was the declining reduction of filtration in the recirculating water test (R0-R10). It was expected that the bag with 20 cm width and 30 cm height would have a similar reduction as in the experiment GAC9, where ammonium hydroxide reduction was over 70 % during a single cycle. Since adsorption would rely on collisions and subsequent absorption and adsorption, it was expected that each cycle would have similar chances, thus the efficiency of ammonium removal should essentially remain constant. Instead, it seems that the occurring levelling off approached 47–48 % instead of 100 %.

The initial concentration of ammonium was much higher than it should have been. The mother solution used was typically 1.15 mg/l, but while the initial concentration in R0-R10 jumped to 2.43 mg/l. One hypothesis was that test water contamination had occurred, another was that the nutrient agar or possibly the quartz sand in the test dust or even the sand filter was responsible for the increase in the NH_4 cations. NH_4 reduction was similar in nature to the response of the other contaminants except that it levelled off at a much lower 47 %.. After removing the additional foreign ammonium from the data, the reduction seemed more appropriate. The experiment was replicated without nutrient broth or sand to determine if either variable was the cause for the increase in ammonium and to observe the response under circulating conditions. Another hypothesis was that the activated carbon was simply being used up because of the exposure to chlorine as well as other ions in the tap water. The centre point bag was reused for the replicate experiments, due to the high volume of GAC in proportion to the amount of water filtered, this seemed unlikely, but a repetition of the experiment seemed to be in order. An additional recirculating experiment called RR0-RR10 was conducted with a similar set-up to the first recirculation experiment (R0-R10). The shorter of the two 190 mm filter housings and the same GACF were used. Due to this, the system volume was altered. Total system volume was 9.28 l for the combined filters + 8.18 l for the hoses, valves and pump totalling 17.46 l in F_W for RR0-RR10 and 17.05 l + 7.95 l (25 l total) for R0-R10 can be seen in Table 24. Samples were taken at times that matched the measurement points of the original experiment (every 120 seconds for R0-R10 and every 84 seconds for RR0-RR10). These corresponded to 0, 0.8, 1.6, 2.4, 3.2 and 4 cycles. Since the water was sampled from the outlet hose, each measurement corresponded to a new cycle. Therefore technically the batches are run through the system 0, 1, 2, 3, 4 and 5 times. Starting concentrations were adjusted poorly due to measurement errors.

Table 24. Additional Recirculating Experiment: Replicated experiment of R data set. Test sand and bacteria were removed. Note that the initial starting turbidity (NTU) values are lower in RR0 compared to the original test Recycling test (R0).

Test name	Height, Width (cm)	Time (minutes)	Batch run /cycles through system	Average turbidity (NTU)	Average NH4 (mg/l)	Turbidity reduction (% NTU)	Ammonium reduction (% NH4)
RR0	30, 10	0.00	0	240.00	2.0400	0.00	0.00
RR2	-	1.24	0.8	24.70	0.957	89.71	53.09
RR4	-	2.48	1.6	10.83	0.963	95.49	52.79
RR6	-	4.12	2.4	5.57		97.68	
RR8	-	5.36	3.2	3.38		98.59	
RR10	-	7.00	4	3.43	0.868	98.57	57.45

NTU reduction was slightly worse in RR0-RR10 despite having lower starting concentrations. Experiment RR0-RR10 ammonium hydroxide reduction was higher than in R0-R10. RR0-RR10 also had lower starting concentrations of ammonium hydroxide; 46.80 % compared to 57.45 % in R0-R10. The 30 cm GACF bag was clearly still able to remove contaminants with no discernible reduction in efficiency. It was evident that the problem lied somewhere else.

An experiment called GAC10 was performed which is summarised in Table 25, but the results do not support this hypothesis. GAC10 had the same experimental setup as GAC1 and GAC9, but with both the 10 and 30 cm long bags stacked on top of each other to represent a 40 cm long GAC bag. Turbidity was reduced from ~ 86 NTU to 12.20 or ~ 89 %, which is a smaller reduction than the 30 cm high GAC bag on its own. However, the result was within 2 standard deviations of the model. Standard error for the model is 4.31. Ammonium reduction was unexpectedly low.

Table 25. Additional GACF Experiment TT10 (40 cm long GACF) results. The results of experiment TT9 (30 cm long bag GACF) is shown to compare the experiments.

Test number/name	Height	Width	Temperature (C)	Average init. turbidity (NTU)	Average ending turbidity	Turbidity reduction (% NTU)	Tested	Average Initial ammonium (mg/L)	Average ending ammonium (mg/L)	Ammonium reduction (%)
GAC9	30.00	19.00	37.80	104.00	8.14	92.17			0.32	72.41
GAC10	40.00	19.00	39.80	85.94	12.20	85.80	TRUE	1.16	0.73	37.07

8 Discussion

The purpose of the experiments was to validate the concept of ShowerMagic – a filtration system for a shower that could greatly reduce water and energy consumption while allowing the users to shower for as long as they liked. The goal was to gain overall knowledge of each of the shower's components and to acquire a model that would allow for optimising the filter sizes. Through a combination of background research, intuitive knowledge and perhaps a disproportionate amount of chance the selected filter sizes yielded results in both the low and high end of the spectrum for the given conditions. This translates into a product concept which is ecologically beneficial and has a real world application.

SF

Using the sand filter, the removal of particles was very successful, removing around 99 % of total suspended solids with the largest filter bag (190 mm diameter) in the recirculating experiment. In the dedicated sand tests: S1-S9, the largest diameter bags removed around

98.5 % of total suspended solids in a single run. The 70 mm and 100 mm filter bags were unable to maintain sufficient flow and the experiments were stopped. This was due to the excessive caking of suspended solids forming on the surface of the bag which increased the resistance of the bag attributing to the pressure drop of the filter bags.

8.1 Optimal SF Dimensions

The results suggest that a width of 20 cm or more and height of at least 10 cm are sufficient. However, the issues with the fabric, caking and usage capacity are still unresolved, so while an even smaller filter bag size may work just as well for a single run, the filter may need replacement more often as dirt accumulates on the filter.

8.2 GACF

8.2.1 NTU Reduction

Height and width are both statistically significant factors for turbidity reduction. Figure 30 shows that the greatest reductions are in the top right hand corner of the contour map: by increasing the width and height there is an increase in the turbidity removal. Looking at Figure 31, it is easy to determine the optimal size for the best turbidity reduction while at the same time keeping the volume of the filter as low as possible. This is possible with a width of around 22 cm and a height of 28 cm. When accounting for GAC voidage the water volume of the filter is under 4 l.

8.2.2 Ammonium Reduction

In Figure 32 one can clearly see the trend of the contour lines heading towards the right very strongly with a slight inflection towards the upper part of the diagram. This would suggest that the width has a more significant effect on ammonium reduction than height. Wider diameters slow the liquid velocity through the filter. Therefore the reaction of removing ammonium is more significantly affected by the speed or the time an ammonium molecule is in contact with an activated carbon reaction site. However, once this criterion is met, the height parameter comes into effect removing more ammonium the higher the bag is. Figure 30 predicts that 100 % turbidity reduction can be achieved with a GACF 34 cm high and 22 cm wide. This means that the same dimensions used for turbidity reduction should also yield around 90–100 % ammonium reduction. The extra GAC experiment did not fit into the model as it should have yielded closer to 100 %, but as can be seen this was not the case. It could mean that the experiment failed due to some experimental error, or that the model is not as representative of the area of the graph as it could be. According to the EU council Directive 98/83/EC ammonium concentrations should be below 0.5 mg/l for drinking water. The average concentration in greywater ranged from 0.3 to 6.3 mg/l. In the conducted experiments ammonium concentrations were slightly above acceptable levels with the exception of experiment TGAC9 which met requirements, however, ammonium hydroxide at such concentrations is not dangerous, especially when ingestion of the shower water should be very low.

8.3 UVGI

In all situations the UV irradiation was sufficient for a log 5 reduction of bacterial concentration. These situations included NTU values of 0, 16, 96.8 and 961. In the combined test around 1 % of the suspended solids (1 g/l solution) passed through the UVGI chamber. According to the estimated calculations the total irradiance was around 56.5 times larger than what was necessary to inactivate the *E.coli*. The UVIR is thus able to disinfect bacteria much more resistant than *E.coli*. Ultraviolet lamps have decreased effectiveness over time. The PURION 90W T5L/4 HO (see APPENDIX 2) lamp used has a 10 000 hour lifetime rating, but efficiency is reduced over time (see chapter 4.2.1 for more information). It is possible that the UV lamp could still remain effective after this time, though minimum dosage requirements should be determined. The lamp will maintain a safe and high level of UVC output above 80 % for the first 2 000 hours of operation, equivalent to 8 000 average length (10 minutes) showers when including a 5 minute start-up time to ensure full lamp output. For a single user, this is almost 22 years of daily showering, see equation 13 and 13.1 below:

$$UV\ lamp\ life = \frac{\left(\frac{Effective\ lamp\ \ output\ h}{Average\ shower+startup\ time}\right)}{Days\ per\ year} \tag{13}$$

$$= \frac{\left(\frac{2000}{0.25}\right)}{365} = 21.82\ years$$

8.4 ShowerMagic Filtration System (Recirculation)

It was discovered that all the test water contaminants decreased further over time. The majority of the reduction occurred during the first run through. Then, at each sequential run through, the reduction slowed down, each test substance tending toward 100 % removal, except for ammonium, which tended towards a 50 % reduction.

8.5 Adjusted ShowerMagic Specifications and Filter Dimensions

ShowerMagic aims to use as little water as possible. Although the system volume of the test setup is around 17–20 l, the total system volume can easily be reduced with an optimized design. The manufactured spacers allow for multiple filter size configurations which accounted for the large volume of the filters, these would not be necessary in a final product. ShowerMagic could work as a multipurpose filter with interchangeable filter bags, components or treatment methods depending on localized water quality and environments. If an adjustable filter volume is required, thicker spacers could easily reduce the volume of unused space within the filter housing. The dispersers for the big, medium and small filter widths were originally around 5 cm from the end caps, but the disperse was reduced to slightly over 2 cm in the Recirculating Water Test without a noticeable change in pressure. These are just a few examples of how filter volume can be minimized.

The pump used is classified as an FTP pump or Leisure Time Pool pump, which has its own cavity for a screen filter – which was not used – and had a total volume of 2.5 l. A more suitable pump would be smaller in volume and would have a smaller power requirement since the pump was significantly throttled. The energy usage of the ShowerMagic system is determined by several components, namely water heating and electrical components.

Heating of the initial water that comes into the system requires the majority of the energy used. A water heater could be used to maintain bathing temperature though it may not be necessary since 60 % (54 W) of the energy consumed by the UV lamp is emitted as heat which also heats the water as it passes through the UVIR. Heat generated from the pump may be utilised in a similar fashion. If heating is required, a more powerful UV lamp would offer a dual benefit since increased dosage would decrease the risk of bacteria getting through the system and the 'lost heat' would actually go to heating the water. Heat losses from showering would need to be established empirically to determine if additional heating is required.

Using the knowledge gained from the experiments, estimates for a working prototype of ShowerMagic system volume can be made (see Table 26). SF, GACF and UVIR volumes are based on the experimental results and estimations are made on pump, disperser and tubing/piping volumes as well as power specifications. The adjusted system volume totals 6.45 l, which leaves 3.55 l for external system volume – the volume of water left for actual showering and collecting the water into a basin before re-entering the purification system. With a flow rate of 10 l/m and 3.55 l of water available for showering it would leave 21.4 seconds for the water to exit the shower head, run down the user's body and be collected back into the system through the shower basin. Free falling water that does not touch the body would take less than a second to reach the basin, which would have rapid water capture with a high angle slope.

Table 26. Adjusted ShowerMagic System Volume and Power Consumption.

Component	Specifications	Power (Wh)	Volume (l)	Height (m)
Pump	~ 120 W	120	0.1	0
SF	25 % voidage		0.7	0.1
GACF	40 % voidage		3.5	0.3
Dispersers + housing			1	
PURION 2500 90W	90 W	90	0.65	0.8
Tubing	1.5 cm diam.		0.5	1.8
Additional components **(Sensors, valves & controller)**	10	10		
	TOTAL	**220**	**6.45**	**3**
Water volume for showering + water collection (basin)			3.55	
	TOTAL		**10**	

8.6 Comparing ShowerMagic to Traditional Showers

8.6.1 Water and Energy Consumption of Traditional Showers

The energy consumed while taking a regular shower is the energy required to heat the water used. Technically one could consider the energy requirements of acquiring, treating, transporting and pressurising the water throughout a water distribution network. However, due to the variables involved, making accurate calculations extend the scope of this thesis. Also, these types of costs are generally hidden within the cost of water bills. It is likely that the energy required for the utilities is greater than the electrical energy of the pump, but this will be omitted from the following equations. Heating water is a very energy intensive process. Equation 14 is used to determine the energy required to heat water:

$$Q = C_p * m * \Delta T * J_{kWh} \tag{14}$$

where Q = Heat transferred [kWh], C_p = Heat capacity of water [4184 J/Kg*K], m = Mass of water [1l water = 1Kg], ΔT = Change in temperature [K], J_{kWh} = One joule is equivalent to 2.78*10^{-7} kWh.

ΔT is the temperature difference between the input (cold tap water) and the output (shower-head) temperature. Average volumetric flow rate is assumed to be 10 l/min where 1 l of water is roughly equivalent to 1 kg. Increasing or decreasing the flow rate will affect the amount of water and thus heating energy required. See Figure 1 for a graph of shower water consumption with various flow rates over time.

8.6.2 Water and Energy Consumption of ShowerMagic

ShowerMagic requires only 10 l of water to be heated, as determined in Chapter 8.5. The sum of electrical energy required to run ShowerMagic comes from the pump (120 W), the UVIR (90 W) and various other electrical components (sensors, solenoid valves and micro-controller, estimated as 10 W) as shown in equation 15.

$$Power_{electrical} = Power_{Pumping} + Power_{UVIR} + Power_{other} \tag{15}$$

where $Power_{Pumping}$ is the energy required to power the pump [W], $Power_{UVIR}$ is the energy required to power the UVIR [W], $Power_{other}$ is the energy required to power all other electrical components (sensors, solenoid valves and microcontroller) [W].

Power consumption in kWh is determined with equation 16:

$$Power\ kWh = \ t\ *\ \frac{Power_{electrical}}{60} \qquad (16)$$

where t is time [min].

More investigation is required to determine if heat energy needs to be added in order to maintain water temperature and if this is even required.

The total power required to operate ShowerMagic is based on equation 17.

$$ShowerMagic_{power} = \mathrm{Q} * 10\ \mathrm{kg}\ *\ Power_{electrical} \qquad (17)$$

8.6.3 Water and Energy Saved by ShowerMagic

The water saved by ShowerMagic can be calculated with equation 18.

$$Water_{saved} = \left(Q_f * t\right) - ShowerMagic_{SysVol} \qquad (18)$$

where Q_f is flow rate [l/min], $ShowerMagic_{SysVol}$ is the total system volume of shower magic or 10 l.

The energy saved by using ShowerMagic instead of a traditional shower increases in relation to shower duration and can be calculated with equation 19:

$$Energy_{saved} = (Q * Q_f * t) - (ShowerMagic_{power}) \quad (19)$$

Figure 33 is based on equations 14-19 visually demonstrates the energy and water saving potential of ShowerMagic with the set variables. The difference in resource consumption would decrease with lower heating requirements and flow rates.

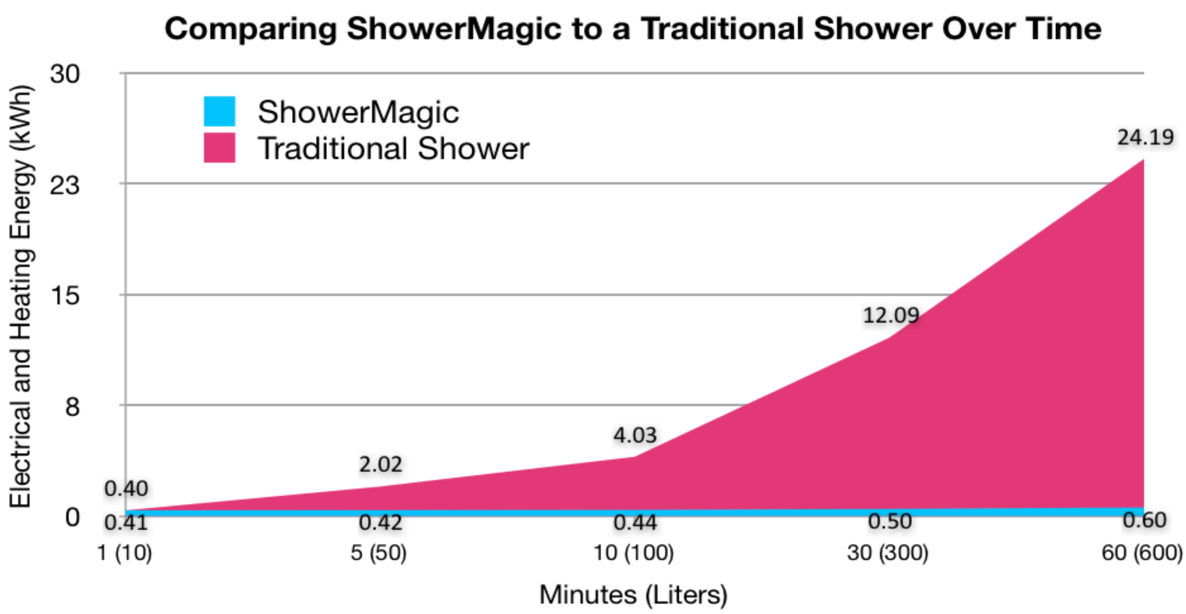


Figure 33. A comparison of ShowerMagic (bright light blue) energy and water consumption to a traditional shower (magenta) over time. Water temperature is raised from 10 to 45 °C with 10 l/min flow rate for both showers. ShowerMagic recycles a constant 10 l of water and requires 220 W/h to operate. Water density is rounded to 1 Kg/l for simplicity's sake.

Chapter 2.1 cited several studies on showering behaviour with average showering time being 10 ± 3 minutes with typical flow rates being slightly less than 10 l/min. If both values are rounded to 10 and it is assumed that a user takes a shower every day, 3.6 kWh of electrical energy and up to 90 l of water would be saved each day. In a month that would amount to circa 110 kWh and ~ 2800 l or 2800 kWh per year and around 33000 l of water. To calculate savings in monetary terms, the current prices that the authors pay for electricity is 0.0761 €/kWh (Ekosähkö, 2013) and 2.81 €/m^3 (1,25 €/m^3 potable water and 1.56 €/m^3 waste water, HSY 2013) for water. Yearly savings would amount to 305.81€, calculated in equation 20.

$$Annnual\ Savings\ (€) = 2800\ kWh \times \frac{0.0761\ €}{kWh} + 33\ m^3 \times \frac{2.81\ €}{m^3} \tag{20}$$

$$= 213.08\ € + 92.73\ € = 305.81\ €$$

Roughly two thirds of the savings would come from the reduction of energy consumption and the remaining third from the reduction of water consumption. Per capita water consumption in Finland is 155 l/day (HSY, 2012) with 40 % or 62 l accounting for personal hygiene, a figure similar to values detected in England (see chapter 2.1). Showers can be assumed to consume on average 60 l per day per capita. ShowerMagic could reduce this to 1/6th. A rough estimate of the water and energy saving potential in Finland with a population of 5.4 million taking 6 minute long showers with a flow rate of 10 l/min:

$$Energy\ Saved = 5.4\times 10^6 * 3.59 \frac{kWh}{day} * 365\ days = 7.08\ TWh \tag{21}$$

$$Water\ Saved = 5.4{\times}10^6 * 50\frac{L}{day} * 365\ days = 98.55\ Mm^3 \tag{22}$$

To put this in perspective, energy production from wind energy in 2011 was 481 GWh (VTT, 2011) or 14.7 times less than the amount of energy that could be saved with the widespread use of ShowerMagic. The water saved could fill 39 000 Olympic-size swimming pools, and while Finland has plenty of water resources, similar reductions in other countries could vastly reduce water stress and the demand on water treatment facilities.

9 Conclusion

9.1 SF Conclusions

During the experimental phase the amount of quartz sand used was too high for most of the filters to handle, other than the largest filters. The larger particle sizes got caught on the surface of the filter fabric. This means that the fabric itself has a pore size smaller than some of the quartz particle sizes. This caused caking on the fabric surfaces of the midpoint and the narrow filters and therefore decreased the flow rate through the filter to an unacceptable level.

Some of the filter bags were easier to make than others because of the varying dimensions. The crucial factor for filter bag quality was to make sure that the circumference of the bag was just right: too much fabric would cause wrinkles and too little would not cover the entire surface area of the filter housing. Both of these cause channelling. The 30 cm long and 19 cm wide bag had basically no channelling and had an excellent fit, while the equivalent 19 cm long bag had channelling up to half way down the bag. Although channelling never went through the entire height of the filter bag, it reduced the amount of water passing through the voids and pores (GAC) of the filter bags and thus may have reduced contaminant removal efficiency. Even when channelling did occur, presumably the GAC bag fabric and GAC helped as well, as seen in the combined experiment (FF). The effect of GAC on capturing particles is not known, but it is assumed that some particles are being adsorbed due to the large surface area caused by the multitude of the pores on the AC, as with the SS in the turbid water. The results of the reciculation test verify this as the measured quantity of suspended particles was less than the mass of the water moisture on the filter paper. More testing is needed in this regard. More testing is also needed to measure how much of the < 6 μm particles are getting through the filter paper, e.g. using the slower but more effective Whatman grade 589[/3] filter paper which has a pore size of > 2 μm.

9.2 GACF Conclusions

The testing of the ammonium concentration did not coincide with the calculations of the concentration. GAC bags were hand washed but the activated carbon was not substituted between experiments. Handling the GAC crushed the granules into a finer dust, which was then washed out. To properly flush the bag, it was placed in the filter housing and compressed – which also caused crushing – and clean tap water was rinsed through it for 10 minutes. This was much more time than was necessary since it appeared that most if not all the GAC dust came out immediately.

When testing the readability of prepared mineral clay samples, it was noticed that they changed quite dramatically over time. A sample starting at 100 NTU may only be 80 NTU maybe even the next day. Mixing the sample agitated the settled particles evenly before the measurements were taken so that the samples represented the water more accurately. Most likely particles are settling rather quickly or flocculating. The reduction of ammonium flowing through the larger bag in experiment AC10 was unexpectedly low. There could have been some other principle at work here, another chemical interfering with the results or an unforeseen reaction with the ammonium on the GAC that influenced the removal efficiency.

9.3 UVIR Conclusions

The PURION 2500 90W also came with an operating power detector (OPD) unit which uses a UV sensor placed in the middle of the UVIR and a circuit with indicator LEDs to display the UV power output of the UVIR. A green LED indicates over 70 % starting output efficiency, yellow indicates a reduced output or an efficiency of under 70 % of starting output and red indicates an efficiency of below 50 % of starting UVC output. The OPD is a simple and rather primitive system of measuring the UV output of the lamp, because the 100 % output limit is calibrated by the user after installing a new lamp. The sensor measures and records the current irradiance irrespective of whether the lamp is outputting at maximum efficiency. This can be problematic if a lamp is already damaged or used, in which case the user would falsely believe that the UVIR is operating at full efficiency. To measure the true output power an additional sensor that gives an actual numerical value would be needed.

Taking all this into consideration when looking at the results, both in the UVIR and combined tests the bacteria reduction is well within acceptable levels. In the UVIR test all the culture counts were of a similar level even when the test water was near 1000 NTU. This is significant because due to the working principle of UVGI, ultraviolet irradiation would be significantly reduced if the light cannot reach the bacteria cells some particles (very few, less than 1% of total introduced) travelled through the ultraviolet irradiation chamber. This had no noticeable effect on the CFU count of irradiated samples.

9.4 ShowerMagic Filtration System Conclusions (Recirculation)

The turbidity and ammonium concentrations were higher than they were supposed to be. This could be due to interactions between the clay, *E.coli* agar solution, quartz dust and ammonia, or due to contamination from an external source. This latter seems unlikely, however, as the changes in the initial concentration were so large and the change in procedure was not very different from previous tests. The sand sample was so small, that the weight of the moisture on the filter paper was greater than the mass of sand that was collected. The filter paper should have been dried before sampling.

10 Future Considerations and Research Plans

10.1 Design Changes

The test rig was made only to allow for rapid testing, and many of the components would not be present in a production model. Figure 34 below shows what a working prototype incorporating many of the features detailed in the following chapters could look like. To endorse a cradle-to-cradle concept ShowerMagic could be produced as a kit, which contains the harder to manufacture components (filter housings, pump and valves, UVIR and electronics) while allowing the heavier and more abundant materials to be sourced locally, for instance the GAC and sand used for the filters as well as the shower stall or room itself. Logistics would be reduced and local suppliers would also benefit. This could also drive down production costs making the technology more accessible to the people that need it most. The burgeoning popularity of 3D printing has also driven down capital costs substantially and could be incorporated in the manufacturing of ShowerMagic components. This would also allow for simple and fast upgrading of the shower to further increase its efficiency as development progresses.

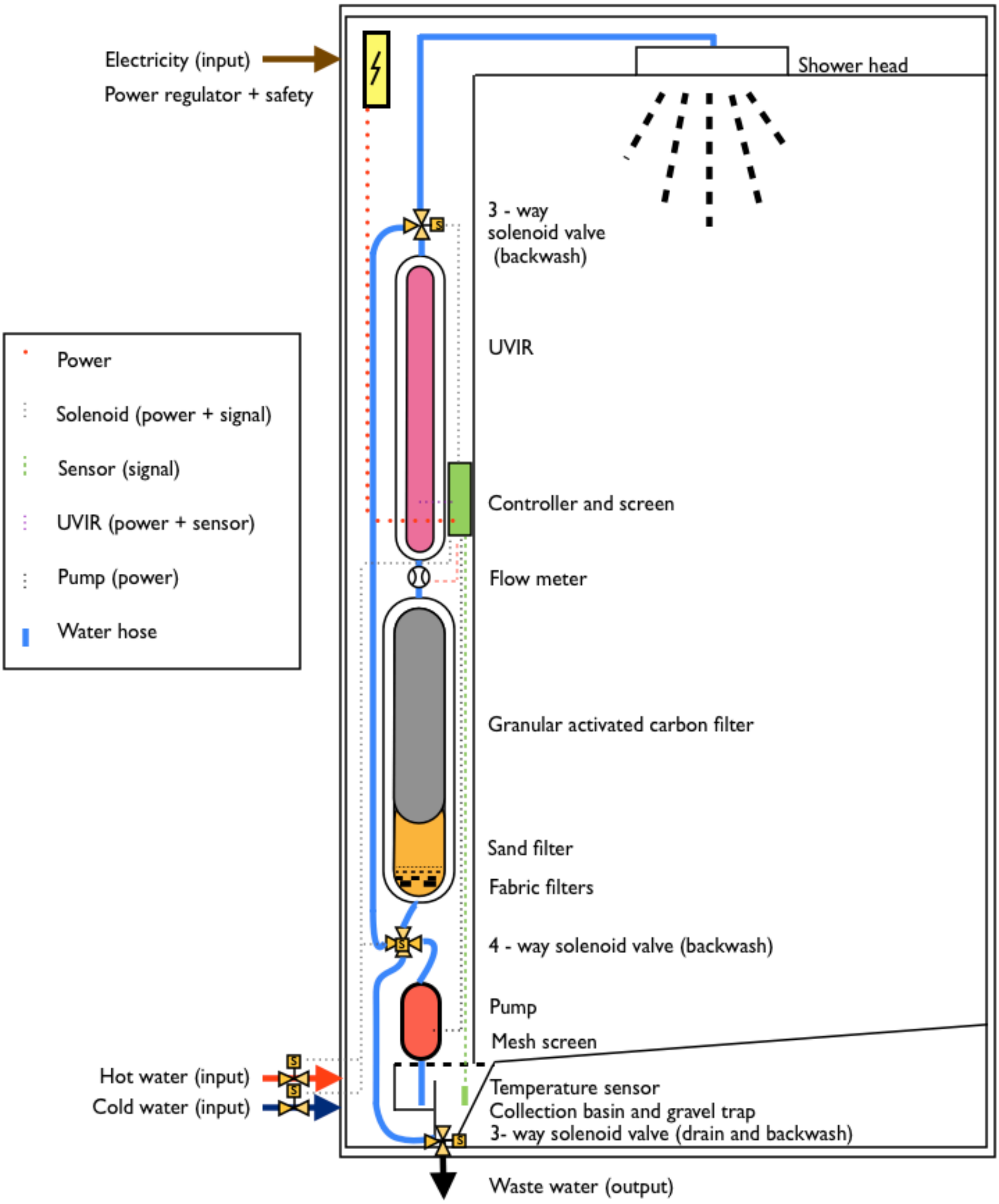


Figure 34. Profile view of ShowerMagic including solenoid valves, controller, pump, filters, UVIR, power regulator, gravel trap, showerhead and sensors as well as wiring and power and water inputs and outputs. Diagram is not to scale.

10.1.1 Screen, Gravel Trap and Backwash System

There are several changes to the actual system that would make it run smoother and reduce its energy costs. The addition of a screen and gravel trap before the filter system would ensure that larger particles were caught before they made it to the filters, thus increasing the useful lifetime of the filters and reducing the maintenance requirements. The addition of access hatches to the sand and activated carbon filters also means that maintenance will be easier and accomplishable by the end user. The addition of a backwash system also increases the longevity of the filters by removing captured particles through the wastewater stream. This could be achieved by pumping fresh water in the opposite direction of normal flow, thus flushing contaminants out of the inside and outside of the bags into a wastewater drain. Additional hoses and valves (mechanical or solenoid) would allow for simple and fast backwashing. Experimentation with the water requirements and effectiveness of backwashing would be required.

10.1.2 Microcontroller and Electronics

The design of ShowerMagic originally planned for the use of a microcontroller and sensors to monitor and control water temperature, flow rates, pressure and pumping power, automatic backwashing (with solenoid valves), filter efficiencies (by monitoring pressure) and UV power output (UV-sensor). This would have the added benefit of simplifying the usability and maintenance of ShowerMagic. Sensor monitoring would also allow users to observe and track their own showering behaviour, gauge the comparative energy and water savings made with the system and possibly program the shower to increase its functions such as cycling through spraying modes or changing the ambiance in the shower. See chapters 10.2.6 and 10.3.1 for more information. Resource limitations and the importance of ensuring that the water was both clean and hygienic meant that practical research into the hi-tech components had to be left out.

10.2 Future Experiments

The experiments conducted in this thesis only investigate a small set of controlled variables and contaminants based on what were found to be the common contaminants in normal showering water. In reality ShowerMagic is a dynamic filtration system that will change depending on multiple, possibly interacting variables. For instance, water hardness, mineral content and bacteria cultures will vary in different geographic regions, as will many other parameters.

10.2.1 Flow Rate as an Additional Variable

The variable width essentially determined the velocity of the water traveling through the filters. This is equivalent to the reaction time. Additional experiment with reaction time as well as retention time (proportional to height and width) may provide useful and interesting results. The complete set of SF experiments were not conducted because of the decrease in flow rate. However, the experiments would be useful to conduct in order to determine how effective the smaller sand bags are when filtration speed is not so important. Slower flow rates are predicted to increase the effectiveness of the filters. 10 l/min was considered to be a suitable maximum flow rate, experiments were conducted in this range to ensure filter performance when the system is at ‘maximum power’. Commercial high pressure showerheads can have flow rates of 5 l/min or less. Hence, it would be interesting to determine how much flow rate can be reduced without compromising the sensory experience of the shower. Filter volume as well as pumping and UVGI power requirements would also be reduced if adequate filtration is possible with smaller filters.

10.2.2 Dedicated Fabric Filter

More research should go into fabric filtration as a filtration step before the SF. An effective way to reduce the pressure drop from fabric filtration would be by capturing consequently smaller particles with multiple fabric filters with reducing pore sizes. Paper filters used in the suspended particle (quartz sand) experimental analysis used vacuum filtration to capture and measure particles that may have made it through the fabric and sand filter. Similar filters could be used in a once per shower manner to greatly reduce the system volume.

10.2.3 Experimenting with GAC

GAC can have varying properties depending on the materials and processes used to produce it. The manufacturing methods allow for different particle sizes, pore structures and overall surface areas accounting for their qualities. Experimentation with different GAC could yield better results. Further experimentation with alternative chemicals (that are also commonly found in shower water) could reveal a better choice of activated carbon. Ammonium hydroxide is present in urine and sweat, but sodium chloride and other salts are more common in shower grey water.

10.2.4 Expanding the Factorial Design

The repeatability of the experiments is good, as can be seen from the centre point replicates in the GAC tests. Additional experiments around the 100 % removal efficiency zones (as seen in the contour maps for turbidity and ammonium reduction) would prove useful and provide a more accurate model of the relationship between the variables for reliable optimisation. The experiment could be expanded to a central composite design to better model the response surface.

10.2.5 UVIR Testing

During the testing of deactivating *E.coli* with the UVIR no upper limit was ever found for turbidity that would reduce the effectiveness of the UVGI by shadowing. To research the limit in which shadowing becomes a problem, the experiments in Chapter 5.4 would need to be repeated with greater turbidity concentrations e.g. 2 000, 5 000, 10 000 and even 100 000 NTU to find out at what point it begins to affect the survival rate of the bacteria. It should be noted that the SF and GACF should stop a very high percentage of the particulate matter. If used, a turbidity sensor could stop the operation of the shower when excessive turbidity is detected.

10.2.6 Human Testing and Filter Capacity

Human testing would be useful in receiving feedback on the system as a whole. This would likely require a long-term research project which would monitor people's opinions on the shower (ideologically and practically) and monitor the effectiveness of the shower over time, with regards to longevity, life cycle assessment, pollutant removal, pressure build up (from contaminants) and most importantly, if it has any unexpected negative impacts on health. Material selection should also be given consideration. The data from this thesis indicates that a controlled study with diligent microbial sampling would be safe to conduct. This hypothetical human test could also determine showering habits first-hand and therefore build up a more accurate measure of how much water and energy is being saved. It would also be possible to monitor the effect of bacterial growth on the drying filter bags when the system is not in use. Many design cycles would likely be required to perfect the system. Understanding how people experience a shower could reveal ways to trick the user into feeling that water temperature or flow rates are higher than in reality. For instance, heat conducted to the feet with floor heating could make the user feel warm even when the temperature of the shower water is lower than usual. Lighting could also alter the experience: red lights create a feeling of warmth while blue lights a feeling of coolness. Recordings of heavy rain or waterfalls could create a sense of showering with much more water than what is actually being used.

10.3 ShowerMagic Potential

10.3.1 Maximising the Efficiency of the System

The results of the experiments clearly show that ShowerMagic has real life potential. ShowerMagic has the potential to reduce both water and energy consumption. With custom-made components ShowerMagic allows a user to shower indefinitely for the equivalent of 1–2 minutes of traditional showering. The true savings of ShowerMagic are heavily reliant on the user's own showering habits: water temperature, flow rate, duration and frequency of use. However, ShowerMagic can easily be considered to decrease showering water consumption fivefold. Water consumption can also be decreased by slowing down the flow rate, which would also allow for smaller filter size dimensions, a lower powered UVIR and smaller pump.

Future developments could increase energy efficiency by using UV-C LED's, which have greater efficiency than low-pressure mercury lamps and by having a more appropriately sized pump. The pumping power could possibly be halved (the pump was heavily throttled during experimentation).

10.4 Applications

ShowerMagic could replace or modify existing shower rooms and stalls and could be a viable option for vehicles and places where it would not be possible to have a normal shower. Mobile homes and boats could reduce the need to store water or purchase expensive water purification devices. ShowerMagic could be utilised in temporary shower stalls for example at festivals or in areas that do not have functioning water treatment networks such as slums or areas devastated by man-made or natural disasters. Hygiene may not be the first aspect that comes into mind when thinking about people in trouble. However, personal hygiene is crucial for maintaining health. ShowerMagic coupled with rain water collection, solar heating, photovoltaic cells, windmills and human-powered devices would offer a low cost and ecologically sustainable method of showering virtually anywhere in the world.

10.5 Market Potential and Competition

Current competitors to ShowerMagic are the Quench shower by Quench, Australia (Quench, n.d.) and Water Recycling Shower by CINTEP, England (CINTEP, 2012).

The Quench shower is similar to the first prototype of ShowerMagic, so basically simply a water basin and a pump. It requires the users to first wash themselves clean after which re-circulation of collected water can begin. There is a mention of filtration but the system is not specified. Disinfection is mentioned to take place only between showers, where a disinfecting rinsing of the recycling system takes place.

The Recycling Shower uses a hydro-cyclone system to allow heavy particles to sink into a wastewater drain with the remaining 70 % of water going through a heat exchanger and pasteuriser. The pasteuriser works to sterilise the water by heating the shower water to 72 °C for 15 seconds, and the heat exchanger is used to heat and cool the incoming and outgoing water of the pasteuriser. While the idea of the Recycling Shower is very similar to ShowerMagic, the working principal is different. Without much technical evidence to go on ShowerMagic still seems to be a more ecological and possibly cheaper technology. The shower by CINTEP only recycles 70 % of the water each cycle meaning that long showers still consume a large amount of water and heat energy is also being lost. A 10 minute 10 l/min shower with ShowerMagic consumes only 10 l while the Recycling Shower would use 18 l and significantly more energy.

Quench claims to sell Recycling Showers but numerous attempts to contact the company via e-mail have failed. CINTEP does not yet produce the recycling shower, but claim to begin sales in 2013. No mention of pricing is available from either supplier. According to a PopSci web article (PopSci, 2012), the cost of developing the CINTEP Recycling Shower is 1.75 million dollars. In comparison, the material cost of ShowerMagic has been under 1 000 €, but laboratories and tools have been provided for free by Metropolia, and there were no labour costs.

Considering how great the current reduction in water and energy consumption with relatively limited resources is compared to traditional showers, and with only the first prototype, ShowerMagic will yield surprising results if research is continued.

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APPENDIX 1. PURION 2500 90W Manual

PURION
the best solution

PURION 2500 for water-disinfection

…is characterized by compact construction and a high degree of efficiency respecting to disinfection and energy consumption. The construction design follows laws, standards and regulations.

manufacturer	PURION GmbH
type	PURION 2500
flow rate	2,5 m³/h drinking water at 36 W
UVC-transmission	90% T_1 cm
temperature of water	2°C to 40°C
reaktor	stl. steel 1.4571
flanges external thread	R 1“
seal	FPM
dimensions (L x Ø in mm)	928 x 42
distance flanges	850 mm
weight	3,4 Kg
life time of lamps	10.000 h
number of lamps	1
dose	400 J/m²
temperature max	40°C
max. working pressure	10 bar
protective system	IP 65
electrical connection (optionally)	230 V/50 Hz or 110 V/60 Hz 24 V DC at 36 W
total power	36 W, 75 W, 90 W
over current protection	10 A

UV Plant PURION 2500 is equipped with a polished stainless steel reactor.
PURION 2500 can be used to disinfect drinking water up to a flow rate of 2.500 l/h and a transmission of at least 90% per cm.

The used UV-lamps are characterized by a long durability and a high degree of efficiency respecting to disinfection and energy consumption.
The power supply can be carried out with 230 V/50 Hz or 110 V/60 Hz or optionally **24 V DC** at 36 W.

To realise higher doses than 400 J/m² UV plant PURION 2500 can Be equipped with UV-lamps characterized by higher radiation power. In this case PURION 2500 can be used for a transmission of at least 60% per 1cm. The power supply is carried out with 230 V/50 Hz or 110 V/60 Hz.
The compact construction design enables an easy replacement of the UV lamp at the end of their useful life.
You don´t need any tool. Also replacement and cleaning of the quartz pipe can be arranged easily. UV disinfection is reached by floating the water through the reactor.
Inside the reactor an UV lamp enclosed in a UV-C transparent quartz pipe is surrounded by the drinking water to be treated.
The small distance of 7,5 mm between the quartz pipe and the inner surface of the reactor ensures optimal irradiation and therefore optimal disinfection of the water.

This UV-plant is applied at:

Drinking water	•
Water of air conditioning	•
Disinfection of permeate	•
Pools	
Aquariums	
Fish ponds	
Storm water of sewage plants	•
Pharmacy	•
Greenhouse	•
Water of domestic use	

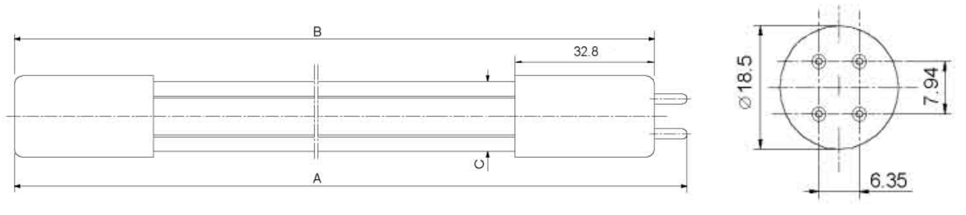
Advantages

- additional chemicals are not required for disinfection
- no change of hydro chemistry
- smell and taste of the water are not influenced by radiation
- installation in conveyor lines
- less required space
- manageable maintenance, small operation expenses

APPENDIX 2. PURION 90W T5L/4 HO Germicidal Lamp Data Sheet

PURION® GmbH	**PURION 90W T5L/4 HO** Germicidal Lamp Data Sheet	**Purion GmbH** **Schubertstraße 18** **98544 Zella-Mehlis** Tel:+49 36824790 87 Fax:+49 3682479086 uv-technology@purion.de www.purion.de

Dimensions	
A -Base face to opposite pin length	**854 mm**
B -Base face to base face length	**846 mm**
C -Diameter	**15 mm**

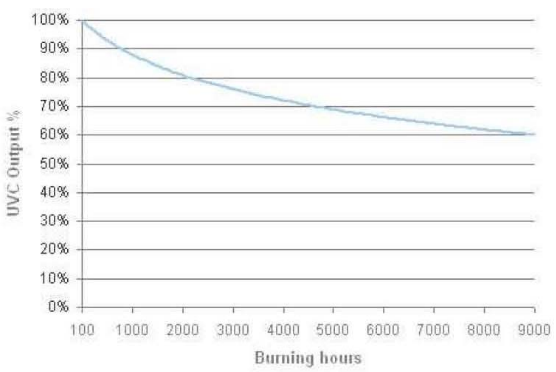


Electrical Data ***(nominal values)***	
Lamp Wattage	**90 W**
Lamp Current Lamp	**800 mA**
Voltage at High Frequency	**113 V**

Physical Data	
UV Output 253.7nm (100hr)	**29 W**
Intensity @ 1m	**265 µW/cm2**
Rated Average Life	**10.000 hrs**

Maintenance curve

The useful life is determined
on the operation condition of the lamp
(for example type of ballast, ignitor used,
cooling conditions, on/off cycle, etc.)



Note: Perf ormance data are v alid under laboratory conditions.

PURION GmbH 2010.03.31

APPENDIX 3. Table Calculating UVIR Irradiation

Variable	flow rate	flow rate	desired dosage	lamp length	outer diameter of quartz sleeve	outer diameter of bulb	inner diameter of shell	lamp UV-output	circumference of lamp	cross-sectional area (for vol)
Unit	l/min	ml/s	μW	cm	cm	cm	cm	μW*s	cm	cm^2
Purion 2500 90W	10.00	166.67	10000.00	80.64	2.50	1.50	4.00	265.00	4.71	7.66
		0.00	10000.00							
volume	**Volume in liters**	**time in tube**	**diameter or irradiance zone**	**circumference of irradiance zone**	**surface area or the irradiance zone**	**diminishing factor (RATIO)**	**exposure time**	**REAL lamp fluence**	**REAL Fluence in irradiance zone**	**Total Irradiance**
cm^3	L	s	cm	cm	cm^2	:	s	μW*s/cm^2	μW*s/cm^2	μW
617.51	0.62	3.71	3.34	10.48	844.99	0.45	3.71	981.84	441.55	373107.34
									Fluence needed for e.coli	**Times more powerful**
								90% reducito	2600.00	143.50
								99% reductio	6600.00	56.53

Calculations are based on equations 5 - 10.

APPENDIX 4. Nutrient Broth and Nutrient Agar Ingredients and Preparation

Making Nutrient broth			0.7	
Ingredient	Mass / Vol			Product
Beef extract	3	g	2.1	LAB M [MC 19]
Bacterial Peptone	5	g	3.5	LAB M [MC 24]
Distilled water	1000	ml	700	
pH 6.6-7-2. Sterilize at 121C for 20 min				
Making Nutriend AGAR				
Nutrient broth + 15g bacterial agar / 1000 ml				
Mix and autoclave for 15 minutes.				
Allow to cool to 50-55 degrees before making pour plates				
Transfer 1 ml of innoculated liquid from erlenmeyer flask in a sterile petridish				
Add Nutrient agar ~20 ml and swirl lightly				
Allow to cool down and solidify				
Place in overn upside down for 2-3 days at 37C for incubation (no mixing)				
26.9.2012				
We made 1.5 l of nutrient broth				
Placed in the autoclave				
Autoclave setup				
fill to 1cm from the forks				
if you use tap water empty afterwards				
put the bottom plate on				
heat to >100C let it steam with valve open (the white switch is to KESTO)				
put in the samples				
close lid, let it heat up till just >100C				
Let the steam out				
Close the pressure valve				
Wait until temperature increases to 120 degrees				
Switch to (KELLO) for 15 min (the 10 min mark).				

OCTOBER 15TH
UV test with tap water and 150 ml nutrient broth filled up to 15 L tap water (~40 degrees C)

Method is basically the same as AC but with modified outlet hose and different filter or in this case UV.
Setup as above (hoses and connections + volume for UV) table. Outlet water into St1 tank. Mixing same as always (1000 rpm). We took 25 ml with micropipette into sterile bottle pre-UV and filled a similar sterile bottle post-UV direct from the hose.

CFU count
MATERIALS
Autoclave all that shit (5ml vol. pipette x2, 5 ml test tubes and caps, and rack, 100 ml + deionized water in erlenmeyer flask, 200ml Nutrient agar; 0.6g beef extract, 1g bacteriological peptone, 3g bacterial agar). Make dilutions in fumehood...
not autoclaved 1000um micropipette and caps, petridishes.
70% denatured ethanol for sterilizing and cleaning.

Dilutions are
10^-1 - 10^-4 for pre-UV
10^0 - 10^-4 for post-UV
pourplate method stuff
incubate for 2 days at 37*

Sample taken ~13:00
Pourplates done ~14:14
Put to incubate at ~37 degrees for 2 days 14:40

APPENDIX 5. Test Procedures for SF, GACF, UVGI and Recirculation Experiments

Quicknotes & obvious stuff

1 L = 1000cm^3

* Filter, # varies according to Height and Width in cm and separated by underscore: e.g. the largest filter is 30 cm in height and 20 cm in width therefore the proper coding is 30H_20W.

The throttling valve will leak when the pump is not on even if it is CLOSED. Keep the pump on during sampling procedures.

Wear gloves and protect the Cw and Fw tanks from outside contamination with cling film / lids.

Make sure there are no bubbles in the system and that maximum flow rates have been achieved. Open the pump viewport which acts like an air release valve. Keep open until water overflows. This can be done while the pump is on (sometimes) but it's better to close V2 or V3 when the pump has been turned off and wait for the overflow.

Mixing should be around 1000 rpm ~ 11 nm torque. Place the mixer to the lowest possible point in Cw to make sure heavy fractions don't settle. Avoid the formation of vortexes.

Preparation / Flushing procedure

Step	Procedure
1	Connect and clamp desired filter
2	Direct outlet hose to drain, Inlet hose from tap or to Fw via the tap
3	Fill the system with fresh water from Fw tank/tap
4	Run the system until there are no bubbles, open the pump viewport after closing either V2 or V3 when the pump is off. The water from a water tank or the filter will fill the pump, wait until it overflows before closing the viewport.
5	Flush for an additional 10 minutes at peak flow
6	Note peak flow rate / no throttle flow in experimental setup table
7	Make sure the water level reaches the bottom of the Cw tank / fill hose: Cw to V1
8	Throttle to 10 L/min flow rate with V3
9	Leaving the pump ON, close V0
10	Set V1 to exclude V2 (no drawing of water)
11	Close V4

Test Procedure

Step	Procedure
	All Preparation steps have been carried out
	Pump is ON, V0 is closed, V1 excludes V2, V2 is closed, V3 is throttled to 10l/min, V4 is closed
11	Fill Fw to 25 L mark
12	Fill Cw to 8 L mark
13	Turn on mixer *note torque and rpm
14	Add 10 g of each test dust fraction to Cw, 50 g total
15	Make sure outlet tube is going to collection tank Sw1
16	- PREPARE to collect water -
17	P1 open V2 and V4 simultaneously
18	**P1** Set V1 to exclude Fw (Cw to V2 is open, water is being drawn)
19	**P2** watches the water level drop from 8 L to 4 L
20	**P1** sets V1 to exclude Cw (so Fw to V2 is open)
21	**P2** opens V0 in Fw tank
22	**P2** watches the water level drop from 25 L to 5 L in Fw
23	**P2** closes V0 in Fw tank to stop water in Cw tank from flowing into Fw tank
24	P1 sets V1 to exclude V2 (no drawing of water)
25	Turn off system/pump (close valves)

Sampling Procedure

Step	Procedure
	All Test Procedure steps have been carried out (St1 should contain 24 L of filtrate)
26	Cover St1 with cling film to protect from dust
27	Set up 200mm diam. büchner funnel to and vacuum suction apparatus
28	Weight Grade 3 (>6um) Whatman filter paper
29	Place filter paper in büchner funnel, turn on the vacuum (tap) and pre-wet the filter paper
30	Pour the filtrate onto the filterpaper (empty the vacuum flask when needed)
31	Dry the büchner funnel and filter paper in an oven for an hour at 100 degrees C
32	Weight the filter paper after brushing dried deposits on the walls of the funnel onto the filter paper
33	Calculate the mass of test dust captured
34	Separate the test dust by the original size fractions if possible

Test Procedure for Testing the Effectiveness of the Activated Carbon Bags

1. Place the appropriate filter in its own casing, clamp into place and connect the hoses.

2. Direct outlet hose to drain. Fill up Fw tank from the tap.

3. Set V_1 to draw from Fw tank (exclude Cw). Start the pump.

4. Ensure that there are no bubbles in the system so that the pump is operating at peak efficiency and note the peak flow rate.

5. Flush the filter for 10 minutes.

6. Throttle the outlet to 10 l/minute.

Preparation Steps for GACF

1. Connect and clamp desired filter to the test rig.

2. Direct outlet hose to drain and inlet hose to Fw via the tap.

3. Fill the system with fresh water from Fw tank with tap water.

4. Run the system until there are no bubbles, open the pump viewport after closing either V_2 or V_3 when the pump is off. The water from a water tank or the filter will fill the pump. Wait until it overflows before closing the viewport / release valve. Flush for 10 minutes at peak flow.

5. Note peak flow rate in the experimental setup table. Close V_0 while it's full of water and take it out of the Fw tank.

6. Turn off the pump.

7. Place the mixer into position (as low as possible in the tank and to the side to prevent vortex formation).

8. Add 2.5 l of ~ 1000 NTU clay water into Fw tank. Fill to 25 l.

9. Take turbidity measurement and adjust if needed. Turn on the mixer at ~ 1000 rpm. Connect the lamp to help see the water level and add 25 ml (1.5 g/l) of ammonium solution. Open V_0

10.Take water sample into 250 ml plastic bottle with cap (label as T# pre-filter).

11. Turn on the pump.

12. Take a sterile 250 ml container labelled correctly, and once the right amount of water has passed through the system, usually so that there is around 8 litres left in the Fw Tank, take the sample.

Taking GAC Samples

1. Measure the turbidity of both the before and after samples using the 'Hanna turbidity meter', making sure that the samples are as homogenous as possible.

2. Take the ammonium samples of the after samples and a few of the before samples.

While taking samples make sure that all the equipment used is clean.

Testing UVGI

Preprocedure:

1. Inoculate 150 ml of nutrient broth with *E.coli* and allow to grow for 2 days in a 37 degree oven.

2. Connect the Fw tank to pump, connect the pump to the UVIR and then have a hose from the other end of the tube running to the sink.

3. Prime the system making sure that there are no bubbles in it and that the pump is running at peak efficiency. Make a quick note of how long it takes to fill a 5 l measuring beaker.

4. Throttle the pump at V_3 to 10 l / min, timing the length of time it takes to fill the 5 L measuring beaker.

5. Close V_0 to ensure the system remains primed and turn of the pump. Then open V_0 while submerged in at least 5 l of water.

5. Fill Fw tank With 40 degree water and the 150 ml of *E.coli* inoculated nutrient broth to 15 l

in the Fw tank.

6. Turn on the ultra violet lamp and place the mixer above the Fw tank and have it mixing the sample water.

7. Take a sterile container and take a sample of the starting concentration in the Fw tank.

8. Turn on the pump: the system will be filled with some fresh water (around 6 litres). Once the Fw tank has drained to at least 8 l, take a sample from the outlet hose using a sterile container.

9. Repeat this procedure for 10, 100 and 1000 NTUs. Adjust the turbidity before adding the inoculated broth using a clay solution and the NTU meter.

Preparation Procedure:

1. Autoclave all the things that will come into contact with the sample (two 5 ml vol. pipettes, 5 ml test pipes and caps, rack, 100 ml deionized water in Erlenmeyer flask, 200 ml Nutrient agar, 0.6 g beef extract, 1 g bacteriological peptone and 3 g bacterial agar). Make dilutions in fume hood. 1000 µm micropipette and caps, petri dishes as well as 70 % denatured ethanol used for sterilising and cleaning do not need to be autoclaved.

2. Using standard pour plate methods make petri dishes for the following dilutions:

10^{-1} - 10^{-4} for pre-UV

10^{0} - 10^{-3} for post-UV

In total there should be 32 petri dishes.

3. Incubate for 2 days at 37 °C.

(left) Ingredients for nutrient agar (right) prepared pour plate samples awaiting incubation.

Recycling Test

Preparation Procedure:

1. Inoculate 150 ml of broth with *E.coli*.

2. Measure out 5 g of each size fraction of quartz (0–56 μm, etc.) so there is a total of 25 g.

3. Prepare a 25 ml of 1.5 g/l volumetric flask of ammonium, as well as a 2.5 l solution of 1 000 NTU water.

The purpose of this is to create a test water solution with 100 NTU, 1.5 mg/l ammonium, 1 g/l of quartz sand and a concentration of *E.coli* mixed in it.

Procedure:

1. Place the Fw tank in the test rig and connect it to the pump. After this put the sand filter and the activated carbon filter in their respective casings. Then connect the hose to the ultraviolet irradiance tube. Then finally after the UVIR, connect the hose to refill the Fw tank.

2. Prime the pump in the usual way and throttle the flow to 10 l / min.

3. Close V_0 and turn off the pump. After this open V_0 while keeping it submerged in some water.

4. Make the test water in the Fw tank. Take a sample of the water.

5. Turn on the pump and let 17 l (the fresh water that was in the system during the priming) go to the sink. Once 17 l has passed through the system put the outlet hose to the sink to empty the Fw tank and start the stopwatch.

6. At every two minutes take a sample from the outlet hose using a 50 ml sterile container. Take samples at 2, 4, 6, 8, and 10 minutes.

8. Take pour plates of all the samples at 10^0–10^-2 dilutions for every sample except for the zero solution which should be 10^-1–10^-4. Measure the turbidity and ammonium concentration using the appropriate machines. At the end of the experiment take 2 l of water into a flask, then use grade 5 filter paper, vacuum flask and a Büchner funnel to find out how much particulate material remains.

APPENDIX 6. Apparatus, Reactants and Reagents Used in SF, GACF and UVIR Experiments

Sand Filter Experiments	Activated Carbon Experiments	UVIR Experiments
Apparatus		
Mesh shaker and screens		
Büchner funnel 200 mm diam.	HI 88713 - ISO Turbidity meter (Hanna Instruments, USA)	5 ml test tubes and stands
Grade 3 Whatman filter paper 185 mm diam.	DR 3900 Spectrophotometer (Hatch, US/	Test tube shaker
Büchner funnel 100 mm diam.	Beakers	Petri dishes
589^3 Whatman filter paper 90 mm diam.	Volumetric flasks	Measuring pipettes
3 L Vacuum flask	Autopipettes	Auto Pipettes
2 L Beaker		Erlenmeyer flasks
500 ml Beaker		Beakers
Rubber bung		Inoculation loops
Tap and rubber tubing		Autoclave
Pipettes (for rinsing)		Laminar flow fume hood
Analytical balance		70% denatured ethanol
Rubber gloves	Rubber gloves	Rubber gloves
Lab coat	Lab coat	Lab coat
Reactants and reagents		
Tap water	Tap water	Deionized water
Quartz sand (0-56 μ m, 56-75 μ m, 75-106 μm, 106-150 μm, 150-212 μm)	Sigma Aldrich Ammonium hydroxide solution (25%)	LAB M Beef extract
	Mineral clay	LAB M Bacterial peptone
		LAB M Agar No.2 Bacteriological
		Escheriachia coli (Migula) Castellani and Chalmers

APPENDIX 7. Pressure Differences and Filter Volumes

Pressure Difference [kPa] Through the Sand Filter

10 litres per minute flow

Viscosity of 0.000653

Permeability Coefficient of 6.2×10^{-6}

	Width								
Height	**0.01 m**	**0.05 m**	**0.1 m**	**0.15 m**	**0.2 m**	**0.25 m**	**0.3 m**	**0.35 m**	**0.4 m**
0.01 m	2.226	0.089	0.022	0.010	0.006	0.004	0.002	0.002	0.001
0.05 m	11.130	0.445	0.111	0.049	0.028	0.018	0.012	0.009	0.007
0.1 m	22.261	0.890	0.223	0.099	0.056	0.036	0.025	0.018	0.014
0.15 m	33.391	1.336	0.334	0.148	0.083	0.053	0.037	0.027	0.021
0.2 m	44.521	1.781	0.445	0.198	0.111	0.071	0.049	0.036	0.028
0.25 m	55.652	2.226	0.557	0.247	0.139	0.089	0.062	0.045	0.035
0.3 m	66.782	2.671	0.668	0.297	0.167	0.107	0.074	0.055	0.042
0.35 m	77.913	3.117	0.779	0.346	0.195	0.125	0.087	0.064	0.049
0.4 m	89.043	3.562	0.890	0.396	0.223	0.142	0.099	0.073	0.056
0.45 m	100.173	4.007	1.002	0.445	0.250	0.160	0.111	0.082	0.063
0.5 m	111.304	4.452	1.113	0.495	0.278	0.178	0.124	0.091	0.070

Pressure Difference [kPa] Through the Activated Carbon Filter

10 litres per minute flow

Viscosity of 0.000653

Permeability Coefficient of 3×10^{-7}

	Width								
Height	**0.01 m**	**0.05 m**	**0.1 m**	**0.15 m**	**0.2 m**	**0.25 m**	**0.3 m**	**0.35 m**	**0.4 m**
0.01 m	46.006	1.840	0.460	0.204	0.115	0.074	0.051	0.038	0.029
0.05 m	230.028	9.201	2.300	1.022	0.575	0.368	0.256	0.188	0.144
0.1 m	460.055	18.402	4.601	2.045	1.150	0.736	0.511	0.376	0.288
0.15 m	690.083	27.603	6.901	3.067	1.725	1.104	0.767	0.563	0.431
0.2 m	920.111	36.804	9.201	4.089	2.300	1.472	1.022	0.751	0.575

0.25 m	1150.139	46.006	11.501	5.112	2.875	1.840	1.278	0.939	0.719
0.3 m	1380.166	55.207	13.802	6.134	3.450	2.208	1.534	1.127	0.863
0.35 m	1610.194	64.408	16.102	7.156	4.025	2.576	1.789	1.314	1.006
0.4 m	1840.222	73.609	18.402	8.179	4.601	2.944	2.045	1.502	1.150
0.45 m	2070.249	82.810	20.702	9.201	5.176	3.312	2.300	1.690	1.294
0.5 m	2300.277	92.011	23.003	10.223	5.751	3.680	2.556	1.878	1.438

Volume [m^3] of the SF and GAC Filters with Voidage

Fractional Voidage = 0.405

	Width								
Height	**0.01 m**	**0.05 m**	**0.1 m**	**0.15 m**	**0.2 m**	**0.25 m**	**0.3 m**	**0.35 m**	**0.4 m**
0.01 m	0.000	0.008	0.032	0.072	0.127	0.199	0.286	0.390	0.509
0.05 m	0.002	0.040	0.159	0.358	0.636	0.994	1.431	1.948	2.545
0.1 m	0.003	0.080	0.318	0.716	1.272	1.988	2.863	3.897	5.089
0.15 m	0.005	0.119	0.477	1.074	1.909	2.982	4.294	5.845	7.634
0.2 m	0.006	0.159	0.636	1.431	2.545	3.976	5.726	7.793	10.179
0.25 m	0.008	0.199	0.795	1.789	3.181	4.970	7.157	9.741	12.723
0.3 m	0.010	0.239	0.954	2.147	3.817	5.964	8.588	11.690	15.268
0.35 m	0.011	0.278	1.113	2.505	4.453	6.958	10.020	13.638	17.813
0.4 m	0.013	0.318	1.272	2.863	5.089	7.952	11.451	15.586	20.358
0.45 m	0.014	0.358	1.431	3.221	5.726	8.946	12.882	17.535	22.902
0.5 m	0.016	0.398	1.590	3.578	6.362	9.940	14.314	19.483	25.447

APPENDIX 8. R Commands

AC1.txt

Test	Height	Width	Area	Velocity	Time	NTU	NH4
T1	10	19.00	283.53	1.47	6.8	34.1	37.0
T2	10	7.00	38.48	10.83	0.9	14.4	7.76
T3	20	10.00	78.54	5.31	3.8	59.6	12.9
T4	20	10.00	78.54	5.31	3.8	57.5	10.3
T5	30	7.00	38.48	10.83	2.77	50.2	10.3
T6	20	10.00	78.54	5.31	3.8	59.0	14.2
T7	20	10.00	78.54	5.31	3.8	58.8	21.8
T8	20	10.00	78.54	5.31	3.8	53.6	16.0
T9	30	19.00	283.53	1.47	20.4	92.2	72.4

```
source ("http://users.metropolia.fi/~velimt/Koesuunnittelu/DOE_functions_v4.2.R")
AC.data <- read.table('AC1.txt', header=TRUE)
Height <- AC.data[,2] # Height
Width <- AC.data[,3] # Width
NTU <- AC.data[,7] # NTU
NH4 <- AC.data[,8] # NH4
x <- AC.data[,c(3,2)] # The independant variables W & H
minx = c(min(Width),min(Height))
maxx = c(max(Width),max(Height))
X <- code(x, minx, maxx, varnames=c('Width', 'Height'))
M3.NTU <- lm(NTU ~ Width*Height + I(Height^2), data = X) #polynomial
M4.NTU <- lm(NTU ~ Width*Height + I(Width^2), data = X)
M3.NH4 <- lm(NH4 ~ Width*Height + I(Height^2), data = X)
M4.NH4 <- lm(NH4 ~ Width*Height + I(Width^2), data = X)
print(summary(M3.NTU)),
print(summary(M4.NTU))
print(summary(M3.NH4))
print(summary(M4.NH4))
par(mfrow=c(3,3))

### NTU contour plots
```

```
quad.plot(M3.NTU,c(0,40),c(0,40),zlevels=seq(0,100,10),minx=minx,maxx=maxx, varlabels = c("Width","Height"), color.palette=rainbow, lwd=1.3, main="NTU reduction (%) Height^2")
text(Width, Height, NTU)
quad.plot(M4.NTU,c(0,40),c(0,40),zlevels=seq(0,100,10),minx=minx,maxx=maxx, varlabels = c("Width","Height"), color.palette=rainbow, lwd=1.3, main="NTU reduction (%) Width^2")
text(Width, Height, NTU)

### NH4 contour plots
quad.plot(M3.NH4,c(0,40),c(0,40),zlevels=seq(0,100,10),minx=minx,maxx=maxx, varlabels = c("Width","Height"), color.palette=rainbow, lwd=1.3, main="NH4 reduction (%) Height^2")
text(Width, Height, NH4)
quad.plot(M4.NH4,c(0,40),c(0,40),zlevels=seq(0,100,10),minx=minx,maxx=maxx, varlabels = c("Width","Height"), color.palette=rainbow, lwd=1.3, main="NH4 reduction (%) Width^2")
text(Width, Height, NH4)
```

Script for Making the Volume Contour Map

```
### Volume contour map with 0.4 voidage (GAC)
width=1:40
height=1:40
W = matrix (width, nrow=40)
A = pi*(W/2)^2
H = matrix (height, ncol=40)
Z <- (A %*% H)*0.4/1000

filled.contour(width,height, Z, plot.axes = { axis(1); axis(2); points(40, 40)}, colour=rainbow,  plot.title = title(main = "Filter Volume (L)", xlab = "Width (cm)", ylab = "Height (cm)"))
```

APPENDIX 9. Analysis of Results: NTU Reduction with Polynomial Fit

```
lm(formula = NTU ~ Width * Height + I(Height^2), data = X)

Residuals:

        1          2          3          4          5          6          7

1.997e-16 -1.721e-16  1.900e+00 -2.000e-01  1.991e-16  1.300e+00  1.100e+00

        8          9

-4.100e+00  1.169e-16


Coefficients:

            Estimate Std. Error t value Pr(>|t|)

(Intercept)   65.412      1.238  52.831 7.68e-07 ***

Width         15.425      1.208  12.766 0.000217 ***

Height        23.475      1.208  19.428 4.14e-05 ***

I(Height^2)  -17.688      1.730 -10.224 0.000516 ***

Width:Height   5.575      1.208   4.614 0.009926 **

---

Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1


Residual standard error: 2.417 on 4 degrees of freedom

Multiple R-squared: 0.9934,     Adjusted R-squared: 0.9867

F-statistic: 149.9 on 4 and 4 DF, p-value: 0.0001312
```

APPENDIX 10. Analysis of Results: NH_4 Reduction with Polynomial Fit

```
lm(formula = NH4 ~ Width * Height + I(Width^2), data = X)

Residuals:

         1          2          3          4          5          6          7
-1.856e-16 -5.149e-17 -2.140e+00 -4.740e+00 -4.922e-16 -8.400e-01  6.760e+00
         8          9
9.600e-01 -4.889e-16

Coefficients:

            Estimate Std. Error t value Pr(>|t|)
(Intercept)   24.655      3.032   8.132  0.00124 **
Width         22.835      2.156  10.591  0.00045 ***
Height         9.485      2.156   4.399  0.01170 *
I(Width^2)     7.210      4.116   1.752  0.15470
Width:Height   8.215      2.156   3.810  0.01893 *
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 4.312 on 4 degrees of freedom
Multiple R-squared: 0.9782,     Adjusted R-squared: 0.9565
F-statistic: 44.97 on 4 and 4 DF,  p-value: 0.001399
```

APPENDIX 11. Used Digital Tools and Media

Photographs were taken with an Olympus E-500 14-45mm 1:3.5-5.6, Olympus OM-1 50mm 1:1.4,Canon Digital Ixus 75 5.8-17.4 1:2.8-4.9 and an Apple Iphone 3 g (2 Mpix). Microscopic imaging was taken with an Evolution MP Color Cybernetics camera with Nikon EPLAN10/0.25 microscope at 100x zoom. Photographs were cropped and colour corrected with Adobe Lightroom 3.0 and Photoshop CS 6.

Tables and graphs were made with R, Microsoft Office 2011 (Apple), iWork, Google Sketch Up, and GoogleDocs. Additional graphics were created or edited in Adobe Photoshop CS 6.