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Developing a Microbial Fuel Cell with Water Filtration Capabilities

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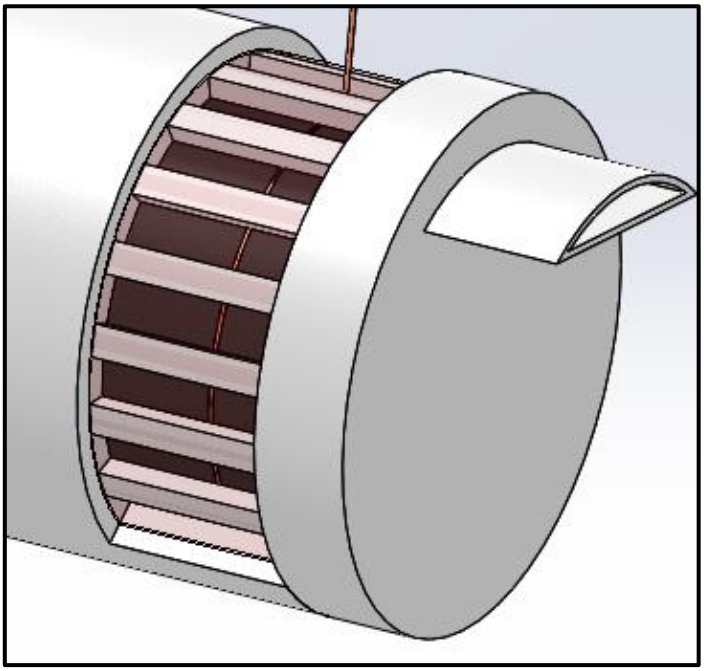
By Kristoffer Solberg Hov



Norwegian University of Life Sciences

A master's thesis in the study of Mechanics and Process Technology

in cooperation with the Faculty of Science and Technology at the Norwegian University of Life Sciences

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Preface

This master's thesis is a result of a project regarding Microbial Fuel Cells and the integration of this technology with water filters. The project is done in cooperation with the Faculty of Sciences and Technology (REALTEK) at the Norwegian University of Life Sciences and makes up the end result of a five-year study of Mechanical Engineering. The project involves many research fields that I have previously not been much in contact with, and this lack of knowledge represented a great challenge. However, my personal motivation for dealing with challenges made me take on this project alone and I have been lucky enough to have some help available.

The chance of making an almost entirely new product interested me and I have learned a lot in a relatively short amount of time compared to the comprehensive project. This newly acquainted knowledge includes particularly information about microbiology and electrical microbiology which, with my background in mechanical engineering, is not what I am expected to know. Nevertheless, I am happy with the results of this project and I hope that this thesis could help future students at tackling several challenges regarding this technology.

I would like to thank my supervisor at REALTEK Associate Professor Carlos Salas Bringas for all the work he has contributed with. This includes thing like creating the project, make me capable of doing the research and the experiments, and for constructive feedback on the setup of the thesis. I would also like to thank Associate Professor at REALTEK Odd-Ivar Lekang for allowing me the use of the facilities at the Aquaculture Research Station and for introducing me to the aspects of water filtration via literature and lectures. Further, I would like to thank Associate Professor at REALTEK Jan Kåre Bøe for motivational help and preparing me for the master project with his guiding throughout the pre-project to this thesis.

In addition, I would like to thank my girlfriend, friends and family for the help and support they have contributed with during this hectic project period.

Ås, May 15th, 2018

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Kristoffer Solberg Hov

Abstract

The world's focus has shifted towards the development and use of renewable energy sources. A contribution to this development is to utilize wasted or untapped energy sources, such as wastewater. Filtration technology has long been used and is continually in developed, but the energy in the filtrated wastewater has not seen the same usefulness. The integration of the Microbial Fuel Cell technology with the filtration of wastewater could be a useful method for producing electricity and utilizing the energy of the wastewater while purifying it.

This thesis is written as a part of a project at the Norwegian University of Life Sciences regarding the integration the Microbial Fuel Cell technology and the water filter technology. The results and discussions in this project is based on a pre-project, existing literature and experimental tests.

The main objective of this project was to develop a solution for production of electricity from a Microbial Fuel Cell as a part of a water filter that utilized wastewater. Challenges regarding this objective included primarily the little initial knowledge of the research fields involved and the time available for the project. With these challenges, the emphasis of the thesis was laid to the creation of several different prototypes and examination of the results from the testing of these prototypes.

Prototypes were developed with different designs and fluids in order to investigate the effects of the different factors. One design factor that was of special interest, was the use of membrane. In addition, a flow simulation was conducted on one of the prototypes, to investigate how the fluids behaved.

The prototypes were tested and the results from the tests were discussed and compared to other research. This led to the development of a *New Design* solution that incorporated recommendations from the discussion of the results of the experimental tests. The *New Design* solution presented a way of utilizing both fluids in motion and stagnant fluids, in addition to other benefits of the design. This was possible because of the design of the different components of the solution. It is worth noting that even though a solution to the main objective of this project has been developed, the solution is based mostly on experimental tests conducted during the length of approximately fourteen days. This might therefore not be the optimal solution for integrating Microbial Fuel Cell technology with water filter technology.

More studies of the *New Design* solution and the integration of the two technologies must be done in order to make the best possible solution. Future work on related projects should focus on specific parts and functions of the *New Design* solution, and longer experimental tests should be conducted. Especially important is the future testing and work on water quality of the fluid exiting the *New Design* solution, as this project mainly focuses on the electric output.

Sammendrag

Verdens fokus har rettet seg mot utvikling og bruk av fornybare energikilder. Et bidrag til denne utviklingen er å utnytte tapte eller ubrukte energikilder, som for eksempel avfallsvann. Filtreringsteknologi har lenge vært i bruk og er i stadig utvikling, men energien i det filtrerte avfallsvannet har ikke vært like godt utnyttet. Integrasjonen av den relativt nye mikrobiologiske brenselscelleteknologien med filtrering av avfallsvann kan være en nyttig metode for å produsere elektrisitet og bruke energien i avfallsvannet mens det renses.

Denne masteroppgaven er skrevet som en del av et prosjekt ved Norges miljø- og biovitenskapelige universitet, og omhandler integrasjonen av to primærteknologier, nemlig mikrobiologisk brenselscelleteknologi og vannfilterteknologi. Resultatene og diskusjonene i dette prosjektet er basert på et forprosjekt, eksiterende litteratur og eksperimentelle tester.

Hovedmålet med dette prosjektet var å utvikle en løsning for produksjon av elektrisitet med en mikrobiologisk brenselscelle som en del av et vannfilter som benyttet avfallsvann. Utfordringer i forbindelse med dette målet inkluderte hovedsakelig liten forkunnskap om de fagfelt som var involvert og tiden som var tilgjengelig for prosjektet. Med disse utfordringene ble vekten av oppgaven lagt til å utvikle flere forskjellige prototyper og undersøke resultatene fra testingen av disse prototypene.

Prototyper ble utviklet med forskjellige design og væsker for å kunne undersøke hvilken effekt de forskjellige faktorene hadde. En designfaktor som var av spesiell interesse var bruken av membran. I tillegg ble en strømningsanalyse gjennomført med en av prototypene, for å undersøke hvordan strømningen utviklet seg.

Prototypene ble testet og resultatet fra testene ble diskutert og sammenlignet med annen forskning. Dette ledet til utviklingen av en *New Design* løsning som inkorporerte anbefalinger fra diskusjonen av resultatene fra de eksperimentelle testene. Den nye *New Design* løsningen presenterte en måte for å utnytte både væske i bevegelse og stillestående væske, i tillegg til andre fordeler med designet. Dette var mulig på grunn av designet på de forskjellige komponentene av løsningen. Det er verdt å merke seg at selv om en løsning på hovedmålet med denne oppgaven har blitt utviklet, er løsningen for det meste basert på eksperimentelle tester som ble utført over en periode på omtrent fjorten dager. Dette er derfor muligens ikke den mest optimale løsningen for integrasjon av mikrobiologiske brenselsceller med vannfiltre.

Flere studier av *New Design* løsningen og integrasjon av de to primærteknologiene må gjennomføres for å kunne lage den beste løsningen. Fremtidig arbeide med lignende prosjekter burde fokusere på spesifikke deler og funksjoner til *New Design* løsningen, og lengre eksperimentelle tester burde foretas. Spesielt viktig er fremtidig testing og arbeide med vannkvalitet på væsken som går ut av *New Design* løsningen, siden dette prosjektet fokuserte på den elektriske produksjonen.

Table of contents

Abbreviations

Appx. -	Appendix
CAD -	Computer Aided Design
Eq. -	Equation
Fig. -	Figure
FT -	Flow-through
MFC -	Microbial Fuel Cell
SDT -	Stagnant Double Tube
SLST -	Stagnant Large Single Tube
SST -	Stagnant Single Tube

Glossary

Aerobic -	Presence of oxygen
Anaerobic -	Absence of oxygen
Anode -	Electrode that gains electrons from the environment
Biofilm -	Group of microorganisms attached to each other and to a surface
Cathode -	Electrode that loses electrons from the environment
Electrode -	Electrically conducting material
Oxidation -	Loss of electrons
Reduction -	Gain of electrons

Units and Symbols

% -	Percentage
ºC -	Degrees Celsius (temperature unit measurement)
g -	Gram (metrical unit of weight measurement)
m/s -	Meters per second (metrical unit of velocity measurement)
mbar -	Millibar (metrical unit of pressure measurement)
ml -	Millilitres (metrical unit of volume measurement)
mm -	Millimetres (metrical unit of distance measurement)
mm/s -	Millimetres per second (metrical unit of velocities measurement)
mm^2 -	Square millimetres (metrical unit of area measurement)
mm^3 -	Cubic millimetres (metrical unit of volume measurement)
mV -	Millivolt (metrical unit of electric potential difference measurement)
MΩ -	Megaohm (SI-unit of electrical measurement)

List of Figures

List of Tables

List of Equations

1. Introduction

The world has gradually changed its focus from using mainly fossil fuels, to a focus more directed towards cleaner energy. This is clearly a long-term struggle for addressing the challenges related to climate change. The Paris Agreement on climate change of 2016 further contributed to this shifted focus, and bonded at the time 175 countries to the promise of striving towards a limit of a 1.5 ºC increase of global temperature [1], [2].

Carbon dioxide (CO_2) levels in the atmosphere is one of the main reasons for the temperature increase and to achieve the temperature goal set by the Paris Agreement, countries must reduce their CO_2 emissions. Among high-income countries, the energy sector is responsible for almost half of the CO_2-eqvivalent emissions [3]. This means that if the countries of the world are going to be able to reduce their emissions, the energy sector would have a large potential to reduce the emissions by converting to cleaner energy sources.

In the USA, 2.5 - 3 % of the total electricity generated is used for treating wastewater [4]. This leaves a potential for new inventions and concepts to be implemented to reduce the energy sector emissions. The integration of MFC-technology with water filters might be able to regain some of the electricity used in the treatment of wastewater. This might help to the reduction of emission from the energy sector by lowering the electric demand of the wastewater treatment.

In recent years the MFC-technology has seen development in making it better and expanding its usage areas. With the growing focus on energy savings and consumption reduction in the world, water filters filtrating wastewater plays an important role. The population on the Earth is increasing, and UN goals have the hope to “ensure availability and sustainable management of water and sanitation for all”, and thus to focus on improving the filtration technologies [5].

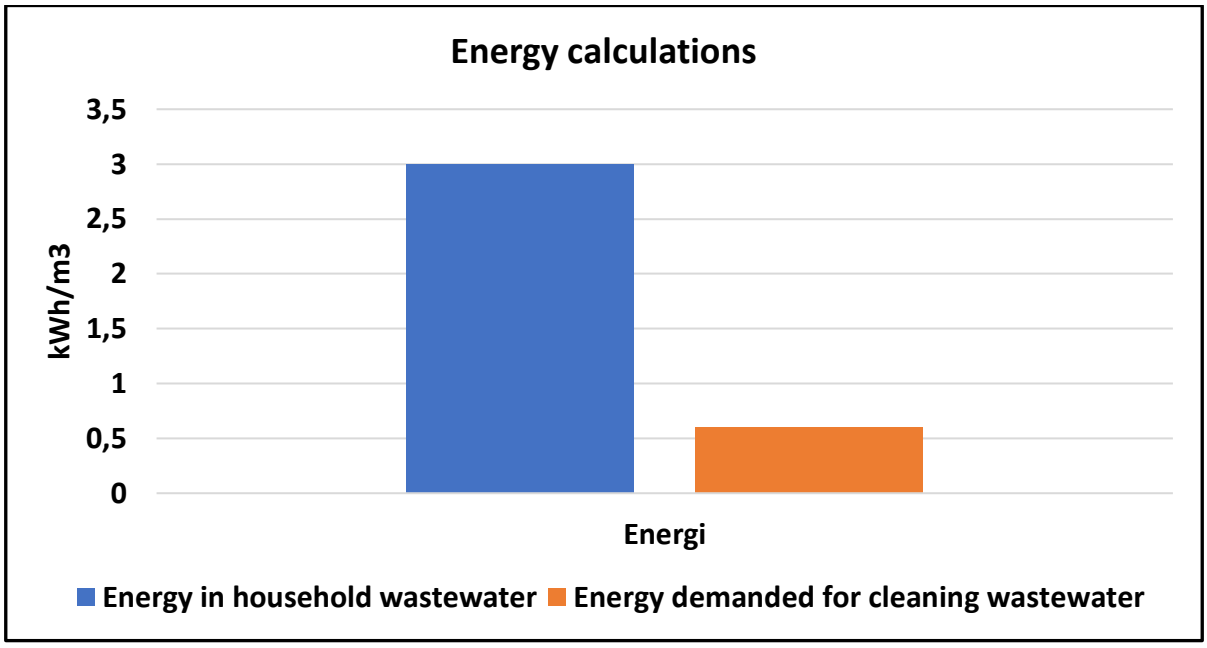

Figure 1: Illustration of the relation between energy available in wastewater from households and energy demanded for cleaning wastewater. Data collected from a presentation by Logan [4].

In addition to the energy used to filtrate water, some energy is lost in simply letting wastewater slip right into the ocean and rivers without attempting to harvest energy from the dissolved nutrients in that wastewater.

Leading American researchers within MFC-technology, like Bruce E. Logan, have made the world aware of this waste of energy and gathered data to illustrate this situation. Figure 1 presents this data and it shows that there is more energy in household water, than is needed to clean wastewater.

An “untapped” source of energy could be accessed by the MFC-technology, as seen by the difference of height between the columns (Fig. 1). An idea for countering the energy spending’s of water filters is to combine these filters with the MFC-technology, and harvesting the energy from the wastewater.

MFCs have been researched and improved continually during the last fifteen years, but not yet seen the breakthrough regarding largescale output of energy [6], [7], [8]. However, a range of different applications of the MFC-technology has been studied and put to use with success, and there still may be areas yet undiscovered by this technology. One area that has been studied by several researchers is the use of MFCs to treat wastewater. However, this project is not focusing on using MFCs to filtrate wastewater, but to integrate MFCs as a part of a water filter in order to regain some of the energy lost in the wastewater treatment process.

This project relies on two separate technologies, with several similarities. The first technology is water filters, which has a long history of improvements and testing. The second technology is Microbial Fuel Cells, which has a relatively short history compared to water filters. These technologies will be put together to develop a MFC with water filtration capabilities. The details of the project regarding this development is further described in the following subchapters.

1.1. Project Aim and Background

This thesis is written in cooperation with the Faculty of Science and Technology at the Norwegian University of Life Sciences. The thesis is a part of a project with the aim to integrate MFC-technology with water filters for filtration of wastewater. The idea was created by Associate Professor Carlos Salas Bringas after a pre-project, *Utvikling av en mikrobiologisk brenselscelle* by Kristoffer Solberg Hov, was completed fall 2017, with the aim to make a design of a working MFC. However, the aim of this project is to make a water filter produce an amount of electricity from the nutrients and chemical reactions that occur in wastewater, with the help of microorganisms in a MFC-system.

This project initially was planned around the experimental testing of different prototypes, and the results from these tests. As a result of the initial prototype tests, the emphasis of the project was shifted to the development of different prototype solutions and the examination of different problems regarding the prototypes.

1.2. Project Objectives

The purpose of this project can be divided into several sub objectives, that in turn leads to the main objective.

1.2.1. Main Objective

The main objective of this project was to develop a solution for production of electricity from a MFC integrated as a part of a water filter for filtration of wastewater.

1.2.2. Sub Objectives

- Determine whether a constructed membrane, separating the anode and cathode, is necessary or beneficial to produce electricity or not, based on literature and experimental tests.
- Investigate the flow of wastewater through a prototype, with the help of computer simulations.
- Produce a design of a solution, that integrates the recommendations from this project based on literature and experimental tests.

1.3. Project Limitations

- There will be no attempt to clarify the electricity production process regarding the microorganisms in detail.
- Certain materials could be more beneficial to this project than those used, but have been disregarded. The materials used is primarily chosen as a result of the research done in the pre-project "*Utvikling av en mikrobiologisk brenselscelle*".
- Time at disposal for this project is in its entirety about four months, and thus some necessary steps in the development of a solution to the main objective may be just described in chapter 7 as future work.
- A new proposed solution is limited partially to the experimental results from the project and might not be optimal for aquaculture facilities.
- Knowledge of the research fields involved in this project is very limited and thus this lack of initial knowledge might affect the results of this project.
- In creation of a new solution, the focus will be on the solutions electric output potential, and not on aspects like water quality.

1.4. Experimental Method

One of the main aspects of this project was to conduct several experimental tests of different prototypes, and interpret the results of these tests. Each prototype-set has its own describing name and the presentation of these experimental tests will follow a certain pattern.

This pattern is as follows; first, the experiments are described, then the materials and the method for conducting the experiments are explained before the results from the tests are presented and discussed. The discussion of the results might be followed up individually by suggestions for further improvements if this is considered possible, as a conclusion to the discus.

It is important to note that initially only one experimental test of a prototype was to be conducted. The other tests in this project where made on the base of the lack of sufficient results from this initial test, and became a fundamental part of this project.

1.5. Structure of the Thesis

- **Chapter 1. Aim and Background:** Describes key facts about the project that is helpful to understand the context of this thesis.
- **Chapter 2. Introduction:** Describes the motivation for the project and the necessary theoretical elements to understand the working principles of the technologies used in this project.
- **Chapter 3. Prototype Designs and Production:** Describes how the prototypes and elements related were made for the experimental tests.
- **Chapter 4. Prototype testing:** Describes the information desired from the experimental tests and the method and materials.
- **Chapter 5. Results and Discussion:** Describes the results of the experimental tests and interpret this information.
- **Chapter 6. New Design Solution:** Describes a solution to a new design, based on the preceding chapters.
- **Chapter 7. Conclusion:** Describes the summary of all the relevant results from this project and describes elements of this project that could be interesting or necessary to further develop.
- **Chapter 8. References**: Describes the literature used during this project and where to find the information used.

1.6. Project Resources

This sub-chapter presents the different resources used in completing this project, including computer software, styles and literature sources. Any illustrations created by this project is not referenced.

1.6.1. Computer Software

1. SolidWorks 2017 Dassault Systems; used for 3D-drawing and computer simulations.
2. Word 2016 Microsoft Office: used for writing this thesis.
3. Excel 2016 Microsoft Office: used for storing data and creating illustrations from data.

1.6.2. Literature

When collecting information from literature, each source of information has been assessed to be reliable based on the authors position and the time the material of the source was published relative to the content of the source. The information is mainly gathered from published material by reliable publishers such as government official websites and scientific journals.

Each source of information is listed in chapter 8. and the reference style is listed according to the IEEE-style. Some internet addresses listed as references in chapter 8. was shortened with the website-tool tinyurl.com, because of their lengths.

1.7. Summary of Pre-project

The report *Utvikling av en mikrobiologisk brenselcelle* by Kristoffer Solberg Hov was a part of a pre-project conducted with the goal of examining and developing a MFC. A prototype was developed through processes of selection of different solutions, materials and architecture. Most of the processes regarding the selection of materials and design was based on collected information from research articles and books.

The goal of the prototype was to be able to produce a small amount of electricity from wastewater. Despite relatively short available time compared to the size of the project and little knowledge on the field of MFCs, a small series of concreate results was created by the pre-project and can be used in this project.

These results are:

- Graphite plates and graphite felt was considered as suitable materials for the use as MFC-electrodes. Graphite felt was bought from FuelCellStore and made available to this project.
- For MFC-membrane materials, the use of Nafion membrane bought from FuelCellStore was regarded as usable and was made available for this project.
- Organic material fluids were also suggested as preferable liquids for the use of electric production in MFCs.

2. Literature Review

This chapter presents key elements for understanding the concepts behind this project, and a short review of some important factors considering electric production from MFCs and usage of wastewater regarding water filtration.

2.1. Microbial Fuel Cell Concept

One of the main technologies in this project is the MFC-technology. The MFC-technology uses microorganisms and nutritious fluid or matter to produce electricity. The MFC consist primarily of two electrodes that is separated from each other, as can be seen in Figure 2. At the anode, bacteria will form biofilm on the surface and start releasing electrons by breaking down the nutrients in the fluid or matter that is around. This process is called microbial metabolism [9], involving the steps of oxidation–reduction reactions [10].

Oxidation-reduction reactions means that electrons are transferred from one atom to another [11]. The electrons released by microorganisms will seek an electron acceptor, for example oxygen. The electrons will seek the path with the least electric resistance, which could be a metal wire, and will arrive at a cathode with surplus of electron acceptors [10]. Following on the next page is a simplified explanation of how the MFC-technology could work. In this example (Fig. 2) a carbon-based water-substrate in the anaerobic chamber is converted by microorganisms to carbon dioxide, free electrons and free protons. In the aerobic chamber these free electrons and protons reacts with oxygen-gas and form water.

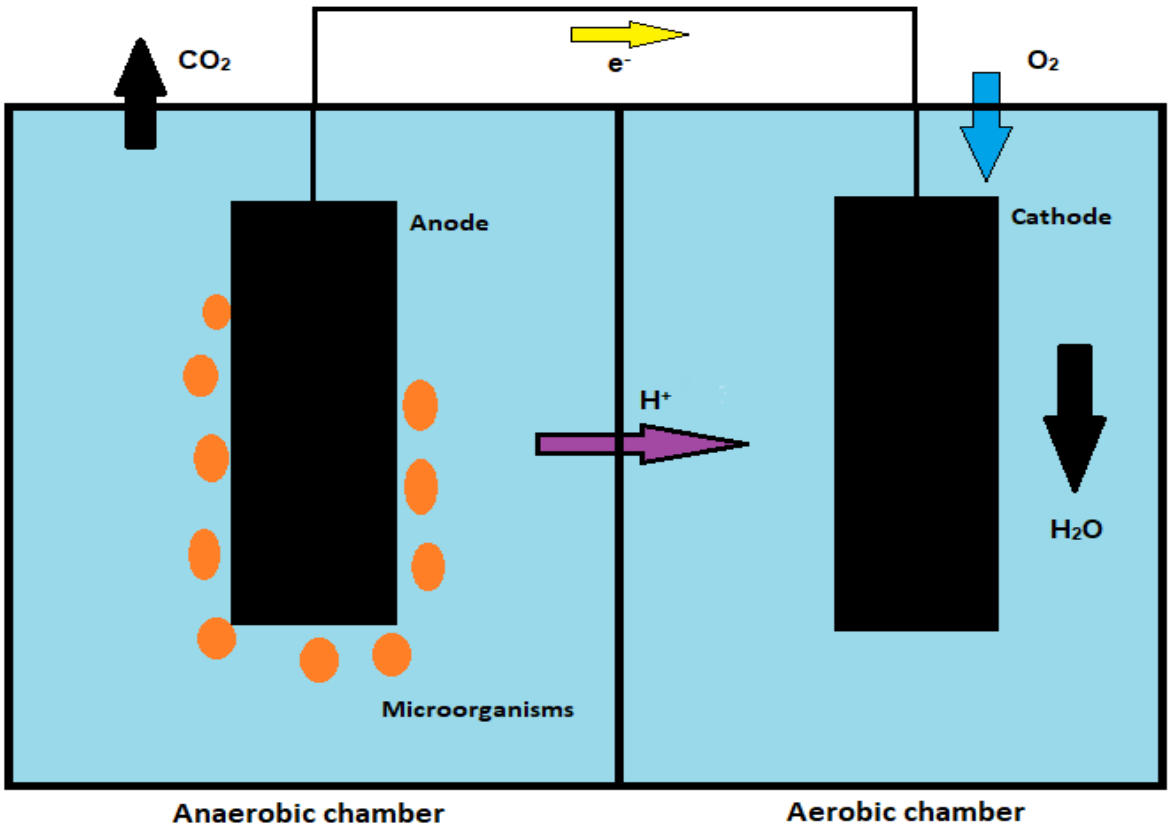

Figure 2: Example of the concepts and setup of a MFC, with protons (H^+), electrons (e^-), carbon dioxide (CO_2), oxygen-gas (O_2) and water (H_2O).

2.1.1. MFC-microorganisms

Many environments on the Earth has a range of different microorganisms that live of the nutrients in their environment and could be utilized by a MFC [6], [12]. However, for this project the focus of design and testing will be dependent on the microorganisms and nutrients that exists in wastewater from fish tanks collected from a water filter.

Especially microorganisms of the Geobacteraceae-family have been proved to be in abundance during tests when harvesting electrons from marine sediments [13], and microorganisms from the Desulfobulbaceae-family from fresh waters [14].

The Geobacteraceae microorganisms can grow at temperatures between 4 - 30 ºC, optimally 22 ºC [15], and the Desulfobulbaceae microorganisms can grow at temperatures as low as -1.8 °C [16]. The microorganisms have the ability to oxidise matter and can transfer electrons to electrodes, or even other microorganisms. This means that even though some microorganisms are not in direct contact with the electrode, electrons can still be supplied to the electrode via other nearby microorganism through connections called nanowires [17], [18], [19].

2.1.2. MFC-mediums

The MFC-technology relies on matter or fluids that are nutritious and useful for the microorganisms in order to release electrons [20], [21]. The fluid does not have to be in motion but must be regularly changed to keep the electric output somewhat constant. In addition to the nutrients, most MFCs are dependent on an oxygen supply in some form or another. This is because the electrons released by the microorganisms wants oxygen as it has a high reduction potential, and is abundant in the form of air [6], [22], [23].

2.1.3. MFC-electrodes

MFCs consists also of several non-biological parts, and among the most crucial parts is the anode, the cathode and potentially a membrane. Anodes and cathodes in MFCs can have many similarities and can even be made of the same material. The important part is that both material is electrically conductive, and can be used in a biological environment.

A large surface area versus volume is an advantage regarding MFC-anodes. This gives the bacteria a large surface area to attach to and pass electrons into the MFC-system, while limiting the size of the MFC. Several different materials have been tested, according to research papers [6], [24], [25], in MFCs regarding electric output. Among the most suitable materials tested in the research mentioned is various versions of carbon-based materials. For this project, a version of carbon felt will be used both as anode and cathode based on this research and the pre-project conducted.

2.1.4. MFC-membrane

In addition to an anode and a cathode, a membrane is very commonly used in MFCs. The membrane is used to separate the anode and cathode chamber, letting only a certain type of particles from one chamber to another. An example of this could be a Proton Exchange Membrane, letting only protons pass and forcing the electrons to reach the cathode chamber only via a metal wire. A membrane is not however necessary to make a MFC work.

Several MFCs have been made and works without actual membranes, using for example the nutrient matter as a separator and thus, by having a certain distance from the anode to the cathode, forcing the electrons to travel via a wire [26].

2.2. Water Filters

The second main technology used in this project is water filters. Water filters exists in many different shapes and sizes, and can consist of different materials dependent on the purpose. Water filters in general has the purpose of removing impurities and harmful particles from the water, relative to the usage of the water. Regarding treatment of wastewater from fish tanks, water filters can be categorized into a few different models.

2.2.1. Water Filter Types

Some examples of water filter models for filtrating fish tank water are Flow-through systems, Bioreactor, Fluid Bed/Active Sludge and Granular Filters/Bead Filters [27]. They are all characterized by using a biological filter, utilizing bacteria for the filtration process. For this project it is beneficial to further examine the Flow-through systems as they are the most relatable to the initial prototypes being developed in this project.

A Flow-through system is a biological filter where a fluid is flowing through a filter, sometimes in addition to some sort of oxygen input [27], [28]. The prototypes being built in this project can be compared to an up/down-flowing Flow-through system. This means that the system is always submerged under the fluid and the fluids passing through is forced through the filter.

This gives the bacteria a relatively large electrode surface area compared to a partially submerged system and renewal of nutrients with potentially good growing conditions for the microorganisms. A disadvantage using this kind of filter is that it needs an external source of oxygen, in order to oxygenate the fluid by the cathode [27].

2.3. Fish Water Filtration

Filtrating fish tank inlet water can be essential for healthy growth of the fish population. Many filters focus on removing harmful or unwanted particles or parasites from a water flow [27], [29]. The intention is first and foremost to protect the fish, but the spread of fish infectious diseases could also harm companies and countries economic situation and the biodiversity in local areas [30].

Another aspect regarding the filtration of fish water is the removal of the fish-toxic ammonia. The ammonia comes as a waste product from the fish, and could have a negative effect, by for example reducing the immune system of the fish and making them more vulnerable to parasites. The removal of ammonia content in water is done through a process called nitrification, and could be done by the microorganisms present in a MFC [27], [31].

2.3.1. Potential for Electric Production

The nitrification process can be conducted in the biofilm produced by microorganisms, and the mass of biofilm will increase as the process continues [32]. Ammoniumion (NH_4^+) is at equilibrium with the harmful ammonia (NH_3), and thus reducing the amount of ammoniumion would also reduce the amount of ammonia [27].

The following equation, Eq. 1, describes the process of ammoniumion removal [27], where ammoniumions together with carbon dioxide (CO_2) and oxygen gas (O_2) converts to ethyl cyanoacetate ($C_5H_7NO_2$), nitrogen dioxide ions (NO_2^-), free protons (H^+) and water (H_2O). The second equation, Eq. 2, describes further the removal process, where nitrogen dioxide (NO_2) together with carbon dioxide and oxygen gas converts to more ethyl cyanoacetate, nitrate (NO_3^-) and free protons.

$$55NH_4^+ + 5CO_2 + 76O_2 \rightarrow C_5H_7NO_2 + 54NO_2^- + 109H^+ + 52H_2O \quad \text{(Eq.1)}$$

$$400NO_2 + 5CO_2 + 76O_2 \rightarrow C_5H_7NO_2 + 400NO_3^- + H^+ \quad \text{(Eq.2)}$$

These reactions, in combination with other nitrite processes, creates a chemical cell that convert chemical energy to electric energy and can release free electrons and thus produce electricity [33].

Apart from the nitrification process, several other reaction processes could release free electrons for the use in a MFC [6]. As mentioned, oxygen plays an important role in many MFCs and will also play a role in the prototypes made for this thesis.

2.3.2. Dissolved Oxygen Amounts

In order to estimate the content of free oxygen molecules in wastewater that would be used by the MFC in this project, the amount of dissolved oxygen had to be measured. The free oxygen molecules are vital for the fish in fish tanks to survive [34] and is also important for many MFCs to work, as mentioned.

With sufficient amount of free oxygen molecules in wastewater at a cathode, all available electrons at the anode can form a current through a metal wire instead of being used at the anode. The amount of free oxygen in water is dependent on factors like surface area available to the air, temperature and pressure, and will decrease if for example the pressure is dropped [35].

When measuring the amount of dissolved oxygen in this project, the amount is illustrated in percentage of air saturation. A test showing a sample of 100 % air saturated wastewater means that the water is containing as many dissolved oxygen molecules as it can in a state of equilibrium and is fully saturated. This in turn means that the percentage of dissolved oxygen is equal to the percentage in the atmosphere at sea level. Water in contact with the atmosphere will slowly absorb oxygen from it until its fully saturated [36].

Wastewater with a low amount, for example 50% dissolved oxygen, is not fully saturated and thus would have less free oxygen molecules in the water compared to fully saturated water, making the environment more anaerobic [36]. And it is this anaerobic condition that is wanted at the anode. At the cathode, it is more beneficial to use fully saturated water, as it would have a higher number of free oxygen molecules available for the oxidation-reduction reactions taking place.

3. Prototype Design and Production

To develop a solution for integrating MFC-technology with water filters, all of the different factors mentioned in the previous chapter has to be taken into consideration. This development started with the creation of prototypes based on the Flow-through system filters mentioned in subchapter 2.2.1. Initially, only two Flow-through prototypes where going to be made to determine whether a membrane was sufficiently effective to the electric production in relation to its market cost. However, early testing indicated that several more experiments had to be conducted in order to investigate which factors that could have an impact on any measured results. Therefore, a series of two Stagnant Single Tube prototypes, two Stagnant Double Tube prototypes and one Stagnant Large Single Tube prototype was built. This chapter presents the construction of these prototypes and the preparing of the wastewater supplied to the FT-prototypes.

3.1. Common materials

Many of the prototypes have been made using the same materials, and they are described as follows:

- **Electrodes (anode and cathode);** AvCarb G200 Soft Graphite Battery Felt from FuelCellStore.com,
- **Outer tube;** TUBE 50ML UHP FC PRK from VWR International,
- **Inner tube;** TUBE 15ML UHP FC PRK from VWR International,
- **Copper wire;** Koblingsledning from Kjell.com,
- **Silicone;** PDMS Sylgard 184 Silicone Elastomer Kit,
- **Thread;** polyester fibre thread from Slojd-Skinn.se,
- **Parafilm;** “M” laboratory film from American National Can,
- **Membrane;** Nafion 211 from FuelCellStore.com,
- **External resistance;** Kjell Academy Motstandssortiment 600-pk (tolerance: ±1%). from Kjell.com.

3.2. Flow-through Prototype Wastewater Samples

The FT-prototypes were dependent on wastewater with different levels of dissolved oxygen amounts to make anaerobic and aerobic areas, following the example in Figure 2. In order to be somewhat sure of the amount of dissolved oxygen in the wastewater supplied to the prototypes, several tests had to made. These tests would lead to a method for preparing of wastewater with approximately continuous amount of dissolved oxygen. A large sample collected from the water filter at the Aquacultural Research Station (Fiskelabben) at NMBU was collected. From this sample, several smaller samples were collected in order to measure the amount of dissolved oxygen and prepare the fluid for the inlets to the FT-prototypes.

3.2.1. Method and Materials

Vacuum was used to lower the pressure of the samples, and reduce the amount of dissolved oxygen amounts in them. Samples with the volume of 36 ml were categorised into the amount of time they spent under vacuum (Table 1).

Table 1: Overview of the number of wastewater samples used in the wastewater sample test and their respective time under vacuum.

Amount of time under vacuum	Number of samples
0	4
5 minutes	2
15 minutes	2
30 minutes	2
1 hour	2
2 hours	2
3 hours	2

Samples were set under vacuum, with the use of a vacuum pump (VCT 80 Pump from VWR International), for the desired amount of time. The vacuum was constantly held at a level between 700-800 mbar. When not under vacuum, the samples were held refrigerated at 4 ºC in non-airtight plastic containers (PS 40 from Rotronic). This temperature corresponded with the lower limits of the growth of some microorganisms, as mentioned in subchapter 2.2.1. The samples were held refrigerated between 15-70 minutes, before the amount of dissolved oxygen could be determined. Refrigeration of the samples at this temperature had the intention of reducing the growth of the microorganisms before the tests could start.

The 3-hours samples and two of the 0-time samples were held in the refrigerator for 24 hours before testing. The testing of the dissolved oxygen amounts was made with an oxygenmeter (OxyGurad Handy Delta from WMT, Accuracy: ±1%).

3.2.2. Results

All the usable data from the tests of the dissolved oxygen amounts in the samples is presented in Table 2. This will be used to set a method for preparation of the wastewater for the FT-prototypes in subchapter 3.2.3.

Table 2: Overview of the results from the wastewater sample test, given with respect to the time in vacuum and treatment of the different samples. Results presented in percentage of dissolved oxygen amounts.

Amount of time under vacuum	Sample 1 (%)	Sample 2 (%)
0	68 ±1	65 ±1
5 minutes	67 ±1	68 ±1
15 minutes	70 ±1	68 ±1
30 minutes	69 ±1	70 ±1
1 hour	58 ±1	61 ±1
2 hours	50 ±1	48 ±1
3 hours (24-hours refrigeration)	99 ±1	98 ±1
0 (24-hours refrigeration)	100 ±1	100 ±1

3.2.3. Discussion and Conclusion

As Table 2 show, the vacuum process did not make any significant reduction of the amounts of dissolved oxygen in the samples before 1 hour had passed in vacuum. The results (Table 2) show that the samples initially were about 67 % air saturated. The lowest amounts of dissolved oxygen reached in this test were made during 2 hours of vacuum, and reached about 50 % air saturation.

The results of the 0-time (24-hours refrigeration) samples show that 24 hours of exposure to air will result in these samples reaching a dissolved oxygen level around 100 % air saturation.

However, if a sample is held for example in vacuum for 2 hours and is taken directly from the vacuum and used, the amount of dissolved oxygen in the sample might not comply with the results from this test. This is because of the amounts of dissolved oxygen in the sample would increase if it is exposed to air, and this might have an impact on any results from the testing of the FT-prototypes. This increase in dissolved amounts of oxygen over time can also be seen by the results from the sample held in vacuum for 3 hours and kept refrigerated for 24 hours, as it has a higher amount of dissolved oxygen than the sample held in vacuum for 2 hours.

Nevertheless, the test concluded that for the inlet to the anaerobe area of the FT-prototypes, samples under 0-time vacuum and 24 hours refrigeration should be used and for the inlet to the aerobe area, samples of 2-hours vacuum should be used. Samples made during 2-hours vacuum were sucked into syringes (Omifix Solo 12 ml from B.Braun) in order to produce a storage of samples that would not be exposed to air.

3.3. Flow-through Prototypes

In order to investigate the effect of wastewater flow through a filter, two prototypes had to be built with the capability of flow. It also had to have the necessary components of a MFC to be able to create and measure the electric output.

3.3.1. Design

Figure 3: Picture of the tubes and lids used for the FT-prototypes.

The initial experiment was designed based on pre-bought inner and outer tubes, shown in Figure 3. The outer tube formed the outer perimeter and thus separated the fluid inside from the surrounding air. The inner tube formed the barrier between the anaerobic and the aerobic areas of the prototype.

The inner tube held the inlet of 50 % air saturated wastewater, and the pressure from a pump forces the fluid through the anode in the prototype. The bottom of the outer tube holds the inlet of fully saturated water.

This fluid supplied the cathode with the oxygen needed for the flow of electrons from the anode to the cathode. The pressure from both inlets will force the wastewater in the prototype up the outer tube, through the cathode, and out of the outlets in the top of the prototype.

Both prototypes will have the same basic design. The difference between the two prototypes is that one will be fitted with a membrane, and holes, separating the anode and cathode. The other will separate the anode and cathode with the inner tube without holes or a membrane.

3.3.2. Production

Oblong holes were all the way around drilled into the inner tube of the FT-prototype with a membrane (Appx. B1), as shown in Figure 4. This allowed for an open path between the anode and the cathode for the protons. After the holes were drilled, a piece of membrane was wrapped around the inner tube and sealed with silicone around the edges of the membrane. The inner tubes of both prototypes were cut (Appx. B1) in order to reduce their lengths and make them fit into the outer tube.

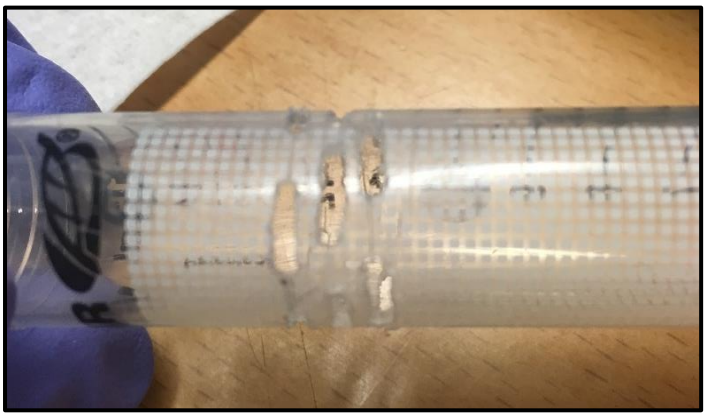

Figure 4: Closeup picture of the holes drilled in the inner tube of the FT-prototypes with membrane.

Holes were drilled in the bottom end of the outer tube (Appx. B2), as shown in Figure 5A, to allow for a fitting of the inlet of fully saturated wastewater. Holes were also drilled in the lids of the inner and outer tubes, as shown in Figure 5B. This allowed the fittings of the inlet of 50 % air saturated wastewater. In addition to these holes, a pair of holes were also drilled in the top of the outer tube in order to allow for the fitting of the outlet of the wasted fluid from the prototypes.

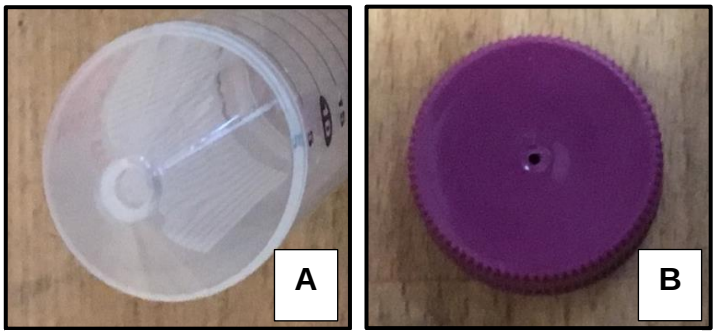

Figure 5: A: Closeup picture of the bottom of the outer tube for the FT-prototype.
B: Closeup picture of the lid for the outer tube for the FT-prototype.

The anodes and cathodes had to be as wide as possible in order to prevent water from flowing around them instead of through. The electrodes also had to be wide in order to prevent them from slipping and thus altering their positions in the prototype during testing.

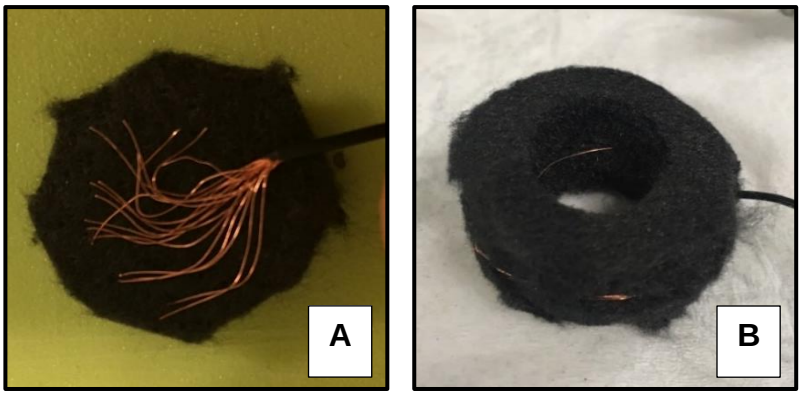

Figure 6: A: Closeup picture of the copper wire being spread between two layers of anode. B: Closeup picture of a cathode assembled with a copper wire.

The electrodes were pressed out into sheets fitting the tubes. A copper wire was then split and spread to cover as much area as possible, as shown in Figure 6A. Another sheet of electrode was then placed on the other with the copper wire, so that the copper wire came between the two sheets, as shown in Figure 6B. The electrodes were sewn together with thread, forced into the tubes and placed at their correct positions. A copper wire, with a 1 MΩ resistance coupled in series, connected the anode and the cathode as shown in Figure 7A.

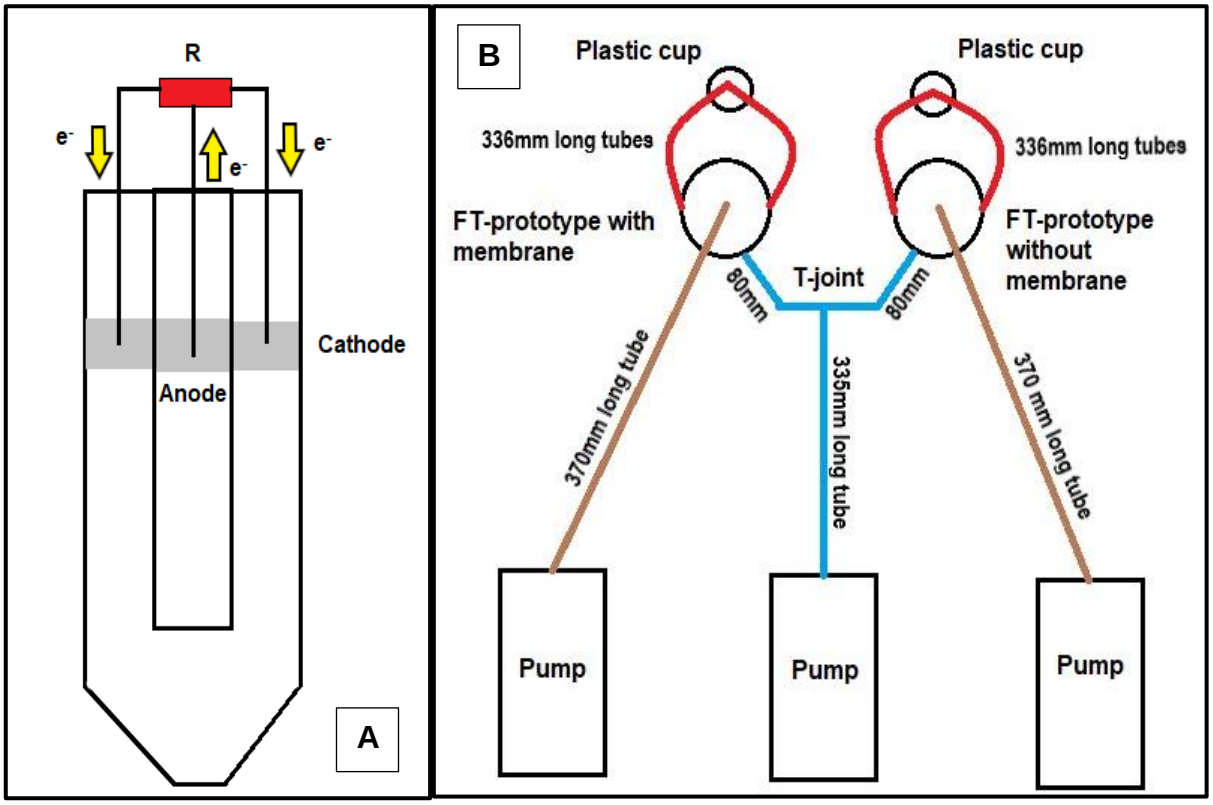

Figure 7: A: Sketch showing the electrical wiring of the FT-prototypes and the SDT-prototypes, where electrons (e^-) flows through a resistance (R). B: Sketch showing the tubing setup of the FT-prototypes for the FT-test. 100% saturated inlet stream showed in blue, 50% saturated inlet stream showed in brown, wasted water outlet tubes showed in red. All tubes shown with indicated lengths.

3.3.3. Tubing and Joints Assembly

This subchapter presents the tubing and joints setup for the FT-prototypes. All dimensions mentioned presents the diameter of the tubes and joints.

4.8 mm joints (Luer to Tubing Coupler Assortment Kit from WPI) were attached to the syringes (Omifix Solo 12 ml from B.Braun) containing 50 % air saturated wastewater. A 3 mm tube (Tygon LMT-55) was attached between the joint of the syringes and a 4.8 mm joint at the inlet of 50 % air saturated wastewater at the top of the FT-prototype.

4 mm tubes (4x6 1788847 GSR from Versilon) were attached at 5 mm joints (Luer to Tubing Coupler Assortment Kit from WPI) at the outlet of the FT-prototypes, and put in plastic cups (PS 40 from Rotronic) covered with Parafilm.

A 4.8 mm joint was attached to the syringe containing fully air saturated wastewater and a 3 mm tube was attached between the joint of the syringe and a T-joint (Luer Valve Assortment from WPI). The connection was then continued from the T-joint with another 3 mm tube to the 2.5 mm joint (Luer to Tubing Coupler Assortment Kit from WPI) at the inlet of fully air saturated wastewater. The same procedure was done for both FT-prototypes, and a simplified illustration of the setup with tube lengths is shown in Figure 7B.

3.4. Stagnant Double Tube Prototypes

In order to investigate the impact on the results from the initial FT-prototype test that the membrane could have had, a couple of prototypes were made with the same design as the FT-prototypes, but without the flow.

3.4.1. Design

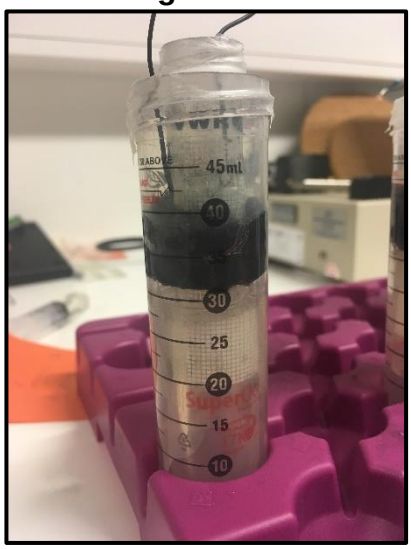

Figure 8: Picture of the SDT-prototype with a membrane.

The design of the SDT-prototypes is based on the design of the FT-prototypes, but without the inlets and outlets. An inner tube will be kept in place in the middle of an outer tube by the cathode. The inner tube of one of the prototypes (Fig. 8) will have holes cut in it, in order to allow the protons access between the anode and cathode through a membrane.

The other prototype will have an inner tube without membrane and holes. The function of the prototypes will be the same as the FT-prototype, but the oxygen needed for the chemical reactions will be supplied from the open top of the prototypes and the fluid in the prototypes will be stagnant (Fig. 8).

3.4.2. Production

The production of the SDT-prototypes will follow the same procedure as the FT-prototypes. Note that no holes for wastewater-inlets and no outlets for wasted fluid will be made, as it is unnecessary. An external resistance of 1 MΩ was coupled in series between the anode and cathode in order to measure the electric output, as voltage drop across the resistance. The electrical wiring of the prototype follows the same setup (Fig. 7) as the FT-prototypes.

3.5. Stagnant Single Tube Prototypes

As several other factors may have had an impact on the results of the initial FT-prototype test, a second set of prototypes were made in order to investigate the effect of different fluids. One prototype was going to contain wastewater and the other containing wastewater with higher amounts of sediments, called sludge.

3.5.1. Design

The design of the SST-prototypes is based on the outer tube alone. The SST-prototypes will be built without membranes, and will use the fluid as a separator between the electrodes. Both electrodes will be connected with a copper wire in order to transfer electrons and to measure the electric output. The anode will be situated near the bottom of the tube, while the cathode will be situated at the top of the tube.

The cathode will be exposed to air at the top, while the anode will be submerged in fluid or sediments. This setup is based on the MudWatt Microbial Fuel Cell Kit from FuelCellStore.com.

3.5.2. Production

In between two sheet of electrode material, a copper wire was spread out and the electrode were sewn together. This procedure was conducted for both the cathode and the anode. The anodes and the cathodes were made slightly larger than the tube, in order to have a tight fit between the tube and the electrodes, and prevent them from altering their positions when they came in contact with the fluids.

The copper wires were coupled with a resistance of 1 MΩ in series as shown in Figure 10. Note that one prototype was filled with sludge (Fig. 11), and the other prototype (Fig 9) was filled with wastewater.

Figure 10: Picture showing the SST-prototype filled with wastewater.

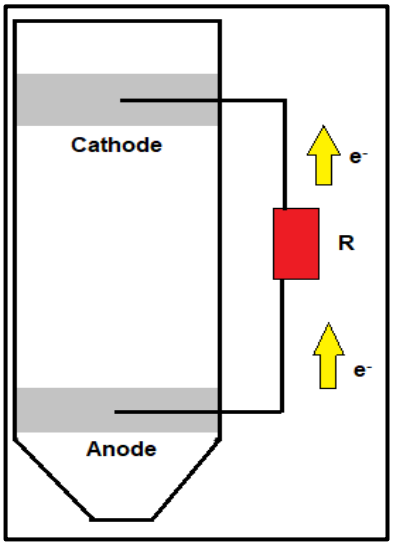

Figure 11: Sketch showing the electric wiring of the SST-prototypes and the SLST-prototype, with electrons (e^-) and a resistance (R).

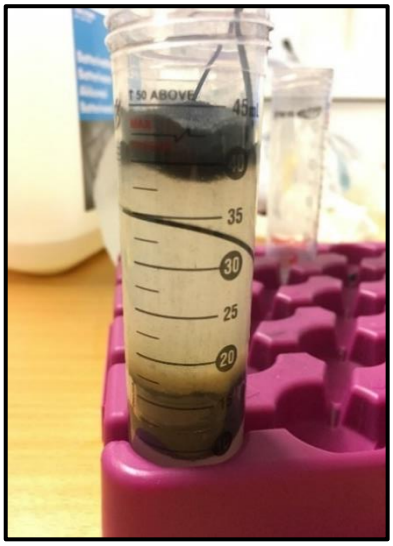

Figure 9: Picture showing the SST-prototype filled with sludge.

3.6. Stagnant Large Single Tube Prototypes

In order to investigate the effect of different sizes of the anode, a prototype with a larger diameter had to be made in order for the electrodes to get a larger surface area than the other prototypes made in this project. The ratio between the surface area of the SST-prototype filled with wastewater and the SLST-prototype (Eq. 3) will be viewed as the only intentional difference between these prototypes, exempting the volume difference.

(Appx.D1) $$\frac{\boldsymbol{SLST-prototype\ surface\ area}}{\boldsymbol{SST-prototype\ surface\ area}} = \frac{\mathbf{5944,68\ mm^2}}{\mathbf{551.55\ mm^2}} = \mathbf{10.78}$$ (Eq.3)

3.6.1. Design

The design of the SLST-prototype is based on the same principles as the SST-prototypes, but with a significantly larger volume and surface area. The submerged anode will be situated on the bottom of the tube and the cathode will be situated at the top, exposed to air. The electrodes will be separated by the fluid and by a plastic container (PS 40 from Rotronic) needed to hold the anode at the bottom.

3.6.2. Production

The production method will follow the same procedure as the SST-prototypes. However, as the anode was too small for a tight fit in the tube (MudWatt Microbial Fuel Cell Kit container from FuelCellStore.com), a plastic container (Fig. 12), containing weights (Pozidriv screws A2 304 from RS), was placed on top of the anode to keep it submerged. This container was sealed as to make sure the content would not obscure with the results of the test.

The anode was place at the bottom, with the weight on top, and the cathode was placed on top of the container containing weights. The electrodes were coupled in series with a 1M Ω resistance as done with the SST-prototypes (Fig. 10).

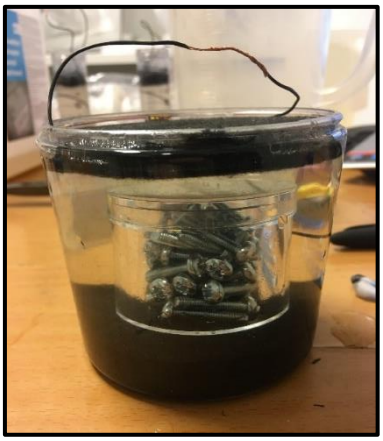

Figure 12: Picture of the SLST-prototype with a plastic container containing weights inside.

4. Prototype Testing

This chapter presents the concept behind- and the goals of the experimental testing conducted in this project. It also describes the method and the materials used for conduction the experimental testing.

4.1. Introduction to the Experimental Tests

This subchapter presents the experimental tests. The concepts and goals of each test is described, and a quick presentation on how the tests were conducted are presented.

4.1.1. Initial FT-prototype test

In order to investigate the potential of electric output from the FT-prototype design, tests had to be made. This also involved the testing of the effect of a membrane-based prototype versus a non-membrane-based prototype. The initial test made with the FT-prototypes were based on the measurement of electric current from the cathode to the anode, without any external resistance.

4.1.2. FT-prototype test

In order to investigate the electric output potential of a MFC integrated with a FT-water filter system, a continues test had to be conducted. The test would be conducted over several days in order to see if there was an increase in electric output and if the output would tend to stabilize. As in the initial flow-through test, it was also a vital point for this test to investigate whether a FT-prototype with a membrane would give a higher output than one without a membrane. This was the second test of the FT-prototypes, due to no usable results from the initial test. This second test was based on measuring the voltage drop over an external resistance.

4.1.3. SDT-prototype test

In order to investigate the effect of a membrane prototype versus a non-membrane prototype, a test with the same design as the FT-prototypes had to be conducted. This would also potentially explore faults with the FT-prototypes. The fluids in the test were stagnant so as to only have the differentiating variable of membrane/non-membrane design present. The wastewater samples filled in the prototypes was taken from the same initial wastewater sample as the in the FT-prototype tests, again as to limit the number of variables impacting the results.

4.1.4. SST-prototype test

In order to investigate the effect of change in wastewater fluids in the FT-prototypes, a test with two different fluids had to be conducted. This test was based on two fluids from a fish water filter, one sample of wastewater and one sample of sludge. The fluids in this test were stagnant and the design of the prototypes were the same, as to only have the differentiating variable of fluids present.

4.1.5. SLST-prototype test

In order to further investigate the effect of different electrode sizes, a test had to be made using a relatively large surface area of the electrodes compared to the electrodes in the other prototypes. This test was conducted in a stagnant fluid situation, and would have the same design as the SST-prototypes, but with a much larger surface area of the electrodes and volume of the tube.

The surface area of the electrodes was increased with a factor of 10.78 (Eq. 3). The wastewater-fluid samples filled in the prototype was taken from the same wastewater-sample as used in the test of the SST-prototype filled with wastewater.

4.1.6. FT-prototype simulation test

In order to determine flow-velocities that may have impacted the results from the FT-prototype test, a simulation of the prototype with flow of a fluid was conducted. The results from the simulation would be used to evaluate which flow-velocities that occurred compared to the size of the surface area of the outer and inner tube. The results of this simulation could be used to evaluate what steps that could be taken in order to make an improved FT-prototype desing. The goal of the simulation was also to further understand the flow pattern inside the FT-prototype. In particular the flow around the inlet of fully air saturated wastewater was interesting, as there was some uncertainty whether some parts of this area were at a constant standstill or not.

4.2. Methods and Materials

This subchapter presents the methods used- and steps taken for conducting the experimental tests in this project. The steps are presented individually for each test, even though some tests might have the same steps. This subchapter also presents the materials used in the tests in the same way as the methods. Measurements of the electric outputs from the tests were taken with the same multimeter (187 True RMS Multimeter from FLUKE), and the measurements of the temperatures during the tests were taken with the same thermometer (LO-10to+360 from Brannan, +-2C at 90C). All the measurements of waste water weight was taken with the same balance weight (ATS60 from AXIS) in all the experimental tests.

4.2.1. Initial FT-prototype test Method and Materials

The settings of the syringe pumps (SP100IZ syringe pump from WPI-europe) were set as follows:

Volume of syringe; 11 ml, Flow-rate; 0.4 ml/hour

The syringes were changed once a day when the measurement of the electric current was conducted with the multimeter. The room temperature and the weight of the wasted water from the prototypes was also measured in order to record any variations that may have had an effect on the results. The electrodes were submerged 8 days in advance of the test in order to let the microorganisms start growing.

The flowrate of fully saturated wastewater measured in advance of the test proved to be uneven exiting the T-joint. This lead to the use of a tightening on the tube leading into the prototype without a membrane, in order to have more even flowrates.

4.2.2. FT-prototype test Method and Materials

The FT-prototype in this test had the same setup as the initial test, but with an external resistance of 1 MΩ coupled in series between the anode and the cathode. The measurements of this test were made with regards to the voltage drop over the external resistance, measured with the multimeter.

The settings of the pumps were set as follows:

Volume of syringe; 11 ml, Flow-rate; 0.4 ml/hour

The syringes were changed once a day when the measurement of the voltage drop was conducted. The room temperature and the weight of the wasted water from the prototypes was also measured to record any variations that may have influenced the results.

Note that the microorganisms had already been in the process of growing for 16 days, because of the initial FT-prototype test. The tightening put in place before the initial FT-test remained in place for this test.

4.2.3. SDT-prototype test Method and Materials

The two SDT-prototypes were each filled with 40 ml of wastewater of the same wastewater sample. The prototypes were set in this state for 12 days without any measurements being conducted, and thus the microorganisms would grow. The anode was submerged completely, while the cathode was partially in contact with the fluid and partially with the air above.

After the first 12 days, the measurements of voltage drop over the external load started, and measurements were taken daily with the multimeter. The room was also measured in order to record any variations that may have had an effect on the results.

4.2.4. SST-prototype test Method and Materials

The SST-prototypes were filled with 35 ml of fluid each and set in this state for 12 days without any measurements conducted, and thus the microorganisms would grow. The prototypes were filled with fluid, so that the cathode was partially in contact with the fluid and the air above and the anode fully submerged. After the first 12 days, the measurements of voltage drop over the external load started and measurement were taken daily. The room temperature was also measured in order to record any variations that may have had an effect on the results. The test would be carried out over several days with stagnant water, in order to record any changes in electric output.

4.2.5. SLST-prototype test Method and Materials

The cathode was filled with 600 ml of wastewater, letting the cathode be partially in contact with the fluid and the air above and the anode fully submerged. The prototype was set in this state for 12 days without any measurements conducted, and thus the microorganisms would grow. After the first 12 days the measurement of voltage drop over the external load started and measurements were taken daily. The room temperature was also measured in order to record any variations that may have had an effect on the results.

4.2.6. FT-prototype Simulation Mesh and Settings

The computer design of the FT-prototype (Appx. B1-B2) would be made as accurate as possible to the real-life prototype in order to get accurate results. Apart from the default simulation settings, the following settings were set:

Input data:
Internal; no gravity. Fluids; water (liquids)

Boundary Conditions:
Inlet-flow top, anaerobic area; 1.11e-10 m^3/s
Inlet-flow bottom, aerobic area; 5.56e-11 m^3/s
Environmental Pressure Outlets; 101325 Pa
Ideal wall (no friction) on the bottom of the outer tube lid.

Mesh:
Global level 5 Auto.

The mesh represents how many elements the prototype is divided into. The finite element analysis is a numerical technique that is used on the elements to determine qualities like flow regarding the design [37]. In order to be confident of an adequate mesh of the prototype, several Global Mesh levels were tested using a straight-line sketch, in a cut-plot of the prototype (Fig. 15), as a reference for the result to be measured at.

The testing of the mesh was done for levels of 3, 4 and 5, and a simulation was run for each level. The results from the flow-velocity simulations were plotted in diagrams (Fig. 13 and Fig. 14), for both the inner and the outer tube, and a comparison of the plots was then made to be able to conclude which level of mesh that was satisfying in terms of giving accurate results.

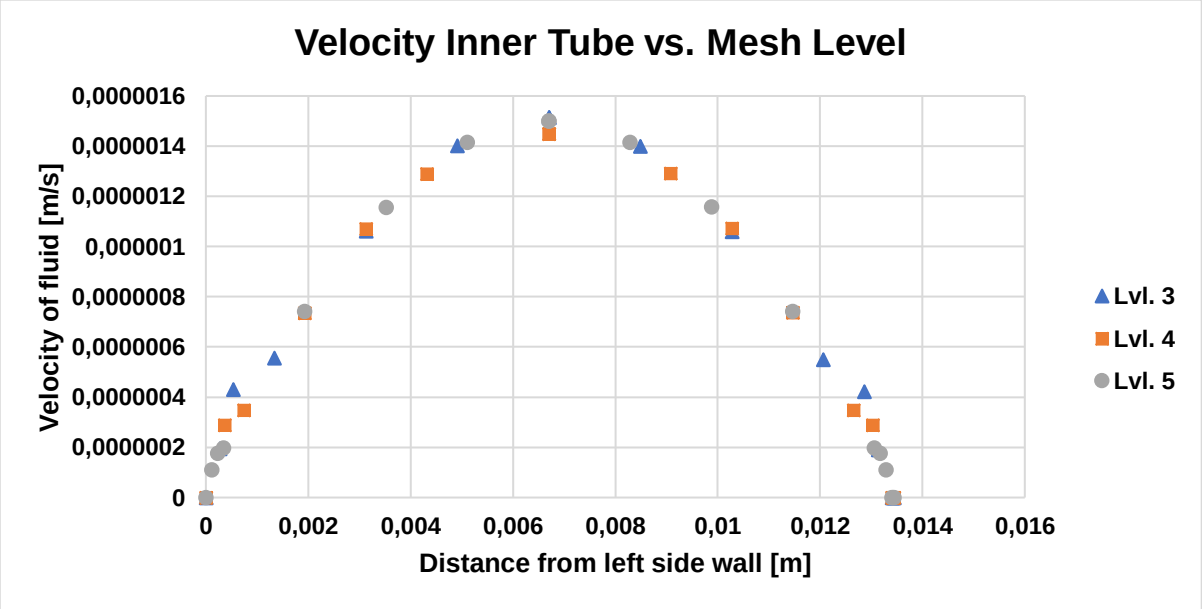

Figure 13: Diagram showing the flow-velocity result from the simulations of the FT-prototype (Appx. C1-C2), with regards to the distance from the left side wall, in a cut-plot, of the inner tube. Plots are categorized into Global Mesh of level 3, 4 and 5.

Figures 13 and 14 tends to show that the meshing in the simulations gave similar results, regardless of the Global Mesh level. However, some result values stand out, in particular the values from the level 3 mesh.

The level 4 and 5 mesh gave about the same tendency of results, but the level 5 mesh has more results to plot. For this reason, Global Mesh level 5 was used in the simulation and was thought to be adequate.

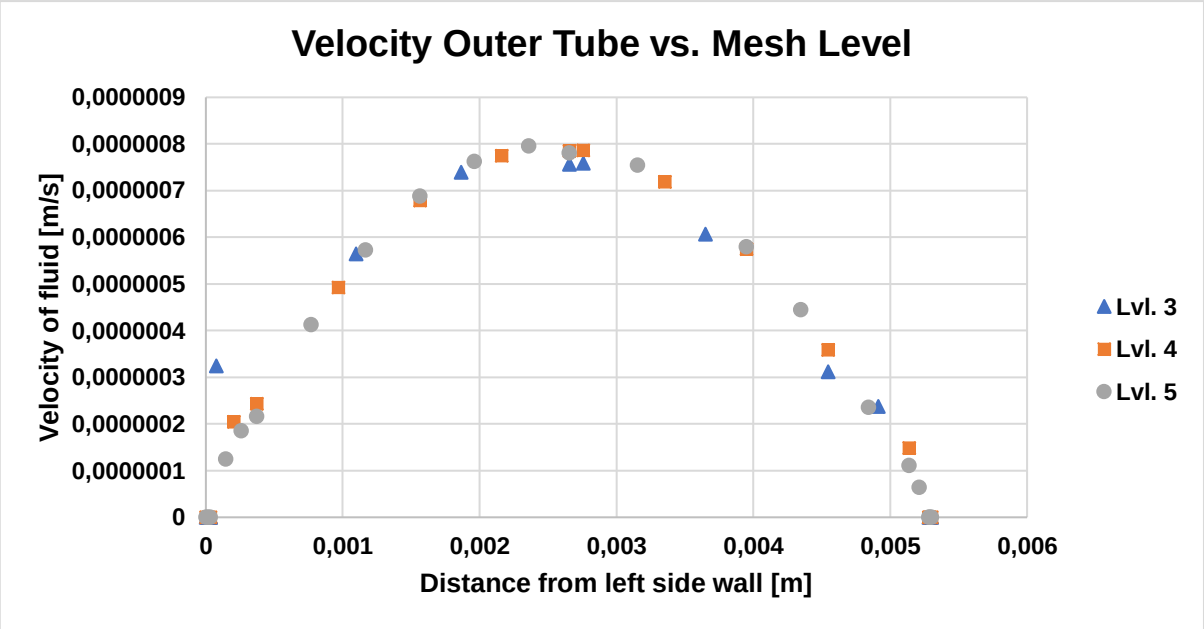

Figure 14: Diagram showing the flow-velocity result from the simulations of the FT-prototype (Appx. C2-C3), with regards to the distance from the left side wall, in the cut-plot, of the outer tube. Plots are categorized into Global Mesh of level 3, 4 and 5.

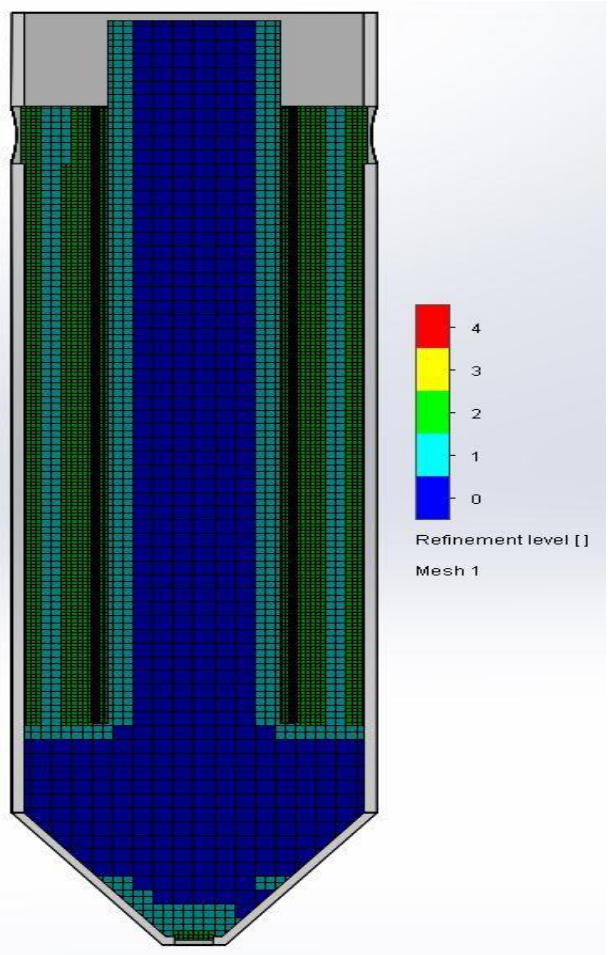

Figure 15: CAD-illustration of the mesh refinement in a cut-plot.

Figure 15 show how the refinement of the level 5 mesh is distributed in the FT-prototype, and that the inner tube has a lower number of mesh-elements than the outer tube. The inner tube could have had less turbulent flow than the outer tube, because the inner tube was filled only by one inlet-flow.

This less turbulent flow could be the reason for the computers choice of a lower mesh refinement in the inner tube, compared to the outer tube. However, this is of no concern when the level 5 mesh was proven to be adequate following the results presented in Figure 13 and 14.

5. Results and Discussion

In this chapter, all results from the experimental tests will be summarized and evaluated. The same is done for the simulation of flow through the FT-prototype. All the information and the different evaluations of the tests and the simulation was used later to make drawings of a new solution to the integration of MFC with water filters. Note that all the electric outputs in mV, is measured with an accuracy of 0.0025 % +5 margin from the multimeter (Appx. E).

5.1. Initial FT-prototype Test Results and Discussion

The initial FT-prototype test did not give any results in the means of electric current measured. This was probably because the electric current that passed from the cathode to the anode was too small for the multimeter to measure. However, some results and experiences from the test could be used develop the design of a new solution. These results came from observing the initial FT-prototype and finding flaws with the design and setup.

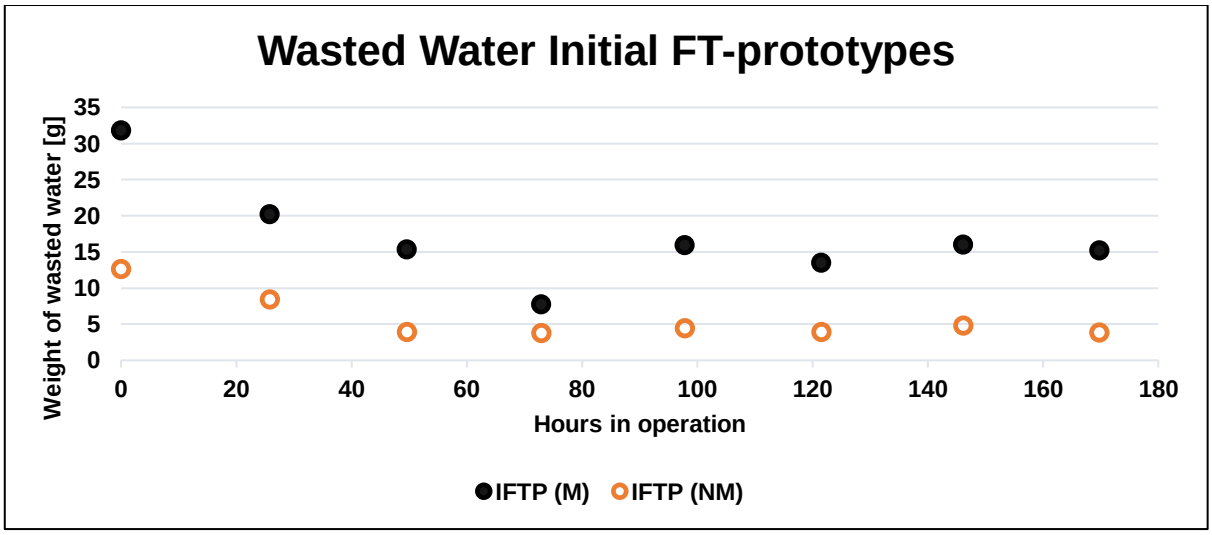

Figure 16: Diagram showing the amounts of measured wasted water from the initial test of the FT-prototype with a membrane (IFTP (M)) and the FT-prototype without a membrane (IFTP (NM)), with regards to the hours the prototypes were in operation (Appx. A1).

Figure 16 show one example of a flaw with the setup of the test. Because of the T-joint used, the prototypes had unequal amounts of fully air saturated wastewater passing thorough them. This is seen in Figure 16 by the uneven weights of wasted water from the prototypes. In addition to this, the tightening itself was very sensitive to motion and the slightest altering of the tube could change the distribution of fully air saturated wastewater. In future tests of a new prototype, the use of a T-joint to distribute fully air saturated wastewater from the same source to different prototypes, is not recommended. Instead, the different prototypes should have individual sources of fully air saturated wastewater, reducing the risk of unequal amounts of fluid entering the prototypes.

Another problem also observed during the testing was the accumulation of air bubbles underneath the anode in the inner tube. This air probably entered from the fully air saturated wastewater inlet, and got trapped under the anode.

The air could have been initially trapped inside the joints or the tubes before testing began, and thus made its way to the anode as the wastewater flow pushed it through the tubes. Having this oxygen in proximity to the anode is not beneficial, as the area around the anode was supposed to be the more anaerobic area. This unexpected oxygen supply to the anode might have caused the electrons to stay in the anode area instead of going through the copper wire to the cathode, and thus reducing the electric current in the copper wire.

However, research have shown that a small increase in dissolved oxygen amounts to the anode does not affect the electric output of a MFC [38]. Not knowing how much oxygen that made it to the anode, in future work with prototypes of this design, it is recommended that a solution is made were the potential air bubbles from the fully air saturated wastewater inlet does not end up at the anode, but more suitable ends up at the cathode. Having this extra oxygen in contact with the cathode might give a positive result regarding the electric current instead of a negative, as is most likely in this case.

5.2. FT-prototype Test Results and Discussion

Following the use of an external resistance coupled in series, electric output in the form of voltage drop could be measured. Note that even though faults like uneven distribution of fully air saturated wastewater had been discovered in the initial FT-prototype test, no action was taken to correct them for this test. This was in order to reduce the chance of more variables differentiating the FT-prototype tests. The following figures shows the data collected from the test in the means of voltage drop across the external resistance (Fig. 17) and output weight of wasted water (Fig. 18).

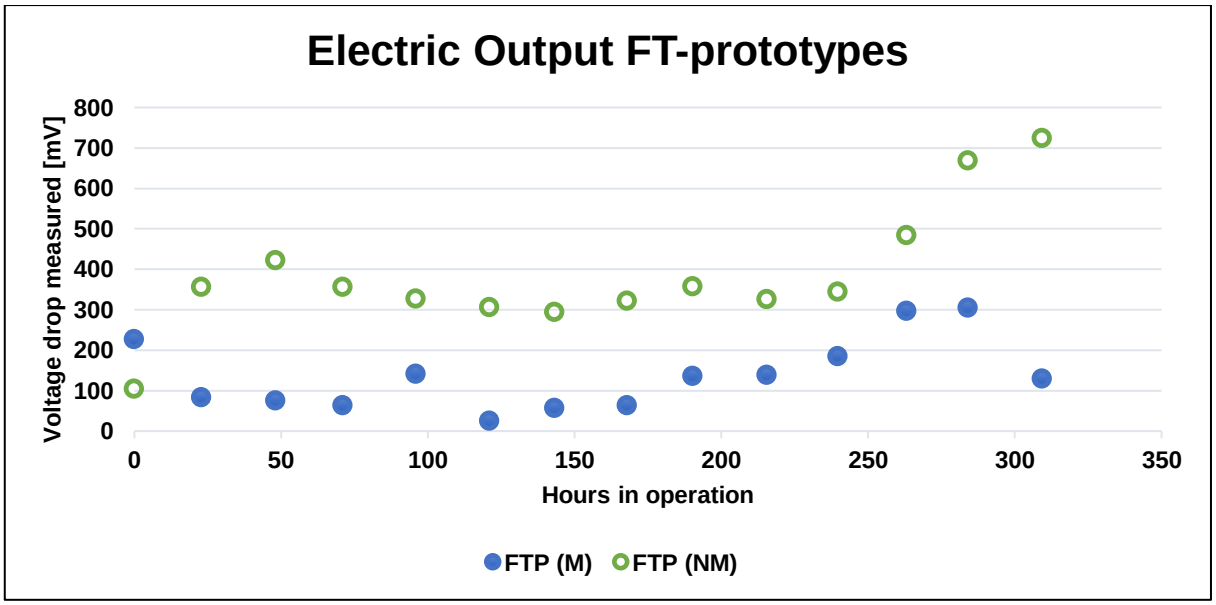

Figure 17: Diagram showing the electric outputs in mV, measured in the test of the FT-prototype with a membrane (FTP (M)) and the FT-prototype without a membrane (FTP (NM)), with regards to the hours the prototypes were in operation (Appx. A2-A3).

Figure 17 show that the FT-prototype without a membrane had the highest electric output, during most of the operational time. This prototype had a relatively large increase in electric output the first 48 hours, followed by a relatively stable electric output period compared to the FT-prototype with a membrane.

At about 250 hours into the test, there is a sudden and high increase in electric output from the FT-prototype without a membrane, that does not tend to stabilise until the end of the test. This sudden increase is also true for the FT-prototype with a membrane, but the electric output from this prototype tend to stabilise much sooner and the output falls in the last 20 hours of the test (Fig. 17). Furthermore, it is worth noting that the FT-prototype with a membrane had throughout most of the operational time a lower electric output than the FT-prototype without a membrane, exempting the first measurement.

This is of special significance to the test results, as this could show that there is more to gain, in the form of electric output, from testing and producing prototypes without membranes, rather than from prototypes with membranes. Comparing this result with other research done of MFCs, the results are more understandable given that there is not a large advantage using proton-exchanging membranes, as Nafion, over no membrane [39], [40], [41], [42]. It has also been shown, by the same research [39], that the cost of the membrane is likely not to be covered by the economic income of the electricity created, over a period of 10 years. These are clear reasons for not recommending membranes in the future solution.

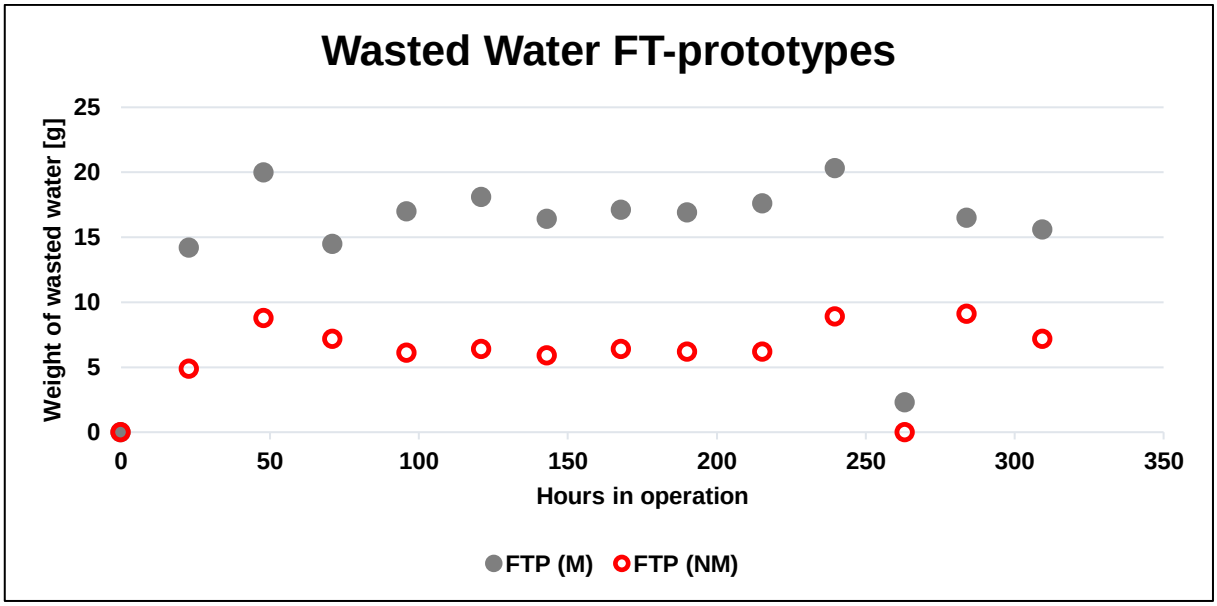

Figure 18: Diagram showing the amounts of measured wasted water from the test of the FT-prototype with a membrane (FTP (M)) and the FT-prototype without a membrane (FTP (NM)), with regards to the hours the prototypes were in operation (Appx. A2-A3).

Figure 18 show a tendency of a higher output of wasted water from the FT-prototype with a membrane than the FT-prototype without a membrane. It is clear that more fluid has passed through the FT-prototype with a membrane. Because both prototypes had their own, equal source of 50 % air saturated wastewater, this inequality of output of wasted water must be because of uneven amounts of fully air saturated wastewater passing through the prototypes.

Given that this means that the FT-prototype with a membrane had more oxygen available at the cathode to attract electrons, the highest measured electric output could have been expected of this prototype. However, this is not the case and several factors could be responsible for this. First, the amount of oxygen available to both prototype cathodes was more than required for the chemical reactions to take place. This would therefore not give the cathode with the most oxygen a benefit.

Secondly, the membrane could have not perform as expected, giving a negative effect on the electric output rather than a positive one. During construction of the FT-prototype with a membrane, liquid silicone was used to glue the membrane to the inner tube. This silicone could have been too little viscose and may have sealed the membrane, making it in effect not work at all. But if this was the only fault, both prototypes should have given about the same values of measured electric output, suggesting there might have been other possible problems involved as well.

An alternative failure, that could have led to a lower level of electric output measured in the FT-prototype with a membrane rather than the one without, is if the silicone seal holding the membrane in place was not entirely watertight. This could have given some of the electrons in the wastewater a more direct path between the anode and cathode, than the path through the copper wire. This could in turn lead to lower electric outputs measured.

At about 260 hours in operation, a rapid decline followed by an equally rapid increase in weight of wasted water can be observed (Fig. 18). This is likely a result of an unexpected stop of flow from all inlets to the prototypes, that lasted for about 20 hours. The stop of inlet flow (Fig. 18) occurs around the same moment as a rapid increase in electric output measured from both prototypes starts (Fig. 17).

This means that the stop of flow could have caused the increase in electric output. This could point towards that a stop of flow in these kinds of prototypes has a positive effect. A continues flow through these kinds of prototypes could therefore have a negative effect on the electric output. This result corresponds to the trend [10], [43] that most MFCs are made not with a flow-through design, but rather with a stagnant design that has its fluids changed at times of low electric output.

5.3. SDT-prototype Test Results and Discussion

The SDT-prototype test was intended to give a clue as to if the trend of a higher output of electricity from membrane-less prototypes was correct, or if an error occurred during the construction or testing of the prototypes with a membrane as its intended variable. The SDT-prototypes had the same design as the FT-prototypes and the following figures should show results from the SDT-prototype test that could be compared to the FT-prototype test.

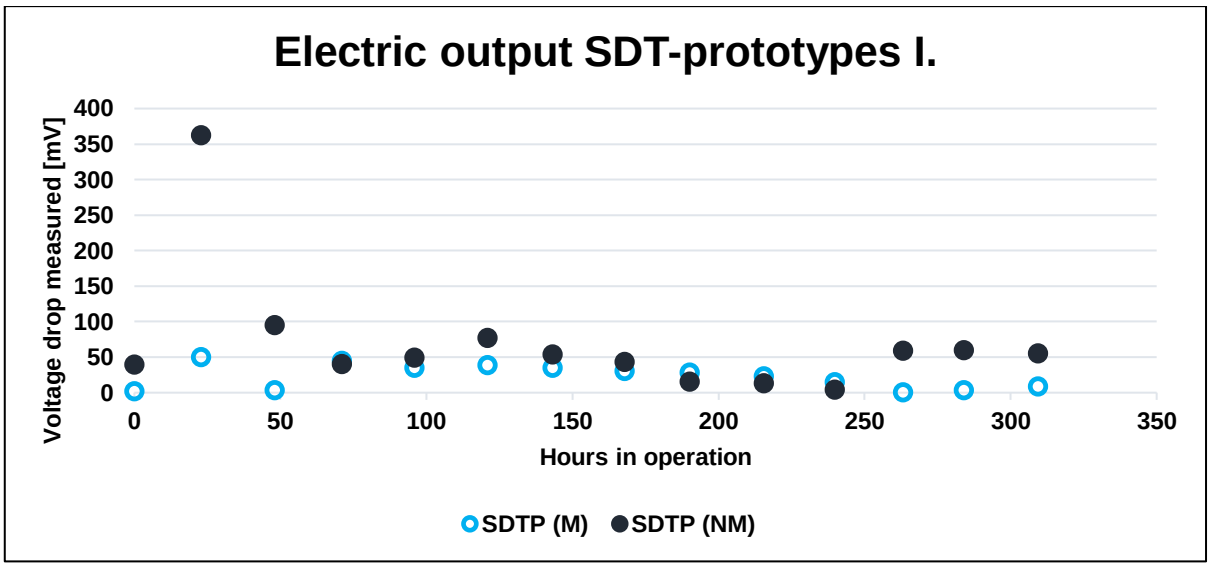

Figure 19: Diagram showing the electric outputs in mV measured from the test of the SDT-prototype with a membrane (SDTP (M)) and the SDT-prototype without a membrane (SDTP (NM)), with regards to the hours the prototypes were in operation (Appx. A4).

Figure 19 show a tendency of a relatively stable and equal electric output from both prototypes from 100 hours into the operation and throughout the test, compared to the first 100 hours of the test. When considering the values of electric output measured from the SDT-prototype with a membrane (Fig. 19), the electric output measured between 0 hours and 48 hours is not consistent with the rest of the test, because of its relative high value compared to the other measured values.

The high value of electric output measured from the STD-prototype without a membrane, at about 35 hours in operation, is much higher than the electric output measured from the SDT-prototype with a membrane. This is also much higher than the measured electric output from both prototypes through the rest of the test. This could be the result of an incorrect measurement taken that day. No factor, including the temperature (Fig. 21) in the room, had changed dramatically in that time period. It is therefore assumed that this is the case of an incorrect measurement. Following, these initial 48 hours will not be taken into consideration in the evaluation of the results from this test.

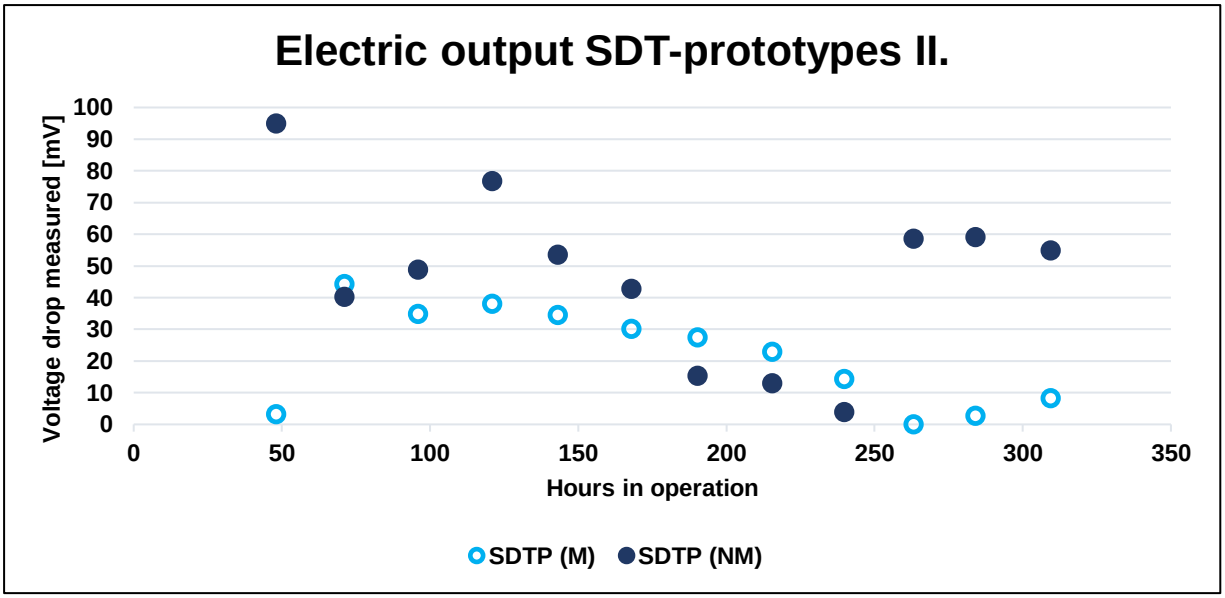

Figure 20: Diagram showing the electric outputs in mV measured from the test of the SDT-prototype with a membrane (SDTP (M)) and the SDT-prototype without a membrane (SDTP (NM)), with regards to the hours the prototypes were in operation (Appx. A4), from 48 hours and throughout the rest of the test.

Figure 20 show a more correct picture of the electric output trend than Figure 19. The SDT-prototype without a membrane tends to give a higher electric output measured than the prototype with a membrane, again pointing towards a recommendation to not use proton-exchanging membranes in a future solution. The graph also tends to show that the SDT-prototype without a membrane has a much more unstable electric output record than the prototype with a membrane, ranging from over 90 mV in measured electric output down to almost 0 mV.

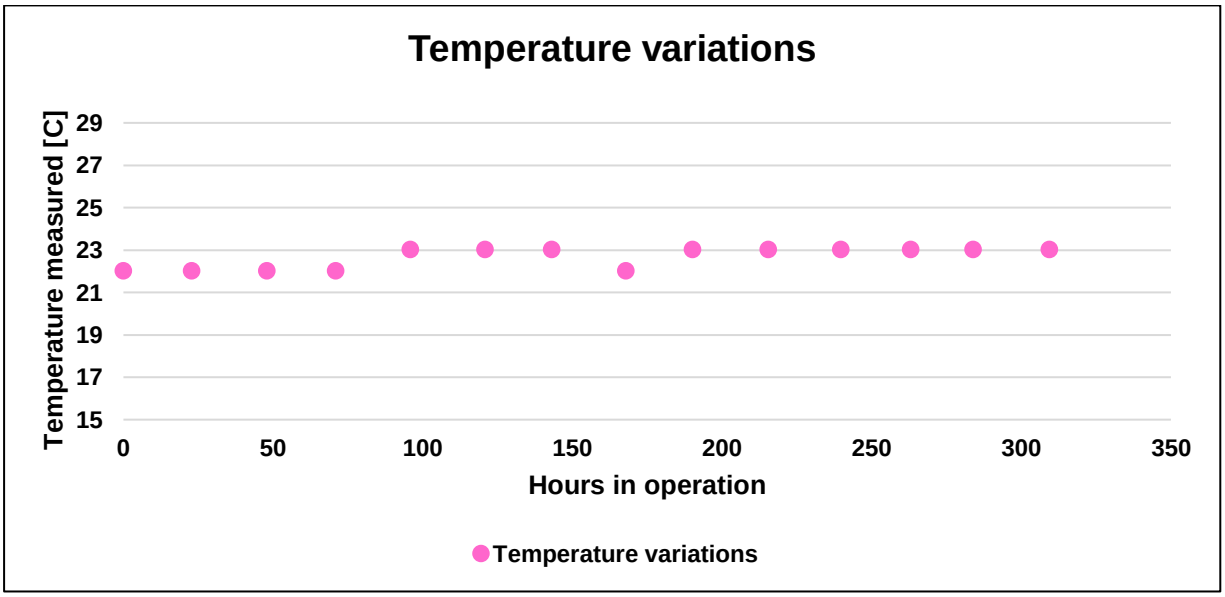

Figure 21: Diagram showing the results from the temperature measurement taken in the SDT-prototype test (Appx. A4), with regards to the hours the prototypes were in operation.

Figure 21 display the result of the measured temperature variations over the operational time of all the tests, excluding the initial FT-prototype test. The tendency of the temperature measurements is a stable temperature at between 22-23 ºC, giving little reason for believing that the temperature was a cause of the variations of the measured electric output from any prototype. Both prototypes in this test were under stagnant conditions, but had the membrane as a difference. It is possible that the membrane gave steadier electric output measured, but nevertheless a lower output than the prototype without a membrane.

5.4. SST-prototype Test Results and Discussion

The SST-prototype test was intended to investigate the difference between a prototype supplied with wastewater versus a prototype supplied with sludge. The following figure show the results from the test.

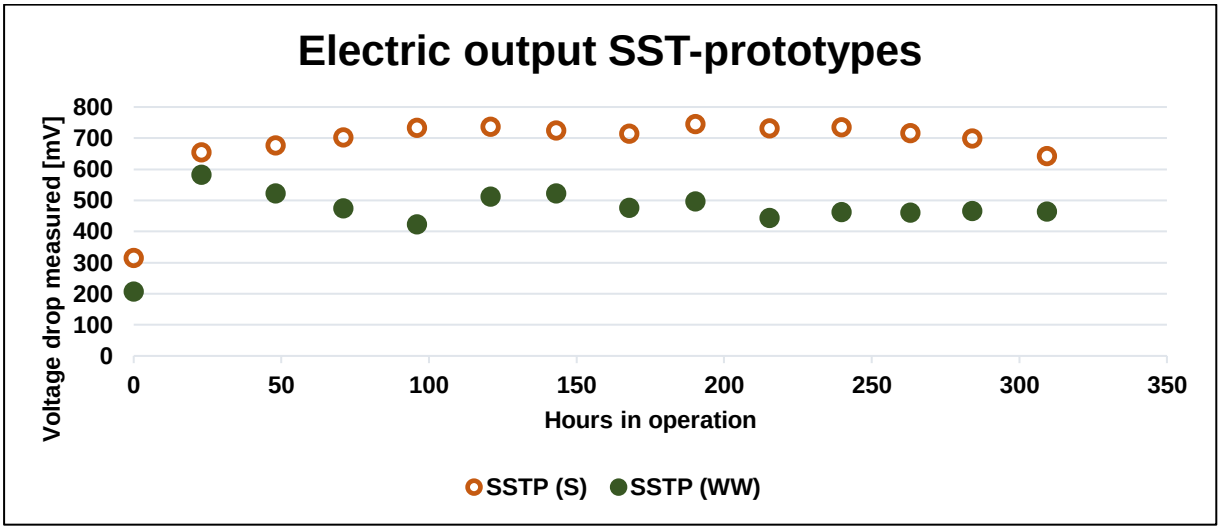

Figure 22: Diagram showing the electric outputs in mV measured from the test of the SST-prototype filled with sludge (SSTP (S)) and the SST-prototype filled with wastewater (SSTP (WW)), with regards to the hours the prototypes were in operation (Appx. A5).

Figure 22 show that the prototype filled with sludge gives a higher electric than the other in the SST-prototype test. This difference in electric output can be measured to about 200 mV over the course of most of the test. Interestingly, both of the prototypes electric outputs tent to be relatively stable compared to the FT-prototypes. The SST-prototype filled with sludge has a slight advantage over the SST-prototype with regard to the stability of the electric output. Research comparing sewage sludge, kitchen waste and cow dung in single chamber MFCs [44] concludes that the most electric output came from the waste with the highest amount of solid in it. The higher electric output from the prototype filled with sludge can be confirmed by this and other research [45], [46], as the SST-prototype filled with sludge had more sediments and solids in it than the SST-prototype filled with wastewater.

5.5. SLST-prototype Test Results and Discussion

The SLST-prototype test was made in order to investigate the effect of increasing the surface area of the electrodes, and comparing the results from this test with the SST-prototype filled with wastewater test results.

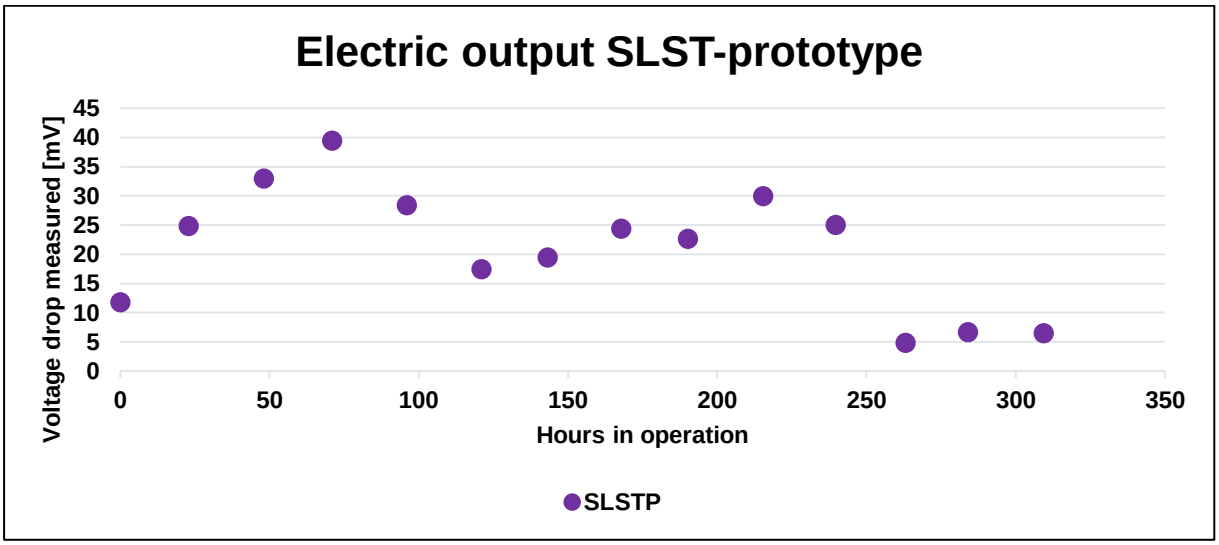

Figure 23: Diagram showing the electric outputs in mV measured in the SLST-prototype (SLSTP) test, with regards to the hours the prototype was in operation (Appx. A6).

Figure 23 show in general a tendency for the SLST-prototype to give a low electric output, also compared to many other of the prototypes tested (Fig. 17, 20 and 22). The electric output from the prototype starts at average values of about 20-40mV in the first 100 hours, and makes its way down to less than 10mV in the end of the test. This shows relatively small initial values of voltage measured compared to SST-prototypes (Fig. 22). These low values could be caused by high amounts of evaporation of the wastewater in the prototype, which is further discussed in subchapter 5.8.

5.6. Flow-through Simulation Results and Discussion

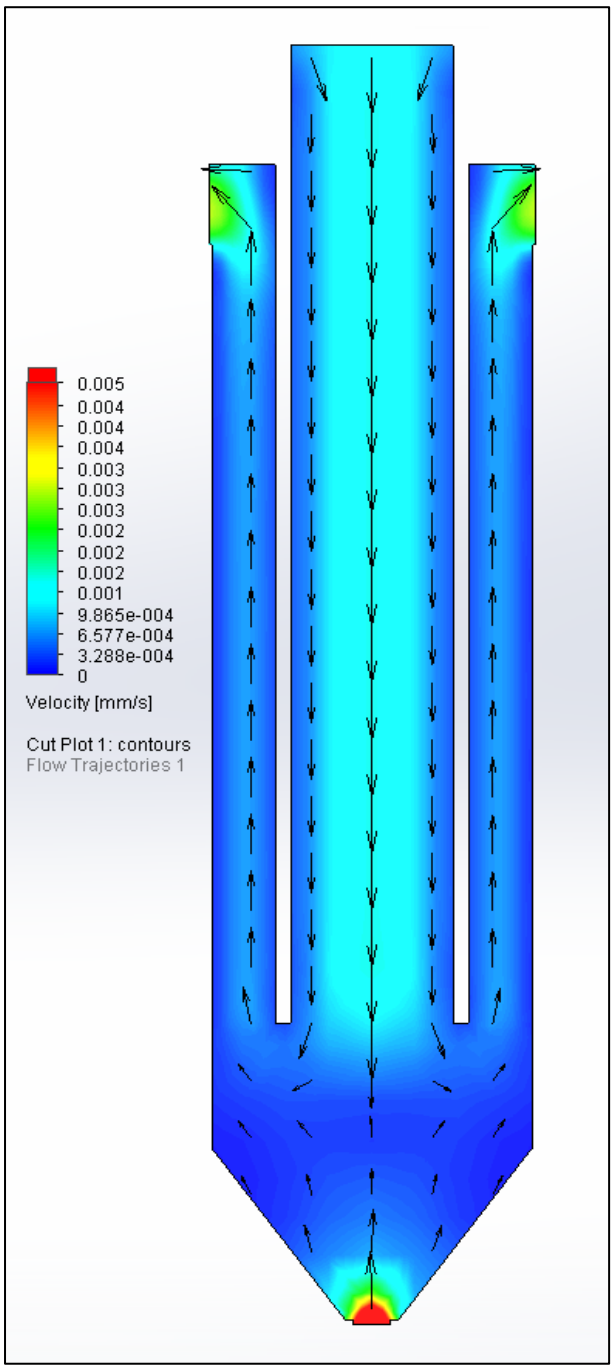

Figure 24: Colour cut-plot of velocities simulated in the FT-prototype, full figure. Velocities represented by varying colours and vectors showing directions of flow.

When analysing results of the simulation, a few of the simulation plots were taken out from the results, as these were considered to be the most relevant. Figure 24 show the flow through the FT-prototype in the means of vectors and a colormap displaying velocity. The figure show a cut-plot of the prototype in its entirety and a clear picture of the flow through the prototype.

The varying colours represent the velocities of the fluid and hence dark blue represent near zero velocities, whereas dark red represent velocities up to 0.005 mm/s. It is clear that the fluid in the middle section of the inner tube has higher velocities than the fluid in most of the prototype. However, some areas stand out with a colour suggesting velocities higher than in the middle of the inner tube.

The following figures shows closeups of the prototype in special areas of interest.

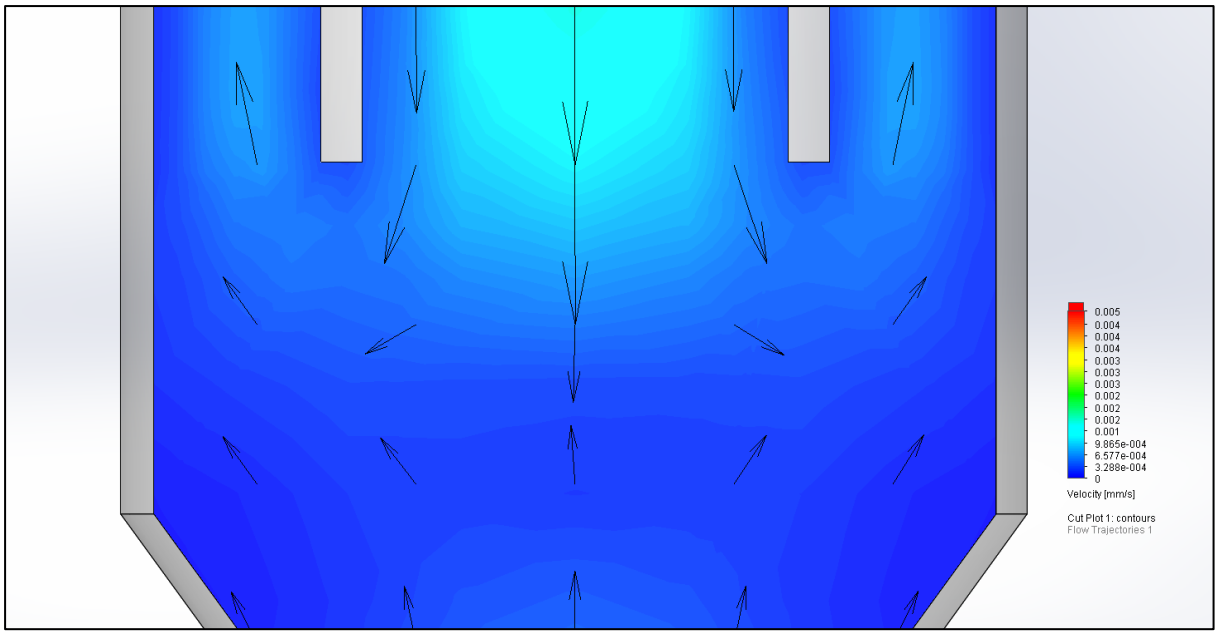

Figure 25: Colour cut-plot of velocities simulated in the FT-prototype at the end of the inner tube. Velocities represented by varying colours and vectors showing directions of flow.

Figure 25 show the flow from the end of the inner tube that meets up with the flow from the bottom inlet. There is a tendency of low velocities in this area, and the flow from the inner tube tends to run towards the bottom for a short while before turning to the sides and up the outer tube. The most interesting result from this figure (Fig. 25) is the velocities of the flow. As mentioned, these dark blue areas represent near zero velocities, although some movement is present, as seen by the vectors (Fig. 24-26). This means that there is always a movement in the prototype, even at the far edges of the bottom part of the prototype.

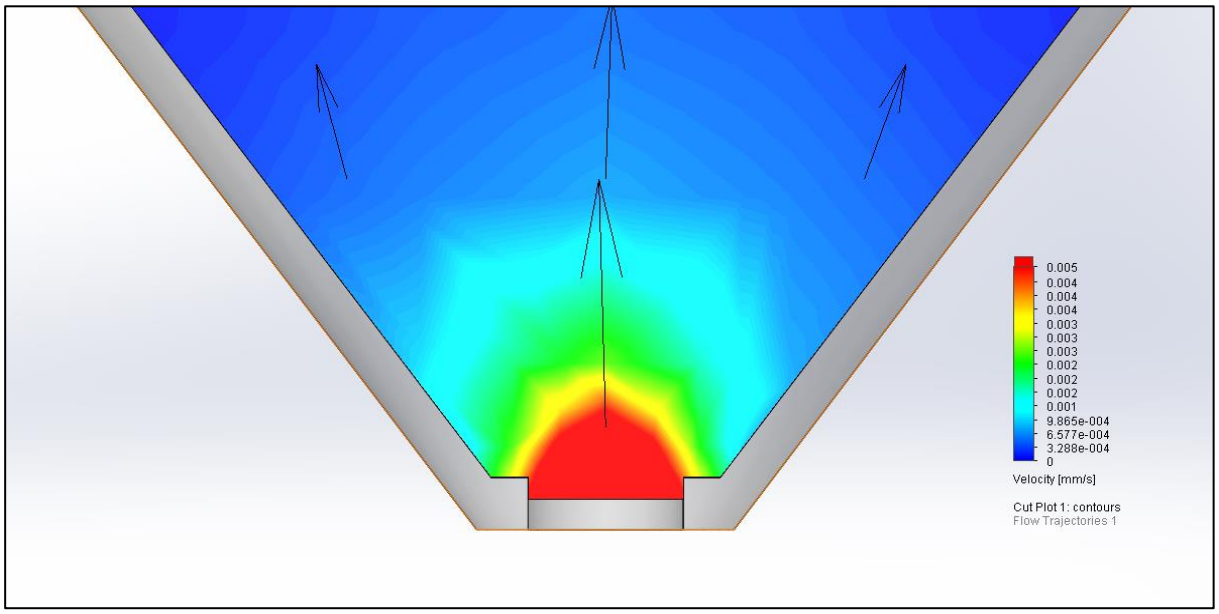

Figure 26: Colour cut-plot of velocities simulated in the FT-prototype at the bottom of the outer tube. Velocities represented by varying colours and vectors showing directions of flow.

The red colour in Figure 26 indicate that this is the area in the FT-prototype where the highest velocities are reached, around 0.005 mm/s. The higher velocities are positive as the force of the flow, in an up-scaled prototype, might be high enough to move sediments on the bottom. This movement could help microorganisms travel through the prototype and settling on the electrodes, and could help prevent clogging of the bottom inlet.

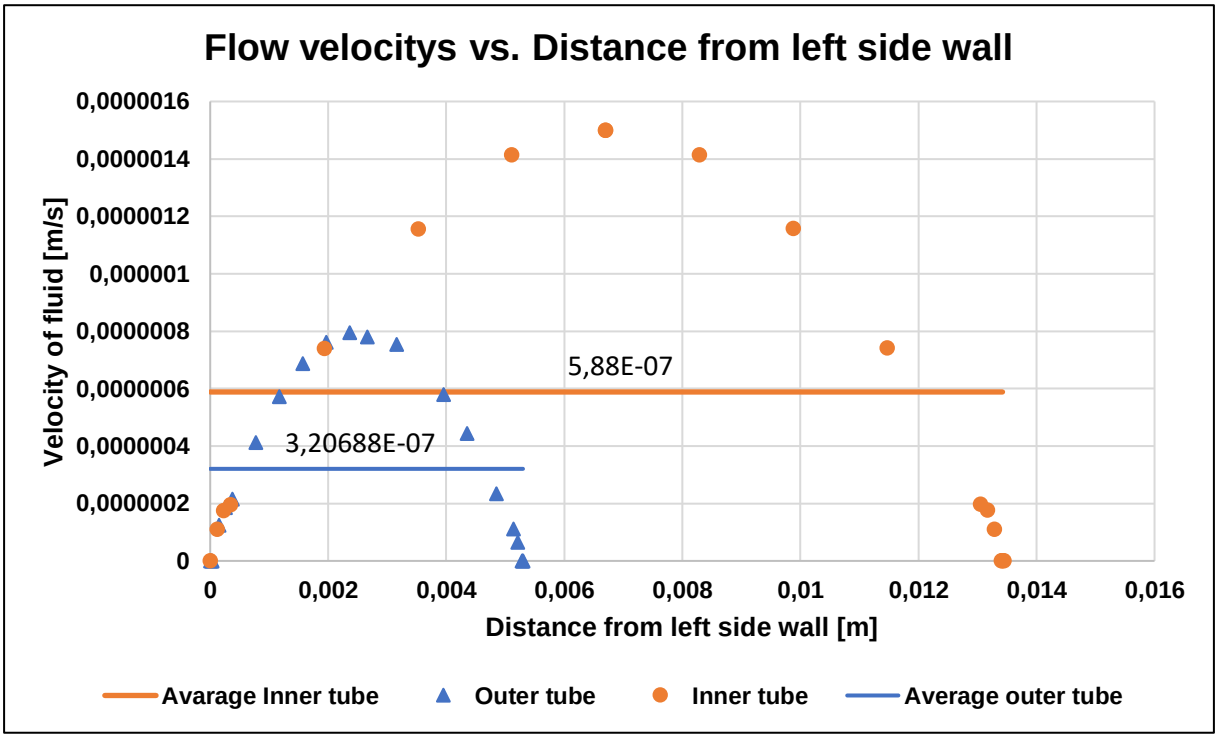

Figure 27: Diagram showing velocities in the inner- and outer tube (Appx. C2-C3), relative to the distance from the left side wall (of the cut plot in Figure 24) in the relevant tube.

Figure 27 show velocities in the inner- and outer tube with higher velocities in the inner tube than the outer tube. The effect of these velocity is impossible to determine out of the simulations conducted in this project, as the inlet flow rates were not varied. However, this simulation gives a comparison displayed in Table 3, of the velocities of the fluid and the surface area and volume of the electrodes. This comparison could be used in the future to investigate factors affecting the electric output of a FT-prototype design, and determine which variable that is the most beneficial to alter.

Table 3: Display of surface area, volume, maximum velocities and average velocities data from the simulation of flow through the FT-prototype (Appx. C2-C3), with regards to the different electrodes.

	Surface area	Volume	Max. Velocity	Avg. Velocity
Anode	141.03 mm^2	1974.42 mm^3	1.50E-06 m/s	5.88E-07 m/s
Cathode	350.48 mm^2	4906.77 mm^3	7.96E-07 m/s	3.21E-07 m/s

5.7. FT-prototype / SDT-prototype comparison

A comparison of the FT-prototypes with the SDT-prototypes shows the possible effect of flow through a prototype. Considering the operational time after 48 hours, the results plotted in Figure 28 shows that the FT-prototype without a membrane gives the highest measured electric output throughout most of the test. Next to this prototype, the FT-prototype with a membrane tends to give the second highest electric output, with an increasing amount of output in the second half of the test.

In this comparison (Fig. 28), both SDT-prototypes gives the lowest electric output and tends to remain at low electric output values throughout the test. These results and comparisons tends to favour the FT-prototypes with flow of fluids when measuring electric output, with a clear advantage to the membrane-less FT-prototype.

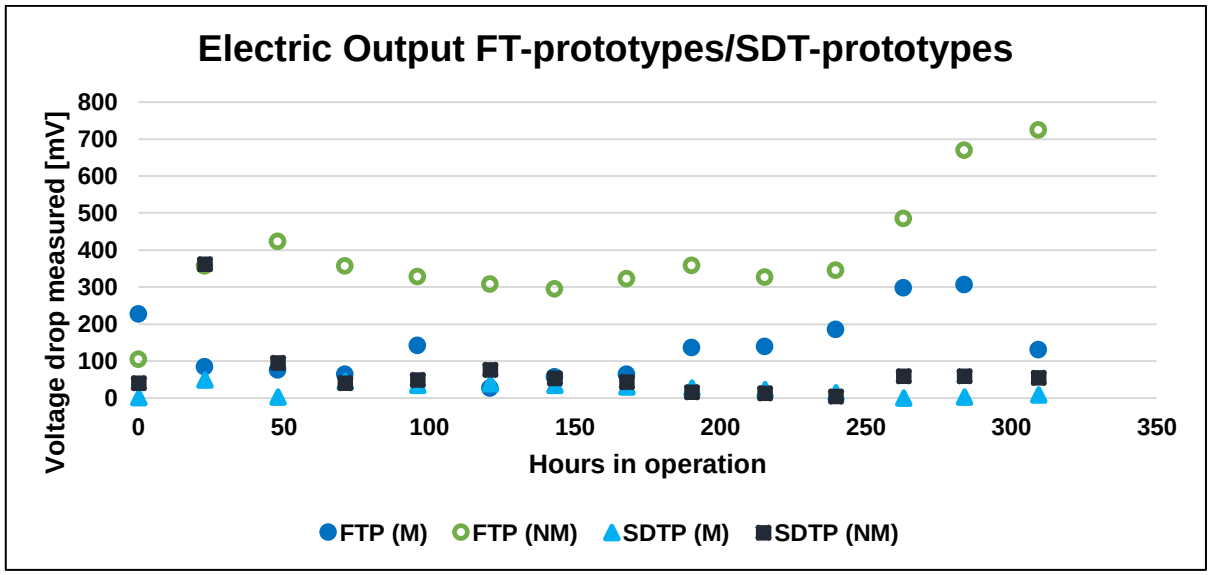

Figure 28: Diagram showing a comparison of measured electric outputs in mV from the tests of the FT-prototype with a membrane (FTP (M)), the FT-prototype without a membrane (FTP (NM)), the SDT-prototype with a membrane (SDTP (M)) and the SDT-prototype without a membrane (SDTP (NM)), with regards to the hours the prototypes were in operation (Appx. A2-A4).

5.8. SDT-prototype / SST-prototype comparison

A comparison of the SST-prototypes with the SDT-prototype without a membrane show the possible positive effect of one design compared to the other. The SDT-prototype with a membrane is excluded from this comparison because of its low electric output and because both the SST-prototypes are membrane-less like the SDT-prototype used in this comparison.

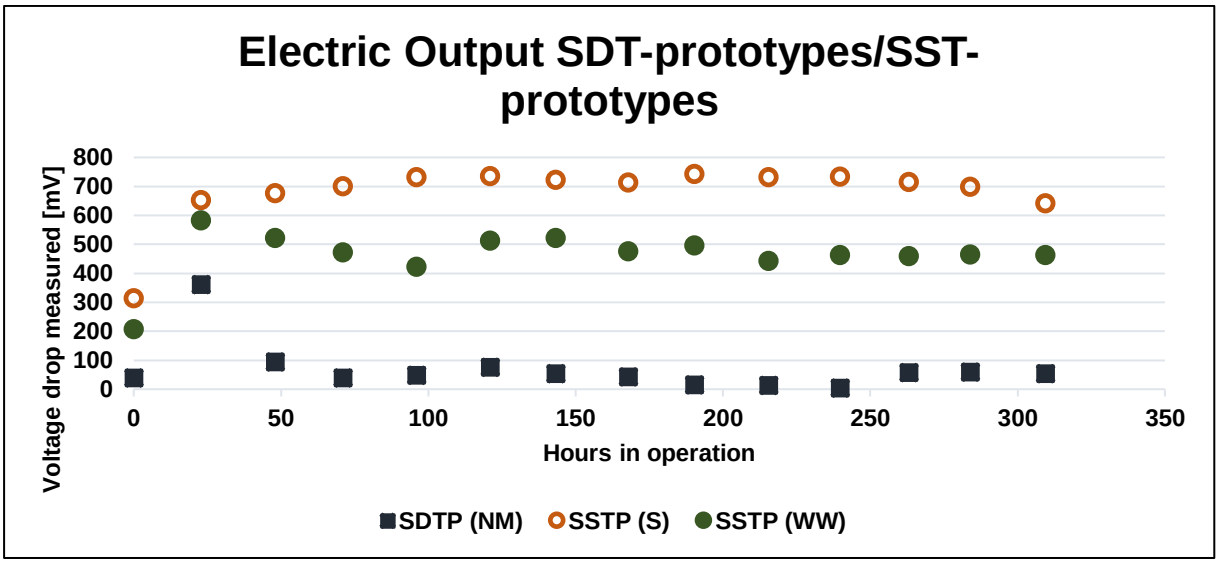

Figure 29: Diagram showing the electric outputs in mV measured from the SST-prototype filled with sludge (SSTP (S)) and the SST-prototype filled with wastewater (SSTP (WW)), in comparison with the results from the test of the SDT-prototype without membrane (SDTP (NM)) (Appx. A4-A5), with regards to the hours the prototypes were in operation.

The results plotted in Figure 29 shows that there is relatively much higher electric output gained from using the SST-prototype design compared to using the SDT-prototype design, regardless of the fluids used. In the comparison between the SST-prototype filled with wastewater and SDT-prototype without a membrane, the prototypes are filled with equivalent fluids, and are almost solely differentiated by the design of the prototypes. The SST-prototype filled with wastewater gives a measured electric output about 19 times higher than the SDT-prototype without a membrane. This is a significant difference, and the results tend to make the SST-prototype design much more efficient in producing measurable electric output from experimental testing.

5.9. FT-prototype / SST-prototype comparison

A comparison of the FT-prototypes with the SST-prototypes show the effect of the design and flow-situation of these prototypes.

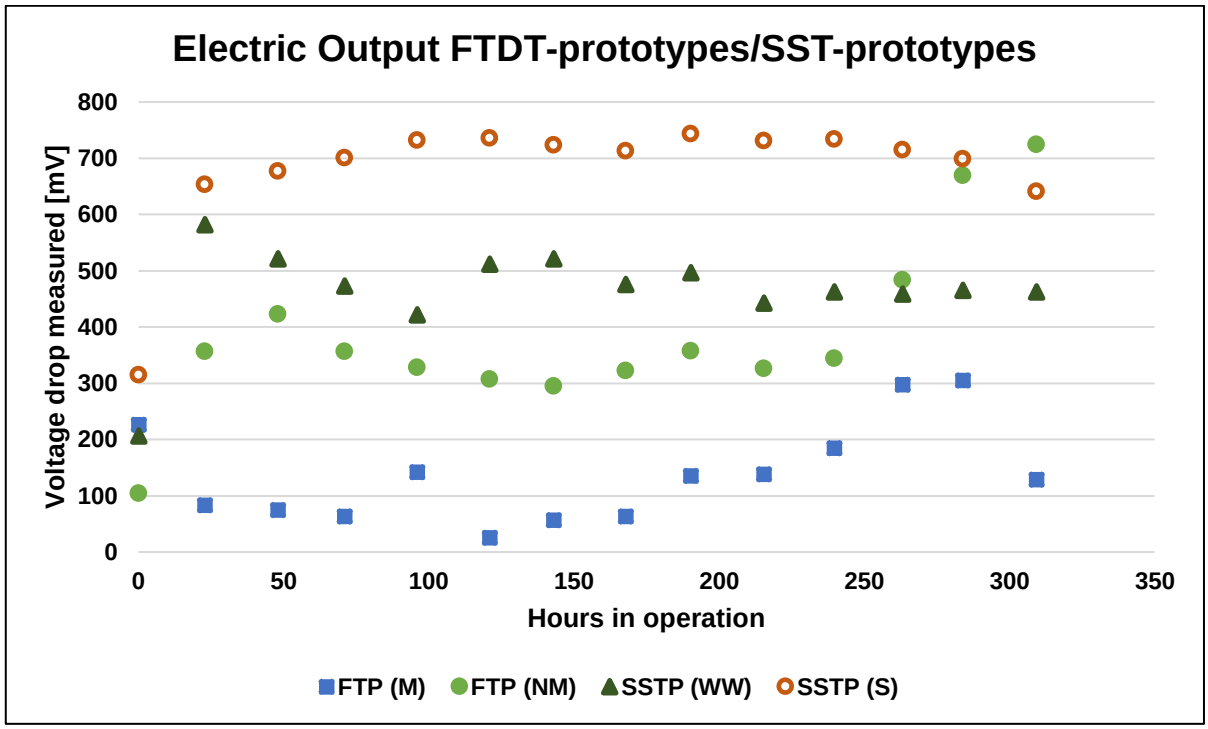

Figure 30: Diagram showing a comparison of measured electric outputs in mV from the FT-prototype with a membrane (FTP (M)), the FT-prototype without a membrane (FTP (NM)), the SST-prototype filled with wastewater (SSTP (WW)) and the SST-prototype filled with sludge (SSTP (S)), with regards to the hours the prototypes were in operation (Appx. A2-A3 and A5).

The results plotted in Figure 30 shows a tendency that the SST-prototypes give a higher measured initial electic output compared to the FT-prototypes, and the SST-prototypes tend to be more stable for a longer period than the FT-prototypes. As the sudden increase of measured electric output from the FT-prototype without a membrane could be the cause of failure, an unexpected stop of flow, it is reasonable to assume that the SST-prototypes would give on average the highest electric output measured. This was especially true for the SST-prototype filled with sludge, as the electric output values was among the highest throughout all the tests made in this project.

From the comparison of the FT-prototypes with the SST-prototypes, the SST-design is recommended for the design of a future solution.

5.10. SST-prototype / SLST-prototype comparison

A comparison of the SST-prototype filled with wastewater with the SLST-prototype show the effect of increasing the surface area of the electrodes. The SST-prototype filled with wastewater is chosen for the comparison with the SLST-prototype because of the similar fluids and designs of the prototypes.

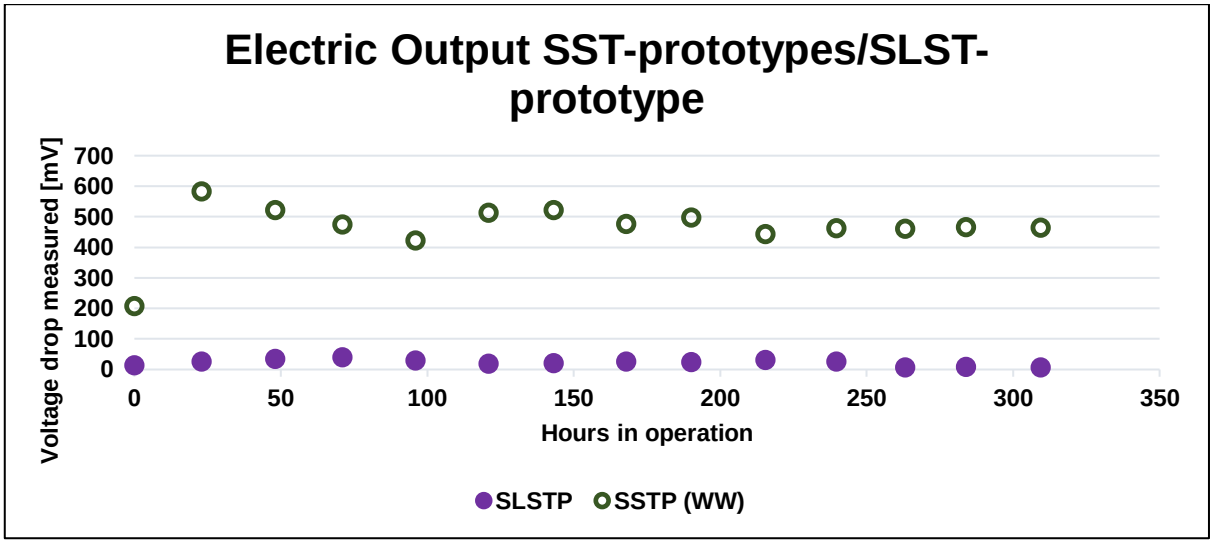

Figure 31: Diagram showing a comparison of measured electric outputs in mV from the SLST-prototype (SLSTP) and the SST-prototype filled with wastewater (SSTP (WW)), with regards to the hours the prototypes were in operation (Appx. A5-A6).

The SLST-prototype gives a lower amount of measured electric output than the other prototype (Fig. 31), and thus the results points to again regard the SST-prototype design as favourable in terms of electric output during experimental tests.

However, it is important to note that the SLST-prototype, with its larger surface area, had also a tendency to lose more fluid due to evaporation than any other prototype. This was observed during the testing of the SLST-prototype, but not recorded. This higher rate of evaporation could have led to more instances of the cathode not being in contact with the fluid beneath, because of the plastic cup containing weights under the cathode. If the cathode was not in contact with the fluid beneath at serval occasions, the overall results from the test would be affected and thus may not represent the true effect of increasing the surface area.

It was expected that the electric output of the SLST-prototype was higher than the SST-prototype filled with wastewater in accordance to other research done [45], [47], [48], because of its larger surface area of the electrodes. Even though this comparison suggests that the prototype with the smallest surface area of the electrodes gives a higher electric output, it is proposed that a future solution is made with electrodes with large surface areas based on other research. However, future solutions should be made with a better design than the SLST-prototype, that always make sure that the cathode is in contact with the fluid.

5.11. Electric Output / Volume Comparison

In light of the fact that the electric output should increase with the size of the anode in MFCs, it is most interesting to compare the prototypes that had the highest electric output of their prototype-design with respect to their anode surface area. These prototypes include the FT-prototype without a membrane, the SST-prototype filled with sludge and the SDT-prototype without a membrane. The comparison will take into account the volume of the prototype anodes.

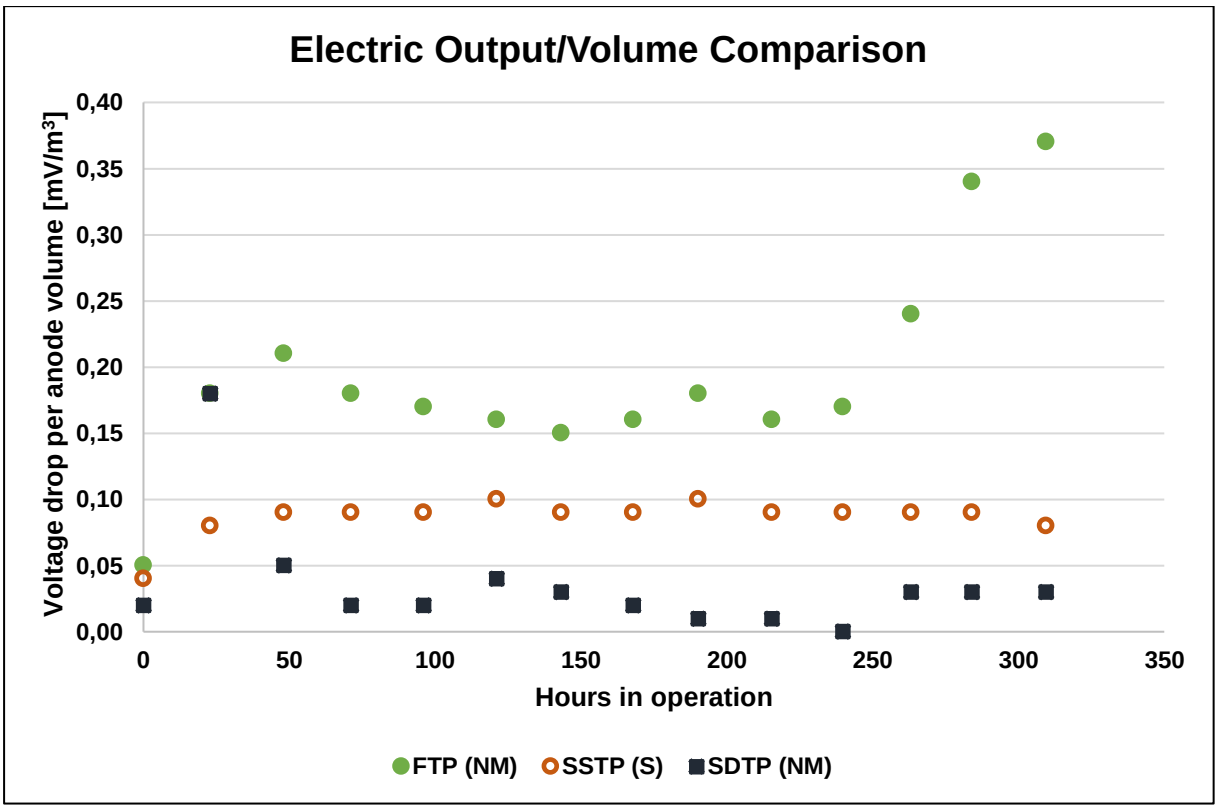

Figure 32: Diagram showing a comparison of electric output in mV between the FT-prototype without a membrane (FTP(NM)), the SST-prototype filled with sludge (SSTP(S)) and the SDT-prototype without a membrane (SSTP(NM)) per anode volume in m³, with regards to the hours the prototypes were in operation (Appx. D1-D2).

The results plotted in Figure 32 shows that if the volume of the anode is taken into consideration, the FT-prototype without a membrane outperforms the other prototypes in terms of electric output per anode volume. It is also worth noting that the SST-prototype filled with sludge outperforms the SDT-prototype without a membrane, suggesting again that the SST-prototype design outperforms the SDT-prototype design.

This comparison (Fig. 32) also suggests that even though the membrane-less FT-prototype had less anode volume because of its design, the flow of wastewater fluid through the prototype gave a higher electric output compared to the SST-prototype filled with sludge. This gives a different perspective regarding the FT-prototype design which in previous comparisons was outperformed by the SST-prototype design. This means that a future solution would benefit by having the flow-through capability.

Also, the FT-prototype had a rapid increase in measured electric output at the end of its operational time, that was most likely caused by a stop of flow. This suggests that a future solution would benefit by having the capability of varying between being in a stagnant and a flow-through condition.

It is possible to discuss if the electric output from the FT-prototype without a membrane would stabilise after the high increase at the end of the test (Fig. 32), if it would lower itself to the original levels, or if the electric output would sink below the original levels before the increase. Research regarding FT-situations [49], [50], [51] tends to show that a reduction in electric output is inevitable when under continues conditions.

However, because of the 14 days duration of the tests made in this project, it is possible that the original levels of electric output before the increase from the FT-prototype without a membrane could have been the results of the microorganisms needing to settle and grow in the MFC. If this was the case it could be expected, based on other research [52], [53], that the electric output would stabilise around the higher values.

On the other hand, the electrodes in the FT-prototypes had been submerged in wastewater fluids for 16 days before the test started. Given that the microorganisms grew in this period, it is reasonable to believe that the sudden increase of measured electric output was not in relation to the microorganisms needing to settle and grow in the MFC. Further testing, with longer test-time duration, is recommended to confirm the causes and effects of an increase in measured electric output from the FT-prototype, like the one showed in Figure 32.

6. New Prototype Design

This chapter presents the forming of the New Design solution to the main objective of this project. This includes a summary of the experimental testing and suggestions, literature reviews, 3D-drawings of the proposed design solution and an overview of the most crucial parts of this new solution.

6.1. Summary of Experimental Test Results and Suggestions

This subchapter presents a summary of the most important proposed solutions from the experimental testing. Following, is a list of elements that might be considered when making the New Design solution that could implement MFC-technology and water filters in a working, large-scale prototype or a new experimental prototype:

- Air can accumulate in undesirable areas if the inlet of fully air saturated wastewater is placed directly under the anode in a FT-prototype design. Relocating the inlet of fully air saturated wastewater, or alternatively block the path of the air bubbles to the anode, is recommended.

- Proton-exchanging membranes are not effective enough to use as membranes, because of its high market price compared to its effect on electric output, versus non-membrane prototypes.

- Using proton-exchanging membranes, and thus situating the anode and cathode close together, could increase the potential for contractual errors in the prototypes and thus reduction of electric output.

- Electric output tends to increase if a lower flow-velocity is used than in the FT-prototype. Stagnant MFCs are the most commonly used design.

- The SDT-prototype design may have a steadier, but lower electric output with the use of membrane.

- Increased amounts of solids in the wastewater tends to give higher electric output. Sludge therefore tends to give a higher electric output than wastewater when collected from fish water filters.

- Large, exposed surface area tends to increase the amount of fluid evaporated, and could be the cause of lower electric output.

- The SST-prototype designs tend to outperform the other prototype designs, in terms of electric output measured.

- Research indicate that larger surface area of the electrodes gives a higher electric output.

- The electric output of prototypes tends to benefit from some flow of fluid flowing through the them.

6.2. New Design Concept

Based on the elements listed in subchapter 6.1. and on the working principles of the MFC, presented in subchapter 2.1., the concept of the New Design solution is presented in this subchapter. The New Design solution will have the same basic design as a SST-prototype, but with the capability of letting fluids flow through it following the principle of Flow-through system filters.

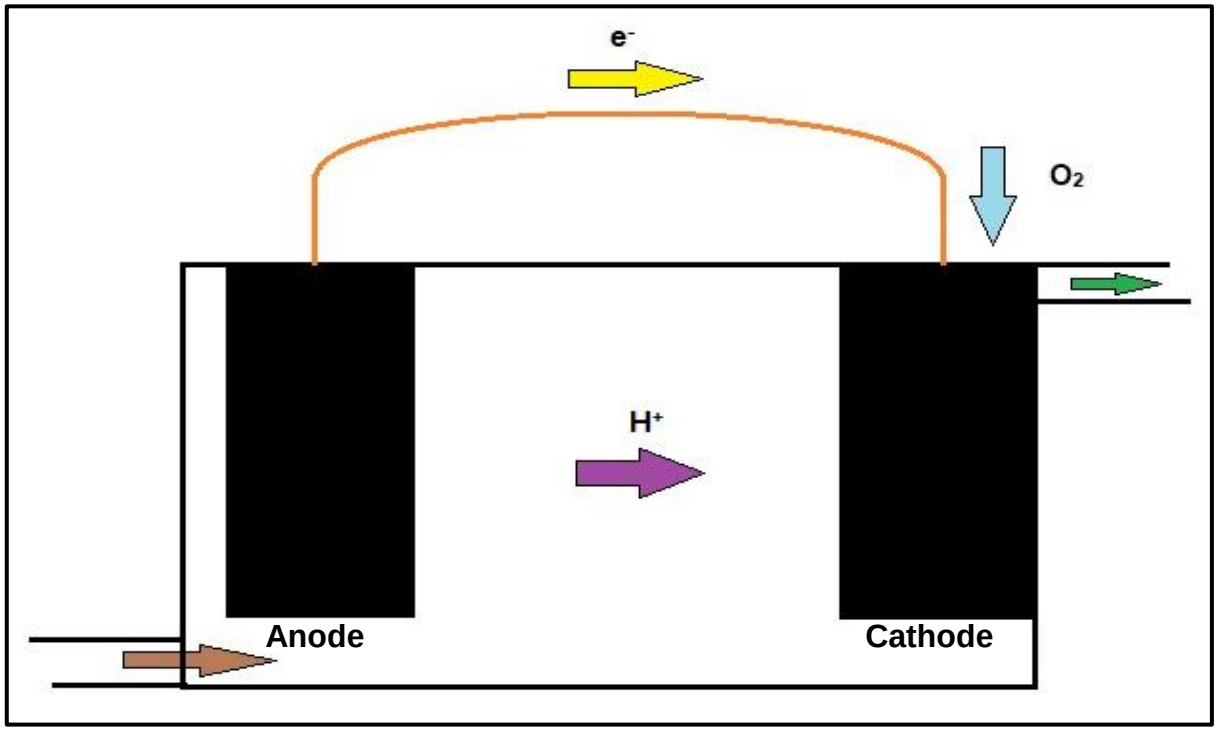

Figure 33: Illustration showing the working principles of the New Design solution. Purple arrow representing the proton (H^+) flow, yellow arrow representing the electron (e^-) flow, brown arrow representing fluid inlet, blue arrow representing the supply of oxygen (O_2) and green arrow representing the fluid outlet.

The New Design solution had to include a solution to most of the problems and suggestions listed in subchapter 6.1. Several recommendations have been implemented in the design and is presented in Figure 33. A tube with both an inlet and an outlet will contain necessary components of a MFC. Fluids will be able to flow into the tube trough the inlet (Fig. 33, brown arrow) and fill up the tube. Microorganisms will grow on the electrodes, and the purification of the fluid and the electron release starts. The electrodes will be connected with a wire, on the outside of the tube, to be able to exploit the flow of electrons from the anode to the cathode. The tube-wall around the cathode consists of an air-breathing membrane to give the cathode a source of oxygen and to keep the fluids inside.

Sediments will settle on the bottom of the tube if the fluid inside is stagnant or consists of sludge. If wanted or needed, the sediments can be removed from the tube by altering the position of the outlet (Fig 33, green arrow) and create a channel along the bottom of the tube. In this position, simultaneously inlet- and outlet flow could empty the tube of sediments or, if wanted, all the fluid inside.

The outlet position could also be moved to the top of the tube, as shown in Figure 33, if a continues flow is wanted. This could give the capability of purifying the fluid while having a continues output of fluid and electrons.

6.3. New Design Solution Illustrations

This subchapter presents illustrations of the New Design solution. These illustrations were not intended to be used to produce a finished, working prototype. Rather, they were intended to give an idea of how a combination of MFC-technology and water filtration could be solved. Subsequently, the following illustrations has no technical details or the dimensions necessary to make a real-life copy.

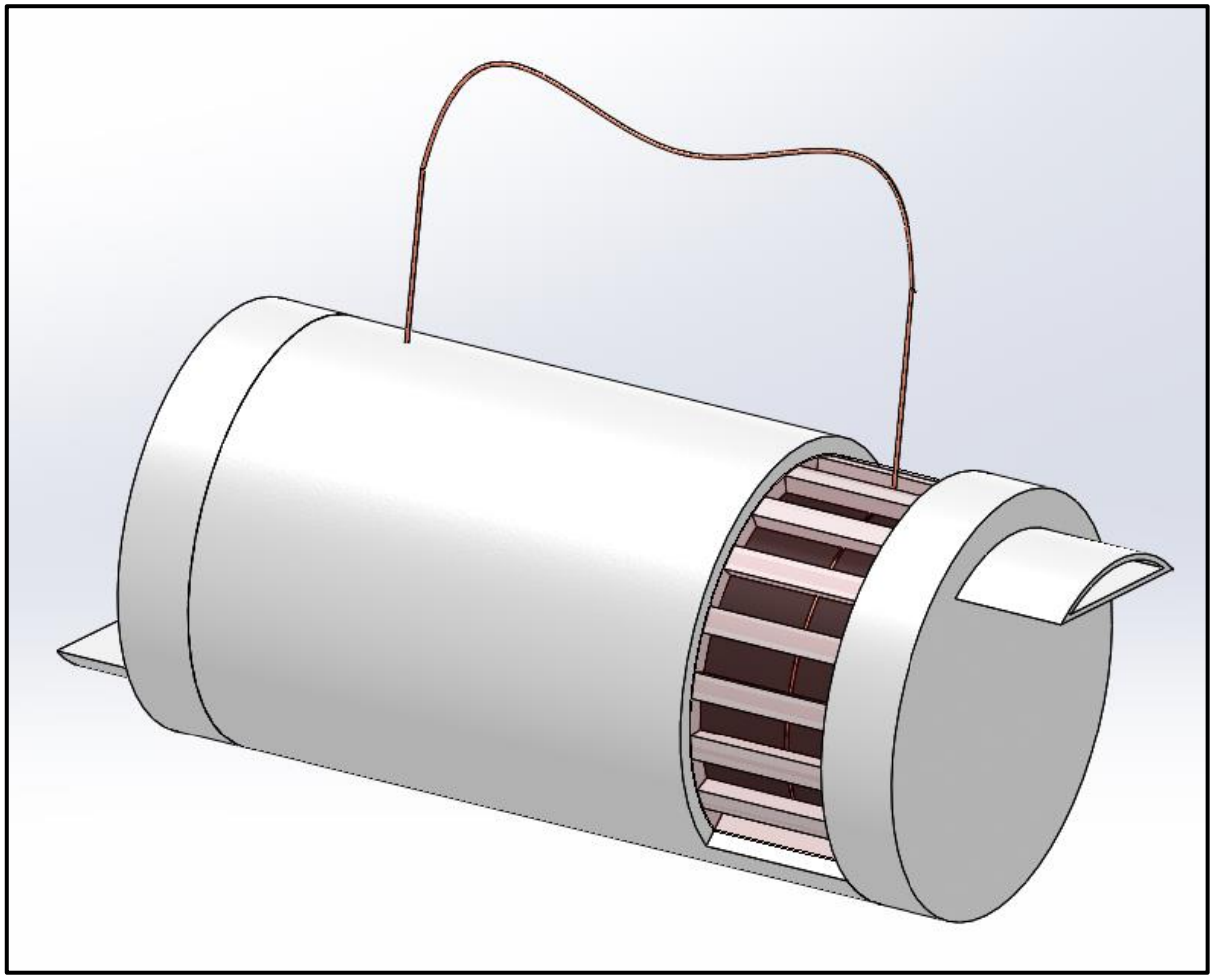

Figure 34: CAD-illustration of the New Design solution, outer top-side view.

In figure 34, the outside of the New Design solution and some of the key elements of the prototype are viewed. The elements consist of the tube itself containing the fluid and the electrodes, the cathode, the air breathing membrane, rotating lids on both ends with inlet/outlet channels and a wire connecting the electrodes.

6.3.1. Tube and electrodes

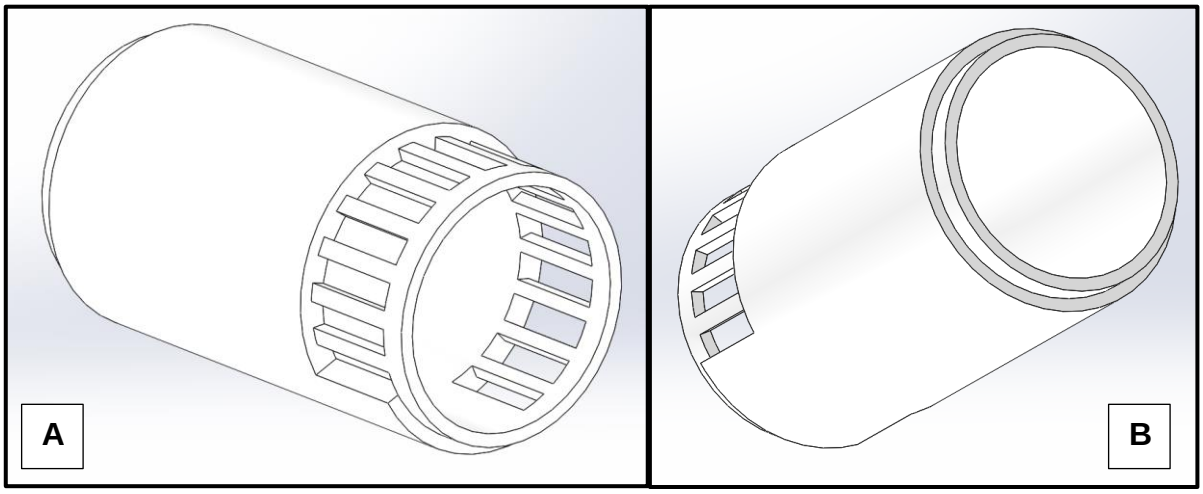

Figure 35: A: New Design solution tube component, CAD-illustration top-side view. B: New Design solution tube component, CAD-illustration bottom-side view.

The tube, shown as a single component in Figure 35 A and B, holds an amount of fluid, together with two electrodes. The electrodes will work as in the SST-prototype test, and will be connected by a wire exiting the tube at two different places. In between two layers of electrode, a metal sheet is placed in order to conduct the electrons efficiently.

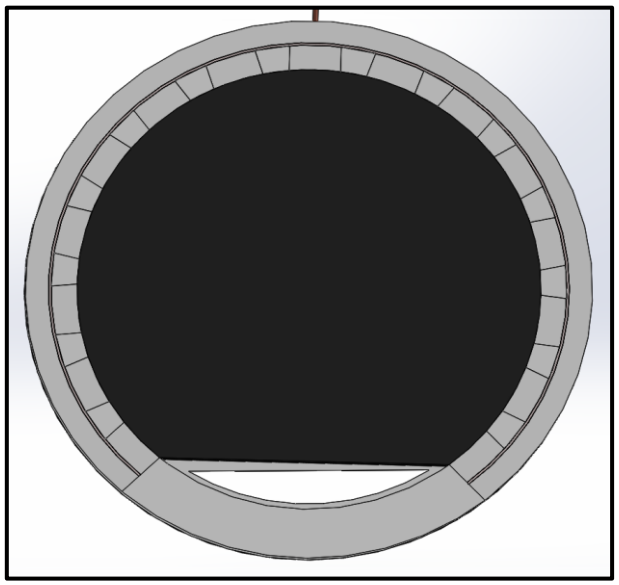

Figure 36: CAD-illustration Cut-view of the bottom channel in the New Design solution tube component with an electrode.

The bottom of the tube is remained clear of electrodes, as shown in Figure 36, to allow passing fluid to fill the tube. The anode has a clearing behind it, towards the lid (Fig. 37), giving the fluid a way to pass in order to fill the tube and to surround the anode with fluid. No membrane will be situated between the anode and cathode, but the electrodes will be situated a distance apart following the recommendations.

The surface area of the electrodes can be increased depending on the material used and/or if the tube-dimension is increased.

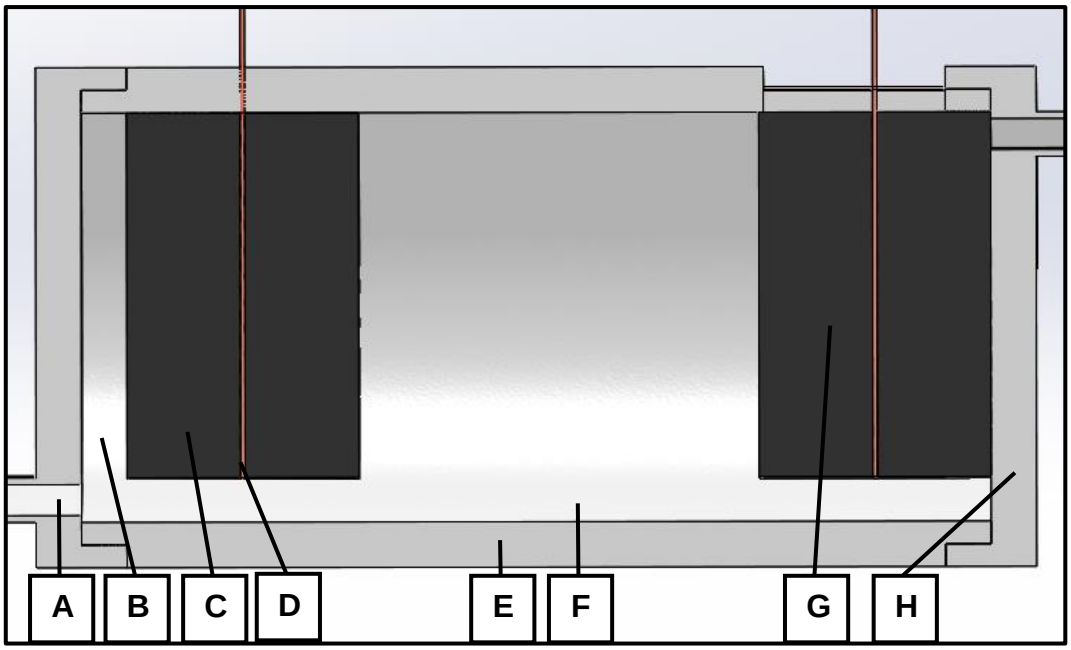

Figure 37: CAD-illustration Cut-view of the New Design solution, side view. A: rotating lid channel, B: clearing, C: anode, D: metal sheet, E: tube, F: tube channel, G: cathode, H: rotating lid.

6.3.2. Rotating lids

Both ends of the tube will be covered with identical lids (Fig. 38A). These lids have a channel and are able to rotate in order to change the position of the channel, either in the flow-through position (Fig. 38B) or in the stagnant/flow-through position (Fig. 38C). The lids should be made in a kind of material that is a not good conductor of electricity. The lids are removable if needed to change or repair components inside the tube. Closed lids remove the undesired effect of evaporation of the fluid caused by large, exposed surface areas, as experienced during the SLST-prototype test.

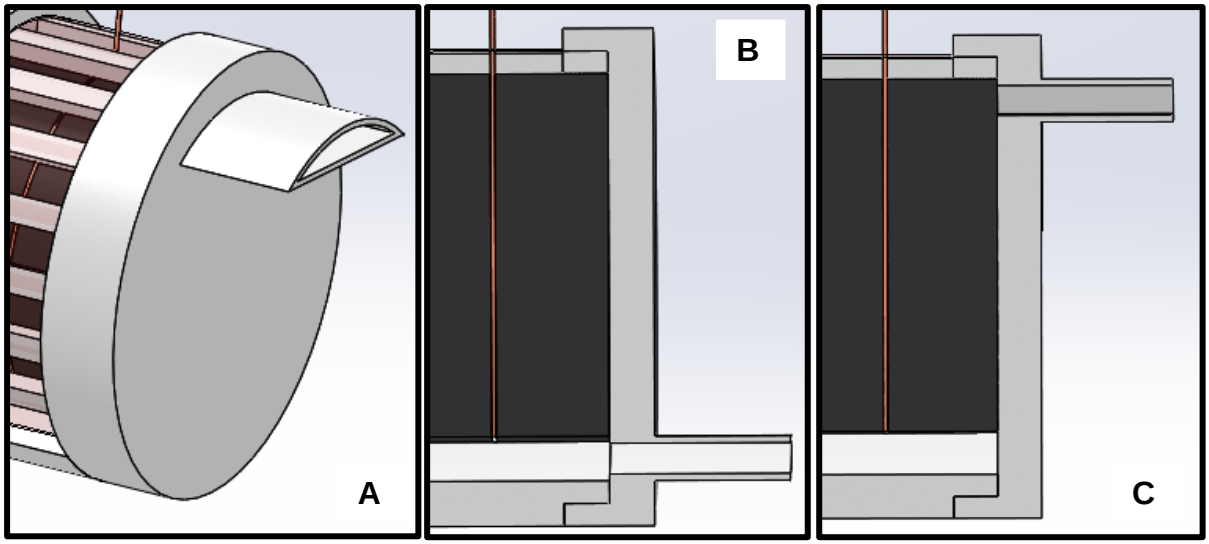

Figure 38: Different CAD-illustration views of the lid. A: 3D-view of the lid on one side of the chamber. B: Cut-view of a lid in a flow-through position. C: Cut-view of a lid in a stagnant/flow-through position.

6.3.3. Flow-through position

In cases where the prototype needs cleaning, because of high amounts of sediment accumulations or lack of nutrients for the microorganisms, the lids can be turned in a flow-through position, as shown in Figure 38B and Figure 39, to allow the emptying of the tube without removing the lids. In addition, purer fluids can be let in through one of the channels to flush out the unwanted substances inside. This position can also be used to fill the tube with the wanted fluid from both sides.

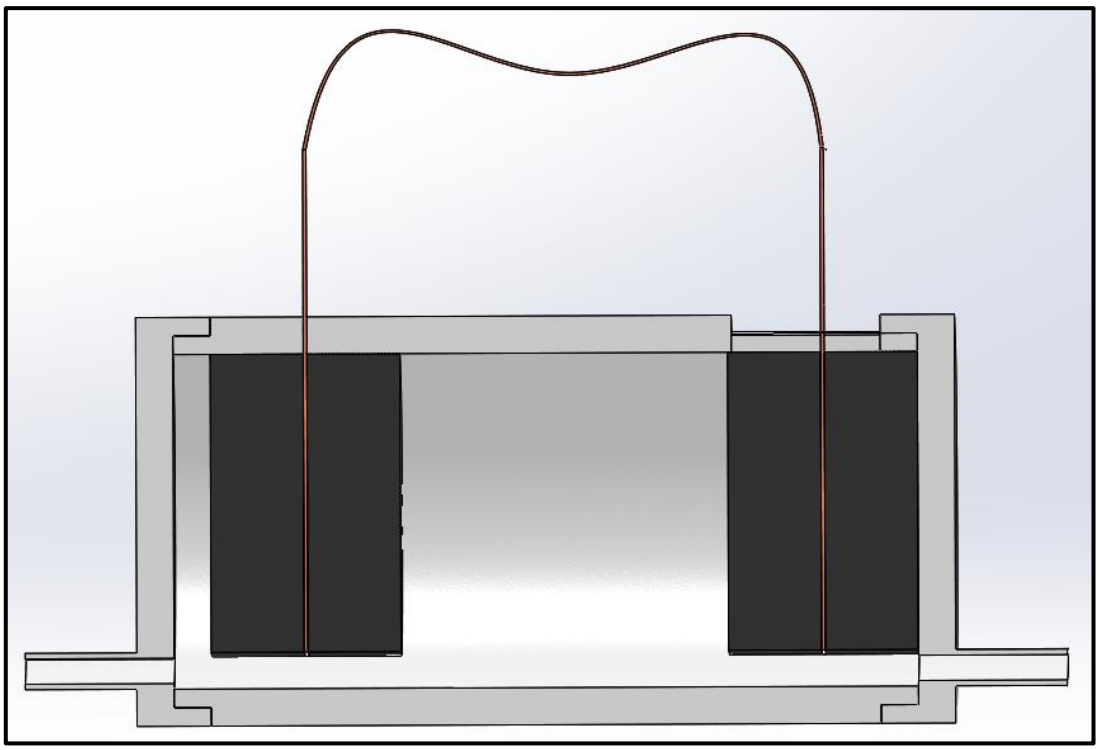

Figure 39: CAD-illustration Cut-view of the New Design solution, in flow-through position.

6.3.4. Stagnant/Flow-through position

To possibly increase the electric output of the prototype, the lids can be turned in a stagnant/flow-through position as shown in Figure 38C, Figure 40 and 41. In this position, given that the channels are closed (Fig. 40), the fluid inside the tube will remain stagnant and could possibly increase electric output, in accordance with the recommendations.

Alternatively, if a constant flow through the prototype is beneficial, the channel at the right-hand side could be opened and fluid could be forced through the cathode (Fig. 41) and be purified in its way out of the tube. Figure 41 illustrates how the flow of fluids could behave in the case of flow-through.

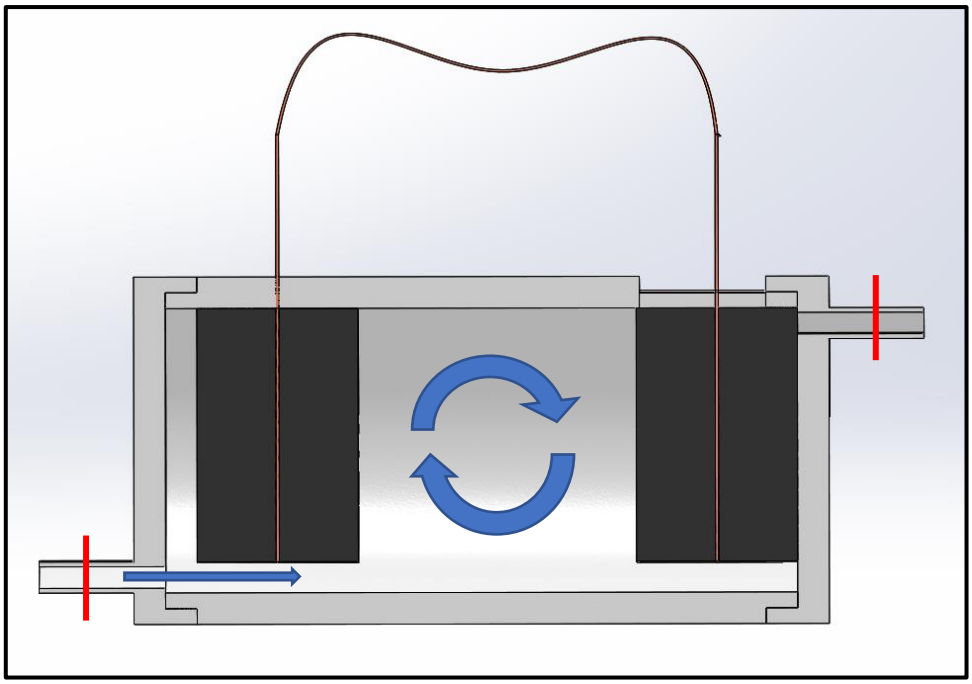

Figure 40: CAD-illustration Cut-view of the New Design solution, stagnant situation. Blue arrows illustrating the potential flow of a fluid and red lines illustrating closed channels.

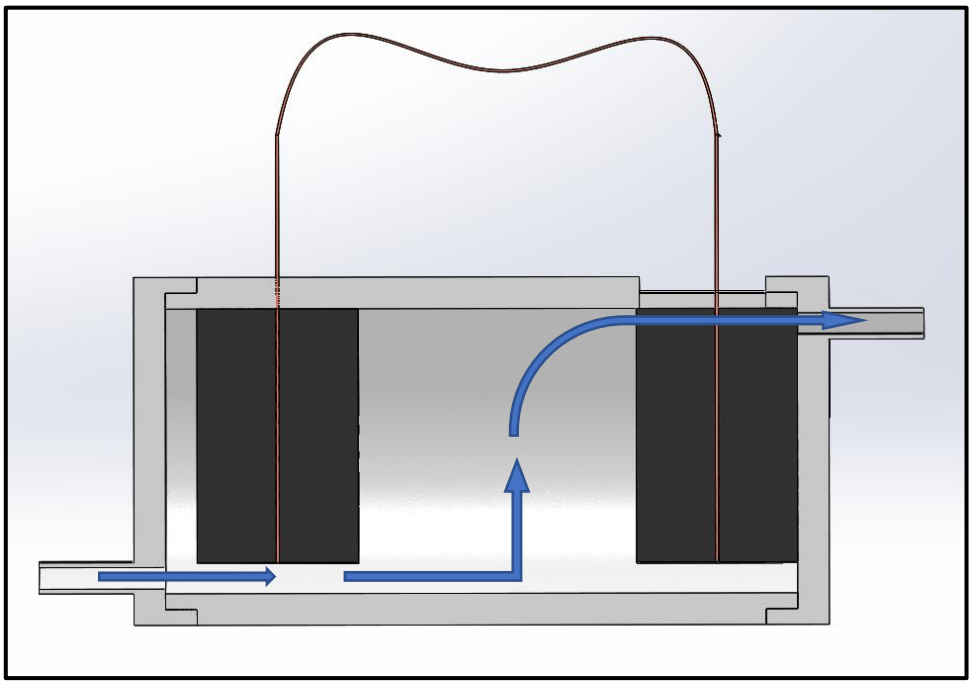

Figure 41: CAD-illustration Cut-view of the New Design solution, flow-through situation. Blue Arrows illustrating the potential flow of a fluid.

6.3.5. Air breathing membrane

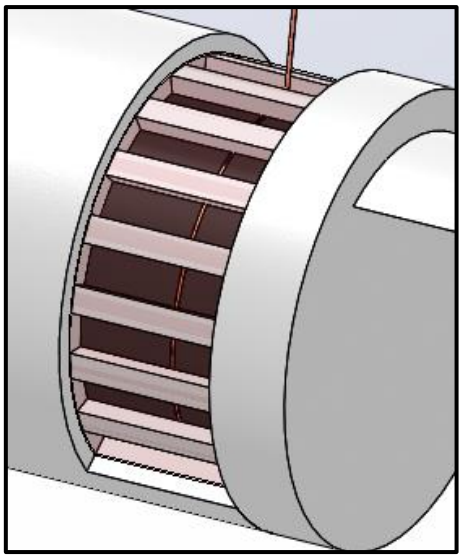

Figure 42: CAD-illustration 3D-view of the air-breathing membrane placed in the New Design solution.

In order to release electrons, the cathode inside the tube should have access to oxygen. In the New Design solution this oxygen supply comes in the form of contact with open air. This is achieved by reducing the tube-material around the cathode, by the means of holes, and exposing the cathode to the surrounding air.

To prevent the fluid from leaking out through these holes, an air breathing membrane is placed over the holes as shown in Figure 42. This membrane should therefore be made of a material that could allow air to pass through, but not allow fluid to pass.

6.3.6. New Design Solution Composition

Here follows an explanation of the composition of the New Design solution, with an CAD-illustration exploded view of the prototype.

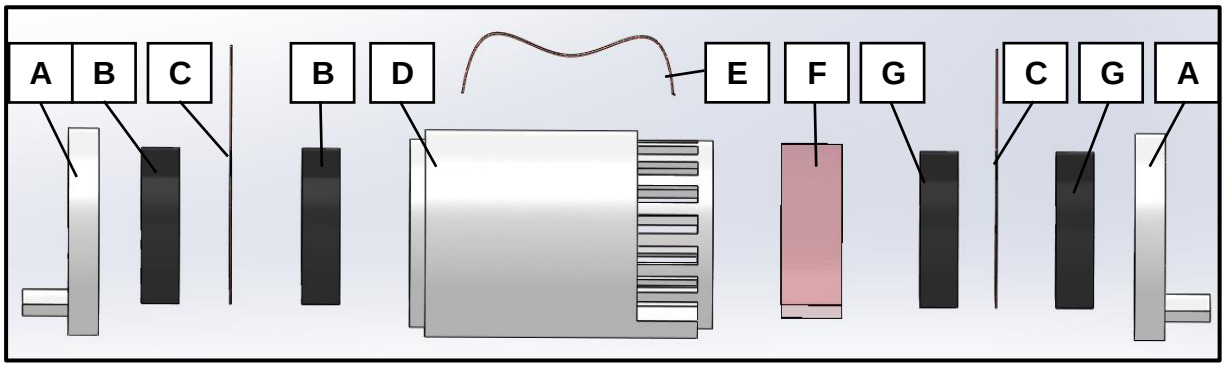

Figure 43: CAD-illustration exploded view of the New Design solution components. A: rotating lid, B: anode, C: metal sheet, D: tube, E: wire, F: air-breathing membrane, G: cathode.

7. Conclusion

This project has resulted in a New Design solution, which integrates the Microbial Fuel Cell technology as a part of a water filter without a membrane separating the anode and the cathode. The solution was made based on existing literature and results from the experiments conducted in this project. Several prototype designs and factors have been tested, and the results from these tests have been compared to each other and to existing literature.

In addition to the experimental tests conducted, a flow-through simulation has been conducted and reported by this project. This simulation resulted in an investigation of the flow in one of the prototypes and a comparison of velocities and tube sizes that could be usable in future work. However, all aspects concerning the integration of Microbial Fuel Cells with water filters has not been reviewed by this project. Future research regarding the New Design solution or similar solutions may find flaws and possibilities for improvement regarding this solution.

The solution developed by this project could be one of the many solutions that is needed to deal with the world's problems regarding sustainable water management and ultimately reduction of global temperature increase. The limitations for this project marks a start for the future work needed to develop the New Design solution further, and to further understand the effects and possibilities of integrating Microbial Fuel Cells with water filters.

7.1. Summary of Results and Recommendations

Following are lists describing the key results produced by this project and recommendations regarding the New Design solution and future work.

Results:

- The components that make up the New Designs solution is primarily its single tube structure with a channel at the bottom and rotating lids with channels situated at the ends of the tube.
- The New Design has the capability of using fluids in both a stagnant and a flow-through situation to produce electricity. It also includes other qualities like easy access to the internal components and the capability of easy cleaning.
- The New Design does not have a proton-exchange membrane separating the anode from the cathode, because of the membranes high marked cost compared to its little effect on electric output.

Recommendations:

- Experimental tests should be conducted over a period long enough to be able to allow electric output values to potentially stabilise.
- When testing different prototypes with flow of fluids, it is preferable to use different sources of fluids for the prototypes instead of sharing one source.
- If the New Design solution is going to be further developed, it is preferable to investigate more concreate aspects of the design and functions separate, instead of looking at many factors at the same time as done by this project.

7.2. Future Work

If the New Design solution and the integration of MFC-technology with water filters is going to be further studied, the amount of work that could be done is substantial. Many of the sources of information used by this project is written in recent years, and thus it is reasonable to believe that more studies will be conducted on these fields during the coming years. Following is a list of the main tasks and aspects that could be considered in further development of the New Design solution and any future work related to this project:

New Design solution:

- Determine what materials that could be used for the different parts, in particular for the electrodes and the air-breathing membrane.
- Complete a design of the New Design solution that could be produced and works, with emphasis on the design of the rotating lids.
- Simulate different fluid- and velocities scenarios for the flow-through of the New Design solution, for improving the design.
- Determine whether the New Design solution could be utilized in real life by comparing its cost to its effectiveness in filtrating water and producing electricity.
- Measure the quality of the wasted water exiting the New Design solution, as this is of importance to the practical use of a water filter integrated with MFC-technology.
- Determine whether the quality of the wasted water is satisfactory, and find possible improvements regarding the New Design solution.
- Investigate when a stagnant or a flow-through situation is preferable, regarding electric output.

MFC-technology and water filters:

- Determine what microorganisms and fluids that can be best utilized to produce electricity while filtrating water.
- Further study the electron production of the microorganisms in MFCs integrated with water filters, in order to find optimal conditions for electricity production and water filtration.
- Finding electrically leading materials that are the most suitable for the conducting of electricity between the electrodes in a biological environment.
- Finding new solutions that could possibly be better in terms of easy mass-production and reduction of negative environmental impacts.
- Calculate the electric potential of utilizing the integration of MFCs with water filters in a larger scale.

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Appendix A1: Results

Initial Flow-through tests

	Day 1	Day 2	Day 3	Day 4	Day 5
Weight of output water Prototype 1 (M)	31,8 g	20,2 g	15,3 g	7,7 g	15,9 g
Weight of output water Prototype 2 (NM)	12,6 g	8,4 g	3,9 g	3,7 g	4,4 g
Current Prototype 1 (M)	0 Ampere	0 Ampere	0 Ampere	0 Ampere	0 Ampere
Current Prototype 2 (NM)	0 Ampere	0 Ampere	0 Ampere	0 Ampere	0 Ampere
Hours in operation	0	25.87	49.63	72.93	97.83
Operational temperature	23 ºC	23 ºC	22 ºC	21 ºC	22 ºC

	Day 6	Day 7	Day 8
Weight of output water Prototype 1 (M)	13,5	16,0 g	15,2 g
Weight of output water Prototype 2 (NM)	3,9 g	4,8 g	3,8 g
Current Prototype 1 (M)	0 micro A	0 micro A	0
Current Prototype 2 (NM)	0 micro A	0 micro A	0
Hours in operation	121.58	146.17	169.75
Operational temperature	22 ºC	23 ºC	22 ºC

Appendix A2: Results

Flow-through test

	Day 1	Day 2	Day 3	Day 4	Day 5
Weight of output water Prototype 1 (M)	0	14.1 g	20.0 g	14.5 g	17.0 g
Weight of output water Prototype 2 (NM)	0	4.9 g	8.8 g	7.2 g	6.1 g
Voltage Prototype 1 (M)	226.5 mV	83.3 mV	74.5 mV	62.7 mV	141.6 mV
Voltage Prototype 2 (NM)	103.8 mV	355.8 mV	422.2 mV	356.4 mV	327.2 mV
Hours in operation	0	22.87	48.03	71.03 mV	95.93 mV
Operational temperature	22 ºC	22 ºC	22 ºC	22 ºC	23 ºC

	Day 6	Day 7	Day 8	Day 9	Day 10
Weight of output water Prototype 1 (M)	18.1 g	16.4 g	17.1 g	16.9 g	17.6 g
Weight of output water Prototype 2 (NM)	6.4 g	5.9 g	6.4 g	6.2 g	6.2 g
Voltage Prototype 1 (M)	25.2 mV	56.3 mV	63.3 mV	135.2 mV	137.8 mV
Voltage Prototype 2 (NM)	306.4 mV	294.2 mV	321.6 mV	356.8 mV	325.5 mV
Hours in operation	120.95	143.12	167.87	190.20	215.45
Operational temperature	23 ºC	23 ºC	22 ºC	23 ºC	23 ºC

Appendix A3: Results

Flow-through test

	Day 11	Day 12	Day 13	Day 14
Weight of output water Prototype 1 (M)	20.3 g	2.3 g	16.5 g	15.6 g
Weight of output water Prototype 2 (NM)	8.9 g	0.0 g	9.1 g	7.2 g
Voltage Prototype 1 (M)	184.5 mV	296.9 mV	305.1 mV	128.9 mV
Voltage Prototype 2 (NM)	343.6 mV	483.5 mV	668.9 mV	723.8 mV
Hours in operation	239.70	263.12	283.97	309.38
Operational temperature	23 ºC	23 ºC	23 ºC	23 ºC

Appendix A4: Results

Stagnant double tube test

	Day 1	Day 2	Day 3	Day 4	Day 5
Voltage Prototype 1 (M)	1.7 mV	49.3 mV	3.2 mV	44.3 mV	34.8 mV
Voltage Prototype 2 (NM)	39.4 mV	362.1 mV	94.9 mV	40.1 mV	48.8 mV
Operational temperature	22 ºC	22 ºC	22 ºC	22 ºC	23 ºC
Hours in operation	0	22.87	48.03	71.03	95.93

	Day 6	Day 7	Day 8	Day 9	Day 10
Voltage Prototype 1 (M)	38.0 mV	34.5 mV	30.2 mV	27.5 mV	22.9 mV
Voltage Prototype 2 (NM)	76.7 mV	53.6 mV	42.7 mV	15.4 mV	12.9 mV
Operational temperature	23 ºC	23 ºC	22 ºC	23 ºC	23 ºC
Hours in operation	120.95	143.12	167.87	190.20	215.45

	Day 11	Day 12	Day 13	Day 14
Voltage Prototype 1 (M)	14.3 mV	0.0 mV	2.7 mV	8.3 mV
Voltage Prototype 2 (NM)	3.9 mV	58.6 mV	59.1 mV	54.9 mV
Operational temperature	23 ºC	23 ºC	23 ºC	23 ºC
Hours in operation	239.70	263.12	283.97	309.38

Appendix A5: Results

Stagnant single tube test

	Day 1	Day 2	Day 3	Day 4	Day 5
Voltage Prototype 1 (Sludge)	314.2 mV	653.2 mV	676.4 mV	700.6 mV	731.6 mV
Voltage Prototype 2 (WW)	206.4 mV	582.1 mV	520.8 mV	472.8 mV	421.8 mV
Operational temperature	22 ºC	22 ºC	22 ºC	22 ºC	23 ºC
Hours in operation	0	22.87	48.03	71.03	95.93

	Day 6	Day 7	Day 8	Day 9	Day 10
Voltage Prototype 1 (Sludge)	735.8 mV	722.8 mV	712.6 mV	743.3 mV	731.1 mV
Voltage Prototype 2 (WW)	511.8 mV	521.4 mV	475.2 mV	496.1 mV	442.1 mV
Operational temperature	23 ºC	23 ºC	22 ºC	23 ºC	23 ºC
Hours in operation	120.95	143.12	167.87	190.20	215.45

	Day 11	Day 12	Day 13	Day 14
Voltage Prototype 1 (Sludge)	733.3 mV	714.8 mV	698.3 mV	640.5 mV
Voltage Prototype 2 (WW)	462.1 mV	458.8 mV	465.3 mV	462.7 mV
Operational temperature	23 ºC	23 ºC	23 ºC	23 ºC
Hours in operation	239.70	263.12	283.97	309.38

Appendix A6: Results

Stagnant large single tube test

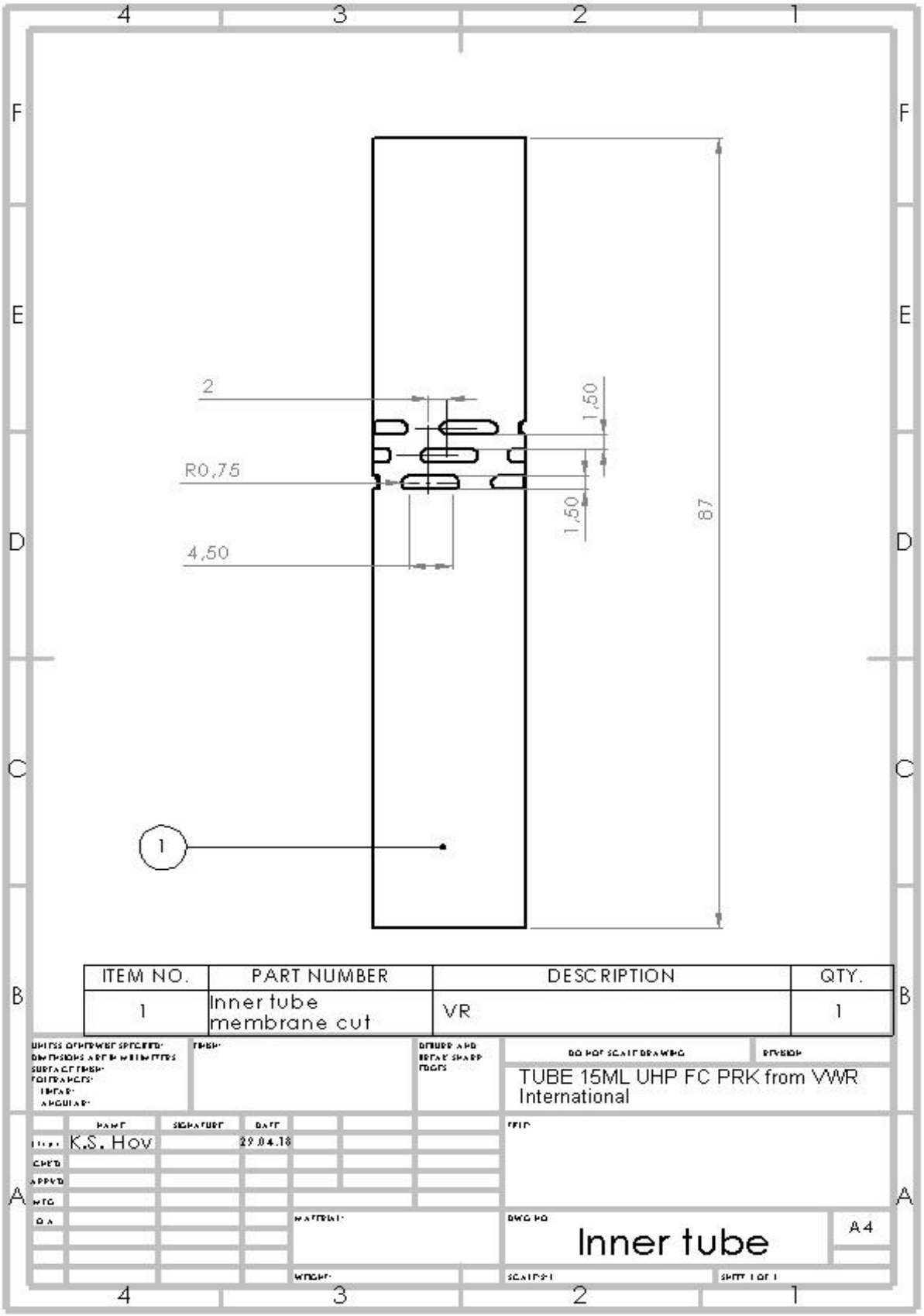
	Day 1	Day 2	Day 3	Day 4	Day 5
Voltage	11.7 mV	24.8 mV	32.9 mV	39.4 mV	28.3 mV
Operational temperature	22 ºC	22 ºC	22 ºC	22 ºC	23 ºC
Hours in operation	0	22.87	48.03	71.03	95.93

	Day 6	Day 7	Day 8	Day 9	Day 10
Voltage	17.4 mV	19.4 mV	24.3 mV	22.6 mV	29.9 mV
Operational temperature	23 ºC	23 ºC	22 ºC	23 ºC	23 ºC
Hours in operation	120.95	143.12	167.87	190.20	215.45

	Day 11	Day 12	Day 13	Day 14
Voltage	25.0 mV	4.8 mV	6.6 mV	6.4 mV
Operational temperature	23 ºC	23 ºC	23 ºC	23 ºC
Hours in operation	239.70	263.12	283.97	309.38

Appendix B1: Flow-through Simulation Drawing

Inner tube holes drawing



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	Inner tube membrane cut	VR	1

	NAME	SIGNATURE	DATE
DRAWN	K.S. Hov		29.04.18
CHK'D			
APPV'D			
MFG			
Q.A			

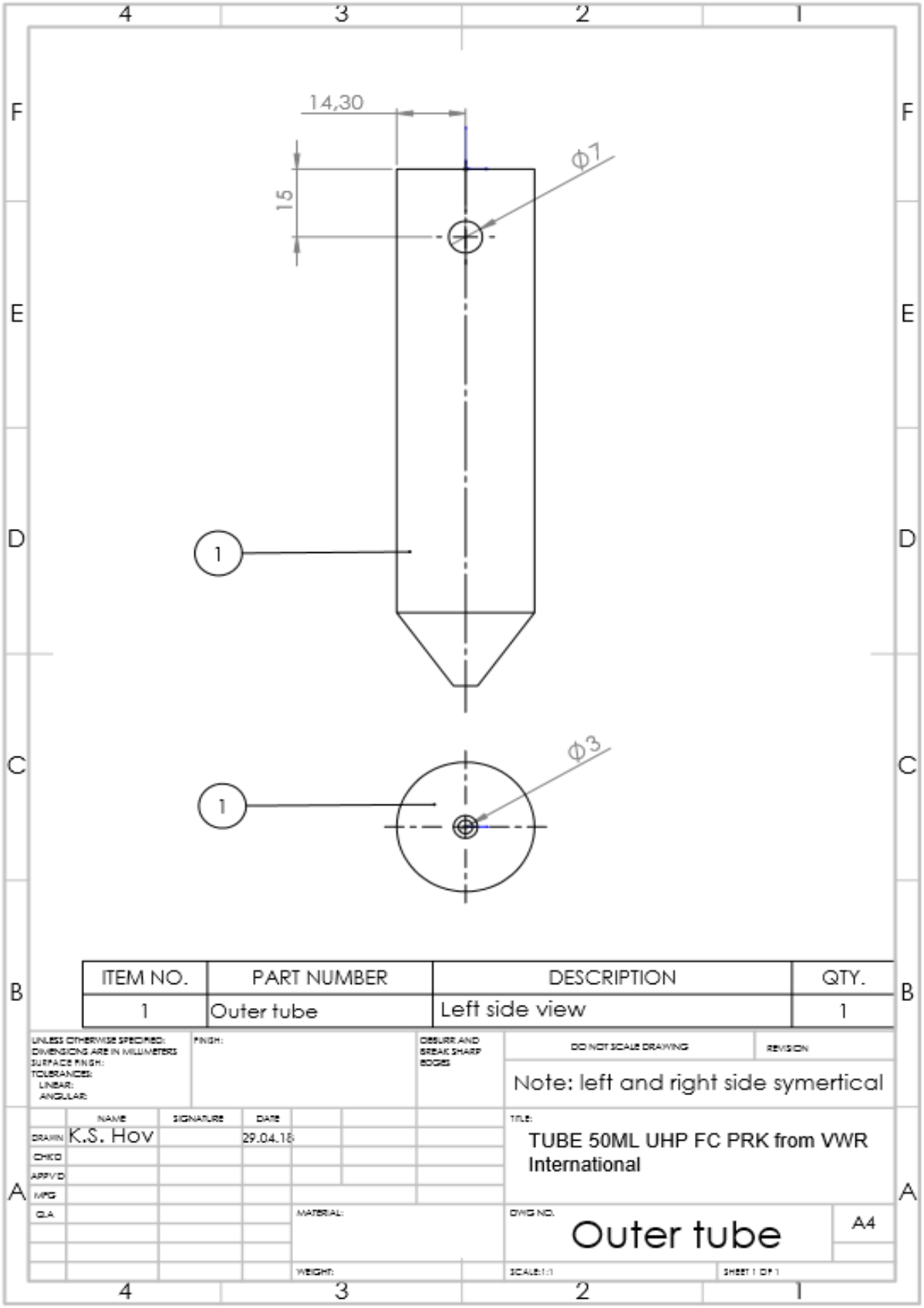
TUBE 15ML UHP FC PRK from VWR International

Inner tube

A4

Appendix B2: Flow-through Simulation Drawing

Outer tube holes drawing



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	Outer tube	Left side view	1

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

Note: left and right side symertical

	NAME	SIGNATURE	DATE
DRAWN	K.S. Hov		29.04.18
CHK'D			
APPV'D			
MFG			
QA			

MATERIAL:

WEIGHT:

TITLE:

TUBE 50ML UHP FC PRK from VWR International

DWG NO.

Outer tube

A4

SCALE:1:1

SHEET 1 OF 1

Appendix C1: Flow-through Simulation Results Data

inner lvl 3		inner lvl 4	
Length [m]	Velocity [mm/s]	Length [m]	Velocity [mm/s]
0	5,29396E-23	0	1,15602E-25
0,00026734	1,95499E-07	0,000370559	2,87681E-07
0,00053467	4,30333E-07	0,000741118	3,47632E-07
0,00133668	5,55983E-07	0,001932785	7,35407E-07
0,00312418	1,06229E-06	0,003124451	1,07072E-06
0,00491168	1,40146E-06	0,004316118	1,29015E-06
0,00669918	1,51417E-06	0,006699451	1,44868E-06
0,0067	1,51411E-06	0,0067	1,44864E-06
0,00848668	1,40049E-06	0,009082785	1,29211E-06
0,01027418	1,05978E-06	0,010274451	1,0729E-06
0,01206168	5,49358E-07	0,011466118	7,37186E-07
0,01286467	4,22157E-07	0,012657785	3,48652E-07
0,01313234	1,91842E-07	0,013028892	2,88424E-07
0,0134	0	0,0134	0
0,01342427	0	0,013424275	0
0,01344855	0	0,013448549	0

Appendix C2: Flow-through Simulation Results Data

inner lvl 5

Length [m]	Velocity [mm/s]
0	2,64698E-23
0,000114693	1,10614E-07
0,000229386	1,76088E-07
0,000344079	1,96398E-07
0,001932968	7,40739E-07
0,003521856	1,1565E-06
0,005110745	1,41403E-06
0,006699634	1,50027E-06
0,0067	1,50025E-06
0,008288523	1,41422E-06
0,009877412	1,15703E-06
0,011466301	7,41292E-07
0,01305519	1,96639E-07
0,013170127	1,76277E-07
0,013285063	1,10721E-07
0,0134	0
0,013424275	0
0,013448549	0

outer lvl 3

Length [m]	Velocity [mm/s]
0	0
1,50E-05	0
3,00E-05	0
3,00E-05	8,23E-10
7,46E-05	3,25E-07
0,00109604	5,65E-07
0,00186212	7,40E-07
0,00265504	7,57E-07
0,00275587	7,60E-07
0,00364941	6,07E-07
0,00454295	3,12E-07
0,0049115	2,39E-07
0,00528004	0
0,00529001	0
0,00529997	0

Appendix C3: Flow-through Simulation Results Data

outer lvl 4		outer lvl 5	
Length [m]	Velocity [mm/s]	Length [m]	Velocity [mm/s]
0	0	0	0
1,50209E-05	0	1,50209E-05	0
3,00419E-05	6,4741E-11	3,00419E-05	3,89629E-11
0,00020115	2,05449E-07	0,000144053	1,2487E-07
0,000372257	2,4358E-07	0,000258064	1,86129E-07
0,000968091	4,9289E-07	0,000372074	2,16644E-07
0,001563924	6,79352E-07	0,000769297	4,13497E-07
0,002159757	7,75635E-07	0,001166519	5,72572E-07
0,002655042	7,85356E-07	0,001563741	6,88791E-07
0,002755591	7,87329E-07	0,001960963	7,62724E-07
0,003351424	7,19171E-07	0,002358185	7,95967E-07
0,003947257	5,75232E-07	0,002655042	7,80854E-07
0,004542953	3,59042E-07	0,00315263	7,54914E-07
0,00513865	1,49228E-07	0,003947074	5,80413E-07
0,005280042	0	0,004344297	4,45169E-07
0,005290005	0	0,004840801	2,35391E-07
0,005299969	0	0,00513865	1,11698E-07
		0,005209346	6,47676E-08
		0,005280042	0
		0,005290005	0
		0,005299969	0

Appendix D1: mV/m^3 Comparison Data

Data calculated and presented are partially collected from information in appendixes A2-A5, and partially from measurements taken during the project. The following table describes the technical information of the anode used in the prototypes:

Table 1.

	FT-prototype	SST-prototype
Diameter	13.40 mm	26.50 mm
Surface area	141.03 mm^2	551.55 mm^2
Height	14.00 mm	14.00 mm
Volume	1974.42 mm^3	7721.70 mm^3

	SLST-prototype
Diameter	87 mm
Surface area	5944.68 mm^2
Height	14.00 mm
Volume	83225.52 mm^3

The following tables (appx. D1 and D2) describe the relationship between the electric output measured as potential drop over the external resistance and the volume of the anode, relative to the time of measurement.

Flow-through test

The relation mV/m^3 was calculated by dividing the measured electric potential drop by the volume of the respectable anodes (Table 1).

	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Day 8
[mV/m^3] Prototype 2 (NM)	0.05	0.18	0.21	0.18	0.17	0.16	0.15	0.16
Hours in operation	0	22.87	48.03	71.03	95.93	120.95	143.12	167.87

	Day 9	Day 10	Day 11	Day 12	Day 13	Day 14
[mV/m^3] Prototype 2 (NM)	0.18	0.16	0.17	0.24	0.34	0.37
Hours in operation	190.20	215.45	239.70	263.12	283.97	309.38

Appendix D2: mV/m^3 Comparison Data

Stagnant Single Tube test

	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Day 8
[mV/m^3] Prototype 1 (sludge)	0.04	0.08	0.09	0.09	0.09	0.10	0.09	0.09
Hours in operation	0	22.87	48.03	71.03	95.93	120.95	143.12	167.87

	Day 9	Day 10	Day 11	Day 12	Day 13	Day 14
[mV/m^3] Prototype 1 (sludge)	0.10	0.09	0.09	0.09	0.09	0.08
Hours in operation	190.20	215.45	239.70	263.12	283.97	309.38

Stagnant Double Tube test

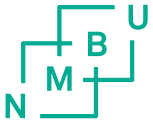
	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Day 8
[mV/m^3] Prototype 2 (NM)	0.02	0.18	0.05	0.02	0.02	0.04	0.03	0.02
Hours in operation	0	22.87	48.03	71.03	95.93	120.95	143.12	167.87

	Day 9	Day 10	Day 11	Day 12	Day 13	Day 14
[mV/m^3] Prototype 2 (NM)	0.01	0.01	0.00	0.03	0.03	0.03
Hours in operation	190.20	215.45	239.70	263.12	283.97	309.38

Appendix E: Section of the Fluke 187 Manual

			Accuracy	Accuracy Dual Display AC or AC+DC [3]		
Function	**Range**	**Resolution**	**DC**	**20 - 45 Hz**	**45 Hz - 1 kHz**	**1 kHz- 20 kHz**
DC mV	50.000 mV	0.001 mV	0.1% + 20	2 % + 80	0.5 % + 40	6 % + 40
	500.00 mV	0.01 mV	0.03 % + 2			
	3000.0 mV	0.1 mV	0.025 % + 5			2 % + 40
DC V	5.0000 V	0.0001 V	0.025 % + 10 [2]			
	50.000 V	0.001 V	0.03 % + 3 [2]			
	500.00 V	0.01 V	0.1 % + 2 [2]			Not specified
	1000.0 V	0.1 V	0.1 % + 2 [2]			Not specified
DC µA	500.00 µA	0.01 µA	0.25 % + 20	1 % + 20	1.0 % + 20	2 % + 40
	5,000.0 µA	0.1 µA	0.25 % + 2	1 % + 10	0.75 % + 10	2 % + 40
DC mA	50.000 mA	0.001 mA	0.15 % + 10	1 % + 20	0.75 % + 20	2 % + 40
	400.00 mA	0.01 mA	0.15 % + 2	1 % + 10	1 % + 10	3 % + 40
DC A	5.0000 A	0.0001 A	0.5 %+ 10	2 % + 20	2 % + 20	6 % + 40
	10.000 A [1]	0.001 A	0.5 %+ 2	1.5 % + 10	1.5 % + 10	5 % + 10

1. 10 A continuous up to 35 °C, less than 10 minutes 35 °C to 55 °C. 20 A overload for 30 seconds maximum.
2. 20 counts in dual display DC or AC+DC.
3. See AC conversions notes for AC mV and V



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