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Basic mathematical modelling for Polymer Woven Fabric performance suitable for low energy filtration systems

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Basic mathematical modelling for Polymer Woven Fabric performance suitable for low energy filtration systems

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DECLARATION

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Declaration letter:

I, Blessing Thokozani Mncube, declare that this dissertation work and the work presented in this thesis is original work. I have not made any foul play from other people/students work or from any other sources except were due referenced in the report.

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PREFACE

This research project was carried out at the Department of Chemical Engineering, Durban University of Technology (DUT), Process Energy and Environmental Technology Station (PEETS), and University of Johannesburg.

Water and wastewater used were from EThekwini Municipality, Durban Metro Southern Works, Veolia Plant, Umgeni River water, Bruma Lake water, City of Johannesburg wastewater treatment plant located next to Soweto, and Decentralized wastewater treatment system located at Newlands. This project was supervised by Prof. S. Rathilal and co-supervised by Professor V. L. Pillay.

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The team helped with stimulation, suggestions, and encouragement. My associate colleagues and mentors from the Durban University of Technology supported my research work. Everyone had input, support is highly appreciated.

DEDICATIONS

I dedicate this thesis to my friends, my family and my late parents.

ABSTRACT

Water is one of the most important and essential resources that people usually misuse and take for granted until it is either gone or unsuitable to be utilized for domestic, industrial or agricultural purposes. The need to explore affordable purification technologies is essential. The filtration processes are innovative technologies that can be employed in water treatment systems or water purification technologies. However, the filtration technologies have one prime limitation factor of which is fouling and biofilm formed on the membrane surface sometimes internal.

Recent advancements in polymer science and textiles have led to developing fabric material that can be used as membranes suitable for emerging economies. For years' people do use fabric to purify river water especially women from rural areas. Yet non-woven materials are used as a membrane by industries as compared to woven fabrics. However, most non-woven fabrics are easily damaged when cleaned with a polymer brush and require periodical replacement. The tapeline and filter manufacture use a woven fabric as a backer before casting or putting a filter on the weave fabric. These prove the fact that any woven fabric can be modified for optimal use.

On the other hand, most Engineers and scientists have not given much attention to woven fabrics as a result, woven fabrics are not employed as membranes. Some scientists and engineers believe that woven fabrics are not suitable for treating water for domestic use. Some believe that some woven fabrics can be used as membranes provided they are capable to remove unwanted materials like bacteria and pathogen.

The aim of this study is to create a full understanding of the factors that affect the fabrics when used as membranes, especially when the polymer woven fabrics are used as filters to treat water and wastewater. It is essentially important to develop standardized procedures or models that accurately describe the textile woven fabrics behaviour when used as filters. The standardized models or procedures will assist engineers and scientists when developing filtration systems using woven fabrics.

The first objective was to evaluate and compare the fabric types that can be used as filters or membranes in water and wastewater treatment processes. The second objective was to identify the applications for woven fabric membranes and evaluate the factors that play a critical role during the filtration process and relationship between those factors. The experimental investigations conducted were to evaluate the (1) main objectives; (2) effect of membrane orientation; (3) effect of feed quality on membrane performance; (4) effect on stable flux quality and quantity of the selected fabrics; (5) effect of fabric type on filtration or microfiltration processes; (6) effect of membrane fouling on membrane performance; (7) develop the basic model suitable in identifying the right fabric for any filtration system operating at low energy.

The experimental investigations conducted were to evaluate the selected woven fabrics that were manufactured in South Africa, easy to clean with a polymer brush. Those woven fabrics were tested using South African river water and wastewater from treatment plants. When evaluating different feed solutions, bio-fouling was considered to be the major limiting factor of woven fabrics, but the feed with a lot of bio impurities can be modified for optimization processes.

Laboratory apparatus and field apparatus was developed to analyze and evaluate the effect and behaviour of fabrics performance, and cake formed on the fabrics. The result clearly states that a solution or wastewater with a lot of biological organisms produce lower flux and also produces a lower critical/stable flux when compared with the solution with more incompressible solids or impurities. The result clearly shows that all selected fabrics can be used as filters however; the polyester fabric was the only fabric that can be used for microfiltration processes suitable to clean water for domestic use. This polyester fabric removes 99.995% of impurities from the polluted waters. The Permeate water quality coming from this polyester fabric was less than 1NTU, before and after stable flux. Other fabrics can be used as filters but not for microfiltration. These three fabrics are not capable of removing micro-impurities (less than 20 micrometres).

The basic mathematical modelling Equation developed, proved that the membrane pore size, driving force, impurities size in polluted water, impurities nature and impurities concentration play major roles in the filtration process especially in stable flux formation. The simple Equation

$\mathrm{F} = \mathrm{Ae}^{-\mathrm{Bt}} + \mathrm{C}$ was discovered to be suitable to evaluate the fabric performance, where *C* is the constant flux value, *A* is the maximum flux value and *B* is the part of the critical area or rate change. The Equation can be applied to most fabrics that are used as filters.

Testing the maximum flux value was critical and achievable when using pure and clean water especially the distilled water. The results show that most solutions with high compressible impurities will take less time to reach a critical or stable flux. The solution or effluent or river water with more bio impurities and more bacteria will have less flux when compared with a solution with more incompressible impurities.

Most polymer woven fabrics do not require any sophisticated technologies or additional chemicals to clean. It can be easily brushed with a polymer brush. Brushing the surface of the fabric with balanced tensile strengths in both warp and weft yarns will not rearrange, damage, or affect the pore size. Only sharp objects can damage the polymer fabrics.

The knowledge of this report will assist in optimising the filtration system operation at low energy when using woven polymer fabrics as membranes for filtration. The basic mathematical model can be useful to engineers and scientists willing to use woven fabrics as membranes. Hence, mathematical modelling is one of the important tools of engineering optimization and design.

This study focuses on the low energy (gravity-driven) systems that treat water and wastewater like Household Point of Use (POU) systems. Other POU systems were tested and compared to POU systems that are made of the Polymer woven fabric. Based on results, it can be concluded that POU's that uses polyester membranes (PWF-POU) are good prospects for area without sophisticated water or wastewater treatment systems since it removes almost all bacteria and impurities. Polyester woven fabrics can be used as a microfiltration membrane not only to process water or wastewater but also to process chemicals, oils, etc. The other selected fabrics that were made of polypropylene filaments need to be modification in order to operate at optimum when cleaning water for domestic and tertiary use. When modifying these polypropylene fabrics, the quality do improved.

NOMENCLATURE

Symbol	Definition	Units
J_C	Critical flux	LMH
J	Flux	LMH
Q_p	Volumetric flow rate	m^3/hr.
Am	Membrane area	m^2
ΔP	Differential pressure	kPa
µ	Viscosity	Pa. s
R_C	Cake resistance	m^{-1}
Rm	Membrane resistance	m^{-1}
R_t	Total membrane resistance	m^{-1}
Cp	Permeate salt concentration	mg/L
d	Diameter	m^2
∂	Density	kg/m^3
T	Time	hour
Z	Twist	m^{-1}
β	Angle	^{o}
Enl	Elongation	%
Q_P	Flow rate	L/hr
A_m	Membrane surface area,	m
ΔP	Transmembrane pressure	KPA
μ	Viscosity	kg/ms
P_{static}	Static pressure	Pa
$P_{filtration}$	Driving pressure	Pa
Δp	Pressure difference across the pore	KPA
l	Pore length.	m
N	Number of pores per square	-
E	Porosity	-

d_o	Diameter of the one warp yarn	m^2
d_u	Diameter of the one weft yarn	m^2
Du	Covered area per weft yarn	m^2
Z_o	Warp covering for warp	-
Z_u.	Warp covering for weft	-
D_m	Diameter of the yarn,	m^2
d_o	Half diameter	m^2
d_u	Half diameter of the yarn	m^2
t	Yarn	Tex
T	Bundle fineness	Tex
m	Fibre mass	kg
M	Fibre bundle mass	kg
l	Fibre length	m
L	Bundle length	m
ρ	Fibre density	kg/m^3
V	Fibre volume	m^3
A	Equivalent cross-sectional area of the bundle	m^2
s	Cross-sectional area	m^2
T	Multifilament yarn fineness bundle	tax
D	Equivalent fibre diameter	m^2
μ	Yarn packing density	%
V_f	Filament volume	m^3
V_y	Total yarn volume	m^3
V_c	Volume of the air	m^3
σ	Stress	Nm
d_o	Pore channel and diameter of the particle	m^2
ΔP	Driving force,	KPA
F_u	Capillary force,	KPA
F_g	Gravity force,	m

F_{yz}	Friction force,	Nm
δ_{yz}	Fabric compressibility force	KPA
Z	Membrane thickness.	m
ΣF,	External forces	KPA
R	Viscous drag per unit mass of the slurry	Nm
ρ_m	Slurry density	kg/m^3
Δt	Time change	min
dx= dg	Differential segment of warp yarn	m
dx	Gap between yarns	m
g	Gap Area	m^2
ρ	Material fibre density	kg/m^3
d	Equivalent fibre diameter	m^2
p	Fiber circumference	m^2
q	Fiber shape factor	-
a	specific fibre surface area	m^2
L	Total length of yarn	m
A	Total surface area of fibres m^2	
V	Total volume of fibres m^3	
V_c	Total volume of fibre assembly	m^3
V_p	Total volume of porosity	m^3
μ	Packing density.	-
Q_f	Feed flow rate	kg/hr
Q_r	Residue flow rate	kg/hr
Q_p	Permeate flow rate	kg/hr
Δx	Thickness of the membrane	m
x_f,	Feed concentration	%
x_p	Permeate concentration	%
x_o,	By-product concentration	%
ε	Fraction pore area	-

k_2	Constant factor	-
p_s	Concentration in the permeate	%
$C_1 = A$	Initial flux or maximum flux	LMH
$k = B$	Rate of separation	-
$J_o = C$	Minimum flux of stable flux	LMH
t_o	Initial time	s
n_p	Number of pores	-
C_m	Concentration of fouling particles	mol/m^3
R_m	intrinsic membrane resistance	m^{-1}
K	Twist intensity	-
Θ	Helix angle of the yarn	^{0}

ABBREVIATIONS

BOD	Biochemical oxygen demand
COD	Chemical Oxygen demand
DEWATS	Decentralized Wastewater Treatment Systems
DOC	Dissolved organic matter
DO	Dissolved Oxygen
DUT	Durban University of Technology
DWAF	Department of water affairs
MF	Microfiltration
MLSS	Mixed Liquor Suspended Solids
MWCO	Molecular weight cut-off
NF	Nanofiltration
NTU	Nephelometric Turbidity Unit
NRF	National Research Fund
PET	Polyester
PETE	Polyester
RO	Reverse osmosis
SS	Suspended solids
TMP	Tran membrane pressure
PDCO	Pore size diameter cut off
R&D	Research and Development
TSS	Total suspended solids

TOC	Total organic carbon
PDCO	Pore size diameter cut off
POU	Point of use
PWF	Polymer woven fabric
PVC	Polyvinylchloride
POP	Polypropylene
UKZN	University of Kwa Zulu Natal
UJ	University of Johannesburg
UF	Ultrafiltration
WHO	World Health Organization
WFM	Woven fibre microfiltration
WFMFM	Woven Fabric Micro Filtration Membrane
WFM	Woven fibre microfiltration
NTU	Number of Transfer Unit

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CHAPTER 1.

INTRODUCTION

1.1. Background

Water is one of the most important and essential resources that people usually misuse and take for granted until it is either gone or unsuitable to be utilized for domestic, industrial or agricultural purposes (Jurkowski, 2008). Water is a necessity of life not only to humans but also to every living being, animals and plants. Water is used to produce power, grow food, manufacture goods etc. Water is fundamental for all life. Without water, no person, plant, animal or living organism can survive (DWAF, 2007; DWAF, 1996). Water is also a habitat to a number of animals and plants. If the surface water is polluted, those animals and plants living in polluted water will be destroyed.

According to the WHO (2012) Joint Monitoring Programme report, more than 700 million people in the world do not have safe drinking water and more than a billion people do not have good sanitation systems. More than a billion people with improved drinking water do not have access to a source that is microbiologically safe to drink (Onda et al., 2012; Bain et al., 2012). For any economy the water treatment is essential. Water and wastewater treatment facilities are needed to grow the economy and protect the environment with its biodiversity. The access to microbiologically and chemically safe water is limited not only in developing countries but also in transition countries and even in remote areas of developed countries (Varbanets et al., 2007).

Globally, there is a water crisis caused by climate change, population growth, pollution and lack of right technologies that can assist for optimum use of water. Water users such as domestic end users, farmers, and industries are forced to look at other means of utilizing water effectively and developing other technologies that can contribute toward water reclamation (WHO, 2007).

Providing access to good, clean sanitation systems into households is the ideal solution to improve people health and limit water pollution. However, the high capital and maintenance costs of piped systems mean that safe piped water and wastewater pipe systems are likely decades away for many emerging and underdeveloped countries especially in rural areas and informal settlements. In many emerging and underdeveloped countries, this issue of safe drinking water is prioritized as compared to sanitation issues. The history shows that humans have been treating drinking water through filtration, boiling and disinfection for centuries (Sobsey, 2002).

The current technologies used for water and wastewater treatment are failing to cope with the demand and most of these technologies are too old to address the ever-evolving challenges within the emerging economy where most people are not skilled and a lot of energy is needed to drive these wastewater and water treatment facilities. Some studies have shown that filtration practices yield improvements in drinking water quality (Sobsey, 2002).

Membrane filtration is one of the technologies that are more favourable and used by most industries that deal with liquid processing. Petrochemical industries, water industries, alcohol industries, food and beverage industries use membranes in the filtration processes. Membrane technologies are capable of removing unwanted materials from the wanted liquid or removing unwanted liquid from the wanted material. Such membrane technologies are widely used in water purification, wastewater treatment, food processing, and medicine separation (Chen and Kim, 2006)

Most water and wastewater treatment facilities have three major process sections. These sections are physical separation, biochemical separation and chemical separation. If membranes are selected correctly, each and every section in water and wastewater treatment facilities can be replaced or optimised by membrane technology. Membrane technology can also be implemented to household’s decentralised systems.

Due to polymer science and technical textile improvement over the years, polymer textile fabrics can also be used as membranes. There are many types of fabrics in general, grouped into two groups. The first group is non-woven fabrics and the second group is woven fabrics. Non-woven fabrics are made of filaments bonded together using mechanical, thermal bonding, sometimes chemical bonding and more. Woven fabrics are made of filaments bonded together to form yarns and yarns are weaved together to form a fabric. Both processes of forming a yarn and fabric are mechanical. Looming machines are used to manufacture the fabrics. Spinning machines are used to manufacture yarns.

The filaments or fibres used to form the fabric are also grouped into two groups. The first group is manmade fibres and the second group is natural fibres. The natural fibres are fibres from plants and animals like cotton and wool. The manmade fibres are polymer filaments like polypropylene and polyester fibres. Some filaments are hydrophilic, some are hydrophobic. Other properties like acidic, alkali, specific gravity, bacteria do affect the filaments. Some bacteria feed on filaments, some filaments dissolve in acidic solution and others in alkali solution.

There have been various attempts to use fabrics as membranes for filtration processes in water and wastewater treatments. Some people have reported that fabric membranes perform well and some people have to criticize fabric membranes for poor performance in water and wastewater treatment. The contradiction is also noticeable in rural areas from underdeveloped and emerging countries. Some women that are still getting water from rivers and lakes use fabric or cloths to screen water, preventing the impurities to enter the water container. Some people drink that water without adding any disinfection. Some women get home after collecting water and add the disinfection or boil it before consuming.

The major challenge or problem is the right tool or right methodology that can be used to select a suitable fabric membrane for a specific application and standardise the right protocols that will prevent people from consuming water full of dangerous impurities like bacteria.

However, there are characteristics within the filtration process that need to be defined in order to develop the standardized methodology and suitable tools for fabric membrane selection. These characteristics can play a major role. Some of these focus on fabric characteristics, some on yarn characteristics, some on filament characteristics and some on fluid quality and quantity.

Generally, there are no uniform design criteria that can be used to ensure the removal efficiency of a membrane process. Dynamic testing is required to demonstrate the ability of a membrane or fabric membrane process to remove a specific target organism or pollutants (EPA, 2006).

The focus of the study was to do a survey of materials used as membranes for filtration and to evaluate the performance of the selected woven fabrics used as membranes for filtration. Most woven membrane materials are dependent on yarn characteristics and type of loom machine used to manufacture the fabric. The yarn twist also pays the critical role as well as the nature of the yarn formation and the capability of the loom machine to produce the required fabric that can be used as filtration membranes. The properties of polyesters and polypropylene filaments like strength, durability, cost, etc. makes the polyester and polypropylene material the most widely used polymers. The geometry of Non-woven and woven fabrics have considerable effects on filtration behaviour.

The woven fabric made from fine twisted polymer filaments can produce a thin layer material that can replace Non-woven fabric materials. Most Non-woven fabrics are bulky and have high fabric density and lower tenacity when compared to woven fabrics. Most of the Non-woven membranes cannot be cleaned with a polymer brush because any friction forces damage the membrane structure and performance. Maintenance costs of changing the Non-woven membranes are high. There is a need to evaluate the polymer woven materials with respect to fouling and productivity to ascertain its sustainability and this is the scope of this study. Noticeable so, some fabrics will be suitable for treating water for domestic use, some fabrics will be suitable for industrial use, and some fabric will be suitable for farming use especial irrigation use and more.

1.2. Objectives and motivation

The aim of this study was to create a full understanding of the factors that affect the woven fabric when used as filtration membranes. In general, it is assumed that most scientists and engineers prefer non-woven fabrics to be used as membranes for filtration systems. In history, woven fabrics were used for many years by the woman from rural areas to remove impurities from surface water. However, the used fabrics were not tested for filtration or microfiltration and never met the filtration requirements. As a result, most scientists and engineers stopped focusing on woven fabrics.

Some scientists and engineers claim that woven fabrics are not capable for filtration operation at low energy and some scientists and engineers argue and believe that in the near future, some woven fabrics can clean water better than non-woven materials. One of the biggest problems of using woven or non-woven fabrics as membranes for purifying water is the decay of permeate flux, which is caused by the phenomenon known as fouling (Cardoso de Oliveira et al., 2012). Cleaning the fouled material required physical or chemical or other sophisticated methods. When creating a system for emerging and underdeveloped economies, the developed system must operate at low energies and be able to be cleaned without applying any expensive methods or chemicals.

The first objective was to evaluate and compare the fabric types that can be used as filtration membranes in water and wastewater treatment facilities. The criteria that was used was permeating quality and flux evaluation and this includes the cleaning protocols for fabric membranes. Reliability, durability, availability, flux behaviour, cleaning protocols, and performance are among the factors that form part of the study.

The second objective was to identify the applications for woven fabric membranes and to evaluate the factors that are playing the major role during the filtration process. This also included the development of a detailed methodology or tools that can assist in evaluating fabrics and possible applications and identifying the suitable application for a particular fabric membrane.

When engineers and scientists do understand the membrane performance better, it will minimise the technical risks that are currently inherent in the filtration technologies and systems. It is very important to develop the standardized models that accurately describe the textile woven fabric behaviour when used as membranes. This is particularly important for fabric membranes, which are usually competing with well-understood traditional separation techniques. Appropriate modelling offers important information about design, optimization, and the economics of membrane units (Shamsabadi et al., 2012).

For fabric membrane technologies to be complete, it is necessary to gain a greater understanding of the fabric membrane performance. At present, most non-woven materials used as membranes have surface and internal separation techniques, making it difficult to reuse and are disposed of when fouled. Bio-fouling was considered to be the major limiting factor of woven fabrics, but the feed with a lot of bio impurities can be modified for optimization processes (Xiao et al., 2013).

For better and more reliable membrane systems to be implemented without the need for time-consuming experimental and pilot studies, accurate and reliable simulations and the development of standardized models or methodologies will be useful. This requires a mathematical modelling approach (Marriott, 2001).

1.3. Approach

The first objective was to evaluate and compare the fabric types that can be used as filtration membranes and microfiltration membrane in water and wastewater treatment facilities or systems. It is possible to evaluate and compare the fabric types that can be used as membranes by identifying and analysing the fabric characteristics that affect membrane performance. The laboratory experiments assisted in minimising the external effect. The field experiments provided us with true data with all internal and external effects present. Both field and laboratory setups had cross flow and dead-end filtration processes. The laboratory experiments were critical in providing the operation effect including the stable flux occurrence. The field work experiment was also critical in providing the behaviour of the membrane in the real-life condition. All the selected fabrics for the study were from South African textile manufactures.

The second objective was to identify the applications for fabric membranes by evaluating the factors that play a major role during the filtration process and analyse the relationship between those factors. The main goals of the study are as follows:

- Develop an approach suitable for fabric selection for filtration or microfiltration systems;
- Evaluate the effects of weave fabric membrane orientation;
- Evaluate the effects of feed quality on membrane performance;
- Identify the factors that affect the stable flux quality and quantity of the selected fabrics;
- Evaluate the effect of membrane fouling on membrane performance and;
- Develop a new approach to membrane microfiltration or filtration processes and fouling control in order to develop a membrane-based system using synthetic fabrics as membranes suitable for water and wastewater treatment systems. That can be used by developing or/and transition countries and identify other applications for woven fabric membranes including developing the basic mathematical model suitable in identifying the right membrane for any filtration system operating at low energy.

1.4. General research questions

Based on theory, what are the major limitations of fabric membranes used in filtration or microfiltration processes, and the available filtration systems?

- What are the operation effects on low energy filtration systems?
- What are the effects of the natural feed on fabric membrane performance?
- Does the fabric structure play a part in fabric membrane performance?
- What factors affect permeate quality and quantity?
- What are the effects of fabric orientation and structure?
- What mathematical expressions can be used to express the flux curve?
- What approaches or protocol can be used to select the fabrics for microfiltration or filtration systems?
- What are the mechanisms of flux stabilization?
- What factors affect the resistance of the fouling layer during the filtration process?
- What best, cheap, reasonable cleaning protocol is more suitable in removing the fouling layer?
- What is the best fabric membrane that is suitable for particular systems?

1.5. Outline of the thesis

In Chapter 2, a review of the literature on water scenario in our societies, impurities polluting water resources, membrane technology, fabrics, yarns, and fouling effects are discussed. Advantages and disadvantages of water and wastewater treatment systems employed to purify water and minimise pollution are also discussed. This Chapter also focuses on technical textile engineering and filtration including differences between natural and manmade filaments.

Chapter 3, identifies a woven fabric and apparatus for the study.

In chapter 4, the properties of the selected fabrics evaluated.

Chapter 5, evaluates the effect of feed quality on membrane performance.

In Chapter 6, the effect of particle characteristics and surface pore blocking on membrane performance is evaluated.

In Chapter 7, the basic mathematical modelling for the woven fabric used as the filtration membrane is developed and discussed.

In Chapter 8, the possible applications for woven fabric membranes and outlined.

Chapter 9, provides the conclusion and

Chapter 10, gives the recommendations for further studies.

CHAPTER 2.

LITERATURE REVIEW

2.1 Water scenario in our societies

Water is a necessity of life not only to humans but also to all living things that include animals, plants and living cells. Water is used for many purposes that include consumption, to produce power, grow food, and manufacture goods and more. (DWAF, 2007; Venture, 2007)

Access to microbiologically and chemically safe water is limited not only in developing countries but also in transition countries and even in remote areas of developed countries (Varbanets et al., 2007).

Water is withdrawn from water sources, processed and made suitable for domestic, industrial, agricultural use and more. After using water, a huge fraction of the used water ends up in wastewater treatment plants before the effluent is discharged into the environment, lakes, or streams, while others are discharged illegally into the environment without any form of treatment. Another small fraction is consumed by nature and evaporates to the atmosphere. Any discharge of waste to the environment has a negative impact to nature and thus causes pollution (WHO, 2012).

About 75% of the earth's surface is covered by water. The distribution of water on the earth is based on human economic needs for freshwater. About 97% of all water is in the oceans. Freshwater accounts for only 3%. Nearly 69% of the freshwater is locked up in glaciers, ice caps and permanent snow cover of both poles, mountainous regions and in Greenland, while 30% of freshwater comes from groundwater.

Only 0.3% of the freshwater on earth is contained in river systems, lakes and reservoirs, which is the water people are most familiar with and the most accessible water source to satisfy human needs in daily lives (Liu, 2011). Adding to accessible water, agriculture accounts for more than 70% of that small fraction of global water use (Alder et al., 1987; Jiu and Fu 2011; Jurkowski, 2008).

Due to climate change and population growth, freshwater is becoming scarce(WHO, 2012). There is a need to come up with technologies that can assist in water optimisations.

2.1.1. MAJOR CHALLENGES

More cleanly fresh water is needed due to population and economic growth. At present, more than one billion people lack access to improved drinking water to a required domestic standard. Microbial pollution as bacteria, viruses, protozoa, or larvae is the main hazard to drinking water and affects the quality so as the suspended solids. On the other hand, water is needed to transport waste. According to the WHO (2012) Joint Monitoring Programme report, more than 700 million people in the world do not have access to safe drinking water; more than one billion people do not have good sanitation systems. Hundreds of millions of people with improved drinking water do not have access to a source that is microbiologically safe to drink (Onda et al., 2012; Bain et al., 2012).

Good Financials, institutional and informational capacity remain the majority issues in developed countries yet skill capacity issues are also added in emerging countries and in underdeveloped countries to address the water and sanitation issues.

Providing access to safe, pathogen-free, reliable piped water supplies into households are the ideal solution to water-borne illness. Providing access to good, clean sanitation systems into households is the ideal solution to improve people health and limit water pollution. However, the high capital and maintenance costs of piped systems mean that safe piped water is likely decades away for many emerging and underdeveloped countries especial in rural areas and informal settlements.

In many emerging and underdeveloped countries, a safe drinking water issue is prioritized as compared to sanitation issues. The history shows that humans have been treating drinking water through filtration, boiling and disinfecting it for centuries (Sobsey, 2002).

Ignoring the sanitation issues is a lot more dangerous to the environment. Scientists claim that more than one billion people do not have good sanitation. Good sanitation needs water for transporting human waste and treating it. Poor sanitation and lack of innovation within the sector leads to environmental pollution.

2.2 Impurities pollute water and water sources

Water is becoming scarce not only in arid and drought-prone areas but also in regions where rainfall is abundant. Water scarcity concerns the number of resources available and the quality of the water because degraded water resources become unavailable for more stringent requirement (Santos et al., 2002).

In order to address the water scarcity issues, the need for protecting the available water and coming up with technologies capable of water reuse must be a priority. Protecting available water means utilising water effectively and minimising pollutants going into water and water sources. Coming up with technologies capable of water reuse means the used water or wastewater needs to be processed and reused without being discharged to the environment or into water and water sources.

Human, animal and plants pollute water, by contaminating water with impurities that are not supposed to be in the water. However, human impurities are more distractive to nature if disposed of carelessly. Water resources like rivers, lakes, underground aquifers, and other sources are polluted on a daily basis, affecting the life of organisms that are depending on water for survival. Human waste, animal waste, industrial chemicals, pharmaceuticals, and other types of pollutants in most cases contaminate water sources (Jurkowski, 2008).

2.3 Innovation needed to address the water pollution issues

In order to address the water scarcity issues, the need for protecting the available water sources needs and the need to clean the polluted water needs to be prioritised. Thus, engineers and scientists have to develop innovative solutions to make water potable, safe to drink by solving limitation factors within the current technologies used to purify water (Jurkowski, 2008).

Most water needs to be reused so that lesser amounts of waters are drawn from water sources. The drawn water from the water sources needs to be recycled and used optimally. The major challenge in recycled water is to process or purify the polluted water into a required specification. The wastewater stream needs to be treated before recycled for optimum use, or to minimise water to be discharged into the environment, lakes, river streams and water bodies like dams. Discharging wastewater illegally into the environment without any form of treatment has a negative impact on nature and causes pollution.

Most storm water drainage systems do not have any form of protection or treatment systems, and most waters from storm water systems end up discharged into the environment without any form of treatment. In the cities or urban areas, automotive activities and humans' activities are major sources of pollution and most of these pollutants end up in the storm water drainage system and water sources.

It is possible to develop systems or technologies that are capable to clean water by removing the unwanted materials like solid waste, microbiology and suspended solids from water. The technologies or systems that are needed in today's pollution dynamic must be capable of processing the wastewater and river water and produce water that is suitable for primary or secondary or tertiary purposes.

2.4 Water and wastewater treatment fundamentals

Today, pollutants are revolving daily to adapt with revolving science. People are genetic engineering or modifying food, chemicals, pharmaceutical chemicals, petrochemical chemicals and more. All the engineered products force some bacteria to revolve too in order to adapt to certain conditions. Some bacteria and revolved bacteria are harmful to humans, animals and plants but some bacteria are more important to biological food chains and biological systems. Most bacteria that are more dangerous to nature are genetically modified bacteria that are formed by human activities that are contradicting the laws of nature. These harmful bacteria are found in water and some are found in wastewater. Today engineers and scientists agree that bacteria evolve daily, however, some believe that revolved bacteria are good for ecosystems and others dispute these claims.

2.4.1 DOMESTIC WATER AND WASTEWATER

Domestic water and wastewater treatment technologies have to guarantee the required quality of treated water or effluents for its final use. For wastewater treatment, this depends on whether the treated effluent will be reused or discharged to the environment. However, state institutions are designed to standardise the water qualities in order to protect nature, humans, animals, and plants.

There is a high number of existing wastewater treatment processes that are capable yet other treatment systems or facilities are still failing to meet the regulatory requirements in treating water and wastewater. Most water and wastewater treatment facilities in South Africa are not capable of producing water suitable for domestic use. Some water treatment facilities still supply drinking water but the quality is compromised due to lots of factors that involve skill issues, technology issues and more.

Currently, the sanitation needs and population growth is one of the major concerns within water and wastewater framework in South Africa. Most wastewater contains human biological waste, chemical wastes that include pharmaceutical chemicals and required adequate time to process alien pollutant and human biological waste.

The human biological waste gets mixed up with natural and manmade impurities sometimes before or after or during processing. Some impurities are organic and some are inorganic compounds and some react to create a good environment for bacteria and viruses to produce and reproduce in numbers. Some of the engineered bacteria and viruses are extremely dangerous and destructive to nature and also to water or wastewater treatment processes. The variations of impurities in the domestic water and wastewater treatment plants have a negative impact on most water and wastewater technologies (Nguyen and Juang, 2013).

Since domestic wastewater and water treatment systems were designed to improve the hygienic standard of people, the older technologies are failing to cope with the demand caused by population growth and urbanization. When the technology fails, the standard is compromised and that technology needs to be replaced or modified. There is a need to have some technologies that do not depend on bacteria for treating waste or pollutant.

2.4.2 INDUSTRIAL WASTEWATER

Industrial wastewaters are more complex compared to domestic wastewater. Industrial wastewaters often contain bio refractory or troubling compounds. Industrial wastewater treatment plants because of their resistance, inhibitory character, or toxicity cannot directly treat bio refractory substances. Accordingly, industrial wastewaters often have to be treated by non-conventional technologies that are able to render them adequate for their final use. The industrial wastewater may contain phenols, surfactants, pesticides, aromatic hydrocarbons, bacteria, genetically modified chemicals and engineered bacteria these problematic compounds in industrial wastewater.

The industrial wastewater substances are toxic non-biodegradable organic pollutants that do not react on biological reactions instead; they destroy some bacteria that are useful in the facilitation of that reaction.

These pollutants need to be removed to avoid associated environmental pollutions. Phenols are crystalline solids at ambient temperature. Surfactants are chemicals designed for cleaning and solubilisation properties. Their molecules have a polar head group (charged or uncharged) and a non-polar hydrocarbon.

As stated by Leung (2007) surfactants are commonly classified according to their ionic properties and thus grouped as anionic (negatively charged), cationic (positively charged), non-ionic (uncharged) and amphoteric (either positively or negatively charged depending on the pH).

Surfactants are used in cleaning and personal care formulations, textiles, household and industrial detergents, paints, polymers, pesticide formulations, pharmaceutical, mining, oil recovery and pulp and paper industry.

Surfactants containing wastewater directly discharged to the river cause foam formation and may origin anomalies to algae growth and toxicity to aquatic organisms. In addition, most companies use a lower grade of water quality for heat transfer purposes (cooling and heating an industrial system) (Jurkowski, 2008).

2.4.3 CONVENTIONAL WATER AND WASTEWATER TREATMENT

Conventional water and wastewater treatment systems consist of chemical, physical, and biological processes. Conventional water and wastewater treatment systems are domestic use processes. The main aim of these processes is to remove unwanted material and neutralise water to some acceptable standards for consumption and discharging to the environment. The conventional water and wastewater treatment systems are vital for humans and nature including the economy.

Oskam (1995) summarized the self-purification processes that improve water quality in off-stream reservoirs.

Table 2.1: Purification processes that improve off-stream water quality

Type of process	Effects
Physical	Equalization of peak concentrations (e. g. chemicals, microbes)
	Exchange of oxygen and carbon dioxide with the atmosphere
	Evaporation of volatile substances (e. g. solvents)
	Settling of suspended solids and adsorbed substances (e. g. turbidity, heavy metals)
Biological	Biodegradation of organic substances
	The die-off of faecal bacteria and viruses
	Nitrification of ammonium to nitrate
	Denitrification of nitrate to nitrogen
	Phosphorus elimination by phytoplankton uptake (in pre-reservoirs)
Chemical	Oxidation of divalent iron and manganese
	Hydrolysis of polyphosphates and organic esters (e. g. phthalates)
	Photolysis of humic substances and poly-nuclear aromatic hydrocarbons

Adapted from Oskam (1995)

2.5 Objective of water and wastewater treatment

Treatment systems are designed to clean water for a required desire. Some water treatment systems clean water for consumption purpose or domestic purpose, some for agricultural purpose, some for industrial purpose, and some for discharging purposes and more.

Most municipalities have water treatment facilities and wastewater treatment facilities. In addition, water products from these treatment plants are used for different purposes and must be in line with local and international water regulation acts or bylaws (DWAF, 2007).

South African water sector is faced with lots of challenges like technology, water loss, skilled people and more. The drastic increases in water demand and huge amounts of wastewater produced by human activities have a negative effect on the sector and also the economy. The climate change has also negativity affected South African rainfall patterns, as a result, the country is facing drought in most regions.

SA and international by-laws apply to all municipalities in South Africa who have to monitor their water quality and quantity. Currently, not all municipalities comply on a continuous basis due to a lack of skill, funding, management capacity and more (DWAF 2007).

The existing water and wastewater treatment systems are failing to cope with demand in South Africa and also in other developing, emerging and underdeveloped countries that are faced with the same challenges. The technical input to optimise these failing processes to meet the current demand is needed. Intensive labour in research and development is needed for designing, testing and installing efficient and inexpensive water and wastewater treatments processes or technologies.

More effort is needed to minimise water loss, minimise pollution, improve the technologies, and promote recycle water so that less water will be drawn from the surface and underground water bodies or sources.

Water treatment systems, especially gravity-driven systems and sand filter systems were developed a long time ago. For years, the common water treatment systems were safe and performing optimally. Today, most of the older systems or technologies are failing due to a number of factors. The water demand is higher than before. Pollution and impurities found in water are higher and more complex than before (Peter-Varbanets et al., 2009).

Most treatments require chemical addition to speed up the treatment process. However, considerable technological development and chemical addition in the systems cannot solve health issues and prevent people from getting sick or causing damage to the environment.

Wastewater treatment systems, especially the conventional septic systems have been used worldwide since the 1900s, mostly in low densely populated areas. However, considerable technological development in the systems cannot be seen to be up-to-date. Further, sedimentation and anaerobic biodegradation are the two fundamental treatment processes involved in the removal of suspended solids and 60-80% and 30-50% BOD removal can be achieved from this system.

In South Africa, there are a number of factors that make a conventional treatment system fail to perform at optimum. In addition, these factors are lack of maintenance, unfavourable site topography and soil characteristics, poor construction design, and inadequate capacity. Consequently, odour and vector problems, as well as surface and groundwater pollution, may occur including death (Bornare et al., 2014).

Decentralised Wastewater Treatment Systems (DEWATS) is another form or system designed to clean wastewater in urban and rural areas since the conventional centralised and decentralised wastewater treatment systems are limited and fail to meet the rapidly growing demand. DEWATS is an alternative system that provides solutions. DEWATS provide treatment for wastewater flows with close COD/BOD ratios from $1m^3$ to 1000 m^3 per day, per unit.

DEWATS can treat wastewater from domestic and some industrial applications especially bio-industries. DEWATS has the primary, secondary, and tertiary treatment for wastewater from sanitation facilities, housing colonies, and public entities like hospitals, or from businesses, especially those involved in food production and food processing. DEWATS are reliable, has greater longevity and tolerance towards inflow fluctuation, cost-effectiveness and, most importantly, low control and maintenance requirements. DEWATS usually function without technical energy inputs. However, the systems do have a limitation when it comes to bacteria removal as stated by Ludwig (1998).

Anaerobic Digestion and Aerobic Digestion is a biological process that happens naturally when bacteria break down organic matter with oxygen or no oxygen present during the reaction. It is effective and requires full-time operation and maintenance. Almost any organic material can be processed with digestion reactors. An astonishing one-third of the world population does not have access to basic sanitation and over one billion people defecate out in the open. In light of the evidence, the world community is making progress in the water sector, however, sanitation is typically the neglected half of the water sector and the sanitation challenge is continuing to create pollution (Rijsberman and Zwane 2012).

There is an imbalance of water supply; water needed for consumption for domestic use, industrial use, agricultural use, and water required by nature at large. The potential danger to health issues due to pollutants that are in the water is another problem that the water sector is facing and needs to be addressed as well as water management and climate change.

Some water pollutants are harmful and can destroy some animal and plant species that depend on water for survival. Furthermore, water and wastewater treatment plants should be balanced to the water-supplied matrix in order to recycle water for optimum use. The existing technologies need to be modified in order to balance water demand with water supply so that water can be shared fairly with animals, plants and humans.

2.5.1. Elements found in Polluted Water

The composition of untreated water from water sources varies drastically. Surface water is more polluted then groundwater (DWAF, 1996). Surface water and underground water contains lots of pollutants, compounds, materials that can be group into the following:

- Water
- Pathogen
- Organics
- Inorganic
- Animals
- Plants
- Gases

2.5.2. Elements found in wastewater

The composition of untreated wastewater varies drastically depending on the type of waste source. Wastewater may contain the following:

- Water
- Pathogen
- Organics (soluble and insoluble)
- Inorganic (soluble and insoluble)
- Animals
- Plants
- Gases
- Poisons
- Pharmaceutical chemicals

2.5.3. Elements of treated water

There are acceptable key parameters that are standardised and depend on water usage. Most treatment systems operate within those parameters, more strictly for water intended for domestic use than water for industrial and agricultural purposes.

2.6 Impurities found in polluted water

It is not possible to understand the system without understanding the impurities that need to be removed in domestic water and in wastewater including the impurities that need to be removed in industrial wastewater.

2.6.1 *SOME BACTERIA AND VIRUSES COMMONLY FOUND IN POLLUTED WATER.*

Bacteria are impurities that are found in untreated water. There are a number of bacteria found in polluted water. For water to be used or discharged to the environment, most of these bacteria need to be totally removed. Some bacteria family trees are as follows:

2.6.1.1 *Actinomycetes*

Actinomycetes are a diverse and large group of gram-positive filamentous and branching bacilli. Actinomycete organisms are bacteria that affect the quality of water. Actinomycete organisms can cause a variety of infections. They may be soil organisms and/or water organisms, which have characteristics common to bacteria and fungi. In the strict taxonomic sense, actinomycetes are clubbed with bacteria in the same class of Schizomycetes but confined to the order of Actinomycetales (Abdelhafez et al., 2012).

Actinomycetes differ from fungi in the composition of their cell wall. They do not have chitin and cellulose, which are commonly found in the cell walls of fungi. The number of actinomycetes increases in the presence of decomposing organic matter. As a result, they are intolerant to acidity and their numbers decline at pH 5.0. The most conducive range of pH is between 6.5 and 8.0. Temperatures between $25^{o}C$ and $65^{o}C$ are conducive for the growth of actinomycetes (Abdelmohsen et al., 2015).

2.6.1.2 *Protozoa*

Vaerewijck and Houf (2015) and Rodriguez-Morales and Castaneda Hernandez (2014) and other scientists agreed that Protozoa is a diverse group of single-cell organisms defined as the first animal. Thus, the ecological role of protozoa in the transfer of bacterial and algal production to successive trophic levels is important. As predators, they prey upon unicellular or filamentous algae, bacteria, and micro-fungi.

They also control bacteria populations and biomass to some extent. Protozoa can survive harsh conditions, such as exposure to extreme temperatures or harmful chemicals, or long periods without access to nutrients, water, or oxygen for a period. Being a cyst enables parasitic species to survive outside of a host, and allows their transmission from one host to another. Protozoa can reproduce by binary fission or multiple fission. Some protozoa reproduce sexually, some asexually, while some use a combination. Protozoa play a useful role in the food chain as a source of food for other bacteria, fish, and other animals. Some protozoa are helpful to humans by eating dangerous bacteria. Unfortunately, other protozoa are parasites and can be harmful to humans by transmitting diseases.

2.6.1.3 *Coliform bacteria*

Coliform bacteria are a commonly used bacterial indicator of sanitary quality of foods and water. They are defined as rod-shaped gram-negative non-spore forming bacteria, which can ferment lactose with the production of acid and gas when incubated at 35°C - 37°C. Coliforms are abundant in the waste of warm-blooded animals, but can also be found in the aquatic environment, in soil and on vegetation, while coliforms are themselves not normally causes of serious illness (Enger et al., 2013).

They are easy to culture and their presence is used to indicate that other pathogenic organisms of faecal origin may be present. Faecal pathogens include bacteria, viruses, or protozoa and many multicellular parasites.

2.6.1.4 *Rotifers*

Rotifers are microscopically bacteria found in any wastewater. Most rotifers are around 0.1 – 0.5 mm long although their size can range from 50 µm to over 2 millimetres and are common in freshwater environments throughout the world. About 25 species are colonial and an important part of the freshwater zooplankton, being a major food source and with many species also contributing to the decomposition of soil organic matter. Rotifers egg can survive the extremely harsh conditions (Wallace and Snell 2010).

2.6.1.5 *Nematodes*

Nematodes or roundworms are bacteria mainly found in the sea, fresh water, and sand. Nematodes are the most diverse and one of the most diverse of all animals. Nematode species are very difficult to distinguish; over 28,000 have been described of which over 16,000 are parasitic. It has been estimated that the total number of nematode species might be approximately more than 1,000,000. It has a digestive system that is like a tube with openings at both ends. Nematodes are mainly found in the sea, fresh water, sand and plants (Singh et al., 2015).

2.6.1.6 *Filamentous organisms*

Filamentous organisms are bacteria. Having a certain amount of filamentous organisms is advantageous because in comparison to the floc-forming bacteria they achieve more efficient nutrient uptake. Furthermore, their prolate build supports their feature to catch floating particles. These advantages front the disadvantages of a lower sludge settle ability, which increases the costs of sludge treatment drastically.

Increased development of filamentous microorganisms causes two extremely undesirable phenomena; bulking sludge and floating sludge.

2.6.2 *UNDISSOLVED AND SUSPENDED SOLID MATERIALS FOUND IN POLLUTED WATER*

2.6.2.1 *Turbidity and Sediment*

Turbidity in the water is suspended insoluble matter including coarse particles (mud, sediment, sand etc.) that settle rapidly on standing.

2.6.2.2 *Sodium and potassium Salts*

These are extremely soluble in water and do not deposit unless highly concentrated. Their presence is troublesome as they are alkaline in nature and accelerate the corrosion.

2.6.2.3 *Chlorides*

Majority of the chlorides cause increased corrosive action of water.

2.6.2.4 *Iron*

Most common soluble iron in water is ferrous bicarbonate. The water containing ferrous bicarbonate deposits becomes yellowish and reddish sediment of ferric hydroxide if exposed to air.

2.6.2.5 *Manganese*

It also occurs in a similar form as iron and it is equally troublesome.

2.6.2.6 Silica

Its presence is highly objectionable as it forms a very hard scale in boilers and forms insoluble deposits on turbine blades.

2.6.2.7 Microbiological Growths

Various growths occur in surface water (lakes and rivers). The microorganisms include diatoms, moulds, bacterial slimes, algae, manganese, and sulphate reducing bacteria and many others. These can cause the coating on heat exchangers, clog flow passages, and reduce heat transfer rates.

2.6.2.8 Colour

Surface waters form swampy areas and become highly coloured due to decaying vegetation. Colour of the feed water is objectionable as it causes foaming in boilers and may interfere with treatment processes. It is generally removed by chlorination or adsorption by activated carbon.

2.6.3 *DISSOLVED SALTS AND MINERALS*

2.6.3.1 *Calcium and Magnesium Salts*

The Calcium and Magnesium salts present in the water in the form of carbonates, bicarbonates, and sulphates and chlorides. The presence of these salts is recognized by the hardness of the water (hardness of water is tested by the soap test).

2.6.4 *DISSOLVED GASES*

2.6.4.1 *Oxygen*

It presents in surface water in a dissolved form with variable percentages depending upon the water temperature and other solid contents in the water. Its presence is highly objectionable as it is corrosive to iron, zinc, brass and other metals. It causes corrosion and pitting of water lines and boiler exchangers. Its effect is further accelerated at high temperatures.

2.6.4.2 *Carbon Dioxide*

It also causes corrosion of stream, water, and condensate lines. It also helps to accelerate the corrosive action of oxygen.

2.6.5 ***OTHER MATERIALS (AS OIL, ACID) EITHER IN MIXED OR UNMIXED FORMS.***

2.6.5.1 *Free Mineral Acid*

Usually present as sulphuric or hydrochloric acid and causes corrosion. The presence is reduced by neutralization with alkalis.

2.6.5.2 Oil

Generally, the lubricating oil is carried with steam into the condenser and through the feed system to the boiler. It causes sludge, scale, and foaming in boilers. Strainers and baffle separators generally remove it. The effects of all the impurities present in the water are scale formation on different parts of the boiler system and corrosion. The scale formation reduces the heat transfer rates, clogs the flow passage, and endangers the life of the equipment by increasing the temperature above safe limits. The corrosion phenomenon reduces the life of the plant rapidly. Therefore, it is necessary to reduce the impurities below a safe limit for the proper working of power plants.

2.6.6 ***CHEMICAL OXYGEN DEMAND (COD)***

COD is a general parameter determining the pollution level of polluted water or wastewater. COD corresponds to the amount of oxygen needed to chemically oxidize all the organic matter present in the wastewater characterized. COD can be used as an indirect estimator of the amount of an organic compound in an aqueous single synthetic solution. However, its main application is directly characterizing the organic load and quality of waters and wastewaters.

COD can be calculated from the concentration of the organic compounds and the total amount of oxygen needed to completely oxidize them. COD can be used to estimate the percentage of sample identification from the ratio of COD calculated from the organic compounds content analyzed by direct methods to the COD analyzed. However, COD generally gives higher deviations.

2.7 Filtration process is the alternative solution

Filtration processes are the fast-growing industries and due to its efficiency, it can replace and optimise most of the processes. Filtration technology is an emerging technology that removes unwanted material from wasted materials. The scope of the filtration process is wider and its operation condition depends on the production quality and quantity, but the huge factor in technology is the membrane. Many factors prevent the public and industries from utilizing this technology at optimum. These factors include durability, reliability and operation cost involved, etc. The driving pressure can be controlled in two ways: by manipulating the flow rate or surface membrane area. The other disadvantage of this process depends on the membrane life span, harsh operation conditions, and substances that can poison the membrane including temperature conditions of the process (Porter et al., 1990).

Filtration is the process of removing suspended solids from liquid by passing the liquid through a permeable fabric or porous bed of materials. In most cases, the permeable fabric or porous bed of materials is called a membrane. The liquid is naturally filtered as it flows through the porous layers of the membrane. Filtrations processes can also be classified into two-operation positions; when the membrane is placed horizontally, it is a dead-end filtration (Figure 2.1) and when the membrane is placed vertically, it is the cross-flow filtration (Figure 2.2).

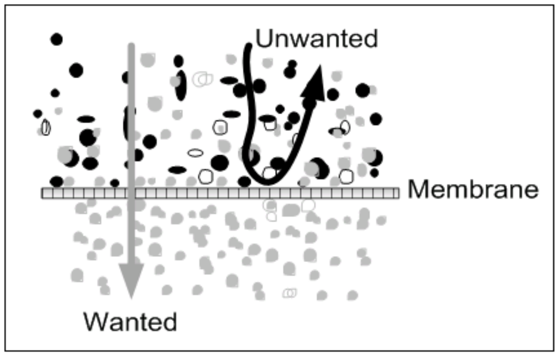


Figure 2.1: Sketch illustrating a dead-end filtration process

(Adapted from Strathmann and Porter, 1990)

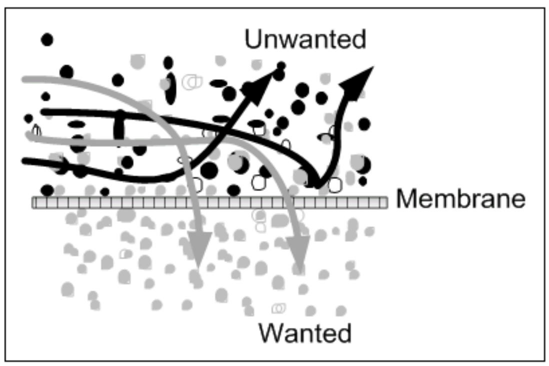


Figure 2.2: Sketch illustrating a Crossflow filtration

(Adapted from Strathmann and Porter, 1990)

In contrast to the dead-end filtration, the use of a tangential flow prevents thicker particles from building up a "filter cake" by a high-velocity gradient near the membrane surface, which assists in reducing the fouling and polarization effects.

For cross-flow filtration, a fluid (feed) stream runs tangential to a membrane, establishing a pressure differential across the membrane. This causes some of the liquid to pass through the membrane and the remaining solid particles continue to flow across the membrane.

2.7.1 Particle – Liquid Separation

The process of forming a liquid with particles through membranes allowing liquid only to pass is called a particle-liquid separation. However, the process is possible when the membrane pores are smaller than the particle of the impurities in the feed solution. Reverse osmosis process, ultra-filtration process, Microfiltration process and general filtration process form part of separations processes. The difference between these separations processes is pore size and driving pressure. However, the evaporation is part of separations processes of which the liquid mixtures is partial vaporization through a non-porous selectively permeable membrane (Porter, 1990).

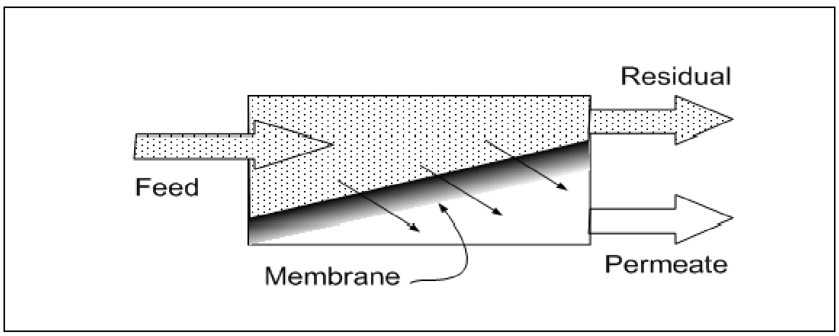


Figure 2. 3: Schematic representation of a simple membrane separation

(Adapted from Porter, 1990)

There are different separations processes that are often applied to the same separation task with the merits of one approach than having to be assessed in comparison to others. As membrane processes, barrier separations add to the inventory of separation science, showing specific advantages in some applications, while competing on equal terms with traditional. The major drive of filtration is based on minimizing the impact of the environment and upgrading the quality of living (Venture, 2007).

- Reverse osmosis is the process of forcing a solvent from a region of high solute concentration through a membrane to a region of low solute concentration by applying a pressure in excess of the osmotic pressure. In most cases, it ranges above 10bars to oppose the equilibrium after achieving the diffusion process (Richard, 2004).

- Ultra-filtration is a filtration process in chemistry that can retain solutes with relative molecular masses in the order of 100s to 1000s. Typical pore sizes are 0.01 - 0.2µm upwards. Ultra-filtration membranes are defined by their nominal molecular weight cut-off (MWCO). The MWCO generally represents the smallest molecular weight for which the membrane has a retention value of more than 90%. The operating pressure for ultra-filtration is usually between 0.1 and 1 MPa (Richard, 2004).

- Microfiltration is a pressure-driven process in which a membrane is applied to separate particles from an aqueous solution. Microfiltration is defined as the filtration of a suspension with colloidal or other fine particles having a linear dimension of roughly 0.2 µm to 10 µm. Typical operating pressure for microfiltration is relatively low, lying between 0.002 MPa and 0.5 MPa. In some cases, it can be lower than 0.002MPa (Richard, 2004).

- Pervaporation is a method for the separation of mixtures of liquids by partial vaporization through a non-porous membrane. The membrane acts as a selective barrier between the two phases, the liquid phase feed, and the vapour phase permeate. It allows the desired component(s) of the liquid feed to transfer through it by vaporization. The separation process is mainly due to polarity difference, and not to the volatility difference of the components in the feed (Richard,2004).

2.8 History of membrane and polymer science

Systematic studies of membrane phenomena can be traced to the eighteenth-century philosopher-scientists. Membranes were discovered back in time before the industrial revolution during the First World War (1914). People in the Iron Age used to use natural resources (plants and animals) as a membrane during the filtration process (Mncube, 2010).

Through the nineteenth and early twentieth century's, membranes had no industrial or commercial uses but were used as laboratory tools to develop physical/chemical theories. New science developments are playing a major role. More polymer chemistry and science has been introduced since then. That has also taken a step up in the growth of membranes.

Today membrane technology or sciences are applied in most areas such as microbiology, biochemistry, industrial separations and environmental protection and more. The history shows that membranes are divided into two groups: synthetic membranes, sometimes called man-made membranes and natural membranes. Almost all-synthetic membranes are made from polymer science. The membrane history reverences a good relationship between membrane technology and the inversion of applied polymer science (Sutherland, 2013).

For membrane separation processes, only driving forces, which induce a significant flux of matter, are of practical importance. These driving forces are hydrostatic pressure, concentration, and electrical potential differences. There are six developed and a number of developing and yet-to-be-developed industrial membrane technologies since there is room for improvement. The four developed industrial membrane separation processes are microfiltration, ultra-filtration, reverse osmosis, and electro dialysis. These processes are all well established, and a number of experienced companies serve the market (Porter, 1990a).

2.8.1 Overview of Membranes

A membrane is a thin, typically planar structure or material that separates two environments. There are two types of membrane materials, synthetic membranes, and natural membranes. All membranes contain holes or pores of finite dimensions or consisting of some form of layered structure that allows some material to pass through while preventing other unwanted materials from passing through the membrane (Richard,2004).

2.8.2 Type of Membranes

Synthetic membranes sometimes called man-made membranes are made of polymers, natural fibres, metals, and concretes. The natural membranes are mainly biological membranes like animal skin and plants.

Today membrane technology or sciences are applied in most areas such as microbiology, biochemistry, industrial separations and environmental protection and more. Synthetic membranes and biological membranes have holes or pores of finite dimensions or consisting of some form of layered structure (Venture, 2007).

a) Microporous Membranes

A microporous membrane is very similar in structure and function to a conventional filter. It has a rigid, highly voided structure with randomly distributed, interconnected pores. However, these pores differ from those in a conventional filter by being extremely small, approximately 0.01 to 10 µm in diameter. All particles larger than the largest pores are completely rejected by the membrane.

b) Nonporous, Dense Membranes

Nonporous, dense membranes consist of a dense film through which permeate is transported by diffusion under the driving force of pressure, concentration, or electrical potential gradient.

The separation of various components of a mixture is related directly to their relative transport rate within the membrane, which is determined by their diffusivity and solubility in the membrane material.

Thus, nonporous, dense membranes can separate permeate of similar size if their concentration in the membrane material (that is, their solubility) differs significantly. Most gas separation, pervaporation, and reverse osmosis membranes use dense membranes to perform the separation. Usually, these membranes have an anisotropic structure to improve the flux (Richard, 2004).

c) Electrically Charged Membranes

Electrically charged membranes can be dense or microporous, but are most commonly very finely microporous, with the pore walls carrying fixed positively or negatively charged ions. A membrane with fixed positively charged ions is referred to as an anion-exchange membrane because it binds anions in the surrounding fluid (Richard, 2004).

Similarly, a membrane containing fixed negatively charged ions is called a cation-exchange membrane. Separation with charged membranes is achieved mainly by exclusion of ions of the same charge as the fixed ions of the membrane structure, and to a much lesser extent by the pore size. Electrically charged membranes are used for processing electrolyte solutions in electro dialysis (Zhou et al., 2008*).*

d) Anisotropic Membranes

The transport rate of a species through a membrane is inversely proportional to the membrane thickness. High transport rates are desirable in membrane separation processes for economic reasons; therefore, the membrane should be as thin as possible. Conventional film fabrication technology limits the manufacture of mechanically strong, defect-free films to about 20-µm thickness. Anisotropic membranes consist of an extremely thin surface layer supported on a much thicker, porous substructure. The surface layer and its substructure may be formed in a single operation or separately.

In composite membranes, the layers are usually made from different polymers. Exclusively the surface layer determines the separation properties and permeation rates of the membrane; the substructure functions as mechanical support. The advantages of the higher fluxes provided by anisotropic membranes are so great that almost all commercial processes use such membranes.

e) Ceramic, Metal and Liquid Membranes

The discussion so far implies that membrane materials are organic polymers and, in fact, the vast majority of membranes used commercially are polymer-based. However, in recent years, interests in membranes formed from less conventional materials have increased. Ceramic membranes, a special class of microporous membranes, are being used in ultrafiltration and microfiltration applications for which solvent resistance and thermal stability is required.

Dense metal membranes, particularly palladium membranes, are being considered for the separation of hydrogen from gas mixtures and supported liquid films are being developed for carrier-facilitated transport processes (Richard, 2004).

f) Biological membranes

In medicine, microbiology, cell physiology, and biochemistry, a membrane is a lipid bilayer typically embedded with proteins, which acts as a barrier within or around a cell. An example is the animal cell nucleus.

Such membranes typically define enclosed spaces or compartments, in which cells may maintain a chemical or biochemical environment that differs from the outside. For example, the membrane around peroxisomes shields the rest of the cell from peroxides, and the plasma membrane separates a cell from its surrounding medium. Such membranes define most organelles (Richard, 2004).

2.8.3 Factors that affect Membranes

Most researchers like Porter (1990), and Al-Malack and Anderson (1997) agree that membrane history reverence a good relationship between the membrane technology and the inversion of applied polymer science. A good membrane should have reasonable porosity and should sustain mechanical, chemical, and thermal stability. Operating conditions such as temperature, pressure, pH, and chemical compatibility should be considered for the selection of a membrane type.

The following factors are taken into account when selecting the membrane:

- Membrane material (polymeric, ceramic, metallic);
- Membrane structure (porous, dense);
- Membrane thickness (thick, thin);
- Membrane texture (symmetrical, asymmetrical, composite);
- Separation mechanism (sieve, diffusion, evaporation, ion exchange);
- Driving force (pressure, activity, electric potential);
- Phases in contact (liquid-liquid, liquid-gas, liquid-solid) and;
- Type of pressure driven membranes (MF, UF, NF, RO).

A membrane of reasonable mechanical strength and one that can maintain a high throughput of the desired permeate with a high degree of selectivity depends on the combination of membrane properties considered based on the classification mentioned above (Richard, 2004).

2.8.4 Operation and maintenance of membranes

A membrane process can be defined as an operation where a feed stream is divided into two streams; permeate, containing material which has passed through the membrane, and a residue, containing the non-permeating species, as shown in Figure 2.4 and Figure 2.5.

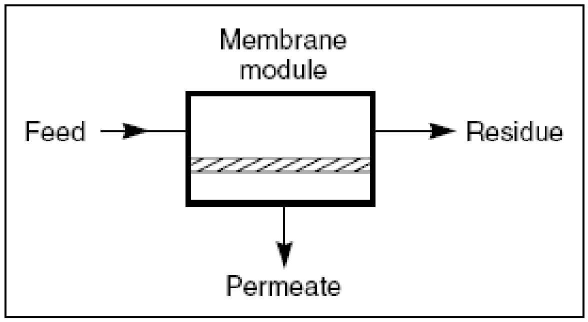


Figure 2.4: Schematic diagram of the basic membrane gas separation process

(Adapted from Peter, 2010)

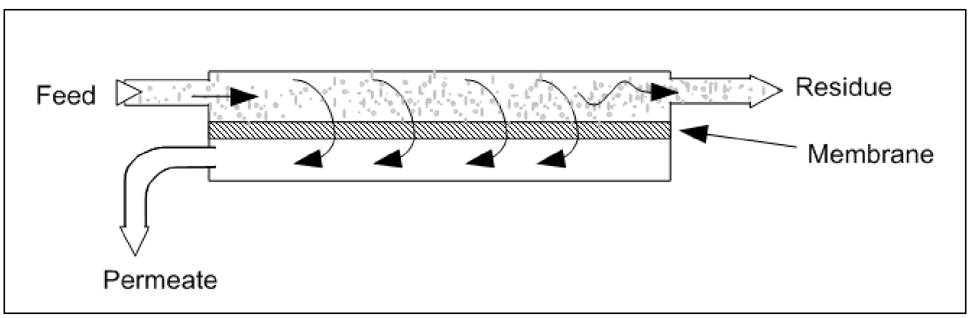


Figure 2.5: Principle of membrane operation

(Adapted from Porter, 1990)

During the filtration process, the feed solution is forced through the filtration systems that consist of the membrane. Both residue and permeate are produced during the operation. However, the deposition of the unwanted material on the membrane will also take place and that process is called fouling.

The permeability of different components in a membrane depends on the mechanism by which the components are transported. The permeability of these membranes is determined by the diffusivities and concentrations of the various components in the membrane matrix and the transport rates are, in general, relatively slow.

Although synthetic membranes show a large variety in their physical structure and chemical nature, they can conveniently be classified into five basic groups:

(1) Microporous media;

(2) Homogeneous solid films;

(3) Asymmetric structures;

(4) Electrically charged barriers; and

(5) Liquid films with selective carriers.

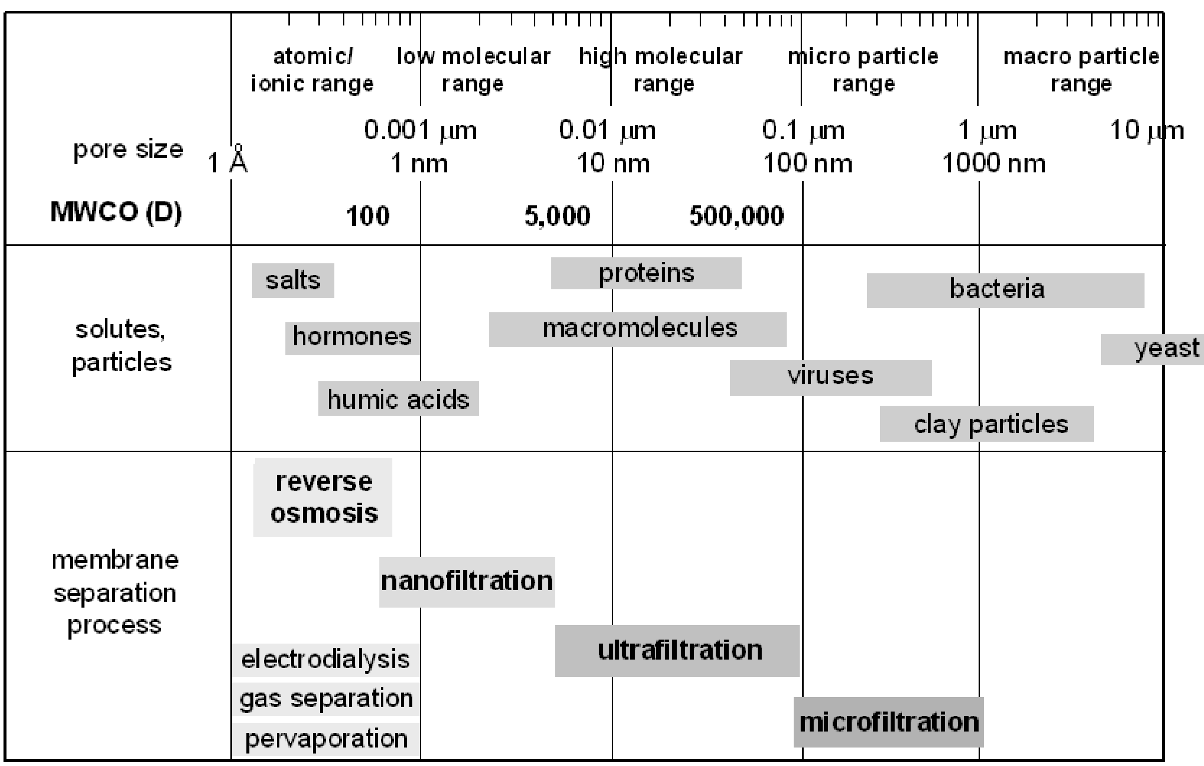


Figure 2. 6: Comparison of various pressure has driven membrane processes

(Adapted from Peter, 2010)

From Figure 2.6, the Microfiltration membranes filter colloidal particles and bacteria from 0.1 µm to 10 µm in diameter. Ultra-filtration membranes can be used to filter dissolved macromolecules, such as proteins from solutions. The mechanism of separation by reverse osmosis membranes is quite different. In reverse Osmosis membranes, the membrane pores are so small, from 3 to 5 ˚A in diameter that they are within range of thermal motion of the polymer (Richard, 2004).

2.8.5 Membrane module Configurations

There are five principal modules currently employed in membrane processes:

1) Pleated cartridge;
2) Plate-and-frame;
3) Spiral-wound;
4) Tubular; and
5) Hollow fibre.

At present, hollow fibre modules, spiral-wound modules and plate and frame modules are the most popular and extensively used modules in membrane/filtration processes.

When designing the modules there are factors that are taken into consideration. In addition, those factors are,

- ✓ Membrane fouling;
- ✓ Cost per unit membrane area;
- ✓ Energy expenditure;
- ✓ Product volume;
- ✓ Quality of the product;
- ✓ Quality of the feed;
- ✓ Maintenance;
- ✓ Reliability and;
- ✓ Availability.

2.8.6 Mathematical Model for membrane filtration

There are factors or aspects to consider when developing a model for membrane performance: the transport of the material across the membrane surface area, the design of the filtration modules and the need of the membrane technology.

2.8.6.1. Membrane Operation Parameters

Membrane filtration system throughput is typically characterized by the system flux, which is defined as the filtrate flow per unit of membrane filtration area, as shown in Equation 2. 1:

$$J = \frac{Q_p}{A_m} \qquad \text{Equation 2.1}$$

The permeate flux, J (L/m^2. hr) is proportional to filtrate flow, Q_P (L/hr) per membrane surface area, A_m (m).

It should be noted that the permeate flux decreases as the filtrate flow decreases when driving pressure is kept constant throughout the operation. This phenomenon takes place in all low energy filtration systems.

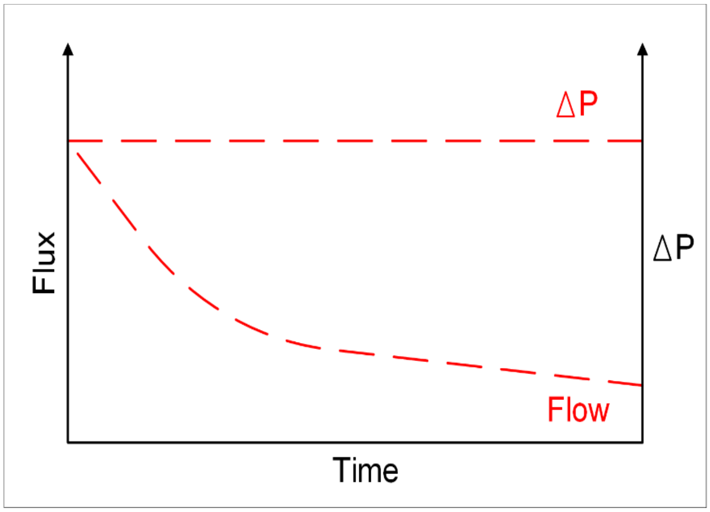


Figure 2.7: Static flux control method and static pressure control method (Constant pressure) (Adapted from Peter, 2010, and Richard, 2004).

Figure 2.7 is the typical behaviour for low energy systems, which the study is focusing on. In order to design a filtration system, a flux prediction Equation, which describes the relationships of the operating parameters, fluid characteristics and membrane properties to the flux, are required. However, the permeate flux of a filtration system is usually unstable and difficult to predict due to the complexity of the system and the membrane fouling that decreases the membrane flux.

$$J = \frac{\Delta P}{\mu(R_m + R_c + R_f)} \qquad \text{Equation 2. 2}$$

Equation 2. 2 represents the simplest resistance-in-series model based on Darcy's law to predict the flux, where J is permeate flux; ΔP is transmembrane pressure; μ is viscosity of the permeate; R_m is intrinsic membrane resistance; R_c is external fouling resistance formed by the cake layer, and R_f is internal resistance due to materials absorbed into the pores. Therefore, in this work, we concentrate on modelling the membrane effect when using woven fabric as the membrane and applying that woven fabric to polluted water (water and wastewater).

The primary goal of this research was to systematically model the performance of a woven fabric used as a filtration membrane for polluted water. The transmembrane pressure is given by the difference between the static pressure (P_{static}) and the pressure imposed by the hydrostatic head or pump through the membrane ($P_{filtration}$):

$$TMP = \Delta P = (P_{static} - P_{filtration}) \qquad \text{Equation 2.3}$$

The trans-membrane pressure (TMP) is the driving force behind the filtration process. Equation 2.1 can be used to predict the permeate flux that remains proportional to hydraulic resistance for porous membrane systems.

The flux is the quantity of material passing through a unit area of membrane per unit time and can be determined by both the driving force and the interfacial region adjacent to it. Under the simplest operating conditions, the resistance to flow is offered entirely by the membrane.

$$J = \frac{\Delta P}{\mu \cdot R_t} \qquad \text{Equation 2.4}$$

The permeate flux, J (L/m^2. hr) is proportional to transmembrane pressure, ΔP (kPa) per viscosity of the permeate, μ (Pa. s) multiplied by total resistance R_t (1/m).

All resistances shown in Equation 2.2 can be measured through a series of filtration experiments by comparing pure water filtration, sludge filtration, and pure water filtration after cake removal. However, the resistances are dependent on a number of experimental conditions, such as biomass characteristic, membrane material, and temperature as stated by Porter (1990) and Richard (2004).

2.8.6.2. *Characteristics of Membranes*

The flux, *J*, is the quantity of material passing through the membrane surface per unit time. It can also be called permeate or filtration velocity and it can be calculated by Darcy´s law (Lojkine et al., 1992).

Reverse osmosis, ultra-filtration, and microfiltration are conceptually similar processes; the difference in pore diameter (or apparent pore diameter) produces dramatic differences in the way the membranes are used.

A simple model of liquid flow through these membranes is to describe the membranes as a series of cylindrical capillary pores of diameter, *d*. Poiseuille's law gives the liquid flow through a pore, *q*:

$$q = \frac{\pi d^4}{128 \mu l} \cdot \Delta p \qquad \text{Equation 2.5}$$

Where Δp is the pressure difference across the pore, μ is the liquid viscosity and l is the pore length. The flux, or flow per unit membrane area, is the sum of all the flows through the individual pores and is given by:

$$J = N \cdot \frac{\pi d^4}{128 \mu l} \cdot \Delta p \qquad \text{Equation 2.6}$$

The number *N* of pores per square centimetre of membrane equal to the pore area and porosity, ε is proportional to the inverse square of the pore diameter which is $1/d^4$. That is,

$$N = \varepsilon \cdot \frac{4}{\pi d^4} \qquad \text{Equation 2. 7}$$

It follows that the flux, given by combining Equations (2.6) and (2.7), is to form Equation 2. 8

$$J = \frac{\Delta p \varepsilon}{32\mu l} \cdot d^2$$ Equation 2.8

The typical pore diameter of a micro-filtration membrane is 10,000 A˚. This is 100-fold smaller than the average normal filtration and is 100-fold larger than the average ultra-filtration pore and 1000-fold larger than the (nominal) diameter of pores in reverse osmosis membranes. Because fluxes are proportional to the square of these pore diameters, the permeate, that is, flux per unit pressure difference $J/\Delta p$ of microfiltration membranes is enormously higher than that of ultra-filtration membranes, which in turn is much higher than that of reverse osmosis membranes. These differences significantly influence the operating pressure and the way that these membranes are used industrially.

$$P_F = P_{L1}(x, t) + P_{S1}(x, t),$$ Equation 2.9

where P_F represents the applied (filtration) pressure, P_{L1} is the local liquid pressure in the pores and P_{S1} is the compressive or effective pressure representing the stress developed by frictional loss inside of the filter cake. Consequently, the local cake parameters: porosity, permeability, and specific resistance were expressed as a function of the local compressive pressure, P_{s1}.

Equation 2.10 be still defined as

$$(P_o - P_l) = \Delta\pi$$ Equation 2.10

Filtration requires a driving force for the process to take place. In some literature, the driving force is called mass transport. This force is better illustrated using the mathematical expression or Equation. That mathematical Equation is called the local mass transport Equation (Richard, 2004).

2.9 Woven fabric used as membranes

Man-made membranes or synthetic membranes can be either woven or non-woven types. Woven membranes have an open space surrounded by fibres, and the orientation is visible, whereas non-woven membranes have random spacers and the orientation of fibres is random.

The woven membranes are woven or weave fabrics. The yarns are woven over and under yarns to form a checkerboard pattern. The simplest weave pattern is called plain weave. This weave is usually the tightest, having the smallest pore openings in the fabric. There other common weave patterns are twill weave and sateen (satin) weave. In most cases, these two weaves, are bulky when compared to plain weave.

2.9.1. Plain weave

Plain weave is the simplest interlacing pattern, which can be produced. It is formed by alternately lifting and lowering one warp thread across one weft thread. Figure 2.8 shows 8 repeats (two in the warp and four in the weft direction) of a plain weave fabric in plain view and warp way and weft way cross-sections through the same fabric (Horrocks and Anand, 2000).

Figure 2.8 illustrates a plain weave either in plain view and/or in cross-section. Record of weave on the pattern paper is represented, of which the warp binding point is dark and the weft binding point-white (see Figure 2.9).

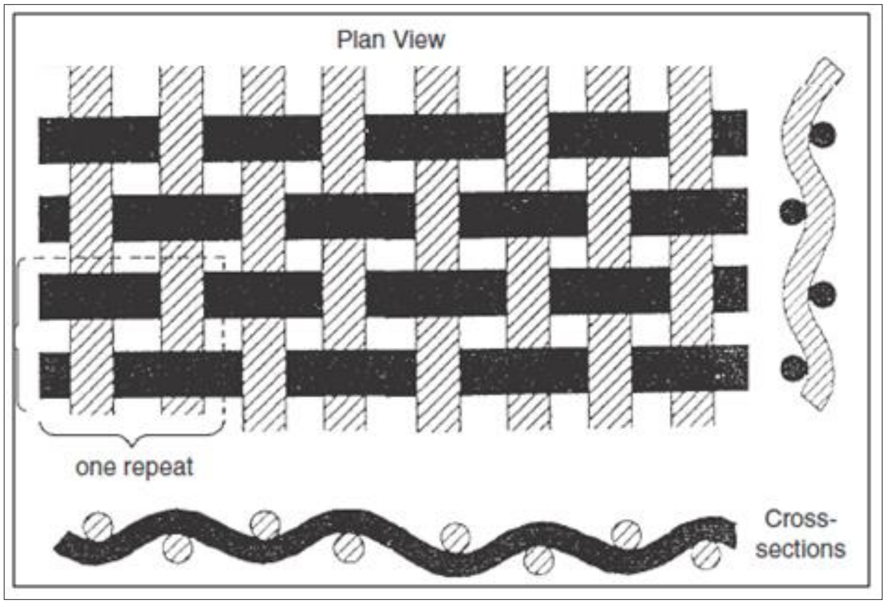


Figure 2.8: Fabric woven with plain weave – plan view (2 x 4 repeats)

(Adapted from Sondhelm, 2000 and Aldderman, 2004a)

A type of shorthand for depicting weave structures has therefore evolved and the paper used for producing designs is referred to as squared paper, design paper or point paper. Generally, the space between two vertical lines represents one warp end and the space between two horizontal lines is one pick. This is further illustrated in Figure 2.9.

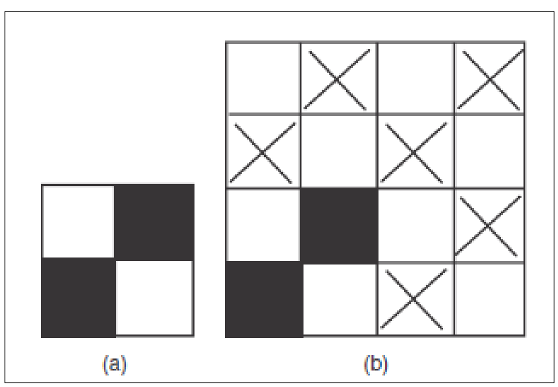


Figure 2.9: Point paper diagram of a plain weave fabric. (a) One repeat, (b) four repeats.

(Adapted from Sondhelm, 2000 and Aldderman, 2004a)

2.9.2. Twill weave

Figure 2.11 is a clear illustration of twill weave. A Twill weave is a weave that repeats on three or more ends and picks and produces diagonal lines on the face of a fabric. Such lines generally run from selvedge to selvedge. The direction of the diagonal lines on the surface of the cloth is generally described as a fabric is viewed along the warp direction. When the diagonal lines are running upwards to the right they are 'Z twill' or 'twill right' and when they run in the opposite direction they are 'S twill' or 'twill left'. For Plain weaves, all pores are the same.

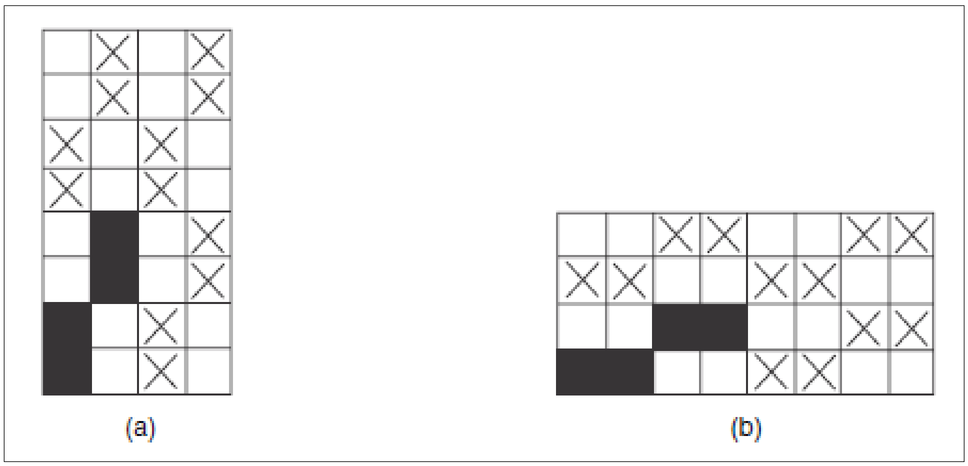


Figure 2.10: Rib fabrics. (a) 2/2 Warp rib (four repeats), (b) 2/2 weft rib (four repeats)

(Adapted from Sondhelm, 2000 and Aldderman, 2004b)

Their angle of yarns interlocking and definition can be varied by changing the thread spacing and/or the linear density of the warp and weft yarns. For any construction, twills will have longer floats, fewer intersections and a more open construction than a plain weave fabric with the same cloth particulars.

2.9.3. Satin weave

Figure 2.11 is a clear illustration of the satin weave. A satin is a warp-faced weave in which the binding places are arranged to produce a smooth fabric surface free from twill lines. Satins normally have a much greater number of ends than picks per centimetre. To avoid confusion a satin is frequently described as a 'warp satin'. A sateen frequently referred to as a 'weft sateen', is a weft-faced weave similar to satin with binding places arranged to produce a smooth fabric free of twill lines. Sateen weaves are generally woven with a much higher number of picks than ends. Satins tend to be more popular than sateen's because it is cheaper to weave cloth with a lower number of picks than ends. Warp satins may be woven upside down, that is as sateen but with a satin construction.

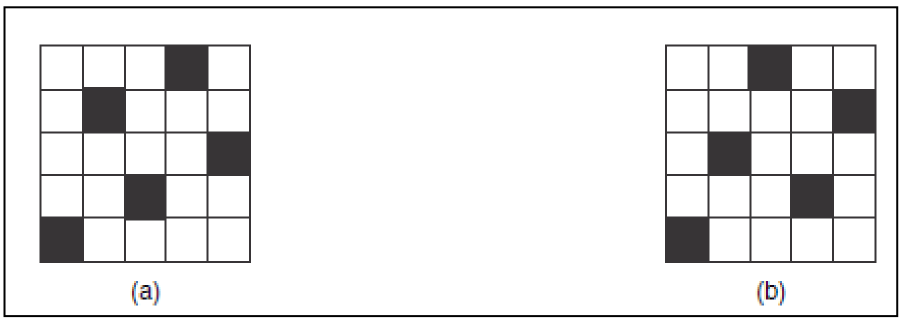


Figure 2.11: 5-End weft sateen. (a) 5-end and two-step sateen, (b) 5-end three step sateen.

(Adapted from Sondhelm, 2000 and Aldderman, 2004c)

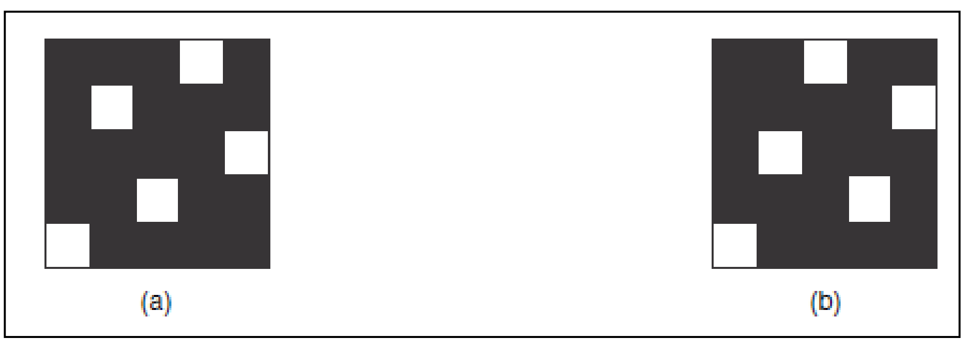


Figure 2.12: 5-End warp satin. (a) 5-end two-step satin, (b) 5-end three step satin.

(Adapted from Sondhelm, 2000 and Aldderman, 2004c)

Figure 2.11 (a) and (b) shows 5-end weft sateen’s with two and three steps, respectively. They have been developed from the 1/4 twill shown in Fig. 2.12(b). Mirror images of these two weaves can be produced. Five-end warp satins with two and three steps are shown in Fig. 2.12 (a) and (b). It is the cloth particulars, rather than the weave pattern, which generally decides on which fabric is commercially described as sateen or a satin woven upside down.

Five-end satins and sateens are most frequently used because with moderate cover factors they give firm fabrics (Sondhelm, 2000).

Different weaving patterns sometimes increase or decrease the open spaces between the fibres. This will affect both fabric strength and permeability. Fabric permeability affects the amount of air or water passing through the filter at a specified pressure drop. A tight plain weave, for instance, has low permeability and is better for the capture of small particles at the cost of an increased pressure drop (Lyndon and Rideal, 2004).

2.10 Weaving – machines (looms) and operations

Whilst the principle of weft interlacing in weaving has not changed for thousands of years, the methods used and the way that weaving machines are activated and controlled has been modified. The productivity of the weaver has increased even more and is likely soon to have increased a hundred-fold. Weaving, which used to be a labour-intensive industry, is now capital intensive using the most modern technology.

The essential operations in the weaving of cloth are as follows:

1. Warp beam is used to feed the looming machine with warp yarns;
2. Warp yarns are used to weave fabric;
3. Shedding, or Harnesses with header flame is used to separate the warp threads into two (or more) sheets according to a pattern to allow for weft insertion;
4. Weft insertion or filling carrier (picking) is used to feed weft yarns;
5. Beating-up or reed is used enforcing the pick, which has been inserted into the shed, up to the fell of the cloth (the line where the cloth terminates after the previous pick has been inserted); and
6. Cloth roller is used to wind the weaved cloth.

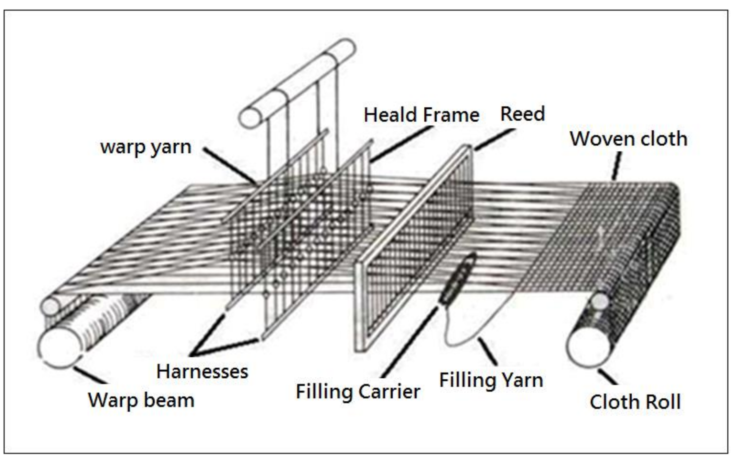


Figure 2.13: Basic structure of the loom

(Adapted from Masajtis, 1998 and Sondhelm, 2000)

Table 2.2: Classification of weaving machines

- ***Single-phase weaving machines***

Machines with shuttles (looms):

Hand operated (handlooms)

Non-automatic power looms (weft supply in shuttle changed by hand)

Automatic weaving machines

shuttle changing

rotary batteries, stack batteries, box loaders or pin winder mounted on the machine (Unifil)

pin changing

Shuttleless weaving machines:

Projectile

Rapier

rigid rapier(s)

single rapier, single rapier working bilaterally or two rapiers operating from opposite sides of the machine

telescopic

flexible

Jet machines

air (with or without relay nozzles)

liquid (generally water)

- ***Multiphase weaving machines***

Wave shed machines:

Weft carriers move in a straight path

Circular weaving machines (weft carriers travel in a circular path)

Parallel shed machines (rapier or air jet)

(Adapted from Sondhelm, 2000 and Aldderman, 2004a)

2.11 Non-woven fabrics used as membranes

Non-woven is a textile structure produced by the bonding or interlocking of fibres, or both, accomplished by mechanical, chemical, thermal or solvent means and combinations thereof. The term non-woven does not include paper or fabrics that are woven, knitted or tufted.

One of the major advantages of non-woven manufacture is that it is generally done in one continuous process directly from the raw material to the finished fabric, although there are some exceptions to this. This naturally means that the labour cost of manufacture is low because there is no need for material handling as there is in older textile processes.

In spite of this mass-production approach, the non-woven industry can produce a very wide range of fabric properties from open waddings suitable for insulation containing only 2–3% fibres by volume to stiff reinforcing fabrics where the fibre content may be over 80% by volume.

Carding machines are mainly used to arrange the filaments. Air, water, mechanical means or solvents are used to lay the filaments or fibres. Chemicals, solvent or needle and stitch used to bond filaments or fibres. (Smith, 2000). Figure 2. 14 illustrates needle bonding.

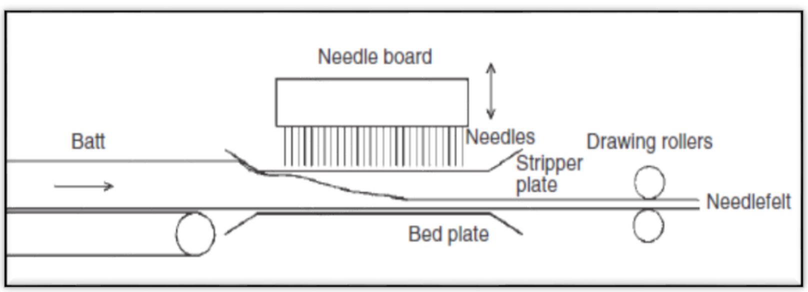


Figure 2.14: Diagram of a needle loom

(Adapted from Smith, 2000)

A manufactured sheet is web or batt of directionally or randomly orientated fibres, bonded by friction, and/or cohesion and/or adhesion is either woven, knitted, tufted, stitch-bonded incorporating binding yarns or filaments, or felted by wet-milling, whether or not additionally needled.

Figure 2.15 illustrates the processes used for web formation and Figure 2.16 shows the processes used for web bonding to form non-woven materials.

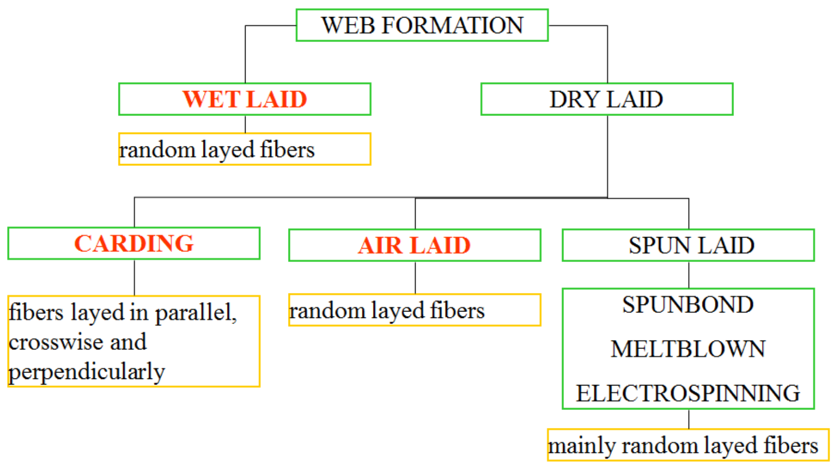


Figure 2.15: Scheme of non-woven s consists of the web formation

(Adapted from Smith, 2000)

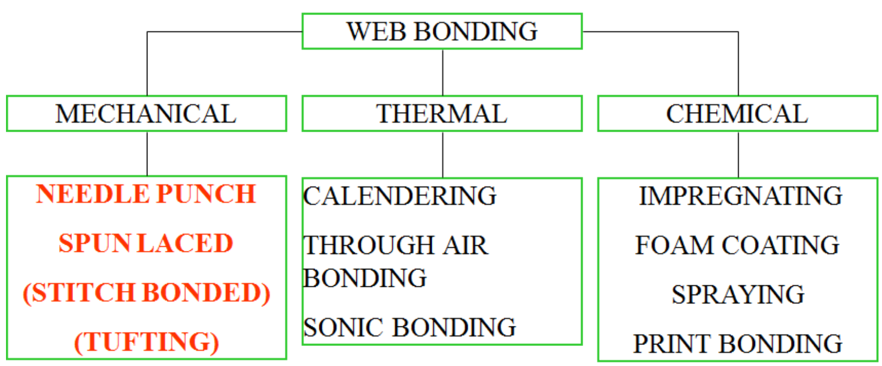


Figure 2.16: Scheme of non-woven s consists of the web bonding

(Adapted from Smith, 2000)

Various membranes are shaped by filament characteristics and bonding characteristics. However, when it comes to woven fabrics, characteristic of fabrics are shaped by weave type, fibre characteristics, yarn characteristics and the loom machine is used for weaving the fabric.

2.12 Membrane or textile treatment or finishing

The name textile finishing covers an extremely wide range of activities, which are performed on textiles before they reach the final customer. They may be temporary, for example, the way bed sheets are pressed before packing, or they may be permanent, as in the case of flame-retardant tenting fabric.

However, all finishing processes are designed to increase the attractiveness or serviceability of the textile products. This could involve such techniques as putting a glaze on an upholstery fabric, which gives it a more attractive appearance, or the production of water repellent finishes, which improves the in-service performance of a tenting fabric.

Thus, a further aim of textile finishing may be described as an improvement in customer satisfaction, which finishing can bring about. This improvement in the perceived value of a product to the consumer forms the basis of modern ideas on product marketing. Technical textiles are defined as those materials with non-clothing applications. Thus, the fashion aspects of textiles will be ignored, although aesthetic aspects of say upholstery and drapes will be covered (Hall, 2000).

Fabrics are usually pre-treated to improve their mechanical and dimensional stability. They can be treated with chemicals or mechanical processes or nanotechnology to give them better cake release properties. Natural fabrics (wool and cotton) are usually pre-shrunk to eliminate membrane shrinkage during operation.

Both synthetic and natural fabrics usually undergo processes such as calendaring, napping, singeing, glazing, or coating. These processes increase fabric life, improve dimensional stability (so that the membrane retains their shape or fit after long use), and facilitate membrane cleaning. Fabric or yarns or filaments are treated to provide hydrophilic or hydrophobic properties.

The finishing processes that are available can be divided into four main groups, which are:

- MECHANICAL PROCESSES: These involve the passage of the material through machines whose mechanical action achieves the desired effects. A heating process, the purpose of which is usually to enhance these desired effects, frequently accompanies this.

These mechanical finishes, which will be discussed in summary later in this section, are:

– *Calendaring:* Compression of the fabric between two heavy rolls to give a flattened, smooth appearance to the surface of the fabric. Figure 2.17 illustrates the effect cost by the calendaring process

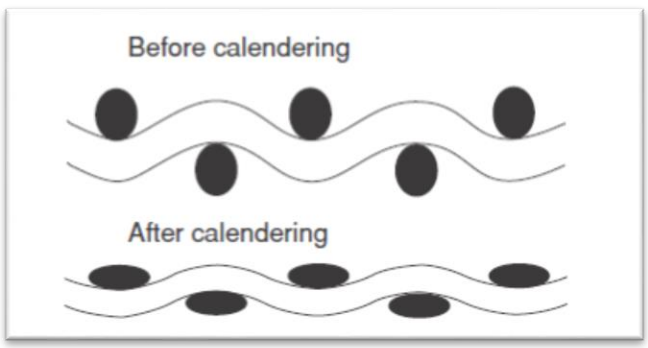


Figure 2.17: Flattening effect on fabric by calendaring (Mechanical process)

(Adapted from Sondhelm, 2000 and Aldderman, 2004a)

– Raising: plucking the fibres from a woven or knitted fabric to give a nap effect on the surface.

– Cropping: cutting the surface hairs from the fabric to give a smooth appearance, often used on woollen goods where the removal of surface hair by a singeing process is not possible.

– Compressive shrinkage: the mechanical shrinking of the warp fibres in woven fabrics so that shrinkage on washing is reduced to the desired level.

- HEAT SETTING: This is a process for the stabilisation of synthetic fibres so that they do not shrink on heating.
- CHEMICAL PROCESSES: These may be described as those processes that involve the application of chemicals to the fabric. The chemicals may perform various functions such as water repellency or flame retardancy or may be used to modify the handle of a fabric. Chemical finishes are normally applied in the form of an aqueous solution or emulsion and may be applied via a variety of techniques, the main one being the pad mangle.

After the padding or the application stage of the chemical finishing the fabric is usually dried to remove the water from the fabric and some form of fixation of the finish is then performed. This commonly takes the form of a baking process, where the fabric is subjected to a high temperature for a short period, which enables the applied chemicals to form a more durable finish on the fabric that would otherwise be achieved.

- SURFACE COATING: is the most important part of the finishing of technical textiles. Most Polyvinyl products are woven products covered by other polymers. The surface coating is used a lot for composite products. A thin film composite membrane is a good example. It can be defined as a multilayer membrane in which an ultrathin semipermeable membrane layer is deposited on a preformed and finely microporous supports structure or woven fabrics. Fibres like glass, ceramics, boron, basalt, carbon, polymer, metal and more are used as reinforcing fibres during surface coating.

Nanotechnology can also form part of the above finishing process. Some nanofibers can be either coated on the fabric or clued using calendaring process or heat setting process or chemical process.

2.13 Fabric or membrane strength and testing

There are three failure mechanisms that can shorten the operating life of a membrane. They are related to thermal durability, abrasion, and chemical attack. The tensile test is used to measure the mechanical failure of the fabric.

A number of standard ASTM tests can be conducted on the membrane and fabric. As with all measurement techniques, the results of these membrane tests are relative. Often for these tests to be useful, they must be conducted over time in order to compare relative degradation. In addition, with some of the newer membranes, some of these tests may not be meaningful. These tests can be used to indicate membrane strength and effect of quality and quantity of the filtration process.

There are more than five of the standard tests performed on fabrics that are used for membranes. Some of these tests may not be of value to other processes. These standard testing are permeability testing, flux testing, flex testing, strength testing, fabric thickness testing, fabric density and more. These tests can be conducted on the membrane operating at high or low pressure, however, for low energy systems, only two tests are important and those tests are permeability quality and quantity that include flux and turbidity.

2.14 Woven fabric membrane modules

In order to understand the behaviour of fabrics used as the membrane, the membrane properties and the solution of the solid-liquid mixture must be described in detail. For this, the plate and frame module, woven fabric membrane and solid-liquid mixture were to be evaluated.

The literature review showed that membrane systems have mainly been studied using simplified models that are based on a number of restrictive assumptions.

1. Dead zones: In most plate and frame systems the outlet position and size is very important and most literature are not clear if the outlet must be on the side or centre and whether the shape must be rectangular or round. This means that more flux if the dead zone is minimized.

2. Driving Force: In most plate and frame systems especially for the low energy-driven systems, most literature is not clear on the relationship between the membrane pressure drop and fouling. Some scientists claim that the increase of fouling is directly proportional to flux or pressure. However, the claims are not taking into account the forces applied to particles or between particles as they move toward the membrane. There are many forces that are critical during filtration of which some of these forces are gravity and molecule forces (Bae and Tak, 2005).

3. Weave positioning: Membranes processes are either Non-woven or woven. The weave position has not been an issue for many years. However, it is clear that the surface of the fabric does have an effect during the filtration process so as then the orientation position. A lot of scientists and engineers consider more of other properties than the orientation position. However, most scientists consider economics first when designing technology or systems.

4. Solution and Membrane properties in most membrane systems, some philosophers assume the fact that cake and other impurities that are formed on the membrane surface or blocked

by membranes affect the permeate quality and quantity. However, it is not clear at what degree. Some philosophers also believed that with time the membrane will be completely blocked. There is a relationship between particle properties and membrane properties that can cause the system to continue operation instead of total blocking. This is further justified by biological science, the human cells are covered by membranes, and these cell membranes are not completely blocked with time. Scientists need to understand the phenomena that keep the membrane performing at maximum fouling (Bae and Tak, 2005).

2.14.1. Plate and frame module

The plate and frame module contains a membrane section and a shell section. The feed is on the shell part and the product goes in the filter part. Figure 2.18 shows the plate and frame setup, the polluted water on the shall or frame side and clean water on the tube or cell or plate part.

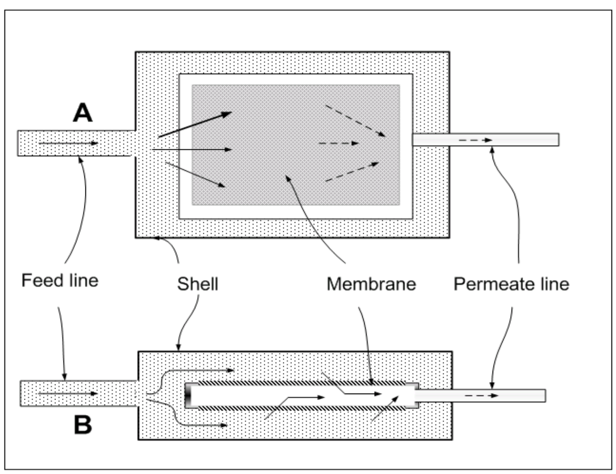


Figure 2.18: Flow pattern for plate and frame single membrane

(A-top views, B-side views)

The feed is on the shell part. The concentration in the shell part increases as the filtration process is in progress. Permeate comes out without any impurities or solids. Note that the term impurities mean the combination of turbidity, bacteria, and suspended solids. The model is derived from dynamic two-dimensional mass, momentum and energy balance. At low energy-driven systems, the driving force is kept constant.

For the systems used for this project, the energy required to drive the system is negligible, approaching zero. Therefore, E_0 was assumed constant and equal to zero. The system has a driving force of 30 cm head and is kept constant.

In order to limit model factors, the following assumptions have been made.

I. The pressure drive and pressure drop for the systems are kept constant. Other relevant values of the required parameters can be obtained from either experimental or theoretical studies.

II. The dead zones for cells were negligible. Other relevant values of the required parameters can be obtained from experimental runs.

III. The effect of the solution concentration changes around each membrane can be described by experimental means. For bundle members, parallel flow module, radical variations on the shell side can usually be neglected, as each membrane will behave in an identical manner. However, the impurities and hydrostatic forces in the liquid will differ.

2.15 Yarns used for woven membranes

The mechanical properties of yarns have a considerable effect on the processing behaviour and performance characteristics of both yarns and fabrics (Liu et al., 2007).

The singles yarn is made either from multifilament or from monofilament. In addition, the filaments are assumed to be cylindrical in shape and so as the yarn. However, all the fibres have the ideal geometry of coaxial helices, which are identical and uniform along their length (Gong and Chen, 2000).

2.15.1. Twist effect

The fibres are assumed to deform without changing their volume when twisted. The stress-strain properties of the twisted fibres cannot be assumed the same as the untwisted yarn (Farris and Rao 2000). Figure 2. 19 shows the type of twisted yarns.

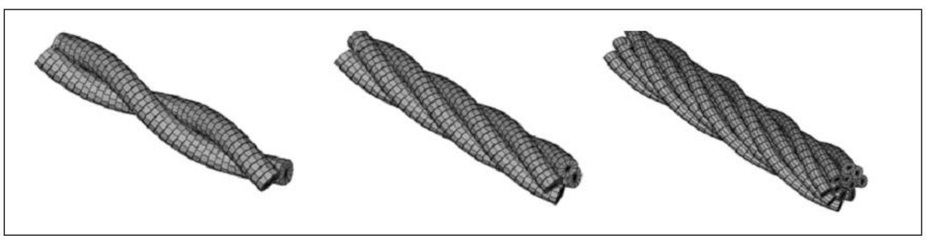


Figure 2.19: Twisted yarn bundles

(Ply yarn twist, four filaments twisted yarn and 12 filaments twisted yarn)
(Adapted from Sondhelm, 2000)

In 1993 Klein proposed a simple analysis to correlate the twist angle of yarn with the yarn modulus (Klein et al., 1993). That particular simple analysis is still in use, however, that particular analysis is not part of the study. However, there are critical points that can assist in providing the needed theory.

2.15.2. Filament size and nature

The fineness determines cross-section of yarn of given thickness. Additional fibres in the cross-section provide not only add strength and weight but also a better distribution in the yarn. Fibre fineness is influenced by spinning limit, the drape of the fabric product, yarn strength, lustre, yarn evenness, handle, yarn fullness, productivity, etc. (Sondhelm, 2000).

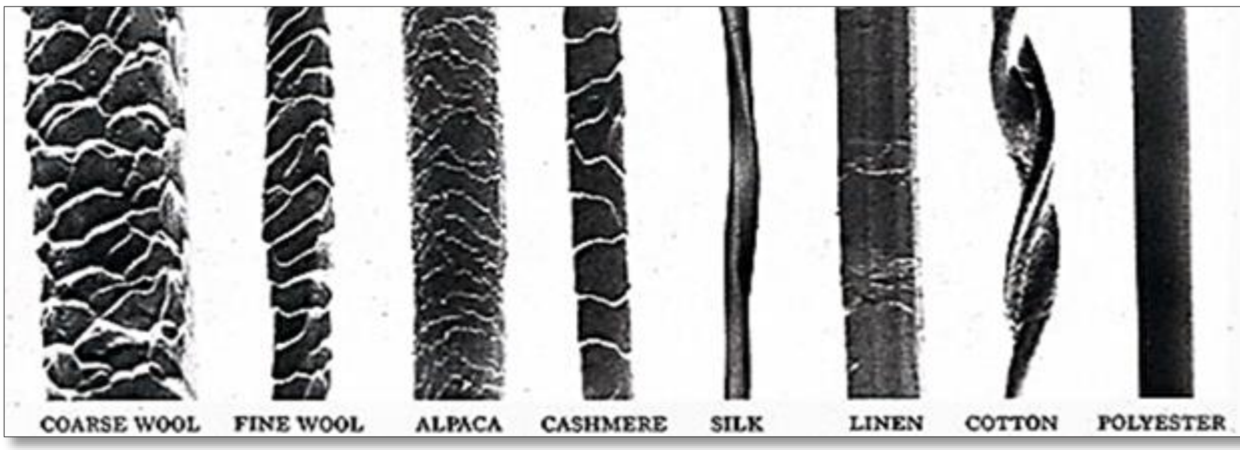


Figure 2.20: Different types of natural and manmade filaments

(Adapted from Sondhelm, 2000)

Figure 2.20 shows the image of natural fibres and man-made or synthetic fibres. Natural filaments are short when compared to manmade filaments. Manmade filaments have a smooth surface when compared to natural filaments. The manmade filaments can be thinner or thicker depending on the final use requirement.

2.15.3. Yarn twist parameter

The bundle is more than one fibre or filament. Twist process is a process used to bind filaments or yarns together in a continuous strand, accomplished in spinning or playing operation.

Theoretically, a packing density of a yarn increases with the increasing of a yarn twist. In a multifilament yarn consisting of fibrous with a constant Tex, a substance diameter increases as Tex of a yarn increases (Sondhelm, 2000).

2.15.4. Fabric or yarn shrinkage

The fibre, yarn or filament shrinkage is generally considered as a huge factor in the textile products. In addition, the structure of the fabrics, yarns or filament that results in dimensional changes becomes a waste if shrinkage was not taken into consideration. There are many mechanisms that cause textile structures to shrink. Thermal shrinkage causes the dimension of a textile specimen to changes when heat radiation or conventional energy is applied. The relaxation shrinkage causes the dimension of a textile specimen changes when recovering from deformation. The swelling shrinkage causes the dimension of a textile specimen changes when swelling (Sondhelm, 2000).

2.15.5. Thermal Shrinkage of polymer fabric or yarn

Polyolefin is inherently prone to degradation by oxidation and heat radiation, which become more serious as the temperature increases. This phenomenon affects the production of polymers during the extrusion. During the production of extrusion filaments, the filaments used are drawn at high temperatures in order to orientate the molecules in the length direction of the material. Afterwards, heat causes certain molecular disorientation coupled with shrinkage in the length direction called heat shrinkage.

Thermal Shrinkage is generally defined as an irreversible shortening of fibre length when exposed to heat radiation. The energy needed to cause shrinking is called the shrinkage work and the stress developed during the shrinking is called the shrinkage stress (mechanically). Under thermal conditions, it is called thermal shrinkage stress.

In general, solids expand on heating and contract on cooling but plastics, mainly polymers, expand on heat and are deformed, where cooling does not return it to its original shape.

The strain associated with the change in temperature will depend on the coefficient of thermal expansion of the material and the magnitude of temperature drop or rise, especially for the crystallized region. Under extremely high-temperature conditions, ordinary crystallized region, structures suffered the most (see Figure 2.22).

2.15.6. Thermal Shrinkage effect

When analysing shrinkage there are aspects that are taken into consideration like shrinkage effect. This means a shrinkage of a specific material takes place at particular energy at a given time period. A shrinkage minimum is different from shrinkage loss. In most cases, it is being used as similar. A shrinkage minimum means a specific material is shrinking at a minimum rate as compared to its potential shrinkage at a given point. A shrinkage loss is shrinkage energy that is given out at a specific period, especially taking place unexpectedly.

Most polymer fibres are made to shrink by the effect of heat energy released in any environment, or in another medium. A great number of different methods in which the changes in length after contraction are measured under defined conditions can determine shrinkage in fibres, yarns, and fabrics.

Shrinkage and shrinkage rate are usually observed through the measurement of the change of the sample length with free ends and through the measurement of the force exerted on the constraints with fixed ends respectively, both as a function of time or temperature.

Shrinkage or shrinkage stress generated is caused by an entropic retraction, when the internal energy of an oriented polymer is elevated by an increase in temperature at ambient temperature. Polymer molecules tend to relax the orientation by retracting from an ordered, extended conformation to disordered, random coiling. This eventually produces a change of length or contraction force.

In polymer fibres, there are two basic contraction mechanisms leading to macroscopic shrinkage that can be distinguished. These are amorphous and crystalline contractions or regions. The other shrinkage mechanism is the crystalline contraction. It occurs, especially in differential shrinkable fibres. This type of contraction is provoked by rearrangement of the crystalline phase, connected with the formation of "perfect" crystallites with folded chains.

The maximum shrinking forces are in crystalline contraction, three to six times lower than in amorphous contraction. Under similar drawing and setting conditions, crystalline contraction does not depend on the type of co-monomer but only on its content.

At higher temperatures, the shrinkage due to recoiling of chains and crystallization processes is concurrent. The amorphous region has more effect than the crystalised part during shrinking when drawing or when pulled under thermal conditions. Figure 2.21 is the image that shows the filament model with amorphous and crystallized regions.

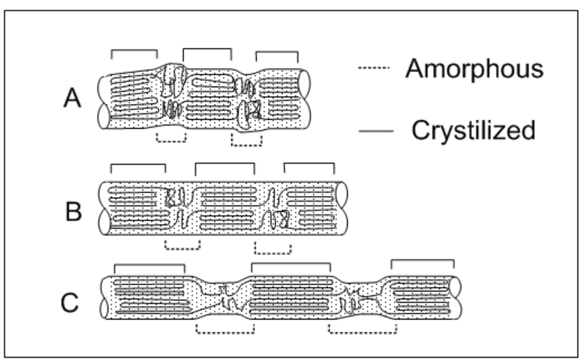


Figure 2.21: Yarn helical model with amorphous a crystallized region

(A - Shrinked filament, B- normal filament, C-Over has drawn filament or yarn)

(Adapted from Morton and Hearle, 1999*)*

From Figure 2.21, crystallized regions have less effect during shrinkage and drawing. A maximum draw is a point at which the fibre or yarn snaps off when it is further drawn (Gupta and Bashir, 2002).

When the fibre is allowed to shrink during heat setting, there are no external constraints to structural re-organization and a significant part of the residual stresses present in the non-heated drawn yarns relaxes (Militký and Kremenakova, 2008).

2.15.7. Thermal Shrinkage residual

The thermal shrinkage residual is a term describing the amount of shrinkage remaining in fabric, yarn, or filament after finishing the thermal process, expressed as a percentage of the dimensions before finishing the thermal process. The potential shrinkage that remains in fibre, yarn, or fabric after treatment is designed to reduce or eliminate shrinkage (Militký and Kremenakova, 2008).

2.16 Woven fabric for filtration and microfiltration

Woven fabrics are stronger than non-woven fabrics because the fibres are twisted to form yarns before they weave to form a fabric. However, the non-woven fabric is made of fibres that are bonded randomly either by chemical or physical bonding. Most non-woven membranes do not last long and can be easily damaged when compared to woven membranes. Any fractional forces applied to non-woven fabrics affect or change the surface bonding structure. When used as the membrane for filtration, pore sizes of the none-woven fabric membrane surface or woven fabric membrane surface become a huge limiting factor. If pores are at microscale than the fabric can be used as a membrane for microfiltration. Nevertheless, if pores more than micro size, it can be used for simple filtration or a backer. In addition, the fabrics can be modified to minimise the pore size using the finishing processes.

2.16.1. MATHEMATICAL MODEL FOR FABRIC USED AS FILTERS

There are factors or aspects to consider when developing a fabric that can be used for membrane purposes. Fabrics are made of yarns (warp and weft) interlacing to each other at an angle. The patterns play a major role when using fabrics as a membrane.

2.16.2. FABRIC PARAMETERS

The variety of fabric structures is divided into four parts as woven, knits, braids and nonwovens. Comparing with other fabrics, woven fabrics display both good dimensional stability in the warp and weft directions and highest cover yarn packing density. One of the most important features for the characterization of woven fabric quality and fabric performance is the tensile properties of the fabric strength (Zeydan, 2010).

Woven fabric is made on yarns. The yarn is woven over and under to form a checkerboard pattern. The simplest weave is the plain weave. Plain weave can be the tightest, having the smallest pore openings in the fabric, depending on the purposes (Mohurle and Thakare, 2013).

Yarns can be either twisted or not, monofilament or multifilament depending on the usage of the fabric. The weaving patterns affect both fabric strength and permeability. Fabric permeability affects the amount of air or water passing through the filter at a specified pressure drop.

A tight weave, for instance, has low permeability and is better for the capture of small particles. The true filtering surface for the woven membrane is not the fabric itself, but the dust layer or filter cake that occurs on top of the fabric (Lyndon and Rideal, 2004).

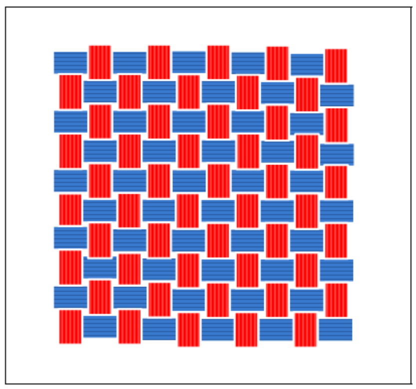


Figure 2.22: Front view is woven fabric from untwisted yarn.

(Adapted from Sondhelm, 2000 and Aldderman, 2004a)

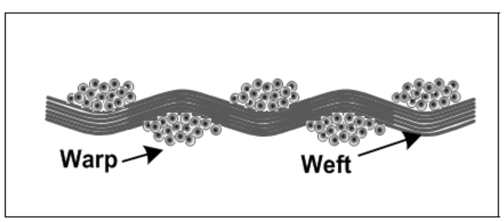


Figure 2.23: Side view of woven fabric from untwisted yarn

(Adapted from Kovar and Dolatabadi, 2008)

There is a relationship or an effect caused by the nature of yarn on fabric characteristics. The twists of the yarn affect the fabric performance and also the fabric texture.

Figure 2.22 is the top view of the fabric made of yarn with small twists or untwisted. Figure 2.23 is the side view of the fabric made of yarn with small twists or untwisted.

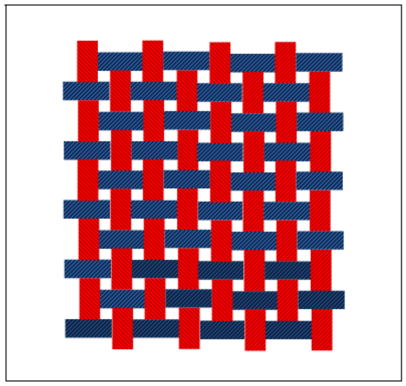


Figure 2.24: Front view of Woven fabric from twisted yarn.

(Adapted from Sondhelm, 2000 and Aldderman, 2004a)

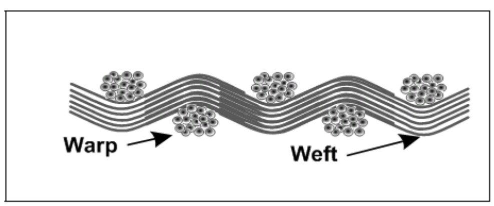


Figure 2.25: Side view of woven fabric from twisted yarn

(Adapted from Kovar and Dolatabadi, 2008)

Figure 2.24 is the top view of the fabric made of twisted yarn and Figure 2.25 is the side view of the fabric made of twisted yarn. The woven fabrics, parallel yarns are only in contact with each other over a fraction of their lengths, and crossover contact may act over relatively complex curved surfaces.

Hence, to produce an analytical model, a number of simplifications are required. Woven fabrics are well known to have non-linear mechanical properties. The tensile behaviour of woven fabrics is non-linear at low tensions, even if the yarn is linear in tension or twisted (Zeydan, 2010).

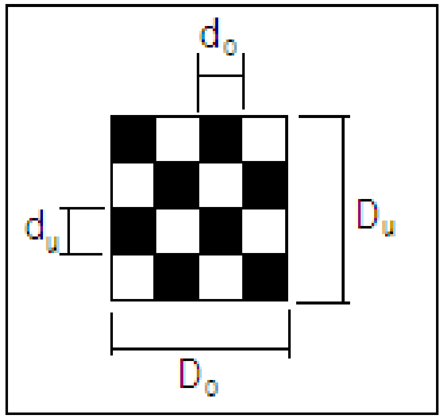


Figure 2.26: Side view of woven fabric from twisted yarn

(Adapted from Sondhelm, 2000, Aldderman, 2004a and Kovar and Dolatabadi, 2008)

From Figure 2.26, the fabric covering created by the same yarn sets warp interlocking with weft. The diameter of the one warp yarn is d_o, and the diameter of the one weft yarn d_u interlock to form the square area of 1 weft yarn x 1 warp yarn. D_o is the covered area per warp yarn sets interlocking with D_u is the covered area per weft yarn sets to form the covered area. The cover area of the fabric is the area that is critical in the filtration process. Equation 2.11 is the warp covering Z_o and Equation 2.12 is the weft covering Z_u.

$$Z_o = D_o \cdot d_o \qquad \text{Equation 2.11}$$

$$Z_u = D_u \cdot d_u \qquad \text{Equation 2.12}$$

Equation 2.13, describing the geometry of the warp yarn segment including the weft yarns, can be derived similarly

$$D_m = \frac{1}{(d_o + d_u)\sqrt{1 - \varepsilon_m^2}}$$ Equation 2.13

D_m is the diameter of the yarn, weft or warp in the fabric, d_o is half the diameter of the yarn above and d_u is the half diameter of the yarn below, while *1-ε* is the space apart.

2.17 Yarn and geometrical properties

Practically, yarn properties are the result of fibre properties, the mutual fibre interactions inside the yarn, and the interactions between yarn and outer influences. The internal structure of yarn is very important especially for the geometrical and mechanical properties of the yarn.

The specific regulations of internal yarn geometry are relatively complicated due to the complex nature of deterministic and random influences. Many mathematical models on this topic were created during the last two centuries.

2.17.1. Yarn fineness and diameter

The fibre or filament fineness, *t* is expressed in Tex or dtex. Tex is actually a fibre mass, *m* in grams per length, *l* in kilometres. There are a number of systems and units that express yarn fineness. The common units for ISO standard are fibre fineness, *t*, bundle fineness, *T* fibre mass, *m*, fibre bundle mass, *M*, fibre length, *l,* bundle length, *L*, fibre density, *ρ*, fibre volume, *V* and equivalent cross-sectional area of the bundle, *A,* cross-sectional area represented by *s*in Equation 2.14 for a filament.

$$t = \frac{m}{l} = s\rho = \frac{\pi\rho d^2}{4}$$ Equation 2.14

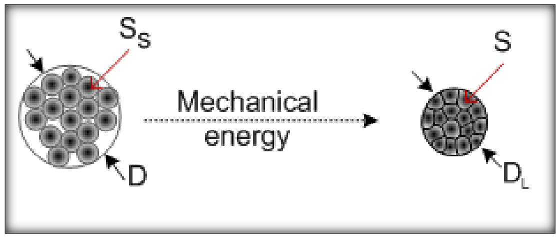


Figure 2.27: Bundle diameter of yarns before and after mechanical twist

(Adapted from Kremenakova et al., 2008)

Assuming that mechanical energy or equipment is used to close the air space between filaments. For multifilament yarn fineness bundle *T* the following mathematical expression or Equation is used to determine the equivalent fibre diameter *D* from the determined cross-sectional area, S, in Equation 2.15 for a yarn.

$$T = \frac{M}{L} = S\rho = \frac{\pi\rho D^2 L}{4}$$ Equation 2.15

2.17.2. Yarn twist

A bundle is more than one fibre or filament. Twist process is a process used to bind filaments or yarn together in a continues strand, accomplished in spinning or plying operation. See Equation 2.16.

$$T = \frac{M}{L} = S\rho = \frac{\pi\rho D^2 L}{4} = \frac{V_y}{L_y}\rho$$ Equation 2.16

When twisting yarn, the fibres are compressed to form what is called a substance diameter, *ds* from real yarn diameter, *D*. From real yarn, diameter and substance diameter it is possible to define yarn packing density μ as a ratio between filament volumes V_f *and* the total yarn volume V_y including the volume of the air V_c (see Equation 2.17).

$$\mu = \frac{V_f}{V_c} \qquad \text{Equation 2.17}$$

Theoretically, a packing density of a yarn increases with the increasing of a yarn twist. If a multifilament yarn consists of fibrous material with a constant Tex, we assume that the substance diameter increases as Tex of a yarn increases. The volume of air between filaments decreases as the twist increases (see Figures 2.28 and 2.29).

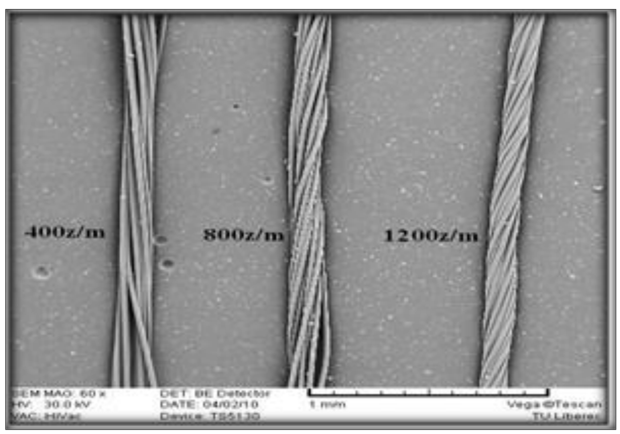


Figure 2.28: Different yarns twist – electron microscope image

(Adapted from Kremenakova et al., 2008)

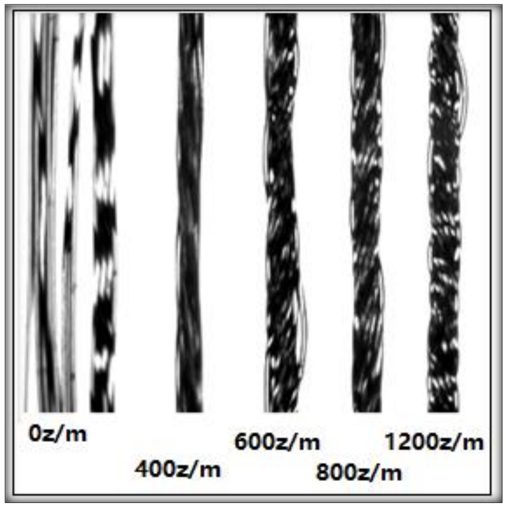


Figure 2.29: Different yarns twist – light microscope image

(Adapted from Kremenakova et al., 2008)

Most twisted yarns can produce woven materials that can be used for treating potable water or wastewater or processing industrial chemicals or processing food and more. However, not all twist provides acceptable woven fabrics that can be used for filtration.

Some twisted yarns may affect the fabric positively and some negatively. Twisted yarns provide a packed yarn. Too much twist will increase fabric density and may have the wrong filtration effect. Some yarns are rotor twisted and some are ply twisted and more. All type o twist does have an impact on fabric performance and physical characteristic (Mncube, 2010).

The image below (Figure 2.30) shows the different types of yarns that affect the formation of the fabric. Textile materials differ considerably from conventional engineering materials in many ways (Ho et al., 2000).

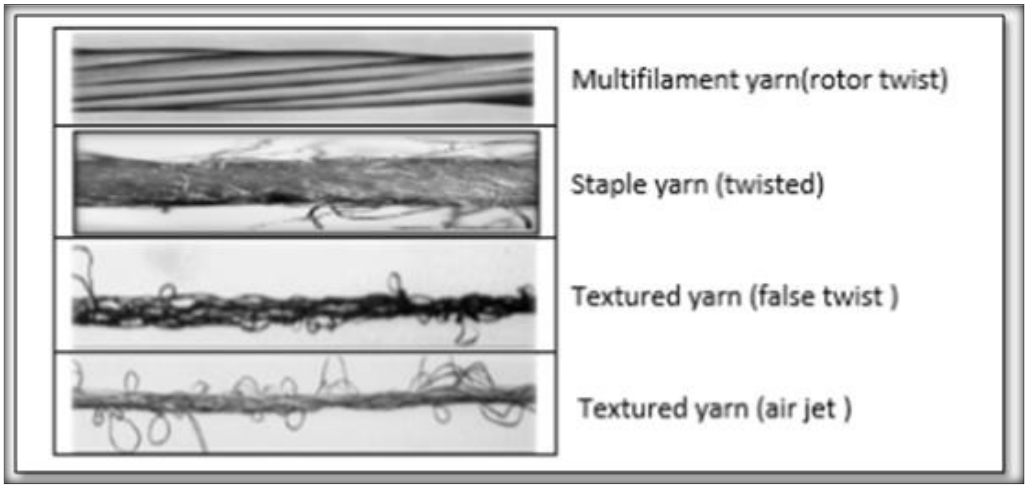


Figure 2.30: Types of yarns that affect the texture of the woven fabrics

(Adapted from Sondhelm, 2000 and Aldderman, 2004a)

Yarn twists affect fabric structures and characteristics. Custom-made fabric structures and characteristics are engineered and fabricated to meet the end-use products. Fibre filaments are bonded or twisted together to make yarn or thread.

The threads are then weaved to form woven membranes or bonded to form non-woven membranes suitable for a specific use.

Equation 2.18 describes the relationship between the Twist intensity, *k* that is directly proportional to yarn diameter *D* and twist *Z* also directly proportional to helix angle of the yarn.

$$tg\beta = \frac{\pi D}{1/Z} = \pi DZ = k = \tan\beta \qquad \text{Equation 2.18}$$

Elongation is a deformation expressed in Equation 2.19. The elongation is a part of the extension through which the fibre does not return on the relaxation of elastic elongation.

$$E_n = \frac{\Delta l}{l_o}$$ Equation 2.19

The stress-strain behaviour of a material determines the material contribution to part strength (or stiffness) and is the relationship between load and deflection in a plastic/amorphous part refer to Figure 2.21. Other factors that affect part strength include part geometry, loading, constraint conditions on the part, and the residual stresses and orientations that result from the moulding process.

$$Stress(\sigma) = \frac{Load\ Force\ (F)}{Cross - sectional\ area\ (A)}$$ Equation 2.20

Commercial polymer filaments have an elongation-at-break in the range of 1% - 25% but this depends on the orientation of a yarn/filament. The stress strains also get affected by the weave pattern and force applied during weaving.

2.18 Membrane fouling

The mechanism of membrane fouling may determine the effectiveness and efficiency of membrane cleaning methods. Fouling may cause a decline in permeate flux. Flushing the membrane surface using water/air and backwashing was widely applied in fabric membrane to remove foulants either deposited inside the membrane pores (standard blocking), at the entrance of membrane pores (complete blocking) or accumulated on the membrane surface cake filtration (Tumpe et al., 1993).

However, the effectiveness and efficiency of membrane cleaning depend not only on the cleaning method itself (intensity and frequency) but also on the fouling mechanism (pore blocking or cake formation or gel formation).

Generally, membrane fouling that can be removed by hydraulic cleaning e. g. backwashing and cross-flushing which is defined as reversible, while fouling that cannot be removed by simple hydraulic cleaning but requires more intensive cleaning (e.g. chemicals) is defined as irreversible fouling (Jiang et al., 2003).

Flux decline in membrane filtration is a result of the increase in the membrane resistance by the membrane pore blockage and the formation of a cake layer on the membrane surface. The pore blocking increases the membrane resistance while the cake formation creates an additional layer of resistance to the permeate flow. Pore blocking and cake formation can be considered as two essential mechanisms for membrane fouling.

During filtration, there is a rapid initial drop of the permeate flux can be attributed to quick blocking of membrane pores. The maximal permeate flux always occurs at the beginning of filtration because membrane pores are clean and opened at that moment.

Flux declines as membrane pores are being blocked by retained particles. Pores are more likely to be blocked partially and the degree of pore blockage depends on the shape and relative size of particles and pores.

The blockage is generally more complete when the particles and pores are similar in both shape and size. Some scientists claim that pore blocking is a quick process compared to cake formation since less than one layer of particles is sufficient to achieve full blocking (Herrera-Robledo and Noyola, 2015).

Further flux decline after pore blockage is due to the formation and growth of a cake layer on the membrane surface. The cake layer is formed on the membrane surface as the amount of retained particles increases. The cake layer creates additional resistance to the permeate flow and the resistance of the cake layer increases with the growth of cake layer thickness. Consequently, the permeate flux continues decreasing with time (Cai et al., 2013).

2.17.1. Factors affecting fouling

- Membrane properties: pore size, hydrophobicity, pore size distribution, and membrane material, fabric finishing.
- Solution properties: solid (particle) concentration, particle size, and nature of components.
- Operating conditions: pH, temperature, flow rate, and pressure.

2.17.2. Fouling characteristics

Adsorption: This occurs when specific interactions between the membrane and the solute or particles exist. A monolayer of particles and solutes can form even in the absence of permeation flux, leading to an additional hydraulic resistance. If the degree of adsorption is concentration-dependent, then concentration polarization exacerbates the amount of adsorption.

Pore blockage: When filtering, pore blockage occurs, leading to a reduction in flux due to the closure (or partial closure) of pores (Herrera-Robledo and Noyola, 2015).

Deposition: A deposit of particles can grow layer by layer at the membrane surface, leading to an important additional hydraulic resistance. This is often referred to as a cake resistance.

Gel formation: macromolecules, the level of concentration polarization may lead to gel formation in the immediate vicinity of the membrane surface, for example, a solution of concentrated proteins.

Large suspended particles: Particles present in the original feed (or developed due to concentration polarization) can block module channels as well as forming a cake layer on the surface (Herrera-Robledo and Noyola, 2015).

Small colloidal particles: Colloidal particles can create fouling layers (e.g. ferric hydroxide from brackish water can become a slimy brown fouling layer). In the recovery of cells from the fermentation broth, some colloids can be present.

Macromolecules: Gel or cake formation on the membrane. Macromolecular fouling can occur within the structure of porous membranes Small molecules like some small organic molecules tend to have strong interactions with some polymeric membranes (e.g. anti-foaming agents, such as polypropylene glycols used during fermentation adhere strongly to certain polymeric membranes) (Jiang et al., 2003).

Proteins: Interactions with surface or pores of membranes.

Chemical reactions: Concentration increase and pH changes can lead to precipitation leading to the scaling of salts and hydroxides.

Biological: Growth of bacteria on the membrane surface and excretion of extracellular polymers (Jiang et al., 2003).

2.19 Porosity of the woven fabric

It is well known, that air and water permeability through fabrics depend on many factors starting with geometrical structure fabric, yarn and filaments or fibres. These properties are connected with so-called porosity. Porosity has a decisive influence on the utilization of the fabric for some technical applications (filters, sails, parachutes) and clothing applications as well. Fabric porosity depends generally on the fabric and yarn construction. It was shown that for tightly woven fabrics, there exists a good agreement between air or water permeability and inter fibre pore volume or porosity (Militký et al., 2011).

In plain or semi plain filter /mesh materials, the pore structure is clearly defined when viewed under a microscope. An aperture can be observed with minimal interference from the warp and weft filaments or yarn. Figure 2.31 shows the fabric that is made of monofilament and Figures 2.32 shows the fabric made of multifilament (Hu, 2004).

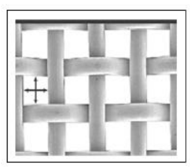


Figure 2.31: Monofilament plain weave membrane

(Adapted from Aldderman, 2004a and Sondhelm, 2000)

Water or air can only pass through the pore between monofilament. The gaps between yarns is the only space that can allow water and air to pass some impurities can also pass if space is wide enough.

Figure 2.32: Computed initial configurations computed for Multifilament plain weave

(Adapted from Aldderman 2004a and Sondhelm, 2000)

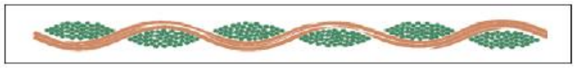


Figure 2.33: Side view for Multifilament plain weave

(Adapted from Aldderman, 2004a and Sondhelm, 2000)

Water or air or impurities can pass through the pore between filaments and yarns if the space is enough.

2.20 Natural fibers and synthetic fibers

a) *Natural Fibre*

Starting with history, in ancient Egypt, linen cloths were usually white. It became a symbol of purity for the Egyptians and was used not only for clothing and household articles but also used for religious practices. Egyptians also produced textiles made of linen, cotton and more. Most cotton was imported from India. Alexander the great introduced cotton from India to Greece and Rome. Cotton textiles were also found in the West Indies and in South America by explorers in the 15th and 16th centuries (Clark, 2005).

Cotton was cultivated by the early American colonists, and after the introduction of the cotton jean by the American inventor Eli Whitney in 1793, cotton becomes the most important staple fibre in the world for its quality, economy and utility (Austin, 1942).

According to Chinese legends, the weaving of silk originated in the 27th century BC during the reign of Emperor Huang Ti, whose wife supposedly developed the technique of reeling the thread of the silkworm for use in weaving (Austin, 1942).

In the western hemisphere, attempts to cultivate silkworm began in 1620 when King James the 1st of England urged the colonists to produce silk instead of tobacco. In the mid-20th century, only Japan and China were exporting silk (Austin, 1942).

For centuries, people had ways of using wood or natural resources to weave and to draw filaments. According to history weaving, one of the first crafts was practised as early as the new Stone Age. In ancient Egypt, the earliest textiles were woven from flux; in India, Peru, Cambodia, woven from cotton; in Southern Europe woven from wool, and in China were woven from silk.

History shows that the ancient people were using non-woven fibres in the form of Non-woven material membranes for filtration purposes. Natural fibres or sand will be packed into a tube and water will flow pass the natural fibres or sand in the tube. Those practices of using natural fibres for filtration processes were tried and tested in the past for centuries and most have advantages and disadvantages.

According to textile engineers, most natural fibres or filaments are staple filaments. Synthetic filaments can be more than 1-meter yet most natural filaments from animals are less than 1meter. Camel fibre is one of the good examples of natural fibres. Camel fibres are hygroscopic (ability to absorb water), at high humidity can absorb up to 33%, and have a low heat conductivity coefficient. Camel fabric absorbs moisture, lets the skin breath, and neutralizes unhealthy substances in the human body. Camel fibres do not electrify at all, does not get dirty easily, have weak tenacity and low tensile strength. They have more resistance in acid then alkalis like wool. The camel fabrics are recommended for health purposes when used as a garment as compared to filtration purposes. Camel fibres (see Figure 2.34 and 2.36) are too bulky to be used as microfiltration material. However, these filaments are too expensive and are not available in most emerging countries. Climate conditions in other parts of the world are not suitable for camel animals.

The human hair is 3 times smaller than camel filament; however, the human hair (see Figure 2. 35) has some similarities with the camel filaments. Camel fibre contains more wax (animal wax). Strong and durable elastic yarn camel fabrics can last longer than normal fabrics.

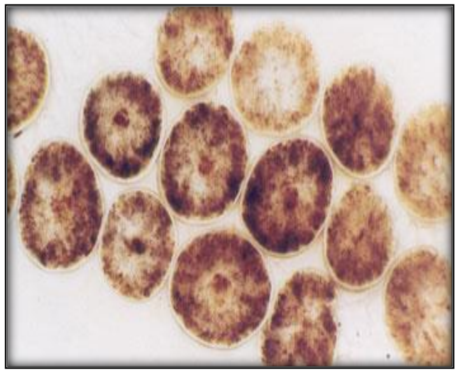


Figure 2.34: Top view of the camel fibres

(Image from the light microscope (1X10^3))

(Adapted from Mncube, 2010)

Figure 2.35: Side view of the human hair

(Image from the light microscope (50X10^3)

(Adapted from Mncube, 2010)

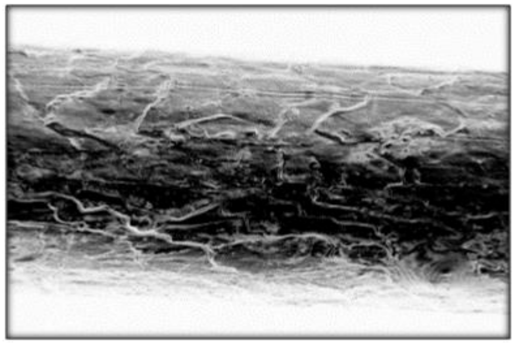


Figure 2.36: Camel filament Image from the confocal microscope

(Image from the light microscope (5X10^3) Adapted from Mncube, 2010)

b) <u>*Synthetic Fibre*</u>

In 1589, the first knitting machine was also discovered after the discovery of ion casting process. Followed by the weaving shuttle machine that was discovered in 1733 (Clark, 2005b). Weave materials were also tested in filtration processes and were not meeting the microfiltration standard requirements. For years, engineers and scientists tried to use the natural fibres and also woven materials for filtration processes and most of them failed to come up with the right technology that meets the microfiltration standards when using woven material as filters. Some engineers and scientists end up believing that weave materials will never meet the microfiltration requirements, while others believe that they will in the near future, provided the right materials and technologies to produce the right woven materials are being discovered.

Synthetic filaments were discovered in the late 1800s. A freshman called Hilair de Chardonnet discovered the nitrate silk in 1891, followed by Viscose silk and Acetate silk discovered by Cross Bevan in 1892 and Schutzenberger in 1894 (Sixta, 2014).

In 1935, the industrialization was booming and companies like DuPont worked with Wallace H. Carothers in developing a Nylon PAD 6,6. In 1942 polyester PET was discovered and manufacture by Whinfield Dickson. Polypropylene was discovered and manufactured by Natta from Italy (Painter and Coleman,2009b).

In 1890, French scientist Count Hilaire de Chardonnet launched the commercial production of artificial fibres. In 1924, the term artificial silk was replaced by the more refined name Nayon of which in 1937 was officially recognized by the US. After 1940, many other synthetic fibres achieved importance in the textile industry (Painter and Coleman,2009a).

Since then, the synthetic fibres drastically replaced natural fibres in clothing, technical textile and more, due to a lot of advantages. Today synthetic fibres are cheaper to develop as compare to natural fibres and more people are using them (Painter and Coleman,2009a).

Various fabrics are shaped by the filament or fibre characteristics and bonding characteristics. All natural filaments come from animals and plants having scales or flakes. The surface is not smooth as compared to synthetic filaments. As noticeable on the image below, only the manmade or synthetic filament is more uniform and has a smooth surface.

Though time, polymer fibres were more available and cheaper than natural fibres. Most people were economically forced to use synthetic fibres. Today synthetic fibres are used more to manufacture woven and Non-woven materials as compared to natural fibres.

Polypropylene fibres are one of the good examples of synthetic fibres. Polypropylene fibres have been produced for over 40 years and have a wide variety of applications including industrial uses, food packaging, membranes and many domestic uses.

Polypropylene fibres belong to the polyolefin fibre group. They were the result of the research work and of the discovery of isotactic polypropylene by Giulio Natta, in 1963, together with K. Ziegler. The term isotactic, which summarizes a concept of molecular structure, can be identified in three ways by their molecular structure. Polypropylene chips can be converted to fibre/filament by traditional melt spinning, though the operating parameters need to be adjusted depending on the final products (Painter and Coleman, 2009b).

Polypropylene fibres have the following peculiar properties: very low specific weight, high tenacity, high resistance to acids and caustic soda, high rubbing resistance, minimal thermal conductivity and low soiling thanks to low electrostatic charges and to water-repellence. Polypropylene fibres are the most used fibres in baby diapers and adult pads, because of the so-called cover, the stock does not absorb liquids, but spreads them to the underlying fluff, thus ensuring that the skin remains dry.

Polypropylene fibres provide excellent resistance to organic solvents, degreasing agents and electrolytic attack. It has lower impact strength, but it's working temperatures and tensile strength are superior to low or high-density polypropylene. Polymer fibres are light in weight, resistant to staining, and have a low moisture absorption rate. Polymer fibres like Polypropylene and polyester fibres are tough, heat-resistant, semi-rigid material, ideal for the transfer of hot liquids or gases. Polypropylene fibres have excellent resistance to acids and alkaline, but poor resistance to aromatic, aliphatic and chlorinated solvents so as polyester fibres.

During the polypropylene fibre production (monofilament), fibre lengths are kept at maximum, to minimize the yarn hairiness and maximize the yarn strength.

Since polypropylene fibres are a polymer, the compound has crystallization and amorphous regions. Both regions play a major role in polypropylene yarn characteristics. The positive characteristics of polypropylene are created during the production period. Polypropylene fibres (see Figures 2.37 and 2.38) and polyester fibres are cheapest polymers and are commonly used.

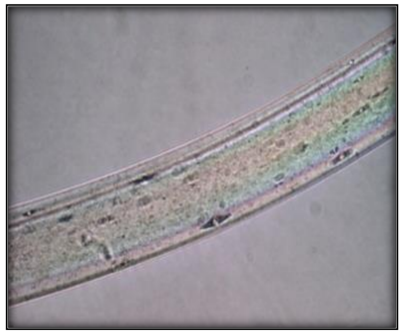


Figure 2.37: Image of POP 20X0. 6 light microscope

(Image from the light microscope (1 X10^3))

(*Adapted from Mncube, 2010)*

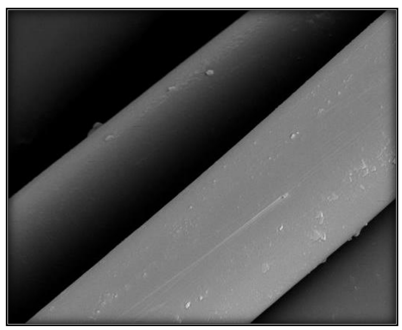


Figure 2.38: Image of POP from 30kv scan electrical microscope

(Image from scan electrical microscope (1 X10^4)

(Adapted from Mncube, 2010)

Due to the advantages of polypropylene and polyester fibres, both of these synthetic polymers are used in filtration. Spun-bonded and melt blown processes are also very important fibre bonding techniques to form Polypropylene and polyester non-woven materials that are used as membranes for air, water and oil filtration.

Most Polymers have a density less than that of water which allows them to float as ropes, nets and other similar applications when compared to natural fibres. The availability, low cost and good resistance to acid and alkaline environments of polypropylene and polyester has greatly influenced its growth and substantial use in technical textile applications.

The polymer fibres are synthetic-based elastomeric polymers with at least 85% segmented polyurethane in their structure. They have rubber-like properties, which means they can be extended up to six or more times their original length (See Figure 2.39). They are used in combination with most natural and synthetic fibres in knitted and woven materials. Tenacity, modulus and percentage elongation ranges for most conventional fibres have more advantages as compare to most natural fibres (Mohsen, 2000).

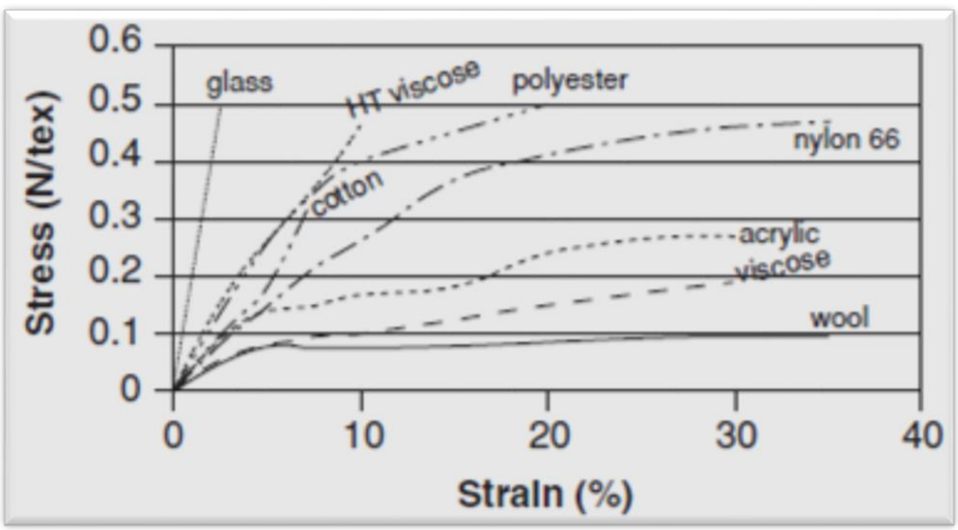


Figure 2.39: Stress/strain behaviour of some common fibres.

(Adapted from Mohsen, 2000)

2.21 Particle size distribution

Filtration is a complex process involving a number of simultaneous elementary processes like complete pore blocking, gradual pore blocking, standard blocking, primary layer formation, and cake formation. However, the fabric can act as a screen and not a filter, allowing a certain size of the particle to pass while screening other particles.

The efficiency of cross flow and dead-end filtration depends strongly on hydrodynamic conditions of the feed and membrane characteristic. In most cases when selecting the filter membranes for cross-flow microfiltration and dead-end filtration processes, the driving pressure, permeate quality, membrane pore size, and feed quantity including the feed characteristic and condition are taken into consideration.

The true filtering surface for the woven membrane is not the fabric itself, but the dust layer or filter cake formed during the filtration. In some cases, the fabric acts as a screen allowing small particles to penetrate the fabric while preventing the bigger particles from passing.

In selecting the membrane, the first important part is the required permeate, before considering the filtration operation conditions and processes. Membrane pore size is determined by the required permeate. The operation and filtration processes are selected based on the feed and membrane characteristic that includes membrane pore size, feed particle size distribution, membrane strength, operation temperature, and pressure.

During the initial part of filtration, the particles smaller than the membrane pore size go through the membrane, bigger particles close or block the membrane pores because are not passing through the fabric or membrane. However, the bigger particles form a cake or layers that create even smaller pore sizes on the membrane.

2.22 Fabric design for microfiltration membrane

Intensive labour in research and development is needed for designing, testing and installing efficient and inexpensive wastewater treatment plants or units depending on polluted effluents and their projected final quality. These innovations shall focus on both onsite and offsite systems herein this report focuses on the membrane optimisation for water and wastewater system operations at low energy. Weave pattern, fabric characteristic and yarn characteristic are critical in designing polymer membrane. When designing the system for filtration, the pore size of the membrane or fabric and the particles size of the impurities become critical. Warp beam or tension beam must be operated accordingly, making sure that the tensions accommodate the weft tension and warp tension according to the required filter material (Mohurle and Thakare, 2013).

2.23 Mechanism for membrane fouling

One of the biggest problems of using membrane is the decay of permeate flux, which is caused by the phenomenon known as fouling. Fouling in mainly a pore blocking caused by compressible material and incompressible material. Several studies indicate that an increase in transmembrane pressure can lead to a positive effect in flux since it is the driving force. However, that becomes a problem for systems that operate at low pressure and systems that maintain the constant pressure during the operation.

When dealing with fouling, water contains impurities that are compressible and also impurities that are incompressible. If the filter pores are bigger, the impurities will pass through the filter and compromises the quality.

The mixture that is consisting of small particles and bigger particles can be separated by fabrics that allow the smaller particles to pass through. However, this process is called screening; some may strongly believe that the process is still called filtration even though small particles are passing.

2.24 Technologies and material used for low energy filtration

Slow sand filters, granular media rapid rate depth filters, and charcoal filters were discovered by accident. Most people in the ancient period were digging a hole in the sand next to a river and drinking water from the hole instead of drinking from the running stream, with an assumption that porous stones and sand do clean water. Porous stones, sands and a variety of other natural materials have been used to filter visible contaminants from water for hundreds of years. Today the sand or natural granule filtering method dominates the current conventional water treatment systems (Kaiser et al., 2002).

Vegetable and animal-derived depth filters are also part of natural methods used by people to clean water that is going to be used for drinking. There are stems that are containing sponge material inside that were used by ancient people to suck water from water sources.

Animal skin and clay pots were also developed by ancient people to collect water, process water and store water. However, ancient people noticed that clay pots allow water to pass through the pores of the pot and so as the pores of the animal skin (Sobsey and Proum, 2007). The British Army began constructing gravity filters with ceramic elements in the 1850s. In the late 1900s, some scientists tested 0.2-micron ceramic candle-shaped filters in Bolivia (Clasen & Boisson, 2006). The global market for ceramic filters consists mainly of candle-style elements used in gravity or pressure (in-line) systems used at the household level by upper- and middle-income consumers concerned about the quality or appearance of their drinking-water (Sobsey & Proum, 2007).

A 1999 study by Anderson Consulting focusing on microbiological-quality ceramic water filters (various brands) showed that sales of 2 million ceramic candle filters were predominantly to developed countries in North America (26% of world sales), the Middle East (20%), the Far East (20%) and the Russian Federation (16%); India represented less than 5% of the market, and sub-Saharan Africa less than 1% (Anderson, 1999).

It was also noted that the overall market for ceramic filters is growing at a rate of 5–10% per year, less than the overall market for household water treatment products.

The ceramic membrane systems and units worked but the production was too low (Clasen et al., 2004). In the late 1900s until the beginning of the 2000s, some entrepreneurs manufactured and sold thousands of ceramic pot filters in Managua, Nicaragua. The membranes work but the production was also too low (Lantagne and Clasen, 2009). Most industries have managed to come up with a wide range of filters since the discovery of polymers (Borucke, 2002). Today the Cartridge Sediment Filters and Non-woven polymer fabric are dominating the water, beverages and oil industries (Varghese, 2002). Pressure or driving force is also a factor for productivity and quality.

2.24.1. Ceramic filters

Ceramic filters have micro-scale pores that are effective for removing bacteria and impurities from water. There are filters made from clay that is often mixed with materials such as sawdust or wheat flour to improve porosity. Ceramic filters are easily assembled, and no component construction is required of the user other than placing the filter into the container (Clasen and Boisson, 2006). Scrubbing the filter with a polymer brush or toothbrush is required monthly as maintenance. Nevertheless, the brushing processes do have an impact on the membrane, since the surface gets damaged.

Figure 2.40: shows the ceramic pot and ceramic candle.

Figure 2.40: Clay pots and ceramic candle on the right

(Adapted from Hoa & Lesjean, 2008)

2.24.2. Bio-sand filters

Bio-sand filters consist of a concrete-coated metal mould filled partially with one layer each of large gravel, small gravel, and clean medium-grade sand. A diffuser plate is placed on top of the sand and water is poured into the remaining space. Bio-sand filters require daily fillings during the 2 to 3 weeks when the biological layer is growing. Bio-sand filters also require regular cleaning, which involves agitating the water above the biological layer. Figure 2.41 shows the Concrete Bio-Sand Filter below.

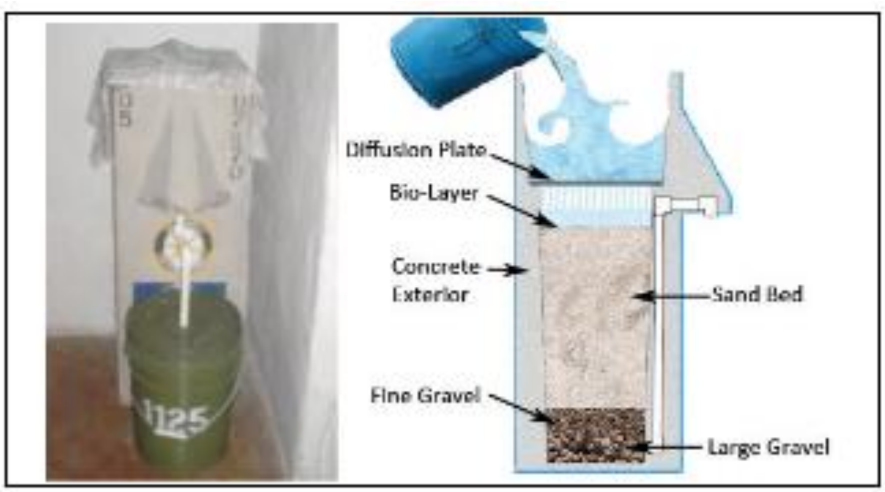


Figure 2.41: A concrete Bio-Sand Filter

(Adopted from Clasen, et al., 2006)

2.24.3. Charcoal and activated carbon filters

Charcoal and activated carbon (AC) is used for water filtration because of their adsorptive properties. These filters capture solid particles in water. Additionally, the filter surfaces chemically interact with organic molecules in order to remove them. Charcoal and AC filtration systems are easy to use and maintain according to the manufactures guidelines. These systems require regular cleaning and filter changes, which require some education and skill.

If regular maintenance schedule is not observed, users may be unaware that the system needs cleaning until signs of contamination are evident.

Figure 2.42 shows the Charcoal and activated carbon (AC) filter the UNICEF, Charcoal and activated carbon up the flow.

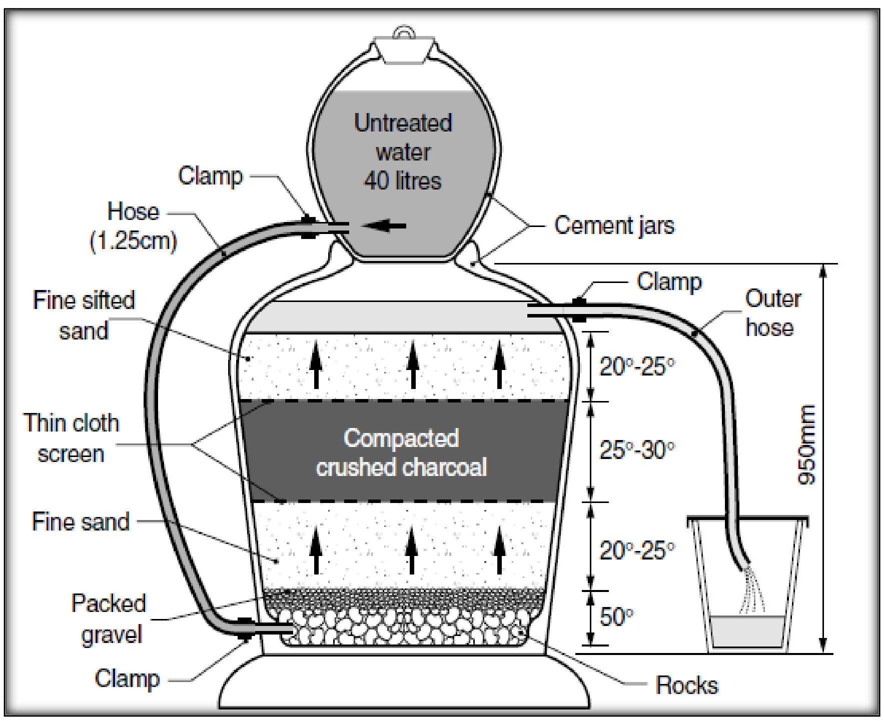


Figure 2.42: The UNICEF up-flow sand filter

(Adopted from Clasen, et al., 2006)

2.24.4. Granular Media and rapid rate filters

Sand, anthracite, sandstone, and charcoal are used as granular media for water filtration in Point Of Use (POU) devices such as the bucket, drum or barrel, roughing, and cistern filters. These granular media are usually negatively charged and may be mixed with positively charged metal oxides and hydroxides of iron, aluminium, calcium and magnesium for more effective adsorption of negatively charged viruses and bacteria.

These filters may also contain antibacterial elements such as silver. Bucket filters consist of two or three buckets or more, one of which is perforated at the bottom and filled with granulated media. Water is passed through this bucket into an empty bucket. Initially, enough water should be passed through the filtering bucket to clean the media.

Figure 2.43 shows the Granular Media filters sometimes known as mineral filters.

Figure 2.43: Mineral Filters

(Adapted from Hoa & Lesjean, 2008)

2.24.5. Polymer and fabric filters

Compressed or cast fibres (e. g. cellulose paper), spun threads (e. g. cotton), and woven fibres (e. g. linen, cotton, polyester, polypropylene and other clothes) are widely used for (POU) water treatment because of their low cost and simplicity. Fabric and fibre filtration involves placing the filter over the opening of a water vessel and pouring the contaminated water through. A cone-shaped filter may also be placed inside a funnel through which the water is poured.

These types of fabrics with bigger pore size are not used as membranes but used as strainers to remove bigger particles or materials like wood and other particles. In most cases, bacteria and other smaller impurities do pass through the fabric pores freely.

Paper and fibrous filters may come in the form of cartridges that are either partially submerged in water or used to pour-through water. For years, polymer cartridge filters have shown significant improvement. On the other hand, woven fabric filters have not made much improvement. However, most cartridges filters require a pressure more than 50mm hydrostatic head.

Figure 2.44 shows the Gravity Driven filtration a system using paper filters

Figure 2.44: Gravity Driven Membrane Disinfection for household drinking water treatment (Peter-Varbanets, 2010)

The ideal systems for rural areas where piped water is still an issue are gravity driven systems. Cartridge filters will not work in remote areas, without pipe water unless people develop systems that will provide enough pressure to drive the cartridge filter systems, which is possible. However, the capital cost will limit underdeveloped areas to develop such systems.

2.24.6. Polymer woven fabric filters

Woven fibres (e.g. linen, cotton, polyester, polypropylene and other clothes) are widely used for POU water treatment because of their low cost and simplicity (Porter et al., 1990). However, the quality was and still not within satisfactory range or was below the drinking water quality standard. Most of these woven fabrics pore sizes were bigger to accommodate microfiltration processes. Most of the woven fabrics were used to filter suspended solids and organic that are visible with naked eye.

2.24.7. Small Scale Filtration System

Modula systems are used by the small-scale system. In order to provide safe drinking water at a local scale and ensure the self-sufficiency of remote communities, many membrane companies have developed their own decentralized treatment unit. Based on the flexibility that the modular configuration enables, a large range of flow capacity exists. Most of the small-scale systems use cartridge filters that are impossible to clean and reuse.

Figure 2.45 shows different types of cartridge filters used by either small-scale filtration systems or pressure driven systems.

Figure 2.45: Stainless steel and Polymer cartridge filter for small scale Filtration systems (Adapted from Hoa & Lesjean, 2008)

Modules are placed in parallel or in series depending on the filtration capacity and quality. Some modules require high pressure; some modules require low pressure. However, most module systems are impossible to clean and most need to be changed frequently.

Figure 2.46 shows different types of small scale filtration systems or pressure driven systems

Figure 2.46: Typical small-scale filtration systems with tubular modules (Adapted from Hoa & Lesjean, 2008)

2.25 Modelling

2.25.1. MODELLING FOR PARTICLE AND CONCENTRATION

During filtration, there is particle transportation that is taking place in any filtration process. Some particles increase with size, while others decrease and others just dissolve in the solution. Particle transport modelling has been considered extensively in both contaminant transport and chemical filtration. However, the particle transport models were used to describe the movement of large particles, such as granular and small particles. This model does not distinguish between filtering and screening since screening is a part of filtration processes.

The particle transport models are very limited and never used or applied to the movement of bacteria, small-suspended solids and more.

The fluid flow through the porous medium is normally determined using Darcy's law, as given in Equation 2.21 below:

$$Q = -k \frac{\Delta P}{\mathrm{L}_0}$$ Equation 2.21

Where: Q is the average flow velocity, k is a proportionality constant related to the flow conductivity of the porous medium with respect to the fluid, ΔP is the net pressure head that causes the flow, and L is the length of the sample in the direction of flow. The pressure difference can be obtained from the Laplace Equation (Equation 2.22).

$$q = -\frac{kA}{\mu} \frac{\Delta P}{\Delta x}$$ Equation 2.22

The slurry velocity is then incorporated in Darcy's law to compute the corresponding hydraulic gradient during filtration. *p* is the particle size that changes at a certain rate at a given time.

$$\frac{dp}{dt} = -\,kp(t_s) \qquad \text{Equation 2.23}$$

$$\left.\frac{dp}{dt}\right|_{t_o} \quad \text{them } \int \frac{dp}{p} = -\,k \int dt \qquad \text{Equation 2.24}$$

$$\left.\frac{dp}{dt}\right|_{t_o} \quad \text{them } p(t) = C_1 e^{-kt} \qquad \text{Equation 2.25}$$

$$\left.\frac{dp}{dt}\right|_{t_s} \quad \text{them } p(t) = C_s \pm C_1 e^{-kt} \qquad \text{Equation 2.26}$$

There are many particles in any solution, some particles dissolve with time and some decay with time until such time was the particles are not decaying any more. Some particles combine with other particles while other particles grow with size special bacteria and organic dyes used in the textile industry and pharmaceutical industries.

Equation 2.27 represent an environment were by the particle decay but not dissolving.

$$\left.\frac{dp}{dt}\right|_{t_s} \quad \text{them } p(t) = C_s + C_1 e^{-kt} \qquad \text{Equation 2.27}$$

Equation 2. 28 represent an environment were by the particle decay and dissolving in the solution.

$p_s < p_o$ then $|p(t) = \ C_1 e^{-kt}|$ Equation 2.28

When it comes to concentration, some particles or impurities in any solution do increase in concentration on the feed side on the membrane side. Bacteria do increase in concentration only if the conditions are favourable for them to grow and multiply with time at a certain rate. However, the bacteria have a certain life span and in most cases, conditions do prevent them to multiply.

$C_s \leq C_o$ then $|c(t) = C_o + C_1 e^{-rt}|$ Equation 2.29

Equation 2.29 is for particle concentrations that are decreasing with time; Where concentration C_s is the final concentration in the solution after population, and C_o is the concentration of bacteria in the solution before population growth. The rate of the particle growth is symbolised by *r*.

2.25.2. MODELLING FOR FABRIC PORES

When it comes to the woven fabric used as a membrane, it is important and easy to model a plain-woven fabric. It must be noted that not all the fabrics are plain weaves. Figure 2.47 below shows an idealized 3D of plain weave fabric geometrical representative unit cell.

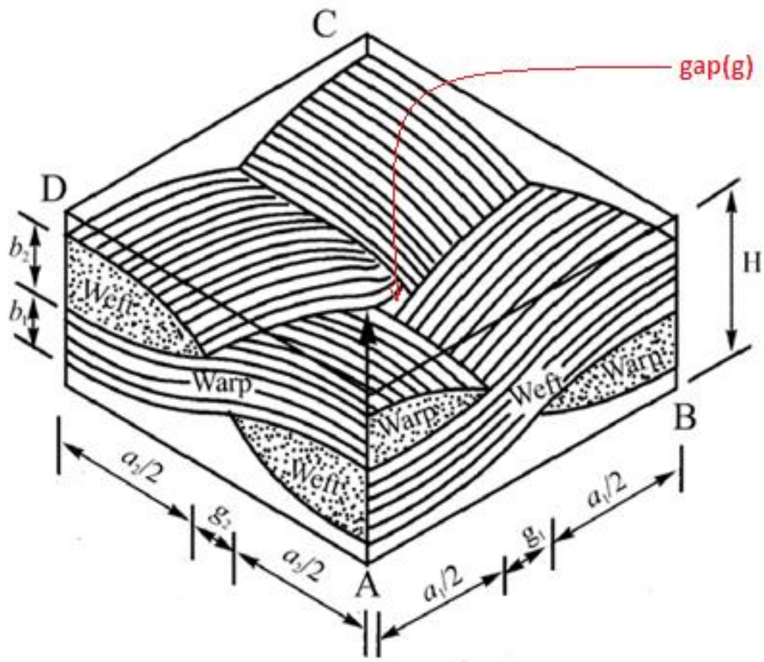


Figure 2.47: An idealized 2D plain weave fabric geometrical representative unit cell (Adapted from Xiong et al., 2009)

From the idealized unit cell (shown in Fig. 2.47) with an idealized cross-section of a typical warp or weft yarn. It is possible to have five variables in the warp and weft yarns being the curved beam width (α1 and α_2), the cross-section height (b1 and b2), the length ($2\alpha_1$+ $2g_1$ and $2\alpha_2$+ $2g_2$) the interstand gap (g_1 and g_2) and sinusoidal crimp amplitude (h1/2 and h2/2). For plain woven fabric, h_1=b_2, h_2=b_1, and the ply plain woven fabric thickness H = h_1+h_2 = b_1 + b_2= h_1+b_2= h_2+b_1

In order to easily calculate the area of the idealized cross-section of a typical warp or weft yarn shown in Figure. 2.47. Below is a simplified cross-section (shown in Fig. 2.48) is implemented to determine the area.

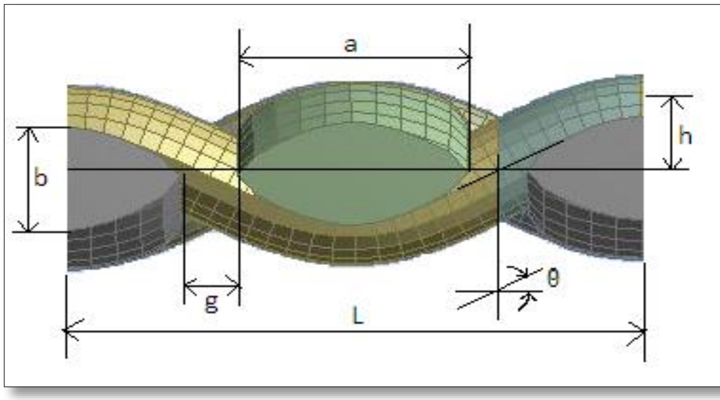


Figure 2.48: An idealized cross-section of a typical warp and weft yarns for weave fabric.

Letting $L_1 = 2a_2 + 2g_2$, $L2 = 2a_1 + 2g_1$, the sinusoidal crimp paths for warp and weft yarns can be then expressed, respectively, as

$$z_1 = \frac{h_1}{2} sin \frac{2\pi x}{L_1} \quad \text{Equation 2.30}$$

$$z_2 = \frac{h_2}{2} sin \frac{2\pi x}{L_2} \quad \text{Equation 2.31}$$

For a differential segment of warp yarn dx = dg (shown in Figure 2.48), the tangent of off-axial angle h can be obtained from Equation 2.30 and Equation 2.31.

By analogy of Equation 2.30 and Equation 2.31 to produce Equation 2.32 and Equation 2.33 below.

$$tan\theta = \frac{dz_1}{dx} = \frac{\pi h_1}{L_1} cos \frac{2\pi x}{L_1} \quad \text{Equation 2.32}$$

$$tan\varphi = \frac{dz_2}{dx} = \frac{\pi h_2}{L_1} cos \frac{2\pi x}{L_2}$$ Equation 2.33

For some woven fabrics that are, not tight enough particles will penetrate through the gap (g) or *dx* between warp and weft.

However, some fabrics that are closely packed, the particles find it impossible to penetrate in the gap (g) between warp and weft. However, water, air, or liquid with low viscosity penetrate within the fabric porosity easily. Some porosity spaces are within filaments or yarns.

When dealing with areas (a) and diameters (d), especial when dealing with fabrics and particles may be confusing if not specified accordingly.

$$d = \sqrt{4s/\pi} = \sqrt{4t/(\pi\rho)}$$ Equation 2.34

Yarn circumference (p) is normally expressed by Equation below

$$p = \pi d(1+q)$$ Equation 2.35

Therefore

$$A = pL = \pi d(1+q)L$$ Equation 2.36

$$a = 4(1+q)/(\rho d)$$ Equation 2.37

$$\mu = \frac{V}{V_c}$$ Equation 2.38

When $V = Ls = L\pi d^2/4$ Equation 2.39

Where *t* is a fibre fineness, *s* is fibre cross-sectional area ρ is material fibre density, *d* is equivalent fibre diameter, *q* is a fibre shape factor, *a* is a specific fibre surface area, *L* is the total length of fibres or filament or yarn, *A* is a total surface area of fibres, *V*is total volume of fibres, V_c is the total volume of fibre assembly, V_p is the total volume of porosity, while µ is the packing density.

Furthermore, the surface area per unit volume of fiber is defined as follows:

$$\gamma = \frac{A}{V} = \frac{pL}{V} = \frac{\pi d(1+q)L}{L\pi d^2/4} = \frac{4(1+q)}{d} \qquad \text{Equation 2.40}$$

$$= a\rho$$

The total volume of the fabric is defined as the follows;

$$V_f = L \times B \times H = H \cdot A \qquad \text{Equation 2.41}$$

Volume of free space among filament is called Porosity at this point the spaces include the size of gaps among weft and warp fibers.

$$V_p = V(1-\gamma) \qquad \text{Equation 2.42}$$

From Equations above, the Equation can be expressed as the equivalent pore diameter (d_p) of which is

$$d_p = \left[\frac{k}{1+q}\right]\left[\frac{1-\mu}{\mu}\right] d \qquad \text{Equation 2.43}$$

$$\frac{dV_p}{dt} = dt \cdot V(1-\gamma) \qquad \text{Equation 2.44}$$

$\left.\frac{dV_p}{dt}\right|_{t_o}$ them $\frac{dV_p}{dt} = -\,V \cdot \gamma$ Equation 2.45

$\left.\frac{dV_p}{dt}\right|_{t_o}$ them $\int \frac{V_p}{V} = -\,\gamma \int dt$ Equation 2.46

$\left.\frac{dV_p}{dt}\right|_{t_o}$ them $V(t) = C_1 e^{-\gamma t}$ Equation 2.47

For volume space within yarns and filaments that are closing during cake formation.

$V_s < V_o$ then $|V(t) = V_p - C_1 e^{-\gamma t}|$ Equation 2.48

From the above Equation $V(t) = V_p - C_1 e^{-\gamma t}$ Equation 2.49

At time t_o the value of V_p it when the membrane is new. However, as time goes on t_s the value will decrease at a certain rate during filtration and cake formation. The porosity volume decreases at a certain rate up to the stage was the volume will not absorb any impurities.

2.25.3. MODELLING FOR WOVEN FABRIC USED AS FILTER

There are essentially two ways of creating models suitable for this work, mathematical and experimental approach. The mathematical modelling is dependent on experimental output. For any mathematical approach, the laboratory experiment and field experiment is very important. A laboratory experiment is a controlled environment however; the fieldwork is the true operation condition without, any control injected into the system.

The Hagen-Poiseuille law for the laminar flow was adapted. Fluid volume per unit time is:

$$Q_1 = \frac{\pi d_p^4}{128\eta} \cdot \frac{\Delta P}{H} \qquad \text{Equation 2.50}$$

Figure 2.49 shows a flow diagram for filtration where the fabric is used as a membrane.

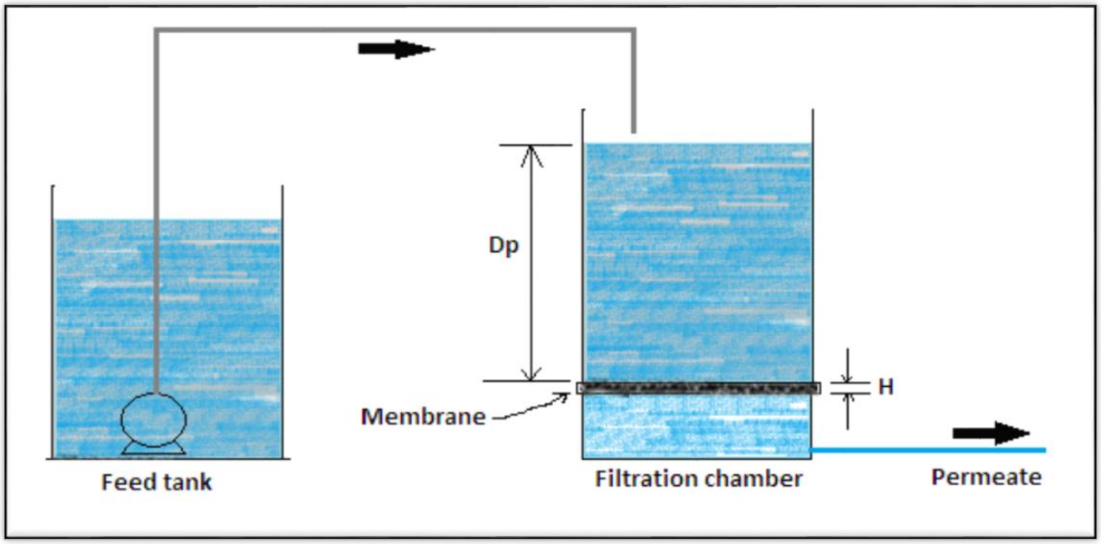


Figure 2.49: Simple filtration process for membrane evaluation

The system operating pressure is D_p. The fabric or membrane is placed horizontally. In this case, there will be a build of cake on the membrane. The fabric used as membrane has the number of pores.

Numbers of (idealized) pores are represented by Equation 2.51

$$n_p = S_p/s_p = 4G(1-\mu)/(\pi d_p^2) \qquad \text{Equation 2.51}$$

Used Equation 2.51 in Equation 2.50 and get the Equation 2.52

$$Q_p = \frac{G(1-\mu)d_p^2}{32\eta} \cdot \frac{\Delta P}{H} \qquad \text{Equation 2.52}$$

When using the equivalent pore diameter, pores within filaments

$$d_p = \left[\frac{k}{1+q}\right]\left[\frac{1-\mu}{\mu}\right]d \qquad \text{Equation 2.53}$$

And the surface area per unit volume of fibre,

$$\gamma = 4(1+q)/d \qquad \text{Equation 2.54}$$

When substituting the Equations to form Equation 2.35

$$Q_p = \frac{G(1-\mu)d_p^2}{32ŋ} \cdot \frac{\Delta P}{H} = \left(\frac{k^2}{2}\frac{G}{\gamma^2 ŋ}\right)\frac{\Delta P}{H}\frac{(1-\mu)^3}{\mu^2} \qquad \text{Equation 2.55}$$

The feed with a specific flow rate Q_f enters the unit and is divided into two streams: Q_p on the permeate side and Q_r leaving on the residue side. These streams have mole fractions of x_f, x_p and x_o, respectively. Hence, we can write the overall mass balance as

$$Q_f = Q_p + Q_r \qquad \text{Equation 2.56}$$

Q_f is the feed flow rate, Q_r is residue flow rate and Q_p is the permeate flow rate. We can also write the component balance as

$$Q_f x_f = Q_p x_p + Q_r x_{rf} \qquad \text{Equation 2.57}$$

The determination of the critical flux depends on several factors such as the feed quality, membrane characteristics, and operating conditions. For filtration, critical flux is defined as the flux, at start-up, below which no irreversible fouling takes place. When fouling does take place J_c is exceeded and fouling occurs.

The cake resistance R_c also increases with increase in time.

Therefore:

$$J = \frac{\Delta P}{\mu(Rm + Rc)} \qquad \text{Equation 2.58}$$

The simplest interpretation of the flux through membranes are the pore flow models. In the simplest pore flow description, the solute particles are not circular and pores go through the membrane. In a given membrane process the flux through the membrane is often a measure for the efficiency. There are, however, other measures for efficiency. Among these are the rejection coefficients. The true, or intrinsic, rejection is a measure of the membranes ability to retain solute particles and is defined as

$$R_{rate} = \left(1 - \frac{c_p}{c_r}\right) 100\% \qquad \text{Equation 2.59}$$

Where c_p is the concentration in the permeate after separation, and $c_r$in the retentate after separation. From Poiscuillc's Equation

$$J_v = k_1 \Delta p \ + k_2 \Delta p \qquad \text{Equation 2.60}$$

$$J_s = k_2 c_m J_o \qquad \text{Equation 2.61}$$

When c_m is the concentration on the membrane surface and k_1 and k_2 are define in Equation 2.62 and Equation 2.63 . Since the transport through the membrane is directly proportional to the pore area on the membrane surface;

$$k_1 + k_2 = \sum_i \frac{\epsilon r_i^2}{8n\Delta x} \qquad \text{Equation 2.62}$$

When η is the viscosity, Δx is the thickness of the membrane and ε is the fractor of a pore area. The solute flux happens through pores larger than sie of the molecule. Hence, k_2 is given by

$$k_2 = \sum_{i, r_i > R} \frac{\epsilon r_i^2}{8n\Delta x} \qquad \text{Equation 2.63}$$

From the equation $v_x \frac{dc}{dx} - D \frac{d^2 c}{dx^2} = 0$ Equation 2.64

When steady state is reached the velocity component perpendicular to the membrane surface will be constant and equal to the volumetric flux, J, through the membrane. Hence,

$$\frac{d}{dx}\left(J_c - D\frac{dc}{dx}\right) = 0$$ Equation 2.65

Hence a differential Equations are formed

$$J_c - D\frac{dc}{dx} = Jc_p$$ Equation 2.66

$$\frac{dJ}{dt} = -\,k \cdot J \cdot (t_s - t_o)$$ Equation 2.67

$\left.\frac{dJ}{dt}\right|_{t_o}$ them $\frac{dJp}{dt} = -\,k \cdot J$ Equation 2.68

$\left.\frac{dJ}{dt}\right|_{t_o}$ them $\int \frac{dJ}{J} = -\,k \int dt$ Equation 2.69

$\left.\frac{dJ}{dt}\right|_{t_o}$ them $J(t) = C_1 e^{-kt}$ Equation 2.70

For Flux's that are decreasing as cake or fouling layer build up during filtration

$J_s < J_o$ then $|J(t) = C_1 e^{-kt}|$ Equation 2.71

For a particle that are growing in the solution

$p_s \leq p_o$ then $J(t) = J_o + C_1 e^{-kt}$ Equation 2.72

From the above Equation, $J(t) = J_o + C_1 e^{-kt}$ applied to all membrane however, some membrane with bigger pores processing a solution with smaller particles may behave different. There are relationships between the pore size, particle size and particle concentration when it comes to filtration (Leilei et al., 2008).

2.26 Summary

More than 70% of the earth surface is water of which 98% of it is seawater. A fraction of clean drinkable water is limited yet the demand is increasing and being polluted daily. Most freshwater is polluted by people, animals, and plants and by industries with toxic waste.

Currently, there are technologies that are used to clean fresh water for domestic, industrial and agricultural use. Most technologies require more land space and energy and skilled operators. Energy can be in the form of power, labour, the addition of chemicals and more. These technologies require research, development, and modification of optimum operations. Currently, these technologies are failing to cope with the demand.

Based on the past research output, it was concluded that more innovation is needed in the water and wastewater sector. One of the innovative technologies that are needed in the sector is reliable membranes. Membranes are made of natural filaments or synthetic filaments. The polymer science revolutions have dominated the synthetic membrane. The term filtration process is general screening also form part of filtration processes. In water and wastewater processes, the microfiltration processes are used due to the fact that water deals with impurities like viruses and bacteria that are micro-sized. Most water impurities range from centimetres to micrometres. The low-pressure membrane filtration processes are gaining considerable acceptance in the drinking water industry over the past twenty years. Fabrics are still used as screens by the rural woman when collecting water from the rivers. Most women from rural areas are not aware that it is possible to use the fabric as a filter rather than a screen.

MF is primarily used for particle removal as a stand-alone treatment, retrofit of existing conventional treatment plants. MF has been demonstrated to be capable of removing bacteria like protozoa, as well as meeting the turbidity requirements of surface water treatment regulations. Most MF uses a woven and non-woven membrane. Most woven membranes are typical fabrics made with monofilament and multifilament, twisted yarns weaved to perfection. The weaving of the fabric is designed to meet the requirement.

The pores sizes of the fabric can be modified for optimal filtration processes. The yarn may be either made from multifilament or monofilament. Textile engineers claim that some suitable fabrics for filtration are a fabric made of a multifilament with twist yarns, while the claims that fabrics pore size are the critical part.

Most low energy systems are gravity driven systems. One of the good examples is the household Point of Use (POU) systems. Household (POU) systems are an important element in the process of reaching the United Nations Millennium Development Goals. If one aims at designing a filtration system for emerging and underdeveloped economies, one must develop a system that works without any power or electricity. POU need only gravity and membrane to treat water. DEWATS also need gravity, reactors and also filters to treat wastewater. Both The POU and DEWATS can be ideal technologies for poor areas. But the membranes and effectiveness of these two technologies remain a limiting factor.

CHAPTER 3.

IDENTIFYING WOVEN FABRICS AND APPARATUS FOR STUDY

3.1. Introduction

Today most filtration processes are using materials like polymers, metals, ceramic and more. However, the market is dominated by polymer filters. Non-woven materials are the most used polymer as compared to woven materials or fabrics. Non-woven material is used in many industries like the automotive industry for air, oil and water filtration. For years, the woven fabric materials were not used for filtration processes because looming machines were not capable of producing fabrics with small pore sizes and balanced tensile strength, suitable for filtration and microfiltration processes. The textile industry has revolved and as a result, most textile companies are capable of producing woven fabrics that can be used for filtration processes and microfiltration (Horrocks and Anand, 2000).

The research in polymer science and technical textile continues to mushroom, producing a plethora of new elastomers, plastics, adhesives, coatings, looming machines, textile machines, fabrics and fibres that are more diverse to address most health, economy, pollution and more challenges in life. The revolving polymer science and technical textile make it possible to develop filtration systems for emerging economies too (Horrocks and Anand, 2000).

Today, there are a number of studies involving woven and non-woven fabric applications. The non-woven fabric studies have been wildly covered in detail. However, the woven fabrics still need more exploration, in other technical fields than being used as clothes.

Most studies covering the woven fabrics used as filtration membranes have too much contradiction. Some researchers believe that woven fabric is capable of processing water and wastewater while other researchers believe woven fabrics are not suitable in filtration processes especially in treating water and wastewater. In general, the fabric can be used as a screen and also as a filter in water and wastewater treatment.

The new literature is gradually being codified and unified with important new theories of the interrelationships among polymer, polymer structure, physical properties, and user behaviour of polymer materials. Thus, the principles of thermodynamics, kinetics, and polymer chain structure work together to strengthen the field of polymer science, especially when used for woven fabrics suitable for microfiltration processes.

The most common polymers used as membranes are polypropylene (POP) membranes and polyester(PETE) membranes. Both of these polymers have been used extensively in filtration membrane applications because polypropylene and polyester are chemically stable, mechanically sturdy and both polymers can be used at relatively low operating temperatures of water and wastewater treatments. Same polymers need continuous evaluation when used as the membrane for filtration especial microfiltration for water and wastewater.

Durban University of Technology (DUT) started using polymer fabrics as a membrane for water and wastewater treatment at the beginning of this century (Mecha and Pillay, 2014), so did the University of KwaZulu-Natal and University of Stellenbosch.

3.2. Polymer fabric use as a membrane

The literature clearly state that treated polymer membranes are offering high permeates. These treated polymer membranes offering good selectivity and flux, and exhibiting a superior anti-fouling property is an excellent filtration membrane. With the film, casting leaching process and the choice of hydrophilic additive, asymmetric polymer membranes can be prepared with controllable pore size and hydrophilic surfaces (Nagai est. al, 2001). Table 3.1 shows the physical specification properties of yarns.

Table 3.1: Physical properties of yarns used for fabrics

Properties	POP	Nylon	PETE	Acrylic	Rayon	Wool	Cotton
Tenacity (N/cm)	4.7	4.7	4.5	2.5	2.5	1.45	2.5
Specific Gravity (SG)	0.91	1.14	1.13	1.17	1.52	1.32	1.54
The yarn weight ratio (Tex/gm2)	1	1.26	1.52	1.3	1.64	1.45	1.69

(Adapted from Franz, 1999, Nagai est. al, 2001 and Horrocks and Anand, 2000)

From (Table 3.1) PETE and POP fibres are stronger than most polymer fibres and natural fibres from a tensile strengths point of view. The durability of these two polymer fibres (POP and PETE) are longer than natural fibres (wool and cotton) that also add to the tensile strength part.

Cleaning POP and PETE with a wool brush or polymer brush does not damage the POP and PETE filaments. POP and PETE filaments are stronger. The life spans of these two polymers (POP and PETE) are also much longer than most polymer and natural fibre filaments.

Properties in Table 3.2 below also show that polymer science material has advantages when compared to natural fibres. Moths and some insects to feed on natural fibres yet are not feed on synthetic fibres.

Table 3.2: Sensitivity of fibres towards pH and moths

Properties	POP	Nylon	PETE	Acrylic	Rayon	Wool	Cotton
Moths/ Insects	Excellent	Excellent	Excellent	Excellent	Average	Poor	Average
Strong alkali (Ph. > 9)	Excellent	Good	Poor	Good	Dissolve	Poor	Average
Strong Acid (Ph. < 5)	Excellent	Poor	Poor	Poor	Dissolve	Good	Poor
Neural (Ph. 5 to 9)	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent

(Adapted from Franz, 1999 and Horrocks and Anand, 2000)

From (Table 3.2), POP and PETE fibres are suitable materials for water and wastewater processing due to their strength to chemical poisoning and towards moths, insects, and bacteria. Washing POP and PETE with weak acid and weak alkali solution will not damage the filaments. POP is the filament that cannot be damaged by strong acid and alkali.

The physical characteristic advantages of POP and PETE fibres was used to search for POP and PETE woven fabric produced in South Africa. There were limited manufactures of POP and PETE fabric in South Africa.

Due to the nature of the study, not all fabrics were going to meet all the microfiltration requirements or filtration requirements. However, the need to further analyse them were critical. If women from rural areas use cloths to screen water, that needs to be understood in dept.

3.3. Membranes and modules

3.3.1. Membrane selection

In South Africa, there are textile companies that are manufacturing technical textile materials used for mining, filtration, geotextile and more. Four woven fabrics were selected from South African local manufactures to be used in this project. These woven fabrics were to be used as a membrane to treat water and wastewater for domestic use. The selected fabrics were made of polyester and polypropylene filaments. A standard protocol or procedure was developed to assist the researchers and fabric users if they aimed to use woven fabrics as membranes. These procedures make it possible for people to analyse fabric capacity to filter liquids.

3.3.2. CRITERIA FOR SELECTING THE RIGHT FABRIC TO BE USED AS A MEMBRANE FOR MICROFILTRATION

The criteria for the woven fabric selection were as follows:

- The woven fabric should be manufactured in South Africa
- The fabric should be woven with polymer yarns
- The woven fabric should give a good permeate quality suitable for domestic, industrial and agricultural use
- The woven fabric should be reliable, have a good or balanced tensile strength
- The woven fabric should have the capacity of treating polluted water and wastewater
- The woven fabric should remove most bacteria to a 4 decimal fraction
- The woven fabric should not require any external driving force besides gravity
- The woven fabric should be inexpensive to manufacture and to install
- The woven fabric should require easy methods to clean, preferable brushing with a polymer brush.

3.4. Fabrics used as membranes for the project

All fabrics used in this study were manufactured by South African manufacturers. Theoretically, porosity and weave structure of the membrane play a major part during the filtration. The cake formed on the membrane also becomes a major factor. Flat sheet modules were developed and were positioned vertically during cross-flow filtration and the membranes or fabrics were positioned horizontally during dead-end filtration. The development of such design started in the twenty-first century and is still in use (Aspelund, 2010).

There are differences between polymer woven fabrics and non-woven fabrics. The non-woven fabrics are wildly used in filtration industries when compare to weave fabrics. However, there is room for woven fabric membranes since the costs of setting up the manufacturing factories for woven fabrics are constantly dropping. This will allow the emerging economy to manufacture woven fabrics that can be used for filtration processes. The woven fabrics used for this research were made of multifilament polymer yarns. The yarns were the jet twist and rotor twists yarns in both weft and warp for all four selected fabrics. The cleaning procedure for the selected membrane was brushing.

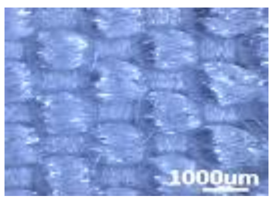
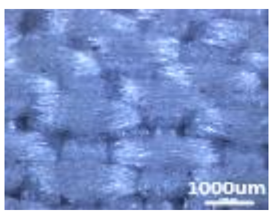
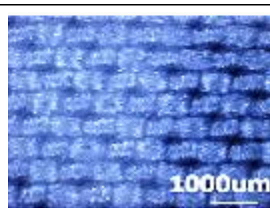
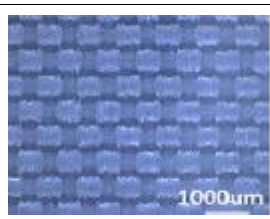
For microfiltration processes, fabrics must have an effective pore size of less than 5 µm or assumed to be 5µm and less. For general filtration processes, fabrics must have an effective pore size of less than 1cm. The suitable fabric that can be used for filtration membrane technology should have the following parameters;

- The woven fabric should have a simple wave that minimises fabric density;
- The woven fabric should give a good, clean water permeate;
- The woven fabric should have high tensile strength and balance;
- The woven fabric should have a smooth surface;
- The woven fabric should have a surface area suitable for brush cleaning;
- The flat sheet should not leak and guarantee a good performance in terms of pathogen removal, high solid rejection and high COD removal;

- The fabric should not leak and guarantee a good removal of pathogens, and solids;
- The fabric should remove about 99.999% of water pollutants to qualify for microfiltration membrane characteristics and the fabric should remove about 99% of water pollutants to qualify for general filtration membrane characteristics or a screener.

The selected membranes were made of polymer multifilaments (see Table 3. 3 below).

Table 3. 3: The selected woven fabrics used in the project.

Membrane no.	Light microscope Images	Summary Description
Fabric 1 or Membrane 1		Polypropylene multifilament yarn Weave type: Plain weave, Jet twisted yarns 19 Weft count and 26 warp count per inch
Fabric 2 or Membrane 2		Polypropylene multifilament yarn Weave Type: Twill weave, rotor twisted yarns 20 Weft count and 33 warp count per inch Modified with warm textile stenter machine
Fabric 3 or Membrane 3		Polypropylene multifilament yarn Weave type: Plain weave, Jet twisted yarns 30 Weft count and 38 warp count per inch
Fabric 4 or Membrane4		Polyester multifilament yarn Weave type: Plain weave, Ply sometimes rotor twisted yarns 46 Weft count and 49 warp count per inch Modified with warm textile stenter machine

3.5. Testing apparatus

There were two types of apparatus used to evaluate the selected fabric performance. The first apparatus was capable of evaluating the membrane during cross-flow filtration and the second apparatus was capable to evaluate membrane performance during the dead-end filtration process. The polymer brush was also selected as the instrument that was used to clean the membrane. Most underdeveloped countries may not have chemicals to clean the membrane; therefore, brushing the membrane was the ideal option for underdeveloped countries. All selected polymer woven fabrics were robust. For crossflow filtration, flat sheet modules were ideal. Polymer fabrics were used as membranes and placed vertically. For dead-end filtration, some fabrics alone were ideal. Polymer fabrics were used as membranes and placed horizontally on the testing apparatuses.

3.5.1 Testing apparatus for cross flow filtration

Membrane modules and membrane housing pack were made in Durban University of Technology, Chemical Engineering laboratory.

3.5.1.1 Membrane Module

Membranes used and selected for the project were a woven fabric. Frames were made of polyvinyl chloride (PVC) material and spacers were propylene. Two woven fabrics were glued to both sides of the PVC frame, with the spacer placed in between the fabrics inside the rectangular PVC frame. The spacer role was to enhance fluid flow internally in the module toward the permeate pipe installed on the PVC frame. The nozzle allowed permeates to flow out of the module, from the nozzle to a tube. The module dimensions used in this project were A4 size for cross-flow evaluation. Figure 3.1 below shows the 3D representation of a single membrane cell and Figure 3.2 shows the 2D representation of a single membrane cell. Figure 3.3 shows the 2D view of a single membrane cell image.

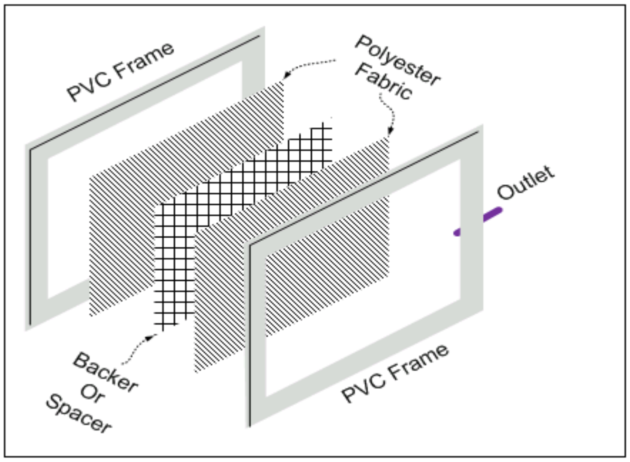


Figure 3.1: 3D of a single membrane cell used for the study

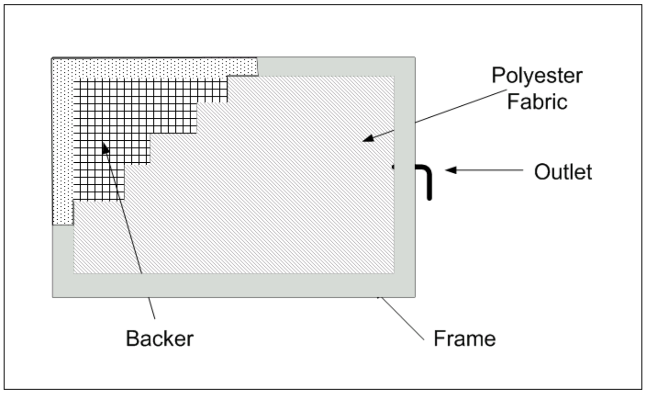


Figure 3.2: 2D of a single membrane cell used for the study

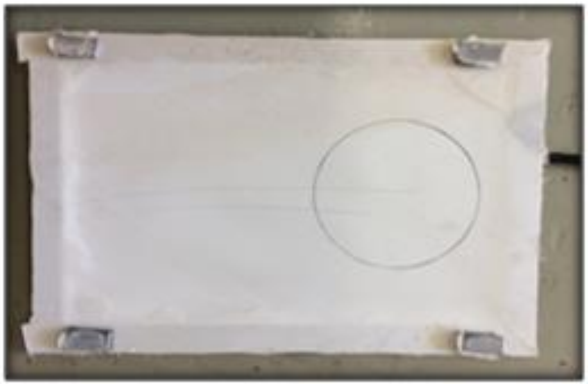


Figure 3.3: Image of a single membrane cell used for the study

3.5.1.2 Membrane pack housing

The membrane pack housing was constructed with Perspex. The pack housing was designed to accommodate more than 15membrane modules at a time. The operational head was 30cm. The membrane pack housing consisted of frames that held the membrane modules. See Figures 3.4, 3.5 and 3.6.

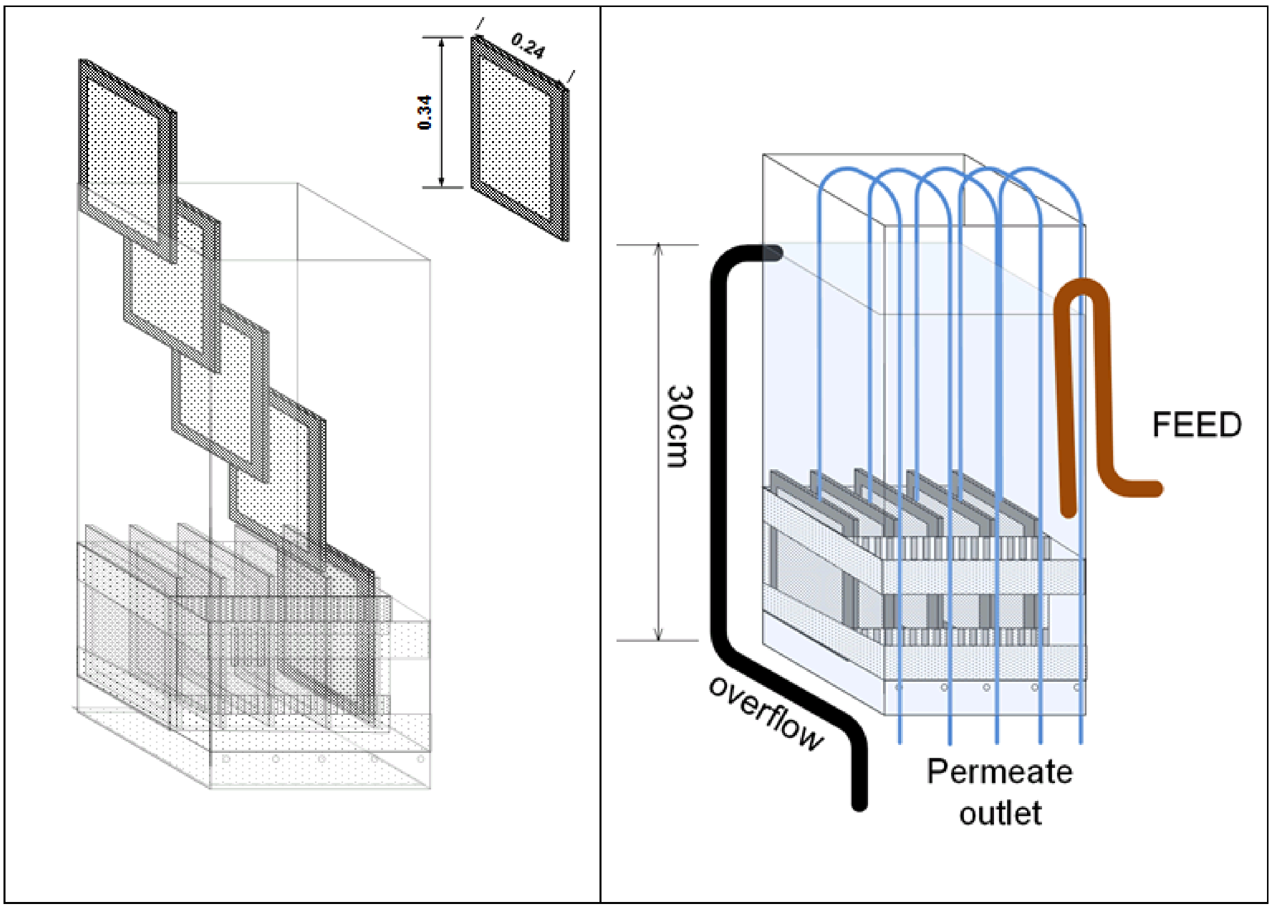


Figure 3.4: Schematic for module and housing of the system used for cross flow filtration

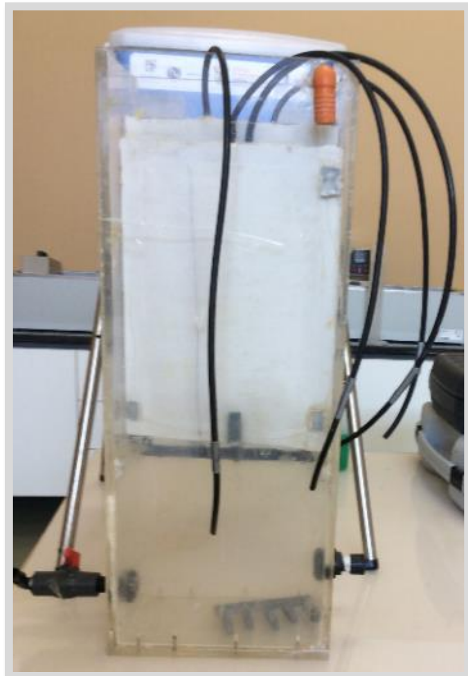


Figure 3.5: One of Module housing with modules inside

This represents a single cell of the membrane stack together to form a membrane system used to evaluate the performance of the system.

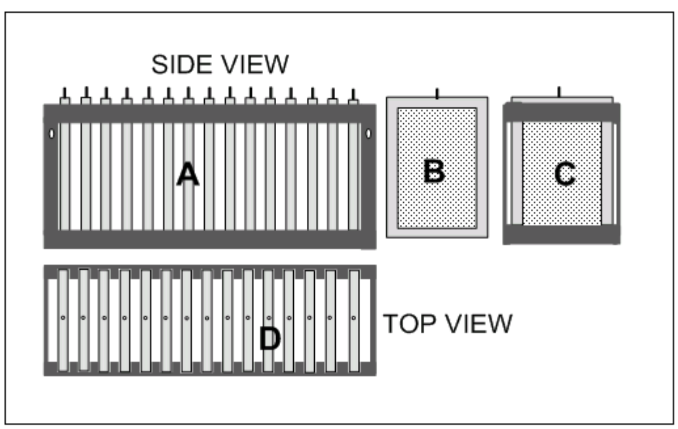


Figure 3.6: Membrane bundle used for the experiment (single membrane combined)

(A-side view of the membrane bundle, B - Single cell, C – Side view of the bundle, D – Top view of the bundle)

The membrane bundle increases the surface area necessary for the filtration process. Ideally, all the membranes perform the same, however in reality, there are factors that affect the membrane performance, and most are linked to dead zone and outlet blockage and leaks.

In this section, the focus is on the dead zone of the single cell/membrane module used to evaluate the performance of the membrane system.

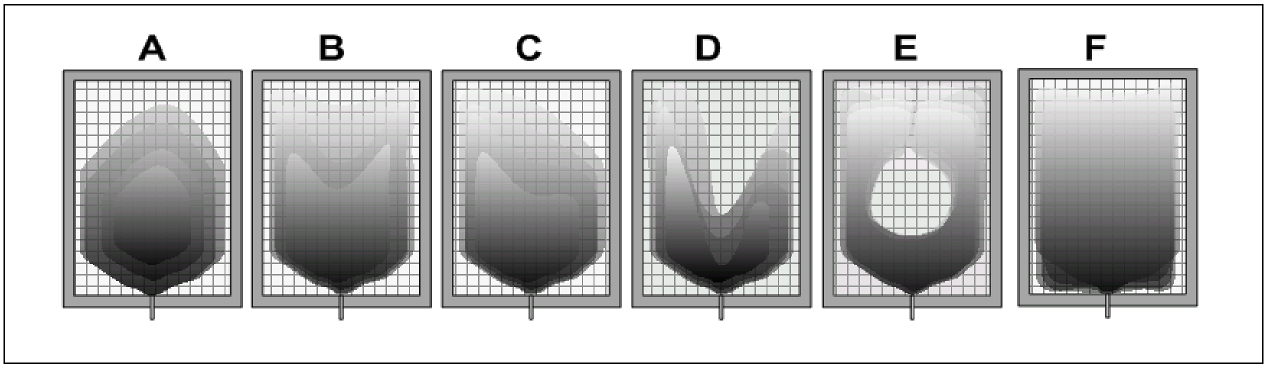


Figure 3.7: Drawing illustrates the membrane dead zones

Due to the low hydrostatic head, a rectangular or square module behaves differently when it comes to the dead zone. Feed, concentration, hydrostatic pressure, backer and permeate forces have major effects on dead end zones for membranes modules. See Figure 3.7.

The ideal module is F (Figure 3.7); all membrane surface areas are active; however, in reality, anything from A to E (Figure 3.7) takes place. The worst module is the one that has the outlet blocked or leaks.

The dead zone is impossible to evaluate, however, does take place in most plate and frame membranes. There are technology and procedures that can assist in evaluating the effective area during the filtration process. The membrane without any spacer was not effective. All the membranes with spacers were more productive than the one with no spacer. Almost half of those membranes without spacers cut the production to less than half.

The membrane system with more than one spacer did not make much of an impact to improve the production. There was no need to add more than one spacer for the experiment.

Membrane orientation has the texture and performance effect on membrane performance. Three types of orientation were used. Warp positioning was 45^o, 90^o and 0^o.

The systems were operated at the 30cm hydrostatic head. The systems consisted of a feed tank, feed pump, filtration tank and the permeate tank. The systems were operated continuously for more than 24 hours. The systems were fed with different solutions that included tap water, wastewater effluents, river water and synthetic solutions. The stable fluxes were determined according to the filtration processes. Samplings were done frequently.

Figure 3.8 shows the diagram of the experimental rig used for laboratory and fieldwork experiment.

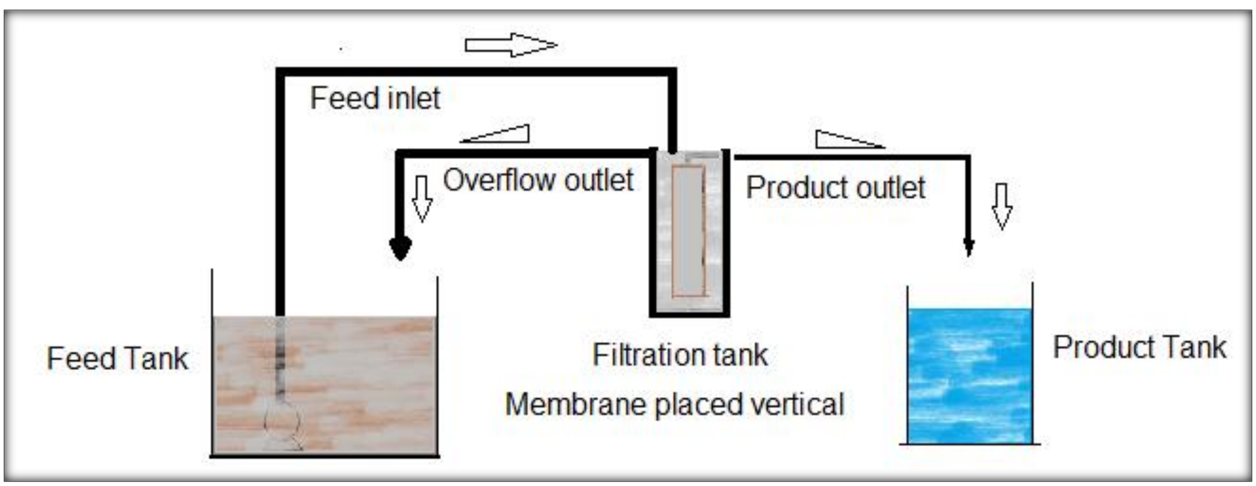


Figure 3.8: Crossflow filtration schematic diagram for a laboratory pilot plant, membrane placed vertically

3.6. Testing apparatus for dead-end filtration

The system was made in Durban University of Technology, Chemical Engineering laboratory. The system was operated at a constant head of 30cm. The process feeds ranged from tap water and river water to a synthetic solution. The bore size was 50 mm. See Figure 3.10 for the apparatus used to evaluate fabrics.

The same procedures of a cross-flow filtration apparatus ware used for dead-end apparatus (see Figure 3.10 and process in Figure 3.9).

Figure 3.9 below shows a process flow diagram of the membrane system used during the study, where the membrane is placed horizontally.

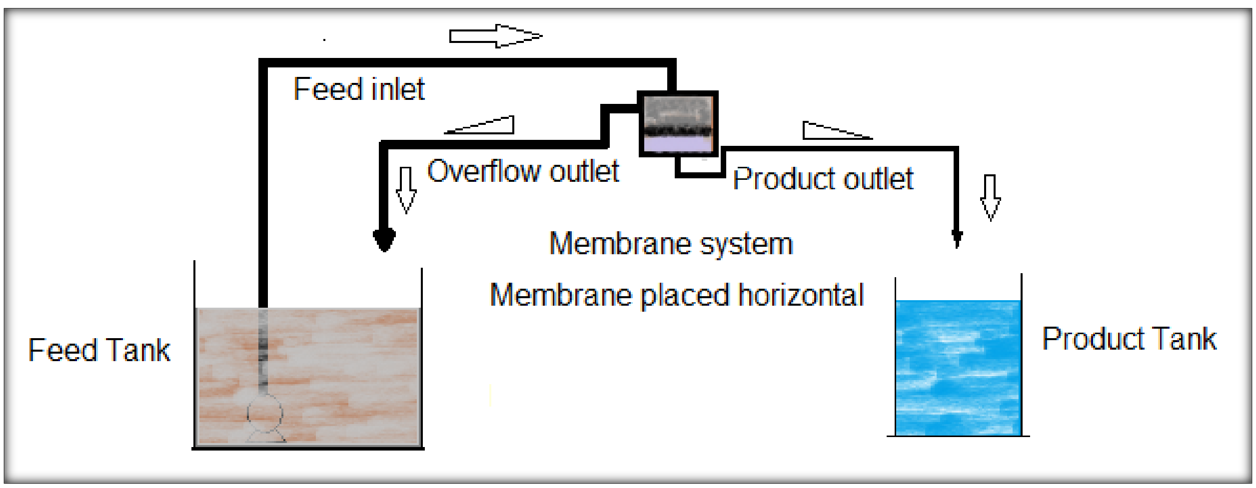


Figure 3.9: Dead-end filtration schematic diagram for the pilot plant, membrane placed horizontally

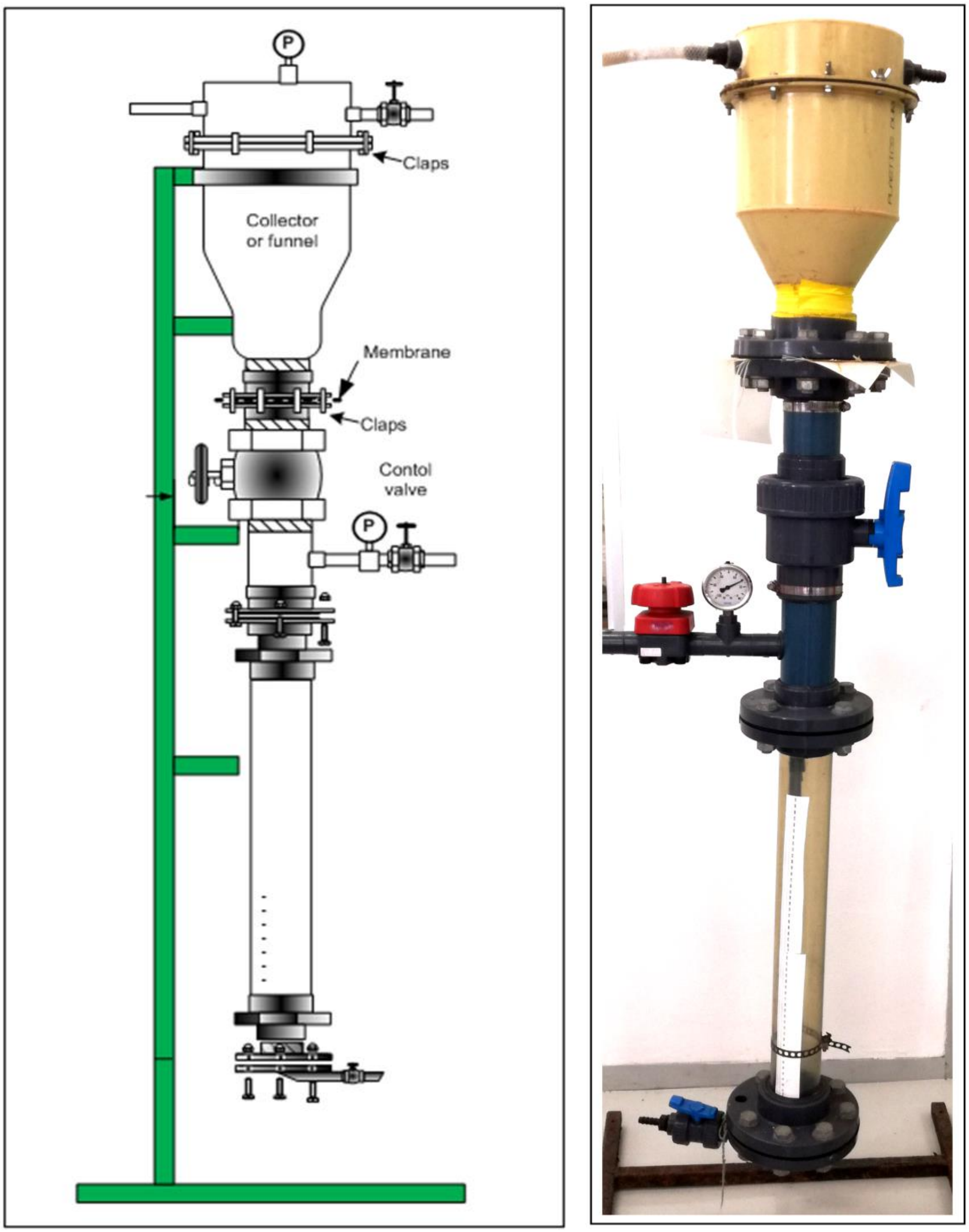


Figure 3.10 : Water permeate tester designed to evaluate the fabric capacity to filter (Fabric placed Horizontally)

3.7. Summary of the designs

There were four woven fabrics selected to be used as membranes for the project of which three of the woven fabrics were made from polypropylene filaments and one woven fabric was made from polyester filaments. All selected fabrics were manufactured in South Africa by local manufacturers.

Woven Fabrics were labelled as membrane 1, membrane 2, membrane 3 and membrane 4.

The membrane modules, A4 in dimension, together with the membrane module pack housing, 500mm x 500mm x 1000mm in dimension, were developed in the Chemical Engineering laboratory at the Durban University of Technology.

For the dead-end filtration system, the system with a 50mm bore diameter was developed in the Chemical Engineering laboratory at the Durban University of Technology. A prerequisite for this is a rigorous mathematical model that can accurately describe whole membrane systems and their building blocks - membrane modules.

Accurate membrane characterisation is of little value if it is only incorporated into an approximate module model. So far, the use of detailed models for membrane separation system simulation and design has hardly been considered.

Existing work has focused on specific separations and a general approach has not been attempted. Until recently, solution difficulties have limited the accuracy of membrane models, however, the use of improved solution strategies combined with increased computational power, facilitates the implementation of more detailed models. Therefore, in this research, many typical assumptions are discarded and the development of a rigorous model for general membrane separation is investigated.

Optimisation design studies of woven fabric membranes used for separation systems have rarely been carried out especially for the low energy systems, and are based on simple models that make a large number of assumptions.

The low accuracy of these models means that the designs advocated are unreliable and that the conclusions presented are highly questionable. The use of detailed models will increase confidence in the proposed designs (Breiman, 2001). Further confidence will be gained if the models have been validated experimentally over a wide range of conditions. In this thesis, these points are addressed. Hence, a new optimal design strategy that incorporates a rigorous mathematical model of a membrane module is developed.

CHAPTER 4.

EVALUATION PROPERTY OF THE SELECTED FABRICS

4.1. Introduction

Theoretically, it is clear that natural fibre can be used as membranes; however, polymer fibres has proven to be more suitable based on economical dynamics, availability, and physical properties of polymer science fibres, which are better than natural fibres. It is also clear that woven fabrics can play a major role in filtration processes just like the non-woven materials. Non-woven polymer materials are not as robust as polymer woven fabric in terms of tensile strength and more. Non-woven polymer fabrics are damaged when cleaning with a polymer brush (Horrocks and Anand, 2000).

Textile industries have managed to develop weaving machines that are capable of producing woven fabrics with small pore sizes making it suitable for membranes with acceptable physical properties. Over the years, most weaving machines have developed some fabrics with warps having or possessing higher tensile strength than wefts. Consequently, it creates a problem on the membrane, especially on pore size. Today looming machines and weaving machines can develop fabrics with balanced tensile strength; less bulky fabric and fabric with good air and water permeate (Sondhelm, 2000).

The process of producing a woven fabric by interlacing warp and weft threads is known as weaving. The machine used for weaving is known as a weaving machine or loom machine. Warp beam, a tension roller, and take-off or cloth rollers are responsible for warp strain/tension, yet the filling carrier or rapier is responsible for weft strain/tension. The harnesses, reed and healed frame are responsible for the pore size of the fabric.

The air and water permeability are dependent on fabric pore sizes. The weave patterns have an effect on fabric volume (Sondhelm, 2000).

Over the years, research and development have managed to optimise most part of the weaving machines like harnesses, reed, heald frame and more. Today, some machines are able to develop fabrics with small pore sizes suitable for filtration processes and screening processes.

The woven membrane is stronger than non-woven membrane when it comes to tensile strength. Non-woven membranes are not stronger due to less bonding forces between yarns or filaments. As time goes one, textile engineers and scientists will find ways of addressing the tensile problem. Most non-woven materials used as membranes have internal filtration, which makes it impossible to clean with a polymer brush when fouled. There is a cost implication when replacing the membrane during the filtration process. The ideal membrane in any filtration process is the membrane that can be cleaned and reused many times without compromising the quality and quantity of the products and production time. Most operations are designed at minimum downtime. If the process demands too much downtime for maintenance, membrane cleaning, membrane replacement and more, the operation or system is too costly to manage. Most filtration systems must have low downtime for cleaning and replacement of the filter. Having the filter that can last longer during the operation is recommended for any operation.

Systems that are low energy driven are good for remote areas, rural areas, undeveloped countries and emerging countries. Systems operating at low energy do not require much energy for operation. Some scientists and engineers claim that the low energy system can operate for longer periods while some dispute these augments. One of the objectives for this project was to evaluate the woven fabrics that are suitable for filtration processes operating at low energy. Hence, the investigations were carried out; (1) to evaluate suitable fabrics for filtration; (2) develop a system or procedure that will assist scientists in evaluating the suitable membrane without delays.

4.2. Definition of fabric filtration for filtration processes

Fabric filtration is a physical separation process in which a gas or liquid containing solids pass through a porous fabric medium, which retains the solids. This process may operate in a batch or semi-continuous mode, with periodic removal of the retained solids from the filter medium. Filtration systems may also be designed to operate in a continuous manner. As with other filtration techniques, an accumulating solid cake performs the bulk of the filtration.

Fabric filtration effectively controls environmental pollutants in gases or liquids. In air pollution control systems, it removes dry particles from gaseous emissions; in water pollution control, filtration removes suspended solids; in solid-waste disposal, filtration concentrates solids, reducing the landfill area required. Often, filtration processes simultaneously reduce air, water, and solid-waste disposal problems (Wang et al., 2004). For fabric filtration to be suitable for filtration processes it must operate within the parameters of filtration, for microfiltration must operate within the parameters of microfiltration, for ultra-filtration must operate within parameters of ultra-filtration. These parameters are mainly pressure and pore size that affect the ability to remove a certain size of particles.

4.2.1. DEFINITION OF THE FABRIC PHYSICAL PROPERTIES AND ORIENTATION

4.2.1.1. THE FABRIC PHYSICAL PROPERTIES

Textile engineers define fabric physical properties and orientation in a relationship between the maximum degrees of overfeeding, the bias angle between the feed direction and the fabric warp or weft, fibre type and fabric mechanical properties, especially fabric formability defined as the product of fabric bending rigidity and fabric longitudinal compressibility.

Yarns can either be twisted or not, monofilament or multifilament depending on the final usage of the fabric or the user requirement. The twisted yarns with multi-filaments not always provide good tensile strength or the good characteristic of the fabric.

During the weaving process, the warp and weft form the orientation angle that has an impact on the filtration process. The weaving patterns and yarn twist affect both fabric strength and permeability. Fabric permeability affects the amount of air or water passing through the filter fabric. Some tight weave fabrics, for instance, have low air or water permeability and are better for the capture of small particles. The true filtering surface for the woven fabric is not the fabric itself, but the dust layer or filter cake that occurs on top of the fabric. However tightly woven fabric can be a true filter that captures small particles and it will not depend on the layer formed on top of the fabric. Sometimes the fabric can be used as a screen, not a filter. The screen is the fabric that allows small particles to pass while preventing the bigger particles. Figure 4.1 is a sketch, showing a side view of a fabric blocking the particles. The other part is the fabric blocking bigger particle, and allowing small particles to flow through the fabric.

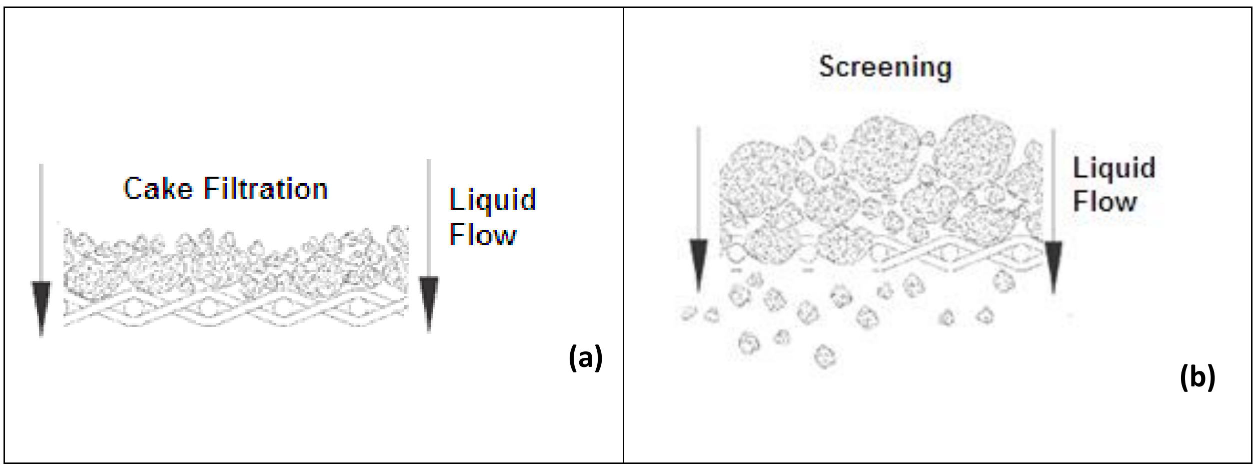


Figure 4.1 : Solid/liquid filtration mechanisms (a) filter, (b) screen

(Adapted from Horrocks and Anand, 2000)

From Figure 4.1 (a) the filter removes almost all the particles this process is filtration. From Figure 4.1 (b) the filter removes almost all the bigger particles and allowing the small particles to pass the fabric this process is screening. Actually, divide small particles from the solution mixture that contain bigger and smaller particles.

Figures 4.2 and 4.3 show the difference between woven and non-woven fibres. Both materials can be used as a filter or as a screen.

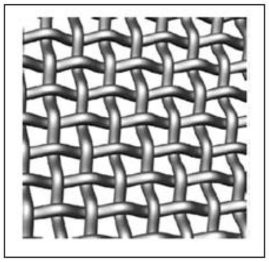


Figure 4.2: Woven structure

(Adapted from Horrocks and Anand, 2000)

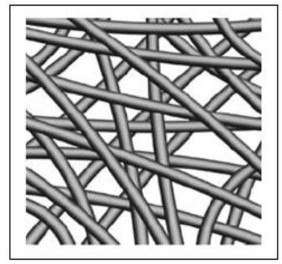


Figure 4.3: Non-woven structure

(Adapted from Horrocks and Anand, 2000)

In non-woven, the pore structure is not clearly defined. Filaments are randomly placed so as the pore sizes are random. For woven fabrics, a plain or semi plain filter /mesh materials warp and weft filaments can be visible and the pore sizes are similar and the same (Eugenio, 2005).

There are methods used for pore size analysis based on testing the permeability of the membrane. These tests also do not provide the actual pore sizes but provide the statistical information necessary to determine the pore size distribution (Weihua and White, 2004).

4.2.1.1. THE WOVEN FABRIC ORIENTATION

As elaborated above, woven membranes have open space surrounded by fibres, and the orientation is visible. Figure 4.4 shows the simple diagram of warp orientation. There were three types of warp orientation used for this orientation study.

Figure 4.4: Modules at different orientation

From Figure 4.4, the warps were positioned in three angles of 0^o, 45^o and 90^o. There is an effect on fabric performance caused by orientation. There is no information available with regard to the impact caused by orientation.

4.3. Equipment set up and experimental procedure

4.3.1. EQUIPMENT SET-UP FOR FABRIC PHYSICAL PROPERTY EVALUATION

4.3.1.1. Fabric volumetric weight

The purpose of this test was to determine the fabric volumetric weight. A number of specimens were taken randomly from the full width of fabrics and were weighed. Two pieces of equipment, the circular weight per metre² cutter and a mass balance, were used in this test. The samples were cut from fabric using a circular cutter and weighted using a mass balance.

4.3.1.2. Fabric Thickness

The purpose of this test was to determine the thickness of the fabrics. A number of specimens were taken randomly from the full width of fabrics and measured using a thickness measuring device. Samples were cut using a blade and the thickness measuring instrument was used.

4.3.1.3. Fabric Tensile Strength

The purpose of this test was to determine the maximum force required to rupture (break) a woven fabric. ASTM D5034 Breaking Strength and Elongation of Textile Fabrics break testing procedure was used. Samples were cut from the selected fabrics, 300 mm long and 12.5 mm wide. The load range was set at 200 N/tex, the speed of the machine was set at 100 mm/min, and the gauge length was at 200 mm for all specimens.

4.3.1.4. Water Permeate Tester

a) Cross-flow filtration

Laboratory systems and also field work systems were used. The systems were operated at 30 cm hydrostatic head. The systems consisted of a feed pump, filtration tank and the permeate tank. The systems were operated continuously for more than 24 hours. The systems were fed with different solutions that included tap water, wastewater effluents, river water and synthetic solutions. The stable fluxes were determined according to the filtration processes. Samplings were done frequently. Figure 3.8 shows the diagram of the experimental rig used for laboratory and field work experiment.

b) Dead-end filtration

The same procedures for cross-flow filtration were used for dead-end apparatus (see Figure 3.9).

4.4. Results and Discussions

There were four woven fabrics selected and used, as membranes for the project of which all selected were polymers. For fabric volumetric weight analyses, random sampling was done from all selected fabrics and the results are summarised in Table 4.1 below.

Table 4.1: Mass of the fabric per unit area.

Membrane :	***Membrane 1***	***Membrane 2***	***Membrane 3***	***Membrane 4***
No of valid data	12	12	12	12
Average [Gsm]	420.33 ± 0.28	251.333 ± 1.69	588.500 ± 1.05	437.333 ± 0.89

Membrane 2 had a fabric volumetric weight that was the smallest and membrane 3 had a fabric volumetric weight that was a lot more than the other fabrics. For fabric thickness, random sampling was done from all selected fabrics and the results are summarised in Table 4.2 below.

Table 4.2: Thickness of the fabric in cm.

Membrane :	***Membrane 1***	***Membrane 2***	***Membrane 3***	***Membrane 4***
No of valid data :	12	12	12	12
Average :	1.114 ± 0.025	0.652 ± 0.003	1.222 ± 0.003	0.554 ± 0.004

Membrane 3 fabric thickness was greater than membranes 1, 2 and 4. The smallest fabric thickness was membrane 4. The membrane or fabric thickness proves that membrane 4 produced membrane modules that were not bulky.

For tensile strength, random sampling was done from all selected fabrics and the results are summarised in Table 4.3 below.

Table 4.3: Tensile strength for all four fabrics

	Weft		Warp	
	Tensile	Elongation	Tensile	Elongation
	kgf	%	kgf	%
Fabric 1 / Membrane 1	55.1 ± 15.25	17. 08 ± 11.54	263 ± 10.25	41.7 ± 10.95
Fabric 2 / Membrane 2	111.5 ± 22.50	116.9 ± 22.25	206.2 ± 23.23	26.14 ± 23.25
Fabric 3 / Membrane 3	102.2 ± 9.35	66.8 ± 14. 25	211.9 ± 10.11	23.0 ± 14.22
Fabric 4 / Membrane 4	170.5 ± 5.40	24.83 ± 2.25	180.1 ± 5.15	26.8 ± 2.20

In general, the polypropylene fibre tenacity is slightly greater than polyester fibre tenacity (see Figure 3.1). The tensile strength test results proved that warp tensile strength for all fabrics were a lot more than weft tensile strengths. Membrane 4 and membrane 2 were treated membranes/fabrics. The weft and warp tensile strength of membrane 4, which was a polyester fabric, had a more balanced weft and warp as compared to other fabrics. For membrane 4, the elongation was also balanced as compared to other fabrics.

The results proved that all polypropylene fabrics warp tensile strengths were more than the warp of the polyester fabric. However, the weft and warp tensile and elongation for all polypropylene fabrics were not balanced. For membrane 1, the warp tensing strength was five times greater than weft and the elongation of the warp was almost double the weft elongation.

The results of membrane 1 proved that the warp and weft yarns have different physical properties. Membrane 4 weft and warp yarns were the same and also the weaving tensions used were balanced.

For water permeate tests, the dead-end filtration process was used to test the fabric resistance. The results proved that membrane 4 has more resistance than other membranes. Other fabrics do not have much resistance. For membranes 1, 2 and 3, water just flows through the fabric without any resistance.

Figure 4.5 shows the behaviour of water permeates for all selected fabrics.

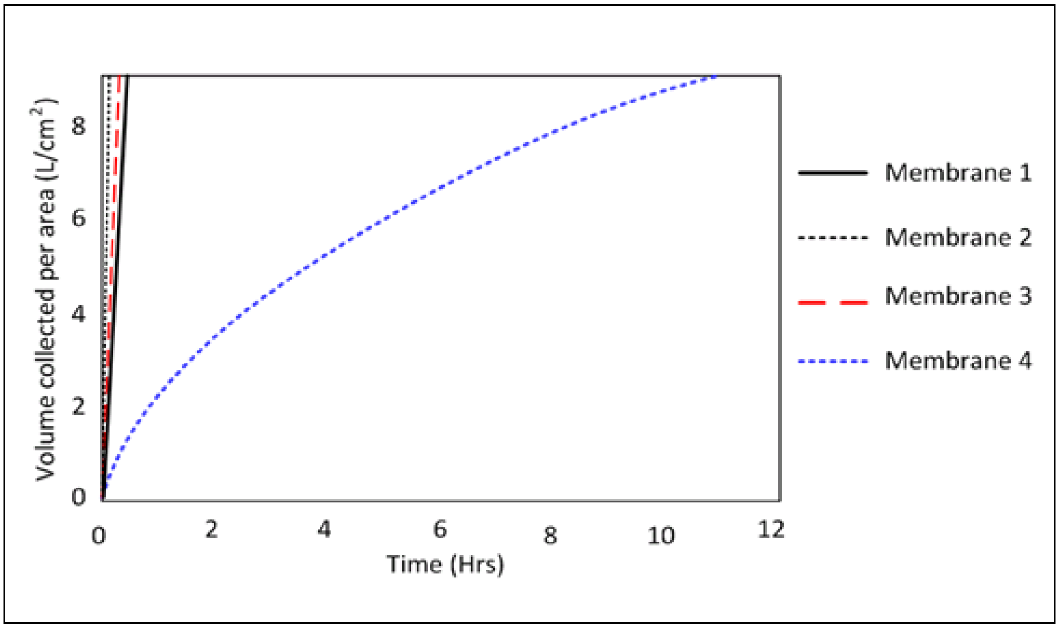


Figure 4.5: Volume collected at 30 cm hydrostatic head.

This proved that membrane 4 has more resistance. The test was critical to understand or evaluate if the fabrics have more pores or large pores. Membrane 1 and membrane 3 have less resistance, proving the fact that membrane 1, membrane 2 and membrane 3 have bigger pore sizes and cannot be used as a filter for microfiltration. However, the test was not sufficient to conclude if membranes 1, 2 and 3 are screeners and not filters.

For crossflow filtration using the effluent from Decentralised Wastewater Treatment Systems (DEWATS), the flat sheet module results proved that membrane 1, membrane 2 and membrane 3 have higher production rates as compared to membrane 4 (see Figure 4.6).

Figure 4.6 shows the flux curves of the selected fabrics when the DEWATS effluent was used as the feed for COD removal where the COD results were taken after 275 hours.

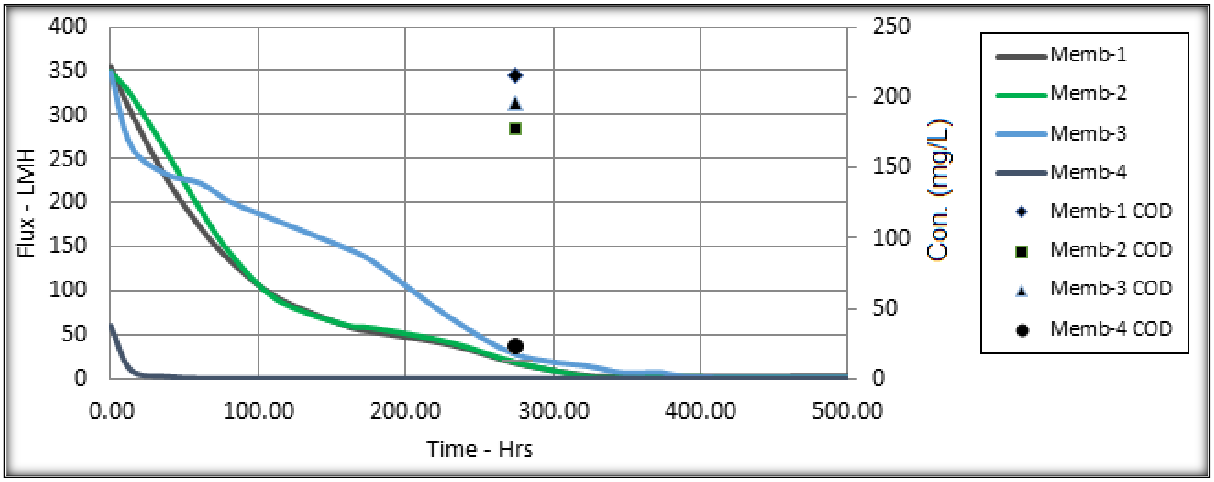


Figure 4.6: Flux curves and COD of all four fabrics used as the membrane.

Figure 4.7 shows the flux curves of the selected fabrics when the DEWATS effluent was used as the feed for coliform removal where the coliform results were taken after 275 hours.

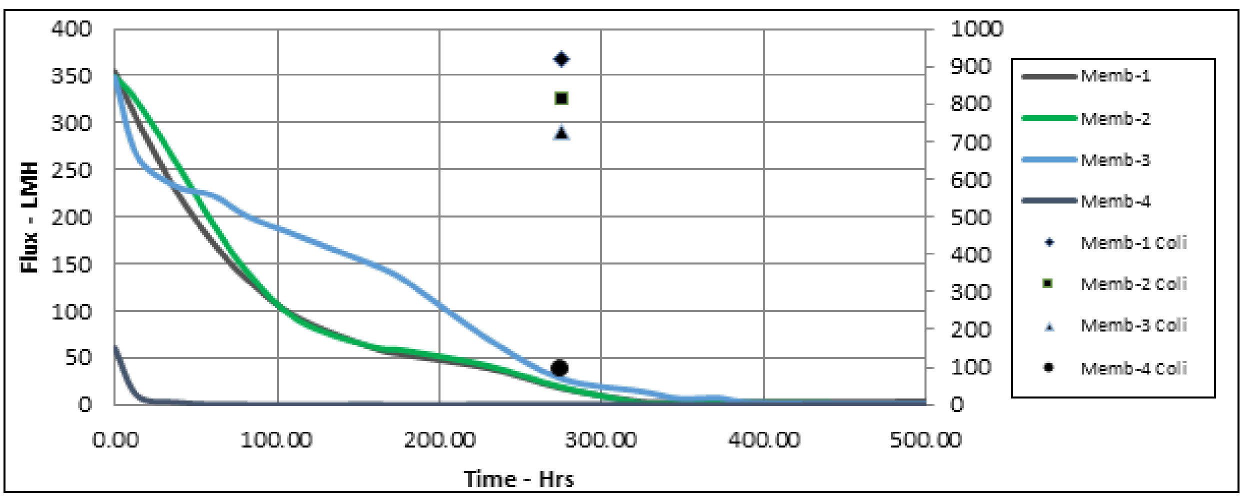


Figure 4.7: Flux curves and Coli form of four types of fabrics.

In Figure 4.6, the COD of DEWATS effluent used as the feed was 450mg/l. After 275 hours the COD of all permeates were also evaluated/tested. Membrane 4 COD reduction was more than 90% yet membranes 1, 2 and 3, after 275 hours, were between 50% and 60% reduction.

In Figure 4.7, the coliforms of DEWATS effluent used, as the feed was 1450000. After 275 hours the coliforms of all fabrics permeate were also evaluated/tested. For membrane 4, the coliform reduction was 99.999%, yet for membranes 1, 2 and 3, after 275 hours, were between 90 and 99.9%.

The e-coli of DEWATS effluent used, as the feed were more than 34500. After 275 hours the e-coli of all permeates were also evaluated/tested. Membrane 4 e-coli reduction was 99.999% yet membranes 1, 2 and 3 after 275 hours were between 90 and 99.9%.

Only membrane 4 was considered to be a fabric that can be used as a filter or membrane for water and wastewater treatment as special for microfiltration processes. The quality of turbidity from membrane 4 was below 1 NTU before and after 1 hour while other membranes produced more than 20 NTU before and after 1 hour of filtration processes. The reduction of bacteria after 20 min was 99.999% for membrane 4, yet all other membranes were not able to remove about 50% of the bacteria even after 1 hour.

Figures 4.8 to 4.13 show the effect caused by polluted water on the selected fabrics. Membrane 4 was the only membrane that had surface separation. Membrane 1, membrane 2 and 3 have internal separation and external or surface separation. The other interesting observation was the fact that membrane 1 and 3 filaments were attracting waste while membrane 2 and membrane 4 filaments were rejecting waste. Filaments used for membrane 2 and membrane 4 were continuous filament; there were no hairiness on the yarns used for membrane 2 and membrane 4. Both fabrics label as membrane 2 and membrane 4 were treated or undergo the finishing treatment.

Figure 4.8 shows the electro scanning images of the used fabrics label as membrane 1, membrane 2, membrane 3, and membrane 4. All fabrics were processing the calcium solution.

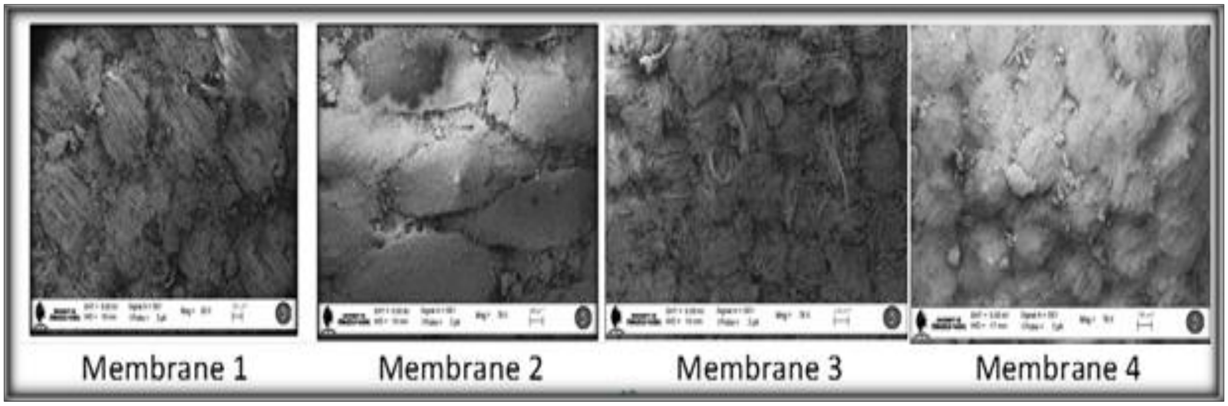


Figure 4.8: Images of the used fabrics

Figure 4.9 shows a camera Image of the used fabrics label as membrane 1, membrane 2, membrane 3, and membrane 4. All fabrics were processing the DEWATS effluent.

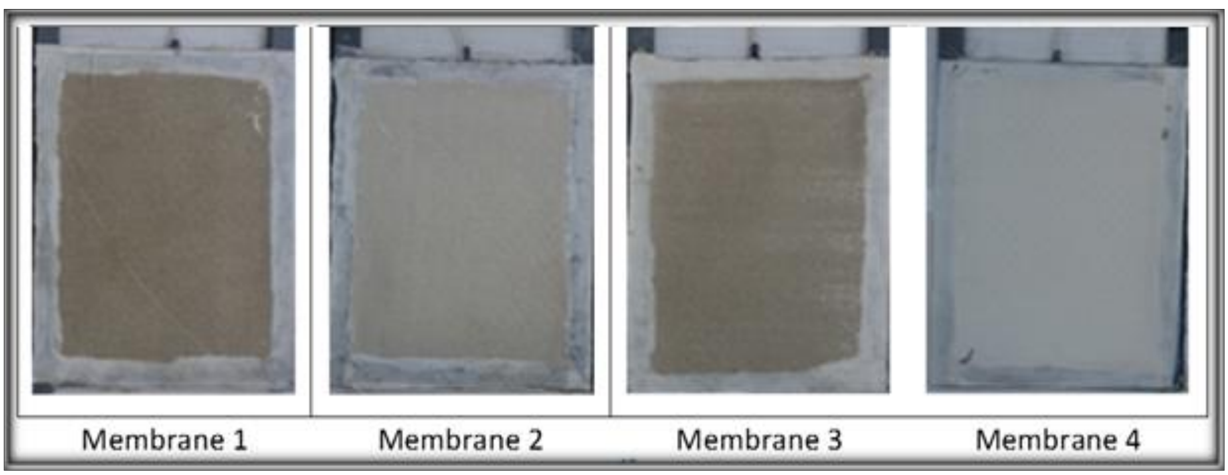


Figure 4.9: Images of the used fabrics

Figure 4.10 shows a camera image and electronic scanning image of the fouled member 1 used for the study.

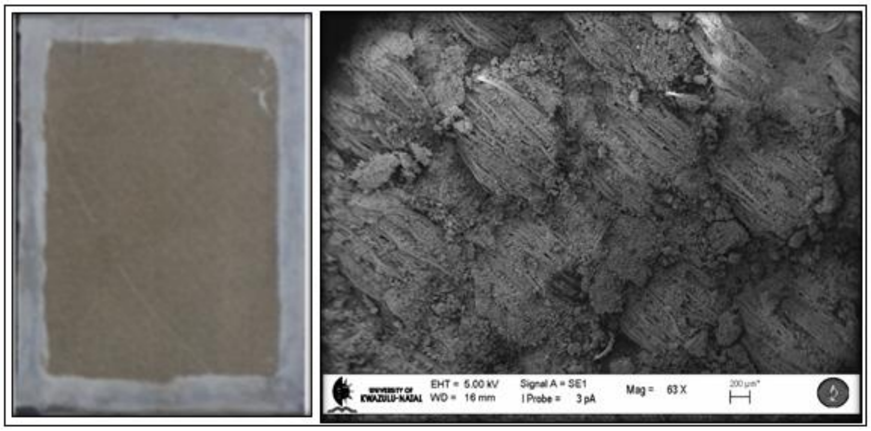


Figure 4.10: Camera Images and electronic scanning image of the fouled membrane 1

The images proved that membrane 1 absorbs too much of impurities from the polluted solution. Most impurities were managing to penetrate the fabric filaments. The reason why the fabric is a lot darker is because of a lot of impurities are trapped in between the filaments.

Figure 4.11 shows a camera image and electronic scanning image of the fouled membrane 2 used for the study.

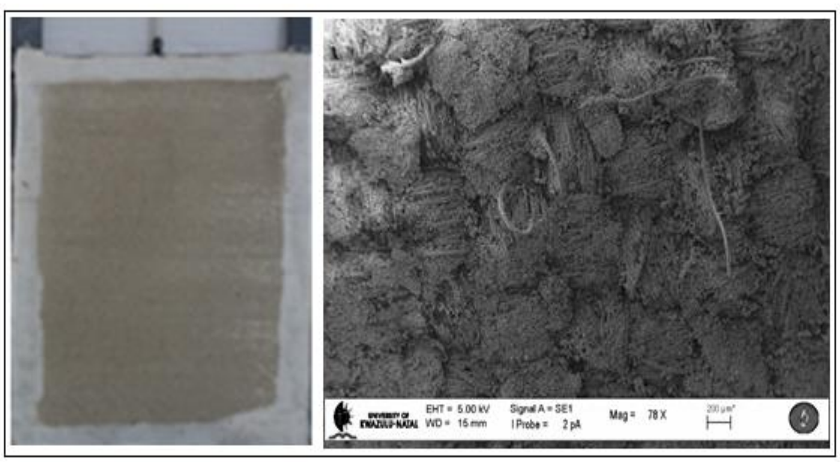


Figure 4.11: Camera Images and Electronic scanning image of the fouled membrane 2

The images proved that membrane 2 absorbs impurities from polluted water. Most impurities were rejected on the fabric surface, while other impurities managed to penetrate the fabric, but not in between the yarn filaments but in between yarns. The reason why the fabric is not that dark as compared to membrane 1, because a lot of impurities are not in-between filaments, but are in between yarns, there are also some in between the filaments.

Figure 4.12 shows a camera image and electronic scanning image of the fouled membrane 3 used for the study.

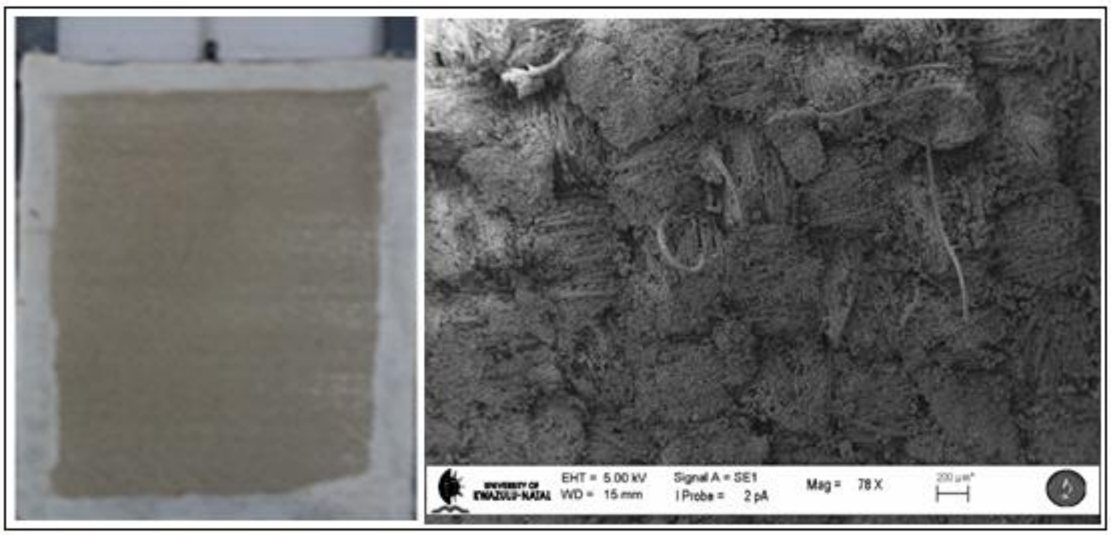


Figure 4.12: Camera image and electronic scanning image of the fouled membrane 3

The images proved that membrane 3 absorbs a lot of impurities from the polluted water. Most impurities managed to penetrate the fabric filaments. The reason why the fabric is a lot darker is is because a lot of the impurities are in between filaments and yarns just like membrane 1.

Figure 4.13 shows a camera image and electronic scanning image of the fouled membrane 4.

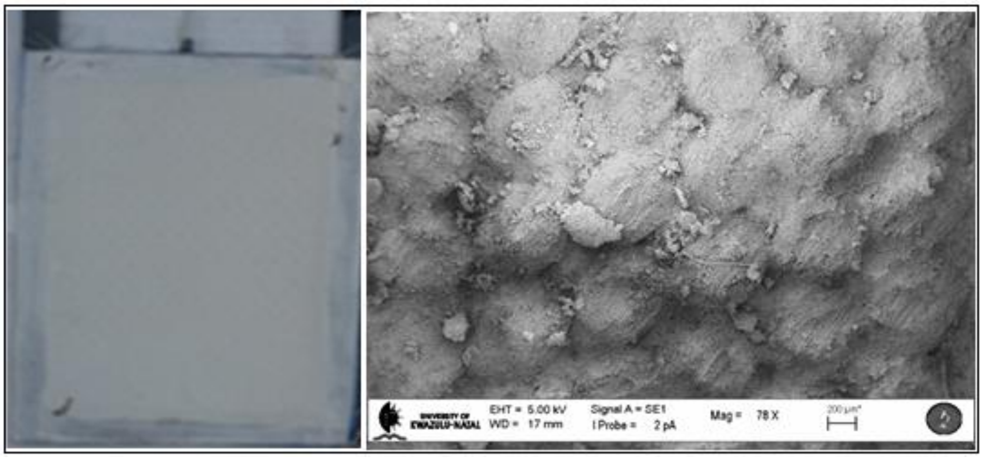


Figure 4.13: Camera images and electronic scanning image of the fouled membrane 4

The images proved that membrane 4 rejects the impurities on the membrane surface. All impurities were rejected on the fabric surface. Impurities will not penetrate in between yarns and also in between filaments. The reason why the fabric is not as dark as compared to membrane 1, membrane 2 and membrane 3 is because a lot of the impurities were rejected from the surface.

The orientation effects were determined on selected fabrics. Each module was made according to the orientation degree positioning (refer to Figure 4.14), according to Warp 0^o, 45^o and 90^o.

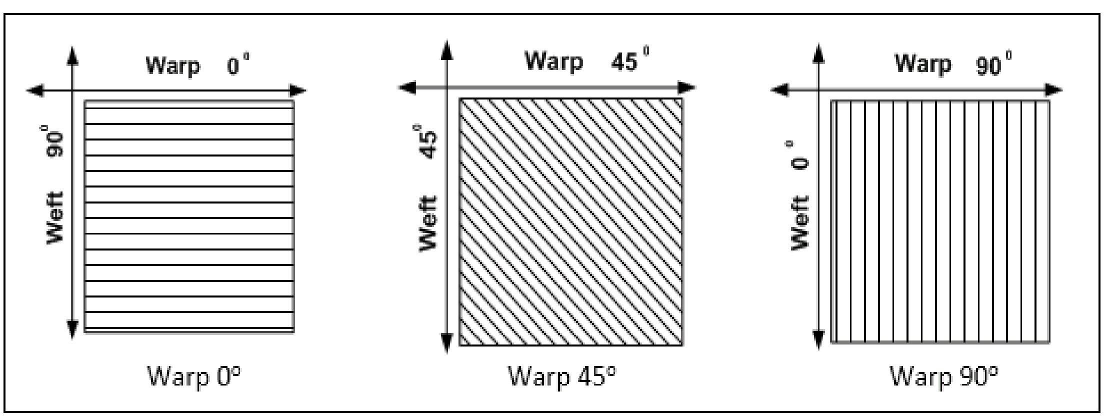


Figure 4.14: Plain weave orientation at different angles (top view and side view)

There were fifteen single modules evaluated at the constant pressure head using tap water and wastewater (DEWATES effluent) as the feed. The data collected during the experiment were analysed.

Figure 4.15 shows the flux behaviour of membrane 1 when DEWATS effluent was used as the feed operated at 300mm hydrostatic head. All fabrics labels as membrane 1 used for this test were new. The same procedure was used for membrane 2, membrane 3 and membrane 4.

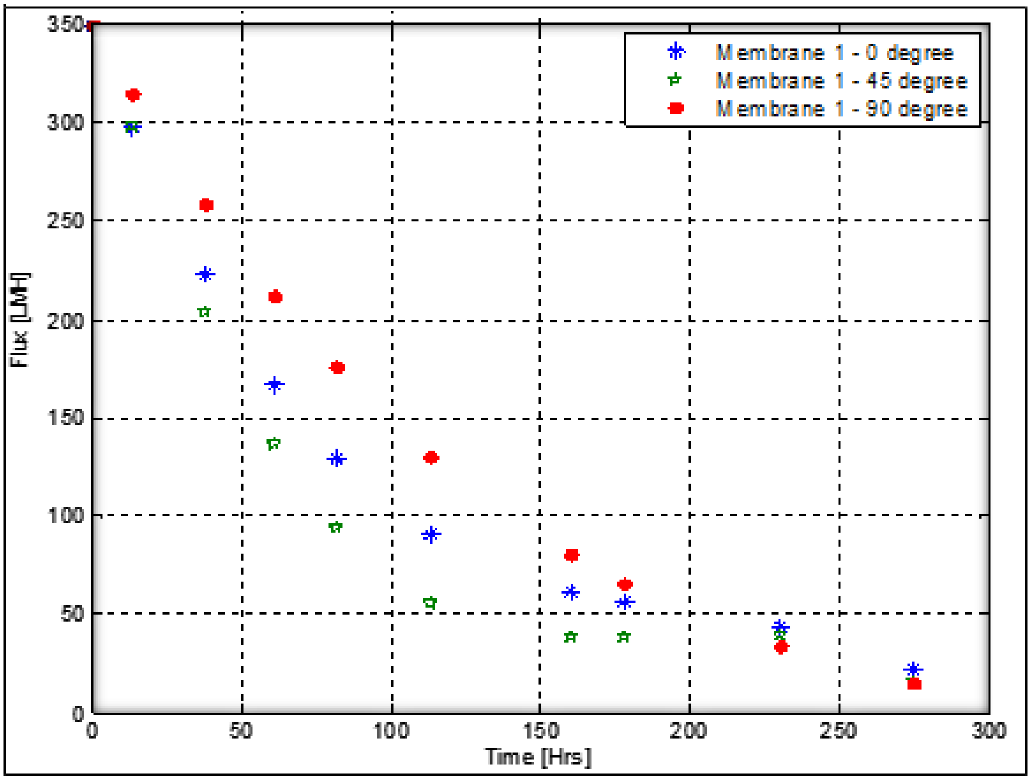


Figure 4.15: DEWATS flux for membrane 1 at different orientation angles

Membrane 1 was not operated at microfiltration parameters. However, the fabric proved that the 90-degree orientation had better productivity as compared to 45 degree and 0-degree orientations.

After 200 hours in operation, while processing the DEWATS effluent, all the orientations behave the same. Figure 4.16 shows the flux behaviour of membrane 2.

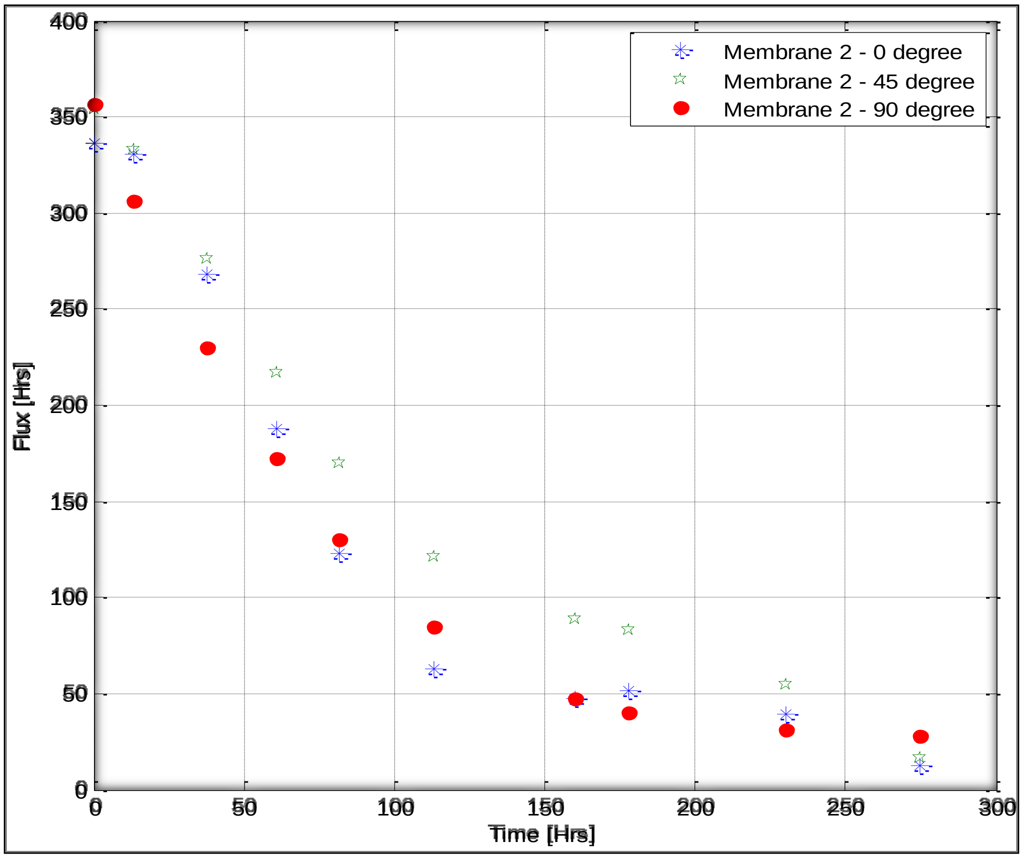


Figure 4.16: DEWATS flux for membrane 2 at different orientation angles

The experiment proved that the 45-degree orientation had better productivity as compared to the 90 degree and 0-degree orientations for membrane 2. After 250 hours in operation all, the orientations behave almost the same. Figure 4.17 shows the flux behaviour of membrane 3.

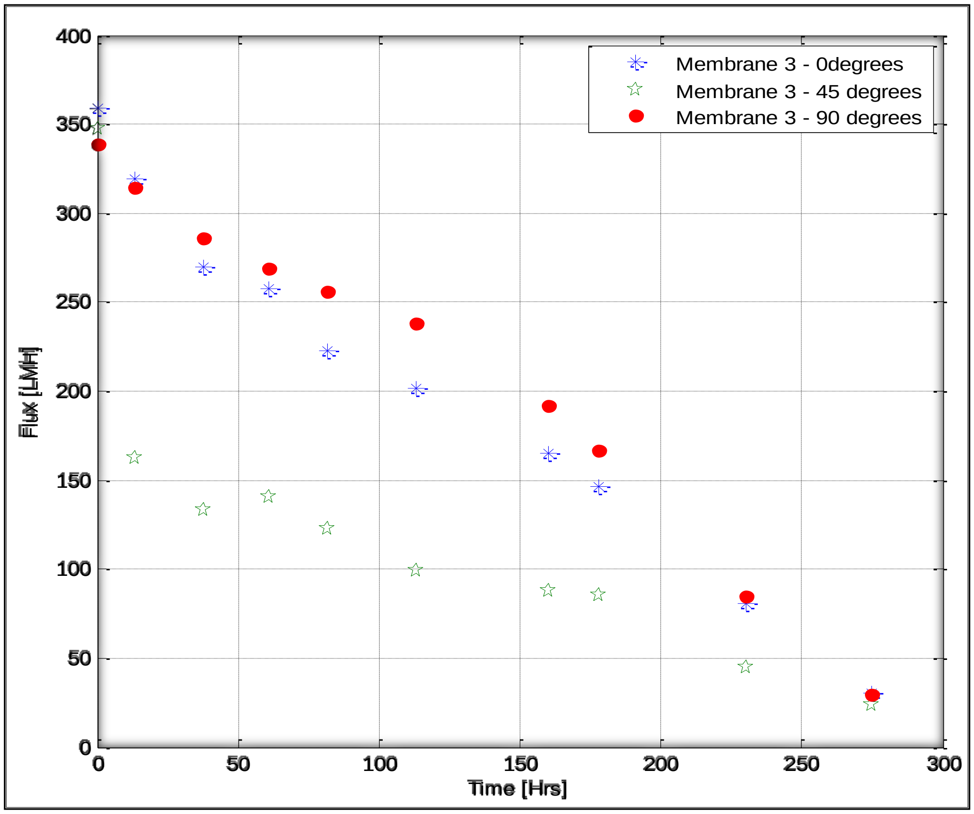


Figure 4.17: DEWATS flux for membrane 3 at different orientation angles

The experiment proved that the 45-degree orientation has worse productivity as compared to 90 degree and 0-degree orientations. After 250 hours in operation, while processing the DEWATS effluent, all the orientations behave the same. Figure 4.18 shows the flux behaviour of membrane 4.

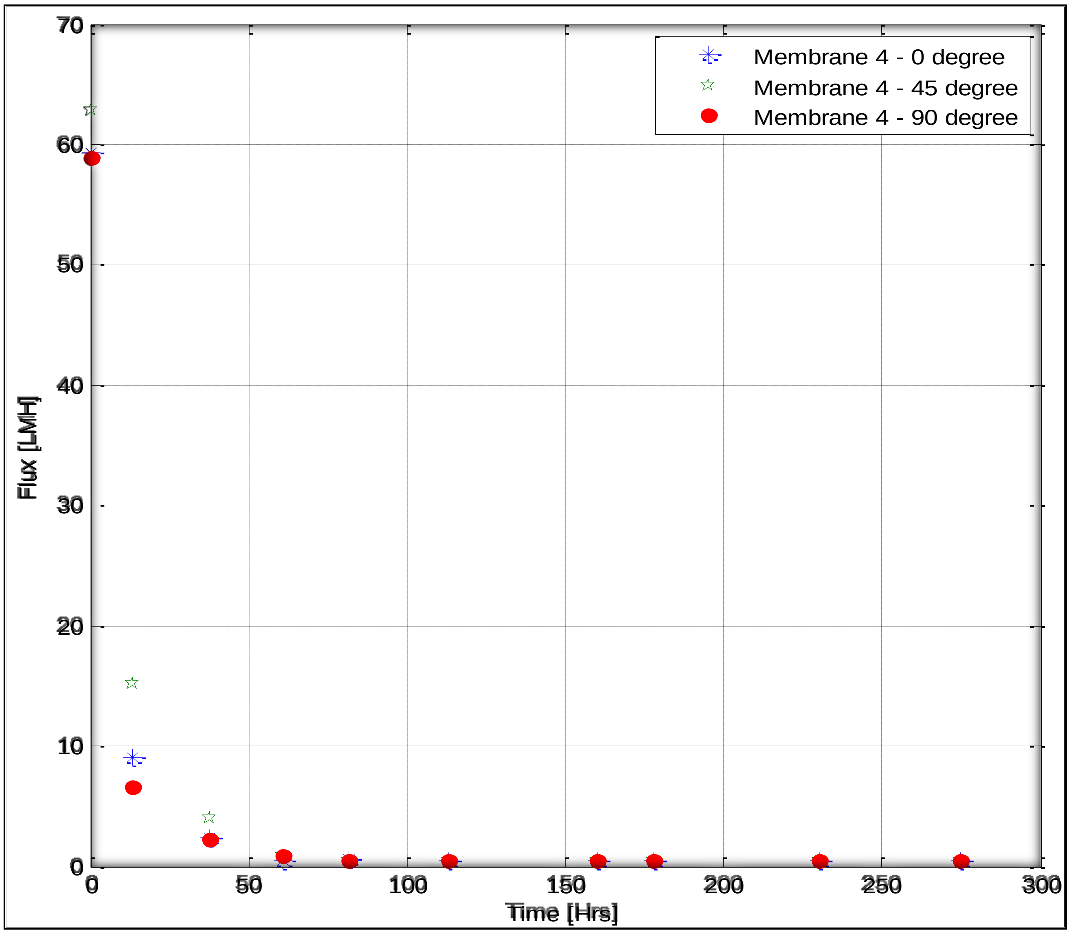


Figure 4.18: DEWATS flux for membrane 4 at different orientation angles

Membrane 4 was the only fabric operation at microfiltration parameters. The experiment proved that the 45-degree orientation had better productivity, after 1 hour in operation, while processing the DEWATS effluent; all the orientations behaved the same. The tensile strengths of the fabrics were balanced together with the elongation.

Figure 4.19 shows the flux behaviour of membrane4 when tap water was used as the feed operated at 300 mm hydrostatic head. All the fabrics used were new.

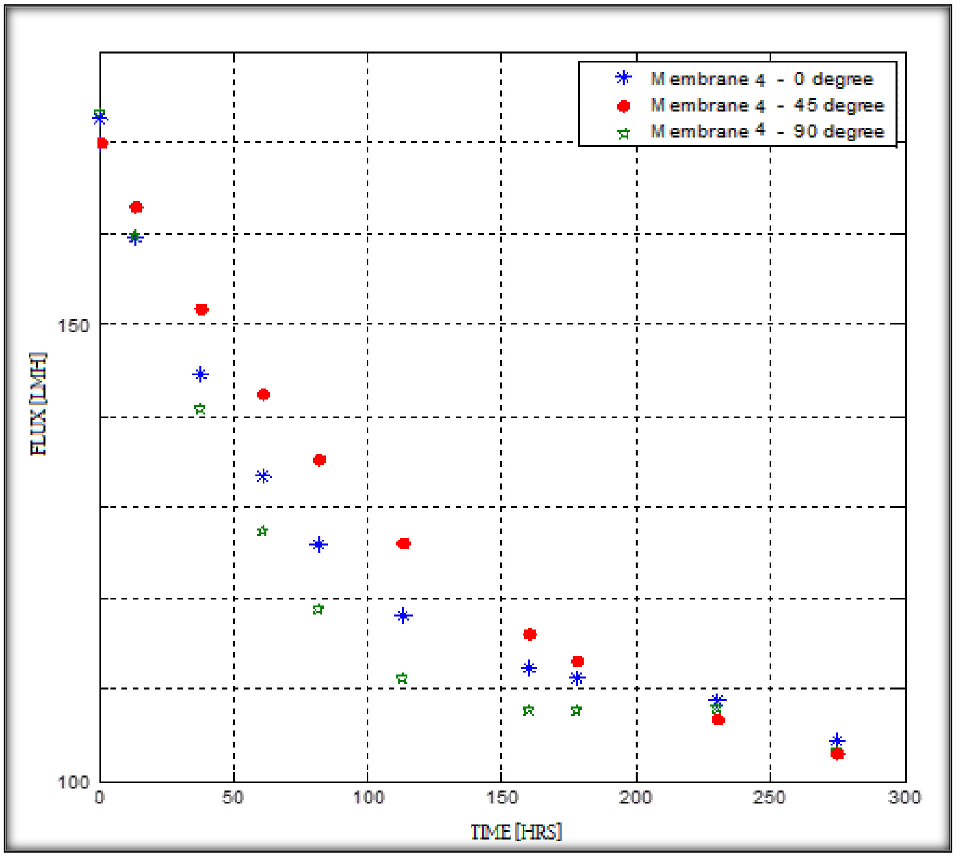


Figure 4.19: Tap water flux for modules at different angles

The relationships between the fabric orientations were supposed to be the same when using tap water as the feed. Since people assume that tap water is very clean, the experiment was long, expecting a maximum constant flux. At first, it was impossible to notice any effect. However, with time, the changes in flux were noted. And also, after 220 hours in operation, while processing the tap water, all the orientations behave the same for membrane 4.

There were many reasons or assumptions to that effect. Assumption 1 was that since the system was open to atmosphere, some dust may have entered into the water or the impurities or bacteria started to grow inside the system. Actually, Figure 4.18, behaviour proves that tap water is not pure or clean. There are impurities in our tap water systems.

The test had to be repeated using DEWATES effluent as the feed and also this time not only new membranes and reused membranes. Figure 4.20 shows how the DEWATS effluent fluxes differ for cleaned and new membranes at different orientations when operating at 300 mm hydrostatic head. Note that all the results were taken in the first 15 - 17 min after the start of the operation.

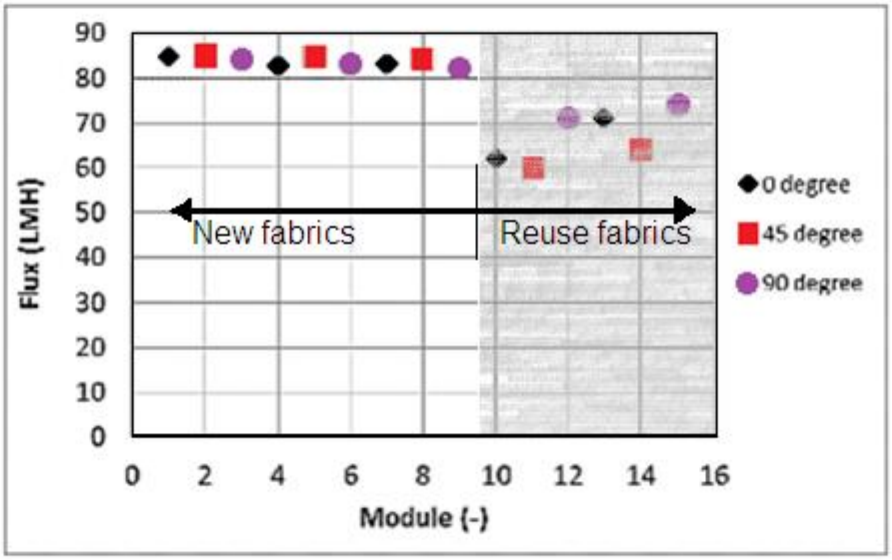


Figure 4.20: Initial flux for modules at different angles

Figure 4.20 shows that the membranes with 45°orientation have high flux when compared to 90° orientation membranes and 0°orientation membranes for new fabrics. However, that was also the case with tap water and when using DEWATS effluent. For dirty membranes or reused membranes after cleaning with a brush, the orientation is not showing any relationships. It was noted that flux for reused membranes were 20% lower than clean or new polyester fabrics/membranes during the start of the operation. After an hour, all membranes were operating the same.

Figure 4.21 shows the initial flux behaviour of membrane 4 when tap water was used as the feed. There were three types of orientation tested on the system operated at 200mm, 300mm, 400mm, 500mm, and 600mm hydrostatic heads. All fabrics used for these experiments were new membranes.

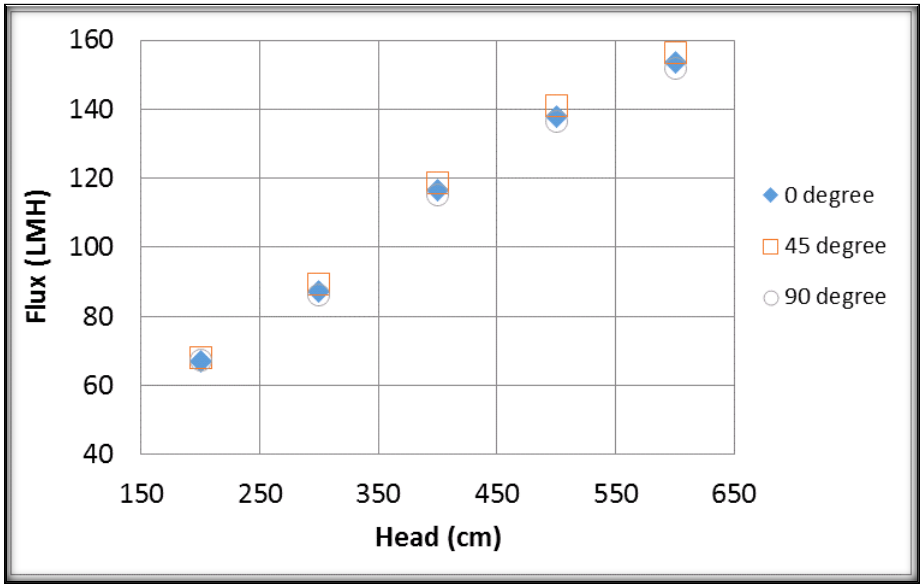


Figure 4.21: Membrane modules with different orientation at a different hydrostatic head

It was observed that the flux increases with the increase in the hydrostatic head only when tap water is used as a feed. It was also observed that flux is higher at 45-degree warp for membrane orientation. The difference between these orientations was at the average of 3% favouring the membrane with 45° warp position and 2% less for 90° warp position. This Figure is significantly small and due to economic reasons, it will be too costly to cut the fabric at a 45° warp position as more fabric will be wasted.

4.5. Summary of the Results

There were four woven fabrics used as membranes for the project of which three of the selected fabrics cannot be used as a filter for water treatment especially the microfiltration processes. Membrane 4, polyester fabric, was the only fabric capable to remove small and micro particles. All three polypropylene fabrics failed to meet the microfiltration requirements due to the fact that pore sizes were a lot bigger to allow micro impurities to go through the fabric. However, these polypropylene fabrics can be used as screeners in water treatment systems.

Polyester fabrics (membrane 4) proved to be suitable to be used for microfiltration because the fabric pore sizes were a lot smaller to prevent even the smallest particle to go through the fabric when used as a membrane. The polyester fabric was capable of separating impurities from the polluted water. Membrane 4 only had surface separation.

The thickness of the polyester fabric was smaller than that of polypropylene fabrics, making it possible to produce membrane modules that are not bulky. For polyester fabric, the tensile strength and weaving tension used were balanced in both weft and warp. Polyester fabric was considered to be a fabric that can be used as a microfiltration membrane. Membrane 4 permeate quality had good turbidity results below 1 NTU before and after 25 minutes during filtration while other membranes produced more than 20 NTU before and after an hour.

Three types of orientations were used. All fabrics selected were analysed for orientation effects. The results favoured the 45^{o}orientation for membrane 4 with a highly productive rate. However, at stable flux, the orientation did not have any impact. This also applied to other fabrics. The 45-degree orientation had 3% more productivity, which is significantly small to make any economic impact. The same behaviour was also observed during clean and fouled membranes. Before the stable flux, the cleaned membranes were 20% less than new membranes. Reused membranes and new membranes at stable flux behaved the same.

CHAPTER 5.

EVALUATING THE EFFECT OF FEED QUALITY ON WOVEN FABRIC MEMBRANE PERFORMANCE

5.1. Introduction

There are many factors that affect the woven fabric when used as a membrane. These factors are the geometrical structure of the fabric and yarn structures that play a major role in air, water permeability, and fabric porosity. The woven fabric membrane pores or fabric porosity has a decisive influence on the utilization of the fabric for some technical applications (filters, sails, parachutes) and clothing applications as well.

Fabric porosity depends generally on the fabric and yarn constructions. It is theoretically proven that for tightly woven fabrics there exists a good agreement between air or water permeability and inter fibre pore volume or porosity (Militký et al., 2011). It is also true that the hydrostatic heads of the membrane play a massive role during the filtration process.

The literature clearly states that polluted water contains many types of impurities that can be grouped into more than four types of impurities.

The impurities were grouped into four types it was; impurities with bacteria, suspended solids, dissolved impurities and turbidity. Turbidity is not an impurity but used to measure a solution haze. One of the objectives for this project was to evaluate the effect of the feed quality on the membrane performance. Hence, the investigations were carried out; (1) to evaluate the effect of the feed quality on membrane performance; (2) to determine the membrane pore blocking and particle distribution for all selected fabrics.

5.2. Definition and determinations of stable flux

5.2.1 Definition of Pure water flux

Scientists like Boddeker (2005) introduced the concept of pure water flux, which is defined as being the hydraulic permeability of pure water and is one of the parameters characterizing porous barriers (Böddeker, 2005). The range is considerable; water flux commensurate with the porosities covered by the filtration spectrum. An expression for water flux through pores is derived from the Hagen-Poisseuille Equation describing hydraulic pressure loss within a capillary duct (laminar flow) as

$$J_v = \frac{\varepsilon d^2}{32\eta\tau}\frac{\Delta p}{z} = L_p \frac{\Delta p}{z} \qquad \text{Equation 5.1}$$

Parameters determining hydraulic permeability are the surface porosity of the model membrane ($\varepsilon = n \pi d^2/4$); the viscosity of the liquid feed within the pore space, η; an adjustable parameter τ, which symbolizes the fact that real pores are neither straight nor uniform (“tortuosity factor”). Flux is seen to depend on pore diameter to the power of four, greatly amplifying the influence of the pore size distribution towards higher than mean pore rating.

5.2.2 Definition of Critical water flux

Böddeker (2005) also introduced the concept of critical flux, which is defined as the lowest flux at a given solute concentration to result in an irreversible deposit on the barrier surface. If pressurized further, the flux remains at the critical level, either by the deposit growing thicker or by mechanical compaction; compaction of the gelatinous deposit eventually may even cause the flux to decline with pressure. However, if the pressure and concentration remain constant then the critical flux remains stable or called a stable flux (Böddeker, 2005).

5.2.3 The critical Flux evaluation method

Some impurities damage the membrane while others affect the membrane performance positively and/or negatively. Some impurities are hydrophilic and some are hydrophobic. Most impurities found in river water and wastewaters are not good for human consumption. The impurities need to be removed from any water that can be used for domestic use, for irrigation, and for industrial use, not all impurities need to be removed. (Santos et. al, 2002).

It is possible to remove impurities from water provided the right technology is used. Not all the impurities have a negative effect on the membrane surface. Some impurities enhance membrane performance.

Pores are more likely to be blocked partially and the degree of pore blockage depends on impurity size, nature and quantity. The blockage is generally more complete when the particles and pores are similar in both shape and size.

The domestic and industrial wastewater contains some biological waste, phenols, surfactants, pesticides, aromatic hydrocarbons and some bacteria. The industrial wastewater substances are toxic and non-biodegradable organic pollutants when compared to domestic wastewater. All the undisclosed impurities form a cake on top of the membrane.

Flux decline after pore blockage is due to the formation and growth of a cake or gel layer on the membrane surface, sometimes in the membrane. The cake layer is formed on the membrane surface as the amount of retained particles increases.

The cake layer creates additional resistance to the permeate flow and the resistance of the cake layer increases with the growth of the cake layer thickness. Consequently, the permeate flux continues decreasing with time (Vorobiev, 2006).

The critical flux was determined according to the flux step method. The membrane flux behaviour was analysed for all used feed solutions. At critical flux, the production rate is low, but on the other hand, prolonging the filtration period. Cleaning of the membrane may not happen regularly. This also prolongs the membrane life. At stable flux, the production quality is extremely good. Solutions that are a lot more concentrated with impurities have a lower production rate. Peter-Varbanets (2010) also identified such behaviour.

Figure 5.1 was the Peter-Varbants results where the hydrostatic header was 50 cm.

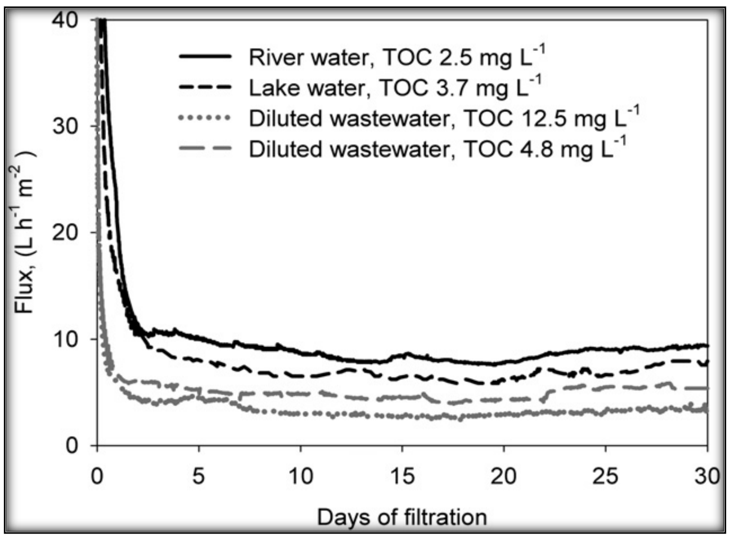


Figure 5.1: Membrane flux during 30 days of dead-end operation for different water types (Adapted from Peter-Varbanets, 2010)

5.3. Equipment set up

5.3.1. The solution used for the study

Bacteria play a vital role in microbial activities specifically for sulphur, nitrogen, fat or biological waste and protein removal in the wastewater. The developed polymer membranes will be used to ensure the quality of effluent by removing the bacteria and the remaining organic and inorganic solids. Most wastewater bacteria are hydrophobic while some are hydrophilic so as the solids in the wastewater. Table 5.1 summarizes the group of impurities found in polluted water or wastewater.

Table 5.1: Polymer sensitivity toward pH and moths, impurity groups.

GROUP	IMPURITIES	DESCRIPTION AND PROPERTIES
GROUP 1	Bacteria and viruses	Most bacteria are colourless. Bacteria are compressible and range in size
GROUP 2	Suspended solids	Suspended solids are divided into two; compressible solids and non-compressible solids. They have different size ranges.
GROUP 3	Dissolved impurities	Most dissolved impurities are not easy to identify but can be tested. Some dissolved impurities have colour but most don't have any colour.
GROUP 4	Turbidity	Impurities that present colour in the solution.

5.3.1.1. Effluent from eThekwini Southern Wastewater Treatment

The eThekwini Southern wastewater treatment works are located in the Mobeni area. The effluent wastewater used for this study was from the secondary clarifier and it was labelled or called Mobeni effluent in this study. The Mobeni Effluent was clear when viewing it with a naked eye. However, Mobeni effluent had more bacteria, less suspended solids and less turbidity. A number of samples were taken randomly from eThekwini Southern wastewater treatment works, before entering the tertiary treatment section.

5.3.1.2. Decentralised Wastewater Treatment system (DEWATS)

DEWATS wastewater treatment plant is located at KwaMashu / Newlands area. The wastewater effluent used for this study was from the digesters and is called DEWATS effluent in this study. DEWATS effluent is not clear, dark when viewing it with a naked eye. However, the effluents have more bacteria, more suspended solids and high turbidity. A number of specimens were taken randomly from DEWATS treatment, before the digester discharge section.

5.3.1.3. Umgeni river water

Umgeni River runs from Drakensberg Mountains to the Durban blue lagoon. Water used for this study was from the sampling point at Durban blue lagoon 20 from the ocean point. Umgeni River is partially clear, viewing it with a naked eye. However, Umgeni river water has bacteria, suspended solids and less turbidity. A number of specimens were taken randomly from Durban blue lagoon 20m from the sea point.

5.3.1.4. Brushkoppies Wastewater Treatment

Brushkoppies wastewater treatment works are located in the Soweto area. The effluent wastewater used for this study was from the secondary classifier and is called Soweto effluent in this study. Soweto effluent from the wastewater treatment plant is clear when viewing it with a naked eye. However, the effluent has less suspended solids, less turbidity and an unknown bacteria content. A number of specimens were taken randomly from treatment before discharged to the river.

5.3.1.5. Bruma Lake water

Bruma Lake dam is situated in the City of Johannesburg area. The water used for this study was from the dam and is called Bruma. Bruma Lake water is partially clear when viewing with a naked eye. However, the effluents have less suspended solids, less turbidity and an unknown bacteria content. A number of samples were taken randomly from the outlet part of the dam.

5.3.1.6. *Algae Solution*

Algae Solution was made in the DUT laboratory and the water was partially clear when viewing it with a naked eye. However, the water with algae had no suspended solids besides algae and less turbidity. A number of samples were taken randomly from the algae laboratory farm.

5.3.1.7. *Synthetic Solutions*

Synthetic solutions were solutions made in the Chemical Engineering laboratory, Durban University of Technology, and in the Unity called Process Energy and Environmental Technology Station, University of Johannesburg. The synthetic solutions were as follows:

Table 5. 2: Synthetic solution recipe

Name	Compound 1	Compound 2	Compound 3
Synthetic 1	100 L DEWATS effluent	10kg Calcium	-
Synthetic 2	100 L DEWATS effluent	1kg Calcium	-
Synthetic 3	100 L Tap water	10kg Calcium	1kg Activated Carbon
Synthetic 4	100 L Tap water	10kg Calcium	1kg bentonite
Synthetic 5	100 L Tap water	1kg bentonite	-

Synthetic solution 1 had more solids, high turbidity and contained bacteria. Synthetic solution 2 had fewer solids, high turbidity and contained bacteria. Synthetic solution 3 had more solids, more turbidity, and no bacteria in the solution. Other solutions used were bentonite mixed with a calcium solution and also a bentonite solution only. All the synthetic solutions had turbidity above 20 NTU.

5.4. Process description

5.4.1. Cross-flow filtration

The feed tank was a plastic 250 L rectangular tank. The filtration tank volume was 350L and made of PVC while the permeate tank was 150 L in size. The permeate tank was made of PVC material. Membrane modules were placed vertically (see Figure 3.4). The aim of this test was to evaluate the effect of the feed quality on membrane performance when the membrane was placed vertically. Figure 3.8 shows a process flow diagram of the membrane system used during the study. Such systems whereby membranes are placed vertically are common. All three tanks used for experiments were open to atmosphere since the system was at constant pressure. The role of the overflow outlet was to ensure that the system operated at 30 cm hydrostatic head. The feed flow rate was not regulated; however, any additional liquid flowed out using the overflow outlet.

5.4.2. Dead-end filtration

The feed tank was a plastic 150 L round tank. The filtration tank volume was 75 L made of PVC and the permeate tank was 35 L made of PVC. Membrane fabrics were placed on top of a 50mm bore pipe (see Figure 3.10). The aim of this test was to evaluate the effect of the feed quality on membrane performance when the membrane was placed horizontally. Figure 3.9 shows a process flow diagram of the membrane system used during the study. Two out of three tanks were open to the atmosphere. The role of the overflow outlet was to ensure that the system operated at a 30 cm hydrostatic head. The feed flow rate was not regulated; however, any additional liquid flowed out through the overflow outlet.

The particle size analyser machine, called Malvern Mastersizer 2000, was used to analyse the particles in 250 ml solution volumes.

5.5. Experimental procedure

5.6.1. Cross-flow filtration

The system was designed for continuous operation; however, it required one feed solution at a time. When changing the feed to another type of solution, it was necessary to change the membrane to a new one and to clean the process to prevent contamination. Experimental work started by determining the pure water flux. Membrane modules were placed vertically in the testing rig. The critical flux was determined according to the simple filtration method. This was done by maintaining the hydrostatic head at 30cm. The stable flux per solution was monitored at a constant hydrostatic head. All tanks were open to the atmosphere. After every critical flux was evaluated, the membrane pack was cleaned by brushing and rinsing using tap water.

5.6.2. Dead-end filtration

The system for dead-end filtration operated the same as the system for the cross-flow filtration system. The difference is that the membranes were placed horizontally on the 50mm bore pipe of the testing rig.

Repeatability

Due to statistical analyses, all tests were repeated more than thirty times. Runs were carried out at various conditions with each condition being repeated at random.

5.6. Results and discussion

All selected fabrics were evaluated. Some of the fabrics were not able to remove all the impurities found in surface water and wastewater. Only membrane 4 was capable of removing all the impurities. The results also show that at stable flux, a formed cake or layer becomes a membrane that is more effective than the polymer fabric used as a membrane.

At stable flux, the turbidity was less than 1 NTU and the membrane removed 99.995% of impurities. The smallest particle size was 0.09 µm which 75% smaller than the smallest bacteria/viruses. At steady flux, even the smallest bacteria could not pass through the membrane and formed a cake. When using Malvern Mastersizer 2000, water was a dispersant with a refractive index (IR) of 1.33. When using Malvern Mastersizer 2000, the permeate quality could not be detected and it was then assumed to be clear of any particles, however, all the other feeds were analysed after processing them using membrane 2 except DEWATS effluent which was not processed using the Malvern Mastersizer 2000.

Figure 5.2 shows the impurity or particle size distribution found in the Mobeni effluent. The mean particle diameter of Mobeni effluent impurities was about 80 um.

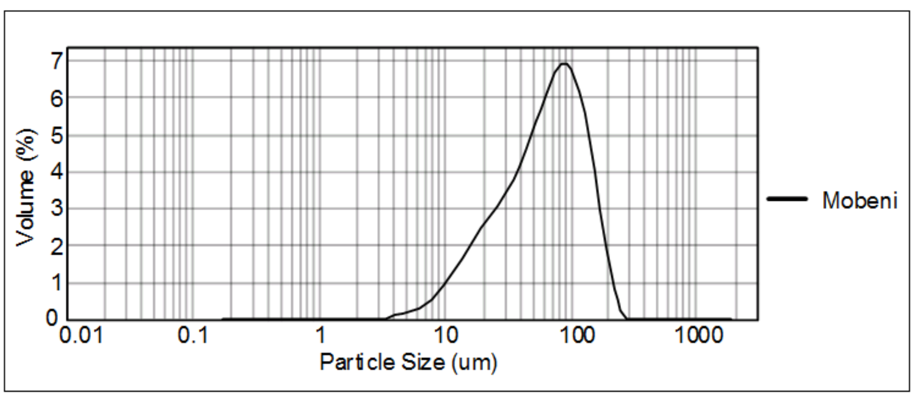


Figure 5.2: Particle size distribution of Mobeni Effluent

The particle size distribution of the Umgeni River obtained is shown in Figure 5.3. The mean particle diameter of the Umgeni river water impurities was about 100 um.

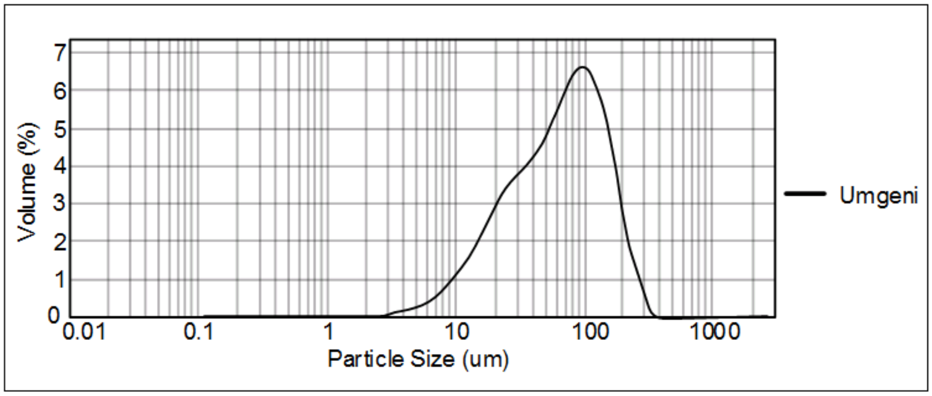


Figure 5.3: Particle size distribution of Umgeni River

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The particle size distribution of activated carbon solution obtained is shown in Figure 5.4. After analysing activated carbon solution impurities using Malvern Mastersizer 2000, the mean particle diameter of activated carbon impurities were about 50 um.

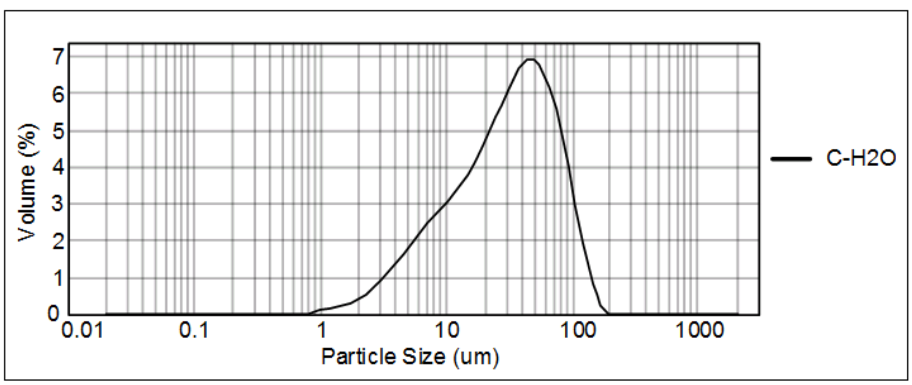

Figure 5.4: Particle size distribution of activated carbon solution

From Figure 5.4, the smallest particle size was 0.09 µm in the activated carbon. The smallest particle was not detected on the permeate product. Weighted residual was 0.269%, the surface weighted mean was 39.797 um, and the specific surface area was 0.3384 m^2/g.

The activated carbon particle RI was 2.420. The active carbon occupied only 0.0170% volume of the total volume. The smallest particle size was 0.09 um which was smaller than the smallest bacteria and the smallest particle was not detected on the permeate product.

The particle size distribution of calcium solution obtained is shown in Figure 5.5 below. After analysing calcium solution impurities using Malvern Mastersizer 2000, the mean particle diameter of calcium impurities was about 20 um.

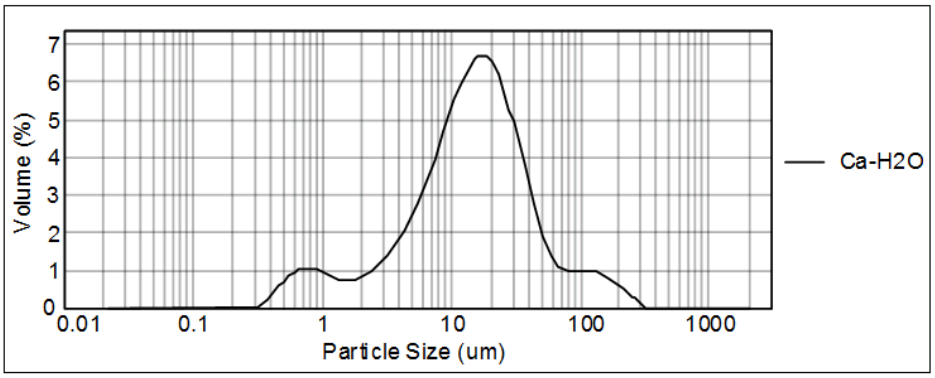

Figure 5.5: Particle size distribution of Calcium solution

When using the lime solution (see Figure 5.5) the weighted residual was 1.206 %, the surface weighted mean was 23.134 µm, the specific surface area was 1.23 m^2/g, and the particle RI was 1.530. The smallest particles occupied only 0.0170% volume of the total volume.

Figure 5.6 below shows the particle size distribution of synthetic and real solutions. The particle sizes were ranging from 0.02 to 3000 µm. Note that membrane 2 was used to process all synthetic solutions before analysing them using Malvern Mastersizer 2000. Membrane 2 was used as a screener, to remove bigger particles.

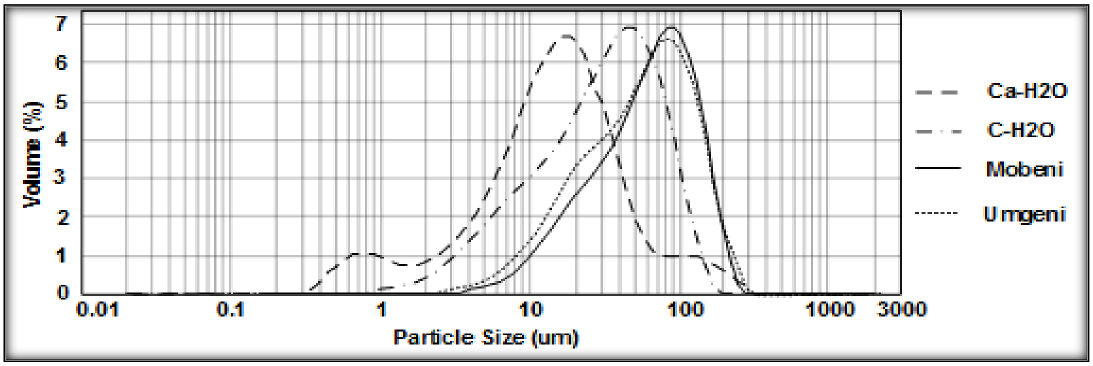

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Figure 5.6: Particle size distribution of feeds

Table 5.3: Physical properties per solution taken from the Durban area.

Membrane :	Units	DEWATS	Mobeni Effluent	Umgeni river
Turbidity range	NTU	41 - 21	16.2 - 11.3	20.2 – 15.6
COD's	-	451	436. 8	144
Coli forms	-	1450000	1070	2012
E-coli	-	345000	300	198630
pH range	-	6.9 - 7.1	6.9 - 7.3	6.3 - 7.2
Ammonia	mg/l	35	68.9	55.3

ISO procedure for water testing was followed when analysing DEWATS, Modeni Effluent and Umgeni river water. Umgeni River was initially assumed to be safer and cleaner than Mobeni effluent sees results Table 5.3. When testing the e-coli and coliforms, it was noted that DEWATS has high bacteria concentration; however, Umgeni River was not expected to be higher than Mobeni effluent. The results prove that Umgeni river water was not safe to drink when not treated because it contains more bacteria.

There was no need to test the physical properties from the samples taken in the Johannesburg area. The samples taken in the Durban area were good enough to understand the river water effluent from conventional wastewater treatment and effluent from DEWATS.

Only three solutions from the Durban area were fed into the systems that used membrane 4. Figure 5.7 shows how the critical flux of cross-flow filtration was determined by using the simple filtration method.

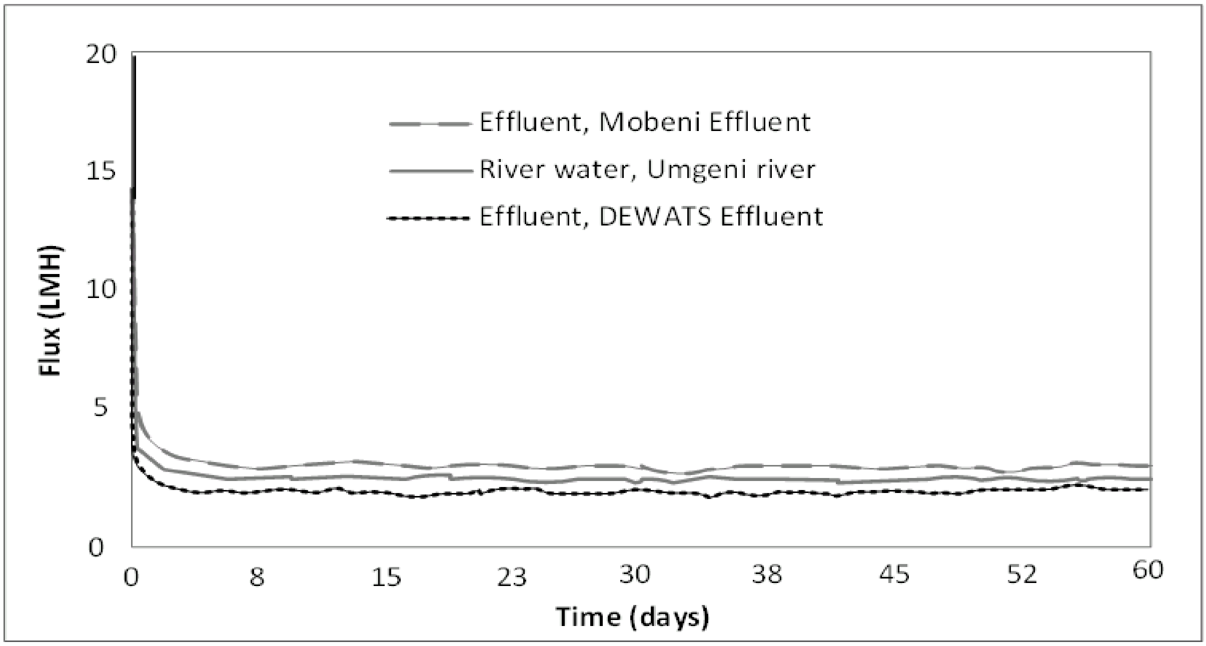

Figure 5.7: Crossflow Critical flux for the membrane with different feeds (membrane 4)

It was observed that the critical flux became stable before 1 hour in operation for all three feeds. It was observed that the stable flux was lower for the solution containing more bacteria, which was the DEWATS effluent. The production was more for the solution with fewer bacteria concentration. In addition, the turbidity of Mobeni effluent feed to the system was lower than Umgeni River feed and DEWATS effluent feed. The permeate turbidities for Umgeni river water, Mobeni effluent and DEWATS were the same, all below 1 NTU.

Figure 5.8 shows the behaviour of membrane 1 used as a membrane for processing DEWATS effluents and Mobeni effluent. Membrane 1 was made of hairiness yarns, particles were trapped by filaments.

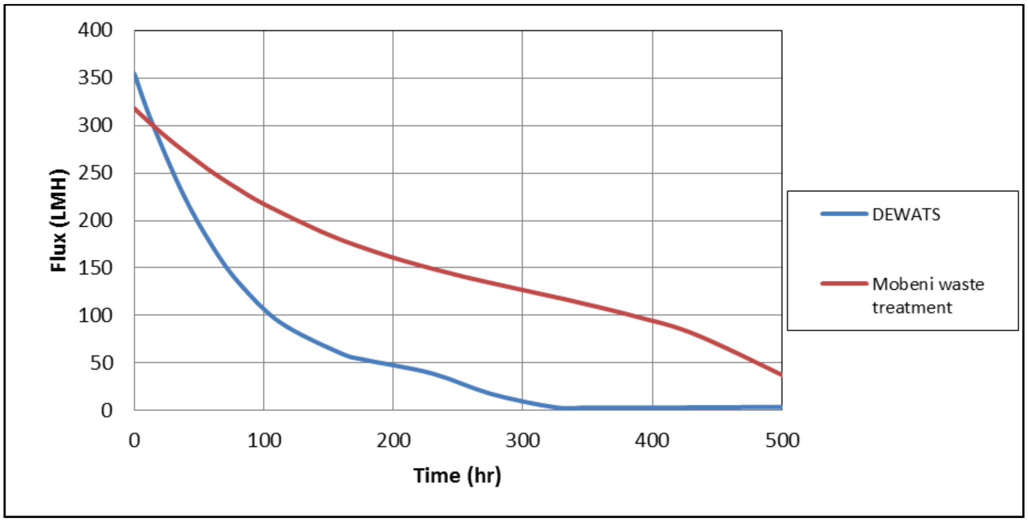

Figure 5.8: Crossflow Critical flux for the membrane with different feeds (membrane1)

Figure 5.9 shows the behaviour of membrane 2 used as a membrane for processing DEWATS effluents and Mobeni effluent. Membrane 2 was made of yarns with less twist, particles were trapped in between filaments however, and there were spaces in between yarns. The fabric was the plain weave. The fabric was also treated giving more productivity.

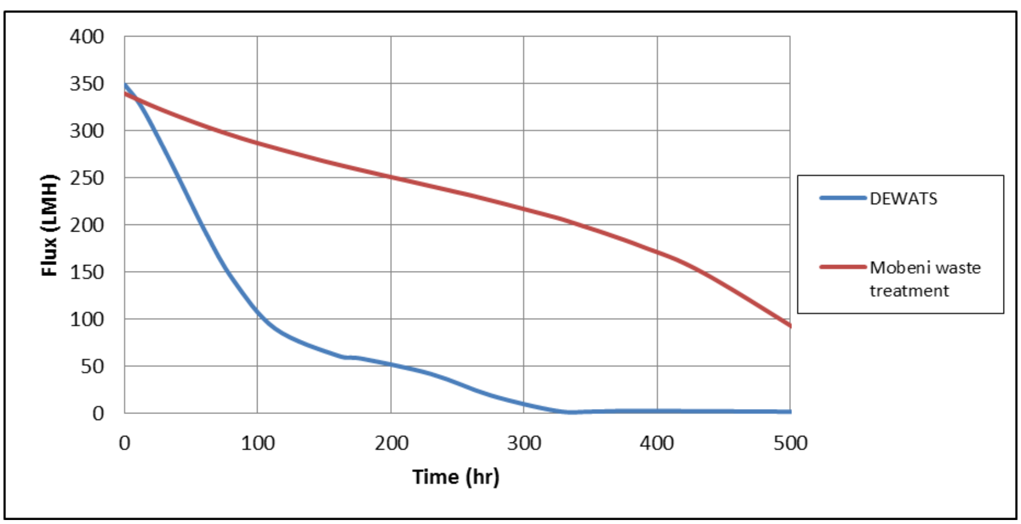

Figure 5.9: Crossflow Critical flux for the membrane with different feeds (membrane 2)

Figure 5.10 shows the behaviour of membrane 3 used as a membrane for processing DEWATS effluents and Mobeni effluent. Membrane 3 was made of staple yarns with fewer twist Particles were trapped in between filaments however, there were spaces in between yarns. The fabric was the plain weave. The fabric was also treated giving more productivity.

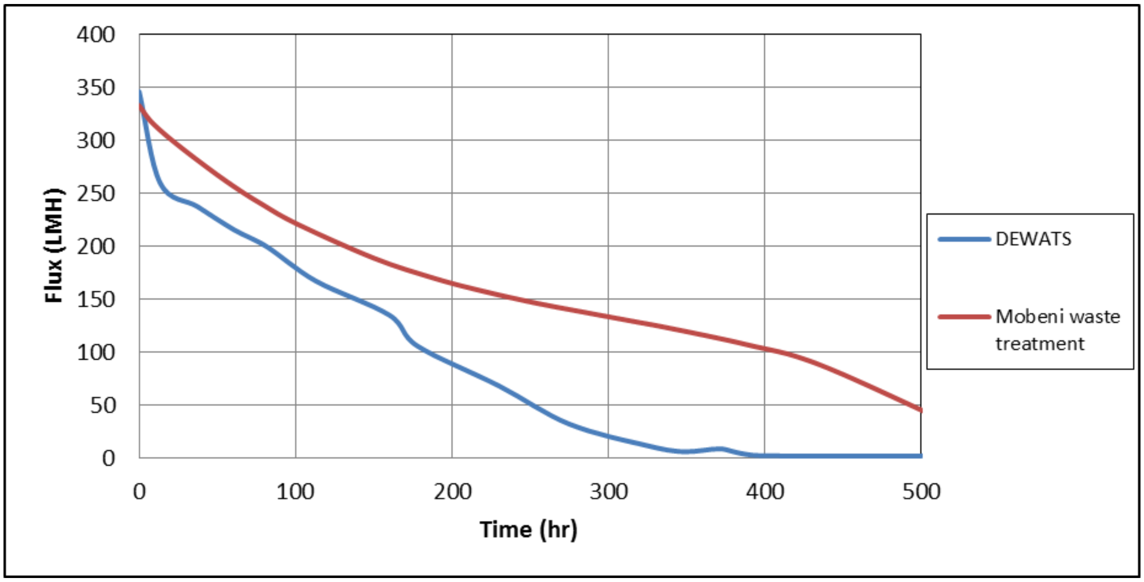

Figure 5.10: Crossflow Critical flux for the membrane with different feeds (membrane 3)

From Figures 5.7 to 5.10, it is shown that a solution with a lot of impurities has a lower productivity rate. Membranes 1 to membrane 3 failed to meet the microfiltration requirements. However, during the experiment, it was easy to notice the impact of feed quality and membrane behaviour.

Only three solutions from the Durban area were fed into the systems that used membrane 4. Figure 5.11 shows how the critical flux of dead-end filtration was determined by using the simple filtration method.

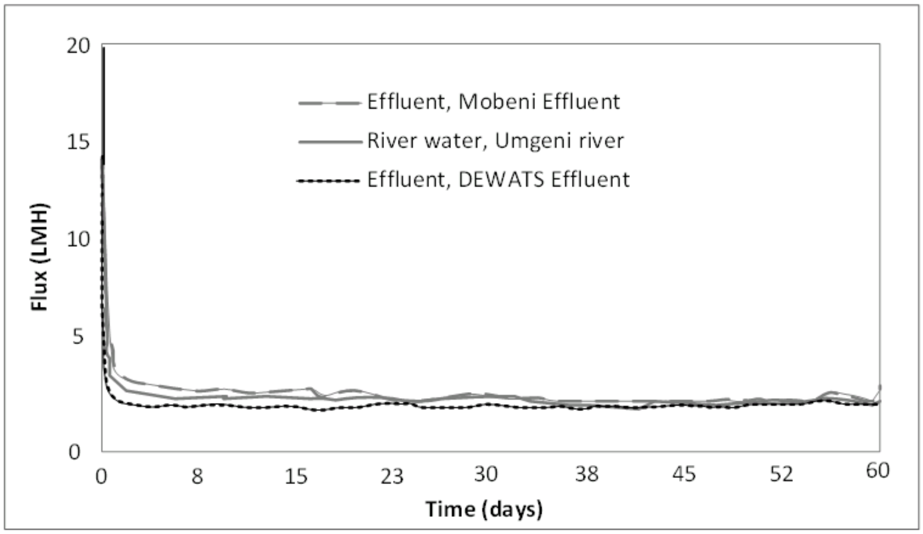

Figure 5.11: Dead-end filtration Critical flux for the membrane with the different feed

It was observed that the critical flux became stable just before 1 hour in operation for all 3 feed solutions. It was observed that the stable flux was lower for the solution containing more bacteria, which is DEWATS. However, the solutions with fewer bacteria were actually decreasing as time goes on. Figure 5.12 shows the accumulation volume behaviour when using different feeds (tap water, river water and effluents) at a constant hydrostatic head of 30 cm using membrane 4.

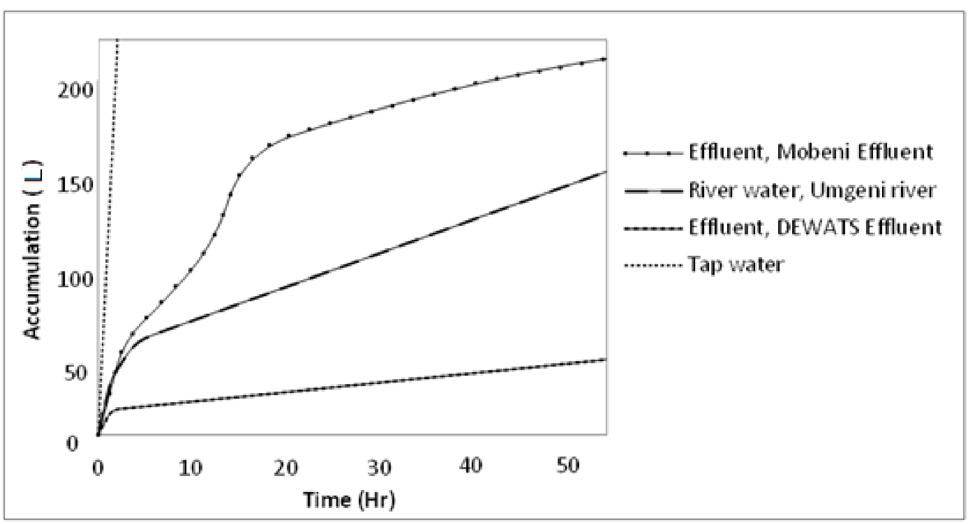

Figure 5.12: Dead-end filtration accumulation during the dead-end filtration (membrane 4)

Figure 5.13 shows the accumulation volume behaviour when using different effluents. Two operation pressures were used (30 cm hydrostatic head and 60 kPa suction pressure).

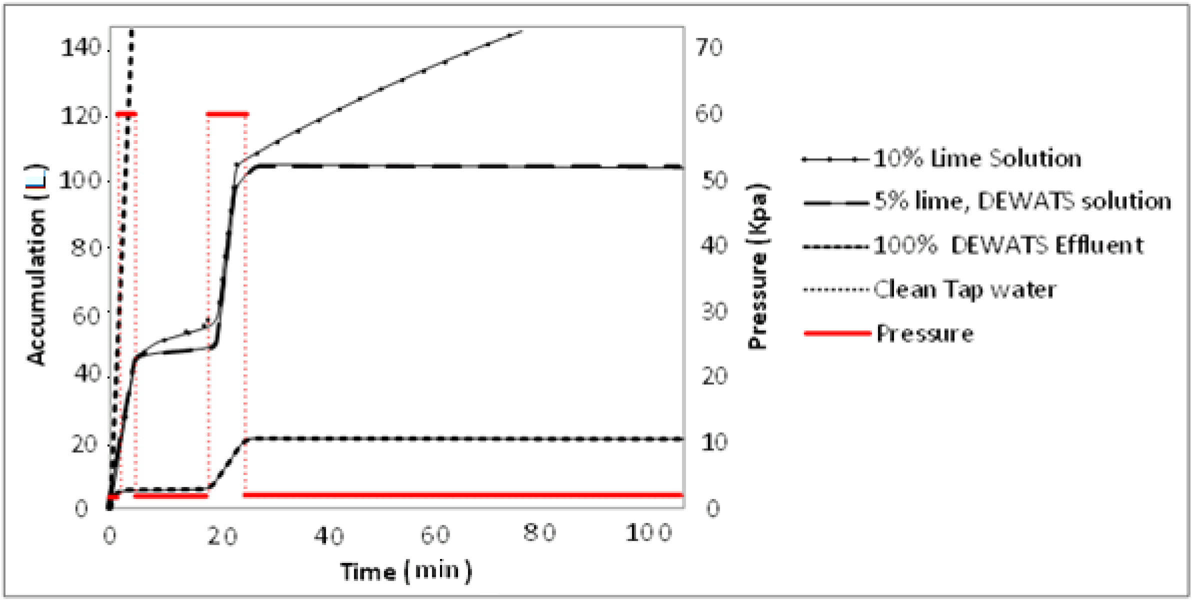

Figure 5.13: Dead-end filtration accumulation operation pressures were 30 cm and 60kPa

When using effluent with the most bacteria and applied pressure, the membrane pores were totally blocked. However, when applying the pressure to the mixture of calcium solution without effluent with bacteria, the membrane does not get blocked completely.

The aim of this study was to establish the effect of feed on pore blocking and look at ways of optimising the membrane performance by modifying the feed. There was a relationship between membrane pores size, bacteria and suspended impurities. After noticing that a solution with more bacteria performs better when adding the incompressible impurities. It was noticed that incompressible solids can be useful in optimizing the filtration processes. The solution or effluent with more bacteria need to be diluted with solution contain incompressible solids, if aim to improve the quality and quantity of the filtration systems.

All type of feeds solutions, effluents and more, with turbidity more than 20NTU, can be processed using membrane 4 was capable to produce a permeate with less than 1NTU and be able to remove all impurities (about 99.999%).

Other fabrics labelled as membranes 1 to membrane 3 proved that the solution with a lot of bacteria and suspended materials block the pores quicker than a solution with fewer bacteria and less suspended materials. These fabric were capable of removing impurities but the quality and cleaning regimes were compromised. These fabrics have internal separation and external separation. For internal separation, it is hard or difficult to brush the impurities off. Membrane 4 was the only fabrics with external separation only. It was noticed that other fabrics can be used as screens in minimising the concentration and preventing other bigger particles from the solution. From this project, clearly noted that people do get benefits in using fabrics as filters, it may not be in the accepTable requirement but do improve the water quality.

5.7. Summary of Results

It was noted that the polluted waters with high bacteria concentration have more blockages than the solution with fewer bacteria. Membrane 4 critical flux becomes stable before one hour in operation for any solution with more or fewer bacteria concentration.

It was noted that the polluted waters with high suspended solids concentration have fewer blockages than the solution with a large number of bacteria or bio-impurities.

However, when adding the incompressible solids to a solution with fewer bacteria concentration and applied force, the membrane pores are partially blocked.

The solution with more bacteria or bio impurities blocks the membrane more than the solution with fewer bacteria or bio impurities.

It was observed that the permeate turbidity was less than 1 NTU for any solution with more or fewer bacteria concentration when the polyester woven fabric is used as a membrane.

The other phenomenon noted was adding a solution with suspended solids improves the permeate quality.

In this case, two fabrics were used, one as the screen and another one as the filter. Membrane 1, Membrane 2 and Membrane 3 performed the same. Membrane 2 was selected to perform as a screen for selected solutions and Membrane 4 was used as the membrane since it is capable of removing all the impurities.

Feed quality and permeate quality of calcium solution and activated carbon solution were the same when used membrane 2 as a filter. Feed and permeate of Umgeni river water and Mobeni effluents were almost the same after processing with membrane 2, but different. Membrane 2 was not removing any small impurities; it was making sure that bigger particles are not passing through the fabric. When membrane 4 was used as the filter, the permeate turbidity was less than 1 NTU for any solutions with more or fewer bacteria concentration.

CHAPTER 6.

EVALUATING THE EFFECTS OF PARTICLE CHARACTERISTICS AND SURFACE PORE BLOCKING ON MEMBRANE PERFORMANCE

6.1 Introduction

It is well known that permeability through fabrics depends on many factors starting with geometrical structure. The fabric used as a membrane for the microfiltration processes is an effective membrane for particle removal in water treatment processes. In most cases, the effect of pore size plays a major role in blocking unwanted particles.

Membrane fouling refers to the deposition or adsorption of material on the surface of the membrane or within the pores. It is a common and costly problem in membrane filtration applications. Fouling causes a decline in permeate flux until a constant flux is reached provided the driving pressure is kept constant. At the constant flux, the permeate quality is also constant and improved. During filtration operation, some pores are blocked while others are partially blocked.

The fabric used as a membrane for water and waste treatment processes must be able to remove micro particles like bacteria and viruses. In most cases, the filtration processes used to remove micro particles are called microfiltration. Any membranes or fabrics that fail to remove a micro particle are not suitable for processing polluted water for domestic use, especially for human consumption.

Membrane fouling refers to the deposition or adsorption of material on the surface of the membrane or within the pores. It is a common and costly problem in membrane filtration applications.

Fouling causes a decline in permeate flux until a constant flux is reached provided the driving pressure is kept constant and sometimes, the concentration too. One of the specific objectives of the study was to evaluate the effect of pore blocking and filter cake build-up. The fouling layer is either on the layer or within the membrane layer.

6.2 Definitions and determination of particle and pore blocking

Microscope image analysis instruments, permeability meters, etc. are used to determine the pore size of the membrane including the pore size distribution. The statistic modelling formulas are used to determine the mean size and size distribution at 95% statistic intervals.

$$s_1^2 = \sum_{i=1}^{n_1} (x_1 = \overline{x_2})^2 \qquad \text{Equation 6.1}$$

Most filter media have irregular pores, which makes the theoretical assumptions suspect and this is especially the case in most of the non-plain twill structures like non-woven material, twill weave structures and others (Lyndon, 2004).

There are methods used for pore size analysis based on testing the permeability of the membrane. These tests also cannot provide the actual pore sizes, but provide the statistical information necessary to determine the pore size distribution. In closely packed membranes are impossible to observe the pore size but can be evaluated using measuring instruments and analysing the data using statistical probability.

Transmittal flux, temperature, operation pressure, permeate quality, permeate quantity and membrane position including the required filtration area are the major filtration design parameters. The other design parameters include membrane fouling, cost per unit area, energy per product volume, maintenance cost, operation cost, installation capital cost and replacement cost.

Membrane filtration flux refers to filtered amounts of water per unit periods, unit flux per sizes - Flux ($m^3/m^2.hr$) = transmittal amount (m^3/h)/square meters of the membrane (m^2) Dominant factors of membrane filtration flux are the type of membranes, operation temperature and quality of feed. Temperature largely affect the flux as the coefficient of viscosity changes according to the temperature of water. When designing the process, sufficient consideration about temperatures and production capability at the lowest degree is required.

Operation pressure and transmittal flux have a proportionate relationship theoretically, but in reality, when the pressure is higher, the increase rate of transmittal flux decreases. If operating pressure is higher, transmittal flux gets larger and the size of the facility gets smaller while designing for the process. Recovery rate estimates the transmittal flux to supply the required water amount. It shows the sufficiency of dealing with filtration. Recovery rate (percentage) = (transmittal flux/supply amount) × 100 or (supply amount-accumulated amount)/supply amount × 100.

Recovery rate is deeply affected by the membrane pollution degree which is estimated by quality, transmittal flux, and cleansing degree. Recovery rates are set around 35 to 60% max.

The concept of pore blocking on the membrane is normally called a fouling or filter cake, which is defined as being the solid or bio particles that form on the membrane while reducing the membrane productivities. Membrane fouling is one of the major limitations of membrane technology.

Fouling can occur due to membrane adsorption, pore blocking, cake layer formation precipitation or biofilm formation (“biofouling”). In the process of biofouling, microorganisms retained by the membrane tend to adhere to the membrane surface (Wang et al., 2004; Porter, 1990).

The brushing effect was determined using image analyses methods. The used membranes were analysed using an image microscope.

6.3 Equipment setup and procedure

A diagram of the experimental rig used for the experiments is depicted in Figure 3. The system was operated at a constant pressure of 30 cm hydrostatic head. The process feed tank, filtration tank and permeate tank were open to atmosphere. The system was fed with different polluted water. The hydrostatic head was controlled at 30 cm. Polyester woven fabric membranes, labelled as membrane 4, was used during the filtration process. The new and used membranes were then prepared for image analysis. In addition, the liquid or feed and permeate samples were taken before and after stable flux and before and after the filtration process. The first synthetic solution was the lime solution (the mixture of 1 kg lime and 10 L of water) and the second synthetic solution was active carbon solution (the mixture of 0.5 kg active carbon and 10 L of water) (see Table 5.2). For brush effect experiments, the membranes that were used during the experiment were cut and analysed using an image microscope. There were three different types of samples. The first samples were the new membrane, the second sample was a cleaned membrane using a brush and the last sample was the dirty membrane. Waxing processes were to sock the fabric in the melted wax and warm the fabric allowing it to absorb more wax in open pores. Then bends all the wax fabrics in making sure that not all the waxed areas were forming the wax cake closing the fabrics completely.

6.4 Analytical methods

The data collected during the experiment was processed using statistical tools. The feed turbidity before the filtration was above 10 NTU. The reason for using different feeds and different fabrics as membranes was to identify the effect of pore blocking on the membrane surface. There are a number of forces affecting the membrane performance. Some of these factors are stress-strain (strength, plastic/amorphous) shrinkage, poisoning, fouling and more. The analytical instruments used during the undertaking of this experiment were a turbidity meter, SEM microscope, light microscope and Malvern Mastersizer 2000.

6.5 Results and Discussion

During the operation, stable flux was observed. The fouled and clean membranes were analysed. Theoretically, clean fresh waters have particle sizes that are very small averaging between 0.0002 to 0.0005 µm and contain traces of dissolved magnesium, calcium, potassium, sodium, etc. In this range, there are no bacteria, viruses, or suspended solids.

The main water problems are bacteria ranging in size from 5 to 12 µm. Filtration processes used to clean water at low pressure are microfiltration. Microfiltration membranes filter colloidal particles and bacteria from 5 to 10 µm in diameter. The microfiltration membrane pore size range is between 0.75 µm to 12 µm yet ultra-filtration pore size range is between 0.008 µm to 0.75 µm and a normal filtration pore size range is from 8 µm and above.

The study was based on evaluating the effects of particle characteristics and surface pore blocking on membrane performance. Figure 6.1 is a simplified diagram for pore blocking of each loop cell.

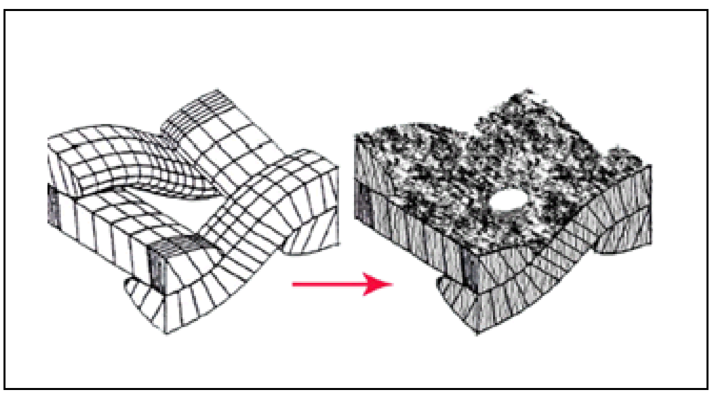

Figure 6.1: Simplified pore blocked of each loop cell

As the filtration takes place, the pore is being blocked up to the point where it cannot be blocked any longer if the static pressure is minimal and kept constant. Equation 6.2 shows the relationship for fouling build-up at a given area.

$$\frac{\partial V}{\partial T} = \partial F \cdot A \qquad \text{Equation 6.2}$$

It is assumed that at steady state of any particle, any forces applied to the particles are at an equilibrium state. The particle moves when one force is greater than the opposing forces.

Figure 6.2 shows the forces that are acting on the particle and membrane pore during cross-flow filtration and dead-end filtration.

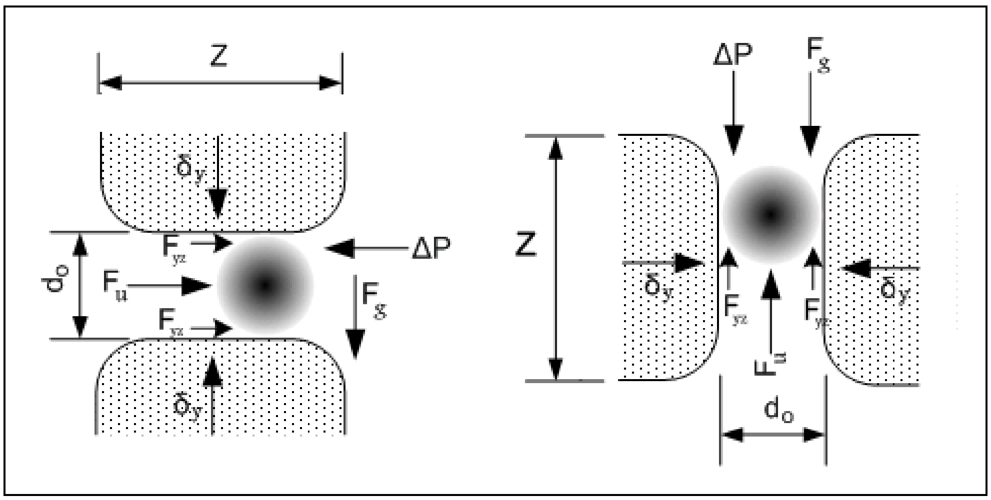

Figure 6.2: Equilibrium of solid particle plugging in a vertical and horizontal pore channel

(do – pore channel, ΔP – Driving force, Fu – capillary force, F_g – gravity, F_{yz}– friction force, δ_{yz}– fabric compressibility force)

(Adapted from Soepyan et al., 2016)

Figure 6.2 shows the incompressible particles in the pore of the membrane placed vertically and horizontally. The diagram shows all the forces acting on the particle. Therefore, d_o is the pore channel and diameter of the particle, ΔP is the driving force, F_u is the capillary force, F_g is the gravity force, F_{yz} is friction force, δ_{yz} is fabric compressibility force, Z is the membrane thickness.

Figure 6.3 shows the forces that are acting on the compressible particle and membrane pore during cross-flow filtration and dead-end filtration.

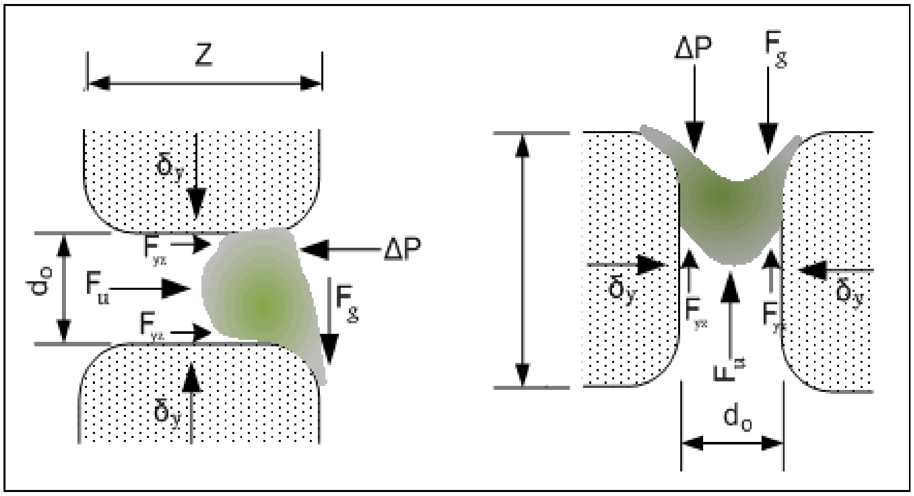

Figure 6.3: Equilibrium of compressible particle plugging in a vertical and horizontal pore channel

(do – pore channel, ΔP – Driving force, Fu – capillary force, F_g – gravity, F_{yz}– friction force,

δ_{yz} – fabric compressibility force)

(Adapted from Soepyan et al., 2016)

The external forces, *ΣF*, include hydrodynamic pressure and the body force of the particle from gravity and viscous drag. The compressibility force of the fabric and capillary force play a part during the filtration(see Equation 6. 3).

$$\sum \mathrm{F} = \frac{\partial P}{\partial Z} V_m - \rho_m g V_m + \rho_m R V_m \qquad \text{Equation 6. 3}$$

Defining *R* as the viscous drag per unit mass of the slurry, the external forces can be determined by the Equation above. By considering a number of elements at the base of interfaces and moving particle within channels. The process predicts the change in slurry density ρ_m and the slurry velocity *u* with the time change *Δt*.

The selected polyester woven fabric membrane pore size was assumed to be in the range between 1 µm to 5 µm, making it possible for the polyester woven fabric to be used as a membrane for microfiltration processes because it is capable in removing all bacteria and solids.

Figure 6.4 shows the flux behaviour when using different effluents at a constant hydrostatic head of 30 cm. With this experiment, only membrane 4 was used.

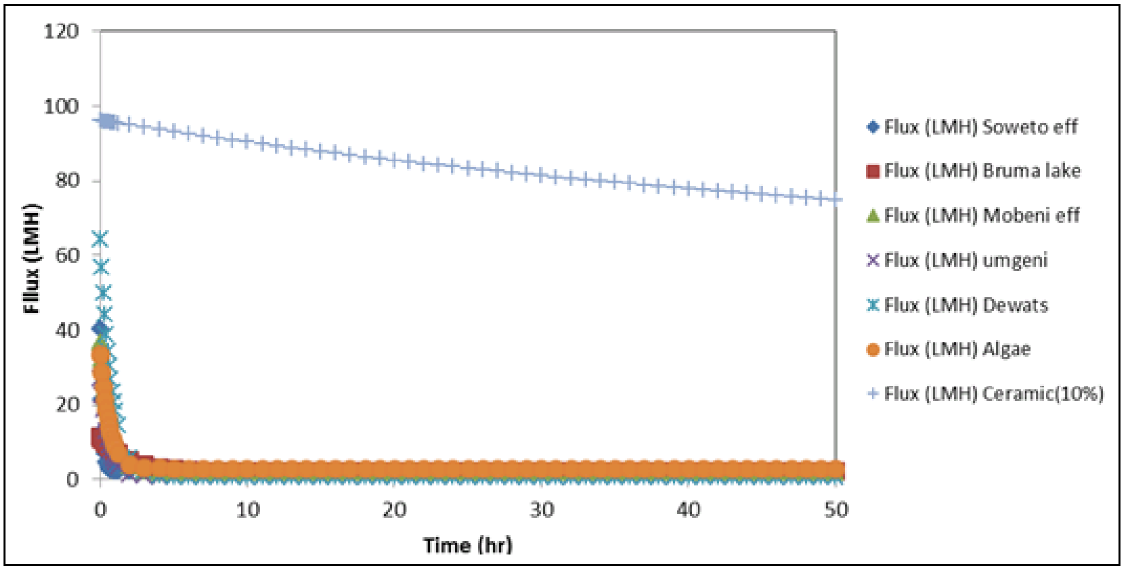

Figure 6.4: Fluxes for different feeds processed using polyester membrane only.

It is well known that bacteria and proteins are compressible and can change shape depending on the force applied or used as operational pressure. When processing the calcium solution with no bacteria or protein or any bio impurities, the flux was extremely high, (see Figure 6. 4). The reason was based on the fact that calcium is an incompressible solution.

Figure 6.5 shows the accumulation behaviour when using different effluents at a constant hydrostatic head of 30 cm. With this experiment, only membrane 4 was used.

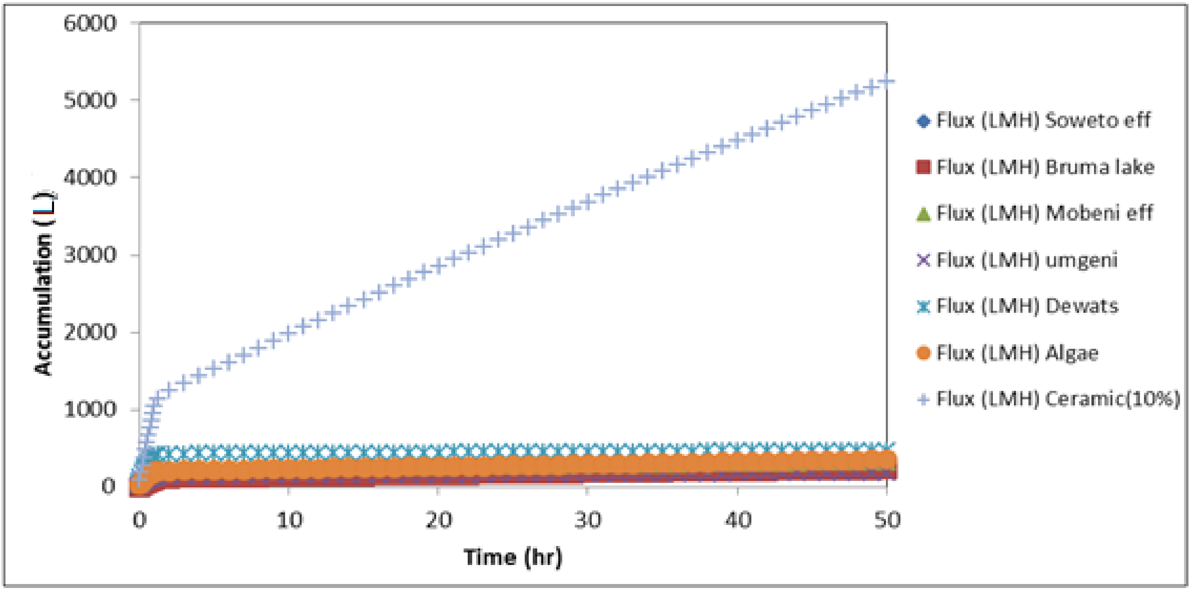

Figure 6. 5: Permeates of different feeds at a given time using the polyester membrane only.

Figure 6.6 shows the flux behaviour when using different effluent at a constant hydrostatic head of 30 cm. With this experiment, only membrane 4 was used. The calcium solution graph is excluded from the graphs below.

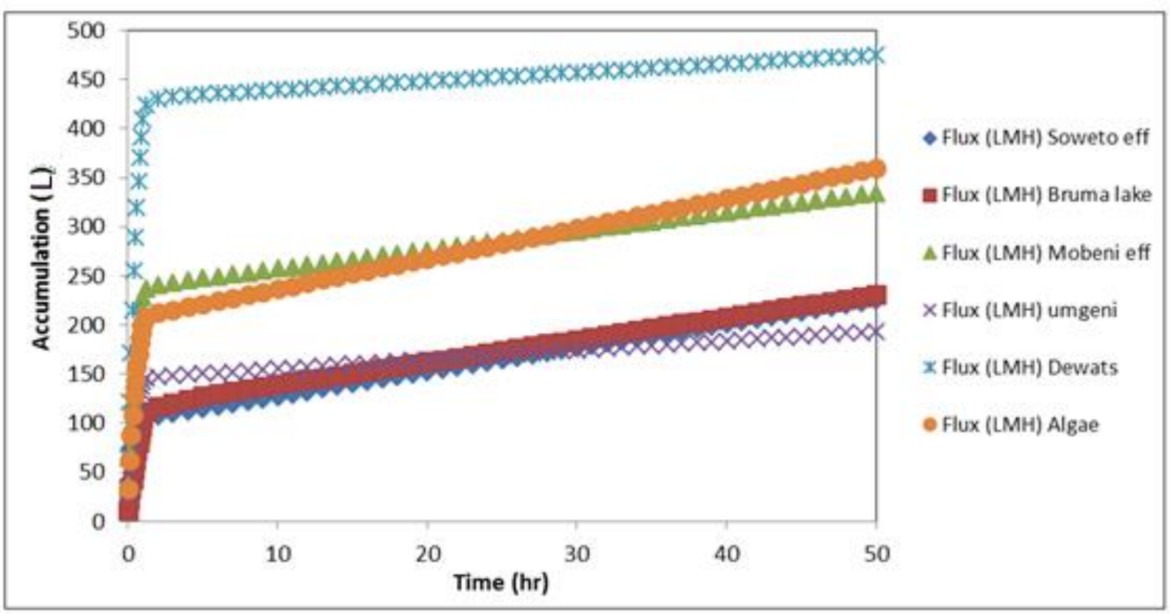

Figure 6.6: Permeate accumulation for different feeds using the polyester membrane.

The Figures show that the solutions with high turbidity, bacteria and less suspended solids have less flux when compared to solutions with high-suspended solids and fewer bacteria.

The membrane 4 selected was made of closely packed multifilaments. It was impossible to see the pore size. However, it was possible to determine the pore size at the beginning of the process and also at constant flux by analysing the feed quality and the permeate quality.

Microfiltration is a pressure-driven process in which a membrane is applied to separate particles from an aqueous solution. Particles accumulate on the membrane until the equilibrium state is reached to form a constant or stable flux.

Abeldelrasoul stated that at constant flux, the cake formed on the membrane surface covered the membranes while balancing all forces acting on the membrane and formed a cake (Abdelrasoul et al., 2013). The microfiltration using a synthetic solution was a steady-state process at constant flux for many days of operation so as all the real solutions.

Abdelrasoul stated that during the filtration, the solid-particles under a low-pressure drive system can rearrange to close the porosity of the cake on the membrane. The smallest particle valued at 0.02um cannot pass through the cake or layer formed on the membrane (Abdelrasoulet al., 2013).

From Figure 6.6, it was noted that real solutions had a bigger particle size as compared to synthetic solutions. Membrane 4 was capable to process all the feed and still remove 99.995% of impurities.

Figure 6.7, shows the electro scanning microscope image for membrane 4. This particular weave fabric was weaved using rotor twisted yarns and are closely packed.

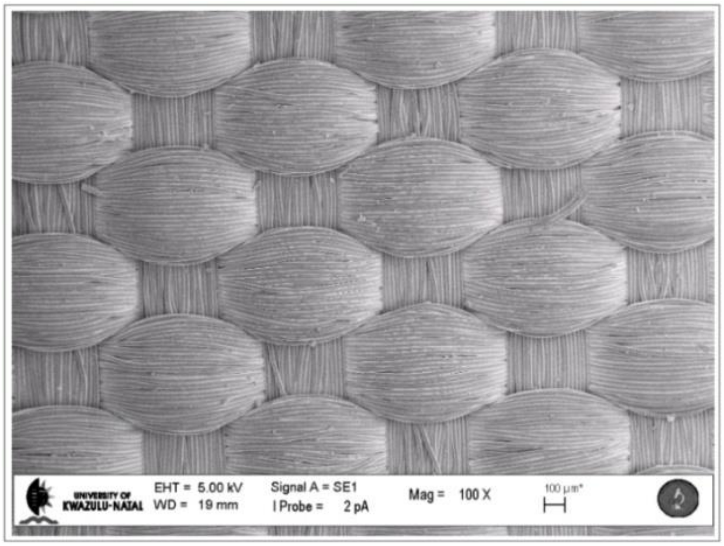

Figure 6.7: Plain weave membrane with normal rotor twist yarns (SEM)

Figure 6.8, shows a fouled membrane. The membrane was used for microfiltration; the feed was DEWATES effluent mixed with Calcium (Khulu 2) powder.

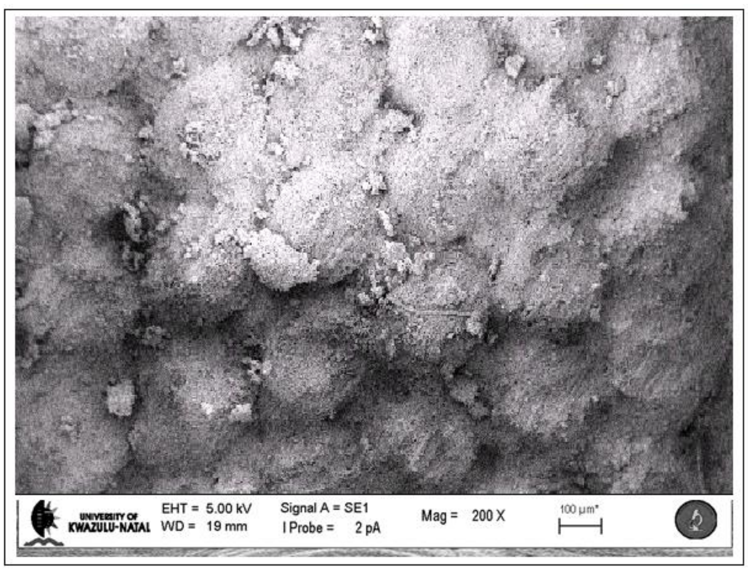

Figure 6.8: Fouled plain weave membrane (SEM)

Figure 6.8 is the image of the dirty membrane before brushing. Figure 6.9 shows a microscopically damaged image on polyester woven fabric membranes used during the study.

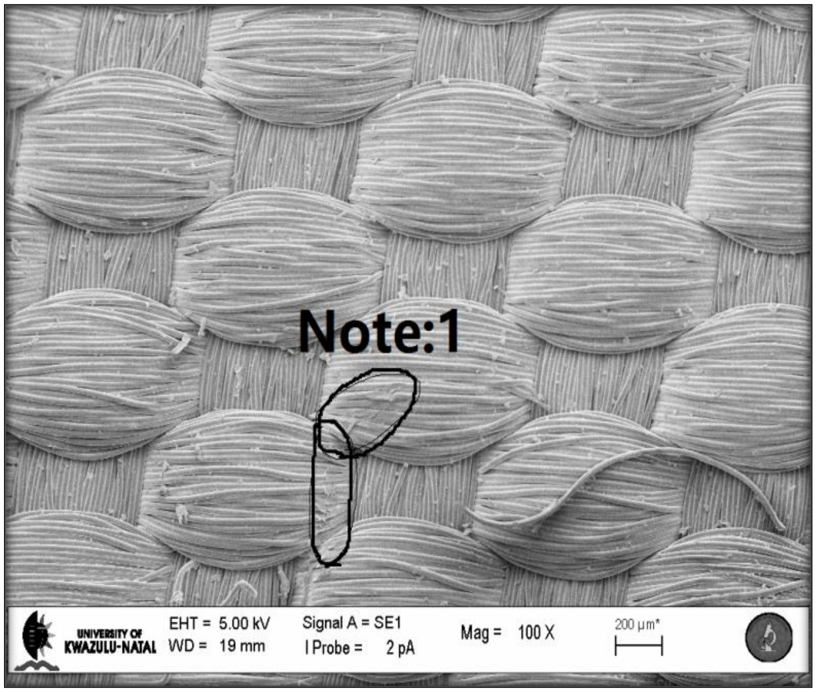

Figure 6.9: Cleaned plain weave membrane (SEM microscope)

The image above (Figure 6.9) was taken using the electron scanning microscope. This particular weave fabric was weaved using rotor twisted yarns. This membrane shows that the polymer brush cleaned the membrane very well. When forcing the brush, the membrane surface is microscopically damaged but the effect is not affecting the membrane pores but removes dirt material on the membrane surface. The microscopically damages are not caused by the brush polymers but are caused by the brush wire. Figure 6.10 shows a clean new fabric. Figure 6.11 shows an old fabric or reused or brush fabrics.

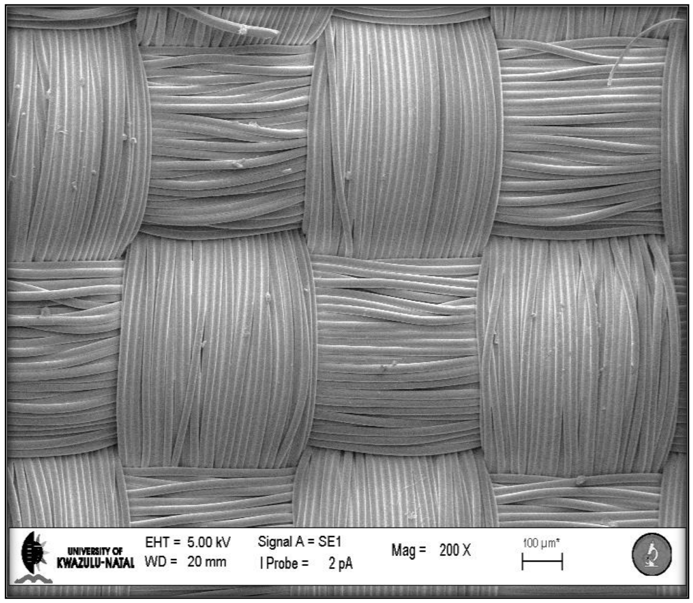

Figure 6.10: New plain weave membrane (SEM microscope)

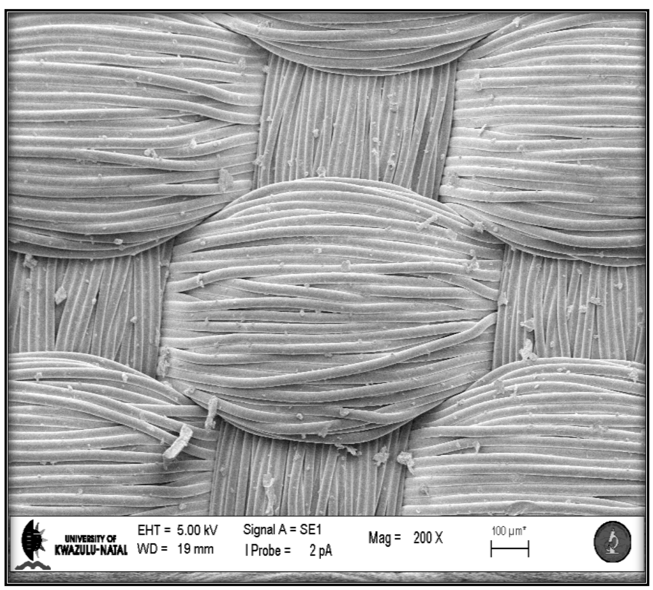

Figure 6.11: Used or brushed plain weave membrane (SEM microscope)

Figure 6.12 is the brush used to clean the polymer fabrics. The brush was made of polymer filaments and wire.

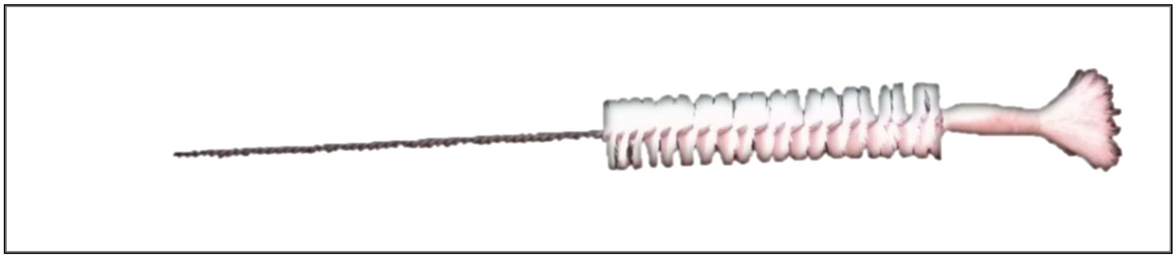

Figure 6.12: A polymer brush used to clean woven fabric

The production rate for the solution with only calcium or incompressible impurities was much higher. The results prove that at low pressure the incompressible particles build up rearrange themselves in the way that only water will pass through the formed layer.

The second experiment conducted was not part of the study but necessary to look at other textile finishing processes that can improve the selected fabric. The finishing process used was textile waxing process. The Figures from 6.13 to 6.16 proved that bulkiest fluffy fabric absorbed a lot of wax. Permeates from all selected fabrics (waxed) improved when using DEWATES effluents as the feed.

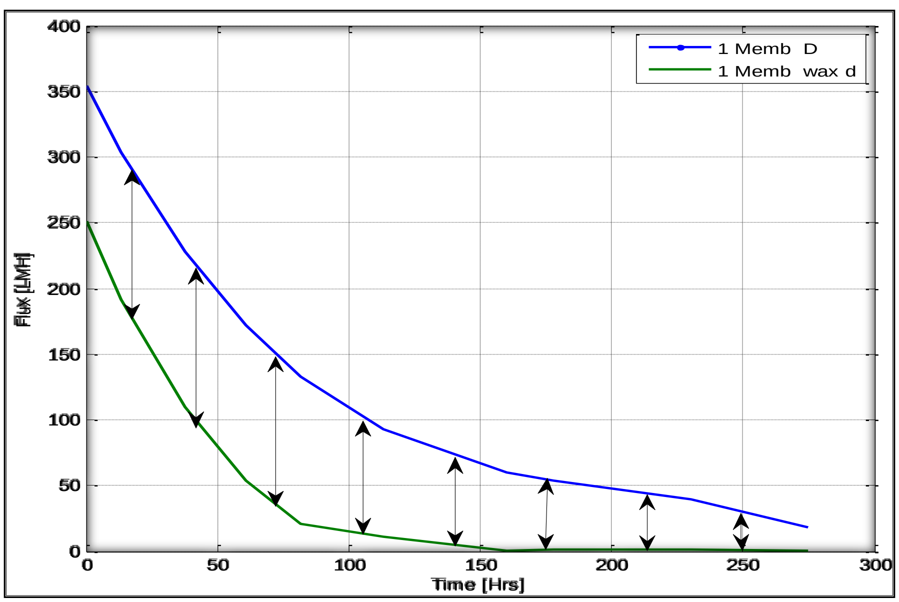

Figure 6.13: DEWATS flux behaviour for wax treated fabric and non-treated for membrane 1

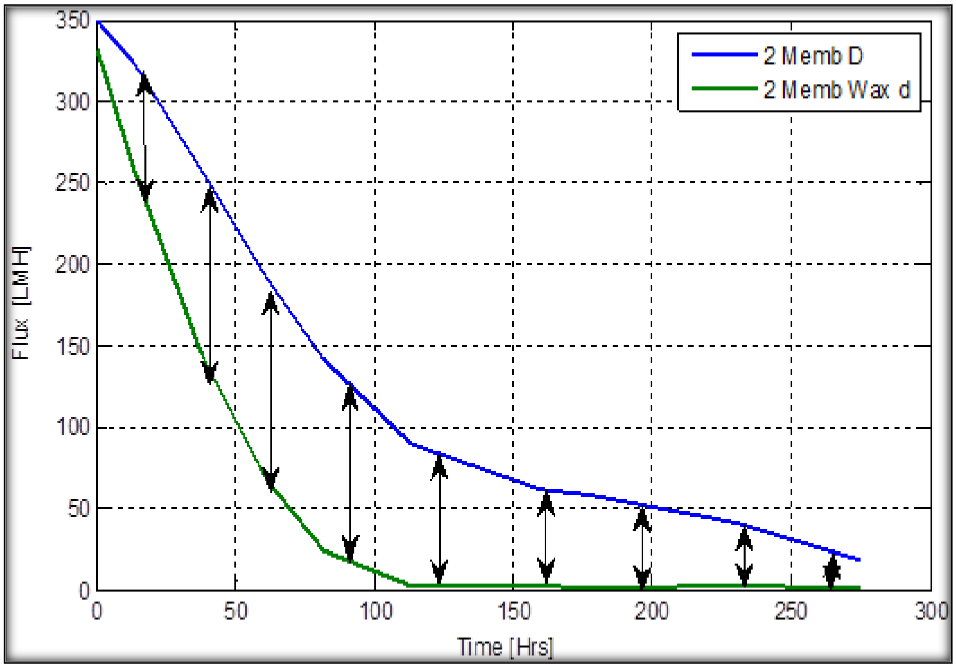

Figure 6.14: DEWATS flux behaviour for wax treated fabric and non-treated for membrane 2

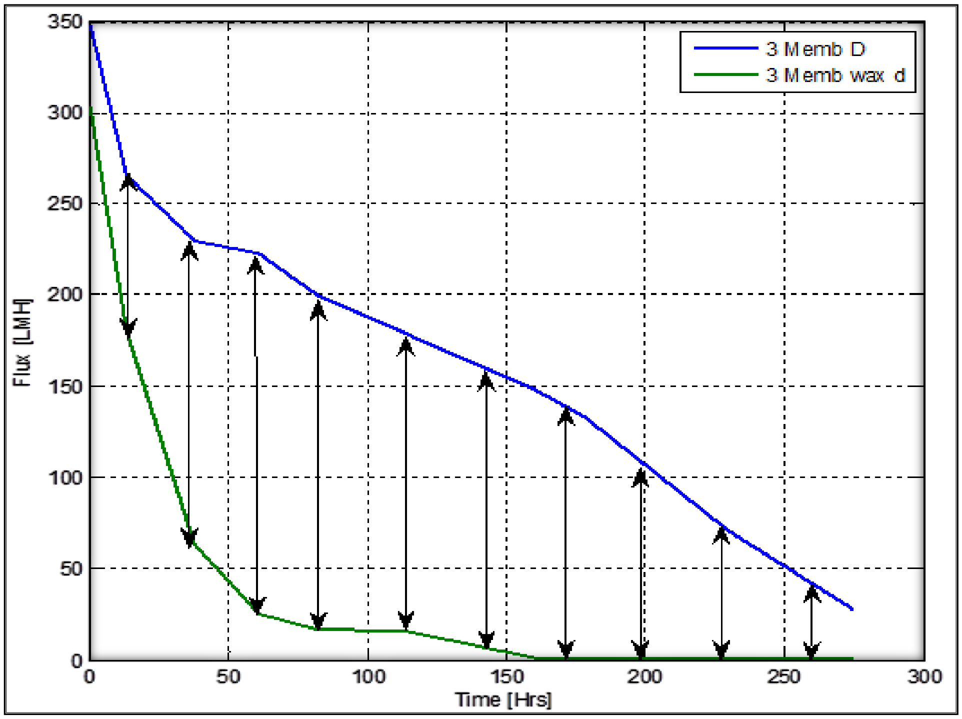

Figure 6.15: DEWATS flux behaviour for wax treated fabric and non-treated for membrane 3

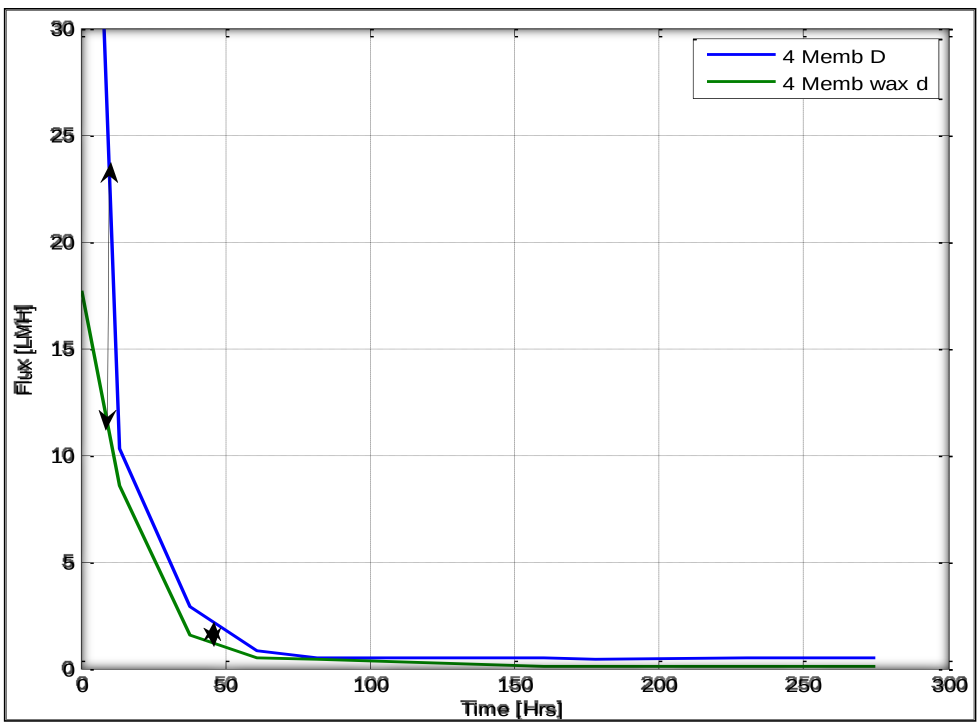

Figure 6.16: Calcium and DEWATS solution flux behaviour for wax treated fabric and non-treated for membrane 4

The flux decreased for all waxed polymer fabrics while the quality also improved. Membranes 1, 2 and 3 can be modified to meet microfiltration requirements.

Without wax, the results were as follows: The Coli forms of DEWATS effluent used, as the feed was 1450000, after 275 hours the coliforms of all fabric permeate were also evaluated/tested. Fabric label as membrane 4, coliforms reduction was 99.999% yet fabrics label as membrane 1, membrane 2 and membrane 3 after 275 hours were in-between 90 and 99%. However, at the initial stage of the process or experiment the fabric label as membrane 4, the coliforms reduction was also 99.999%, yet other three fabrics were not able to remove about 50% of the bacteria even after 1 hour. Same with COD and E-coli test polyester fabric removed 99.995% and polypropylene fabrics removed around 50%. When it comes to turbidity, polyester fabric permeate was low then 1NTU and polypropylene were above 5NTU.

The results proved that any fabric can be modified to suit the filtration needs. All fabrics can be modified to suit filtration range or ultrafiltration or microfiltration or reverse osmoses. All selected fabrics can undergo the textile finishing for modification purposes to meet or suit filtration range or ultrafiltration or microfiltration or reverse osmoses.

Polymer fabrics are used by petrochemical industries, mining sectors, water sectors, for food processing and more. Membrane 4 or polyester woven fabric can be used to process most liquid from water to hydrocarbon liquids, provided that the liquid is in the range of 4 pH and 10 pH.

6.6 Summary of Results

The particle size of the feed and permeate were analysed using the Malvern Mastersizer 2000 for fabric label as membrane 4. The results show that at stable flux, the turbidity was less than 1NTU. The results also showed that permeate was cleaner than tap water, with no particles identified or picked up by the instrument, Malvern Mastersizer 2000.

During the filtration, the solid-particles under a low-pressure drive system can rearrange to close the porosity of the cake on the membrane. The smallest particle valued at 0.02 um cannot pass through the cake or layer formed on the membrane or polyester membrane. It was observed that at critical flux the membrane 4 is more powerful to remove all the bacteria and suspended solids.

It was observed that the polluted water with incompressible solids only can operate for days, weeks and months without reaching a constant stable flux of 2LMH when using membrane 4. The results proved that the fabric can process any type of solution and still produce a good permeate quality. For solutions with no bio impurities, the flux or production is much higher than solutions with bio impurities that are compressible.

In addition, it was observed that the polymer brushes do not affect the membrane or woven surface. However, if the polymer brush is applied poorly the sharp objects on the brush can affect the membrane, especially the metal or wires. The polymer brush alone will not damage the membrane but effectively remove impurities and dirt on the membrane surface.

One of the rare textiles finishing processes was used in membranes that were not suitable for water treatment. After waxing them, it was noted that the one with bulky staple filaments absorbed more wax. Also noted that all of them performed better after waxing and the permeate quality improved. The disadvantage is that permeate contained small pieces of wax. After warming the permeate, wax's were removed from permeate and the permeate quality was lot more clear and wax fee.

CHAPTER 7.

THE BASIC MATHEMATICAL MODELLING FOR WOVEN FABRICS USED AS A FILTRATION MEMBRANE

7.1. Introduction

During any form of filtration, there are three main characteristics that are critical. The first one is membrane characteristics, two is the solution characteristics and lastly is the impurities characteristics. The membrane characteristics include the ability to filter, pore sizes, thickness, tensile, bonding or weaving pattern and cleaning regimes. The solution characteristics include the type of impurities, concentration of impurities, viscosity, etc. The impurities characteristics include the nature of impurities (compressible or not), particle size, a concentration of particles, the ratio of impurities in the solution, etc.

The mathematical modelling is essential to filtration systems for optimization purposes and understanding the filtration membrane behaviour. To describe and optimise the filtration systems, it is necessary to create and understand the mathematical behaviour of the low energy filtration system membranes that use polymer woven fabrics as membranes. The three main characteristics are taken into account as well as the operational parameters.

During filtration, permeate flux decreases as the processing time goes on. This phenomenon is directly related to membrane fouling, which is the main restriction of membrane usage. Membrane fouling can be categorized into two kinds: internal fouling caused by pore wall adsorption and blocking, and external fouling due to the formation of the cake layer on the membrane surface. The fouling mechanisms triggered great interest among scientists, engineers and technicians. Adhesion of foulants such as proteins, microbes, polymer colloids, and inorganic particles is the main contribution to membrane fouling (Chen and Kim, 2006).

Membrane fouling can be improved or limited by optimizing the operating conditions, especially the feed quality and membrane cohesion forces. The fouling rate is directly linked to the number of particles brought to the membrane surface and therefore the flux declines. However, a flux, which is too low, would result in higher operational costs if pressure is applied to improve the flux or higher capital costs to build the system with a larger surface area. Most commonly, fouling is assessed from inferred measurements of permeation rate and/or permeates quality (Kujundzic et al., 2004).

Farina and Fusi (2006) state that when a fluid flows through a deformable porous medium the forces associated with the flow deform the porous solid and compressible particles. In turn, the deformation of the porous medium influences the flow and operational pressure. The competition among the stresses in the solid and the stresses in the fluid determines the evolution of the system, which is very different from that observed when the interaction between the flow and the deformation of the solid porous medium is absent (Farina and Fusi, 2006). See Figure 6.2 and 6.3.

Since mathematical modelling is essential to filtration systems for optimization purposes, it is necessary to create a good model of the low energy filtration system that uses polymer woven fabrics as membranes and was an objective of this study. Hence, the investigations carried out were (1) to evaluate flux behaviour in the form of a mathematical Equation; (2) develop a model that will assist scientists and researchers in evaluating the suitable woven fabric that can be used as a filtration membrane without delays in the design phase.

In most cases when selecting the filter membrane for cross-flow filtration and dead-end filtration process, the driving pressure, permeate quality and quantity including the feed characteristic and condition are taken into consideration. However, the most important part in any fabric, woven or non-woven, is the membrane capacity to remove unwanted material from a desired product or liquid. This study shows that hydrodynamic conditions caused by the feed quality are also a major factor, so as the membrane pores and operational conditions (Sombatsompop, 2007).

7.2. Definition and determinations of mathematical model for woven fabric used as a membrane for low energy microfiltration

7.2.1. DEFINITION OF MATHEMATICAL MODELLING

Briefly, mathematicians are in the habit of dividing the universe into two parts: the mathematics, and everything else, that is, the rest of the world, something called "the real world". Mathematical modelling is the process of using various mathematical structures – graphs, Equations, diagrams, scatter plots, tree diagrams and so forth – to represent real-world situations. The model provides an abstraction that reduces a problem to its essential characteristics.

When it comes to modelling, the emerging economy needs are more based on technologies that are easily found, not require too much capital cost and high maintenance cost. Woven fabrics become ideal since most women from rural and underdeveloped areas are using woven fabrics to screen water. However, most people are not clear about the difference between screening water and filtering water and benefit from both processes. The filter for water must operate at microfiltration, ultrafiltration and reverse osmoses filtration levels. The selected woven polyester was for microfiltration and polypropylene fabrics were suitable for screening since they were not able to remove micro impurities like bacteria. However, both polyester and polypropylene fabrics were robust.

7.2.2. MATHEMATICAL MODELLING EVALUATION METHOD

Mathematical models are used for better understanding if simplified for homogenous heterogeneous problems. The models that describe the flux through the membrane differ as the membrane considered changes from being very dense to become more porous (Vinther et al., 2015).

There are three parts that are playing a major role in filtration; one is the behaviour of particles in the solution. The second part is the behaviour of the woven fabric and lastly is the filtration operational conditions. These are three parts includes three main characteristics of which are membrane characteristics, solution or impurities characteristics and operational condition characteristics.

During filtration, there is a particles transportation that is taking place in any filtration process. Some particles increase with size, while others decrease and others just dissolve in the solution. Particle transport modelling has been considered extensively in both contaminant transport and chemical filtration. The particle transport models are very limited and never used or applied to the movement of bacteria, small-suspended solids and more. And also during filtration, some living organisms like bacteria grow, reproduce and some died.

For particle characteristics; Equation 2.28, ($p_s < p_o$ then$|p(t) = C_1 e^{-kt}|$) represents an environment whereby the particle decays and dissolves in the solution (living organisms population drop or die of the solution). However, the bacteria have a certain life span and in most cases, some conditions prevent them from multiplying.

For Solution characteristic; Equation 2.29, ($C_s \leq C_o$ then$|c(t) = C_o + C_1 e^{-rt}|$) is for particle concentrations that are decreasing with time; where concentration C_s is the final concentration in the solution after population growth, and C_o is the concentration of bacteria in the solution before population growth. The rate of the particle is symbolised by r.

For membrane characteristic; Membrane 4, z_1 or $z_2 < z_{1 \text{ or } 2}$ of Membrane 1 or membrane 2 or membrane 3. The sinusoidal crimps for membrane 1 or membrane 2 or membrane 3 area lot more than membrane 4.

Membranes 1, 2 and 3 were not balanced when it comes to tensile strength and elongations meaning the crimp angles for warps were smaller than that for weft. However, membrane 4 was balanced when it comes to tensile strength and elongation meaning the crimp angles for warps and weft were almost identical. For volume space within yarns and filaments that are closing during cake formation. Equation 2.48 ($V_s < V_o$ then $|V(t) = V_p - C_1 e^{-\gamma t}|$), at the time t_o the value of V_p it when the membrane is new. However, as time goes on *(t_s),* the value of V_s will decrease at a certain rate during filtration and cake formation. The porosity volume decreases at a certain rate up to a stage where the volume will not absorb any impurities or build-up any more.

The Equation $J(t) = J_o + C_1 e^{-kt}$ represented the decreasing flux and also can be expressed in the form of *A, B* and *C* to form an Equation $J(t) = Ae^{-Bt} + C$ of which $C_1 = A$ is the initial flux or maximum flux. The value of $k = B$ is the rate of separation and $J_o = C$ is the minimum flux of stable flux. The Equation was obtained using statistical tools and mathematical software's and a programme like math lab and Q expect the programme to get this Equation $J(t) = Ae^{-Bt} + C$.

This Equation $J(t) = Ae^{-Bt} + C$ applied to all membranes however, some membranes with bigger pores processing a solution with smaller particles may behave slightly different however, the Equation applied to all fabrics. There are relationships between the pore size, particle size particle concentration and operational condition that include quality and driving force when it comes to filtration.

7.3. Equipment setup and process description

The diagram of the experimental rig used for the experiments is depicted in Figure 3.8 for cross flow and 3.9 for dead-end filtration.

For any mathematical approach, the laboratory experiments and field experiments were very important. The laboratory experiment is in a controlled environment. However, the fieldwork is operated under true conditions. The approach was essential to address the physical, operational, and other characteristics, which are relevant for the research, optimization, and knowledge transfer point of view.

The dynamics within this research were more complex especially for practical applications and lack of equipment. It was necessary to introduce admissible simplifications. The complications within this study manifested during the experiment.

When it comes to filtration, each molecule, atom, or cell has the attracting or repelling force within and between two or more elements or compounds. The kinematic pairing and repelling of molecules ware also observed as one of the phenomena that play a major role during the filtration. The system energy and molecular kinetic energy were noticeable during the experimental analyses. Other dynamics within this study were compressibility of matters and their characteristics.

This knowledge will assist in optimising the systems when using polymer fabrics as membranes for filtration. Hence, mathematical modelling is one of the important tools of engineering optimization and design. With the development of numerical mathematical and informatics, a new approach to the creation of a simulation model was formulated using mathematical computerised tools. The developed systems proved that the combination of analytical and experimental approaches was necessary for the success of this study (Hassan and Chowdhury, 2011).

Another method is to modify the thermodynamic potential of the membrane surface by using low surface energy materials that reduce the chemical free energy change upon absorption of foulants.

The focus of this study was on the effects of fouling on the polymer used as a membrane in the filtration systems. Another approach was employed to deal with the membrane operation cost and membrane optimisation. Low energy filtration systems operating at low pressure can be one of the solutions to the filtration problems needed by emerging and underdeveloped economies.

7.4. Mathematical description of stable flux

The simulation model of the filtration flux for polyester woven fabric was created using Logger Pro, Q-expect, Math lab and Simulink and more. The Equations of the flux for the selected membranes were set with logger Pro Q-expect, Math lab and Simulink and more. The conditions were based on the experimental results and realistic/ideal assumption.

The filtration driving force was kept constant at 0. 03m. Theoretically, for any type of pressure filtration, the filtration rate per unit area or flux J will be proportional to the pressure drop ΔP across the membrane or filter divided by the resistance to flow (Lyndon, 2004).

The resistance term consists of two parts: the resistance of the cake which accumulates on the upstream surface of the membrane R_C and the resistance contributed by the membrane itself R_m. The synthetic solution was only forming a cake, not a bio-film. This is due to the continually increasing thickness of the cake build up to a point where gravity started to play a part in its compaction under the very low pressurized conditions of filtration. The effect of pore plugging within the membrane was observed and evaluated (Porter et al., 1990).

When F expresses flux, R resistance, the concentration of the solution and volume collected at the given time. It is assumed that at a stable flux, forces are at equilibrium state unless the impurities change the characters and the flux will change.

7.5. Mathematical Simulation

Water, bacteria, suspended solids and membrane structure requires a multistage modelling. Multistage modelling allows the system to analyse the complex heterogeneous properties of the solution and weave structures of the membrane.

Polymer materials are subjected to the laws of the universe. There are forces that exist within atoms, molecules, compounds, material and more. These forces have attraction ability and repelling ability depending on the nature of the material and forces.

Due to these forces, fouling resistance is caused by solute adsorption into the membrane pore and gel formation. It should be noted that the permeate flux remains constant if less force is applied to drive the process pressure. The fabrics used as membranes are the main components for filtration and the fouling layer is the main component for stable flux after the forces are at equilibrium.

7.6. Filtration and Design Optimization

Filtration takes place when the wanted liquid passes through the membrane surface area of the membrane at a given time, while the unwanted materials do not pass through the membrane. The solid materials then build up and form the cake or a thin layer or gel layer that becomes a supper membrane sometimes.

Sometimes the thin layer or gel layers do not become a supper membrane but a barrier. When the right operational pressure is applied, the thin layer does not compress and becomes a barrier even though the solution contains the compressible solids like gel and bacteria.

In general, it is known that during the filtration process the bigger and compressible particles in the solutions will block the pores. In addition, it is known that any liquid flows toward less resistance area. That means that the solution with less concentration of impurities will not plug the pore quicker as compared to the solution that is concentrated with impurities. In general, it is known that impurities are different in characteristics. The particle characteristic includes physical and chemical properties. Some impurities are organic, some inorganic, some easily compressible, some are hard, some have colour pigments, and some are colourless and more.

There is an effort to balance filtration forces that apply to a particle and filter material during the filtration process. The forces are within the distribution of masses, concentration, driving force, compliance, passive resistance, and other kinetics of mechanics caused by membrane and fluids including particle characteristics in the fluid. It is practically impossible to evaluate and eliminate some forces during the filtration process. However, the behaviour of each fabric performance can be evaluated.

To develop an approach suitable for fabric selection suitable for filtration or microfiltration systems one needs to focus on the quality, quantity, operational condition, cleaning protocol and design parameters like available space and required flow rate.

Figure 7. 1 shows the steps that need to be followed when selecting the fabrics for filtration processes. The following steps were used during the study, this particular step may change according to the engineer or scientist design needed. However, the following step was very critical for the study.

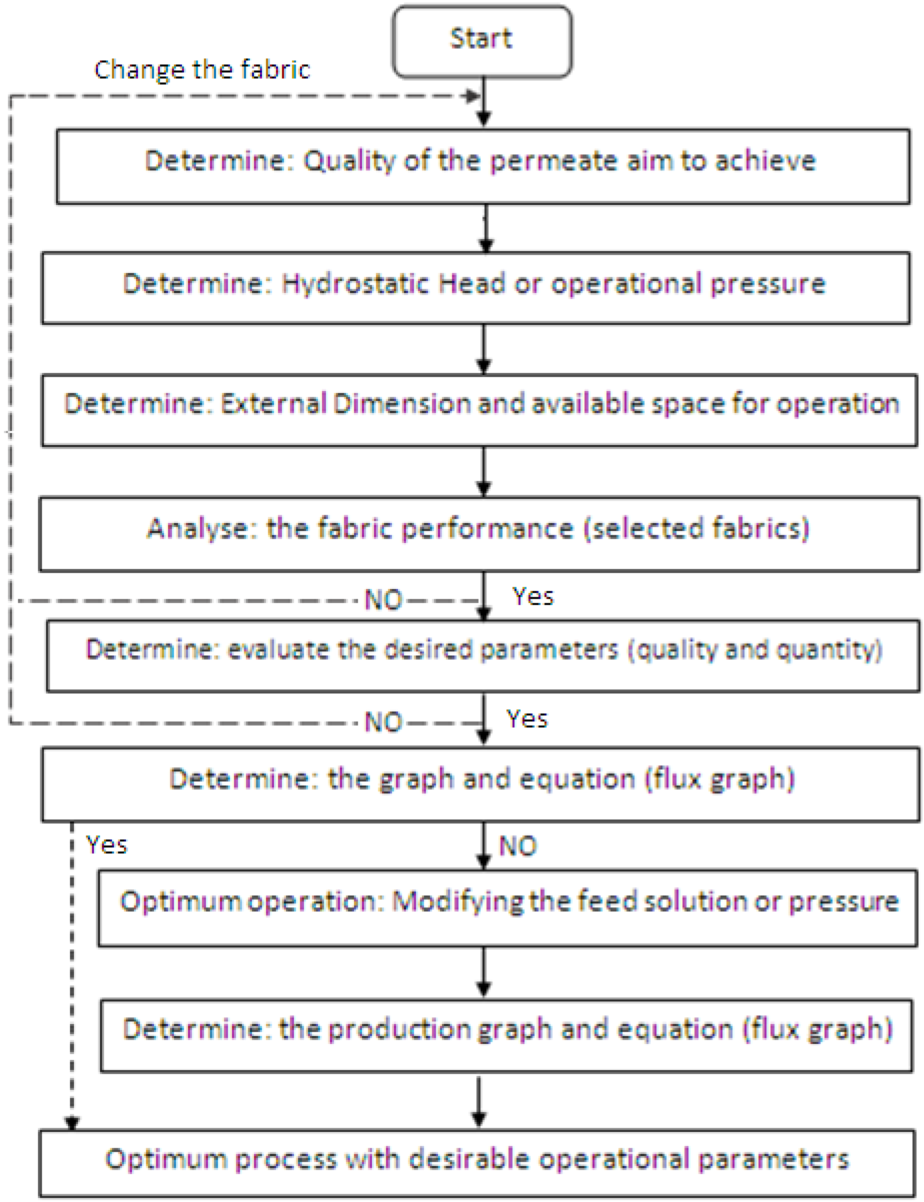

Figure 7.1: Process needed when design an optimum membrane system

Figure 7.1 has critical steps that are important when selecting the fabric for a filtration process. These steps were developed during a series of experiments. It was observed that some fabrics are suitable for general filtration processes aimed at removing impurities like stick, wood and more. Other fabrics can be specialised to be used in microfiltration processes or ultrafiltration processes or other processes. It all depends on the desired requirements.

Most studies focus on using general membranes in treating river water and wastewater. However, the novelty of this study is to zoom in at polymer woven fabrics that can actually be used to process water and wastewater and replace fabrics that are not cleanable and not capable to perform as membranes.

Out of the four fabrics selected, all can be used as membranes but applied for different solutions in water and wastewater treatment systems because all have different characteristics and performance to one another. Membrane 4 can be used as microfiltration while the other fabrics can still be used as membranes or screens but not for microfiltration processes. Membrane 4, is the fabric that can be used to process water for domestic use, yet membrane 1, 2, and 3 can be used to process water for industrial and irrigation use. When it comes to wastewater treatment facilities, these fabrics membrane 1, 2, 3 and 4 can be used in different stages for optimising purposes.

Figure 7.2 is a perfect setup that is relevant to evaluate the fabric according to de desired operational specifications.

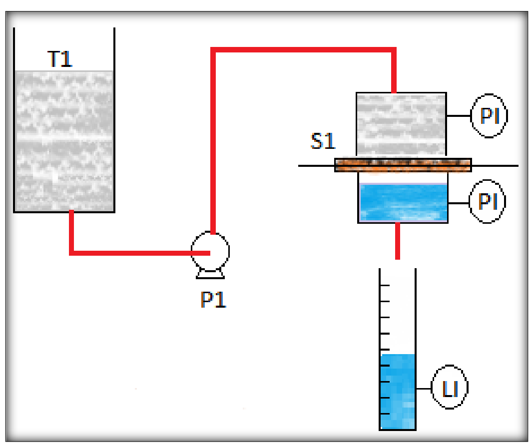

Figure 7.2: Simple setup for evaluating fabric performance

From Figure 7.2, the real solution in the feed tank, *T1* was pumped to the filtration chamber, *S1* where the fabric is placed either vertically or horizontally.

The pump provided the operational pressure. Pressure indicators, *PI* provided the pressure drop across the filtration chamber. The product or permeate was collected while measuring quality and quantity.

7.7. Other parameters that affect the fabric performance

With the use of theoretical knowledge and practical experience for particle transportation, it remained a challenge to do the filtration modelling especially when there are a lot of unknown dependent and independent variables. There are number of external factors that play major role in any filtration system. Those external factors are weather, temperature, concentrations, bacteria nature and more. In order to develop a mathematical model, some assumptions needed to be created to minimise the effect of unknown variables. Assumptions are not always recommended in mathematical modelling but necessary in eliminating some external and internal factors.

The following parameters were critical during the study and some were monitored and evaluated. Some had a positive impact while some had a negative impact during the study:

- *pH* - the solutions used for the study were from Gauteng and Kwa-Zulu Natal. pH ranged between 6 and 8.

- *Concentration* – it was observed that the solution concentrations changes for both laboratory and field pilot plants. The concentrations were also periodical and changed according to the weather as well.

- *Temperature* – During the experiment, it was also observed that the temperature of the solutions changed according to weather. Some solutions were dropping with 3 - 9 degrees at night and increasing during the day for both laboratory and field work.

- *Capillary force* – capillary force was not the same for each membrane cell and not the same for each solution.

- *Viscosity* – viscosity was not the same for all solutions. The viscosity also gets affected by the temperature of the solution.

- *Chemicals* – chemicals in the solution were also noted especially for the DEWATES and Bruma lake water. The weekend samples were soapier and bubbles were observed. The turbidities were lower than usual and proved that people were doing washing on weekends and adding a lot of washing chemicals.

- *Weathe*r – Besides the temperature, samples taken during summer were different from winter samples. Umgeni water samples deviated drastically. In summer, samples have less turbidity whereas in winter samples have high turbidity values and more bacteria.

- *Bacteria concentration* – at first the effluents were assumed to have more bacteria then river water. However, during the experiment, some effluents were not concentrated on bacteria as compared to other samples from the rivers.

- *Suspended solids* – river waters were assumed to have more suspended solids than effluents. However, during the experiment, some effluents were concentrated with more suspended solids as compared to other samples from the rivers.

- *Compressibility* – most organic material and bacteria are compressible, yet most inorganic and most suspended materials are not compressible. It was assumed that all samples with fewer bacteria will have a high flux. In this case, river water was going to have better flux. Nevertheless, experiments proved otherwise.

- *The mechanical and operational approach affects weave characteristic* - The water permeates test results varied, proving that the membrane pores size distribution were not the same.

- *Yarn characteristic* – yarn characteristic played a major role in fabric density and fabric performance.

Particle transport models were used to describe the movement of large particles, such as granular to plug the pores. The particle transport model mainly depends on the movement of bacteria, suspended solids, and fluids. It was assumed that at any steady state of the particle, the friction forces and stresses acting on the projected particle are the same and remain constant at constant flux.

7.8. Results and discussion

The dynamics within this research was more complex especially for practical application and it was necessary to introduce certain admissible simplifications. The complications within this study manifested during the experiment.

Figure 7.3 shows the behaviour of different solutions in membrane 4. The fabric was able to deal with impurities with small diameters. In addition, the fabric was able to operate as a micro filter.

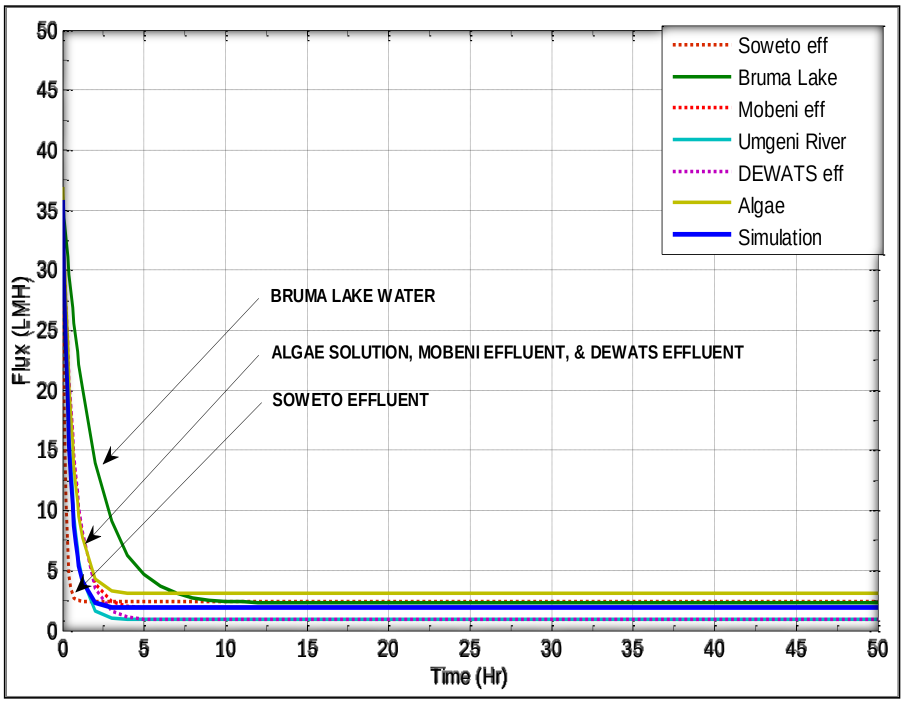

Figure 7.3: Flux for a different solution with different characteristic (high range)

The results (Figure 7.3) shows that at sTable flux, a formed cake becomes a membrane that is more effective than the polymer fabric used as a membrane. At sTable flux, the turbidity for all liquids or solutions were below 1NTU after processing with membrane 4.

For river water, the sTable flux was supposed to be above or more than the effluents. The results show that the sTable flux for river waters are more than effluents, meaning productivity is higher.

However, Umgeni river water was behaving as an effluent meaning Umgeni river contained a lot of compressible impurities. Bruma Lake water had fewer bacteria, fewer organics as well as less suspended solids meaning the concentration of impurities in the Bruma Lake water was low.

Figure 7.4 shows the behaviour of the membrane 4 (polyester membrane) when using different effluents

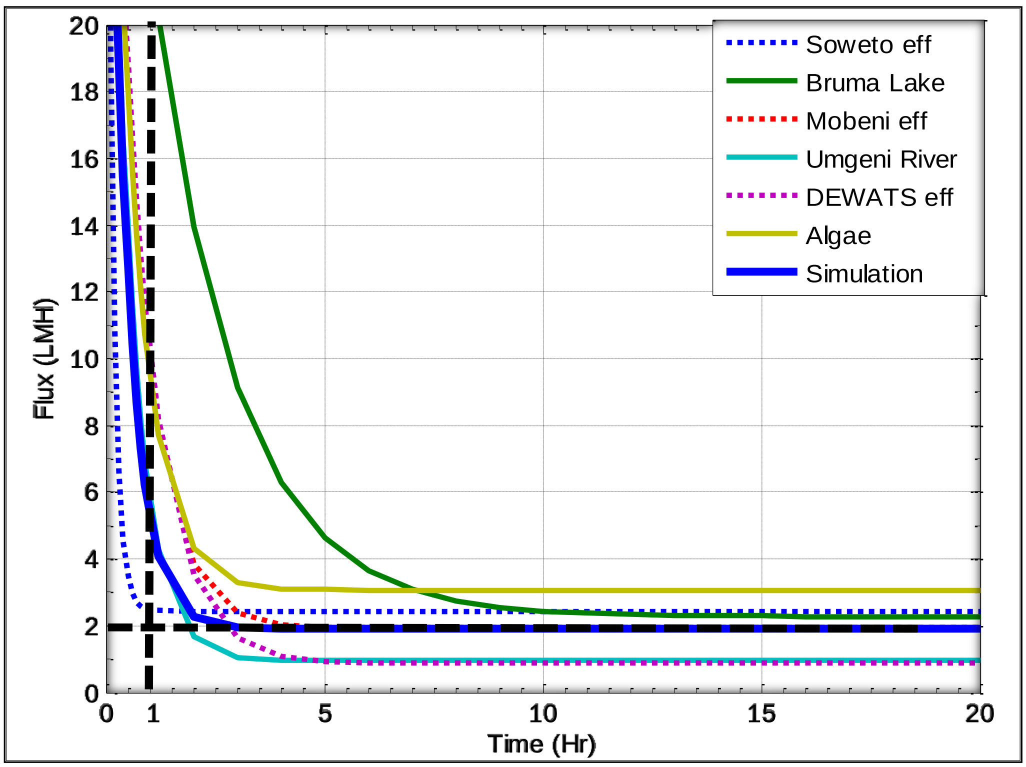

Figure 7.4: Flux for a different solution with different characteristic (low range)

When using membrane 4 as a membrane for the system operating at 30 cm hydrostatic head the minimum flux was 2LMH at sTable flux which took place before an hour.

However, if the process solutions contained less compressable impurities the sTable flux will take place after 1 hour, not before an hour when using membrane 4.

When using the derived Equation $J = Ae^{-Bx} + C$, to all fabrics, it was noted that there is a directly proportional relationship between pore sizes of the fabric and also the particle size of the solution aimed to be filtered. Membrane 4 has very small pore sizes and it was able to remove impurities from river water and wastewater.

The Equation ($J = Ae^{-Bx} + C$) was derived from Darcy's law and Hagen-Poiseuille law for laminar flow. The Carman-Kozeny Equation was also used.

Table 7.1: Different feeds with different properties and behaviours on membrane 4.

	DEWATS Effluent	Umgeni water	Mobeni Effluent	Bruma Lake water	Soweto Effluent	Algae solution	10% calcium Solution
A	63.62	26.37	35	29.272	38.085	38.42	36.7865
B	1.278	1.934	1.437	0.5327	6.9505	1.656	0.017055
C	0.8886	0.9547	1.939	2.281	2.441	3.071	59.405
	Real solution	Real solution	Real solution	Real solution	Real solution	Real solution	Synthetic solution

When water with impurities pass through membrane 4, the separation of impurities from the water depends on many factors starting with the geometrical structure of the membrane, pore size, particle size and particle characteristics of the impurity and more.

During experiments, it was a challenge to evaluate the time it takes for cake formation on the membrane surface. During the experiment, it was clear that the solution or a feed with more bacteria or biological impurities have less flux than the solution with solid particles. In addition, the solution with fewer impurities takes a longer period to reach a stable flux.

Solids under a low-pressure drive cannot rearrange to close the porosity of the cake formed on the membrane unless high pressure is applied (Abdelrasoul et al., 2013).

From a derived Equation from derived from Darcy's law. It was noted that some particle in any solution decay while others dissolve in the solution at a given rate so as bacteria, some dies.

Figure 7.5 shows the behaviour of particles when they are decaying and dissolving in the solution. Some particles reach the level where they will not dissolve any more.

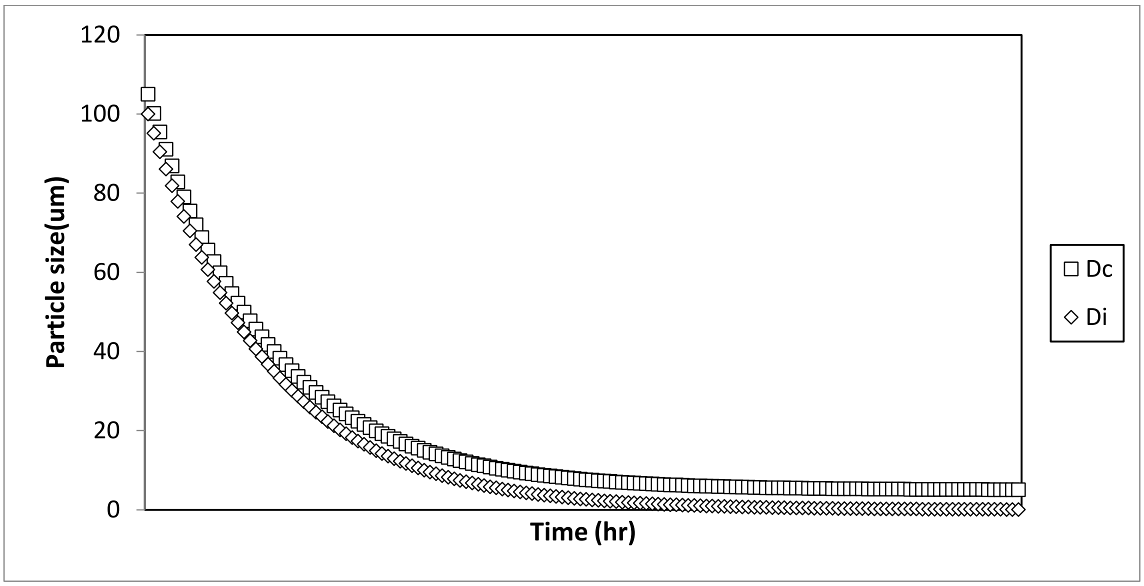

Figure 7.5: Particles that are decaying and dissolving in solutions

(Dc- Decay, Di-Dissolve)

Figure 7.5 shows that some particles dissolve while others die in the solution which depends on the nature of the solution and impurities that include the operation conditions. Some particles will dissolve with time. Some particles will decay up to the point that they will not decay any more. Figure 7.5 was a result of processing with the polluted solution with the compressible solution and a polluted solution with compressible and incompressible.

It was also noted during the experiment that the porosity of any fabric changes during the filtration as the impurity build ups on the fabric. The porosity of the fabric is reduced by the build-up of impurities in or on the fabric. The build-up was noted to all fabrics selected.

The experimental results and simulation proved that a solution with fewer compressible impurities like bacteria has a high constant flux *C* value when compared to other solutions especially the solution with high bacteria concentration. The initial flux called pure water flux *A* before the impurities blocked some pores are influenced by the fabric characteristics only. The value of *B* is the flux decay rate.

Figure 7.6 shows simulation results when the minimum flux is kept at 2LMH.

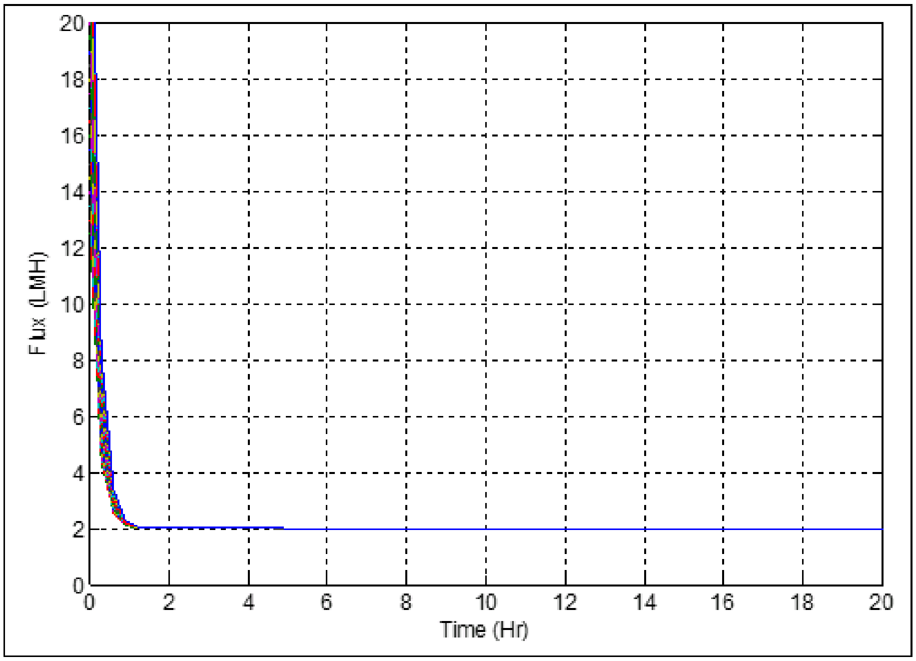

Figure 7.6: Flux with different water flux

The maximum flux of any membrane is an initial flux or called pure water flux. In the Equation, $J = Ae^{-Bx} + C$ the value of A is the maximum flux that occurs before the impurities blocked some spores on the membrane. This value is influenced by the fabric characteristic only if the filtration process operates at low energy. However, if the pressure increases, this value will also increase.

Figure 7.7 shows simulation results when the minimum flux is kept a 2LMH and the maximum flux is kept constant at 17LMH.

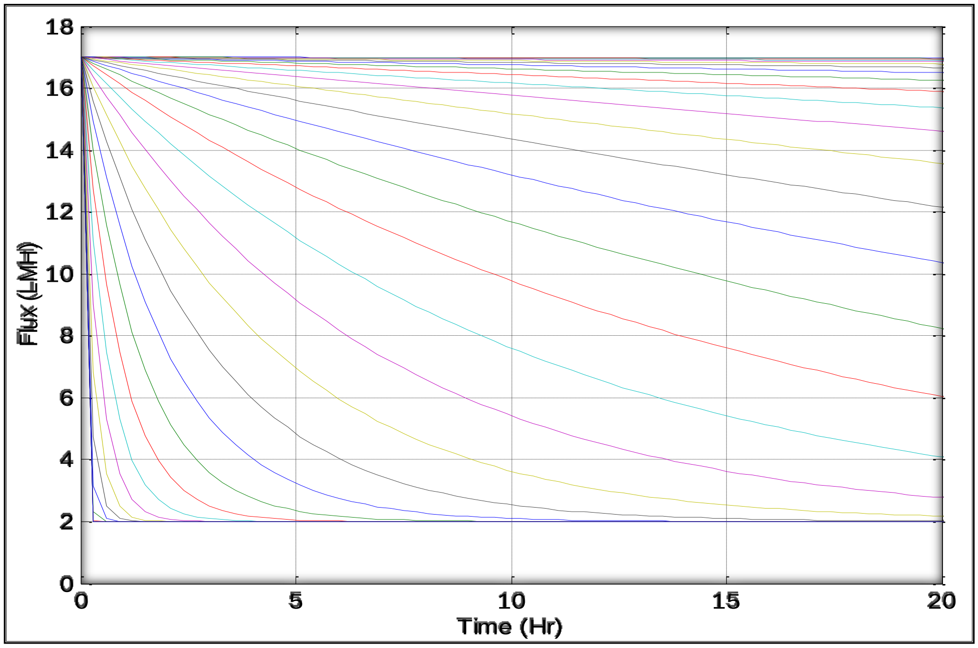

Figure 7.7: Flux with different flux in declining rates

In this Equation, $J = Ae^{-Bx} + C$ the value of B is the flux decay rate. When the value of B is small, it means that it will take a long time to reach a stable flux. The value of B is influenced by membrane characteristics, feed characteristics, particle characteristics and process operational characteristics.

If the membrane pores are bigger than most particles, some particles are screened while other particles pass. The cake formation on the membrane will take a longer time to form. If the membrane pores are too small that impurities block them, the flux declines at a high rate.

If the concentrations of the feed solution contain more compressible particles, the flux declines at a high rate. If the concentrations of the feed solution contain more incompressible particles, the flux will take longer to reach a stable flux.

Particles characteristics include the nature of particles and the size of particles. Nature of particles or impurities means whether the particles are compressible or not.

Figure 7.8 shows simulation results when the maximum flux is kept at 17LMH and the flux rate is kept constant.

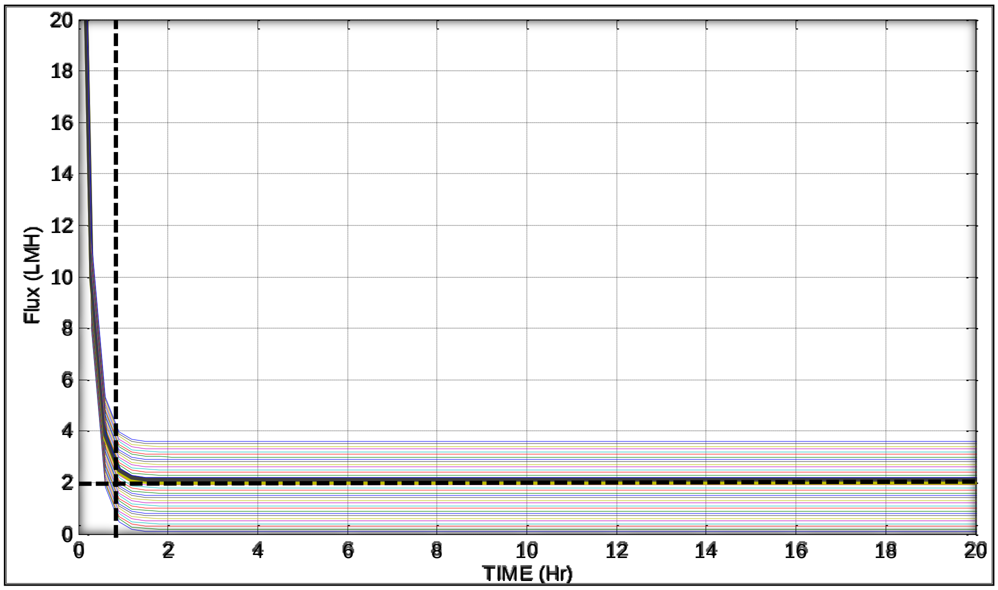

Figure 7.8: Flux with different stable flux values

In this Equation $J = Ae^{-Bx} + C$ the value of C, when compared with other solutions especially the solutions with high bacteria concentration and low bacteria concentration from the experiment. The experimental results and simulation proved that a solution with fewer compressible impurities like bacteria has a high constant or stable flux. The value of *C* is influenced by particle characteristics only.

Results clearly proved that the selected fabrics can be used as membranes but applied in different processes. Fabric label as membrane 4 is the suitable fabric for microfiltration while fabrics label as membrane 1, membrane 2, and membrane 3 can be used for general filtration or screeners but not in the microfiltration range.

These fabrics are not recommended to process water at the final stage before used for domestic or discharged to the environment. These fabrics labelled as membrane 1, membrane 2 and membrane 3 can be used to remove bigger impurities but not micro impurities.

Membrane 4 can produce permeates with less than 1 NTU while other fabrics produce permeates with more than 5 NTU if used to process water and wastewater.

Membrane 4 also produces permeate with no traces of bacteria, yet other fabrics produce permeates with a lot of impurities and bacteria. The results show that the pore size of membrane 4 is less than 2. 0 µm while other fabric pore sizes were more than 20 µm.

The Equation; $F \ or \ J = Ae^{-Bx} + C$ was found to be significant in understanding the fabric behaviour when used as a membrane, where *C* is the constant flux while *A* is the maximum flux that can be determined using water permeate tester. The value of *A* can be used at the time slightly greater or equal to zero. Value of *B* is the part of the critical flux decay rate.

When designing the optimum filtration system for water or effluent treatment, there are major priorities that need to be taken into account, like water intake quality, product nature and driving heads (pumping stations, groundwater wells, water treatment plants, high lift pumping stations, radiant, water storage facilities, or booster pumping stations). However, it is not limited to these major priorities.

Some of the basic data needed include the following:

- Water demand (population density)
- Available surface area
- Operation specification
- Design specification

If the degree of risk of failure is high, the technologies need to be evaluated through review of sequential stages of new technology development.

The view sequential stages are as follows:

- Theoretical concept
- Development at the laboratory or bench-scale
- Evaluate the technology physical part
- Experimental stage consisting of pilot-scale program and field application testing
  Extensive pilot or full-scale testing
- Established performance record.

When it comes to designing the filtration system, the designer is encouraged to consider the following list:

- Maximum rate
- Rate capacity
- Ability to treatment
- Quantity of reject
- Optimum location
- Climate factor
- Operation condition
- Feed quality
- Operational and design specification Issues
- Safety issues
- Maintenance issues
- Material issues and
- Cost issues (capital, maintenance and operation)

The above list inspired by a lot of design manuals, literature and books, and such a list is also applicable to woven fabrics if selected to be used as a membrane. To simplify the list, the major requirements when designing the systems that use filtration and have the ability to treat at a reasonable cost. The proposed system must meet the filtration requirements and economics first before looking at other components within the design list.

The liquid always flows toward fewer resistance areas (bigger pores). When a thin layer covers all pores, constant flux is achieved, provided the operation pressures remain constant. For a solution with less concentration, the system takes longer to reach a stable or constant flux. However, if the solution contains a lot of compressible impurities, the stable or constant flux will be reached within less than an hour of operation.

The incompressible impurities in the solutions produced filter cakes that did not block the filter pores totally in order to improve sTable flux while not affecting the quality of the permeate. The solution to the filter can be mixed with the solution with high suspended solids. The solution with suspended solids can be recycled to improve the permeate production (Ho et al., 2000).

The mathematical Equation $F\ or\ J = Ae^{-Bx} + C$ is suitable for modelling and also proved that the membrane filtration can be easily evaluated. Points *A*, *B*, and *C* are a critical point in designing the optimum filtration system when evaluated correctly.

Figure 7.9 shows the simulated flux results and experimental flux results for membrane 4 to process DEWATS effluent.

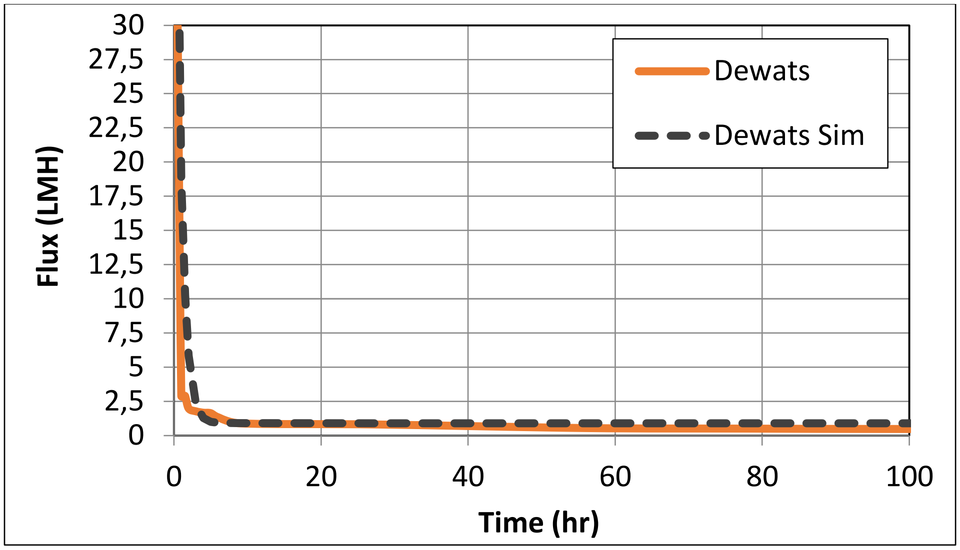

Figure 7.9: Experimental and simulated flux for membrane 4 processing DEWATS effluent

Figure 7.9 proved that the simulated flux results and experimental flux results are almost identical. The correlation coefficient, R (x, y) was 0.966. Variances ratio was 1.20. Variances were equivalent. The Variance critical value was 2.02.

Figure 7.10 shows the simulated flux results and experimental flux results for membrane 4 to process Umgeni river water.

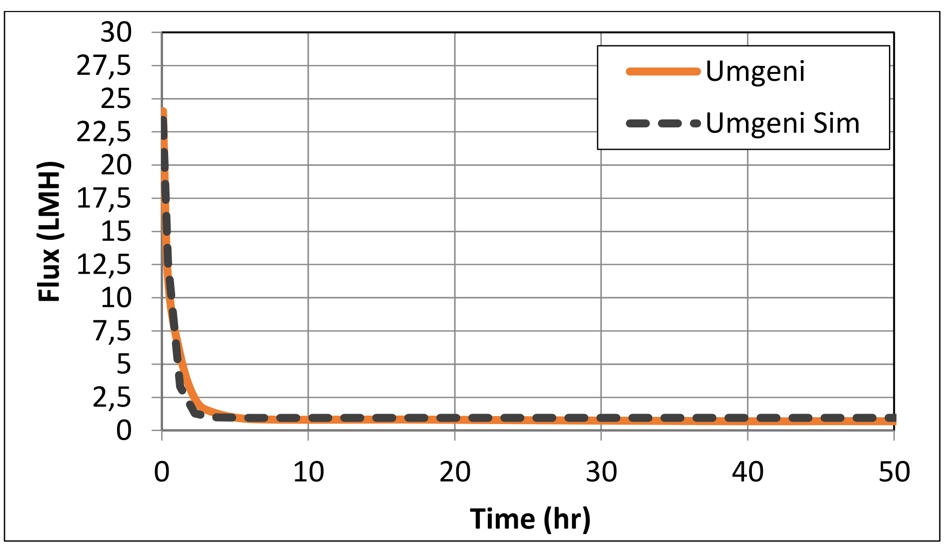

Figure 7.10: Experimental and simulated flux for membrane 4 processing Umgeni River

Figure 7.10 proved that the simulated flux results and experimental flux results are almost identical. The correlation coefficient, R (x, y) was 0.99. Variances ratio was 1.02. Variances were equivalent. The Variance critical value was 2.81.

Figure 7.11 shows the simulated flux results and experimental flux results for membrane 4 to process Mobeni tertiary effluent.

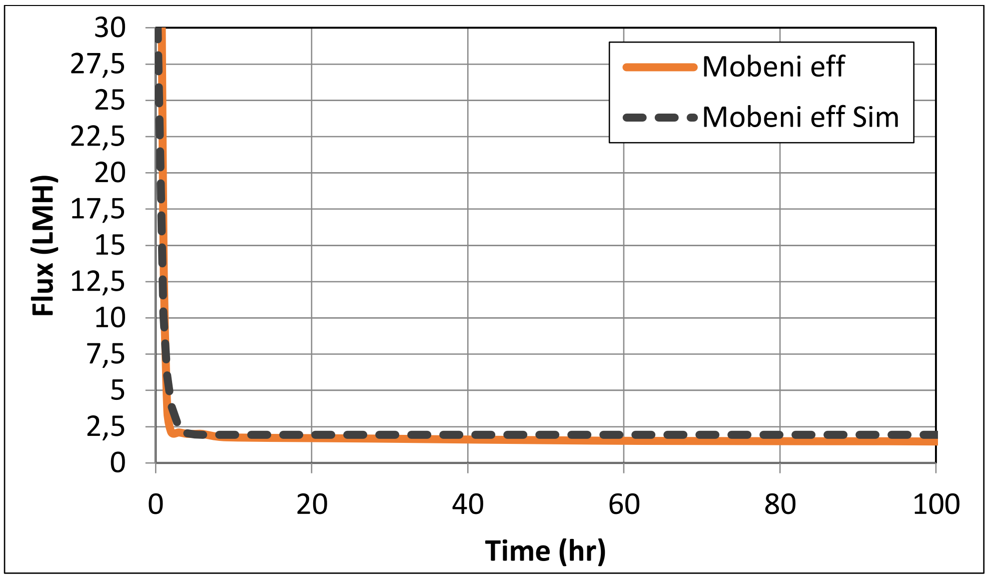

Figure 7.11: Experimental and simulated flux for membrane 4 processing Mobeni effluent

Figure 7.11 proved that the simulated flux results and experimental flux results are almost identical. Correlation coefficient, R (x, y) was 0.99. Variances ratio was 6.5. Variances were equivalent. The Variance critical value was 2.08.

Figure 7.12 shows the simulated flux results and experimental flux results for membrane 4 to process Bruma lake water.

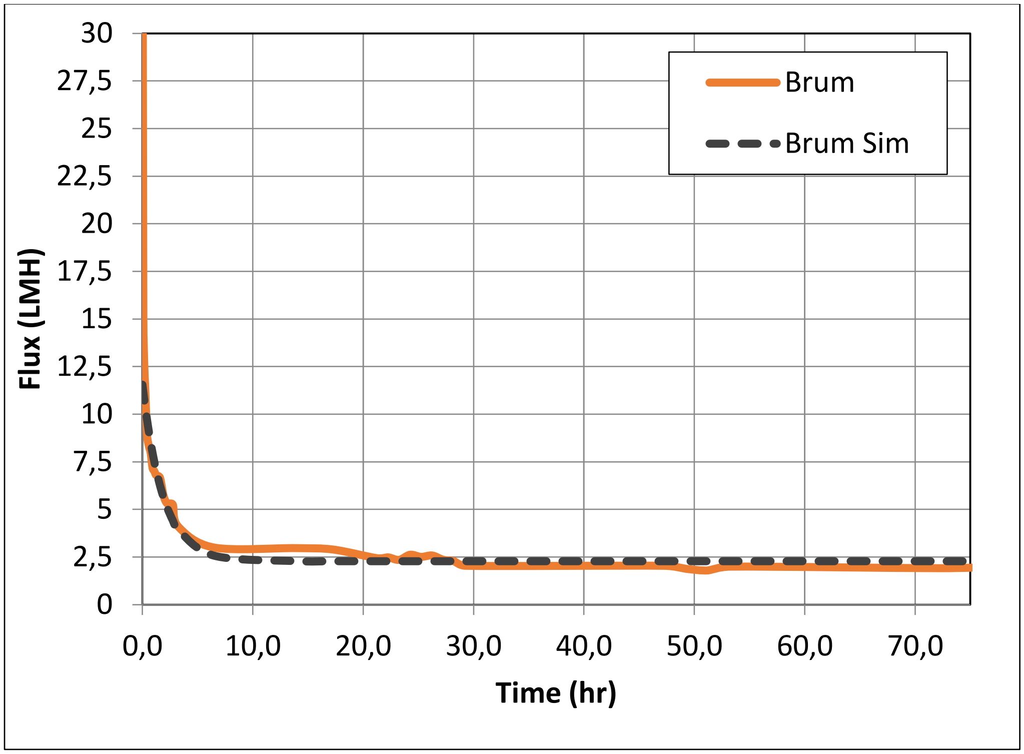

Figure 7.12: Experimental and simulated flux for membrane 4 processing Bruma lake water

Figure 7.12 proved that the simulated flux results and experimental flux results are almost identical. Correlation coefficient, R (x, y) was 0.73. Variance ratio was 5.6. Variances were equivalent. The Variance critical value was 2.02.

Figure 7.13 shows the simulated flux results and experimental flux results for membrane 4 to process Soweto tertiary effluent.

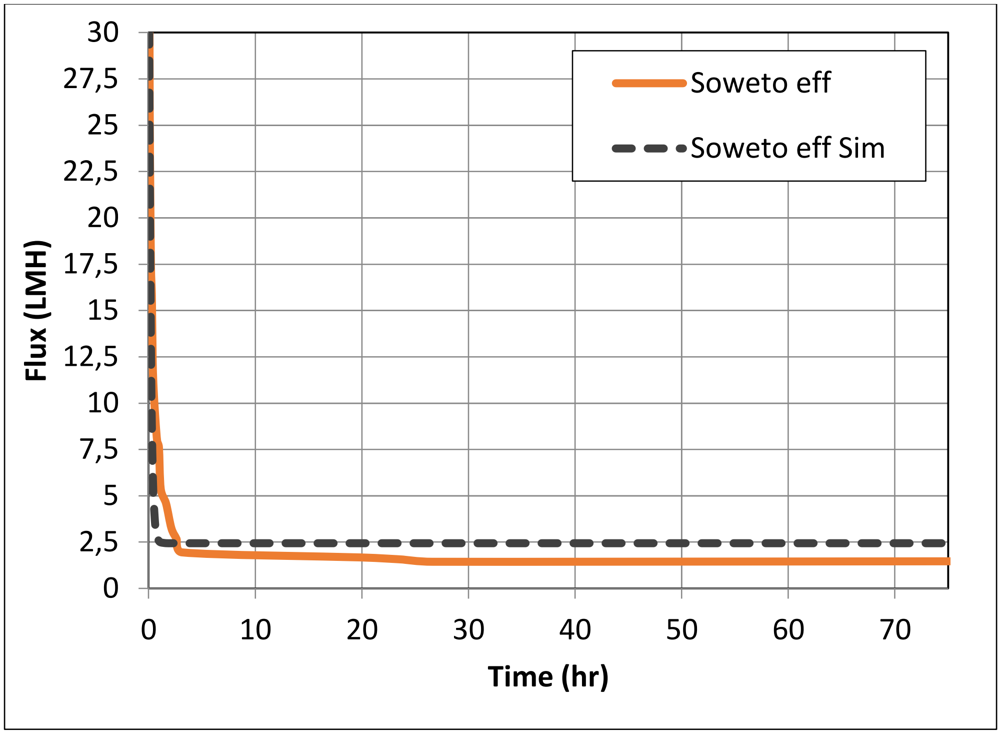

Figure 7.13: Experimental and simulated flux for membrane 4 processing Soweto tertiary effluent

Figure 7.13 proved that the simulated flux results and experimental flux results are almost identical. Correlation coefficient, R (x, y) was 0.97. Variances ratio was 1.74. Variances were equivalent. The Variance critical value was 2.12.

Figure 7.14 shows the simulated flux results and experimental flux results for membrane 4 to process the algae solution.

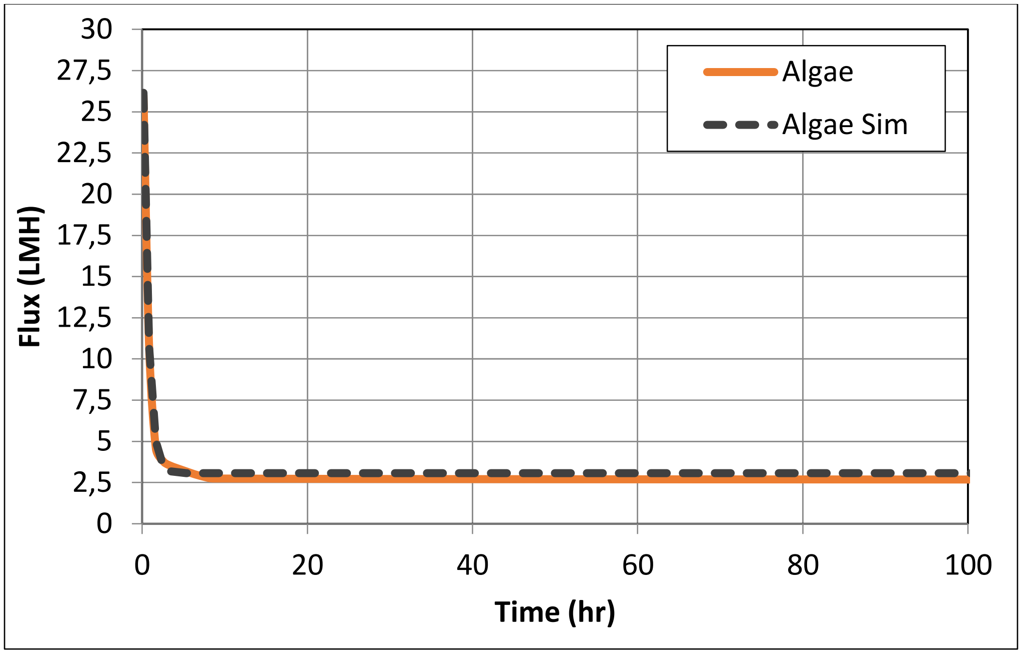

Figure 7.14: Experimental and simulated flux for membrane 4 processing algae solution

Figure 7.14 proved that the simulated flux results and experimental flux results are almost identical. Correlation coefficient, R (x, y) was 0.9991. Variances ratio was 1.01. Variances were equivalent. The Variance critical value was 2.64.

Figure 7.15 shows the simulated flux results and experimental flux results for membrane 4 to process ceramic solution.

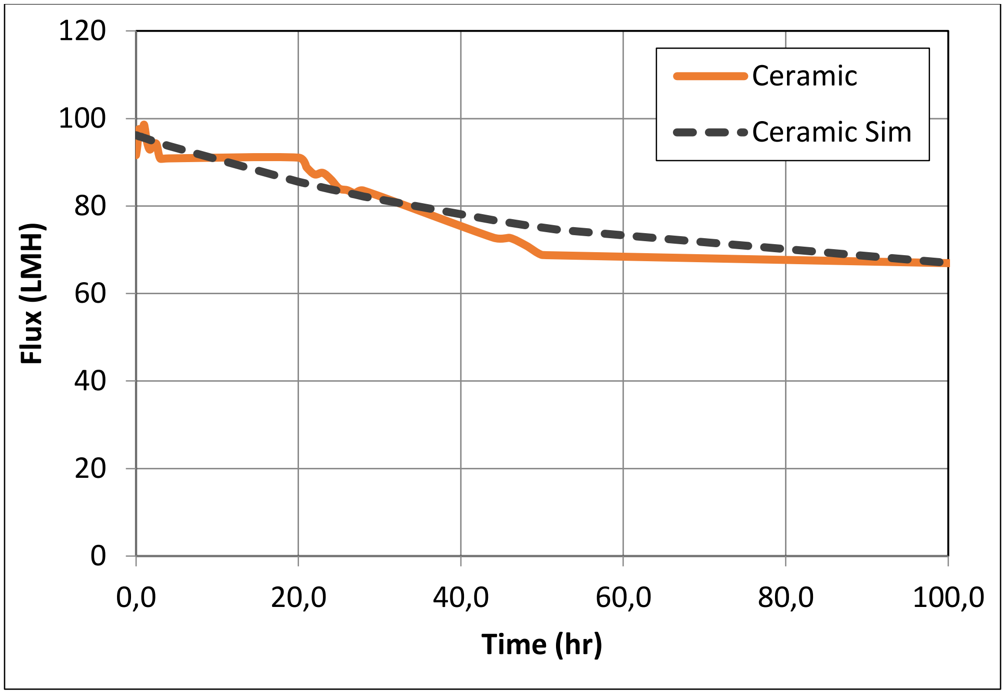

Figure 7. 15: Experimental and simulated flux for membrane 4 processing ceramic solution (Khulu 2, 20 um ceramic powders)

Figure 7.15 proved that the simulated flux results and experimental flux results are almost identical. Correlation coefficient, R (x, y) was 0.95. Variances ratio was 1.14. Variances were equivalent. The critical value was 1.85.

7.9. Summary of the results

The modern challenges for membrane separations today are wide. There are ranges of processes require more sophisticated approaches for the detection and remediation of fouling, i. e., the association of solutes, particulate matter, and colloids on and/or within a membrane. Most commonly, fouling is assessed from inferred measurements of permeation rate and/or permeates quality.

However, in this study pure water flux, critical or stable flux and flux declining rate were used as the parameters to measure the impact of feed quality on woven fabric performance especially in identifying fouling factors affecting the woven fabrics used as membranes for filtration.

During the experiment, fabrics labelled as membrane 1, membrane 2, membrane 3 and membrane 4 were selected and tested locally. Water that comes out from those fabrics were still containing impurities especially fabrics label as membrane 1, membrane 2 and membrane 3 proving the fact that these fabrics did not design for the micro range. However, the fabric labelled as membrane 4 produced better water quality that can be used for domestic use. This proves the point that not all fabrics are capable to treat water for domestic use, industrial use and agricultural use or irrigation. Some fabrics are performing as membranes while other fabrics perform as sieve or screener, only removing bigger particles.

During experiment and simulation, it was noted that internal separation and also external separation take place during filtration, the only external separation that making it possible to brush with polymer brush if the fabric is made of polymer filaments.

The fabric label as membrane 4 is capable of removed 99.995% of impurities that include bacteria, incompressible particles, compressible particles, and more. The fabric produces permeate that is less than 1NTU.

The studies prove that the feed quality, operation parameter and weave characteristic of the fabric do play the role in membrane performance. The study proves that the thin layer or cake can be modified to provide good quality and quantity of permeate. Adding the incompressible impurities in the solutions that contain compressible impurities is the solution to improve the quality and quantity of the filtration processes that are using woven fabric as membranes. This theory of adding incompressible particles to improve the system is also supported by most scientists.

It was observed that the critical flux decreased with the increase of bacteria or bio impurities or compressible impurity concentration. It was also observed that critical flux increases with an increase in incompressible particles in the solution. The selected polyester fabric, when used as the membrane, can process wastewater and river water and polluted water. Since water and wastewater treatment systems have stages, all selected fabrics can be used at the different station of water and wastewater processes. For example, membrane 4 can be used at the final stage. Membrane 3 can be used as the bed for crawling bacteria. Membrane 2 and membrane 1 can be used in water and wastewater treatment as the strainer. However, the recommended fabric for that part must be made using monofilament.

The mathematical Equation ($F = Ae^{-Bx} + C$) derived from Darcy's law, and Hagen-Poiseuille law for the laminar flow was suitable for the study and also the Carman-Kozeny Equation was also used. The modellings were based on particle, concentration and membrane pore characteristics.

Critical point *C* should be the point used to design the membrane capacity when operating at minimum quantity. Point *A* is the fabric water permeates or maximum production rate. *B* Is the value that describes the declining part of permeate or proved the cake build-up ability on the membrane. This value *B* can easily show if the solution is too concentrated or containing compressible or incompressible impurities. Other may conclude and say the value of *B* is the flux-decaying rate.

Point C value is a stable flux, can be modified by modifying the feed, adding Particles that are incompressible and bigger then pore size of the membrane into the feed solution. If the solutions have more impurities that are not compressible, the stable flux will increase so as productivity. Provided the operation pressure is kept constant.

The study proved that the pore size of the membrane must be smaller than the impurities smallest particles. If the fabric pores sizes are bigger than the impurities. The fabric will not qualify to be used as the filter. From four fabrics used for the study, membrane 4 qualified to be used as a microfiltration membrane for processing water for domestic use.

During experiments and simulation, it was observed that not all the fabrics can process water and be used as a microfiltration membrane but can still be used as filters for other purposes.

When comparing the simulated flux values using the mathematical Equation ($F = Ae^{-Bx} + C$) with experimental flux values using Trilo Byte QC expert software, it was noted that the values were almost identical and average correlation coefficient R(x,y) was at 0.95. This means that the simulated results were identical to experimental results for only membrane 4. See Appendix 7 to 14.

It was clear that the quality of the feed solutions and the nature of the fabric do have an impact on membrane performance.

CHAPTER 8.

IDENTIFYING THE POSSIBLE APPLICATIONS FOR WOVEN FABRIC MEMBRANES

8.1. Introduction

Emerging and underdeveloped countries, economics and capacity remain an issue that needs to be addressed. The maintenance part needs to be at the minimum, and also the technologies need to be simplified when aiming to develop systems suitable for emerging and underdeveloped countries. However, the durability and reliability are also critical when designing the system for remote areas like rural areas and informal settlements.

Most low energy systems are used at household levels, or in small communities like villages. Low energy systems are systems dependent on natural recourses for operation. Most low energy systems operate with the gravitational force only. For years, these low energy systems were used to clean water, filter fermentation alcohols and more. These household systems were made of natural fibres like ceramics, wool, etc. Polymer woven fabrics were not in use for low energy systems like household Point of Use systems (POU).

POU systems have become the most suitable methods for the treatment of water in the rural areas and in areas that depended on surface water as it has many advantages. Recently the low energy systems are used to treat water especially during times when areas are affected by natural disasters like hurricanes, earth quick, floods, droughts and more. In most areas, the infrastructure gets affected after the natural disasters and the POU has become an emerging technology to provide clean drinkable water. Unfortunately, there is no POU used for sanitation systems other than the bucket system, which is a toilet that has the bucket inside used to collect human waste.

Most low energy systems like POU's were designed for water treatment and not for wastewater treatment. There is a need for developing a wastewater treatment facility that can be used at household levels. DEWATS is one of the systems that are still in use at village levels. The DEWATS can be applied at household levels. The septic tanks and other sanitation systems are potential systems for polymer woven fabrics.

8.2. Definition and determinations of technologies and material used as a membrane for low energy filtration

According to history, animal furs were used for human covering, since 30 000 BC. Hand twist yarns and woven fabric utilization started in North Africa and the Middle East around 7000 BC. China also started silkworm breeding in around 3200 BC, India followed with silkworm breeding, and they also discovered cotton. The first cotton cloth was discovered around 2000 BC. (Clark, 2005). For years, people were and still use weave material to purify water. Women from rural areas are still going to rivers to collect water. If water is polluted, they will use clothes to remove impurities. The method is known to be unhealthy since clothes and other garments were not developed for water treatment.

Potable water treatment can primarily be divided into household treatment, conventional water treatment and industrial wastewater treatment. There are three main impurities that need to be removed in any polluted water, viz. organic material, inorganic material and bacteria. The most common impurities found in polluted water are suspended solids, bacteria and turbidity.

Treatment systems must be able to remove impurities like bacteria and suspended solids and are able to produce solutions with turbidity of less than 5NTU.

When developing any technology suitable for water treatment or wastewater treatment, it is ideal to start with household technologies before introducing the technology into conventional water treatments or industrial wastewater treatments (Clasen, 2009). Evaluating the polymer woven fabrics as membranes for household Point of Use systems (POU) was an ideal start and comparing it with the current technologies was also an objective of this study.

Small scale systems or POU systems have become the most suitable methods of treating water in rural areas and in areas that depend on surface water. Most POUs are gravitational driven systems. It does not require large volumes of water and is not affected by difficult topography or dispersed settlement (Chollom et al., 2017).

Most small scale systems may not require electricity (Sobsey, 2002). Although small scale systems have huge advantages, factors like lack of durability, short operational lifespan and lack of sustainability of the system have proven, over the years, to be major challenges in the implementation and survival of these systems in rural communities (Chollom et al., 2017).

8.2.1. SUITABLE USE FOR POLYESTER WOVEN FABRIC (PWF)

Woven fibres (e.g. linen, cotton, polyester, polypropylene and other cloths) are not widely used for POU water treatment but used as screener because of their low cost, availability, simplicity and the quality was not within satisfactory range or was below the drinking water quality standard. Most of these woven fabrics pore sizes were bigger to accommodate microfiltration processes. Most of the woven fabric were used to filter suspended solids and organic that a visible with naked eye. Due to innovation, there are now woven fabrics with micro pore sizes suitable for micro filtration suitable for POU water treatment.

Figure 8. 1 is the image of the POU designed in SA to clean river water. Figure 8. 2 is the filter cartridge made of polyester fabric and polypropylene casing.

Figure 8. 1: RSA designed - POU

Figure 8. 2: Polyester woven fabric used as the membrane for microfiltration treatment

In South Africa, the University of Stellenbosch and the Durban University of Technology, working with South African textile companies, developed the polyester woven fabric (labelled as membrane 4) that is suitable for microfiltration. The woven fabric membrane produces better quality water and also better turbidity range below 1 NTU. The system that uses this woven fabric is capable of removing 99.900% to 99.999% of impurities. The fabric is capable of operating as a microfiltration membrane.

The University of Stellenbosch and the Durban University of Technology used the Polyester fabric as a membrane for POU systems. Most POUs using this polyester fabric are able to operate in a wider range of polluted water. This polyester woven fabric is robust, and pores are not visible (see images above, Figure 8.1 and Figure 8.2). This polyester woven fabric is being tested in the field with more than 1000 units distributed in Bizana Eastern Cape and Limpopo South African. The results of these units are astonishing. More than 95% of these units are still in use for more than 500 days and the community acceptance is high. More communities want more of these filters.

8.2.2. SUITABLE USE FOR POLYPROPYLENE WOVEN FABRICS (POPWF)

Membrane 1, membrane 2 and membrane 3 were made of polypropylene yarns. Not all the polypropylene fabrics were suitable for treating water up to acceptable standards. They were not designed for microfiltration. These fabrics can separate impurities from water but not for micro impurities. These fabrics can operate as screens in water treatment, used to capture bigger particles or impurities. The preferable fabric is fabric labelled as membrane 2 and membrane 1. Membrane 3 can be used as a bacteria bed for crawling bacteria. Some wastewater treatment needs a balanced ratio of free-swimming bacteria and crawling bacteria. Most Swimming bacteria feed on impurities found in domestic waste especially human waste; other bacteria feed on human waste and smaller bacteria. Bacteria that are feeding on bacteria are not good swimmers and need a good bed to crawl. For screening or to use the fabric and replace the screening bar grid, the fabric with monofilament is ideal.

8.3. Materials and methodologies

The polyester woven fabric selected as the microfiltration membrane is made of a multifilament with rotor twist yarns, 560 dtex yarns (membrane 4) while polypropylene woven fabrics (membrane 1, membrane 2 and membrane 3) were not suitable for microfiltration. All the selected fabrics were manufactured in South Africa.

The real solutions and synthetic solutions were used in this study to evaluate the woven fabric performance and compared with other results from the literature. The solutions were river water, tap water, sewer water, wastewater and also synthetic solutions mainly calcium solutions and polluted water mixed with activated carbon. Each experiment was repeated to test for repeatability. There were two types of experimental apparatus used. One was capable of evaluating the performance when membranes were placed vertically (Figure 3.8) and the other were designed to evaluate the membrane performance when the membranes were placed horizontally (Figure 3.9).

The POU systems were also used in most polluted water from biogas reactors (Figure 8.1), different setup/design below (Figure 5). This particular polyester woven fabric membrane can be cleaned with a polymer brush. The reason for membrane cleaning is to recover the flux of the fouled membrane to its original flux close to original flux. Since these fabrics have surface or external fouling, brushing off fouling is possible.

8.4. Results and discussion

There are a wide range and application of POU technologies. In general, there are many advantages and disadvantages offered by POU technologies for water and wastewater purification. Low productivity remains the main disadvantages of POUs. However, when it comes to quality, most POUs are able to produce better quality water.

Table 8.1: Production rate for the available POU's including and cartridge filter.

Technology	Ceramic	Sand filter	Mineral filter	PWF-POU	Cartridge filter
Production (max)	1-2 L/Hr. 20 L/day	1-50L/Hr. 50 L/day	1- 50L/Hr. 75 L/day	2-150 L/Hr. 2 000 L/day	>20 L/Hr. >2 000 L/day
Removal ability	> 99.99%	80 - 99.9%	80 - 99.9%	>99.995%	>99.995%
Cleaning effect	Complicated	Complicated	Complicated	Brush	Replacement
Driving pressure	< 50mm	< 50mm	< 50mm	< 50mm	> 50mm

Table 8.2 has a list of POU technologies that are currently in the market and tested in the laboratory.

After analyzing the polyester woven fabric Point of Use (PWF – POU), it was clear that a PWF – POU can produce a minimum of 2L/hr. when processing the highly polluted water and produce up to 150L/hr. when processing less polluted water with low compressible impurity concentration.

Table 8. 2: Filters and filtration media for the treatment of household water

TYPE OF FILTERS	TYPE OF FILTER MATERIAL	YEAR TESTED AND REFERENCE	EFFECT ON PERFORMANCE
Slow Sand filter	Sand, gravel, diatomaceous earth, other minerals	Ancient method *Kaiser et al., 2002*	High in principle but often low in Practice. Impurity removal < 99%
Granular media, rapid rate depth filter	sand	Ancient method *Hoa et al., 2008*	High in principle, removal < 99%
Vegetable and animal-derived depth filters	Coal, sponge, charcoal,	Ancient method *Sobsey, 2002*	Practice. Impurity removal < 99% Not used in most places
Charcoal filter	Granules of coal	Ancient method *Kaiser et al., 2002*	Remove suspended solids taste, odour, and colour
Ceramic filter	Ceramic, Clay, another mineral	Ancient method Tested in 1827 *Anderson, 1999*	Varies from high to low (with pore size and composition)
	0.2-micron ceramic candle-shaped filters	Since 1999, Bolivia, Brazil, Switzerland, the United Kingdom *Clasen et al., 2006*	Varies from high to low (with pore size and ceramic filter quality)
	Ceramic Pot	1999-2004, Managua, Nicaragua. Cambodia *Lantagne, 2001*	Remove >90% suspended solids, bacteria taste, and colour. Low flow
Bio-Sand Filtration	Slow Sand filter	2004-7, Cambodia and worldwide *lantagne, 2001*	Remove suspended solids, and bacteria. Low flow
Cloth filter	Woven Cotton cloth, linen and other clothes), wick syphons made of wool thread	350 to 425 BCE, Most countries in Asia and Africa *Austin, 1942*	Remove suspended solids, < 90% bacteria
Polymer filter	Non-woven, charcoal, polymers (polyester or polypropylene)	1999 -2005 Haiti *Borucke, 2002 and Varghese, 2002*	Remove suspended solids, >90% bacteria taste, odour, and colour
Cartridge Sediment Filters	Polymer Non-woven fibres polypropylene	Since the late 1900s *Hoa et al., 2008*	Remove suspended solids, >90% bacteria taste, odour, and colour
	Polymer cast, and excluded material (PVC, PP, PET, etc.)		
Polymer woven Filters	flat sheet woven fibre microfiltration membrane	2002, Vietnam	Remove suspended solids, >90% bacteria taste, and colour
	flat sheet woven fibre microfiltration membrane	2001, South Africa *Chollom, et al., 2017*	Remove suspended solids, >90% bacteria taste, and colour. High flow

(Adapted from *Kaiser et al., 2002; Hoa et al., 2008; Sobsey, 2002; Anderson, 1999; Clasen et al.,2006; Lantagne, 2001; Austin, 1942 Borucke, 2002; Varghese, 2002 and Chollom, et al., 2017*)

The results of PWF – POU are astonishing, placing the PWF-POU in the advantage when comparing it with others. The household cartridge filters are mostly processing municipality water and operate at high pressure. The household cartridge filters are the point of use system but they do not operate at low energy. Remote areas like the rural area will not be able to use the household cartridge filters if they do not have municipality piped water or electricity for pumping water from storage tanks.

The capability of polyester woven fabrics (PWF) is vital to develop systems that are suitable for household levels, community and small town or village sizes. Polypropylene monofilament weave fabric can also be used with this PWF in developing the water or wastewater treatment for villages and small towns. Membrane 2 can be used instead of Polypropylene monofilament weave fabrics too. The reason for selecting monofilament is to prevent internal fouling from taking place in the yarns.

Figure 8.3: Filtration processes used in drinking water production classified according to their application domain and their removal characteristics with respect to living and non-living material (Servais et al., 2005 and Hulsmann, 2005).

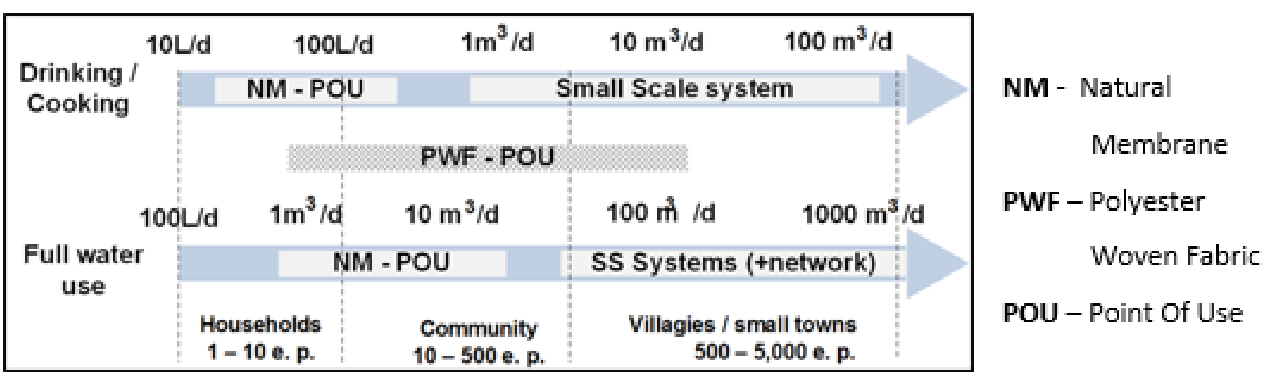

Figure 8.3: Ranges of the water facilities for small supply – (adapted from Hulsmann, 2005)

Therefore, results proved that POU made of polyester woven fabric is able to produce drinkable water with better quality and quantity. The results from particle size distribution instrument, Malvern Mastersizer 2000, proved that particles from all solutions with particles ranging from 3mm to 0.2 um. The instrument fails to detect any particles from permeate or from the product coming out from woven fabric membrane, assuming that all products or permeates from PWF-POU were clean of any impurities. When testing the e-Coli and coliform in permeates, the results proved to be better than the water acceptable range for domestic use.

This particular polyester woven fabric membrane can be cleaned with a polymer brush without damaging the fabric surface. The flux improved after brushing.

Figure 8.4: Analyzing membrane 4 in polluted water and wastewater effluents, it became necessary to test the fabric for more complicated solutions. There were four complicated solutions tested. Those solutions were polluted water from bathroom showers, polluted water from washing machines and polluted water from two different biogas reactors (chicken waste, cow waste).

Figure 8.4: Ranges of complicated feeds to PWF-POU

From Figure 8.4 Image 1 shows the feed from cow waste used as the feed for biogas reactors. Image 2 shows the feed from cow waste and chicken waste used as the feed for biogas reactors. Image 3 shows the feed from a solution made of polluted water from showers and washing machines. The results proved that the membrane can still do the work effectively.

From the images 1, 2 and 3, the fabric is effective in removing impurities but not colour pigments and also dissolved materials like soapy or foamy components. The flow rates from these solutions were more than the flux of DEWATS and Mobeni wastewater effluents. The reason was based on the fact that these solutions contained suspended solids and dissolved impurities without much of bio impurities like bacteria and more.

It was observed that this polyester fabric does not remove colour particles where most colour pigments are less than 1 µm and do not remove dissolved impurities like soap compounds. The turbidity was also less than 1NTU. Even though there were colours in samples, it looked cleaner than tap water.

The petrochemical industries use a lot of polymer fabrics in the extraction processes including solvent recovery plants. All selected fabrics can be used in any process provided they meet the process requirements. After testing Membrane 4, it proved to be able to process solvents, naphthalene, paraffin and more. During fabric, waxing it was noticed that membrane 4 is more effective to liquid with a viscosity less than 1 centipoise at 20^{o}C. When processing liquid with a viscosity above 1 centipoise, a warming process is required to melt the liquid but cannot be close to 30% of the polyester melting point.

There were other experiments done to test the capacity and characteristics of the polyester fabric. One of the experiments conducted was not part of the study but necessary to look at the effect of oil or petrochemical oils when using membrane 4. The polyester fabric was used as a membrane to remove a mixture of powders like PVC, calcium, and trioxide from PVC paste made to manufacture tarpaulin products. The oil mixtures were separated from PVC paste.

The oils mixtures were a combination of organic oils and also petrochemical oils. Some of the oils were chlorinated paraffin, PVC stabilizer called BAEROSTAB, deoxidized soybean oil, neonol or oxyethylated monoalkyl phenol. The fabric was also tested on ethylene methyl acrylate syrup, also capable of removing impurities from ethylene methyl acrylate syrup but the flow rates were compromised.

Figure 8.5: the illustration of the continues filtration operation and POU operation (Filtration batch operations).

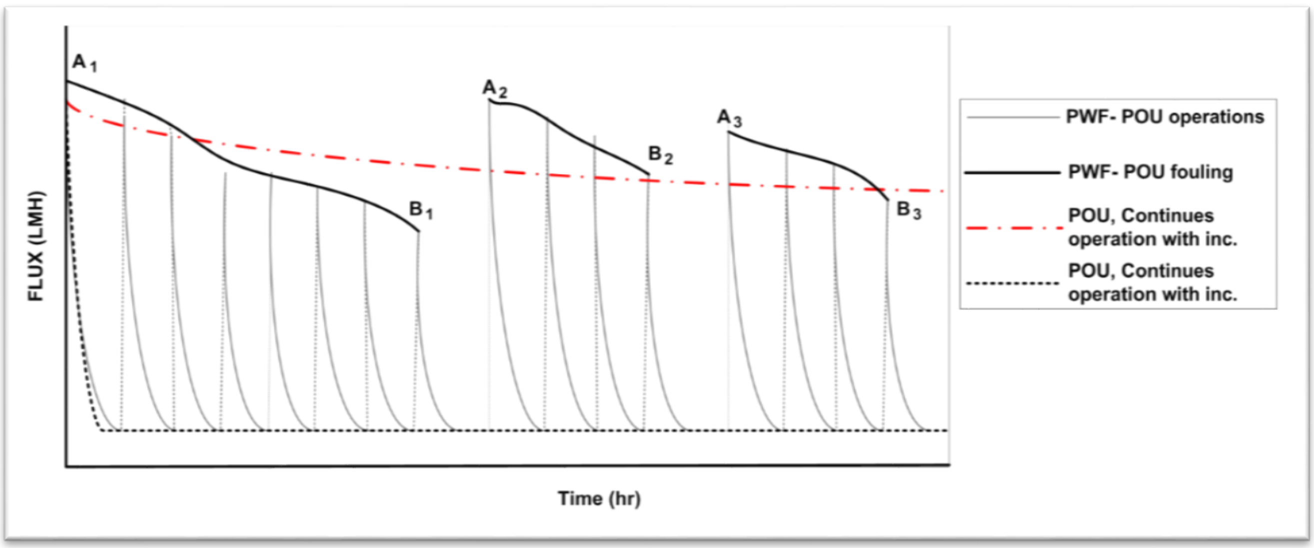

Figure 8.5: Illustration of PWF-POU batch system and POU continues systems or units.

(A_1 – new membrane, B_1 – membrane need to be cleaned, A_2 – brushed membrane, B_2 – membrane need to be cleaned, A_3 – brushed membrane, B_3 – membrane need to be cleaned)

For POU units or systems operation continuously, the solution with incompressible impurities will have high production rate as compared to a solution with a lot of comprisable impurities. The illustration above shows that the PWF - POU production is much higher than stable flux/ fouled POU. PWF – POU after brushing do recover the production rate.

8.5. Conclusion

This study was aimed to identify the possible applications for woven fabric membranes, evaluate the type of gravity-driven membrane material used systems suitable for emerging and underdeveloped economies, and evaluate the membrane performance.

Fabrics were evaluated with respect to fouling, flux recovery and cleaning methods. It was found that fabrics labelled membrane 1; membrane 2 and membrane 3 were not possible to clean with a polymer brush only. It was also found that some membranes required backwashing when cleaning while other fabrics like Polyester woven fabric (membrane 4) can be easily brushed since the fouling takes place on top of the fabric and not internally like other fabrics. Polyester woven fabric is able to handle all types of solutions or liquids provided that the liquid does not poison the fabric.

Most common gravity driven membrane materials are used in POU systems. POUs are susceptible to damage if not properly handled because most of them are made of concrete or ceramic. However, the Polyester Woven Fabric is stronger and the PWF-POU is not fragile. Factors such as durability, short operational life span and lack of sustainability of the POU system have proven over the years to be major challenges in the implementation and survival of these POU systems in emerging and underdeveloped areas including rural communities. The PWF - POUs were found to be sustainable with respect to durability, reliability and acceptability. These PWF - POU units can potentially play a major role in household water treatment in preventing diarrhoeal disease among vulnerable populations especially in emerging and underdeveloped areas. The POU can be used and provide clean water in many areas including areas like refugee camps, and more also noticed by Liu (2015). Polyester Woven Fabric can be used as a microfiltration membrane not only to process water and wastewater but also to process chemicals and oils. Other fabrics cannot be used in POU's but as screens and in reactors for crawling bacteria as beds are much more needed, especially membrane 3. PWF was also tested in the effluent, the fabric is suitable to clean any effluent too.

8.6. Summary of the results

Most low energy systems are gravity driven systems. One of the good examples is the Household Point of Use (POU) systems. Household Point of Use (POU) systems are an important element in the process of reaching the United Nations Millennium Development Goals. The centralized systems are often deficient or non-existent in developing and transition countries. Most water-quality problems are due to hygiene factors and pathogens. A range of decentralized systems is available to counter these problems, including thermal and/or UV methods, physical removal and chemical treatment (Peter-Varbanets at al., 2009).

This study focused on systems that treat the potable water and wastewater with no energy used and only gravity-driven systems. There are a lot of membrane systems that are capable of removing pathogens and turbidity. Most underdeveloped and transition countries rely on systems that are gravitationally driven to clean water, thereby avoiding the use of pumps and electricity. On the basis of the present literature data, all small-scale systems require electricity and pumps except POU systems. Furthermore, in the available literature, the performance of highly fouling water types has not been reported. For such cases, more extensive studies are required. It can be concluded that POU that uses polyester membranes (PWF - POU) are good prospects for decentralized systems since it removes almost all bacteria and impurities. The POU systems have low-cost maintenance and do not require any skill for the operational part, and it suitable for developing and transition countries.

Polyester Woven Fabrics can be used as a microfiltration membrane not only to process water or wastewater but also to process chemicals and oils including in the food processing. Polypropylene fabrics selected were not able to process water but can be useful in screening bigger impurities and used bacteria bed for reactor systems.

CHAPTER 9.

CONCLUSION

Water is one of the most important and essential resources that people usually misuse and take for granted until it is either gone or unsuitable to be utilized for domestic, industrial or agricultural purposes. Water is a necessity of life not only to humans but to every living being including animals and plants. Water is also a habitat to a number of animals and plants.

In some parts of the world, fresh water is very limited, just like South Africa forcing the water users to search for better technologies that will enable people to reuse water. Filtration processes proved to be one of the technologies that can address water issues and assist the water users for water optimization.

Most filters today are made of polymers and are non-woven polymers. Polymer science is growing very fast, in this century. It is easier to produce polymer fibres as compared to natural fibres. Natural fibres like cotton and wool are good because they provide comfort qualities needed by human beings when used as garments and not as membranes.

Most emerging countries like South Africa have economical and skills issues when compared to developed countries. The challenges are mountainous in underdeveloped countries. Most countries use polymer fabrics as membranes, but most of the membranes that are in use are not woven materials.

This study aimed at evaluating woven fabrics performance when used as membranes, develop a basic mathematical model that is simple to apply and understand and lastly identifying the possible application for woven fabrics suitable for emerging and underdeveloped economies faced with skill issues, economy and capital costs for cleaning water and transporting water.

In general, membranes that are made of natural fibres are reported well on literature. They are not user-friendly in a low skilled market and production costs are also alarming. Membranes that are made of non-woven materials are flooding the market and also reported well in literature. They are not user-friendly too. In a low skilled market, production costs are lower and the maintenance parts are also alarming. The non-woven membranes are practically impossible to clean with a polymer brush because the filtrations take place inside the membrane and not on the surface of the membrane. Brushing the non-woven membrane actually destroys the surface structure. Most non-woven membranes or filters are replaced when no longer performing at the desired requirement.

On the other hand, for most weave fabrics, the fouling takes place on the surface of the fabric and other fabrics the fouling take place inside and on the membrane surface. If the impurities or unwanted material is on the surface, it can be brushed off easily. If most impurities are passing through the fabric pores easily, that particular fabric is not suitable to be used as a membrane but can be used as a screen if allowing smaller particles and screening bigger particles.

There were two main objectives for the study. The first objective was to evaluate and compare the fabric types that can be used as membranes in water and wastewater treatment facilities. The criteria that were used were permeate quality, flux and cleaning protocols for fabric membranes. Reliability, durability, availability, flux behaviour, cleaning protocols, and performance, are among the factors that form part of the study especially forming part of objective one. The second objective was to identify the possible applications for woven fabric membranes and evaluate the factors that are playing a major role during the filtration process and the relationship between those factors.

The experimental investigations conducted were to evaluate the (1) main objectives; (2) effect of membrane orientation; (3) effect of feed quality on membrane performance; (4) effect of stable flux quality and quantity of the selected fabric; (5) effect of fabric type on filtration or microfiltration processes; (6) effect of membrane fouling on membrane performance; (7) develop the basic mathematical model suitable in identifying the right membrane for any filtration system operating at low energy; (8) identify the possible applications for woven fabric membranes.

The experimental investigations conducted were to evaluate selected woven fabrics, manufactured in South Africa. The selected fabrics were tested, evaluated and used for water and wastewater treatments. The solutions used for this study ranged from real solutions to synthetic solutions. Some solutions consisted of a lot of bacteria and less suspended solids. Some solutions consisted of a lot of suspended solids and fewer bacteria. The impact on membrane pore blocking was compared. The fabric properties were determined according to international standards ISO and ASTM. There were four woven fabrics selected and used as membranes for the project of which three of the selected fabrics were made of polypropylene and one made of polyester fabrics. All polypropylene woven fabrics failed to meet the microfiltration requirements when analysed. Polyester fabric was able to treat water, wastewater and remove micro particles and bacteria. However, all four woven fabrics were analysed to provide a clear understanding of factors that force women from rural areas to use fabrics to remove impurities from river water, and also provides a clear understanding of factors that are forcing water treatment companies to ignore woven fabrics to be used as membranes.

During the experiments, bacteria and suspended solids were blocking the fabric pores. There was an interconnection relationship between turbidity and impurity concentration and bacteria concentration in water. Some testing instruments like bacterial count instruments, turbidity meter and more, assisted in evaluating the polyester fabric and polypropylene fabrics performance. The polyester fabric was capable of removing more than 99.995% of the impurities that includes bacteria and solids from the initial stage and at stable flux. Polypropylene fabrics were capable of removing more than 70% of impurities that includes bacteria and solids after 250 hours. At the initial stage of the filtration, these Polypropylene woven fabrics were only capable of removing bigger impurities.

The results proved that solutions with more suspended solids and fewer bacteria produce better flux quantity than the solution with less suspended solids and more bacteria or bio impurities when using the polyester weave fabric. However, the quality of permeate remains constant regardless of any feed quality once reach a stable flux. The polyester woven fabric can process any feed from more than 300 NTU turbidity to 1 NTU turbidity with the permeate quality remaining the same but the production rate varies, however, once the stable flux is reached the production rate will remain constant.

The results show that a cake formed on the so-called membrane during the filtration acts as the supper membrane that reduces the permeate quantity while improving the quality. However, the formed layer can be modified by modifying the feed concentration. It was observed that the solution with a lot of compressible impurities produces permeate with low productivity, but when adding the incompressible impurities in the feed, the permeate productivity improved. In short, the results proved that a permeate quantity can be improved by adding incompressible particles to the feed solution.

2 µm was assumed to be a pore size of polyester fabric. However, after analysing permeate samples that were using polyester fabric as the membrane, it was noted that the smallest particle size was 0.2µm, fail to pass through the polyester membrane and thin layer during the filtration. The smallest particle size was 75% smaller than the average smallest bacteria. It was clear that this selected polyester fabric has an ability to produce high-quality permeate for a long time at stable flux.

The selected polyester weave fabric was a plain weave, made of rotor twisted yarns with 5.6 tex. The yarns were made of polyesters multifilament fibres and the fabric was treated with the finishing process making it possible to have a surface separation only.

Fabrics were labelled as membrane 1, membrane2, membrane 3 and membrane 4. For membrane 2, fabric volumetric weight was the smallest and a membrane 3 fabric volumetric weight was more than other fabrics. For membrane 3, fabric thickness was greater than all other membranes. The smallest fabric thickness was membrane 4. The membrane or fabric thickness proves that membrane 4 will not produce a bulky membrane module. Only membrane 4 had balanced elongation and tenacity for warp and weft.

Membrane 3 fabric was having a lot of volumetric weight and fabric thickness. This alone proved the fact that this fabric has more crimp angle, while membrane 4 has the lowest crimp angle.

For a dead-end filtration, flat sheet module results proved that membrane 4 has more resistance than other membranes. For membranes 1, 2 and 3, water just flows through the fabrics without much resistance proving that these membranes have the bigger pore sizes; all the other fabric selected can be modified through textile finishing processes to meet the needs. Waxing was a finishing or modifying process used to optimise the fabrics. There were drastic changes after applying wax. Permeate improved but the products contained wax. Melting wax was a costly method used to remove wax from permeate water.

Membrane 4 was the only membrane that has surface separation. Membrane 1, membrane 2 and membrane 3 have internal separation and external separation. The other interesting observation was the fact that membrane 1 and membrane 3 filaments were attracting waste while membrane 2 and membrane 4 filaments were rejecting waste. Filaments used for membrane 2 and membrane 4 were continuous filaments. There were staple filaments on membrane 1 and membrane 3.

The selected polyester fabric was suitable for treating the drinking water and wastewater effluent systems. The selected polypropylene fabrics were suitable to be used as screens, blocking the bigger particles if used for drinking water treatment systems and wastewater effluent treatment systems.

The other phenomena on these polypropylene fabrics can also be used as a bed for bacteria, especially crawling bacteria. These fabrics have wide application uses. Due to its strength, the fabrics can last more than 5 years in operation and are robust.

Fouling takes place on top of polyester weave fabric. Fouling takes place on top and inside the polypropylene weave fabric. Brushing the polyester and polypropylene woven fabric is recommended but in favour of polyester since is the only woven fabric with balanced tensile strength in waft and warp. 90% or more can be recovered when brushing the polyester membrane. Less than 60% can be recovered when brushing polypropylene fabrics. The internal fouling will require back flushing or sophisticated protocols to clean. These weave fabrics (polyester and polypropylene) are suitable for an emerging economy where skill is still an issue. Cleaning the polyester membrane does not require any sophisticated technology or additional chemicals to clean the polyester membrane. Brushing the surface of the polyester and polypropylene membranes/fabrics will not damage the fabrics; only the sharp object can damage the fabrics or membranes.

A basic mathematical model of the membrane processes has been created. The developed basic mathematical model proves that membrane characteristics and impurities of the solutions play major roles during the filtration.

The mathematical Equation $F = Ae^{-Bx} + C$ was derived from Darcy's law and Hagen-Poiseuille law for laminar flow. Carman-Kozeny Equation was also used. The models were based on particle characteristics, concentration characteristics, membrane pore characteristics and filtration operational condition.

The mathematical model can be applied to other fabrics that can be used as membranes. These models will assist engineers and scientists in evaluating the performance of fabrics or membranes. The simple Equation $F = Ae^{-Bx} + C$ was the significant discovery, where C is the constant flux, while *A* is the maximum flux and *B* is the part of the critical rate.

Pure water permeate tester was critical to evaluate not only the maximum permeate of the membrane but also obtaining the possible value of *A*. The value of *A* can be used at the time equal to zero. Results show that the greater the value of *B* the shorter the time to reach a stable flux. However, when *C* is less than 2LMH that means the solution or effluent or river water contains more organics and more bio impurities that include bacteria for polyester weave fabric. Note that the membrane does not remove any dissolved substances.

The polyester weave fabric can also be used in the food processing industry, chemical industry, water industry, wastewater industry and more, provided the solution pH does not poison the fabric filaments or fibres. The polyester weaved fabric is highly recommended to be used in microfiltration processes suitable for treating water for domestic use and wastewater treatment systems.

From this study, it is very clear that those women that are collecting water from rivers are not using cloths or woven fabrics as membranes. These women are using these fabrics as screeners just to remove solids like wood, sticks, etc. Most of these women add disinfection before drinking the water. This is the clear indication that these women know that these common fabrics used, as garments are not able to remove micro impurities like bacteria and more.

The knowledge in this study will assist in optimising the systems when using polymer fabrics as membranes for filtration, especially the basic mathematical model can be useful for engineers and scientists willing to use fabrics as membranes.

The developed system proved that the combination of analytical and experimental approach was necessary for the success of this study.

In addition, some women that are using any fabric will know that some fabrics are not good filters for water treatment. Polyester Woven Fabric can be used as a microfiltration membrane not only to process water and wastewater but also to process chemicals and oils.

CHAPTER 10.

RECOMMENDATIONS FOR FURTHER STUDIES

Currently, woven polymer fabric membranes have not been successfully scaled up, especially for low energy systems and energy systems. There are several problems with woven polymer fabric membranes; the relationship of the weave structure, yarn twists and fouling of the membrane, have positive and negative impacts on fabric performances.

The system used in this study was of relatively low-pressure systems, not high-pressure systems. The next step should focus on evaluating the effect of twisted and untwisted yard used for woven polymer fabric membranes in both low energy systems and high energy systems.

The woven polymer fabric membranes also could be adapted to run a batch and continuous processes. These woven fabrics are capable to process not only river water or wastewater but also to process the chemicals and food processes. From experience, most woven fabrics are being used in petrochemical industries especially in the lube oil refinery section. Yet there are not many studies conducted on woven fabric membranes used in petrochemical industries.

The polyester woven fabric membranes have possibilities to operate at high pressure due to its tensile strength. The pressure effect on the fabric needs to be evaluated as well.

Polypropylene has a lot of advantages as compared to polyester. There should be a study that gives an overview of the effect that makes it impossible to manufacture a woven fabric that can be used as a membrane for microfiltration. All polypropylene fabrics selected can be modified; the next step is to apply nanotechnology to these fabrics. They have lot of disadvantages to offer textile engineers.

CHAPTER 11.

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APPENDIX

EQUATIONS

$$\mathrm{J} = \frac{\mathrm{Q_p}}{\mathrm{A_m}}$$ Equation 2. 73

$$J = \frac{\Delta P}{\mu(R_m + R_c + R_f)}$$ Equation 2. 74

TMP = ΔP = (P_{static}- $P_{filtration}$) Equation 2. 75

$$\mathrm{J} = \frac{\Delta \mathrm{P}}{\mu \cdot \mathrm{R_t}}$$ Equation 2. 76

$$q = \frac{\pi d^4}{128\mu l} \cdot \Delta p$$ Equation 2. 77

$$J = N \cdot \frac{\pi d^4}{128\mu l} \cdot \Delta p$$ Equation 2. 78

$$N = \varepsilon \cdot \frac{4}{\pi d^4}$$ Equation 2. 79

$$J = \frac{\Delta p \varepsilon}{32\mu l} \cdot d^2$$ Equation 2. 80

P_F=$P_{L1}(x, t)$ +$P_{S1}(x, t)$, Equation 2. 81

$$(P_o - P_l) = \Delta\pi$$ Equation 2. 82

$$Z_o = D_o \cdot d_o$$ Equation 2. 83

$$Z_u = D_u \cdot d_u$$ Equation 2. 84

$$D_m = \frac{1}{(d_o + d_u)\sqrt{1 - \varepsilon_m^2}}$$ Equation 2. 85

$$\mathrm{t} = \frac{\mathrm{m}}{\mathrm{l}} = \mathrm{s}\rho = \frac{\pi\rho\mathrm{d}^2}{4}$$ Equation 2. 86

$$T = \frac{M}{L} = S\rho = \frac{\pi\rho D^2 L}{4}$$ Equation 2. 87

$$T = \frac{M}{L} = S\rho = \frac{\pi\rho D^2 L}{4} = \frac{V_y}{L_y}\rho$$ Equation 2. 88

$$\mu = \frac{V_f}{V_c}$$ Equation 2. 89

$$tg\beta = \frac{\pi D}{1/Z} = \pi DZ = \text{ƙ} = \tan\beta$$ Equation 2. 90

$$E_n = \frac{\Delta l}{l_o}$$ Equation 2. 91

$$Stress(\sigma) = \frac{Load\ Force\ (F)}{Cross - sectional\ area\ (A)}$$ Equation 2. 92

$$Q = -k\frac{\Delta P}{\mathrm{L}_0}$$ Equation 2. 93

$$q = -\frac{kA}{\mu}\frac{\Delta P}{\Delta x}$$ Equation 2. 94

$$\frac{dp}{dt} = -kp(t_s)$$ Equation 2. 95

$\frac{dp}{dt}\Big|_{t_o}$ them $\int \frac{dp}{p} = -k\int dt$ Equation 2. 96

$\frac{dp}{dt}\Big|_{t_o}$ them $p(t) = C_1 e^{-kt}$ Equation 2. 97

$\frac{dp}{dt}\Big|_{t_s}$ them $p(t) = C_s \pm C_1 e^{-kt}$ Equation 2. 98

$\frac{dp}{dt}\Big|_{t_s}$ them $p(t) = C_s + C_1 e^{-kt}$ Equation 2. 99

$p_s < p_o$ then $|p(t) = C_1 e^{-kt}|$ Equation 2. 100

$$z_1 = \frac{h_1}{2} sin\frac{2\pi x}{L_1}$$ Equation 2. 101

$$z_2 = \frac{h_2}{2} sin\frac{2\pi x}{L_2}$$ Equation 2. 102

$$tan\theta = \frac{dz_1}{dx} = \frac{\pi h_1}{L_1} cos\frac{2\pi x}{L_1}$$ Equation 2. 103

$$tan\varphi = \frac{dz_2}{dx} = \frac{\pi h_2}{L_1} cos\frac{2\pi x}{L_2}$$ Equation 2. 104

$$d = \sqrt{4s/\pi} = \sqrt{4t/(\pi\rho)}$$ Equation 2. 105

$$p = \pi d(1+q)$$ Equation 2. 106

$$A = pL = \pi d(1+q)L$$ Equation 2. 107

$a = 4(1+q)/(\rho d)$ Equation 2. 108

$$\mu = \frac{V}{V_c}$$ Equation 2. 109

$$V = Ls = L\pi d^2/4$$ Equation 2. 110

$$\gamma = \frac{A}{V} = \frac{pL}{V} = \frac{\pi d(1+q)L}{L\pi d^2/4} = \frac{4(1+q)}{d} = a\rho$$ Equation 2. 111

$V_f = L \times B \times H = H \cdot A$ Equation 2. 112

$V_p = V(1-\gamma)$ Equation 2. 113

$$d_p = \left[\frac{k}{1+q}\right]\left[\frac{1-\mu}{\mu}\right] d$$ Equation 2. 114

$$\frac{dV_p}{dt} = dt \cdot V(1-\gamma)$$ Equation 2. 115

$\left.\frac{dV_p}{dt}\right|_{t_o}$ them $\frac{dV_p}{dt} = -V \cdot \gamma$ Equation 2. 116

$\left.\frac{dV_p}{dt}\right|_{t_o}$ them $\int \frac{V_p}{V} = -\gamma \int dt$ Equation 2. 117

$\left.\frac{dV_p}{dt}\right|_{t_o}$ them $V(t) = C_1 e^{-\gamma t}$ Equation 2. 118

$V_s < V_o$ then $|V(t) = V_p - C_1 e^{-\gamma t}|$ Equation 2. 119

$V(t) = V_p - C_1 e^{-\gamma t}$ Equation 2. 120

$$Q_1 = \frac{\pi d_p^4}{128\eta} \cdot \frac{\Delta P}{H}$$ Equation 2. 121

$$n_p = S_p/s_p = 4G(1-\mu)/(\pi d_p^2)$$ Equation 2. 122

$$Q_p = \frac{G(1-\mu)d_p^2}{32\eta} \cdot \frac{\Delta P}{H}$$ Equation 2. 123

$$d_p = \left[\frac{k}{1+q}\right]\left[\frac{1-\mu}{\mu}\right]d$$ Equation 2. 124

$$\gamma = 4(1+q)/d$$ Equation 2. 125

$$Q_p = \frac{G(1-\mu)d_p^2}{32\eta} \cdot \frac{\Delta P}{H} = \left(\frac{k^2}{2}\frac{G}{\gamma^2\eta}\right)\frac{\Delta P}{H}\frac{(1-\mu)^3}{\mu^2}$$ Equation 2. 126

$$Q_f = Q_p + Q_r$$ Equation 2. 127

$$Q_f x_f = Q_p x_p + Q_r x_{rf}$$ Equation 2. 128

$$J = \frac{\Delta P}{\mu(Rm + Rc)}$$ Equation 2. 129

$$R_{rate} = \left(1 - \frac{c_p}{c_r}\right)100\%$$ Equation 2. 130

$$J_v = k_1\Delta p + k_2\Delta p$$ Equation 2. 131

$$J_s = k_2 c_m J_o$$ Equation 2. 132

$$k_1 + k_2 = \sum_i \frac{\epsilon r_i^2}{8n\Delta x}$$ Equation 2. 133

$$k_2 = \sum_{i, r_i > R} \frac{\epsilon r_i^2}{8n\Delta x}$$ Equation 2. 134

$$v_x \frac{dc}{dx} - D\frac{d^2c}{dx^2} = 0$$ Equation 2. 135

$$\frac{d}{dx}\left(J_c - D\frac{dc}{dx}\right) = 0$$ Equation 2. 136

$$J_c - D\frac{dc}{dx} = Jc_p$$ Equation 2. 137

$$\frac{dJ}{dt} = -\,k \cdot J \cdot (t_s - t_o)$$ Equation 2. 138

$\left.\frac{dJ}{dt}\right|_{t_o}$ them $\frac{dJp}{dt} = -\,k \cdot J$ Equation 2. 139

$\left.\frac{dJ}{dt}\right|_{t_o}$ them $\int \frac{dJ}{J} = -\,k\int dt$ Equation 2. 140

$\left.\frac{dJ}{dt}\right|_{t_o}$ them $J(t) = C_1e^{-kt}$ Equation 2. 141

J_s<J_o then $|J(t) = C_1e^{-kt}|$ Equation 2. 142

$p_s \leq p_o$ then $J(t) = J_o + C_1e^{-kt}$ Equation 2. 143

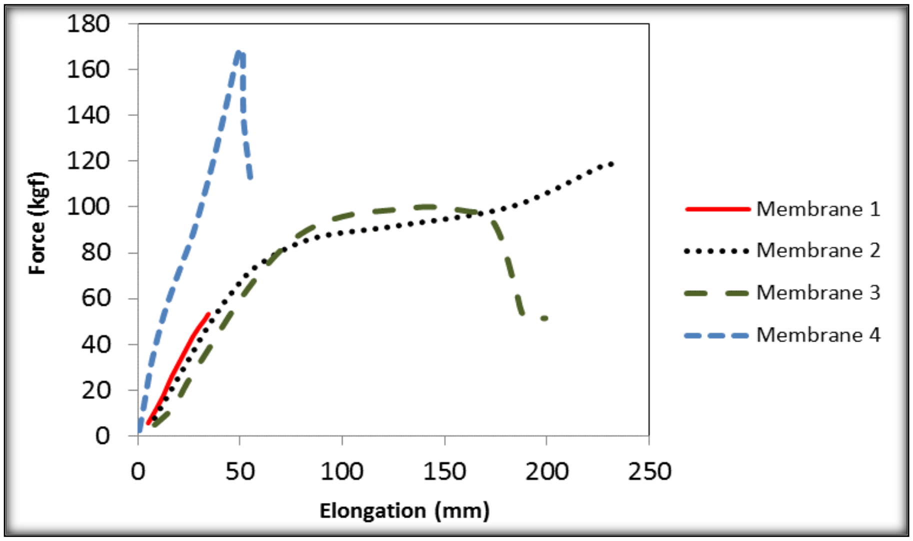
$$J_v = \frac{\varepsilon d^2}{32\eta\tau}\frac{\Delta p}{z} = L_p\frac{\Delta p}{z}$$ Equation 5. 2

$$s_1^2 = \sum_{i=1}^{n_1}(x_1 = \overline{x_2})^2$$ Equation 6. 4

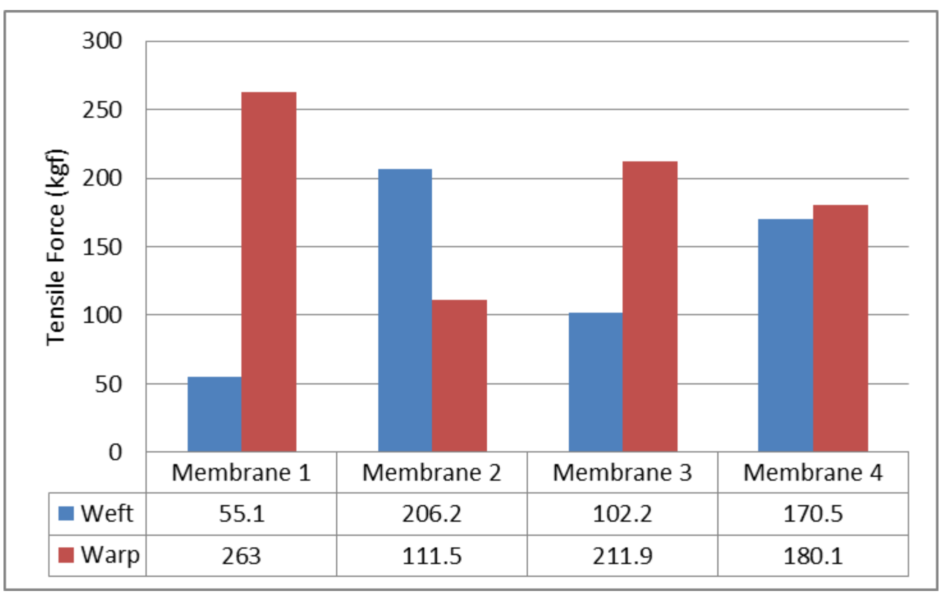
$$\frac{\partial V}{\partial T} = \partial F \cdot A$$ Equation 6. 5

$$\sum \mathrm{F} = \frac{\partial P}{\partial Z}V_m - \rho_m g V_m + \rho_m R V_m$$ Equation 6. 6

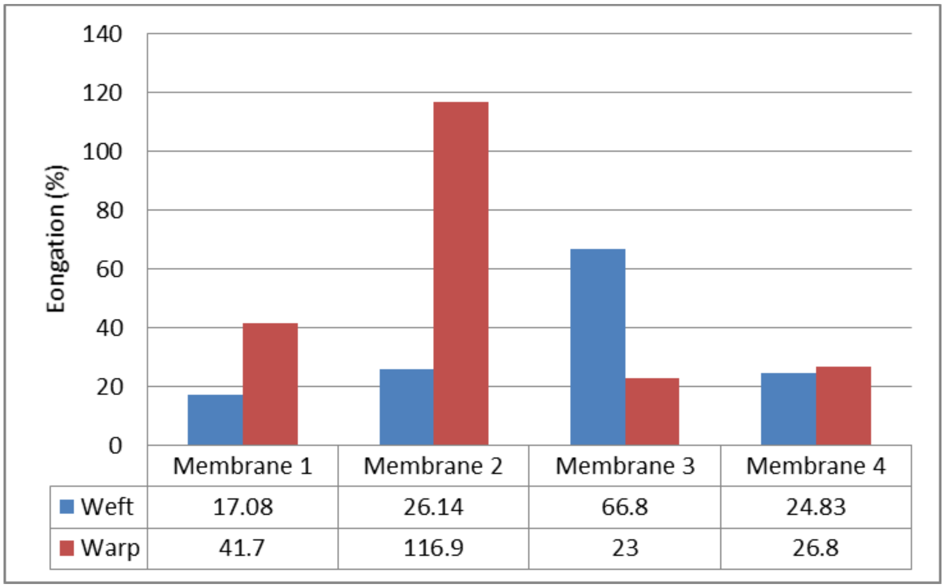
GRAPHS



Appendix 1: Warp Tensile strengths and elongation for all selected fabrics to be used as membranes

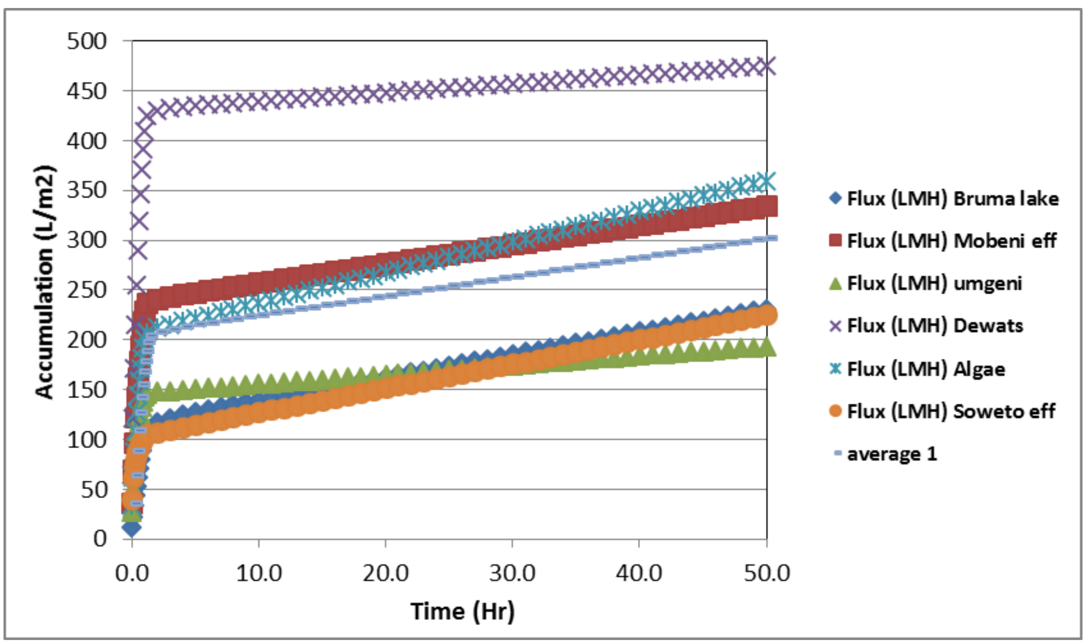


Appendix 2: Tensile strengths for all selected fabrics to be used as membranes

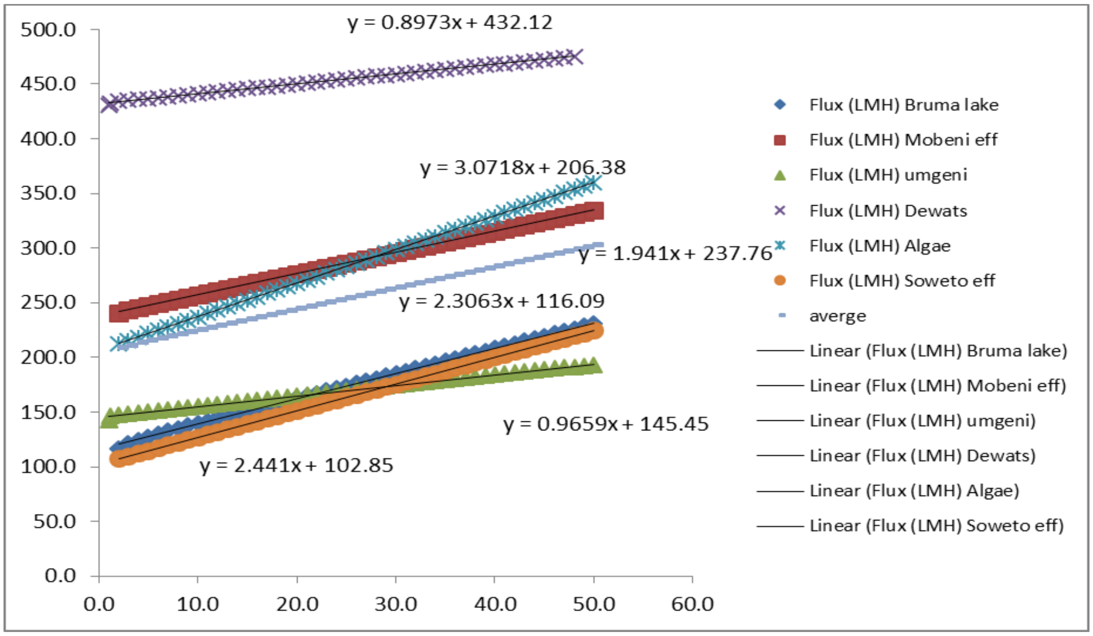


Appendix 3: Elongation for all selected fabrics to be used as membranes

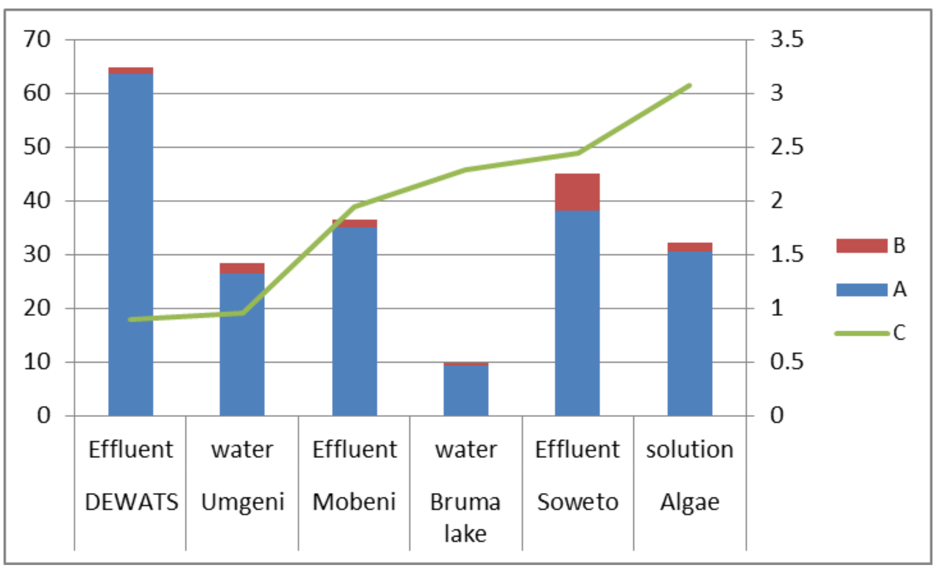
MATHEMATICAL MODELLING FOR MEMBRANE 4



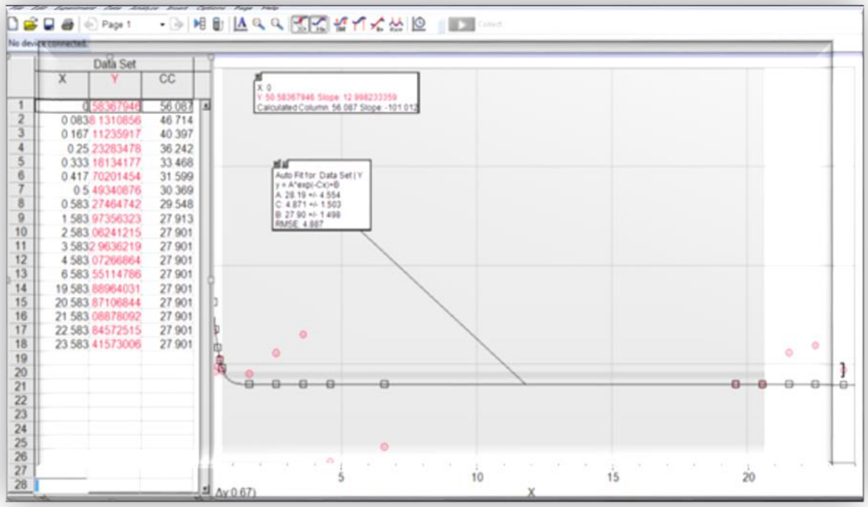
Appendix 4: Membrane 4 performance at different feeds



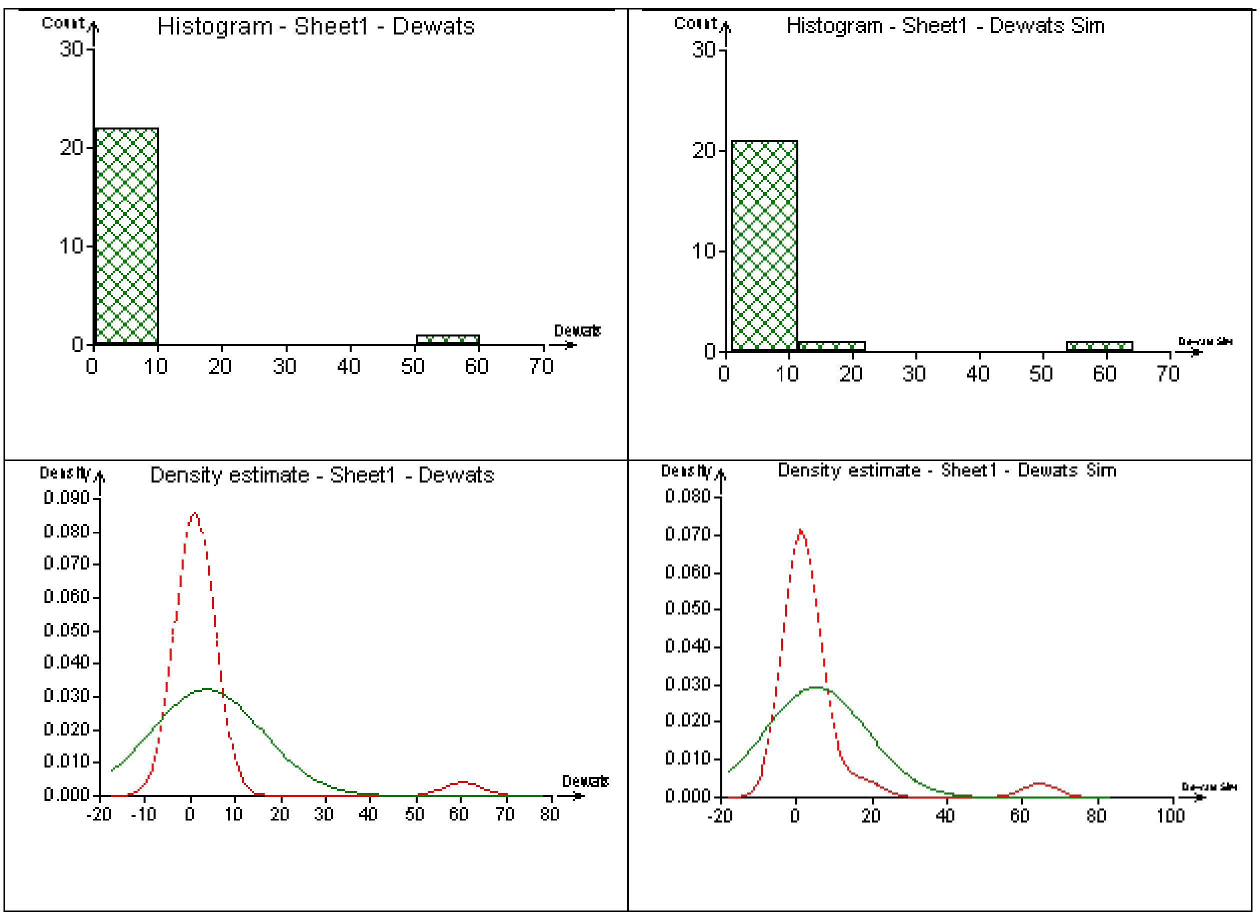
Appendix 5: Membrane 4 performance at different feeds



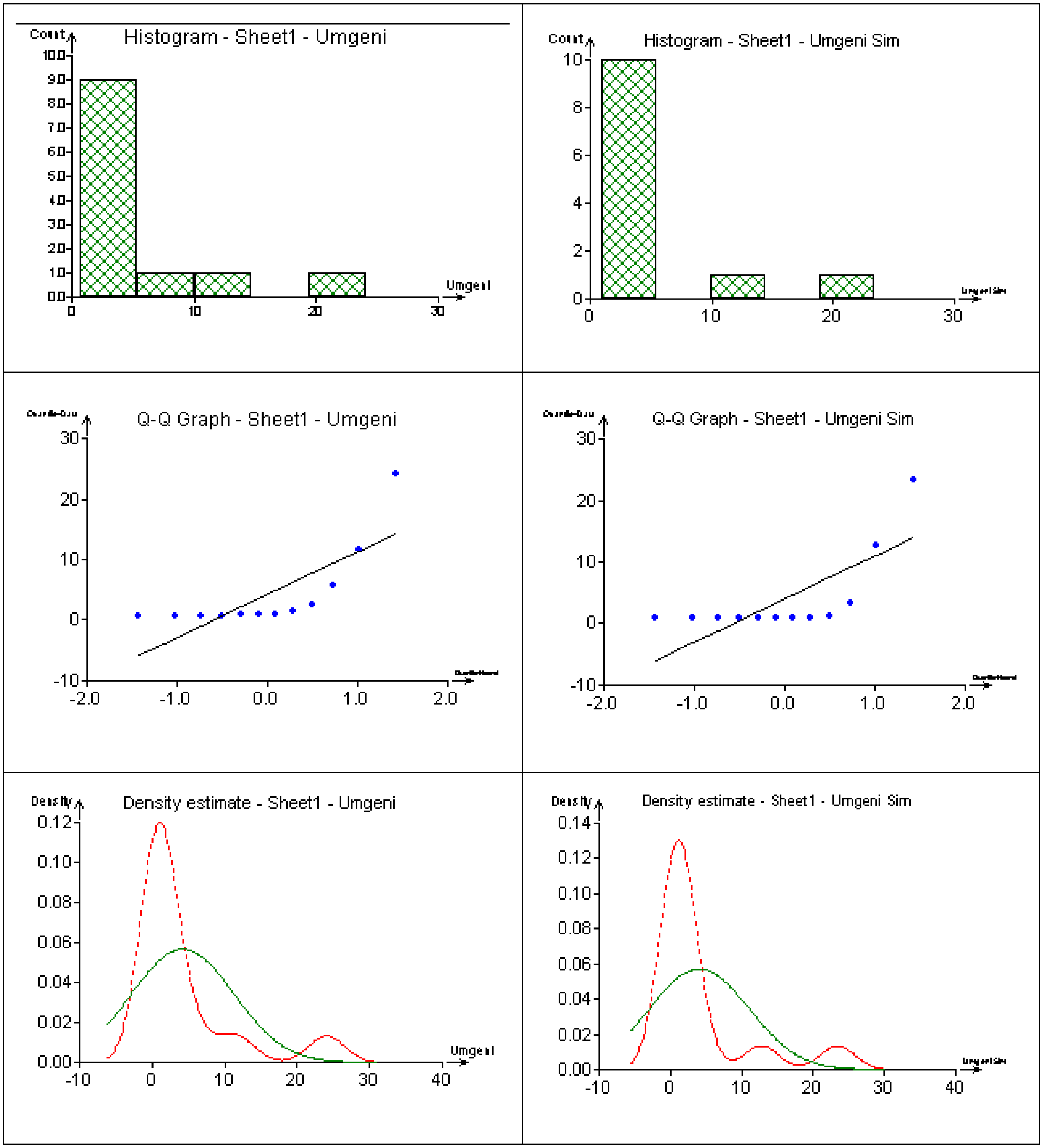
Appendix 6: Membrane 4 performance at different feeds



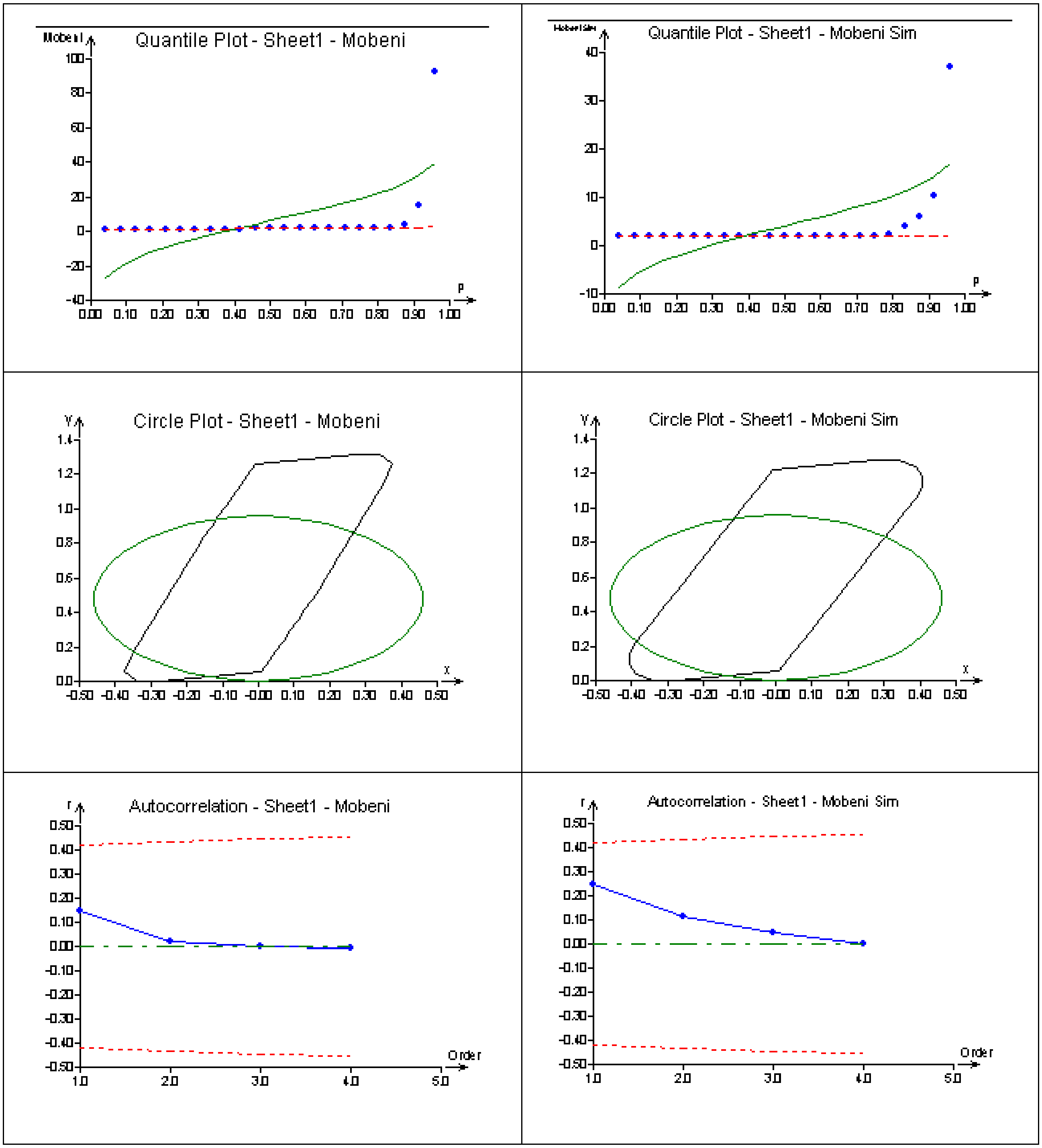
Appendix 7: Software image used to analyses membrane 4 behaviours



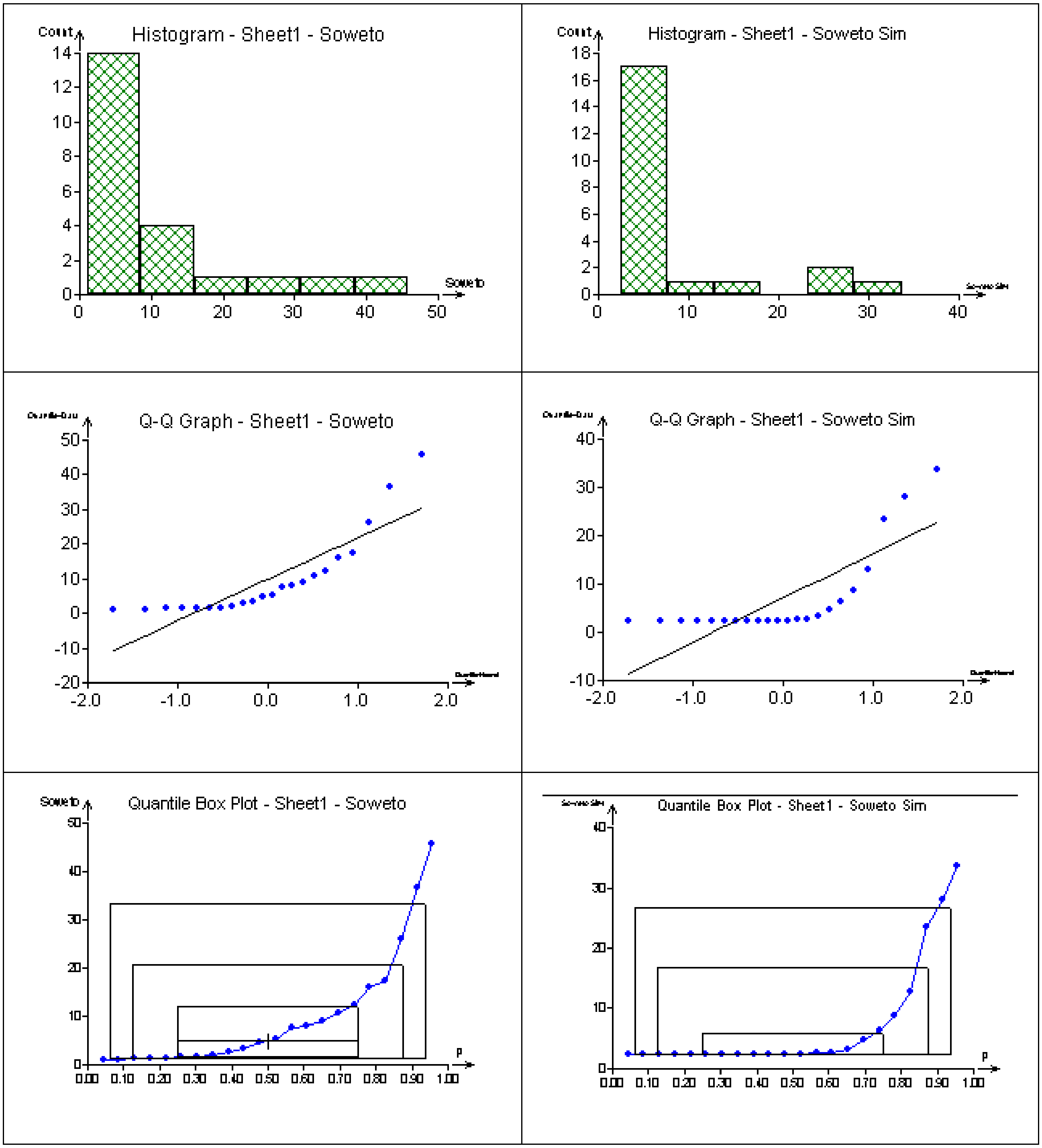
Appendix 8: Experimental and simulated results for Dewats when using membrane 4.



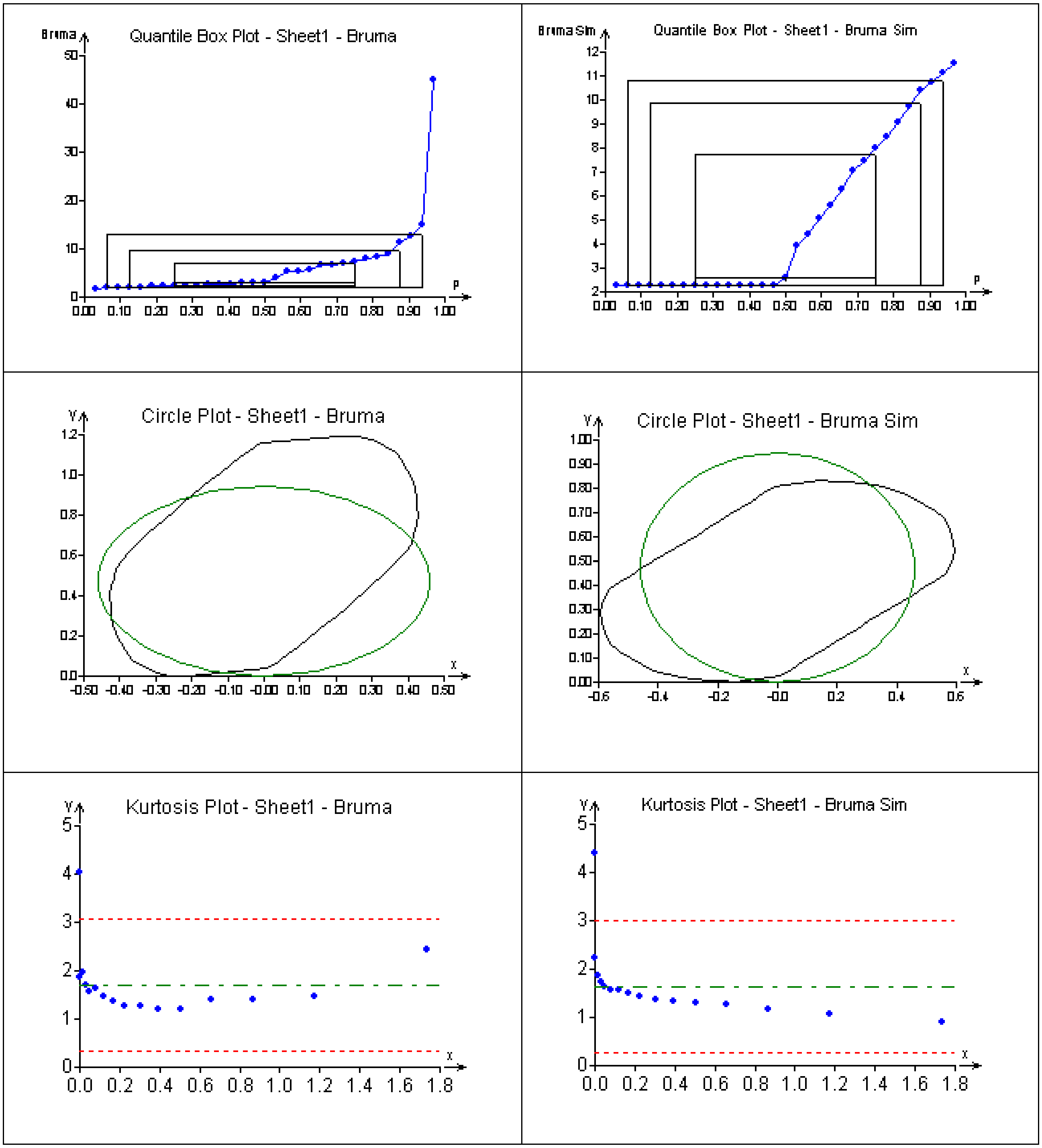
Appendix 9: Experimental and simulated results for the Umgeni River when using membrane 4.



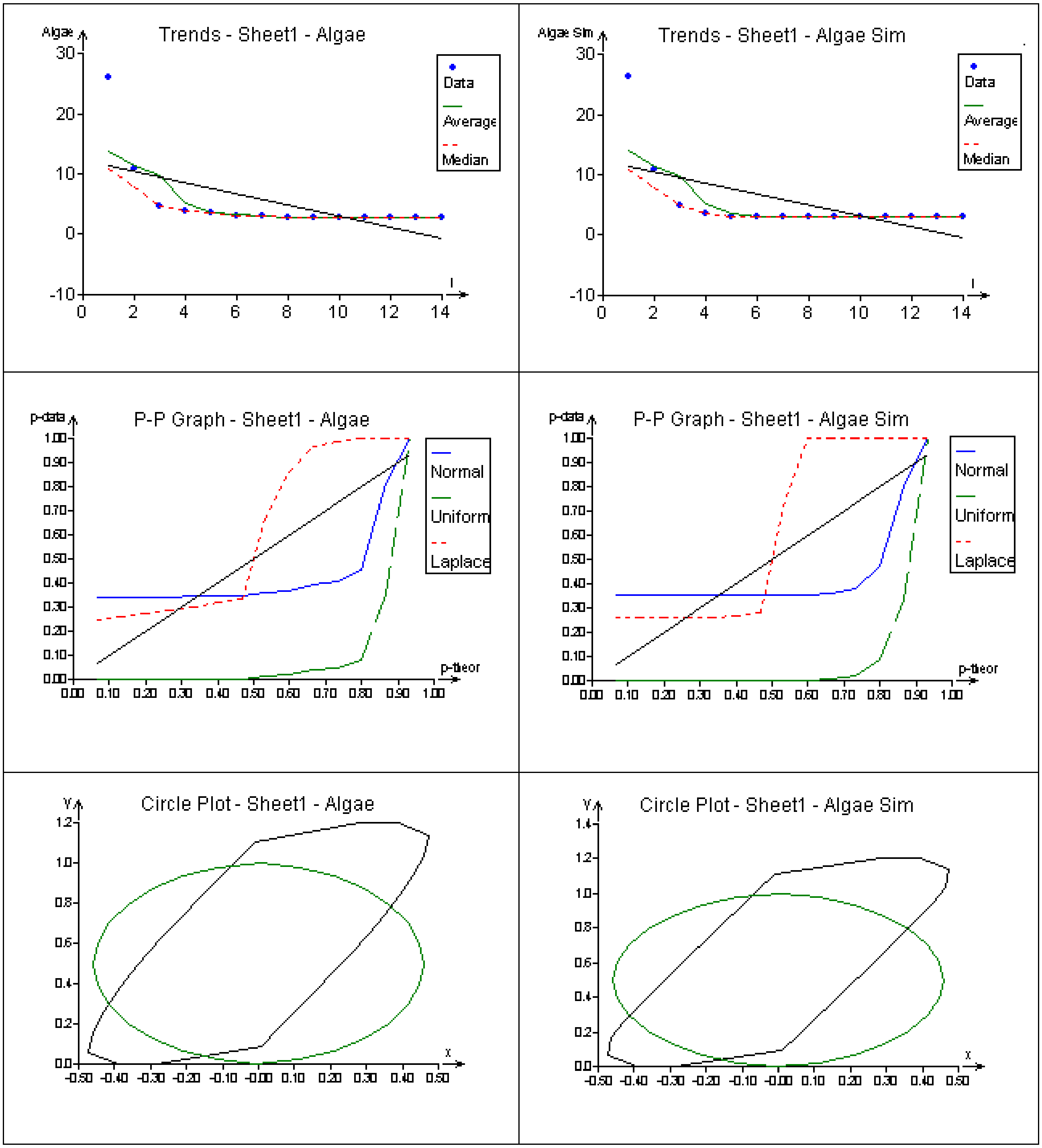
Appendix 10: Experimental and simulated results for Mobeni Effluent when using membrane 4.



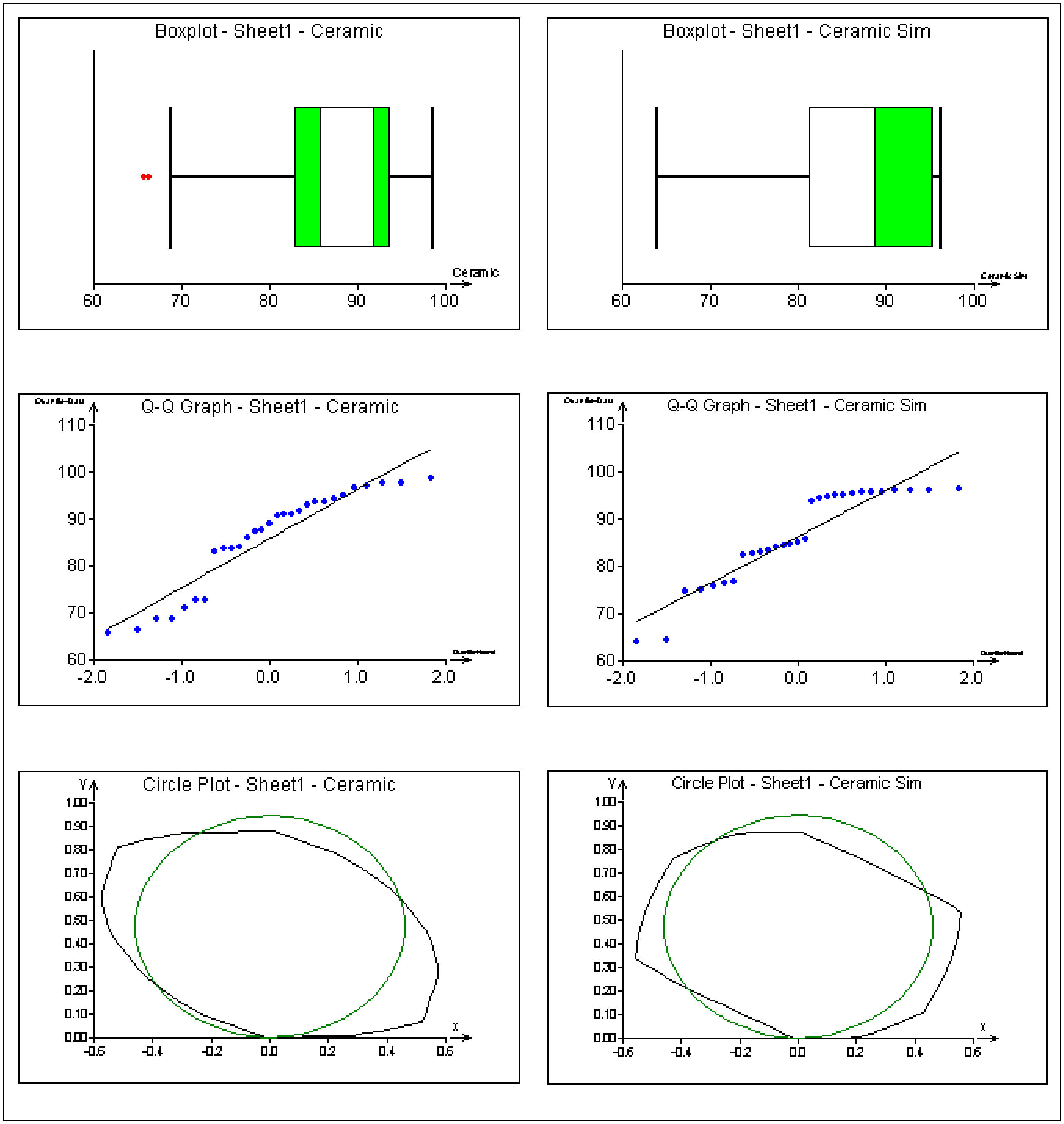
Appendix 11: Experimental and simulated results for Mobeni Effluent when using membrane 4.



Appendix 12: Experimental and simulated results for Bruma lake when using membrane 4.



Appendix 13: Experimental and simulated results for algae solution when using membrane 4.



Appendix 14: Experimental and simulated results for the ceramic solution when using membrane 4.