Energy Reduction in a Woven-Fabric Immersed Membrane Bioreactor

by

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DECLARATION

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ABSTRACT

Most developing countries, including South Africa, currently face a substantial challenge in providing satisfactory sanitation for all its inhabitants. Small-scale sanitation plants have the greatest potential to overcome this challenge, especially for decentralized areas. Currently such systems are available; however these systems are extremely expensive and complicated, especially in terms of the running costs. In recent years there has been a major shift towards immersed membrane bioreactor (IMBR) technology in the wastewater treatment industry due to the advantages that IMBRs offer over conventional wastewater treatment plants.

The major hindrance to the implementation of IMBRs in developing economies is due the costliness and the lack of durability of the current membranes being used. A novel woven-fabric microfilter (WFMF) is currently produced in South Africa from woven polyester which resembles the features of a microfilter and harbours the characteristics to make IMBRs sustainable and affordable. An IMBR which makes use of the WFMF is known as the woven-fabric immersed membrane bioreactor (WF-IMBR).

The overall aim of this study is to reduce the energy consumption in the WF-IMBR to make it an affordable technology. The following are the key objectives of this study:

I. Improve the mechanical design of the WFMF membrane module;
II. Improve the air-scour regime of the WF-IMBR;

To start the investigation, a pilot plant rig was constructed and set-up at Zandvliet wastewater treatment works (WWTW). Preliminary experiments were done to evaluate the WFMF module design and modify it in order to decrease the inherent pressure drop which would reduce the energy consumed to withdraw permeate from the system. By inserting a more rigid spacer and by including two larger permeate outlets the overall pressure drop was decreased by 90%.

Experiments were then performed to investigate the effect of different process conditions. A surprising result, which suggested that less fouling occurred when operating the system without scouring the membrane; led to further investigation of this phenomenon on a lab-scale basis.

Lab-scale results confirmed this phenomenon and also gave rise to a new operating regime, known as intermittent air-scouring. Across all three activated sludge feeds from different WWTWs investigated, there was a clear indication that operating with intermittent air-scouring and with air-

scouring resulted in the lowest fouling rate. This was significantly less than operating with continuous air-scouring.

Furthermore, increasing the air-scour rate during continuous air-scouring trials resulted in higher fouling rates. A three factor two level factorial experiment was then performed to investigate the effect of the three main parameters which could potentially increase the effectiveness of the intermittent air-scouring regime. Results showed that filtration duration was one of the more important operational parameters during intermittent air-scour trials. It was hypothesised that longer filtration durations allowed for a protective cake layer to form on the membrane surface which kept the membrane clear of organic substances which has a higher fouling potential.

Implementing these findings on the pilot plant rig, confirmed intermittent air-scouring to be the most practical and feasible air-scour regime which reduced air-scour costs by 95%. Further investigations should be done to determine an optimum operating point for intermittent air-scour regime on the pilot plant rig.

OPSOMMING

Alle ontwikkelende lande, insluitend Suid-Afrika, het tans 'n aansienlike uitdaging in die verskaffing van bevredigende sanitasie vir alle inwoners. Kleinskaalse sanitasie plante het die grootste potensiaal om hierdie uitdaging te oorkom, veral vir gedesentraliseerde gebiede. Sulke stelsels is tans beskikbaar maar,is baie duur en ingewikkeld , en die bedryfskostes is hoog. 'n Groot verskuiwings na IMBR tegnologie in die behandeling van afvalwater het die afgelope jare plaas gevind as gevolg van die voordele wat IMBRs bied teenoor die konvensionele afvalwater tegnologie.

Die groot hindernis vir die implementering van IMBRs in ontwikkelinde ekonomieë is tewyte aan die beskostigbaarheid en die gebrek aan duursaamheid van die huidige membrane wat gebruik word.'n Oorspronklik geweefstof microfilter(WFMF) is tans geproduseer in Suid – Afrika uit geweefde poliëster wat dieselfde voorkom as 'n mikrofilter en ook dieselfde eienskappe as 'n IMBR bevat om dit volhoubare en bekostigbaar te maak.'n IMBRs wat gebruik maak vandie WFMF staan bekend as die "woven-fabric immersed membrane bioreactior" (WF-MBR).

Die oorhoofse doel van hierdie studie is om die energie verbruik in die WF-IMBR te verminder om dit 'n bekostigbare tegnologie te maak. Die volgende is die belangrikste doelwitte van hierdie studie:

I. Verbeter die meganiese ontwerp van die WFMF membraan.
II. Verbeter die lug-skure prosedure van die WF-IMBR.

Om die ondersoek mee te begin, was 'n loodsaanleg gebou en op Zandvliet WWTW opgerig. Voorlopige eksperimente is gedoen om die WFMF membraanontwerp te evalueer en te verander om sodoende die huidige druk te verminder, wat die energie verbruik van die stelsel ook sal verminder. Deur van 'n meer solide opening gebruik te maak en ook deur die insluiting van twee groter afsetpunte het die algehele druk met 90% afgeneem.

Meer eksperimente was uitgevoer om die effek van verskillende prosese te ondersoek. 'n Verrassende resultaat, het getoon dat, wanneer die stelsel sonder lug gebruik word, dit tot minder aangroei lei. Hierdie resultaat het tot verdere ondersoek van hierdie verskynsel op 'n laboratorium-skaal basis aanleiding gegee.

Laboratorium-skaal resultate het hierdie verskynsel bevestig en ook aanleiding tot nuwe bedryfstelsel prosedure gegee, wat bekend staan as intermitterende lug-skuur. Al drie geaktiveerde slyk monsters van verskillende afvalwater plante wat ondersoek was,was daar 'n duidelike

aanduiding dat die prosedure met intermitterende lug-skuur tot gevolg gehad dat die minste hoeveelheid besoedeling aansienlik minder is as die prosedure met deurlopende lug-skuur.

Verder, die verhoging van die lug-skure koers tydens die deurlopende lug-skuur proewe het tot hoër aangroei hoeveelheid gelei. 'n Drie- faktoor twee- vlak- faktoor eksperiment was toe uitgevoer om die effek van die drie belangrikste veranderings ondersoek wat potensieel die doeltreffendheid van die onderbroke lug-skuur prosedure kan verhoog. Resultate het getoon dat die belangrikste faktor die tydsduur van die filtrasie was. Dit het daarop neer gekom, die feit dat meer filtrasie tyd toegelaat word om 'n beskermende slyk laag te vorm op die membraan oppervlak wat die membraan skoon hou van stowwe soos EPS wat 'n hoër aangroei potensiaal het.

Implementering van hierdie bevindinge op die loodsaanleg bevestig dat intermitterende lug-skuur die mees praktiese en haalbare lug-skuur prosedure is wat lug-skure koste met 95% verminder het. Verdere ondersoeke moet gedoen word om 'n optimale bedryfstelsel vir intermitterende lug-skuur prosedure op die loodsaanleg te bepaal.

DEDICATION

I devote this thesis to my extraordinary family. My parents, Japie and Cathleen Deelie, let's be honest, this would not be possible at all if it wasn't for the two of you and I would not be where I am today without you. You have always been there for me and your unconditional love and support has guided me through life and allowed me to overcome any obstacle that I have faced. Thank you for your continuous encouragement, inspiration and love. Your support has motivated me to achieve and expect only the best in all aspects of my life. My only sibling, Elmor Deelie, thank you for being there whenever I needed someone to talk to and always letting me know that I am capable of doing so much more and that I should never sell myself short in any aspect. I love you all and thank you for everything.

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Most of all, I want to give the utmost praise to my LORD and SAVIOUR JESUS CHRIST who is always there no matter how the dire situation and who I could always turn in times of sadness or rejoice.

Proverbs 3:5-6 "Trust in the LORD with all your heart and do not lean on your own understanding. In all your ways acknowledge Him, And He will make your paths straight."

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

NOMENCLATURE

Symbols

$A_{surface}$	The total surface area of the membrane	[m^2]
$A_{m, eff}$	Effective membrane surface area	[m^2]
A_{wd}	Nominal Pure water permeability by diffusion	[LMH/barg]
e_{mech}	Mechanical energy	[kJ/kg]
F	Membrane fouling rate	[$m^{-1}s^{-1}$]
g	Gravitational acceleration	[m/s^2]
J	Permeate flux	[l/m^2h (LMH)]
J_{crit}	Critical flux	[l/m^2h (LMH)]
J_{wd}	Pure water flux	[l/m^2h (LMH)]
$L_{m, eff}$	Effective membrane length	[cm]
$L_{m, total}$	Total membrane length	[cm]
P_{Abs}	Absolute pressure	[barg]
P_{Atm}	Atmospheric pressure	[barg]
P_{Vac}	Vacuum pressure	[barg]
ΔP	Pressure drop	[kPa]
R_m	Intrinsic resistance to the membrane	[m^{-1}]
R_C	Cake resistance	[m^{-1}]
R_{tot}	Total resistance	[m^{-1}]
TMP	Transmembrane pressure	[kPa]
$\dot{V}_{Feed}$	Volumetric flow rate of the feed	[l/h]
$\dot{V}_{Permeate}$	Volumetric flow rate of permeate	[l/h]
$V_{reactor}$	Volume of the reactor vessel	[l]

$\dot{V}_{Throughput}$	Volumetric flow rate through the reactor	[l/h]
$W_{m,\ eff}$	Effective membrane width	[cm]
$W_{m,\ total}$	Total membrane width	[cm]
z	Elevation distance	[m]
ρ	Density	[Kg/m^3]
θ	Hydraulic retention time	[h]
Δπ	Osmotic pressure opposite the applied TMP	[barg]
μ_v	Viscosity	[Ns/m^2]

Acronyms

BOD	Biological oxygen demand
CAS	Conventional activated sludge
CEB	Chemically enhanced backwash
CFV	Cross-flow velocity
COD	Chemical oxygen demand
CP	Concentration polarization
DE	Dead-end
DO	Dissolved oxygen
DOTM	Direct observation through the membrane
EPS	Extracellular polymeric substances
FS	Flat-sheet
GF-CEB	Gravity-fed chemically enhanced backwash
HRT	Hydraulic retention time
ID	Inner diameter
IMBR	Immersed membrane bioreactor
MBR	Membrane bioreactor
MF	Microfilter or Microfiltration

MLSS	Mixed liquor suspended solids
NF	Nano-filtration
NTU	Nephlemetric turbidity units
PE	Persons equivalent
PF	Particle filtration
PS	Pumps setting
PWF	Pure water flux
RAS	Returned activated sludge
RO	Reverse osmosis
SMBR	Side-stream membrane bioreactor
SMP	Soluble microbial products
SRT	Sludge residence time
TMP	Transmembrane pressure
TDS	Total dissolved solids
TS	Total solids
TSS	Total suspended solids
UF	Ultrafiltration
VSS	Volatile suspended solids
WAS	Wasted activated sludge
WF-IMBR	Woven- fabric immersed membrane bioreactor
WFMF	Woven-fabric microfilter
WRC	Water Research Commission
WWTW	Wastewater treatment works

CHAPTER 1. INTRODUCTION

1.1. Background

South Africa, like most developing countries, faces an immense challenge in providing sufficient and satisfactory sanitation for all its inhabitants. The lack of satisfactory sanitation is the key source of contamination of water resources in under-developed regions (Adewumi, et al., 2010). Adequate sanitation can reduce this contamination, and hence increase the water resource available for utilization. Better health and reduced environmental contamination also has a positive impact on the economy (Govender, et al., 2011). Decentralized, small-scale sanitation plants have the potential to overcome these challenges, and could therefore make a large contribution to the implementation of sanitation in rural areas; such as, farms, remote areas, small communities, villages and other areas in need of sanitation (Pillay, 2010).

In recent times there has been a swing towards implementation of immersed membrane bioreactor (IMBR) technology for the treatment of both domestic and industrial wastewater due to the numerous advantages that IMBRs offer over conventional wastewater treatment plants (Hülsen, et al., 2016; Phan, et al., 2014; Ding, et al., 2013). The main advantage being that it is able to provide a consistently high product quality; simply due to the fact that the membrane is responsible for the final separation and therefore the product quality is not dependant on the skill of the operator, unlike for conventional activated sludge (CAS) processes (Cicek, 2003). In addition, IMBRs generally require a smaller footprint since such systems are compact; this is due to the fact that biological degradation, product separation as well as product disinfection can occur in a single reactor vessel and/or process step. The membrane bioreactor (MBR) process typically only requires about 50% of the land area of a CAS process for the same throughput (Meng, et al., 2009). Furthermore, IMBR systems are generally more versatile and adaptable since they can handle shock loads and large variations in organic loadings, without any effect on the product quality. Lastly, IMBRs allow for a much more stable biological system since higher mixed liquor suspended solids (MLSS) levels (approximately 4 times higher than CAS processes) can be achieved and it is estimated that the MBR process only produces half as much sludge as the CAS process (Huang & Lee, 2015).

Nonetheless, there is a general perception that IMBR technology is complex and requires highly skilled operators; hence not being applicable for decentralized sanitation in developing regions. Although the few industrial IMBRs and large-scale domestic wastewater IMBRs in the country are typically sophisticated plants, this does not need to be the case for small-scale package plants (Pillay, 2010). The major hindrance to the implementation of IMBRs in developing economies is due the costliness, the lack of durability of the current membranes being used, as well as inevitable fouling that membranes are prone to (Judd, 2011). Existing IMBR systems are extremely expensive due to the fact the most membranes are delicate and could be damaged by air-scouring, drying-out or most forms of physical abrasion (Chollom, et al., 2016). The need to constantly replace these membranes over-shadows its undeniable ability to provide sanitation to numerous communities worldwide.

A novel woven-fabric microfilter (WFMF) is currently produced in South Africa from woven polyester which resembles the features of a microfilter (Chollom, et al., 2016). Initial investigations have shown that this membrane is much more robust than most commercial membranes on the market, as well as being significantly less expensive, especially since it is locally produced (Cele & Pillay, 2010). The advantages of these membranes are that they can be dried out, can withstand vigorous air-scouring and are mechanically stronger than other membranes (Chollom, et al., 2016; Thy, 2010). By using this membrane in IMBR systems one could negate most of the stigma being placed on existing membrane systems since they harbour the characteristics to make IMBRs a sustainable and affordable.

Previous studies have shown that the woven-fabric immersed membrane bioreactor (WF-IMBR) is promising (Cele & Pillay, 2010) and to further explore the possibility of the implementation of WF-IMBRs in South Africa, Water Research Commission (WRC) Project K5/2287 was introduced. This project was focused on the development of a WF-IMBR package plant for decentralized sanitation. Part of the project was to firstly design a 30 persons equivalent (PE) plant and then to reduce the energy requirements of this technology. There are two main aspects to energy reduction in the WF-IMBR, which this study will focus on. Firstly, the permeate pumping energy requirements would need to be addressed, which is directly related to the mechanical geometry of the WFMF module design in terms of the inherent pressure drop along the module. Secondly, the air-scouring energy requirement, which is responsible for approximately 80% of the energy consumed by IMBR systems, would need to be addressed. This can be done by either determining the lowest effective air-scouring rate for sustainable operation or by adjusting the air-scouring operating regime; this project will investigate the feasibility of both approaches.

1.2. Objectives and Sub-Tasks

1.2.1. Objectives

The overall aim of this study was to reduce the energy consumption in the WF-IMBR. The following are the key objectives of this study:

I. Improve the mechanical design of the WFMF membrane module;
II. Improve the air-scour regime of the WF-IMBR;

1.2.2. Sub-Tasks

In order to achieve each of the objectives as set out for this study, a list of tasks were detailed to outline the scope and breakdown the objectives into smaller tasks, as follows:

i. Design a 30 PE WF-IMBR pilot plant;
ii. Procure the necessary resources and construct a pilot plant at Zandvliet WWTW with the relevant equipment and instrumentation in order to perform and document various experiments on the WF-IMBR;
iii. Evaluate the initial baseline performance of the pilot plant in terms of operating flux and transmembrane pressure;
iv. Reduce the energy consumption for pumping by re-designing the WFMF modules to reduce the pressure drop across them;
v. Re-evaluate the modified WFMF module in terms of operating flux;
vi. Construct a laboratory-scale WF-IMBR;
vii. Investigate the effect of various air-scouring regimes on different samples of activated sludge’s on a lab-scale WF-IMBR;
viii. Validate the laboratory-scale results on the pilot plant at Zandvliet WWTW.

1.3. Approach

The project had two main aims; to improve the mechanical design of the WFMF membrane module and to improve the air-scour regime of the WF-IMBR. Firstly a WF-IMBR pilot plant was designed, constructed and erected to Zandvliet wastewater treatment works (WWTW), Western Cape.

Before attempting to improve the mechanical design of the WFMF module, baseline experiments were done to examine the state of the initial module design. It could immediately be noticed that there was definitely an issue with the initial design of the WFMF since Transmembrane-pressures (TMP) were much higher than anticipated and the flux was not too favourable either, even after applying a chemical clean to ensure the integrity of the membrane.

A new WFMF design had been designed and employed, by using a more rigid and robust spacer with sufficient permeate flow capabilities, as well as by increasing the size and number of the permeate outlet nozzles. This resulted in the TMP being reduced tremendously and as a result the operating flux obtained was much more attractive. Following flux-step experiments, a critical flux had been determined; but it was soon noticed that stable sub-critical operation was not possible.

Various experiments were then done on the WF-IMBR system to investigate the air-scouring regime and its effect on stable operation by using the resistance profiles to represent the extent of fouling under different conditions. Investigating the effect of air-scour rate, flux and MLSS concentration were amongst the experiments done in order to find a better air-scouring and operating regime. However, the results obtained were completely contradictory to what is usually observed.

To further investigate these results as well as various air-scouring regimes, it was then decided to construct a lab-scale WF-IMBR rig in order to examine whether the results obtained on the Zandvliet activated sludge trials were reproducible when investigating other samples of activated sludge from different wastewater treatment plants in the Western Cape area. Experiments were done to investigate the extent of fouling at a high flux as well as a low flux by altering the air-scouring operating protocol, which ranged from operating with continuous air-scouring to none at all.

After proving that results obtained had been reproducible on various samples of activated sludge, a factorial design was done on the Zandvliet WWTW activated sludge for intermittent air-scouring, the parameters investigated was the air-scour rate, air-scour duration and the filtration duration. To further verify the results obtained on the laboratory scale experiments, final validation experiments were carried out on the pilot plant rig, specifically to investigate the effect of intermittent air-scouring compared to operating with continuous air-scour and not scouring at all. Investigating the relative ease of cleaning was also used to determine the extent of fouling.

1.4. Thesis Organisation

Figure 1-1 and Figure 1-2 illustrates a flow diagram for the various chapters and sub-chapters that this thesis encompasses. After Chapter 1, which states the problem statement and objectives, a literature study (Chapter 2) was done to summaries the various ideologies needed to understand the approach, terminology and general concepts used throughout the investigation.

Chapter 3 was mainly based around completing the first objective of the study. It gives insight into the design, construction and implementation of the pilot plant rig as well as the procedures used to reduce the inherent pressure drop of the WFMF module, which would potentially lead to reduced energy consumption and consequently reduced operation costs.

Chapter 4 and 5 were based around evaluating the WF-IMBR at different process conditions and operating regimes on a pilot and lab-scale respectively, with the latter being done on a variety of sludge feeds from different wastewater treatment plants.

Experiments were then done to evaluate the effect of various continuous air-scour rates, as well as which parameters might have an effect on the efficiency of the intermittent air-scour regime, this was summarised in the first sub-section in Chapter 6. Thereafter this chapter endeavoured to apply the principles discovered on the lab-scale trials, on the pilot plant rig. A brief summary on permeate quality analysis was done to conclude this chapter.

The results of all the chapters were summarised along with the conclusion and future recommendations in chapter 7.

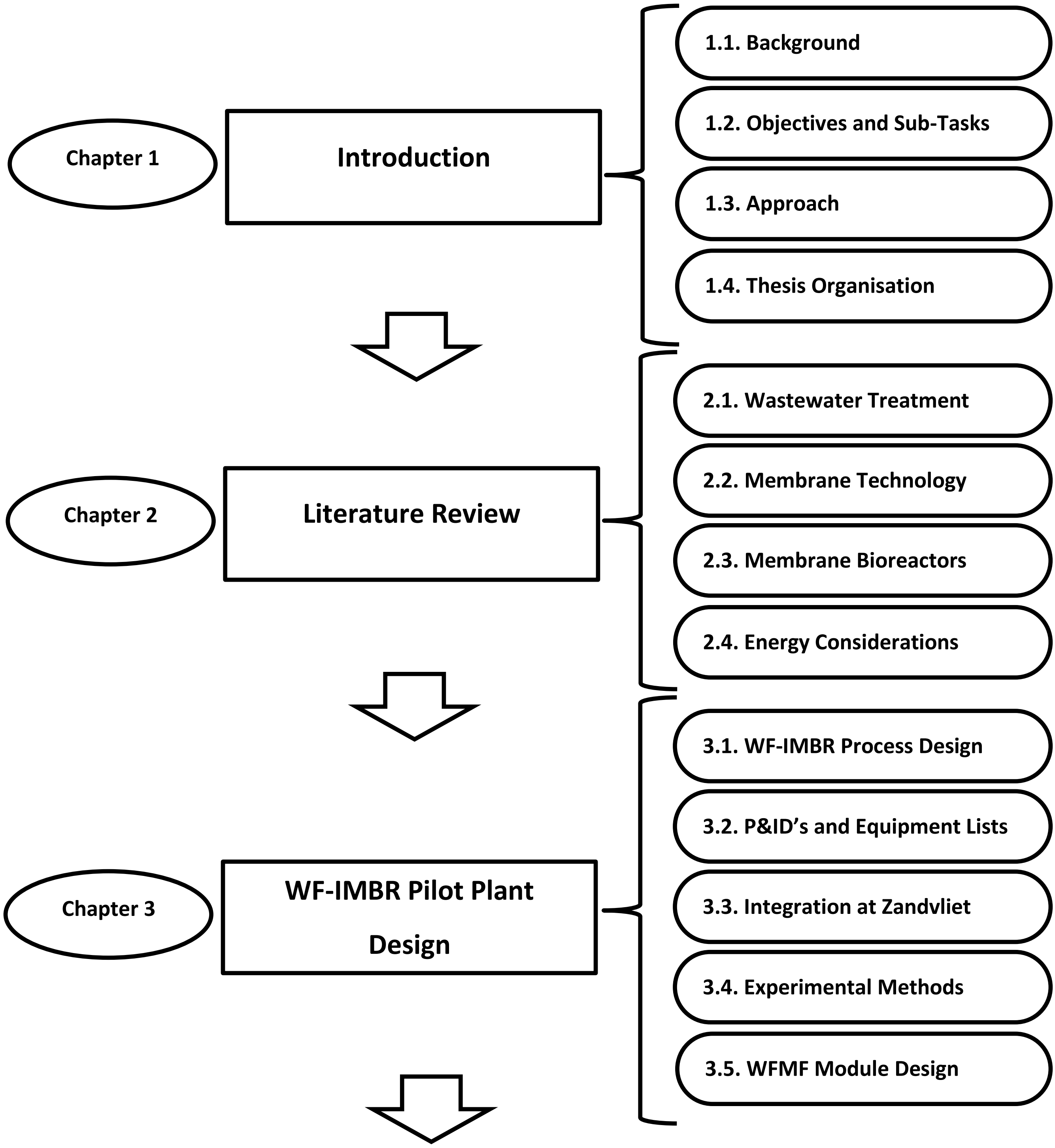


Figure 1-1: Thesis Layout Part 1

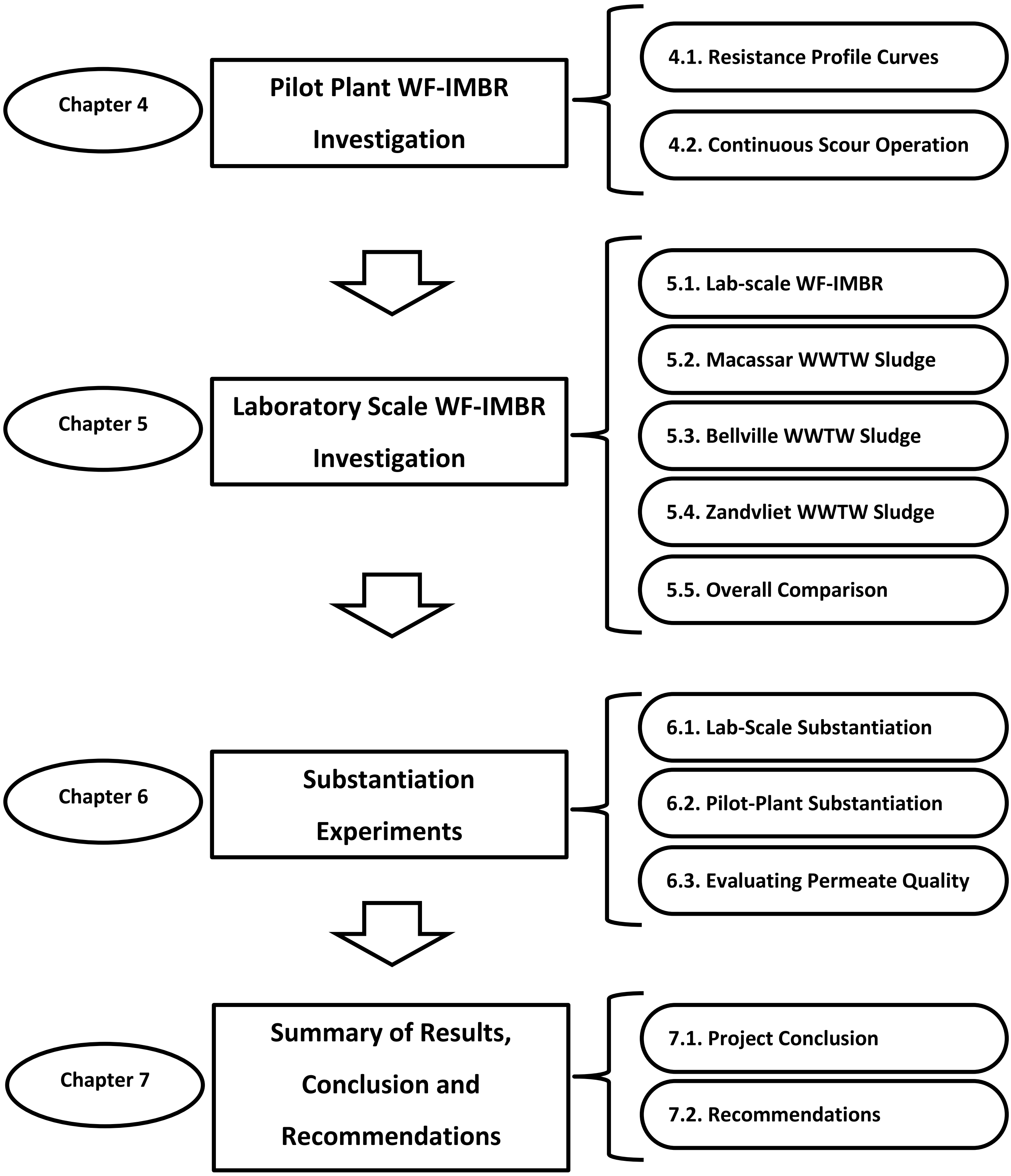


Figure 1-2: Thesis Layout Part 2

CHAPTER 2. LITERATURE REVIEW

The aim of this chapter is to give a brief overview of wastewater treatment, specifically the activated sludge process. Thereafter, membrane technology will be introduced, along with basic terminology, theories as well as the particulars of the woven-fabric flat-sheet membrane; which is a unique robust membrane unlike the conventional membranes used in most MBR operations. Moreover, a detailed overview of membrane bioreactors will be given; especially the immersed membrane bioreactor (IMBR) which exemplifies the best aspects of both the activated sludge system as well as membrane separation processes. To conclude this chapter, a brief look into energy considerations will be done.

2.1. Wastewater Treatment

2.1.1. Overview

Wastewater is the term given to spent or used water with dissolved or suspended solids which is discharged from homes, commercial establishments, farms and industries (Mara & Horan, 2003). There are four components to domestic wastewater. These include wastewater from commercial, domestic or industrial users; storm water runoff; infiltration and inflow. Industrial wastewater varies in quantity, composition, and strength depending on the industrial source (Michelcic & Zimmerman, 2010).

The main purpose of municipal wastewater treatment is to prevent the pollution of a receiving surface water or groundwater (Mara & Horan, 2003). The following are examples of pollutants associated with untreated wastewater: dissolved oxygen depletion, oxygen-depleted solids, nutrients that cause eutrophication, chemicals that exert toxicity and pathogens (Michelcic & Zimmerman, 2010; Mara & Horan, 2003).

Conventional wastewater treatment is widely used however its limitations include a large footprint and substantial capital costs (Judd, 2011). Treatment plants also require a certain level of operator knowledge and skill, which could adversely affect the product quality.

The main contaminants found in wastewater is organic compounds, volatile organic compounds, suspended solids, toxic metals, priority pollutants, microbial pathogens, heavy metals, parasites and nutrients, such as nitrogen and phosphorus (Bitton, 2005).

Various different types of secondary treatment methods exist; these include trickling filters, rotating biological contactors, lagoons and conventional activated sludge (CAS) (von Sperling, 2007). The most common approach is the CAS option which uses microorganisms to break down organic material, with the aid of sufficient aeration (Judd, 2011).

2.1.2. Conventional Activated Sludge (CAS) Process

The activated sludge process is widely used for the treatment of both domestic and industrial effluent (von Sperling, 2007), this is the process employed by most municipalities to effectively treat wastewater, as illustrated in Figure 2-1. The CAS process consists essentially of an aerobic treatment that oxidises organic matter to CO_2 and H_20, NH_4, and new cell biomass (Judd, 2011). Air is provided by using diffused or mechanical aeration. The microbial cells form flocs which are allowed to settle out leaving water in the supernatant (Bitton, 2005).

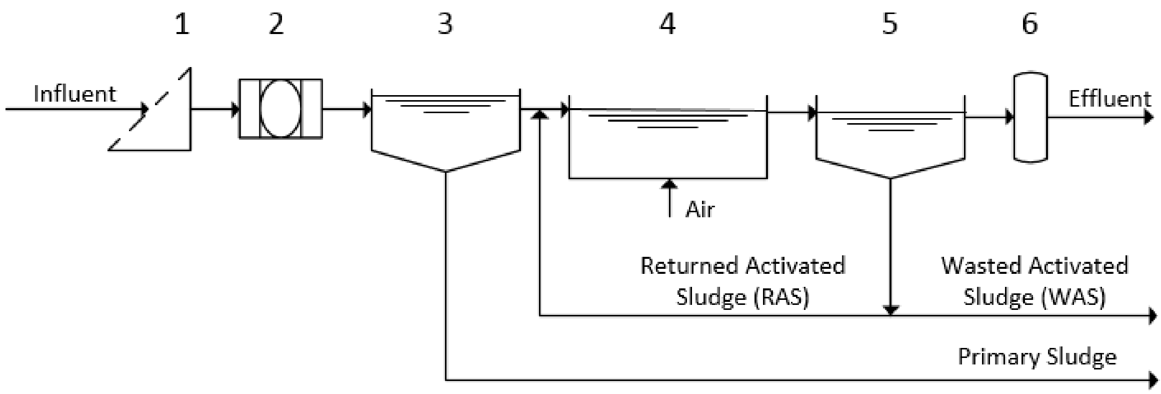


Figure 2-1: The Conventional Activated Sludge Process (Adapted from (Judd, 2011))

(1: Screen, 2: Grit Chamber, 3: Primary Sedimentation Tank, 4: Aerated Reactor, 5: Secondary Sedimentation Tank, 6: Sand Filtration and Disinfection)

Municipal wastewater treatment plants consist out of four sections, namely: Pre-treatment, primary treatment, secondary treatment and tertiary treatment (Judd, 2011).

2.1.2.1. Preliminary Treatment

Preliminary treatment of wastewater consists of initially screening the feed in order to remove the larger unwanted material and coarse solids. The screen is coupled with a grit chamber; together they prepare the wastewater for further treatment by removing oily scum, floating debris and grit. These unwanted contaminants could inhibit biological process and/or damage mechanical equipment downstream if not removed (Michelcic & Zimmerman, 2010). Depending on the effluent to be treated additional pre-treatment may be required such as air-stripping, neutralization or air flotation in order to remove unwanted chemicals, especially for industrial effluents (Judd, 2011).

2.1.2.2. Primary Treatment

Primary treatment in the activated sludge process mainly consists of a primary sedimentation tank better known as a primary clarifier. The objective of this clarifier is to separate the debris-free wastewater into a liquid stream (overflow) and a solids stream (underflow) (von Sperling, 2007). This is done using the principle of sedimentation which allows solid-liquid separation by exploiting the tendency of particles in suspension to settle out of the fluid (Michelcic & Zimmerman, 2010).

The liquid stream, which is sent to the biological reactor, contains dissolved organics, floatable solids and dissolved ammonia. In some wastewater treatment plants skimming would be used to remove the floatable materials. The solids stream, which exits at the bottom of the clarifier, is usually sent to an anaerobic digester for further treatment (Zahrim, et al., 2011). This stream usually contains most of the suspended solids, BOD and phosphates (Michelcic & Zimmerman, 2010).

2.1.2.3. Secondary Treatment

The primary objective of secondary treatment is to remove the residual organics and suspended solids that could not be removed during primary treatment. Secondary treatment usually consists of biological treatment coupled with a clarifier.

A. Biological Treatment

Biological treatment processes are those which remove dissolved and suspended organic chemical constituents through biodegradation, as well as suspended matter through physical separation. Bio-treatment demands that the appropriate biological reactor conditions prevail in order to maintain sufficient levels of living microorganisms for satisfactory removal of organics (Judd, 2011). A good measure of this is biochemical or chemical oxygen demand (BOD or COD), which are indirect measurements of organic matter levels; subsequently both refer to the amount of oxygen needed for the oxidation of the organics (Judd, 2011). Microorganisms depend on the organic substrate as a source of food and generate cellular material from this organic matter (Bitton, 2005). These organisms can either be aerobic or anaerobic (Mara & Horan, 2003). Furthermore, additional modifications can be made to the CAS process which account for nutrient removal, these regimes will subsequently be discussed:

i. Aerobic Treatment

Aerobic treatment is used to remove organic compounds (BOD or COD) and to oxidize ammonia to nitrate (Judd, 2011). Oxygen is the final electron acceptor in aerobic processes and therefore it is vital that an adequate amount of oxygen is bubbled through aerobic treatment systems. The lower limit of satisfactory dissolved oxygen levels is 2 mg O_2/l. Fine-pore diffusion is usually preferred since it reduces energy costs by 50% when compared to coarse bubble diffusers (Michelcic & Zimmerman, 2010).

ii. Anaerobic Treatment

Carbon dioxide is the final electron acceptor for the oxidation of organic carbon in anaerobic processes. Unlike aerobic oxidation, anaerobic oxidation is only a partial combustion process and produces less energy resulting in a much slower process (Skouteris, et al., 2012). Therefore these reactors require larger volumes to match the throughput of aerobic oxidation. Other disadvantages of anaerobic oxidation are the pungent odour that is associated with it as well as the fairly prolonged start-up procedure. On the other hand, where aerobic processes require large amounts of energy, anaerobic systems produce biogas which could be used as an energy source. Moreover, anaerobic processes also have a much slower sludge production rate (Michelcic & Zimmerman, 2010).

iii. Modifications to Conventional Activated Sludge

Secondary treatment is sometimes inadequate to satisfactorily treat the receiving water. Additional removal of pollutants such as nitrogen and phosphorus is required in such instances (Petrie, et al., 2014). Nitrification is the conversion of ammonia to nitrite and then nitrate with the aid of specialized genera of lithotrophic bacteria. *Nitrosomonas* bacteria convert ammonia to nitrite and *Nitrobacter* bacteria convert nitrite into nitrate (Michelcic & Zimmerman, 2010). Nitrification, needing oxygen as final electron acceptor, occurs in aerobic systems.

Another important modification to CAS processes is the removal of phosphorus. Some sort of coagulant dosing is usually used for the complete removal of phosphorus (Skouteris, et al., 2012). Traditionally, chemicals such as alum, ferric sulphate and ferric chloride have been added to remove phosphorus by precipitation (Petrie, et al., 2014). These chemicals can be added during primary or secondary treatment (Michelcic & Zimmerman, 2010).

B. Secondary clarifier

The two streams that exit the secondary clarifier, which works on the same basic principles as the primary clarifier, is the clarified effluent stream which is sent downstream for further treatment and the liquid-solid sludge stream comprising largely of microorganisms (Cele & Pillay, 2010). A portion of this liquid-solid stream is pumped back to the biological reactor, this is known as the returned activated sludge (RAS). The remainder of the sludge is removed from the system and is processed for disposal; this is known as the waste activated sludge (WAS) (Michelcic & Zimmerman, 2010). It is always vital to control the amount of activated sludge wasted since this ultimately controls the biomass concentration within operating limits (Bitton, 2005).

2.1.2.4. Tertiary Treatment

The final treatment step usually involves refining the clarified effluent stream. Some wastewater treatment plants make use of sand filter in order to remove any pathogens and other organics which may have seeped through (von Sperling, 2007). Additionally, before any flow measurement or discharge, the clarified water is to be disinfected (Michelcic & Zimmerman, 2010). Disinfection is the destruction of microorganisms capable of causing diseases and is essentially the final barrier against human exposure to pathogenic microorganisms. Some disinfectants are employed for oxidation of organic matter, iron and manganese (Bitton, 2005). Disinfectants and disinfection techniques include: liquid sodium hypochlorite, chlorine dioxide, chlorine gas, ozonisation and exposure to ultraviolet light (Michelcic & Zimmerman, 2010).

2.1.3. Product Quality

In South Africa the use of water is governed by the National Water Act, No 36 of 1998 as amended. The act states that: "… water extracted for industrial purposes shall be returned to the source from which it was abstracted, in accordance with quality standards gazetted by the Minister from time to time". Table 2-1 summarised the limits of wastewater discharge into water sources in South Africa.

Table 2-1: Wastewater limit values applicable to discharge of wastewater into a water resource

Variable and Substances	Existing SA General Standards	Existing SA Special Standards
Chemical Oxygen demand (mg/l)	75	30
Ionized and unionized ammonia (mg/l)	3	2
Nitrate (as N) (mg/l)	15	1.5
PH	5.5-9.5	5.5-7.5
Phenol index (mg/l)	0.1	-
Suspended solids (mg/l)	25	10
Phosphorous (mg/l)	10	1
Total cyanide (mg/l)	0.02	0.01
Total arsenic (mg/l)	0.02	0.01
Total boron (mg/l)	1	0.5
Total cadmium (mg/l)	0.005	0.001
Total chromium VI (as CR VI) (mg/l)	0.05	0.02
Total copper (as Cu) (mg/l)	0.01	0.002
Total iron (as Fe) (mg/l)	0.3	0.3
Total lead (as Pb) (mg/l)	0.01	0.006
Total mercury (as Hg) (mg/l)	0.005	0.01
Total selenium (as Se) (mg/l)	0.02	0.02
Total Zinc (as Zn) (mg/l)	0.1	0.04
Faecal coliform per 100 ml	1000	0

2.2. Membrane Technology

2.2.1. Overview

A membrane is merely a material that permits some physical or chemical components to permeate more readily than others; it is therefore perm-selective (Judd, 2011; Arndt, et al., 2016). Membrane technology refers to the process of separating particles, based on differences in permeability, through a porous membrane (Tarragona, 2005).

In 1907, Bechold introduced the theory of ultrafiltration and described it as forcing solutions at high pressures through membranes (Strathmann, 1981). These membranes had been prepared by impregnating filter paper with acetic acid and in 1962, Loeb-Sourirajan invented the asymmetric membrane which initiated the introduction of practical membrane applications (Tarragona, 2005).

There is a general propensity for molecules to move from high concentrations to lower concentrations; and this net movement of permeable substances across the total surface area of the membrane is known as the permeate flux, or more commonly as the flux (Strathmann, 1981). The substance that permeates through the membrane is known as the permeate; which is usually the desired product of membrane separation. The substance that is rejected due to its inability to diffuse through the membrane is known as the retentate and is usually added back to the feed stream to be filtered again (Allman, 2012; Judd, 2011).

On the one hand, membranes offer various advantages over existing physio-chemical treatment processes. Firstly membrane processes can separate for an extensive selection of separation needs, ranging from a molecular scale to particles that can be seen by the naked eye (Judd, 2011). In general energy requirements for membrane applications are minimal since no phase change is necessary, unless a large amount of energy is required to achieve desired operating pressures (Braak, et al., 2011). Membrane operations are therefore exceptionally cost effective since no additional chemicals are required and the flow sheet for most membrane applications is usually straightforward. Membrane technology produces a very high and consistent product quality which is independent of the feed quality or the operator skills (Neal, 2006).

On the other hand, membrane technology has been associated with various downsides which tend to restrict the growth of membrane applications in the separation industries, especially the water treatment industry (Judd, 2011). The major shortcoming that has been identified is the problem with fouling (Heijman & Vantieghem, 2007; Zhang, et al., 2006; Drews, 2010). Fouling increases the hydraulic resistance of the membrane and therefore increases operational costs (Choi, 2003; Braak, et al., 2011).

2.2.2. Membrane applications, operation and arrangements

2.2.2.1. Applications

Since the mechanism of separation is permeability, the separation process would be problem specific. Therefore, depending on the nature of the substances that are to be desired in the permeate; a variety of membranes could be used. There are five main membrane types, based on their pore size distributions, namely: particle filtration (PF), microfiltration (MF), ultrafiltration (UF), nano-filtration (NF) and reverse osmosis (RO) (Munir, 2006; Judd, 2011). Figure 2-2 displays the representation of the different separation applications for each type of membrane (Zeman & Zydney, 1996).

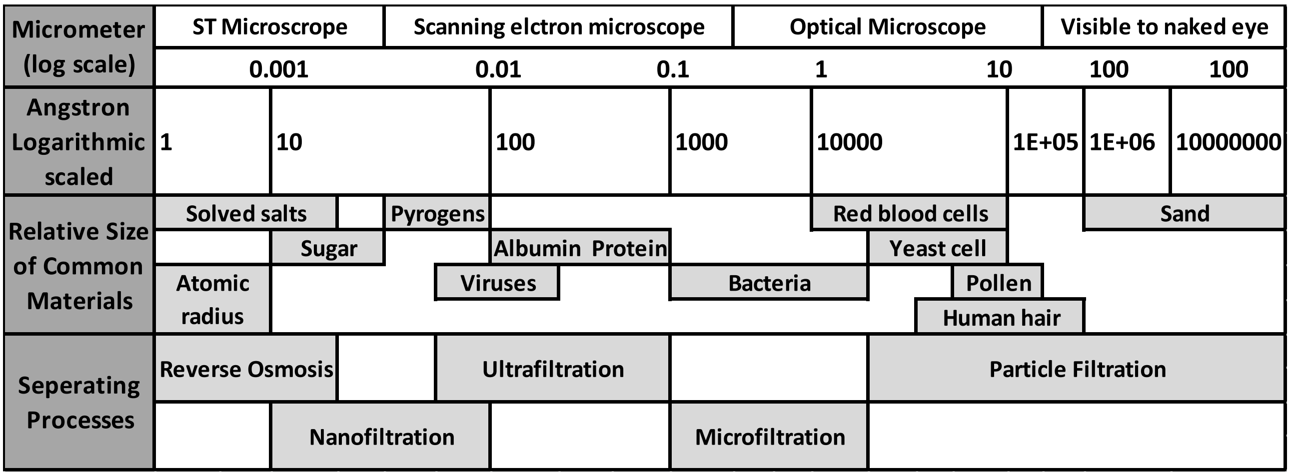


Figure 2-2: Separation applications for different membrane types (redrawn from (Zeman & Zydney, 1996; Judd, 2011))

2.2.2.2. Modes of operation

In order for the separation process to take place two types of systems can be employed; namely, submerged or pressure driven. Submerged membranes use a suction pump on the permeate side to cause a pressure difference (vacuum) which consequently allows separation; these are usually found in membrane bioreactor (MBR) applications. Pressure driven membranes are characterised by either cross-flow, dead-end or hybrid operations (a combination of cross-flow and dead-end) (Munir, 2006).

Dead-end operation, on the one hand, is unique since all the feed material is forced through the membrane, usually using gravity, or in some processes a pump is also used, as shown by Figure 2-3 (a). Dead-end operation is therefore a batch process since there is only one outlet, which is the filtrate; hence these modules need constant cleaning or replacing to guarantee efficiency (Munir, 2006; Vera, et al., 2015).

A Cross-flow operation, on the other hand, allows continuous operation by allowing the rejected material to move along in the retentate stream which is to be joined with the feed stream again, as shown by Figure 2-3 (b) (Bacchin, et al., 2005). This continuous mode of operation needs a feed pump to create turbulent conditions which will aid the permeate to filter through the membrane perpendicular to its feed flow, hence the name cross-flow filtration (Mhurchu, 2008).

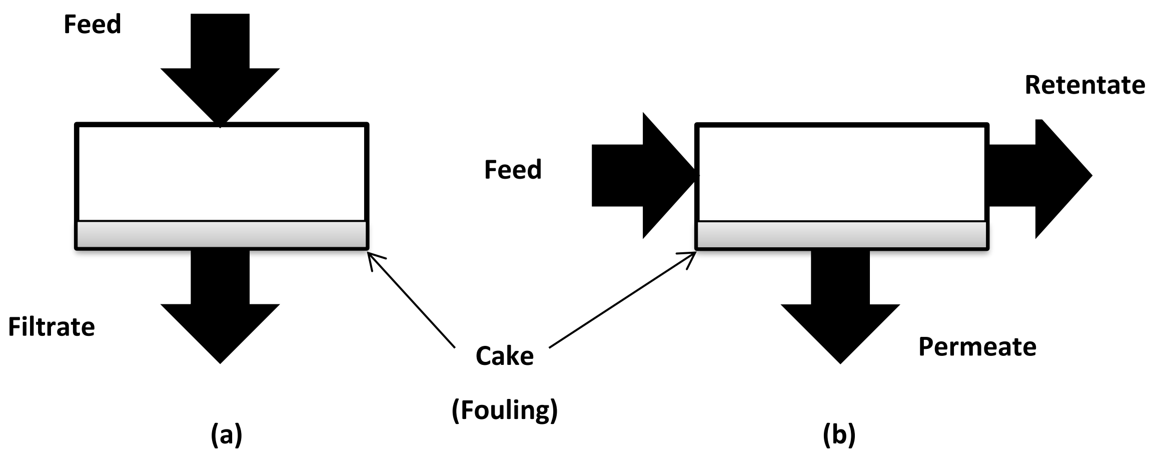


Figure 2-3: (a) Dead-End and (b) Cross-Flow Operations

The major advantage of cross-flow operations is that filter cake can be continually washed away which decreases fouling considerably, whereas dead-end operation will always form filter cake, which reduces the permeate flux with time (Munir, 2006). Figure 2-4 illustrates the difference in fouling and flux performance over time for dead-end and cross-flow operations (Mhurchu, 2008; Judd, 2011).

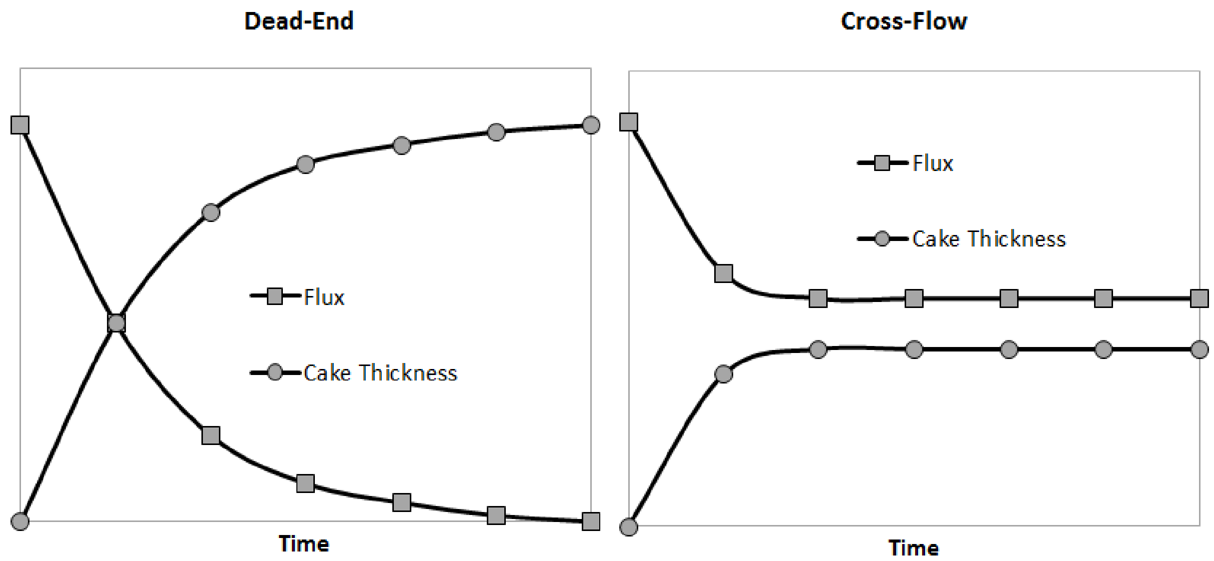


Figure 2-4: Cake thickness and flux against time for dead-end and cross-flow operations

2.2.2.3. Module arrangements

Different types of membrane module arrangements exist which are either based on planar or cylindrical geometry. These include flat-sheet modules, tubular modules, capillary modules, hollow fibres, pillow-shaped and spiral-wound modules (Judd, 2011). Module selection is primarily based on the mode of operation and each module arrangement has various practical benefits and limitations (Muric, et al., 2014).

This specific investigation makes use of flat-sheet membranes with a spacer in-between the membrane sheets. This is therefore known as outside-in filtration since the permeate is collected in the inside of the membrane module (Cele & Pillay, 2010).

2.2.2.4. Membrane materials

There are two main classes of membranes materials for the water treatment industry, viz., ceramic and polymeric. Membranes are usually fabricated to have a high surface porosity and narrow pore size distribution; in order to have as a high a throughput and selectivity as possible (Judd, 2011). The material should also have a high resistance to thermal and chemical attacks, that is, extreme temperatures, oxidant concentration and/or pH (Muric, et al., 2014).

A. Ceramic

Membrane separation using ceramic membranes has been an important instrument for several industries. These membranes are usually fabricated from inorganic materials such as alumina, zirconia, silica and titanium (Fujioka, et al., 2014). Ceramic membranes are generally made in shapes of tubular capillaries and are generally for crossflow operations (Muric, et al., 2014).

Compared to their polymeric equivalents, ceramic membranes are physically and chemically more durable, making them ideal for applications under extreme conditions (Fujioka, et al., 2014). These membranes have been more commonly used in the water treatment industry due to its inexpensive manufacturing costs (Muric, et al., 2014).

B. Polymeric

Polymeric membranes are of primary interest in separation industries since they are economically, practically beneficial and very competitive in terms of performance. Most polymeric membranes are typically hydrophobic, with the exception on polymers such as cellulose acetate, which is not used at all in commercial MBRs (Judd, 2011). Polymeric membranes could be made hydrophilic with the addition of the appropriate blend of polymers, which would be advantageous for water treatment applications (Muric, et al., 2014). The WFMF used in this study is a polymeric membrane.

2.2.2.5. Woven fabric micro-filter (WFMF)

A. Overview

The membrane which is of particular interest in this study is the woven fabric micro-filter (WFMF, which is developed by a South African company. In previous studies it was shown that this woven polyester fabric had a good potential for use as an immersed membrane which offers numerous potential advantages over the current commercial inversion-cast flat-sheet membranes (Cele & Pillay, 2010; Chollom, et al., 2016). The WFMF is depicted in Figure 2-5.

According to Thy, woven membranes are made from woven polymeric layered material. In the case of woven flat-sheet membranes, as used in this study, a supporting structure that is porous is inserted between the woven flat-sheets (Thy, 2010). The difference between woven and non-woven membranes is that the non-woven membrane have pores whereas the woven membrane surface is made from fibres that are tightly woven (Pillay, 2010).

Non-woven membranes are currently used in membrane separation technology. The advantage of the woven membrane over the non-woven membrane is that it can be cleaned easily and its separation ability is not destroyed upon drying after cleaning (Pillay, 2010). Thus further studies, such as the proposed investigation, are to be implemented to investigate the feasibility of using the woven membrane in wastewater treatment and other commercial industries.

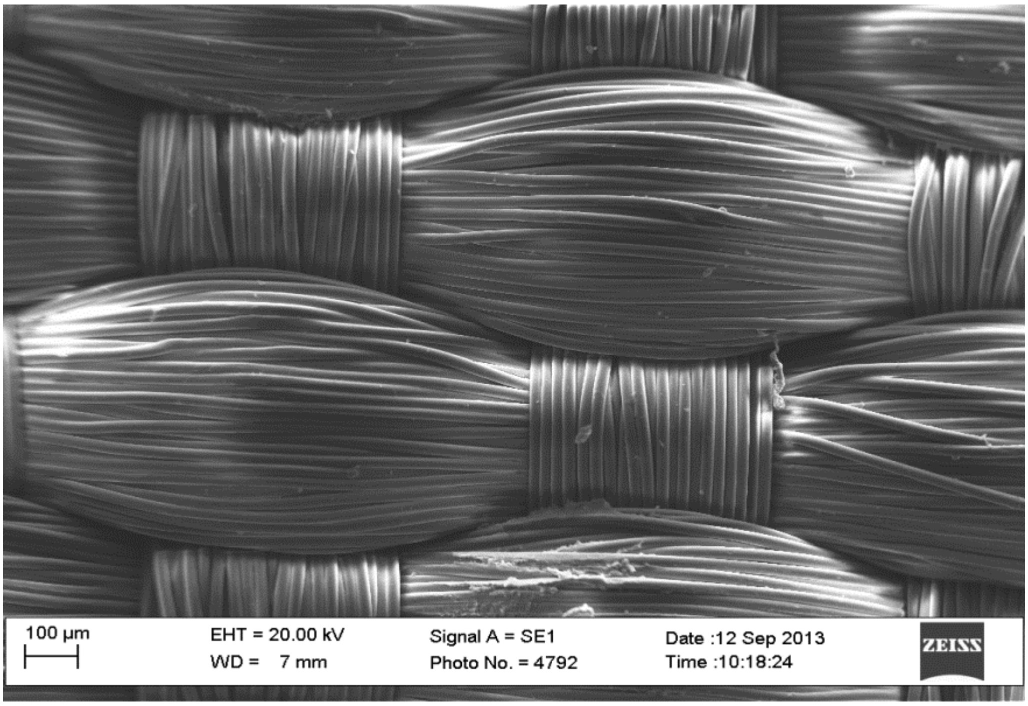


Figure 2-5: An SEM of the WFMF used in this study

B. Advantages and Disadvantages

As previously mentioned, the WFMF offers numerous advantages as summarised in Table 2-2 (Chollom, et al., 2016; Thy, 2010; Cele & Pillay, 2010).

Table 2-2: Advantages and disadvantages of the WFMF

Advantages	Disadvantages
• Can withstand most forms of physical abrasion and is therefore more robust than most commercial membranes;	• The WFMF is a relatively new membrane and is therefore an unproven technology;
• Can be left to dry completed without destroying separation ability;	• Cannot be backwashed at high flow rates such as commercial membranes;
• If mass produced these membranes could be less than a quarter of the cost of current commercial membranes making them extremely cost effective;	• The WFMF is a loose microfilter, which generally produces permeate turbidities between 0.5 and 1 NTU, whilst commercial micro-filters are tight microfilter which produce a permeate turbidity of less than 0.5 NTU.
• These membranes are locally produced and readily available;	
• These membranes are easy to clean and do not require exotic chemicals. In the worst instance, they may be cleaned using household bleach.	

2.2.3. Membrane Fouling

This subsection will give insight into membrane fouling mechanisms, types and reversibility.

2.2.3.1. Overview

As briefly stated, membrane fouling has become the leading factor behind the limited application of membranes in separation based industries. Membrane fouling refers to the continuous process which results in decreased membrane performance caused by either pore blockage, concentration polarization or by deposition on the membrane surface; this causes a decrease in the effective membrane surface area and hence the membrane performance (Field, et al., 1995; Howell, et al., 2004; Shi, et al., 2014). Filtration will always lead to an increase in the resistance to flow, regardless of the flow operation (Defrance & Jaffrin, 1999). Fouling may result in an increase in operational costs, due to an increased energy demand, additional labour for maintenance, cleaning chemical costs, and a shorter membrane life. It requires effective and efficient methods for its control and minimisation (Shi, et al., 2014). Filtration proceeds according to a number of widely recognized mechanisms, which will be discussed further in this sub-section.

2.2.3.2. Mass transport

During microfiltration, the driving force for mass transport through the membrane is the transmembrane pressure (TMP), which is the applied pressure differential across the membrane (Belfort, et al., 1994). The TMP can be created by either applying a vacuum on the permeate end or by increasing the pressure on the feed end.

The main models for fouling mechanisms, which have their origins in early filtration studies are as follows and are depicted in (Tarragona, 2005; Judd, 2011):

a) Complete blocking;
b) Standard blocking;
c) Intermediate blocking and
d) Cake filtration.

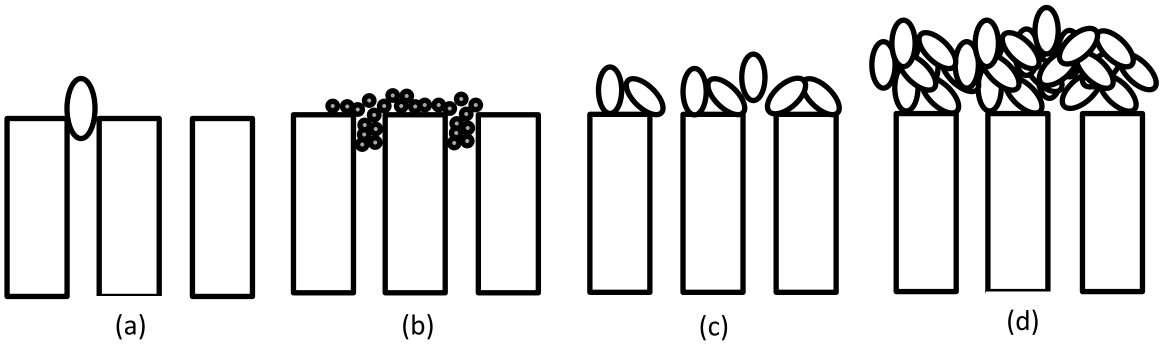


Figure 2-6: Fouling mechanisms

2.2.3.3. Fouling mechanisms

As briefly mentioned in Section 2.2.3.2, there are four main mechanisms for fouling; these mechanisms can be classified into larger groupings which will be discussed in more detail.

A. Concentration polarization

For membrane filtration process, the overall resistance at the membrane is increased by a number of factors which are as follows (Judd, 2011):

a) The concentration of rejected solute near the membrane surface;
b) The precipitation of soluble macromolecular polymeric and inorganic substances; and
c) The accumulation of retained solids on the membrane surface.

All of the above contribute to membrane fouling and (a) and (b) are promoted by concentration polarization (Judd, 2011). Concentration polarization (CP) can be defined as the accumulation of solutes or particles in a thin layer next to the membrane surface, which is a natural phenomenon of membrane filtration (Wang, et al., 2014). This CP layer can decrease the permeate flux due to an increased resistance to liquid flow. CP can be alleviated by increasing the cross-flow velocity or the aeration rate in aerated IMBRs.

B. External fouling

Deposition of macromolecules, particles and colloids on the membrane surface will lead to external fouling. The two main forms of external fouling is cake layer formation or gel layer formation. Cake layer formation occurs due to the accumulation of retained solids on the surface of the membrane, whereas gel layer formation usually results from precipitation of soluble macromolecules, inorganic solutes and colloids (Wang, et al., 2014).

C. Internal fouling

Adsorption and deposition of solutes and finer particles within the internal structure of the membrane is known as internal fouling. Pore blocking, pore narrowing and adsorption of foulants on the pore walls are examples of internal fouling (Wang, et al., 2014).

2.2.3.4. Forms of membrane fouling

Membrane fouling can be categorized into biofouling, inorganic fouling or organic fouling, depending on the foulant. Cleaning is usually based on what type of fouling has formed.

A. Biofouling

This form of fouling is formed due to deposition and growth of microorganisms on the surface of the membrane. This is also termed biofilm or biocake (Wang, et al., 2014). Biofouling is also regarded as the adsorption of organic matters produced by microorganisms. The dominant foulants in biofouling are not only biosolids but also include some organic matters (Meng, et al., 2009).

B. Organic fouling

Organic fouling is caused by the deposition of polysaccharides, proteins, humic acids and other soluble or colloidal organic substances (Wang, et al., 2014). In most instances a gel-like layer can form due to continuous organic fouling. Soluble microbial products (SMP) and extra polymeric substances (EPS) are regarded as key membrane organic foulants (Le-Clech, et al., 2006).

EPSs are key biological substances, which largely control the properties of sludge flocs, which includes; adhesion, hydrophobicity, flocculation and settling. EPSs exhibit a three dimensional, gel-like, highly hydrated matrix; where the microorganisms are embedded and immobilized. This structure is a result of complex interactions within the EPSs components where hydrogen bonds, linkage and multivalent cation bridging effects are alleged to play an important role (Lin, et al., 2014). EPSs can block pores, adhere to membrane surface, affect the cake structure and induce an osmotic effect (Judd, 2011).

C. Inorganic fouling

Inorganic fouling, or scaling, result from the chemical precipitation of inorganic crystals and/or biological precipitation of inorganic complexes (Meng, et al., 2009). The metal ions and the anions can react which leads to chemical precipitation, which occurs if the saturation concentrations are exceeded on the membrane surfaces or other specific sites. (Wang, et al., 2014)

2.2.3.5. Reversibility of membrane fouling

Depending on the extent of fouling, based on either the mechanism or the type, there are four main extents of reversibility, which is based on the attachment strength of fouling materials to the membranes or the method used to recover the initial permeability of the membranes.

A. Reversible fouling

Also termed removable or temporary fouling, reversible fouling results from the loose attachment of foulants onto the membrane surface. These can usually be easily removed by physical cleaning methods. Cake layer formation is regarded as the major factor which causes reversible fouling (Wang, et al., 2014). For long-term operation, the dominance of reversible fouling can be a result of poor sludge filterability and/or low efficiency of physical cleaning (Meng, et al., 2009).

B. Irreversible fouling

Irreversible fouling stems from the formation of a strong matrix of fouling layer with solutes during continuous filtration. Reversible fouling can be transformed into irreversible fouling over long periods of operation. Irreversible fouling cannot be removed by physical cleaning methods alone, hence why it is sometimes termed physically irreversible fouling (Wang, et al., 2014).

C. Irrecoverable fouling

Once a membrane is fouled after long-term operation, the original membrane permeability is never recovered (Wang, et al., 2014). This resistance termed irrecoverable fouling, permanent fouling or long-term irreversible fouling cannot be readily removed through chemical cleaning. This form of fouling builds up over years and ultimately determines the life-span of a membrane (Judd, 2011).

D. Residual fouling

Residual fouling cannot be removed by chemically enhanced backwash or maintenance cleaning but can be removed by recovery cleaning (Wang, et al., 2014; Judd, et al., 2003).

2.3. Membrane Bioreactors

This subsection will give a brief overview and background on membrane bioreactors (MBRs); it will then explore the different types of bioreactor configuration before shifting the main focus over to immersed membrane bioreactors (IMBRs); which is used in this study. The subsection will conclude with fouling in MBRs and operation parameters used in MBRs and IMBRs.

2.3.1. Overview

Membrane Bioreactors can be described as systems integrating biological degradation of waste product with membrane filtration used to filter the effluent (Cicek, 2003). Accordingly, membranes can be used along with pre-existing CAS treatment plants and could eventually replace the need of a secondary clarifier (Gander, et al., 2000).

MBRs provide substantial enhancement in efficacy over conventional biological treatment technologies for wastewater treatment and reuse (Le-Clech, et al., 2005). Such systems have proven reasonably effective in removing organic and inorganic contaminants as well as biological entities from wastewater (Cicek, 2003). With an average growth rate of 10.9% per annum, the MBR applications have been growing considerably faster any other advanced wastewater treatment process as well as other membrane technologies; the market has also assumed to have doubled every seven years (Drews, 2010).

On the one hand, Although MBRs provide a way of intensively biologically treating high COD wastewaters, they are limited like most other membrane systems due to fouling and MBR performance inevitably decreases with filtration time (Gander, et al., 2000; Le-Clech, et al., 2006). Fouling is therefore the major drawback and process limitation to this technology and has been under investigation to alleviate this issue since its initial conception (Le-Clech, et al., 2003).

On the other hand, the advantages that MBRs have over existing wastewater treatment techniques outweigh the disadvantages. These advantages include the following (Cicek, 2003; Le-Clech, et al., 2005; Gander, et al., 2000; Meng, et al., 2009):

a) Highly improved effluent quality free of any pathogens and bacteria;
b) Higher organic ad volumetric loadings;
c) Smaller footprint and reactor requirements;
d) Lower sludge production; and
e) Ultimately a much better control of the biological activity.

2.3.2. Membrane Bioreactor Configurations

There are two types of configurations for the membrane array; the membranes can be either inside the biological reactor or outside the reactor (Le-Clech, et al., 2005), as illustrated in Figure 2-7.

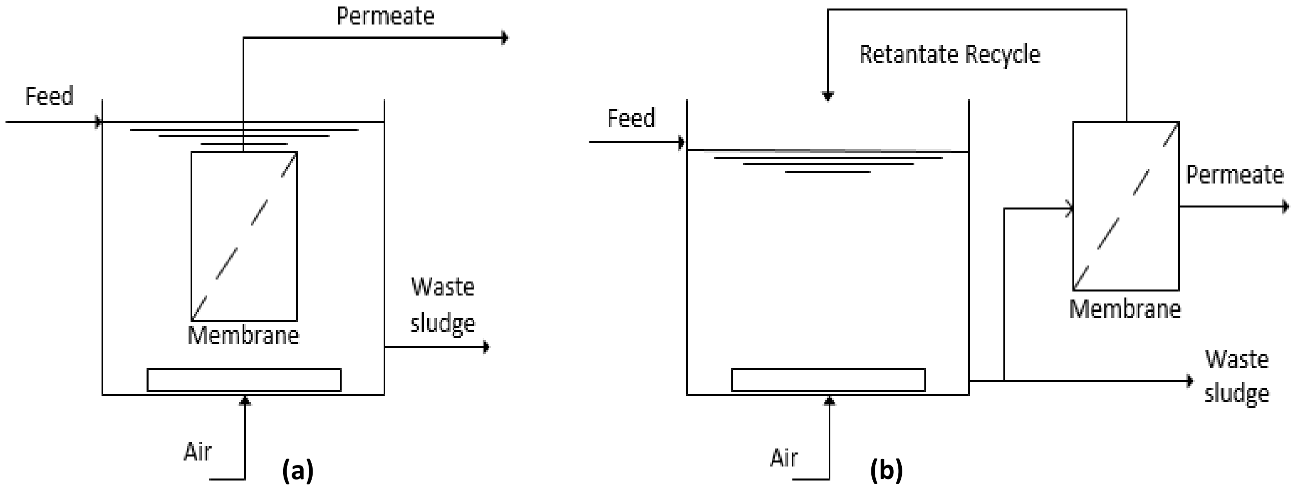


Figure 2-7: Comparison of the (a) Immersed Membrane Bioreactor and (b) Side-stream Membrane Bioreactor.

In the Side-stream configuration, a recirculation pump is used to provide a crossflow at the surface of the membrane, which reduces the deposition of suspended solids (Le-Clech, et al., 2005). It was found that the side-stream configuration uses much more energy than the submerged configuration due to the recycling stream. The high-velocity pumping of microorganisms through membranes could also harm them, which makes the side stream configuration less noteworthy (Gander, et al., 2000).

The submerged configuration, on the other hand, operates more cost effectively than the side-stream configuration with respect to energy consumption as well as cleaning requirements, since the aeration needed for biological degradation can be used to scour the surface of the membrane, ultimately reducing fouling (Gander, et al., 2000). A complete list of advantages and disadvantages are summarized in Table 2-3.

Although there appears to be many advantages of using side-stream MBR, the disadvantages tend to overshadow it. The key factor which makes the submerged configuration, also known as immersed membrane bioreactors (IMBR), more feasible, is due to the continuous air-scouring of the membrane surface which reduces operational costs in IMBR systems.

Table 2-3: Advantages and disadvantages for IMBRs and SMBRs (Modification of (Judd, 2011)).

Submerged MBR (IMBR)	Side-stream MBR (SMBR)
Advantages: • Small footprint • Complete solid removal from effluent • Less regular membrane cleaning required • Lower operational costs	**Advantages:** • Complete solid removal from effluent • Large biomass concentration capacity • Rapid start-up • Low sludge production • High loading rate capability
Disadvantages: • High aeration rates- Higher energy requirements	**Disadvantages:** • Severe membrane fouling • High pumping costs • Process complexity • High cleaning requirements • Aeration limitations

2.3.3. Immersed Membrane Bioreactors

In an IMBR, shear stress is created by aeration, which not only provides oxygen to the biomass, but also maintains the solids in suspension and scours the membrane to limit membrane fouling (Meng, et al., 2008; Le-Clech, et al., 2005; Drews, 2010).

2.3.3.1. Fouling in IMBRs

As for all membrane processes, IMBRs are ultimately restricted by the propensity of the membrane to foul, which leads to a decrease in permeability and requires regular chemical and physical cleaning. Compared to other membrane process, fouling is more complex in MBRs due to a greater number of contributing factors, these include; Membrane related factors, Biomass related factors and operating conditions (Guglielmi, et al., 2007; Singhania, et al., 2012).

Fouling in MBR processes results from the interaction among the mixed liquor and the membrane. The three main mechanisms responsible for membrane fouling are (a) pore narrowing which is attributed to adsorption of soluble and micro-colloidal substances having a size much smaller than the membrane pore size, (b) pore plugging, due to the deposition of particles having the same size as that if the membrane pores and (c) cake layer formation on the membrane’s surface (Krzeminski, et al., 2017).

Even though air-scouring is used to mitigate fouling, the aeration intensity also has an impact on the organic matter fractions and consequently influences the fouling rate. High air-scour rates can lead to a severe breakup of sludge flocs, and promote the release of colloids and solutes from the microbial flocs to the bulk solution. Even though the shear is supposed to limit biofouling, the formation of a biofouling layer is never completely avoided in practice. Ultimately, the permeate flux would eventually decrease steadily (Ding, et al., 2016; Menniti, et al., 2009).

It is also evident that increasing the aeration rate leads to an increase of the concentration of dissolved oxygen (DO). This concentration of DO would also have an effect on the properties of the suspended sludge, such as the floc structure, particle size distribution and the content of extracellular polymeric substances (EPS), and these factors would therefore also have an impact on the permeate flux (Ji & Zhou, 2006; Ding, et al., 2016).

2.3.3.2. Extracellular polymeric substances (EPS) fouling

Membrane fouling in IMBR's is a result of the interactions between the sludge suspension and the membrane unit. Membrane fouling is directly affected by sludge suspension which is composed of varied salts, organic substances, colloids, cells and sludge flocs. EPS have been found to be the key substances, which have complex interactions or relationship with the membrane foulants and fouling mechanisms in MBRs (Lin, et al., 2014).

Although there is no clear reasoning on the precise phenomenon occurring on the membrane surface during biomass filtration, many publications suggest that EPS play a major role during fouling formation (Le-Clech, et al., 2006; Gui, et al., 2002; Zhang, et al., 2006; Lin, et al., 2014). It has been postulated that it is more the carbohydrate fraction from the soluble microbial product which is responsible for severe fouling in IMBRs. EPS have therefore found to be the main source of fouling in MBRs and also have the highest fouling potential (Drews, 2010; Campo, et al., 2017).

EPS can block pores, adhere to membrane surface, affect cake structure and induce osmotic effects, showing profound effects on membrane fouling. The extracted EPS alone had a specific filtration resistance in the order of 10^{16} - 10^{17} m^{-1} kg^{-1}, which is at least 1000 times higher than the filtration resistance of sludge flocs (Lin, et al., 2014). Furthermore, EPS can be regarded as the medium of the membrane fouling process in MBRs, through which, other foulants directly or indirectly play roles in membrane fouling (Luna, et al., 2014).

Lastly, EPS possess complex properties including surface charge, hydrophobicity and adhesive properties. These properties play crucial roles in flocculation, stability, adhesion and dewatering behaviours of sludge flocs, which in turn plays a role in membrane fouling (Campo, et al., 2017).

2.3.4. Fouling Control in MBRs

There are two main approaches that can be used for fouling control, namely; Preventative and curative methods (Guglielmi, et al., 2007; Judd, 2011; Wang, et al., 2014; Pollice, et al., 2005).

2.3.4.1. Preventative measures

It may be possible to prevent fouling before its occurrence by methods such as pre-treatment of the feed streams, chemical modification to improve the anti-foulant properties of a membrane, and the optimisation of the operational conditions (Shi, et al., 2014). The preventative approach mainly employs physical measures which may be combined with the application of chemicals at lower concentrations in an attempt to maintain permeability without resorting to curative methods (Singhania, et al., 2012). Physical methods can also include pre-treatment with screening (Zahrim, et al., 2011). The two main preventative techniques include operating at sub-critical conditions, by operating below the critical flux to minimize the fouling rate (Howell, et al., 2004), and by air-scouring the membrane continuously and sufficiently (Guglielmi, et al., 2007; Van Kaam & Anne-Archard, 2006). These two will be discussed further.

A. Sub-critical operation

Sub-critical operation is made possible by operating at a permeate flux that is below the critical flux of the system. The critical flux is defined as the permeate flux at which fouling begins to occur (Judd, et al., 2003). Alternatively, the critical flux can be defined as the 'first' permeate flux for which fouling becomes predominant; being then well differentiated from limiting flux, which is the 'last' flux reachable (Bacchin, et al., 2005).

There are a few different ways to measure the critical flux. The following sub-sections summarize the different procedures that could be used.

i. Determination from flux-pressure observations

The critical flux can be obtained from flux-TMP measurements using two methods, either flux or pressure stepping (Bacchin, et al., 2005). These experiments can either be done by imposing a pressure and measuring a flux or by imposing a flux and measuring a pressure. In both cases the critical flux is where the flux-TMP relationship becomes non-linear.

For both operations it is essential that the flux is initially sub-critical and then increased to the critical flux and then beyond the critical flux (Bacchin, et al., 2005). If initially the flux is higher than the critical flux, then there irreversible fouling deposits will affect any subsequent measurements (Choi, 2003).

On the one hand, constant pressure experiments permits the determination of a steady state flux. The system is self-regulated since the fouling will decrease the flux; hence reducing the fouling rate (Bacchin, et al., 2005). This can be repeated at different pressures until the effect of fouling is noticed, as illustrated by Figure 2-8. The pressure stepping method allows for the steady sate flux to be determined; indication of fouling is then given by flux decline. Problems arise however since it is very difficult to control the TMP at a low enough value to measure the critical flux and therefore the constant flux method is preferred (Wu, et al., 1999).

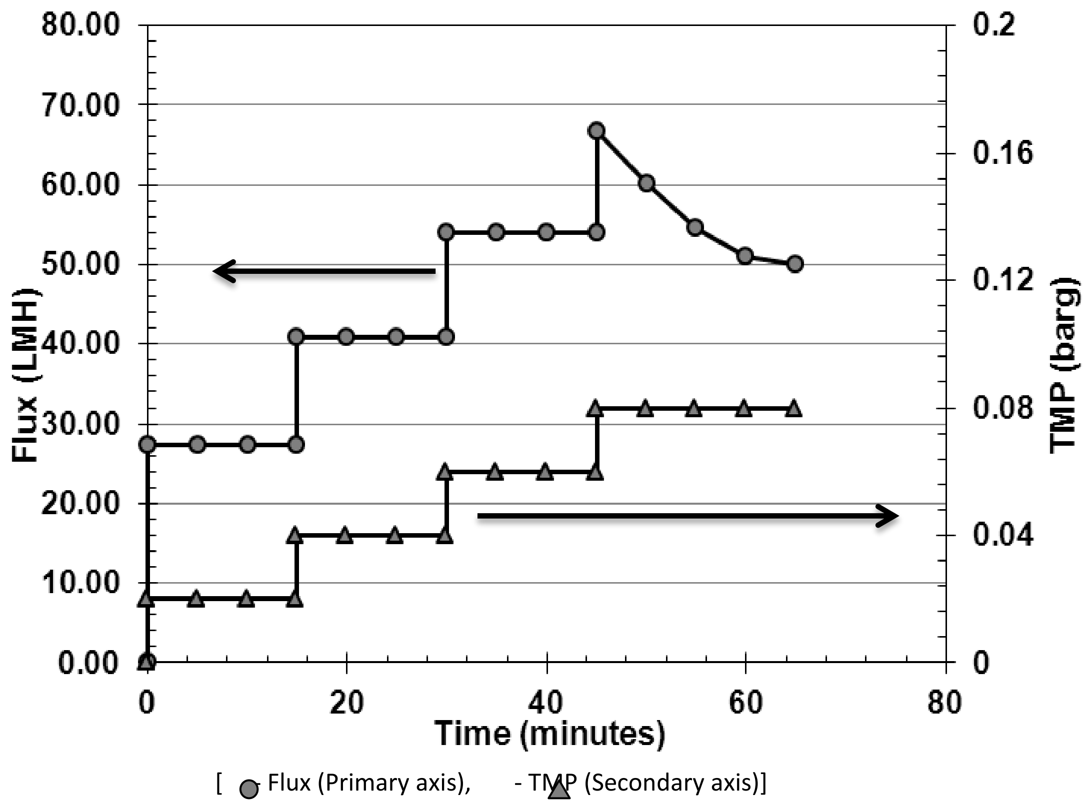


Figure 2-8: Example of the pressure stepping method (redrawn from (Tay, et al., 2007))

On the other hand, constant flux experiments, or flux stepping experiments, currently leads in the presence of evaluating the fouling phenomena (Bacchin, et al., 2005). By using this method one will be able to determine the fouling rate for a given flux, thus the variation of the resistance with time. Constant flux operations are achieved by imposing constant permeate suction through the membranes and then measuring the corresponding TMP. The TMP should remain constant at each flux used and an increase in the TMP indicates fouling and therefore the critical flux has been exceeded. The total resistance should be calculated at each flux step to inspect any deviations since there can be a flux above the critical flux at which the TMP will appear to remain uniform with time because a new steady state is quickly obtained, Figure 2-9 illustrates this method. (Bacchin, et al., 2005; Li, et al., 2013)

As mentioned, the flux stepping method is the most reliable when quantifying the fouling rate. It should also be noted that when operating above the critical flux, i.e. super-critical operation, there will be an inevitable decrease in flux which results from an increase in TMP. Therefore regardless of which approach is used, both the flux and TMP should be measured at regular intervals to ensure that the critical flux has not been exceeded.

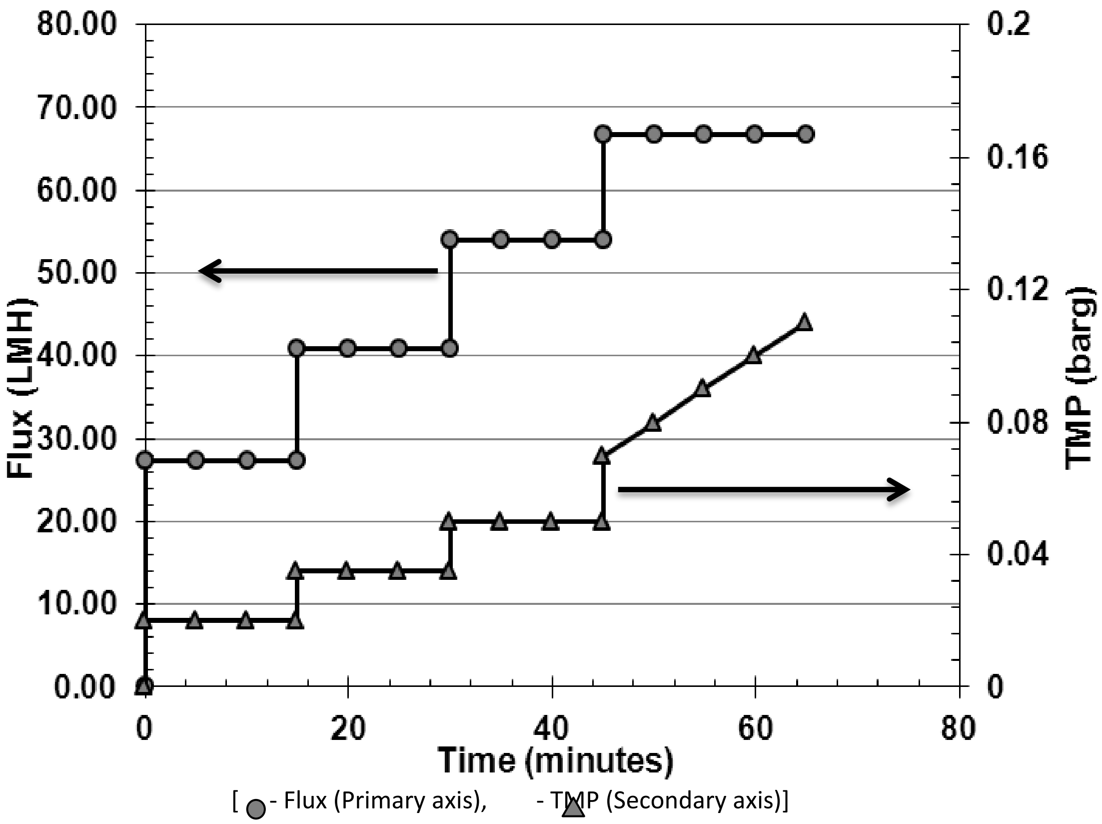


Figure 2-9: Example of the flux stepping method (redrawn from (Li, et al., 2013))

ii. Other methods for determining critical flux

There are two other methods that are generally used to measure the critical flux. These are however are not used in this experimental study.

The first method is direct observation through the membrane (DOTM); this method requires the use of a microscope to look through transparent membranes to observe if any irreversible fouling occurs. The main restrictions are that the membranes would have to be transparent and only large particles would be seen (10µm). (Bacchin, et al., 2005)

The second method called the mass balance method. This is achieved by applying a mass balance; the concentrations of particles in the outlet stream can be monitored and compared to that of the other streams. The adsorption of particles are found by measuring the concentration when there is no flux, any decrease in the particle outlet concentration not caused by adsorption is caused by irreversible fouling (Bacchin, et al., 2005).

B. Continuous air-scouring

Air-scouring or air sparging is another form of preventative fouling control measures. By promoting turbulent conditions, with induced air-scouring, at the membrane surface, concentration polarisation (CP) related fouling can be reduced (Guglielmi, et al., 2007). Turbulence can be promoted by increasing the cross-flow velocity (CFV), whereas for an IMBR, this can only be achieved by increasing the membrane aeration (Judd, et al., 2003; Van Kaam & Anne-Archard, 2006).

For IMBRs, it has been reported the one of the most effective measures to reduce membrane fouling is by increasing the aeration intensity (Ding, et al., 2016; Le-Clech, et al., 2003). The use of scouring agents in MBR systems has also been studied and is one of the most promising techniques to mitigate membrane fouling. Filtration always induces the build-up of a dynamic membrane layer on the membrane surface providing additional resistance (Aslam, et al., 2017). However, the aeration intensity also has an impact on the mixed liquor organic matter fractions and correspondingly influences the fouling rate (Ding, et al., 2016).

The effect of shear, promoted by air-scouring, is intended to increase the back transport, discouraging large particle deposition on the membrane and promoting mass transfer of liquid through the membrane and also ameliorates clogging (Judd, 2011). Unfortunately, turbulent flow regimes can only reduce the thickness of the laminar boundary layer whereas scouring agents (particles) are able to cross this layer and breakdown the membrane layer (Aslam, et al., 2017).

2.3.4.2. Curative measures

These techniques include backwashing and chemical cleaning; they are only employed after the membrane has been fouled. Membrane cleaning is usually classified into in-situ and ex-situ cleaning. It is then further categorized into physical, chemical and biological cleaning according to fouling removal mechanisms used. (Wang, et al., 2014; Drews, 2010)

A. In-situ and ex-situ cleaning

This type of cleaning measure basically refers to whether the membrane is to be cleaned inside the bioreactor, which is known as in-situ cleaning; or removed from the bioreactor, which is known as ex-situ cleaning. In general in-situ cleaning is preferred for MBRs and in-situ cleaning can and is usually performed more frequently. In general in-situ cleaning is performed every 10 minutes whereas ex-situ is performed once every 6 months; however this all depends on the membrane fouling conditions. (Wang, et al., 2014)

B. Physical, chemical and biological cleaning

This is based on fouling removal mechanisms and can be generally categorized into four types. These methods can be used separately, but in practice they are usually combined for a greater effect.

i. Physical cleaning

This ranges from scrubbing the membrane with a coarse brush to dislodge particles (ex-situ), to periodically back flushing the membrane the membrane in-situ. Back flushing is achieved by reversing the flow, or relaxation, which is simply ceasing permeation whilst continuing to scour the membrane (Judd, 2011). In general, physical cleaning is used to remove reversible fouling and is less effective than chemical cleaning.

ii. Chemical cleaning

Unlike physical cleaning, chemical cleaning is applied to remove irreversible fouling with the aid of chemical reagents. These include bases (caustic soda), acids (hydrochloric, sulfuric, oxalic and citric) and oxidants (hypochlorite and hydrogen peroxide) (Drews, 2010). Chemical cleaning can be applied for in-situ maintenance cleaning or in-situ and ex-situ intensive recovery cleaning. Recovery cleaning is usually done ex-situ since this requires the membranes to be soaked in high concentrations of chemical reagents (Wang, et al., 2014).

iii. Physio-chemical cleaning

It should be noted that chemical cleaning can also be used in conjunction with physical cleaning. This type of cleaning is known as physio-chemical cleaning, which refers to physical cleaning with the addition of chemical agents to enhance effectiveness (Wang, et al., 2014). The classic physio-chemical cleaning method used in MBRs is by adding a low concentration of chemical cleaning agent to the backflush water, also known as chemically enhanced backwash (CEB) (Judd, 2011). CEB is generally referred to as maintenance cleaning.

iv. Biological cleaning

Biological or biochemical fouling broadly refers to the use of cleaning mixtures which contain bioactive agents to remove membrane foulants. These are used to achieve biochemical cleaning of membrane, I.e., enzymatic approach, energy uncoupling, and quorum quenching (Wang, et al., 2014).

2.3.5. Operational parameters

The key operational parameters which define any membrane process, especially MBRs are listed in the following subcategories.

2.3.5.1. Transmembrane pressure (TMP)

The suction pressure on the permeate outlet, better known as the transmembrane pressure (TMP), is arguably the most important parameter since it is usually gives the first indication of fouling. The TMP can be calculated using Equation 2-1 (Cimbala & Cengel, 2004).

Equation 2-1

$$TMP = P_{Vac} = P_{Atm} - P_{Abs}$$

Where P_{Vac} is the vacuum pressure, P_{Atm} is the atmospheric pressure and P_{Abs} is the absolute pressure.

2.3.5.2. Permeate flux

Of particular interest is the determination of the permeate flux. The permeate flux through a porous membrane is often described as the applied transmembrane pressure driving force, divided by the resistance to mass transfer and the permeate viscosity (Miller, et al., 2014). This flux can also be defined as the volumetric flow rate across the membrane surface, per unit area of the membrane surface. The preferred units for flux are l/m^2 written as LMH (Espinasse, et al., 2002).

Equation 2-2

$$J = \frac{\dot{V}}{A_{surface}} = \frac{TMP}{\mu(R_m + R_c)}$$

2.3.5.3. Membrane characterisation

When clean (deionized) water is pumped across the membrane walls, the only resistance experienced is that of the clean un-fouled membrane. This technique will provide us with clean membrane resistance for a certain flux and TMP. This flux is known as the pure water flux which increases linearly with the TMP needed to impose it; plotting this would result in a pure water flux curve (Arndt, et al., 2016).

Before any experiments can be done on the membrane, the pure water flux and the clean membrane resistance should be calculated, as provided by Equation 4-1 and Equation 2-4 respectively. The osmotic pressure,$\Delta\pi$, is zero for pure solutions. (Merdaw, 2010)

Equation 2-3

$$J_{wd} = A_{wd}(TMP - \Delta\pi)$$

Equation 2-4

$$R_m = \frac{1}{\mu \cdot A_{wd}} = \frac{TMP}{J_{wd} \cdot \mu}$$

2.3.5.4. Air-scour rate

A previously mentioned, air-scouring the membrane is used to keep the membrane surface clear of CP and should therefore promote back transport as well as reducing flux decline. It has been well documented that one of the most effective methods to reduce fouling is by increasing the air-scour intensity (Ding, et al., 2016; Le-Clech, et al., 2003; Maqbool, et al., 2014).

It is documented that the fouling rate decreases exponentially with increasing air-scour rate and that the effects of scouring aeration intensity and permeate flux on the fouling rates were also found to be independent of one another (Ding, et al., 2016; Al-Malack, 2007; Van Kaam & Anne-Archard, 2006). Furthermore, increasing the coarse bubble aeration intensity increased permeability at a given MLSS concentration. Lastly, an optimal air-scour rate was reported and aeration intensities smaller or larger than this optimal value had a negative impact on membrane permeability. Large air-scour rates lead to severe breakup of sludge flocs, and promote the release of colloids and solutes from the microbial flocs to the bulk solution (Ding, et al., 2016).

The rate at which the membranes are to be scoured is always of interest since this will determine how feasible the aeration operation is (Al-Malack, 2007). The units that are given to quantify is usually given as L/min or L/minute/module as measured by a rotameter.

2.3.5.5. Sludge and hydraulic retention time

For slow rates of microbial growth, relatively long hydraulic retention times (HRTs) are required. HRT, θ, is quantified in hours and is defined as the specific time period spent in a given control volume, usually expressed in terms of reacting a certain biomass concentration (Michelcic & Zimmerman, 2010). This simple equation is shown by Equation 2-5.

Equation 2-5

$$\theta = \frac{V_{reactor}}{\dot{V}_{Througput}}$$

Alternative methods to increasing the HRT, other than increasing the reactor volume, include retaining the biomass by allowing them to settle out then to be recycled. MBRs permit longer sludge residence times (SRTs) without requiring the HRT to be increased (Judd, 2011). The SRT or the sludge age refers to the time (days) that the biomass resides in the reactor.

2.3.5.6. Suspended and dissolved solids

The biological reactor sustains a wide variety of microorganisms comprising of bacteria, fungi, rotifers and protozoa. This mixture of liquids, waste solids and microorganisms is called the mixed liquor. A measurement of total suspended solids (TSS) obtained from the Bioreactor is termed the mixed liquor suspended solids, expressed in mg/l. Other solid concentration measurements include, total dissolved solids (TDS) and volatile suspended solids (VSS). Figure 2-10 illustrates the basic technique that is followed to quantify the solid composition of the wastewater.

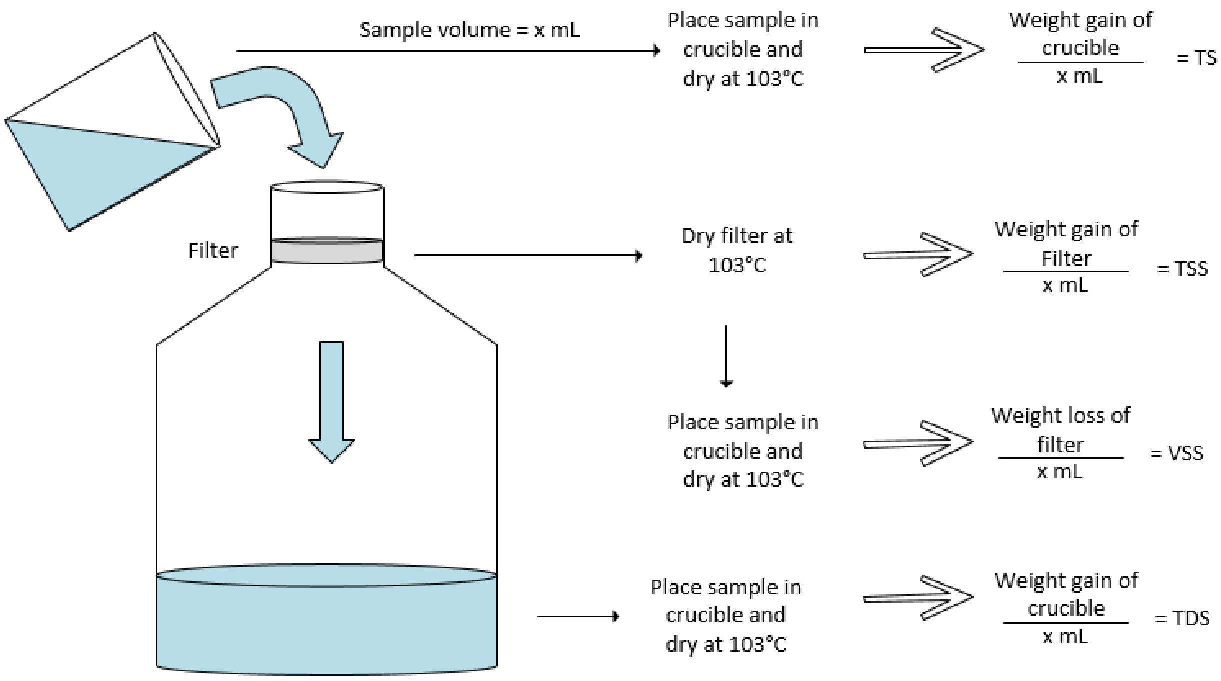


Figure 2-10: Quantification of solids in wastewater

2.3.5.7. Turbidity

Turbidity is mainly the measure of ''cloudiness'' of a sample. It therefore quantifies the clarity of the water and is commonly expressed as Nephlemetric turbidity units (NTU). Turbidity is measured using a Nephelometer (turbidity meter). Suspended solids and colloidal matter, such as clay, silt and microscopic organisms cause turbidity.

Turbidity needs to be constantly measured not only to see if the membrane is operating properly, but also to get some idea of the permeate turbidity trend with time.

2.3.5.8. Overall Organic Compounds

Organics can be quantified by using various techniques. It can be measured by the oxygen required to oxidise the organics, such as: biological oxygen demand (BOD), which is the amount of oxygen required to biologically degrade the biodegradable organics and chemical oxygen demand (COD), which is the oxygen required to chemically degrade all organics. It can also be quantified using volatilisation, which would indicate all species of carbon (degradable or not), however this would require fairly expensive equipment. Lastly, it can also be measured by absorbance in ultraviolet spectrum (Michelcic & Zimmerman, 2010). The following procedure should be followed to determine the COD, using a spectrophotometer, a thermal reactor and COD test kits.

i. Take samples from the IMBR feed as well as the permeate.
ii. All biological flocculants have to be removed prior to COD analysis, to avoid any interference.
iii. A 3 ml sample of both the permeate and the feed is then to be collected in separate pipettes and then added to a sample of COD reagent and then shaken vigorously.
iv. Both samples then need to be put in a thermo-reactor for 2 hours at 148 °C.
v. After cooling the mixtures, they can then be inserted into a spectrophotometer to record the COD.

2.3.5.9. Dissolved oxygen

Dissolved oxygen (DO) is a measure of the amount of oxygen dissolved in an aqueous solution. Sufficient oxygen is required since majority of the BOD is degraded in the presence of oxygen. In practice, dissolved-oxygen concentrations in the biological tank are kept between 1.5 and 4 mg/L, with 2 mg/L being a common choice (Michelcic & Zimmerman, 2010).

Any DO level greater than 4 mg/L do not contribute to improving the operation, but could increase the operational costs due to excessive aeration. Low oxygen levels on the other hand can lead to sludge bulking, which is basically the abundance of filamentous organisms with poor settling characteristics. The DO can be simply measured using a Dissolved Oxygen Meter. Aeration rates from literature, as well as pre-screening experiments will be used to determine operating range of aeration rates which will be needed to keep the DO at approximately 2 mg/L (Judd, 2011).

2.4. Energy considerations in an IMBR

2.4.1. Overview

It has been well documented that the most energy intensive aspect of IMBRs is the pumping and the air-scour requirements. The average value of energy consumption per unit volume of permeate produced was between 0.2 and 0.4 kWh/m^3 with respective consumptions of 80-90% for membrane scouring and 10-20% for pumping for permeate extraction (Braak, et al., 2011). The overall energy requirements of the WF-IMBR can therefore be reduced by reducing the energy required for air-scouring and permeate pumping requirements.

2.4.2. Pumping requirements

A pump transfer's mechanical energy to a fluid by raising its pressure, therefore the pressure of a flowing fluid is also associated with its mechanical energy. In fact, the pressure unit PA is equivalent to N/m^2 = N.m/m^3 = J/m^3, which is the energy per unit volume. Therefore permeate pumping requirements relates directly to the pressure drop the pump needs to overcome, which is represented by Equations 2-6 to 2-10, derived from the conservation of energy principle (Cimbala & Cengel, 2004).

Equation 2-6
$$\dot{E}_{in} - \dot{E}_{out} = \frac{dE_{CV}}{dt}$$

Where $\dot{E}_{in}$ and $\dot{E}_{out}$ are the total rates of energy into and out of the control volume, respectively, and $\frac{dE_{CV}}{dt}$ is the rate of change of energy within the control volume boundaries. Energy of a flowing fluid can therefore be expressed as follows:

Equation 2-7
$$e_{mech} = \frac{P}{\rho} + \frac{V^2}{2} + gz$$

Where P/ρ is the flow energy,$V^2/2$ is the kinetic energy and gz is the potential energy of the fluid, all per unit mass. The mechanical energy change of a fluid is therefore represented as follows:

Equation 2-8
$$\Delta e_{mech} = \frac{P_2 - P_1}{\rho} + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1)$$

Equation 2-9
$$\Delta e_{mech} = \frac{\Delta P}{\rho} + \frac{\Delta V^2}{2} + g\Delta z$$

Assuming the velocity and elevation remain constant, the mechanical energy can be represented as follows:

Equation 2-10
$$\Delta e_{mech} = \frac{\Delta P}{\rho}$$

The pressure drop along a typical IMBR system comprises of a series of pressure drops across various components and orifices along the permeate route. The main contributors to the pressure drop in the case of the WF-IMBR is the WFMF membrane resistance, which cannot be altered, and the module resistance; which consists of the flow properties inside the module as well as through the outlets of the modules into the manifold and then to the pump. The pumping requirements can therefore be greatly reduced by reducing the pressure drop across the WFMF module, which is what will be investigated to satisfy the first objective of this study.

2.4.3. Air-scour requirements

A study about energetic expense in MBRs outlined the importance of air-scouring in IMBRs. It was found that the costs of aeration in submerged systems were found to represent more than 90% of the total costs (Braak, et al., 2011). Due to aeration being an essential tool in fouling control, it cannot be removed but should be optimized in terms of minimizing the air-scour rate or duration required. Energy consumption in IMBRs is therefore considered to be three times higher than in CAS systems (Gabarrón, et al., 2014).

The aeration flow is a basic parameter for the management of membrane aeration. Since it has a noticeable influence on the fouling, it needs to be reduced to limit running costs (Van Kaam & Anne-Archard, 2006). Studies have shown that there exists a threshold value for airflow, beyond which no improvement in filtration can be reached. Operating beyond this aeration rate, results in unnecessary running costs. The existence of this threshold value or plateau can be linked to the fact that the rising velocity of bubbles is not proportional to air flowrate (Braak, et al., 2011). This threshold value is an important factor in IMBRs and can be measured through experimental analysis.

Strategies to optimise the air-scour rates for membrane cleaning remain a challenge in terms of energy consumption (Judd, 2011). Energy-savings solutions include the utilization of membrane aeration for biological purposes, implementation of simulation modelling and automatic control for biological aeration optimization, improving configuration of the membrane module, aeration system, and tank geometry, as well as aeration patterns (e.g. pulsed aeration or intermittent aeration) to improve efficiency of membrane air-scouring (Gabarrón, et al., 2014).

Furthermore, an IMBR system could benefit vastly from using intermittent air-scouring to periodically remove reversible fouling at regular intervals, which could have a tremendous effect on the energy requirements. This study will investigate the viability of using this kind of operating regime to satisfy the second objective of this study.

CHAPTER 3. WF-IMBR PILOT PLANT DESIGN

This chapter will mainly aim to address the first objective of this study i.e. to improve the mechanical design of the WFMF module. Firstly the design process of the WF-IMBR will be outlined in Section 3.1, followed by the P&IDs and equipment schedules in Sections 3.2. Section 3.3 will give a brief overview of Zandvliet WWTW and the process description. Section 3.4 will then address the experimental protocol used and then to conclude this chapter, the modification of the WFMF will be addressed in Section 3.5.

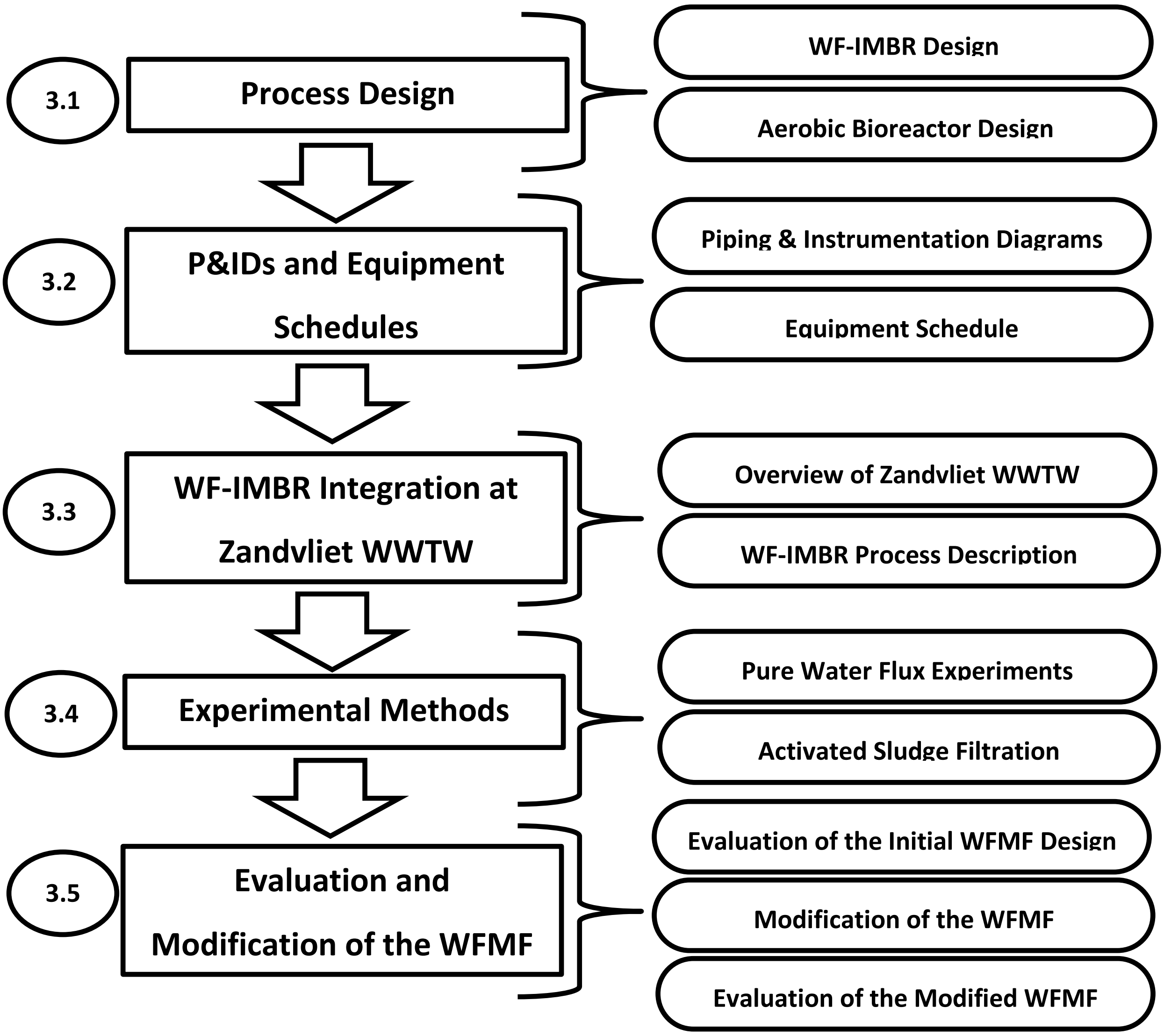


Figure 3-1: Flow chart of Chapter 3

3.1. WF-IMBR Process Design

To adequately design the WF-IMBR system, the membrane tanks as well as the biological reactor needed to be designed appropriately. For the scope of this project, only the aerobic bioreactor and the IMBR were investigated and no attention was paid to the anaerobic or anoxic zones which could further aid the biological degradation process.

3.1.1. Immersed Membrane Bioreactor Design

The two main parameters that either define or restrict the design of the WF-IMBR system is the desired production capacity as well as the effective surface area of the membrane pack available. The design criterion stipulates the development of a WF-IMBR system for a 30 PE unit as well as the design to be based on previous studies on the WF-IMBR.

3.1.1.1. WFMF membrane pack design

The existing module consisted of a rectangular PVC frame onto which the membrane was glued on both sides. Each module had been fitted with an internal mesh which helps keep the two membranes apart, and also allows for fluid flow inside the module. Permeate was removed from the module through 2mm outlet nozzles and a central PVC manifold, as shown in Figure 3-2.

Figure 3-2: Initial WFMF membrane pack consisting out of 19 modules

The initial WFMF membrane module design used in previous studies consisted out of 19 modules, each with an effective membrane length of 45.5 cm and the effective membrane width of 29.5 cm.

Therefore each membrane has an effective surface area of 0.27 m^2 and thus the total surface area for the 19 modules is 5.1 m^2, as summarised in Table 3.1.

Table 3-1: Dimensions of a single module

Total Length (cm)	$L_{m, total}$	50.5
Total Width (cm)	$W_{m, total}$	34.5
Effective Length (cm)	$L_{m, eff}$	45.5
Effective Width (cm)	$W_{m, eff}$	29.5
Effective surface area (m^2)	$A_{m, eff}$	0.27

The spacing between the modules has a major influence on flow patterns within the IMBR as well as the effectiveness of air-scouring. The spacing used between the 19 modules was approximately 5 mm, which allows adequate space for bubble formation and fluid flow. The membrane pack was constructed by drilling four holes into the PVC frame of each modules and then connecting them by means of a threaded rod, kept apart with nuts.

3.1.1.2. WF-IMBR production capacity

The minimum amount of water that should be available per person in terms of government policy is 25 l/person/day; however in developed areas moderate to high water usage would range between 80 and 145 l/person/day, with high usage ranging between 130 to 280 l/person/day (CSIR Building and Construction Technology, 2005). A basis of 100 l/person/day will be used, since this would be an adequate amount of water usage for decentralized areas, which is the key area of focus for this investigation.

The proposed design for the WF-IMBR system is to have a process where two IMBRs are used in parallel. In terms of the design, it would be more beneficial to design the IMBRs to be able to serve 30 people each. This would allow for the design criteria to be fulfilled when only operating one train, as well as ensuring that the plant can run continuously even when maintenance or cleaning needs to be done on either of the IMBRs. Furthermore, designing a pilot plant rig with two trains would allow for future expansion as well as allow the possibility of performing two experiments simultaneously.

In order to provide sufficient sanitation for at least 30 people for an entire day, a permeate flow rate of 125 l/h would be required and hence a minimum flux of at least 24.5 LMH should be imposed, which is in line with most reported literature as well as what was recorded at Merebank. Due to the fact that one IMBR train satisfies the design criteria, emphasis will only be put on one IMBR train for the remainder of this study. Table 3-2 tabulates the persons equivalent for operating fluxes ranging from 23 LMH to 30 LMH.

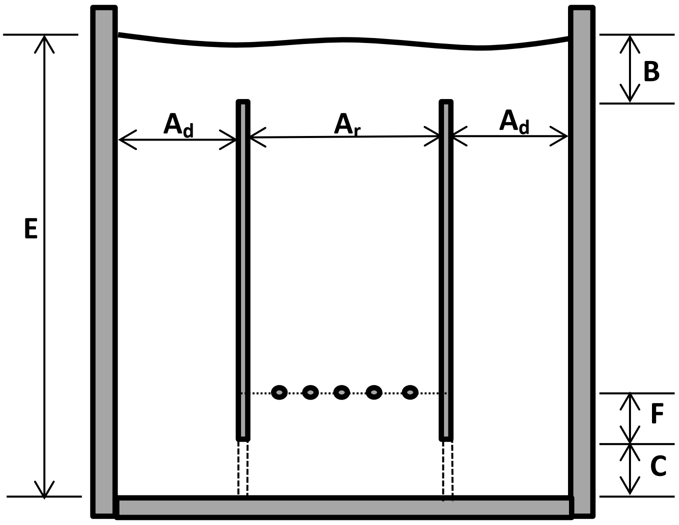
Table 3-2: Persons equivalent for various permeate fluxes for a single membrane pack

Permeate flux (LMH)	23	24	25	26	27	28	29	30
Permeate flow rate (l/h)	117.3	122.4	127.5	132.6	137.7	142.8	147.9	153.0
Persons equivalent (PE)	28.2	29.4	30.6	31.8	33.1	34.3	35.5	36.7

3.1.1.3. Membrane stand design

The membrane stand was designed to have a duel function; it was not only responsible to house the membrane pack firmly in the centre of the MBR tank but it was also fitted with an air diffuser at the bottom of the stand. The air diffuser geometry consisted out of five 20 mm PVC pipes perforated with 2mm diameter holes spanning the entire length of the membrane pack connected to a manifold situated on the outside of the membrane pack fixed with a hose adaptor.

The main function of the air diffuser was to allow for adequate air-scouring of the outer surface of the membranes; in order to prevent fouling and sludge consolidation and also to ensure that the biomass remained suspended. Various membrane pack geometries exist for satisfactory air-scouring; therefore an optimal geometry based on previous studies was employed before entering experimental work. The design of the membrane stand is crucial in determining whether unhindered free circulation of biomass will occur through and around the pack, or whether there would be restrictions leading to poor circulation. The important geometry aspects of the membrane stand are depicted in Figure 3-3 (Hamann, 2010):



A_d	Area of down-comer area
A_r	Area of the riser section
B	Clearance between the top of the membrane stack and the liquid level
C	Bottom entry clearance for fluid recirculation
F	Position of air diffuser relative to the top of the bottom entry clearance
E	Total liquor head in the vessel

Figure 3-3: Important dimensions in membrane stand design

The effect that each of the parameters listed in Figure 3-3 has on stable operation has been studied and reported in WRC Project K5/1369. The higher the A_d/A_r ratio, the faster the velocity profile will be. This was found to be the most significant variable throughout the IMBR hydrodynamic investigation and large A_d/A_r ratios are to be favoured since this also allows for a more uniform cross-flow through the membrane pack. It was found that lower A_d/A_r ratios caused cake layer formation in the centre of the membrane pack (Hamann, 2010). Furthermore it was also found that the diffuser should be located just above the bottom entry. With the help of these guidelines a membrane stand and a suitably sized MBR tank could be designed and fabricated. The membrane pack fabricated is displayed in Figure 3-4.

Figure 3-4: IMBR membrane stand

3.1.1.4. *Air-scour intensities*

The optimum air-scour rates determined in previous studies on the WF-IMBR (Cele & Pillay, 2010) were found to be approximately 10L/min/module. Thus, for a membrane pack of 19 modules each, the overall air flow rate required would be approximately 190 L/min per pack. The coarse bubble membrane aeration also contributes to the biological degradation, therefore the biological process aeration can be reduced (Judd, 2011). Operating at lower aeration intensities are found to improve air-scouring efficiency (Hamann, 2010), hence the instrumentation panel was designed in such a way that the air-scour rate can be altered and recorded to be able to investigate a rage of air-scour rates.

3.1.1.5. *IMBR vessel design*

The membrane tank itself does not need to be as large as biological reactor; however it should have adequate space to accommodate a membrane pack and allow them to be removed and inserted with ease. A 500 L PVC tank satisfies these specifications whilst also ensuring that the down-comer area is large enough for uniform air-scouring, as depicted in Figure 3-5.

Figure 3-5: IMBR tank at Zandvliet WWTW

3.1.2. Aerobic Bioreactor Design

The permeate throughput would be approximately 125 l/h when operating at 24.5 LMH; therefore the inlet flow rate should be more or less the same to ensure there is no overall accumulation in the system. The hydraulic retention time (HRT) needs to be defined in order to determine the size of the aerobic bioreactor. A review paper compiled by Michelle Gander (Gander, et al., 2000), shows that the organic removal is usually greater than 95% even with short HRT's of 4 -7.5 h. The Kubota full-scale MBR plant operates optimally at an HRT of 6 hours (Judd, 2011). Various articles define the optimal HRT to be different depending on operational conditions. An HRT of 6 hours was used for a single MBR train; however the vessel was sized large enough to reach HRT's of 12 hours in case both trains were to be operated simultaneously. Therefore a 1500 L tank was used as the aerobic bioreactor tank with ample flexibility at an estimated throughput of 250 l/h and an approximate total volume of 2500 L when both WF-IMBRs are in operation.

The main aim of an aerobic reactor is to provide an environment for optimal oxygen transfer to the biomass. This can be achieved by the use of a fine bubble disc diffuser situated at the bottom of vessel. The practical range for adding oxygen to the aerobic tank is generally between 100 and 150 mg O_2 /(l.h) (Judd, 2011). The primary goal for optimal oxygen diffusion would be to maintain the dissolved oxygen between 2 mg/L and 3 mg/L.

3.2. WF-IMBR P&ID's and Equipment Lists

3.2.1. Piping and instrumentation diagrams

Figure 3-6 is a P&ID of the proposed set-up which gives a general idea of what instrumentation and equipment was used, Figure 3-7 on the other hand, is also a P&ID however it includes the control panel, which is necessary to mount the instrumentation and also shows what other equipment will be placed inside the container which will primarily serve to house and protect valuable process units.

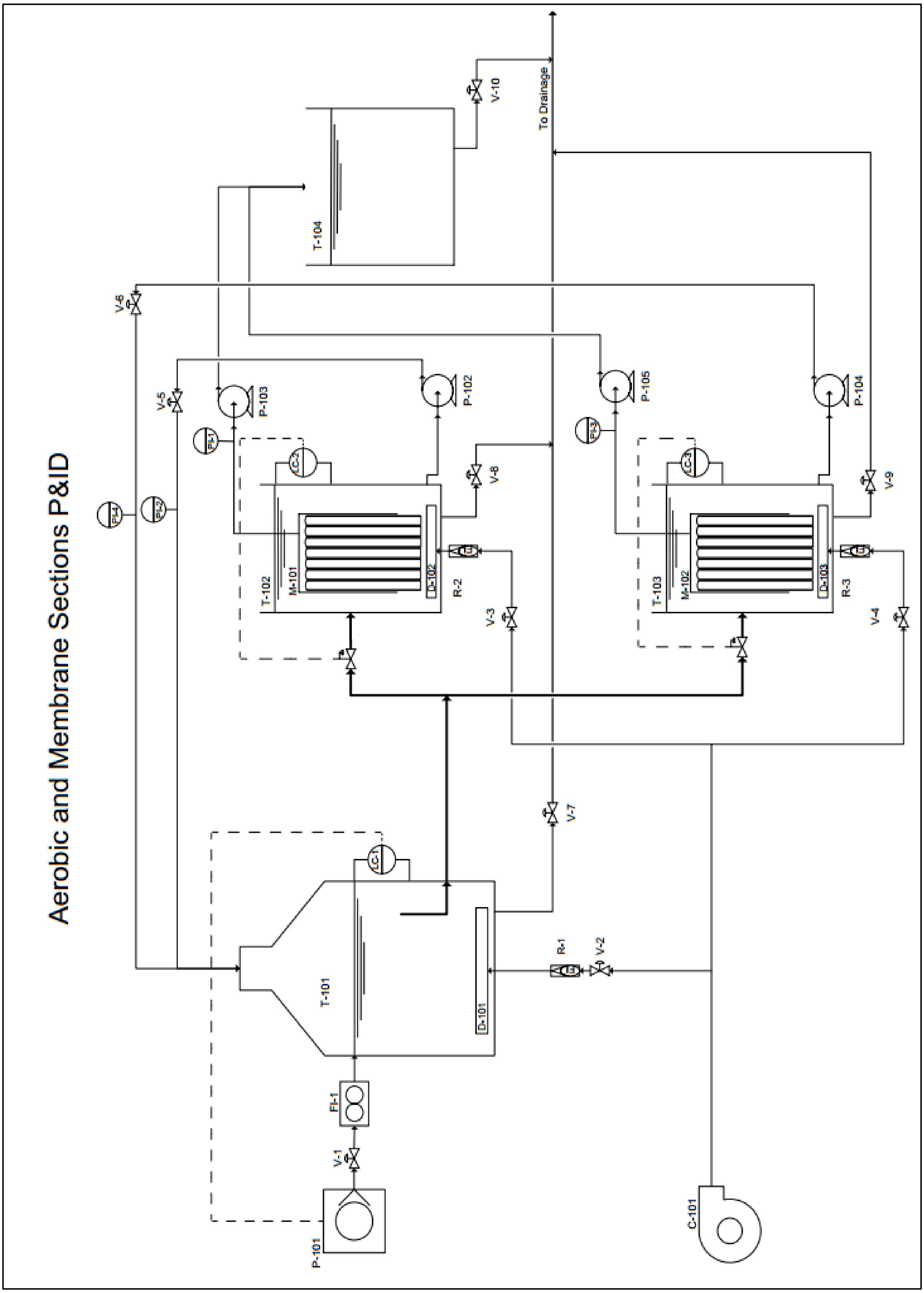


Figure 3-6: Set –up P&ID for two WF-IMBR trains

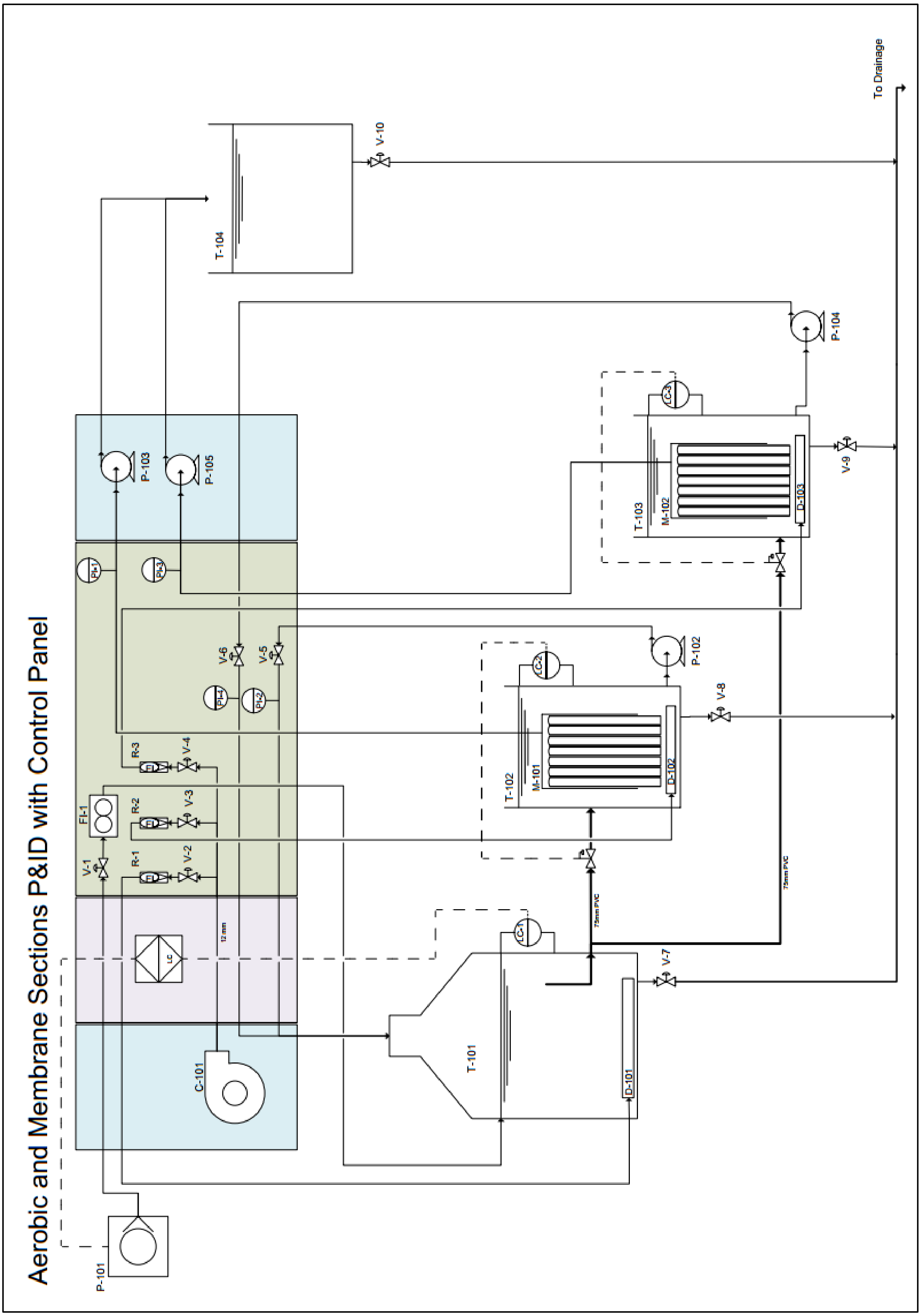


Figure 3-7: Set-up P&ID including container & control panel for two WF-IMBR trains

3.2.2. Equipment schedules

Table 3-3 summarises all the equipment that was required to construct the WF-IMBR system and Table 3-4 summarises the instrumentation and valves that was be installed on the WF-IMBR rig.

Table 3-3: Equipment list

Tag	Item	Function
T-101	Aerobic Tank	Operates as a feed tank as well as aerobic bioreactor
T-102	IMBR Tank 1	Tank in which the membrane pack is submerged: 250 l
T-103	IMBR Tank 2	Tank in which the membrane pack is submerged: 250 l
T-104	Permeate Tank	Tank for storage of the permeate: 150 l
P- 101	Submersible Pump	The feed pump for the process: 70 l/min with a bypass for pressure relief.
P-102	Centrifugal Pump	The recirculation pump needed to recycle the biomass from T-102 to T-101.
P-103	Peristaltic pump	Variable speed permeate pump, used for permeate suction as well as to maintain an operating flux.
P-104	Centrifugal Pump	The recirculation pump needed to recycle the biomass from T-103 to T-101.
P-105	Peristaltic pump	Variable speed permeate pump, used for permeate suction as well as to maintain an operating flux.
C-101	Primary Blower	An air blower used to aerate the biological reactor as well as scour the membrane surface.
C-102	Secondary Blower	A secondary blower to assist the primary blower.
D-101	Diffuser	Round disc diffuser needed to form smaller bubbles optimal for biological aeration.
D-102	Diffuser	Three rod diffusers perforated with 15 2mm diameter holes each. Used to allow the correct velocity profile for optimal membrane scouring
D-103	Diffuser	Three rod diffusers perforated with 15 2mm diameter holes each. Used to allow the correct velocity profile for optimal membrane scouring
M-101	Membrane pack	19 woven fibre flat-sheet membranes, spaced 5 mm apart combining to an overall effective surface area of 5.1 m2 installed in a membrane casing.
M-102	Membrane pack	20 woven fibre flat-sheet membranes, spaced 5 mm apart combining to an overall effective surface area of 5.1 m2 installed in a membrane casing.

Table 3-4: Valves and instrumentation list

Tag	Item	Function
FI-1	Cumulative Flow meter	Needed to measure the cumulative intake of wastewater into the WF-IMBR system through P-101.
LC-1	Level control	A mercury ball level controller attached to T-101 to ensure that it doesn't run dry or over flow, by sending an Off/On signal to P-101.
LC-2/3	Float control valve	A ball float submerged into T-102/T-103 linked to an inlet valve, which maintains the level in the tank.
LC-3	Float control valve	A ball float submerged into T-103 linked to an inlet valve, which maintains the level in the tank.
PI-1	Pressure gauge	A negative gauge needed to measure the suction pressure of P-103 and hence measure the Transmembrane Pressure (TMP).
PI-2	Pressure gauge	A positive gauge placed on the recycle line to measure the output pressure of P-104 and hence check for faults. (could be omitted)
R-1	Rotameter	These will be used to measure the inlet air flow rate into D-101.
R-2	Rotameter	These will be used to measure the inlet air flow rate into D-102.
R-3	Rotameter	These will be used to measure the inlet air flow rate into D-103.
V-1	Control valve	A diaphragm/ball valve needed to control the total inlet of raw wastewater into the system.
V-2	Control valve	Globe valves (or mechanical air regulators) needed to control the air flow rate into D-101.
V-3	Control valve	Globe valves (or mechanical air regulators) needed to control the air flow rate into D-102.
V-4	Control valve	Globe valves (or mechanical air regulators) needed to control the air flow rate into D-103.
V-5	Control valve	A diaphragm/ball valve needed to control the total rate of the recycle stream from T-102 to T-101.
V-6	Drainage valve	A diaphragm/ball valve needed to control the total rate of the recycle stream from T-103 to T-101.
V-7	Drainage valve	Drainage valves situated at the bottom of T-101 used to drain all or some of its contents.
V-8	Drainage valve	Drainage valves situated at the bottom of T-102 used to drain all or some of its contents.
V-9	Drainage valve	Drainage valves situated at the bottom of T-103 used to drain all or some of its contents.
V-10	Drainage valve	Drainage valves situated at the bottom of T-104 used to drain all or some of its contents.

3.3. WF-IMBR integration at Zandvliet WWTW

3.3.1. Overview of Zandvliet WWTW and WF-IMBR

The WF-IMBR pilot plant rig was based strictly on locally available inexpensive components; it was also designed to be semi-automated so that it can be a stand-alone unit, based on the design of the WF-IMBR used in previous investigations. It was proposed that the plant was to be situated at Zandvliet Wastewater Treatment Works in Macassar, Western Cape due to the fact that there is an existing IMBR 'Zeeweed' system and results could be compared if need be. An aerial view of Zandvliet WWTW is shown in Figure 3-8.

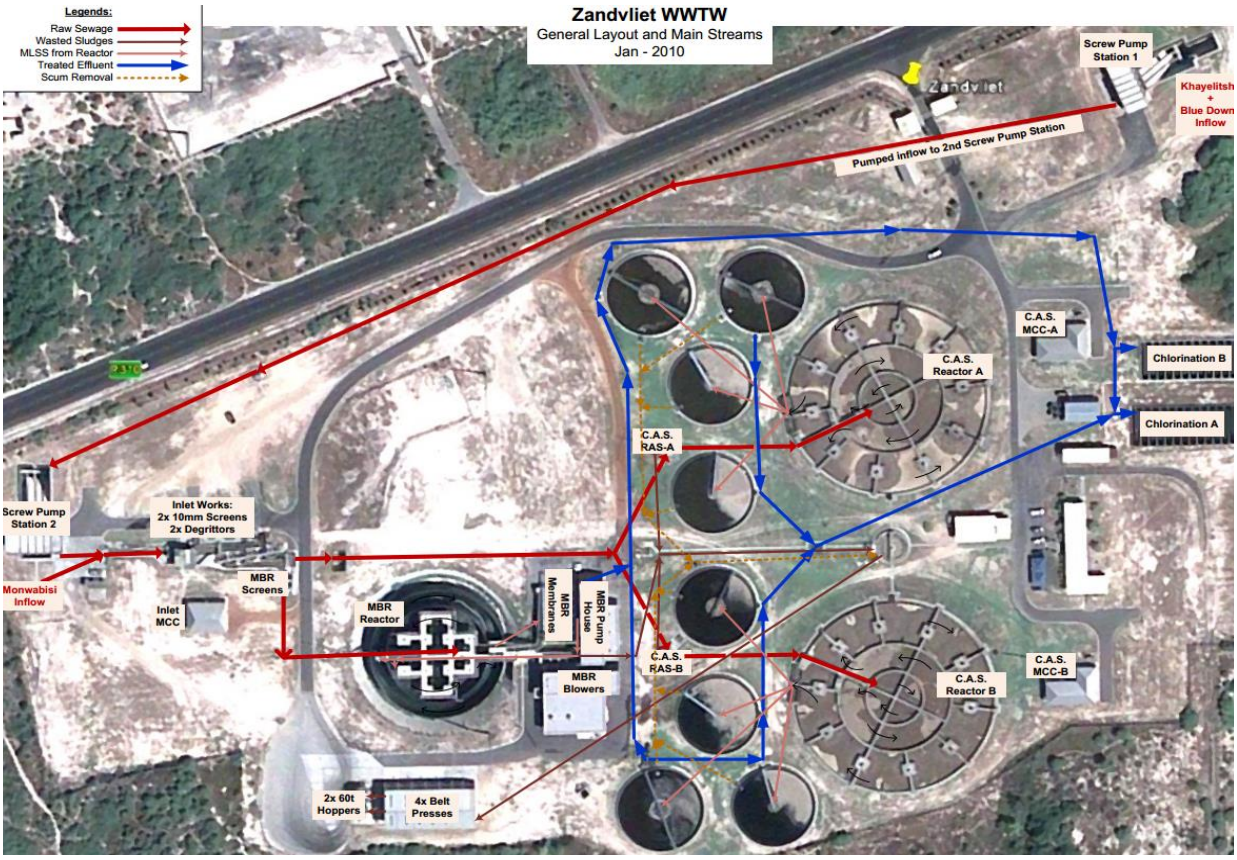


Figure 3-8: Aerial view of Zandvliet WWTW

Figure 3-9, shows an aerial view of Zandvliet WWTW which is zoomed into the MBR and the WF-IMBR pilot plant location. The raw sewage man-hole was located about 100 meters away from the pilot plant rig. The sampling points which were used during preliminary investigations were situated much closer to the WF-IMBR plant and could be fed to the rig using gravity, the two sample points used throughout this study is depicted by Figure 3-10. Figure 3-11 shows the direction of flow into and out of the bioreactor at Zandvliet for the two streams used.

Figure 3-12 to Figure 3-15, depicts photos taken of the pilot plant rig and its associated components.

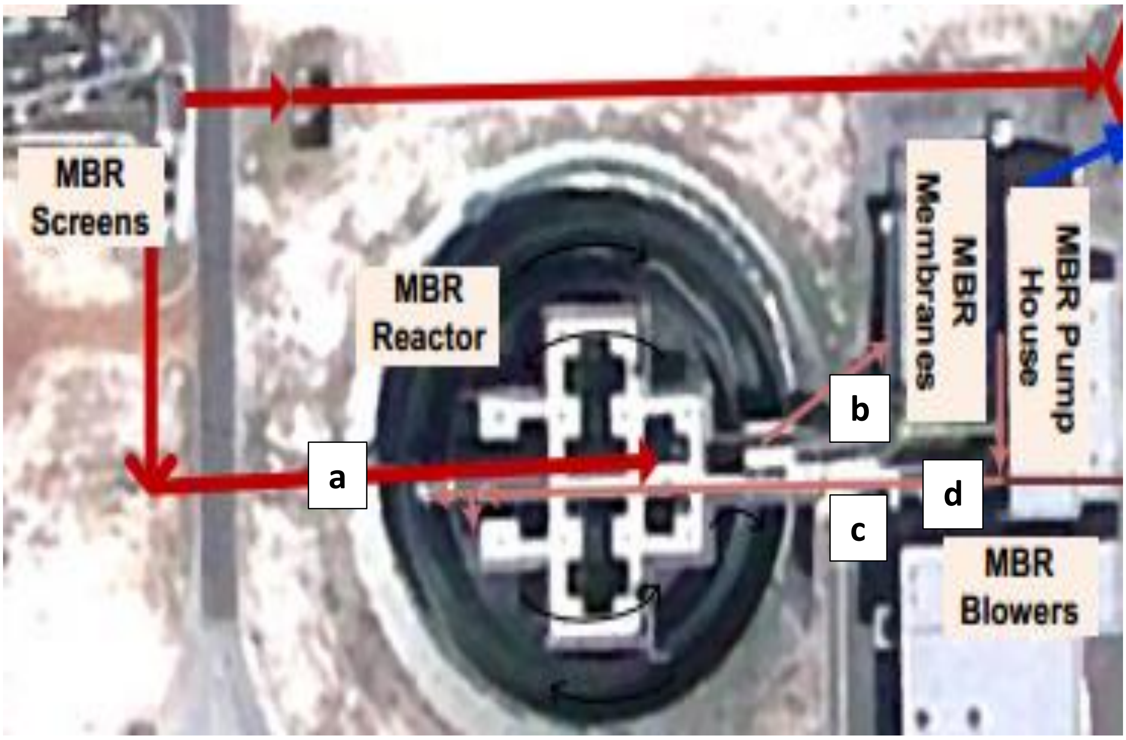


Figure 3-9: Aerial view of Zandvliet MBR plant (a) Raw Sewage Manhole (b) Activated Sludge from Bioreactor (c) Returned Activated Sludge from MBR (d) WF-IMBR system

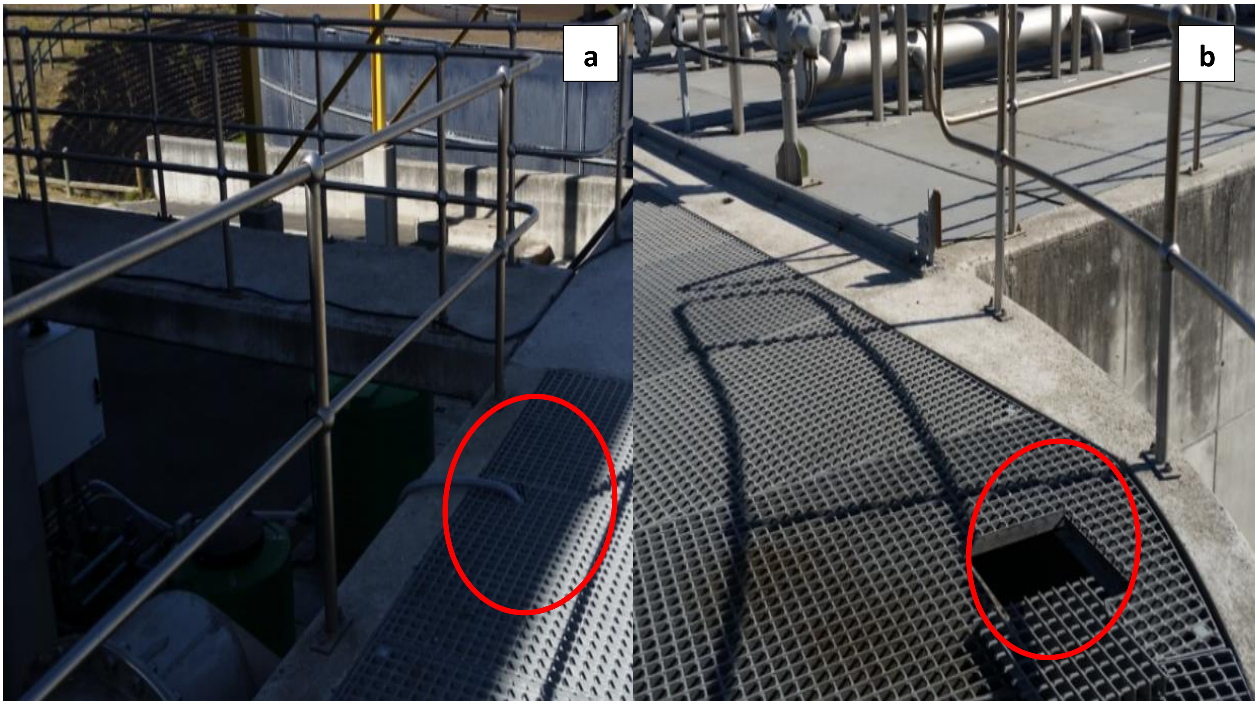


Figure 3-10: Sampling points for the (a) Returned Activated sludge from the MBR (b) Activated sludge being sent to MBR

Figure 3-11: Activated sludge entering the MBR plant and being returned to the Bioreactor

Figure 3-12: WF-IMBR Pilot plant rig

Figure 3-13: WF-IMBR Pilot plant instrumentation and control panel

Figure 3-14: WF-IMBR Pilot plant equipment: Recirculation pumps and blowers

Figure 3-15: WF-IMBR Pilot plant Bioreactor internals: Diffuser and level float switch

3.3.2. WF-IMBR Process Description

Wastewater from either the raw sewage feed or the returned activated sludge (RAS) from the Zandvliet WWTW was pumped into the aerobic biological reactor vessel by means of a submersible pump situated at the inlet of the plant to able to feed the system with raw sewage. Alternatively a gravity fed line from either the RAS stream or the feed to the MBR could also be used to fill up the process units with activated sludge. The raw sewage feed pump was fixed and enclosed in a 1mm aperture screening cage, to ensure that no large solids were fed to the system; this apparatus was then submerged, by means of a chain, into the raw sewage inlet manhole at Zandvliet WWTW. The pump cage could be cleaned by scrubbing it with a coarse brush in order to dislodge any solids stuck in the mesh openings. In order to be able to fully control the flow rate of raw sewage into the system, a controlled recycled line stemming from the immediate outlet of the submersible pump was installed. This ensured that even low sewage feed flowrates could be attained by allowing a portion of the pumped sewage to be returned back into the cage. The main outlet feeding the system was also fitted with a valve in case further fine-tuning or throttling was required.

The level in biological reactor was maintained with the help of a level float controller; which ensured that raw sewage could always be added to the system and also to ensure that the desired residence time could be adhered to. A low level inside the bioreactor would initiate the raw sewage feed pump and a subsequent high level would then terminate it. Due to the fact that a highly expensive magnetic flow meter would be required to quantify the total volume of raw sewage fed to the plant, a simpler and cost-effective alternative was used to measure this. A batch counter was installed into the control panel which counted the amount if times the feed pump would switch on. Every time the pump switched on a certain measured volume would enter the system and hence the total volume fed to the plant could be calculated. The feed from the bioreactor to the membrane bioreactor was designed in such a way as to ensure adequate retention time in the bioreactor, as well as ensuring no back flow from the membrane bioreactor vessel and vice versa. This was done by extending a pipe to the inside of the bioreactor (stemming from the bioreactor outlet); to a suitable level within the bioreactor to ensure that there will still be outflow. A soft dome air diffuser capable of blowing fine bubbles, for optimal oxygen transfer, was also placed in the centre of the bioreactor. The biomass would then flow freely by means of gravity to the membrane tank through the extended pipe.

A WFMF membrane pack, consisting of 19 WFMF flat-sheet modules, was then lowered into a membrane stand fitted with air diffusers. Each of the membranes was connected to a peristaltic pump by means of a central manifold extending the length of the membrane pack. This pump would apply a partial vacuum to the membrane pack to create a large enough pressure drop to allow water to diffuse through the membrane walls and into the permeate tank for storage and further analysis. The pressure drop, or TMP, across the membrane pack was measured using a Bourdon negative pressure gauge. The membrane pack, situated in the membrane stand, was then lowered into the centre of membrane bioreactor.

In order for the biomass to circulate through the system a centrifugal pump was used to recycle a portion of the biomass back to the biological reactor and also to ensure that the IMBR does not overflow, whilst ensuring good mixture throughout the system. Dry run protection was implemented on the centrifugal pumps by means of a level float controller. These pumps would switch off once a low level in was reached in the IMBR and would subsequently switch on after high level was reached. MLSS concentration was maintained by sludge wasting; this was done by draining a certain amount of sludge from IMBR. The WF-IMBR pilot plant is depicted in Figure 3-16.

Figure 3-16: WF-IMBR pilot plant set-up at Zandvliet WWTW

3.4. Experimental Methods

Before commencing with the evaluation of the initial WFMF module design, it is important to give detailed insight into the basic experiments that will be used to characterise the performance of the WFMF module. There are two main groups of experiments that can be done to evaluate the performance of the WF-IMBR i.e. experiments on potable water and experiments on activated sludge.

3.4.1. Pure water flux experiments

Initial experiments are usually done with clean potable water to characterize the filtration resistance of the membranes. Theoretically, the only resistance experienced should be that of the clean un-fouled membrane. This technique will provide us with the membrane resistance for a certain flux and TMP. This flux is known as the pure water flux which increases linearly with TMP. Plotting the imposed flux against the corresponding TMP would result in a graph known as the pure water flux curve, which is a linear curve. Before any experiments are to be done on the WFMF, the pure water flux experiment should be done. This is not only used to characterise the clean state of the WFMF, but it will also give a good indication on the hydrodynamic capability of the membranes at various fluxes.

3.4.2. Activated sludge filtration experiments

After doing the pure water flux experiments the WFMF should be ready to be examined on an activated sludge feed. For these set of experiments, the activated sludge feed would either be the returned activated sludge (RAS) from the MBR at Zandvliet WWTW or the activated sludge feed to the MBR at Zandvliet WWTW. The main difference between these two feeds is that the RAS would generally have a higher mixed liquor suspended solids (MLSS) concentration and therefore a higher fouling potential.

3.4.2.1. Critical flux experiments

As mentioned in Chapter 2, the critical flux concept has been around for a while and is one of the key experiments done on membrane systems to ensure optimal operation. In theory, when operating below the critical flux, there should be minimal to no fouling experienced.

Critical flux experiments can either be done by pressure stepping or flux stepping methods. In the case of small-scale IMBRs, operating at constant pressures proves to be problematic since pumps which are best capable for permeate suction (vacuum) operations are peristaltic pumps and these tend to operate best when used for constant flux operation and therefore the flux stepping method was used to investigate the critical flux. The flux-stepping method was executed as follows:

i. The WF-IMBR system (the IMBR tank) was filled up with either returned activated sludge from the Zandvliet WWTW IMBR or the feed to the Zandvliet WWTW IMBR, depending on what concentration was desired. By mixing the two feeds, one could also potentially manipulate the MLSS to a desired concentration;
ii. One of the two blowers was then switched on and the aeration rate could be selected by reading the corresponding flow rate on the rotameter whilst adjusting the needle valve. The air-scour rate to be investigated was selected accordingly;
iii. After ensuring that the membrane pack was adequately submerged in the membrane tank and that all process connections were tightened, the permeate pump was switched on;
iv. The lowest possible permeate flow rate was then selected by adjusting the pump setting;
v. After operating at a specific flow rate for 10 minutes, the next highest pump setting was investigated, hence the term flux stepping;
vi. At least 3 TMP readings were taken during the course of the 10 minute flux step;
vii. This process continued until a point had been reached where was a notable increase in TMP over the flux step duration;
viii. The flux at which TMP increases at a constant flux is known as the critical flux;
ix. The experiment was then allowed to continue for a couple of minutes to show the degree of TMP increase. This TMP increase could then be used to determine the fouling rate above the critical flux.

3.4.2.2. Continuous filtration experiments

The ultimate goal behind the critical flux investigation was to determine an optimal flux in terms of productivity for which no noticeable fouling would occur. Any flux below the critical flux is known as the sub-critical flux and the process of operating at this flux is termed sub-critical operation. Subject to critical flux results, subcritical operation was to be tested until noticeable fouling would occur.

During these continuous filtration experiments also known as sub-critical operation experiments (if operating below the critical flux), the TMP as well as the flux was measured at regular intervals to ensure that the system could operate stably and that no irreversible fouling was occurring. These results were illustrated by plotting flux and TMP on a single graph against the filtration time.

3.5. Evaluation and Modification of the WFMF

To address the first objective of this study, i.e. improve the mechanical design of the WFMF membrane module, the initial design of the WFMF needed to be evaluated to ensure that a baseline performance was documented. After establishing a baseline, the module was then modified in terms of reducing the overall pressure drop, which in this regard would consequently decrease the energy usage of the WF-IMBR. To complete the first objective, the modified WFMF membrane module design was then re-evaluated and compared to the initial design.

Lastly, various cleaning methods were investigated to ensure that the newly designed module would have a reliable cleaning regime which would return the membrane to its initial clean membrane state. This was not only vital to ensure that the membrane pack could be cleaned effectively but also to confirm the integrity of subsequent experiments done on the WFMF pack throughout the study.

3.5.1. Evaluation of the initial WFMF module design

After successfully commissioning the pilot plant IMBR at Zandvliet WWTW, the next step was to evaluate the baseline performance of the initial WFMF module design, which was used in previous studies. It was essential to evaluate the module in terms of operating flux and its corresponding TMP since this is directly linked to the energy consumption of the WF-IMBR system. Higher TMP's, in this regard, correlates to a higher pressure drop across the system; therefore more energy would be required to withdraw permeate since the filtration resistance would be higher for a specific flux. This has a direct impact on the energy required to operate at a specific flux since the permeate pump would need to overcome this pressure drop to produce permeate from the system; hence a lower filtration resistance, i.e. high flux and low TMP, is desired.

The initial evaluation consisted of doing experiments to measure the flux and the corresponding TMP's at increasing pump speeds with pure water as well as returned activated sludge from the Zandvliet WWTW MBR plant. Permeate quality in terms of turbidity was also measured to ensure that there were no leakages in the membranes which could affect the results.

3.5.1.1. Pure water experiments on initial WFMF module design

Figure 3-17 depicts the attained flux and corresponding TMP's at various pump speed settings using potable water. Prior to this experiment the membrane pack was soaked in a dilute bleach solution overnight, followed by scrubbing the membrane with a course burette brush the following morning to ensure that there was no residual fouling from previous experiments.

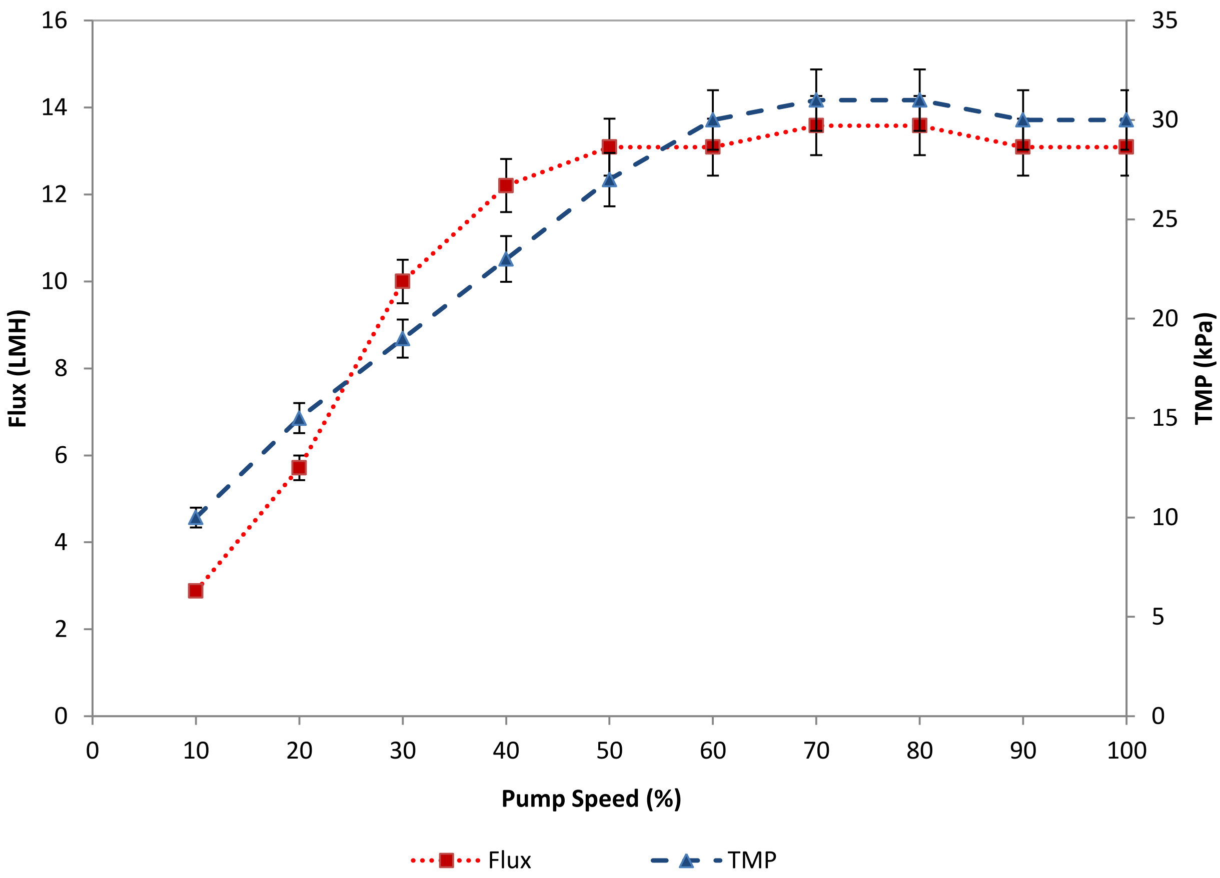


Figure 3-17: Flux and TMP profiles for the initial WFMF module design using potable water at various pump speed settings

It is evident from Figure 3-17 that the membrane pack couldn't operate effectively above 50% pump speed setting. TMP and flux were both expected to increase linearly with the pump setting, which is not the case since the TMP and flux seems to remain more or less constant after the 50% pump setting. Another perturbing aspect was that the maximum flux attained on the pure water was only around 14 LMH, which is extremely low.

3.5.1.2. RAS experiments on initial WFMF module design

Before making any conclusions on the performance of the initial WFMF membrane pack based on the potable water experiments, it was decided to perform a similar experiment using the RAS which had an MLSS concentration of approximately 8.3 g/l. Experiments were done using a continuous arbitrary air-scour at a rate of 150 l/min (7.9 l/min/module).

Figure 3-18 shows that for the first 4 pump speed settings (10 % to 40%), the TMP and flux both increased with the pump setting. However, after the fourth pump setting, the flux and TMP both decreased, which could be attributed to a defect in the WFMF module design, however this was not for certain. Besides the fact that there is a slight decline in flux (from 4.3 LMH to 4 LMH) at the 20%

pump setting, the TMP's and fluxes remained constant at the different pump settings investigated; which could imply that little to no fouling took place during this experiments.

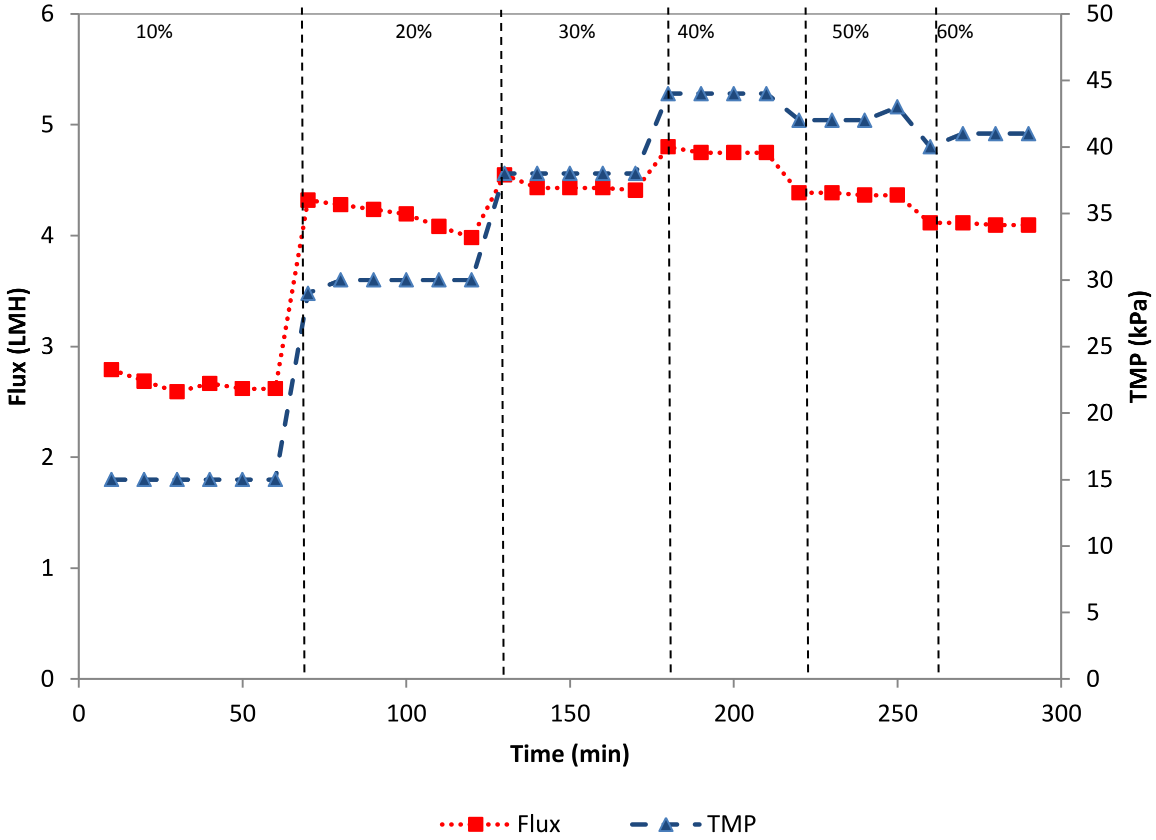


Figure 3-18: Flux stepping experiments on the initial WFMF module design using Zandvliet RAS (8.3 g/l) with continuous air-scouring (7.9 l/min/module)

In addition, the permeate quality was also evaluated by measuring the turbidity every 10 minutes throughout the duration of the experiment. Figure 3-19 shows that although the initial permeate quality was around 2.6 NTU, it dropped down to below 1 after 50 minutes of operation and then stabilized at around 0.6 NTU for the remainder of the experiment. This would suggest that the integrity of the membranes were withheld throughout the experiment and that the decline in TMP at higher pump setting could not be credited to leakages occurring.

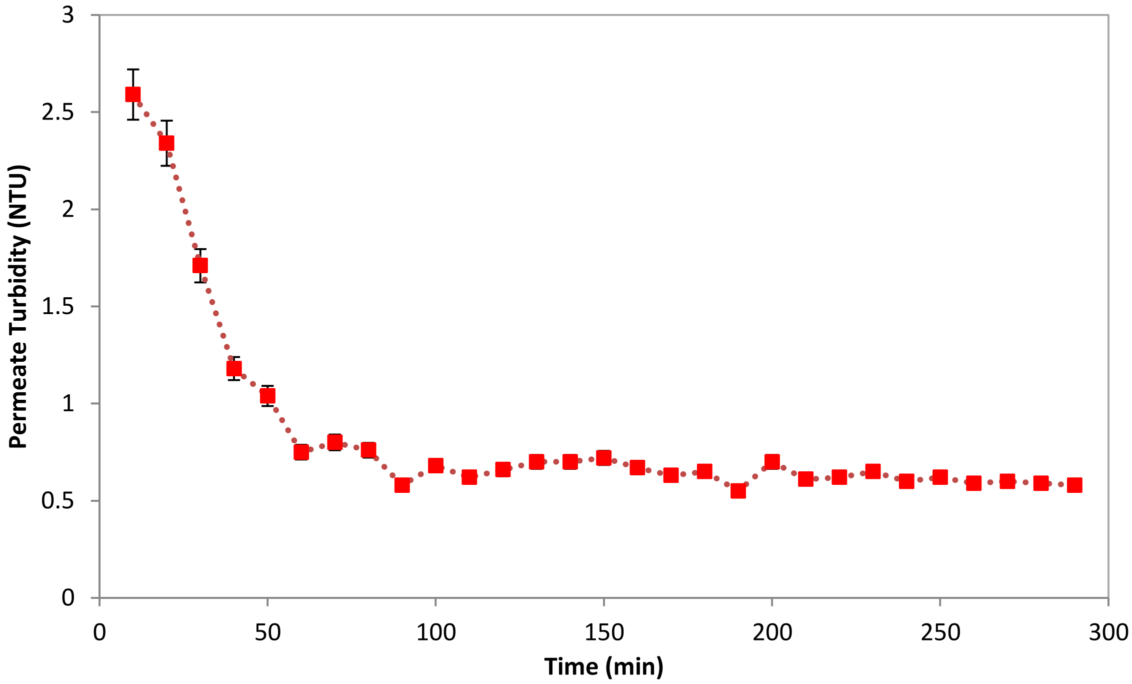


Figure 3-19: Permeate turbidity for flux stepping experiment on the initial WFMF module design

Overall it could be concluded, from the baseline experiments on the initial WFMF module design, that there was a limitation in the attainable operating flux; which is due to a high filtration resistance. To decrease the resistance and consequently decrease the energy consumption, the WFMF module would need to be modified to reduce its inherent pressure drop.

3.5.2. Modification of the initial WFMF module design

After evaluating the initial WFMF design, it was clear that the membrane pack could not operate at the high fluxes (approx. 30 LMH) anticipated. It was then decided to decrease the overall pressure drop on the membrane pack, in order to increase the operating flux and consequently reduce the energy consumption of the permeate pump. Various steps were taken to do this, which will be discussed in this sub-section.

3.5.2.1. Fitting an additional permeate outlet

Experiments using potable water were done using a single module to compare a module with one outlet to one with two outlets. The results, as illustrated by Figure 3-20, show that there was a significant decrease in the overall resistance, since the TMP decreased and the flux increased when an additional outlet was installed. Although fitting an additional permeate outlet could assist in alleviating some of the resistance, there was still a constraint after the 50% pump setting.

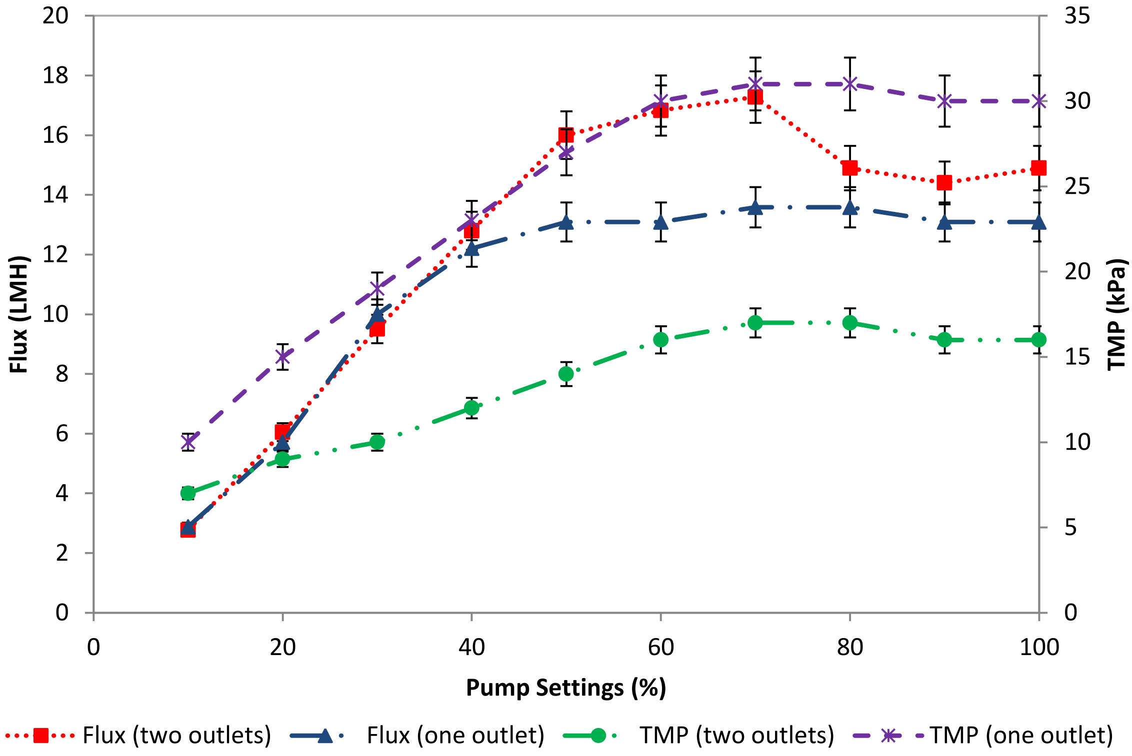


Figure 3-20: TMP's and Fluxes to compare one permeate outlet to two permeate outlets per module using potable water.

The entire membrane pack was nonetheless altered to include two permeate outlets per module as shown in Figure 3-21.

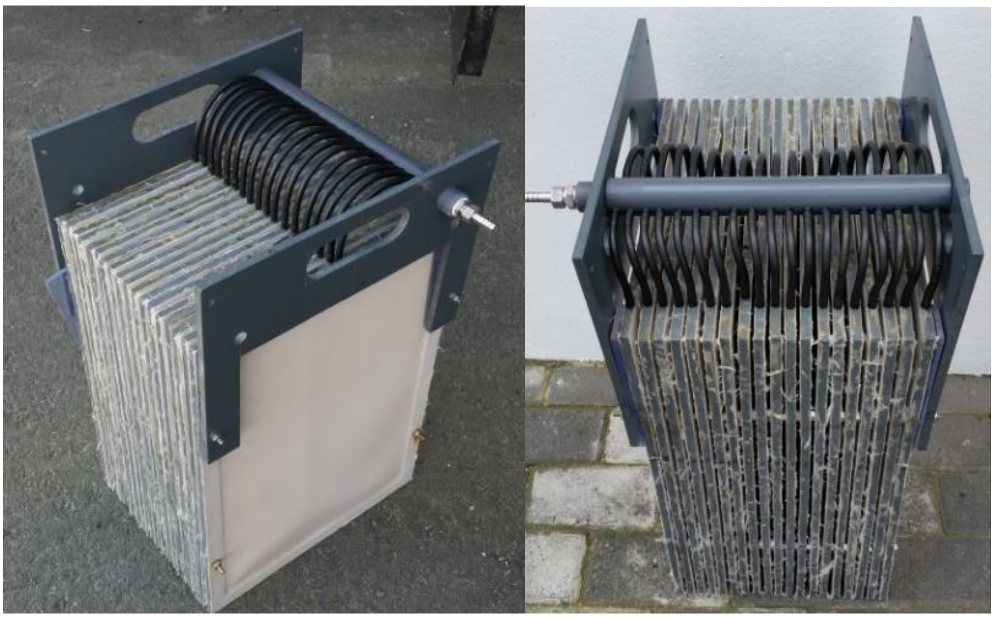


Figure 3-21: Initial pack with one permeate outlet (Left); Modified pack with two permeate outlets (Right)

Experiments were subsequently performed on the modified membrane pack with two permeate outlets per module. Zandvliet WWTW returned activated sludge (RAS) with an MLSS concentration of 9.2 g/l was used and a continuous air- scour rate of 150 l/min (7.9 l/min/module) was employed. The TMP and flux profiles for the duration of this experiment are illustrated in Figure 3-22, and the pump speed setting for each step is shown at the top of the graph.

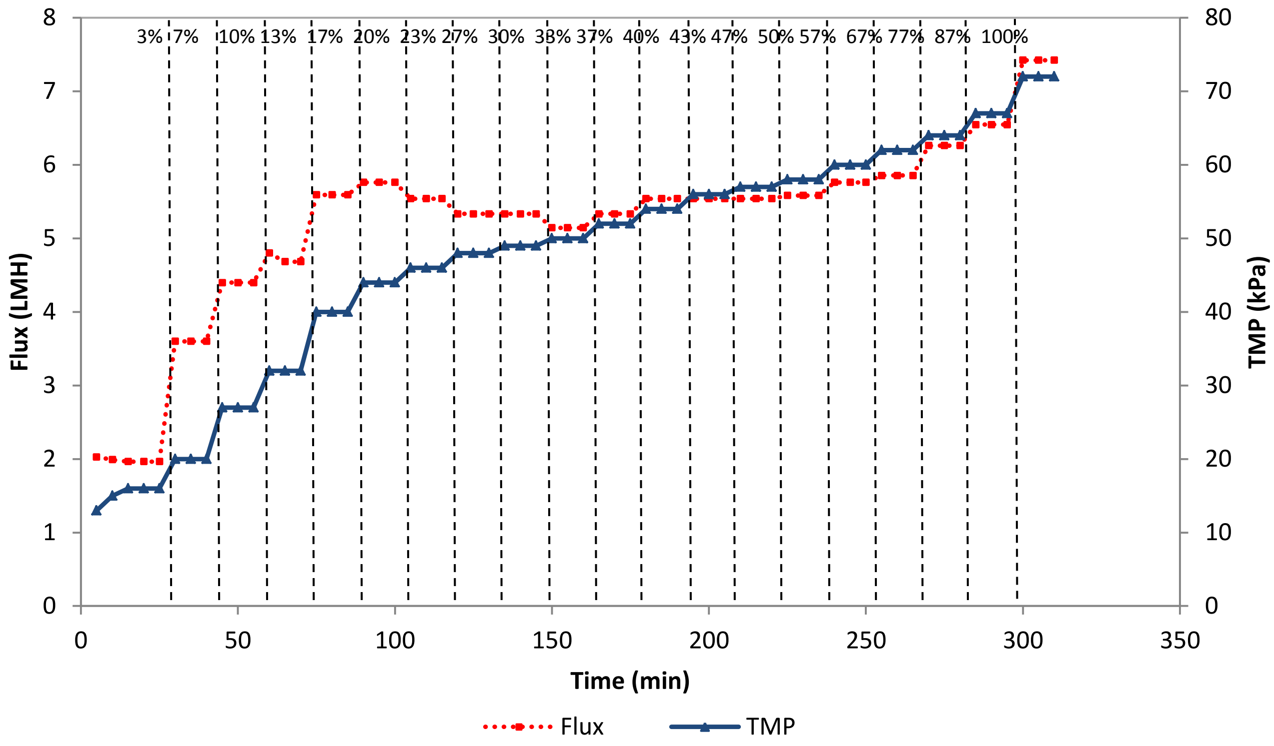


Figure 3-22: Flux stepping experiments on Zandvliet Activated Sludge

Closer examination to Figure 3-22 shows that, with an exception to the 3% pump setting, there is no TMP increase during operation at any particular flux. Furthermore, it can be seen that the highest flux obtained was around 7 LMH, which is still much lower than what is expected. In addition, there is a drop in flux after the 20% pump setting which continues to remain more or less constant until it starts to increase again at the 77% pump setting. A similar phenomenon was noticed when doing PWF experiments, which could be credited to the spacer being too thin, which causes a flow restriction inside the module. Despite adding an additional permeate outlet on each module, the TMP's were still extremely high. Additional modifications were therefore required to further decrease the pressure drop and to ensure less flow restriction within the WFMF membrane module. This was done by replacing the initial spacer with a more spacious and rigid one.

3.5.2.2. Inserting a more rigid membrane spacer larger permeate outlets

To further reduce the overall resistance of the WFMF module, new membranes were fabricated to include a better spacer and larger permeate outlets. The permeate outlets were increased from an inner diameter (ID) of 2 mm, to an ID of 5 mm. Figure 3-23 depicts the initial WFMF with the narrow permeate outlet and thin spacer. The final module included two 5mm ID stainless-steel outlets on each module and as well as on the manifold, shown in Figure 3-24.

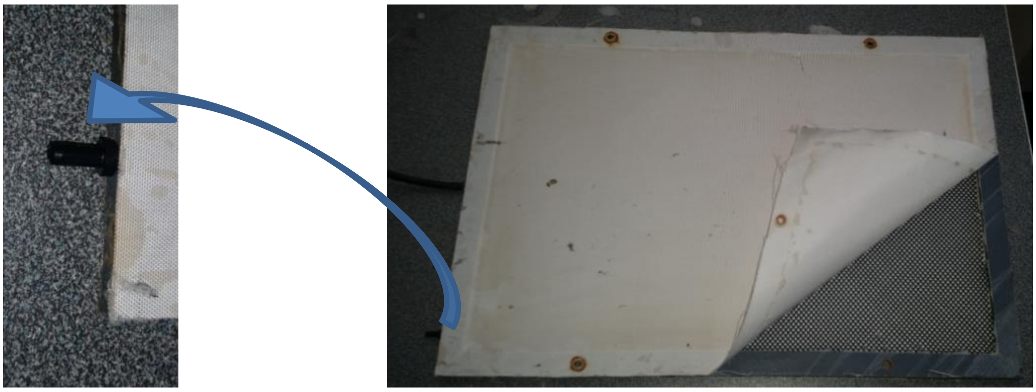


Figure 3-23: Initial membrane design, with 2mm ID outlet (Left) and membrane with a single 1mm thick spacer (Right)

Figure 3-24: WFMF membrane pack with larger permeate outlets (ID =5mm)

After evaluating numerous spacer options, to replace the single 1mm thick spacer mesh initially used, it was decided to use two Nelton Meshes; cut and placed in a specific way to allow optimal permeate flow and minimal pressure drop within the module. Figure 3-25 depicts the comparison of the two spacers.

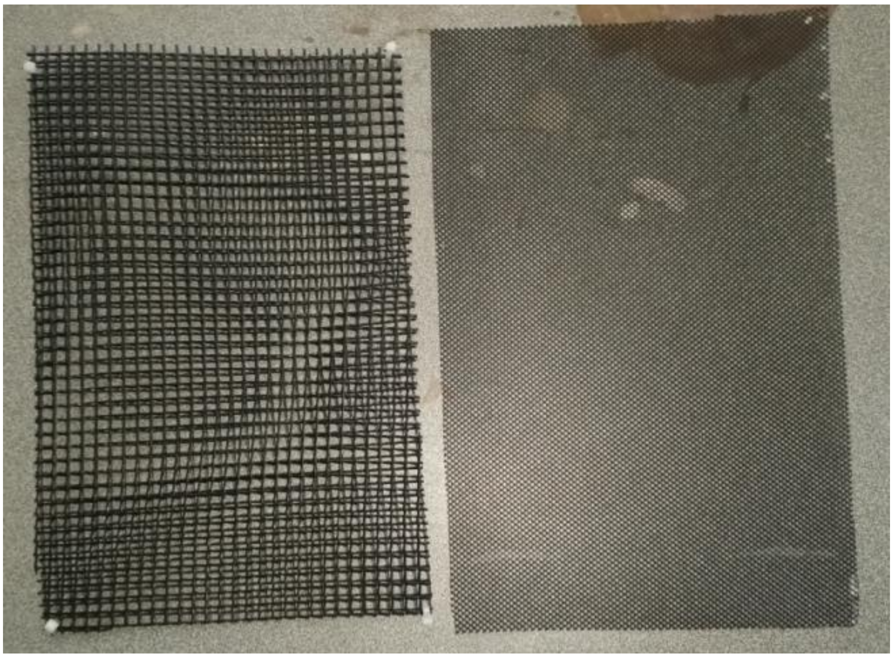


Figure 3-25: Photo comparison of the new spacer with larger apertures (Left) and the initial membrane spacer (Right)

The Nelton Mesh was cut in a way to form horizontal and vertical flow channels, as shown in Figure 3-26. Two meshes were used and placed with the horizontal channels facing and fitting into each other; whilst the vertical flow channels face to the outside, which should allow optimal permeate flow within the module. Figure 3-27 shows a side view cross-section of the two spacers. The main problem with the initial membrane spacer is that the membrane would wrap tightly on the spacer which caused a flow constriction within the module and subsequently increased the pressure drop.

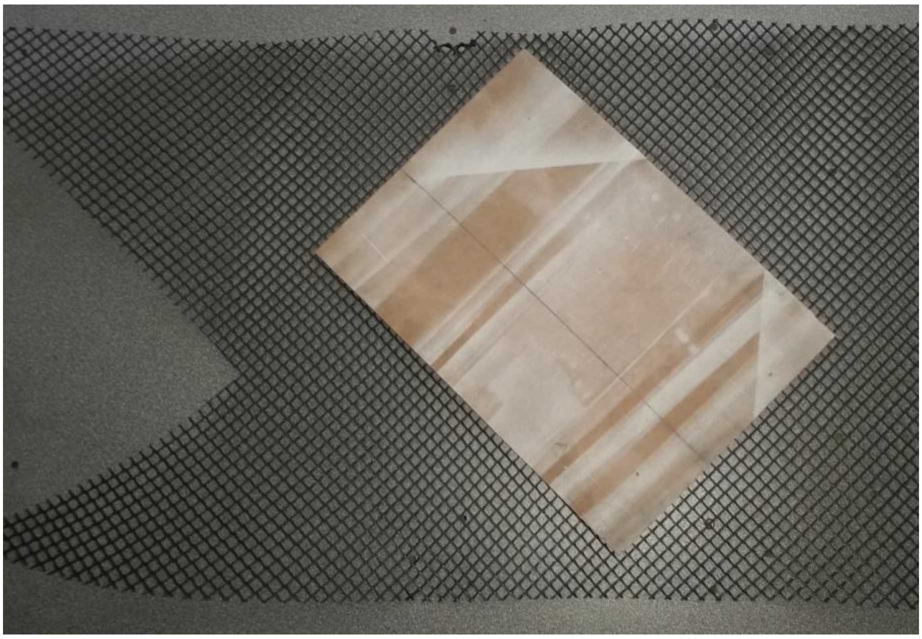


Figure 3-26: The Nelton mesh cut diagonally to form flow vertical flow channels.

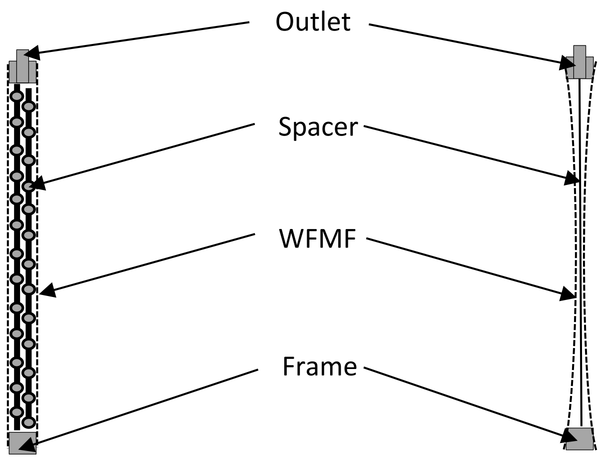


Figure 3-27: Comparison of the membrane spacers. Nelton Mesh membrane spacer (Left); Initial membrane spacer (Right)

3.5.3. Evaluation of the Modified WFMF Design

After modifying the WFMF membrane pack, the modified pack was evaluated by doing PWF experiments, flux stepping experiments as well as continuous filtration experiments.

3.5.3.1. Pure water flux on modified design

Figure 3-28 illustrates the PWF curve for the modified WFMF membrane pack, it can be immediately noticed that both the TMP and flux increased linearly and uniformly as expected.

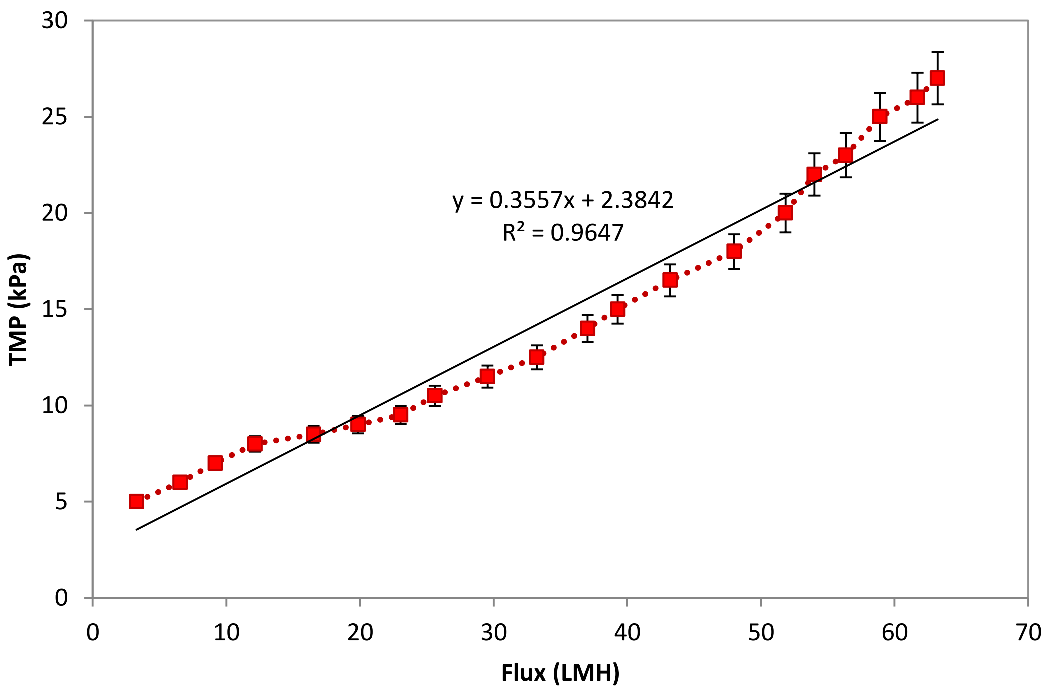


Figure 3-28: Pure water flux curve for the modified WFMF design

The results displayed in Figure 3-28 could imply that the limitation observed in the initial module design was alleviated to a great extent, resulting in much higher operating fluxes and lower TMP's. In this regard, the first objective of this study has been completed since the overall pressure drop has decreased drastically making the modified WFMF membrane pack much more energy efficient when compared to its original design.

3.5.3.2. Flux stepping experiments on modified design

Experiments were then done on Zandvliet WWTW returned activated sludge (RAS) which had an MLSS concentration of 10 g/l. By using a continuous air-scour rate of 160 l/min (10 l/min/module) the modified WFMF membrane pack was evaluated at increasing pump speed settings at 15 minutes per setting. Figure 3-29 shows that the TMP and flux both stayed constant at each step, until the 45% pump setting. It can promptly be seen that not only are higher fluxes attainable with the modified design but there has been major decrease in TMP's also. The sharp increase in TMP, which is followed by a decrease in flux, suggests that the critical flux has been exceeded. For this specific experiment, the critical flux is estimated to be around 25 LMH.

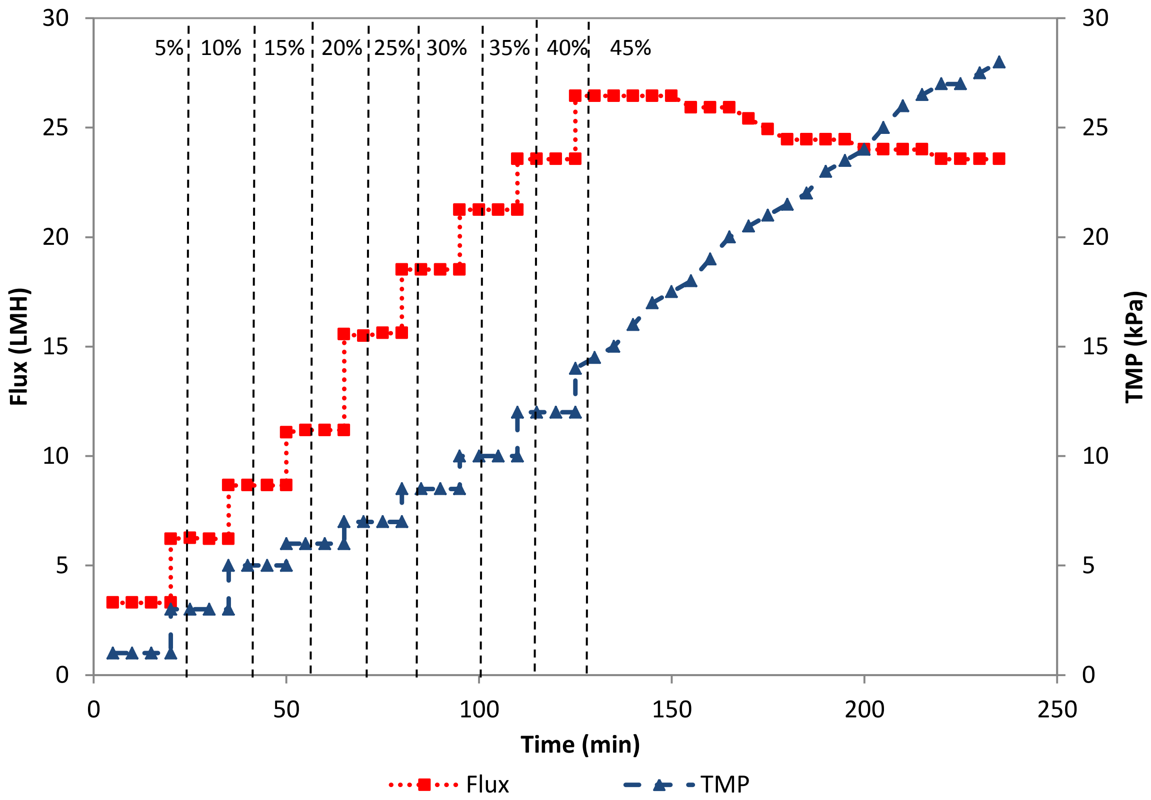


Figure 3-29: Flux stepping experiment on Zandvliet Returned activated sludge

3.5.3.3. *Continuous filtration and repeatability*

Theoretically, when operating below the critical flux, there should be minimal fouling. However, this was not the case for the WFMF as seen in Figure 3-30, which shows the flux and TMP profiles for two runs operated at 20% pump speed on an MLSS concentration of 10 g/l and an air-scour rate of 10 l/min/module.

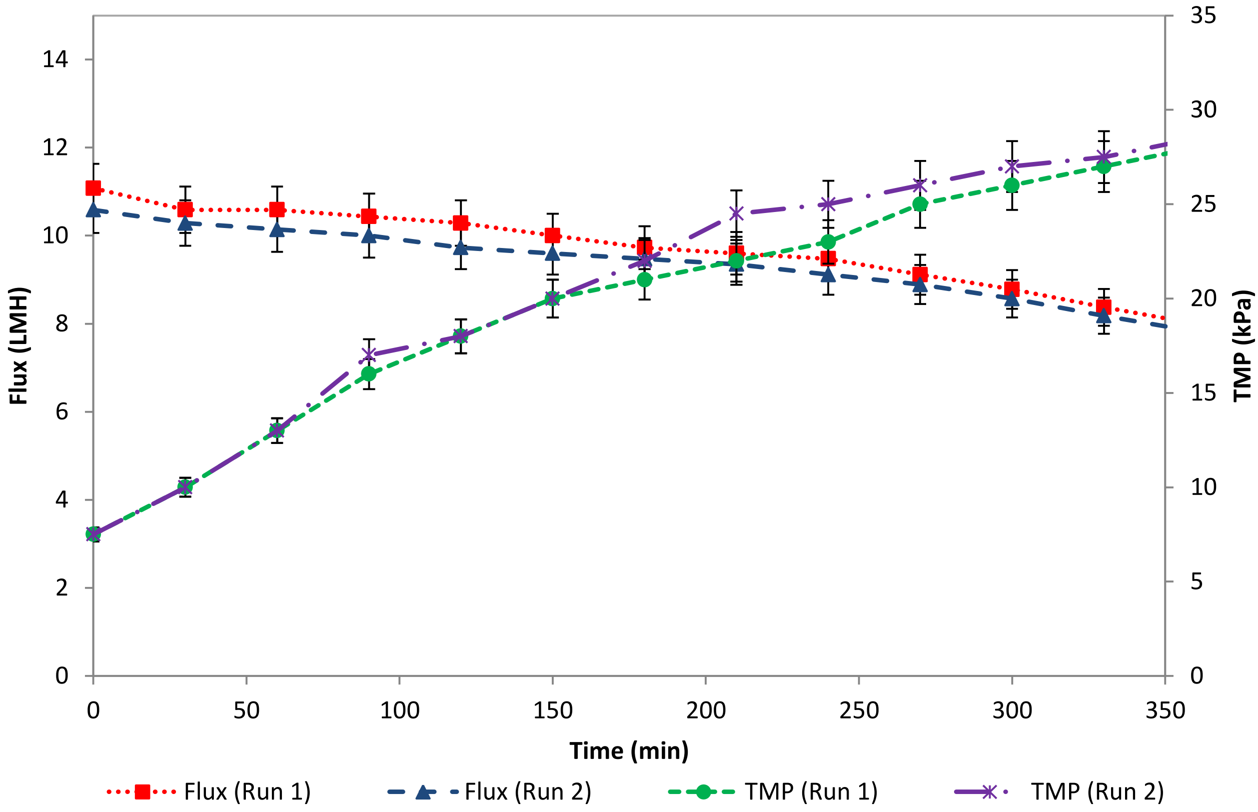


Figure 3-30: Sub-critical runs on an MLSS concentration of 10 g/l using an air-scour rate of 10 l/min/module at a pump setting of 20%

Figure 3-30 suggests that the initial flux was approximately 11 LMH, which is well below the critical flux, but the increase in TMP as well as the decrease in flux shows that fouling does possibly take place over time. A promising deduction from Figure 3-30 is that the two experiments had more or less identical TMP increases as well as flux decreases. This suggests that the experiments are well repeatable.

Most of the science concerning limiting fouling in MBRs revolves around the critical flux theory. This is based on the dynamics of particles being deposited on to the membrane and particles being scoured away from the membrane, and predicts that for a specified air-scour rate there will be a flux below which no net fouling will occur. Due to that fact that sub-critical operation with continuous air-scour does not seem possible, other operating regimes were investigated; which is discussed in the following chapter.

All subsequent experiments were performed at least more than once to ensure that the results are repeatable and therefore upholding the integrity and reliability of the results obtained on the WF-IMBR system. For most of the experimental results which were graphically displayed, only the average curve of the repeated experiments was plotted. The repeatability graphs for each of the repeated experiments are represented by error graph plots which are all displayed in Appendix B.

3.5.3.4. Recovery cleaning the modified WFMF

Before commencing to evaluate the performance of the modified WFMF membrane pack, it was of high importance to determine an appropriate cleaning procedure. In previous studies done on the WFMF for potable water production, filtering of activated sludge and filtering of sludge from an anaerobic reactor, the membranes were easily cleaning simply by brushing them, or by soaking them in dilute sodium hypochlorite overnight followed by brushing.

Following the critical flux experiment shown in Figure 3-30, the membranes were cleaned by only brushing them; this however did not recover the pure water flux. The membranes were then cleaned by leaving them to soak in a dilute sodium hypochlorite solution overnight, which also failed to restore the pure water flux.

Due to the fact that cleaning methods used in previous studies did not seem to restore the pure water flux of the W-MF after operating on the returned activated sludge from the Zandvliet WWTW MBR, alternative methods were then investigated to ensure that the membranes could be cleaned as effectively as possible to ensure that subsequent experiments would not be effected by a previously fouled membrane. The results of these investigations are summarized in Figure 3-31.

Various methods and intensities of cleaning the WFMF exist, ranging from only scrubbing the membrane surface to applying a slow chemically enhanced gravity-fed backwash were investigated. It is clear from Figure 3-31 that scrubbing the membrane did not remove the foulants and although a hypochlorite soak gave a better performance, the flux was still not restored. A hypochlorite flux gave a very good flux recovery, whilst a hypochlorite soak followed by a slow gravity-fed hypochlorite backwash restored the flux fully.

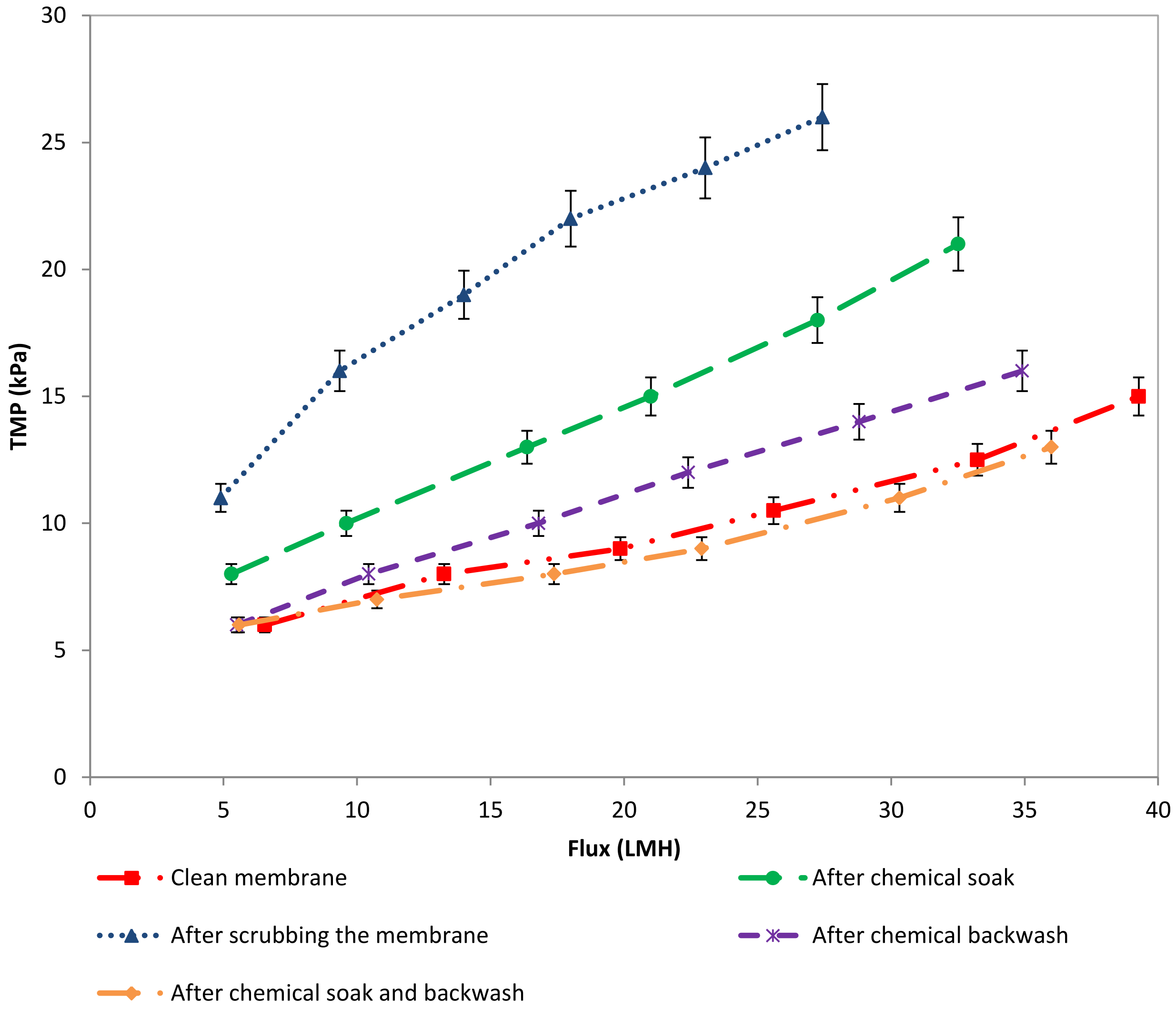


Figure 3-31: Pure water flux curves after various cleaning regimes

Figure 3-31 is very indicative of organic fouling of the membranes. Furthermore, it seems as though the organics have penetrated deep into the membrane, hence the need for a backwash. The type of fouling experienced by the WFMF will be discussed in the chapters to follow.

After every experimental run, regardless if fouling occurred or not, it was imperative to clean the membrane; hence eliminating variation between experimental runs by ensuring all experiments start off using an un-fouled membrane pack. The following procedure was always followed:

i. Chemical soak: The membrane pack was soaked in dilute sodium hypochlorite overnight;
ii. Chemical gravity-fed backwash: Dilute sodium hypochlorite was fed using gravity head through the permeate outlet for a duration of 30 minutes the following morning;
iii. Pure water flux experiment: The pure water flux was examined to ensure the membrane was clean. If not, then step ii was repeated until the membrane was adequately cleaned.

CHAPTER 4. PRELIMINARY WF-IMBR INVESTIGATION

The results obtained and experimental protocol used during the preliminary investigation on the pilot plant WF-IMBR situated at Zandvliet wastewater works will be discussed in this chapter. Firstly the resistance profile curves will be explained in Section 4.1. Thereafter, Section 0 will present the preliminary investigation using continuous air-scour at various process conditions, viz. investigating the effect of operating flux, the effect of continuous air-scour rates and the effect of MLLS concentration. A flow chart of how the chapter is organised can be found below in Figure 4-1.

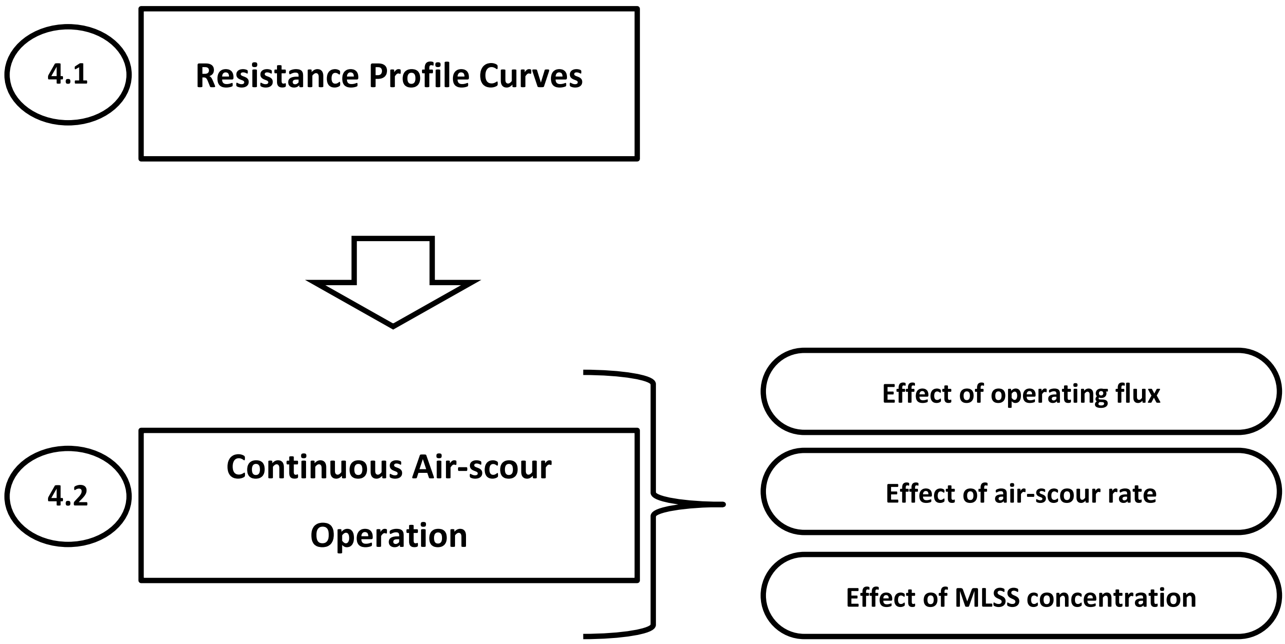


Figure 4-1: Flow chart of Chapter 4

4.1. Resistance Profile Plots

Although all investigation done in this chapter were performed at a constant flux, i.e. the suction pump connected to the membrane pack was set to a specific pump speed setting to withdraw permeate at a specific rate; in true constant flux operation, the TMP (ΔP) would increase as fouling increases, hence plotting ΔP against time would indicate how fouling increased with time.

In practice, since a peristaltic pump was used as the permeate pump, the flux does not actually remain constant, but decreases as ΔP increases. This was already noticed in Chapter 3 as illustrated by Figure 3-30. Hence it becomes very difficult to interpret and quantify the fouling behaviour from the ΔP profile alone. Plotting the total resistance increase with time would give a better indication of the rate of fouling since it is calculated using the TMP and the flux, as follows:

Equation 4-1

$$R_{tot} = \frac{\Delta P}{\mu \cdot J}$$

Where: J = permeate flux (LMH or l/(m^2.h));

ΔP = Transmembrane pressure drop (Pa);

μ = Permeate viscosity (Pa.s);

R_{tot} = Total resistance = membrane resistance + resistance due to fouling (m^{-1}).

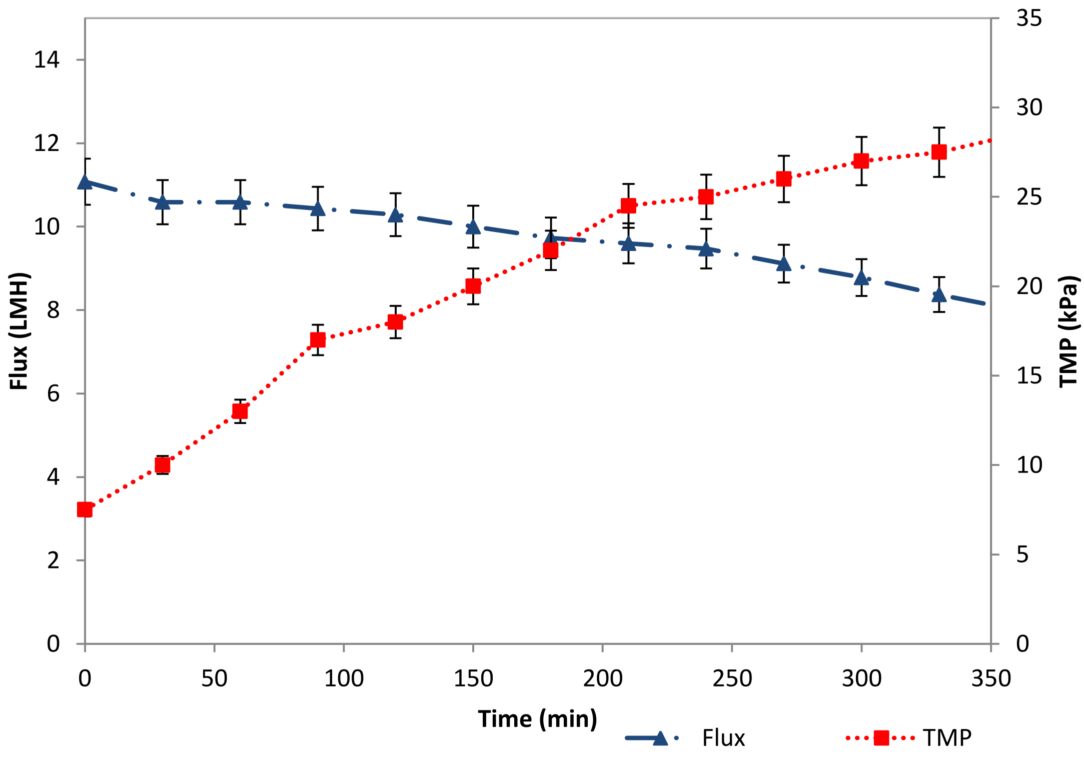


Figure 4-2: An example of TMP and flux profiles representing fouling for a single experimental run

It should be noted that since the membrane resistance remains constant, the total resistance increase is a true representation of fouling. Figure 4-2 represents a typical graph showing TMP increase coupled with flux decrease for a single experimental run and Figure 4-3 represents the corresponding graph showing the resistance profile plot for the same experimental run, by applying equation 4-1 to each of the data points.

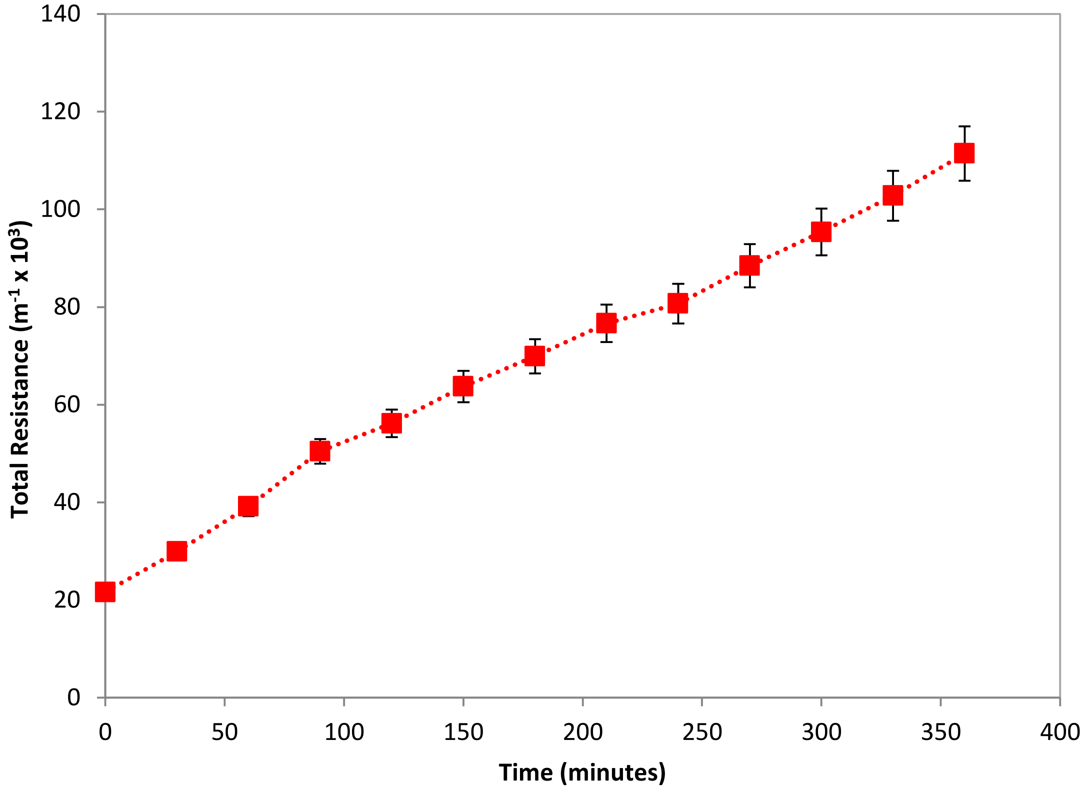


Figure 4-3: An example of resistance profile representing fouling for a single experimental run

Henceforth, for the continuous filtration experiments done in this chapter, the results for a single experiment will be given as one fouling resistance curve, representing both the flux and the TMP curves for that experiment. For the results presented hereafter, operation at different initial fluxes will be represented by the pump speed setting, due to the inevitable decrease in flux.

4.2. Continuous Air-Scour Operation

After the WFMF had been modified and re-evaluated, it was observed that contrary to initial expectations, the WFMF could not operate at a sub-critical flux without progressive fouling occurring. To ensure effective energy reduction within the WF-IMBR, the air-scour rate and air-scour efficiency would need to be investigated further. By operating at lower air-scour rates the WF-IMBR system would be more energy efficient. The most common approach to air-scouring is by using continuous air-sour operation which is achieved by operating with continuous air- scour and continuous filtration.

The main parameters which affect the fouling rate are the air -scour rate, the operating flux as well as the MLSS concentration. These parameters were investigated in a completely randomized order, to determine their respective effects on the fouling rate. Operation without air-scouring was also investigated, which was initially to be used as a base-line performance. Activated sludge being sent to the MBR at Zandvliet was used to fill the IMBR tank and the respective investigations as listed in the following sub-sections were done to investigate the effect of the parameters listed above.

4.2.1. Effect of operating flux

In order to confirm that sub-critical operation is indeed impossible, four different pump speeds were investigated as summarised in Table 4-1. Pump speed indicated the initial flux, as discussed in Section 4.1 and each experiment was performed twice to determine whether the results obtained were repeatable. The repeatability graphs are displayed in Appendix E, which confirms that the experiments are in actual fact repeatable. The average of the results obtained from both runs at various pump speeds, as per Table 4-1, is illustrated in Figure 4-4.

Table 4-1: Order and details of effect of operating flux investigations

Experiment	MLSS (g/l)	Pump Setting (%)	Initial Flux ($L/m^2.h$)	Air-scour rate (l/min/module)
1	7.6	20	11	7.5
2	7.7	20	10.6	7.5
3	7.8	10	5.8	7.5
4	8.0	10	5.9	7.5
5	7.6	25	14.6	7.5
6	7.9	25	14.4	7.5
7	7.5	33	19	7.5
8	7.6	33	18	7.5

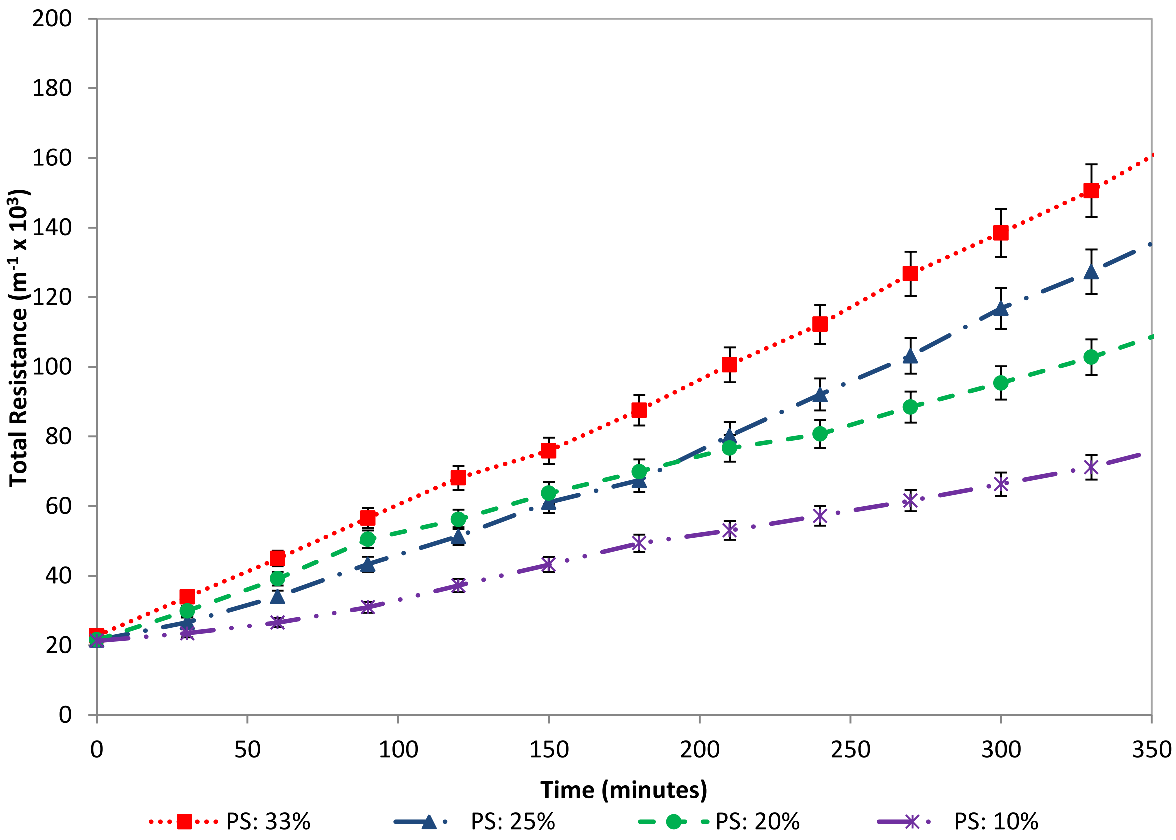


Figure 4-4: Fouling resistance as a function of initial flux using an air-scour rate of 7.5 l/min/mod on a MLSS concentration of 7.5-8.0 g/l

Figure 4-4 shows that regardless of the initial flux, ranging from 5.8 to 19LMH, there always seemed to be a progressive increase in the total resistance, suggestion that some sort of fouling is occurring and validating the initial suspicion that stable sub-critical operation is not achievable. It is possible that the critical flux trials may have over-estimated the true critical flux or that there may have been changes in the activated sludge since the critical flux trials. However, since even low fluxes of 5.8LMH could not produce stable operation it can be concluded that there is no feasible flux that can allow this system to operate at sub-critical conditions. As expected, there appears to be a distinctive trend in operating at different pump settings i.e. the fouling rate increases with an increase in pump speed.

It was feasible that the air-scour rate used was possibly insufficient to ensure effective scouring. Hence the next parameter to investigate and increase was the effect of the air-scour rate.

4.2.2. Effect of air-scour rate

The sludge used during these trials had a much higher MLSS concentration than the previous set of experiments. The MLSS concentration ranged between 9.1 g/l and 9.9 g /l for the various experiments done. Three different air-scour rates as well as no air-scouring were investigated at two different pump settings (20% and 33% pump settings). The details of the experiments are summarised in Table 4-2.

Table 4-2: Order and details of effect of air-scour rate investigations

Experiment	MLSS (g/l)	Pump Setting (%)	Air-scour rate (l/min/module)
1	9.5	20	0
2	9.7	20	7.5
3	9.8	33	10
4	9.9	33	7.5
5	9.7	20	12.5
6	9.9	33	0
7	9.1	33	12.5
8	9.2	20	10

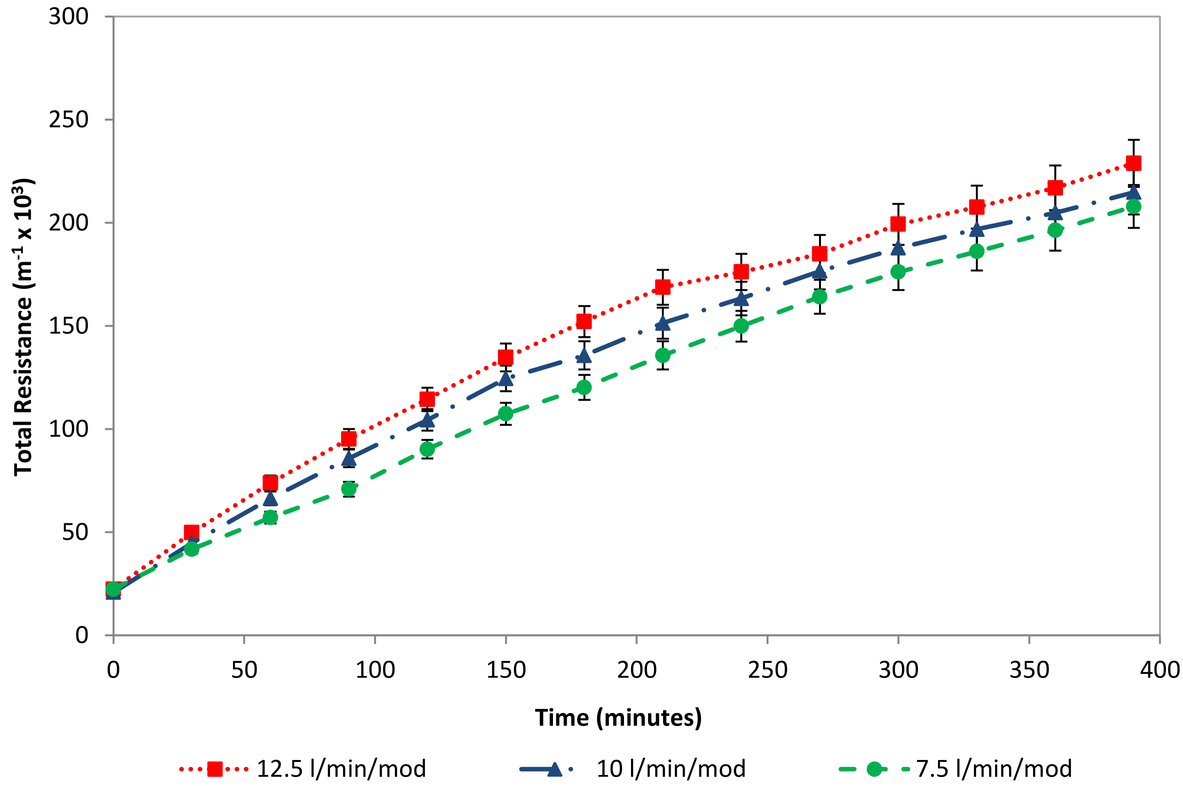


Figure 4-5: Fouling resistance as a function of air-scour rate using the 20% pump setting on a MLSS concentration of 9.2-9.7 g/l

The most notable observation from Figure 4-5 is that operating without air-scouring the membranes at all actually produced the lowest fouling rate. Furthermore, it was also expected that the fouling rate would be inversely related to the air-scour rate, which is clearly not the case. Unlike Figure 4-5 where a clear distinction can be seen between the different air-scour rates, Figure 4-6 shows that the three air-scour rates gave more or less identical results. This could suggest that there is an interaction between the air-scour rate and the operating flux. Nonetheless, the most significant observation is that once again operating without scouring the membranes gave a considerably lower fouling rate.

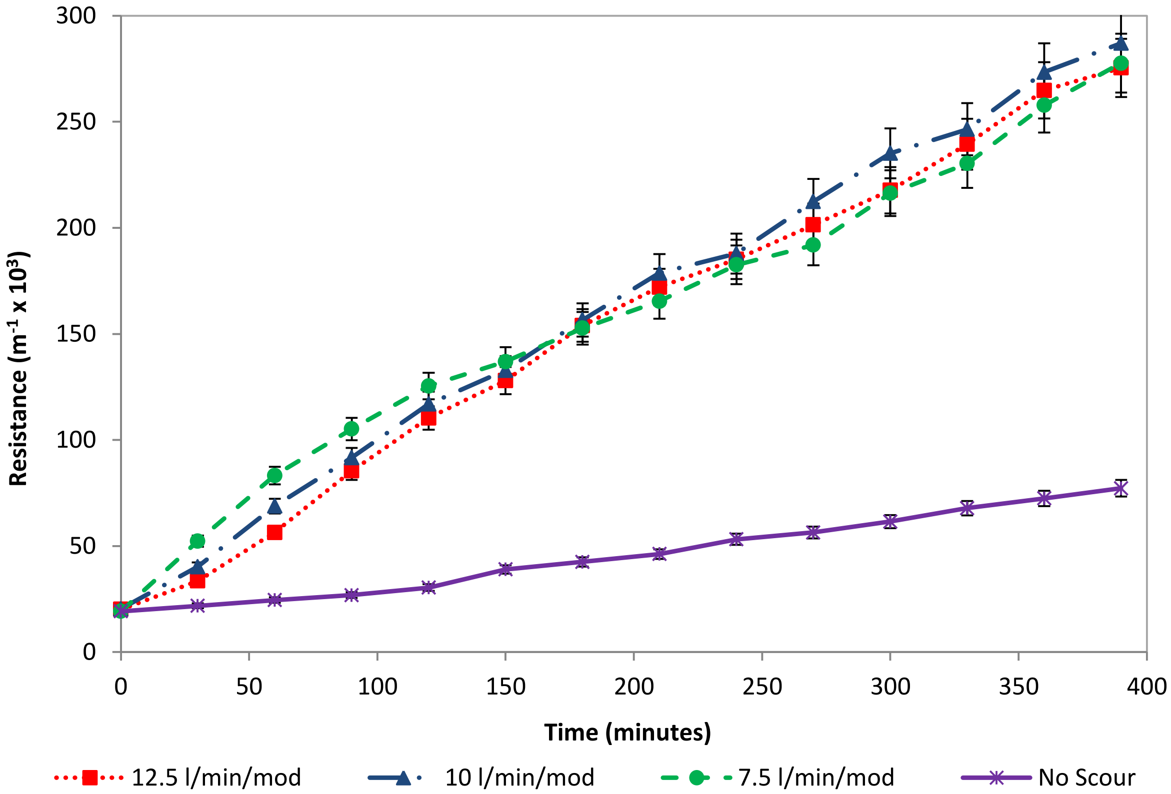


Figure 4-6: Fouling resistance as a function of air-scour rates using the 33% pump setting on a MLSS concentration of 9.1-9.9 g/l

When comparing Figure 4-5 and Figure 4-6 it is once again evident that operating at a higher pump setting results in a higher fouling rate. However, when operating without scouring it is apparent that operating at a higher pump setting results in a lower fouling rate. This unexpected phenomena as well as the fact the fouling rate increases directly with the air-scour rate needs to investigated further to determine whether this is actually the case for different samples of activated sludge or whether it is distinctive to activated sludge from Zandvliet WWTW. To do this, a laboratory scale set-up was constructed and those results will be discussed in Chapter 5.

4.2.3. Effect of MLSS Concentration

Prior to switching over to the laboratory scale investigation, it was of great interest to investigate the effect of the MLSS concentration on the fouling rate, which is also expected to have a profound effect. By using results obtained from previous trials done to determine the effect of the operating flux (7.5 g/l) and the effect of the air-scour rate (10 g/l), along with a new run which was done by filling up the IMBR with RAS (12g/l); the effect of the MLSS concentration could be examined at a continuous air-scour rate of 10 l/min/module and a pump setting of 33%. The results for this investigation are depicted in Figure 4-7.

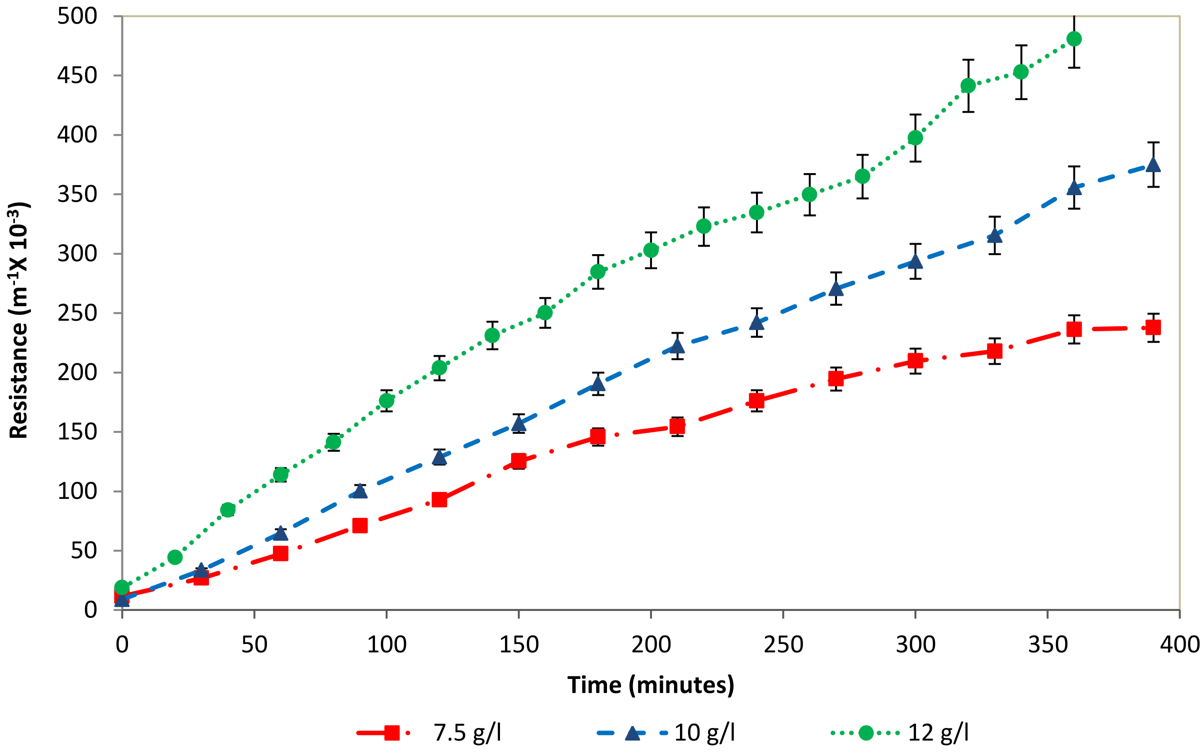


Figure 4-7: Fouling resistance as a function of MLSS concentration using the 33% pump setting and air-scour rate of 10 l/min/module

Figure 4-7 shows that the concentration of the MLSS does play a large role in the fouling rate. These results are in agreement with literature since higher MLSS concentrations promote a higher fouling rate.

CHAPTER 5. LAB SCALE INVESTIGATION

The results obtained in the Chapter 4 were contradictory, therefore to further validate the results that were obtained on the pilot plant, an identical lab-scale WF-IMBR was set-up to investigate different operating regimes, reproducibility and repeatability on activated sludge samples from three wastewater treatment plants around the Western Cape. The first sub-section gives insight into how the lab-scale set-up was designed as well as the experimental methods employed in this chapter (Section 5.1). The subsections to follow include the results of the experiments done on Macassar (Section 5.2), Bellville (Section 5.3) and Zandvliet's (Section 5.4) Activated Sludge samples. Thereafter a comparison of the results obtained from the three Wastewater Treatment Works was discussed and summarised in Section 5.5 .

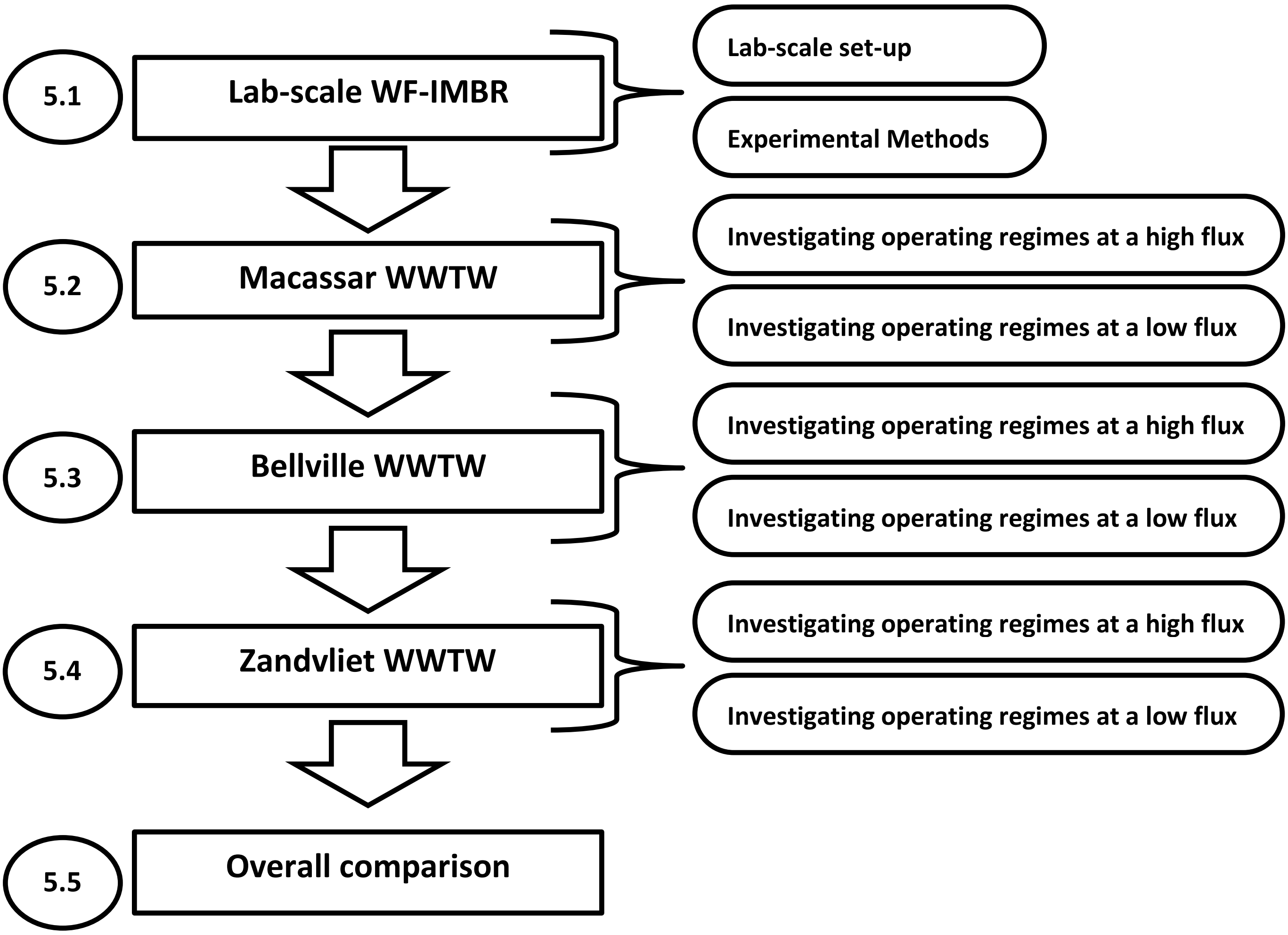


Figure 5-1: Flow chart for Chapter 5

5.1. Lab-scale WF-IMBR Investigations

The investigations at Zandvliet WWTW indicated the very peculiar yet interesting observation that fouling was reduced when there was no air-scouring of the membrane. In order to further investigate these peculiar results obtained whilst operating the WF-IMBR on the Zandvliet WWTW activated sludge an identical lab-scale WF-IMBR was designed and constructed. This was done to establish whether these results were unique to the activated sludge at Zandvliet, or whether the phenomenon would also occur on activated sludge feeds from other wastewater treatment works. Two other wastewater treatment works were selected for this investigation and are listed as follows:

i. Macassar WWTW: Macassar employs a conventional wastewater treatment process, and the feed used in investigations was the returned activated sludge from the post-digester settler.
ii. Bellville WWTW: The Bellville plant had just installed an IMBR unit and the feed sample used in investigations was the same activated sludge that feeds the Bellville IMBR unit.

5.1.1. Lab-scale set-up

The laboratory scale WF-IMBR rig consisted of three membrane modules in a tank fitted with pipe spargers for air-scouring; the permeate flux and air-scour rates could also be independently varied. The construction of the membrane modules and housing was identical to that of the pilot plant, except for scale. The P&ID of the lab-scale rig is shown in Figure 5-3, and a picture of the rig is shown in Figure 5-2.

Figure 5-2: Lab-scale WF-IMBR rig

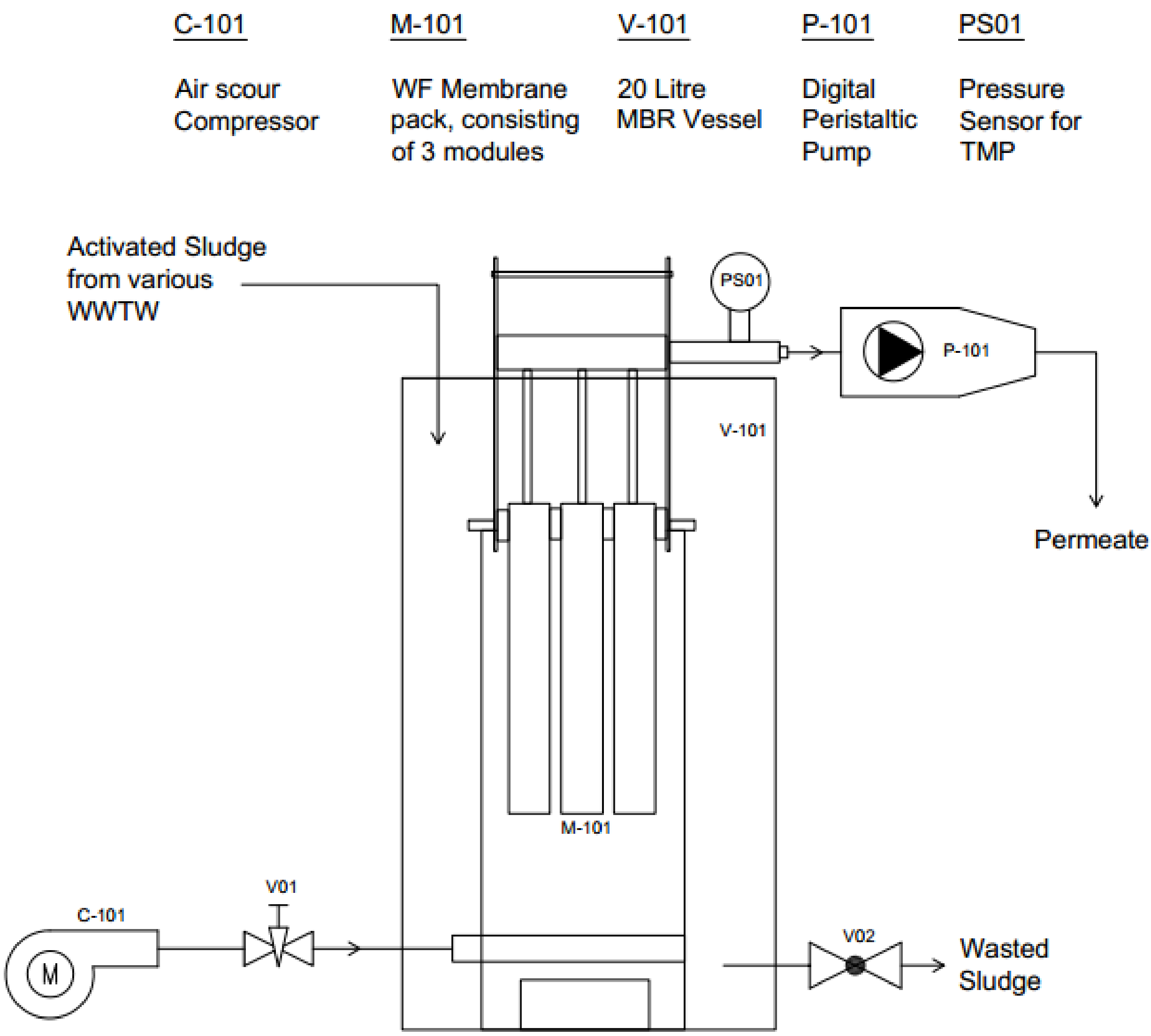


Figure 5-3: P&ID for the lab-scale WF-IMBR rig

As seen in Figure 5-3, the set-up consisted out of a compressor (C-101) coupled with a needle valve (V01) to allow fine tuning of the air-scour rate and a peristaltic pump (P-101) fitted with a pressure gauge (P01) to be able to read the corresponding TMP at the pre-set pump setting. Three identical membrane packs (M-101 A/B/C) were fabricated and were used interchangeably during the subsequent experiments.

The operating procedure used was much the same as for the pilot plant. An air-scour rate and an initial flux were set and then TMP as well as flux profiles were monitored over time; from this a total resistance plot with time was developed.

The Pilot plant rig was operated at fluxes between 6 LMH and 20 LMH, which are typical for many commercial IMBRs. It was endeavoured to operate the lab-scale set-up at the same fluxes; however, these fluxes were too low to be maintained on the lab-scale rig. Accordingly, the lab-scale rig was operated at two initial fluxes i.e. a low flux, which was approximately 30 LMH and a high flux, which was approximately 140LMH. Although both these fluxes are significantly higher than what was used on the pilot plant rig, the main intention was to compare the fouling characteristics of the different feeds. Therefore, there high fluxes would be acceptable since the fouling rates of the different feeds would be equally affected.

The conventional approach to IMBR operation is to operate at the highest feasible air-scouring rate. However, as continuously noted in the previous chapter, higher air-scouring rates do not necessarily result in lower fouling rates. Therefore an alternative operating strategy would be as follows:

i. Operate the WF-IMBR without scouring the membrane (dead-end filtration mode);
ii. Periodically scour the membrane to remove or minimize the accumulated sludge layer, whilst the system is off (relaxation mode);
iii. Operate the system in dead-end filtration mode again.

The above mentioned operating strategy is known as intermittent air-scouring and will be investigated as a possible solution to reducing the energy requirements of the system as well as ensuring that no extreme sludge consolidation will occur which might need energy intensive methods to clean or a substantial amount of permeate.

Henceforth, in addition to investigating the effect of continuous air-scouring and no air-scouring, intermittent air-souring will also be investigated. By scouring the membrane at intermittent intervals, one could perhaps find a balance between being able to keep the membrane surface clear of sludge consolidation as well as being able to reap the apparent benefits of filtering without scouring the membrane surface.

As previously mentioned, it should be noted that for these lab-scale experiments 3 different membrane packs were developed to ensure that experiments could be continued whilst the other two packs were being cleaned. It was of great importance to ensure that all three packs (M-101 A.B/C) used had identical pure water flux curves to ensure that the results were reproducible and repeatable, regardless of which pack was being used for the experiment. The cleaning regime used during these trials was therefore more intensive to ensure that the pure water flux curves before any experiment was identical to the pure water flux obtained on a clean un-fouled WFMF membrane pack.

5.1.2. Experimental methods

The following operating procedures were followed for each of the experiments done in this chapter on the activated sludge samples obtained from the various wastewater treatment works:

1) **Sample Collection and Storage:**
    a) Activated sludge samples were collected from the feed to the MBRs at various wastewater treatment plants in 25 litre containers, viz. Zandvliet, Macassar and Bellville WWTW's;
    b) Obtained samples was then stored in a fridge to minimize biological activity.
2) **Experimental Preparation Procedure:**
    a) A pure water flux experiment was performed on the membrane pack (M-101 A/B/C) to be used, to ensure that the membrane was clean;
    b) In the event that the PWF was not achieved, additional cleaning measures had to be taken;
    c) It was ensured that the drainage valve (V02) had been completely closed;
    d) The aeration pipe was connected onto the membrane stand, which was placed in the middle of the MBR vessel (V-101);
    e) It was also ensured that the pressure sensor (PS01) had been opened to atmosphere by opening the latch situated at the top of the sensor;
    f) The MLSS of the feed to be investigated was measured after removing it from storage;
    g) The sample was then poured into V-101 and the remainder was placed back into storage;
    h) The membrane packs (M-101 A/B/C) were placed into the membrane stand and it was ensured that the peristaltic pump (P-101) tubing had been inserted correctly before closing the latch on situated on the pump head of P-101;
    i) Thereafter it was then decided which operating procedure was to be investigated (Continuous, intermittent or no air-scour).
3) **Experimental Execution Procedure:**
    a) **General (Before all experiments)**
        i) The compressor (C-101) was switched on and the air-scour rate to be investigated was selected by adjusting the needle valve (V01) and reading the value from the rotameter;
        ii) P-101 was switched on and the pump speed was selected by adjusting the RPM on the digital screen;
        iii) The timer was started as soon as the first drop of permeate had reached the measuring cylinder;
    b) **Continuous air-scour**
        i) At each time interval, including t=0 (which was when the first drop of permeate had reached the measuring cylinder), the following information needed to be gathered:
            (1) TMP: This was obtained by reading the pressure from PS01;
            (2) Permeate Flowrate: This was measured by using a measuring cylinder and a stopwatch. The flowrate was determined by calculating how long it took to collect a predetermined volume of permeate;
            (3) Permeate Turbidity: The turbidity was measured to ensure the integrity of the membrane was upheld throughout the duration of the experiment.

ii) During the experiment, additional activated sludge from the same WWTW was used to keep the level in V-101 constant since the permeate was not recycled back into the system;

iii) After the last reading was taken, the experiment was officially done.

c) Intermittent air-scour

i) At each time interval, including t=0 (which was when the first drop of permeate had reached the measuring cylinder), the following information needed to be gathered:

(1) TMP: This was obtained by reading the pressure from PS01;

(2) Permeate Flowrate: This was measured by using a measuring cylinder and a stopwatch. The flowrate was determined by calculating how long it took to collect a predetermined volume of permeate;

(3) Permeate Turbidity: The turbidity was measured to ensure the integrity of the membrane was upheld throughout the duration of the experiment.

ii) After the selected filtration duration was achieved (which was 5 minutes for all the experiments done in this chapter), P-101 was switched off;

iii) C-101 was then switched on for the specific air-scour duration (this was for 30 seconds for all the experiments done in this chapter), thereafter it was switched off again;

iv) After the air-scour was completed, P-101 was then switched on again;

v) Steps vi-viii were repeated after the filtration duration was reached again;

vi) During the experiment, additional activated sludge from the same WWTW was used to keep the level in V-101 constant since the permeate was not recycled back into the system;

vii) After the last reading was taken, the experiment was officially done.

d) No air-scour

i) For these experiments C-101 was not switched on and the biomass was manually stirred at regular intervals to ensure that the sludge does not settle;

ii) At each time interval, including t=0 (which was when the first drop of permeate had reached the measuring cylinder), the following information needed to be gathered:

(1) TMP: This was obtained by reading the pressure from PS01;

(2) Permeate Flowrate: This was measured by using a measuring cylinder and a stopwatch. The flowrate was determined by calculating how long it took to collect a predetermined volume of permeate;

(3) Permeate Turbidity: The turbidity was measured to ensure the integrity of the membrane was upheld throughout the duration of the experiment.

iii) During the experiment, additional activated sludge from the same WWTW was used to keep the level in V-101 constant since the permeate was not recycled back into the system;

iv) After the last reading was taken, the experiment was officially done.

4) <u>Post-Experimental Procedure:</u>

a) P-101 and C-101 was then switched off, where necessary;

b) M-101 A/B/C was then removed from V-101 and photos were taken;

c) V-101 was then drained of all its contents and then stored before disposing appropriately;

d) M-101 A/B/C was rinsed off prior to chemical cleaning, which consisted of chemical cleaning similar to what was done on the pilot plant trials;

5.2. Macassar WWTW activated sludge experiments

5.2.1. Investigating operating regimes at a high flux

The first set of experiments done on the Macassar WWTW activated to investigate different operating regimes were done using the 5% pump setting; which imposed an initial flux of 140 LMH. Continuous air-scour was maintained at 10 l/min/module and intermittent air-scour was achieved by scouring every 4 minutes for 1 minute at a rate of 10 l/min/module. The details of the experiments performed are summarised in Table 5-1 and Figure 5-4 illustrates the respective average resistance profiles.

Table 5-1: Order and details of experiments done on Macassar WWTW activated sludge at 5% pump setting

Experiment	MLSS (g/l)	Operating mode	Air-scour rate (l/min/module)
1	10.2	No air-scour	0
2	10.2	Continuous air-scour	10
3	10.2	Intermittent air-scour	10
4	10.2	No air-scour	0
5	10.5	Continuous air-scour	10
6	10.5	Intermittent air-scour	10

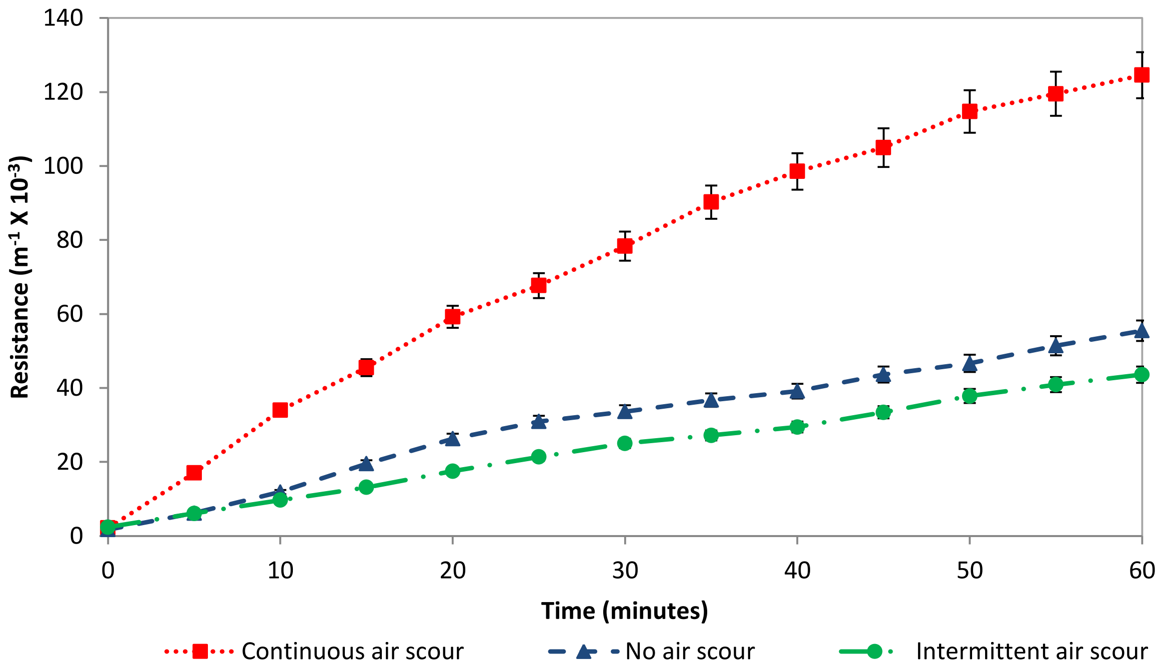


Figure 5-4: Fouling resistance for Macassar WWTW activated sludge (MLSS = 10.3 -10.5 g/l) for different operating regimes using a pump setting of 5%.

Figure 5-4 shows that the lab-scale results are in general agreement with the pilot plant results, which suggests that there is a higher fouling rate when operating with continuous air-scour (34 $m^{-1}s^{-1}$) compared to no air-scour (14.94 $m^{-1}s^{-1}$). Furthermore, operating with intermittent air-scour results in the lowest fouling rate (11.45 $m^{-1}s^{-1}$). In this instance, by operating with intermittent air-scour, the WF-IMBR system could benefit from advantageous aspects of operating with and without air-scouring the membrane; hence the low fouling rate achieved. The main difference between intermittent air-scour and no air-scour is that, during intermittent air-scour the membrane surface could be cleaned at regular intervals, which decreased the extent of sludge consolidation. Photos of the membranes taken after the various trials are shown in Figure 5-5.

Figure 5-5: Lab-scale comparison of the WFMF after continuous air-scouring (Left), intermittent air-scour (middle) and after no air-scour (Right) on Macassar WWTW activated sludge at using 5% pump setting.

Furthermore, it can be seen from Figure 5-5 that during continuous air-scour trials the WFMF membrane surface was always kept clean and that no sludge consolidation could occur; there was also no sludge build-up between the modules. During the no-scour trials however, it can be seen that the entire active area had been completely covered with a thick layer of consolidated activated sludge, which was expected. For the intermittent air-scour trials, there seems to be some form of marginal sludge consolidation, but most of the membranes had been kept clear of substantial sludge consolidation. The fact that operating without air-scouring provides the lowest fouling rate regardless of the sludge layer formed, gives good insight into the type of fouling that is causing the high fouling rate, which is discussed in Section 5.5.

5.2.2. Investigating operating regimes at a low flux

The second set of experiments done on the Macassar Wastewater Treatment Works activated sludge were done using the 1% pump setting; which imposed an initial flux of 27 LMH. Continuous air-scour was maintained at 3 l/min/module and intermittent air-scour was achieved by scouring every 4 minutes for 1 minute at a rate of 3 l/min/module. The details of the experiments performed are summarised in Table 5-2 and Figure 5-6 illustrates the respective average resistance profiles.

Table 5-2: Order and details of experiments done on Macassar WWTW activated sludge at 1% pump setting

Experiment	MLSS (g/l)	Operating mode	Air-scour rate (l/min/module)
1	8.2	No air-scour	0
2	8.2	Continuous air-scour	3
3	8.2	Intermittent air-scour	3
4	8.4	No air-scour	0
5	8.4	Continuous air-scour	3
6	8.4	Intermittent air-scour	3

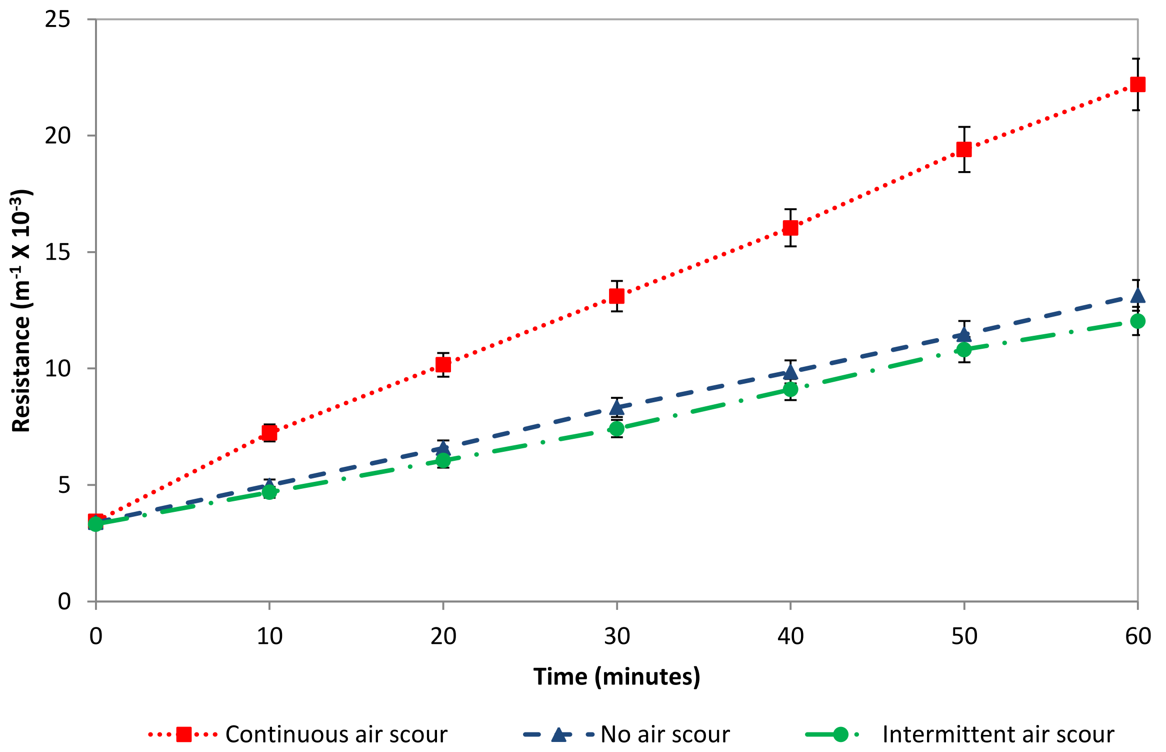


Figure 5-6: Fouling resistance for Macassar WWTW activated sludge (MLSS = 8.2-8.4 g/l) for different operating regimes using a pump setting of 1%.

Once again it can be seen that Figure 5-6 shows that the lab-scale results are in general agreement with the pilot plant results. Operating with continuous air-scour (5.21 $m^{-1}s^{-1}$) yielded a higher fouling rate when compared to no air-scour (2.71 $m^{-1}s^{-1}$). Moreover, operating with intermittent air-scour resulted in a slightly lower fouling rate (2.42 $m^{-1}s^{-1}$) than operating with no air-scour, similarly to what was achieved when operating the 5% pump setting. Photos of the membranes taken after the various trials are shown in Figure 5-7.

Figure 5-7: Lab-scale comparison of the WFMF after continuous air-scouring (Left), intermittent air-scour (middle) and after no air-scour (Right) on Macassar WWTW activated sludge at using 1% pump setting.

Once more it can be seen from Figure 5-7 that during continuous air-scour trials the WFMF membrane surface was kept clean and that there was also no sludge build-up between the modules either. During the no-scour trials however, it can be seen that majority of the active area had been covered with a thick layer of activated sludge. For the intermittent air-scour trials, there seems to be minimal sludge consolidation and most of the membranes had been kept clear of considerable sludge consolidation.

5.3. Bellville WWTW activated sludge experiments

5.3.1. Investigating operating regimes at a high flux

The first set of experiments done on the Bellville WWTW activated to investigate different operating regimes were done using the 5% pump setting; which imposed an initial flux of 140 LMH. Continuous air-scour was maintained at 10 l/min/module and intermittent air-scour was achieved by scouring every 4 minutes for 1 minute at a rate of 10 l/min/module. The details of the experiments performed are summarised in Table 5-3 and Figure 5-8 illustrates the respective average resistance profiles.

Table 5-3: Order and details of experiments done on Bellville WWTW activated sludge at 5% pump setting

Experiment	MLSS (g/l)	Operating mode	Air-scour rate (l/min/module)
1	7.9	No air-scour	0
2	7.9	Continuous air-scour	10
3	7.9	Intermittent air-scour	10
4	8.3	No air-scour	0
5	8.3	Continuous air-scour	10
6	8.3	Intermittent air-scour	10

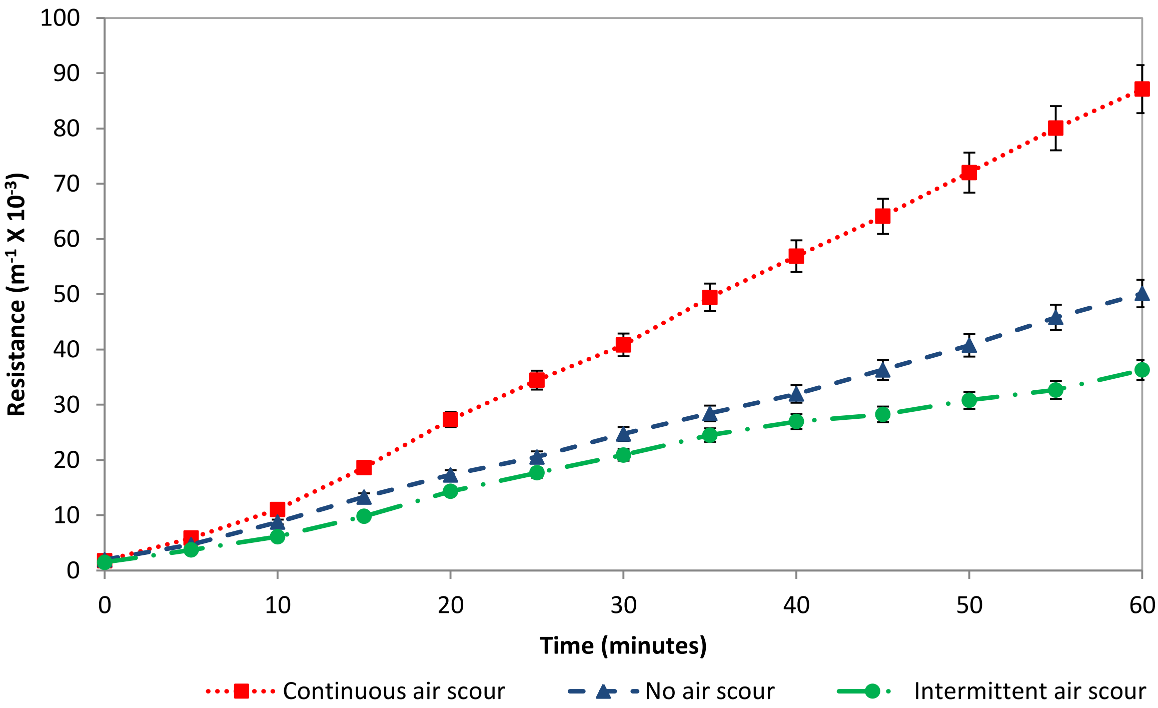


Figure 5-8: Fouling resistance for Bellville WWTW activated sludge (MLSS = 7.9 -8.1 g/l) for different operating regimes using a pump setting of 5%.

Similar to what was observed in the Macassar trials, Figure 5-8 shows that there is a higher fouling rate when operating with continuous air-scour (23.71 $m^{-1}s^{-1}$) compared to no air-scour (13.38 $m^{-1}s^{-1}$). Additionally, operating with intermittent air-scour results in the lowest fouling rate (9.67 $m^{-1}s^{-1}$). Photos of the membranes taken after the various trials are shown in Figure 5-9.

Figure 5-9: Lab-scale comparison of the WFMF after continuous air-scouring (Left), intermittent air-scour (middle) and after no air-scour (Right) on Bellville WWTW activated sludge at using 5% pump setting.

Once more it can be seen from Figure 5-9 that during continuous air-scour trials the WFMF membrane surface was kept clean and that there was also no sludge build-up between the modules either. During the no-scour trials however, it can be seen that majority of the active area had been covered with a thick layer of activated sludge. For the intermittent air-scour trials, there seems to be minimal sludge consolidation and most of the membranes had been kept clear of considerable sludge consolidation.

5.3.2. Investigating operating regimes at a low flux

The second set of experiments done on the Bellville Wastewater Treatment Works activated sludge were done using the 1% pump setting; which imposed an initial flux of 27 LMH. Continuous air-scour was maintained at 3 l/min/module and intermittent air-scour was achieved by scouring every 4 minutes for 1 minute at a rate of 3 l/min/module. The details of the experiments performed are summarised in Table 5-4 and Figure 5-10 illustrates the respective average resistance profiles.

Table 5-4: Order and details of experiments done on Bellville WWTW Activated sludge at 1% pump setting

Experiment	MLSS (g/l)	Operating mode	Air-scour rate (l/min/module)
1	8.8	No air-scour	0
2	8.8	Continuous air-scour	3
3	8.8	Intermittent air-scour	3
4	8.8	No air-scour	0
5	9.1	Continuous air-scour	3
6	9.1	Intermittent air-scour	3

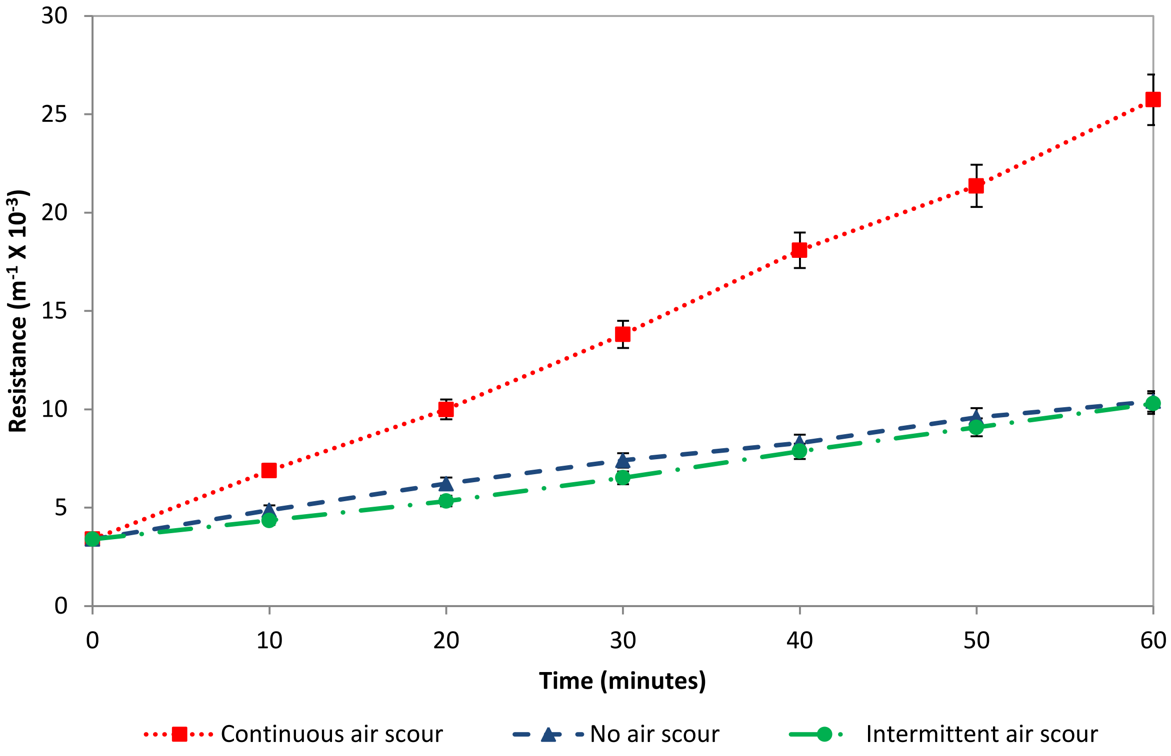


Figure 5-10: Fouling resistance for Bellville WWTW activated sludge (MLSS = 8.8-9.1 g/l) for different operating regimes using a pump setting of 1%.

Once again it can be seen that Figure 5-10 shows that the lab-scale results are in general agreement with the pilot plant results and the results obtained on the Macassar WWTTW activated sludge feed. Operating with continuous air-scour (6.20 $m^{-1}s^{-1}$) yielded a higher fouling rate when compared to no air-scour (1.95 $m^{-1}s^{-1}$). Furthermore, operating with intermittent air-scour resulted in similar fouling rate (1.91 $m^{-1}s^{-1}$) when compared to operating with no air-scour.

Furthermore, it can be seen from Figure 5-11 that during continuous air-scour trials the WFMF membrane surface was kept clean and that there was also no sludge build-up between the modules either. During the no-scour trials however, it can be seen that almost the entire active area had been covered with a thick layer of activated sludge; there was also a substantial about of sludge consolidation between the modules. For the intermittent air-scour trials, there seems to be almost no sludge consolidation and most of the membrane active area had been kept clear of considerable sludge consolidation, there was also minimal sludge build-up between the membranes similarly to what is noticed after continuous air-scour.

Figure 5-11: Lab-scale comparison of the WFMF after continuous air-scouring (Left), intermittent air-scour (middle) and after no air-scour (Right) on Bellville WWTW activated sludge at using 1% pump setting.

5.4. Zandvliet WWTW activated sludge experiments

5.4.1. Investigating operating regimes at a high flux

The first set of experiments done on the Zandvliet WWTW activated to investigate different operating regimes were done using the 5% pump setting; which also imposed an initial flux of 140 LMH. Continuous air-scour was maintained at 10 l/min/module and intermittent air-scour was achieved by scouring every 4 minutes for 1 minute at a rate of 10 l/min/module. The details of the experiments performed are summarised in Table 5-5 and Figure 5-12 illustrates the respective average resistance profiles.

Table 5-5: Order and details of experiments done on Zandvliet WWTW Activated sludge at 5% pump setting

Experiment	MLSS (g/l)	Operating mode	Air-scour rate (l/min/module)
1	9.5	No air-scour	0
2	9.5	Continuous air-scour	10
3	9.5	Intermittent air-scour	10
4	9.5	No air-scour	0
5	9.7	Continuous air-scour	10
6	9.7	Intermittent air-scour	10

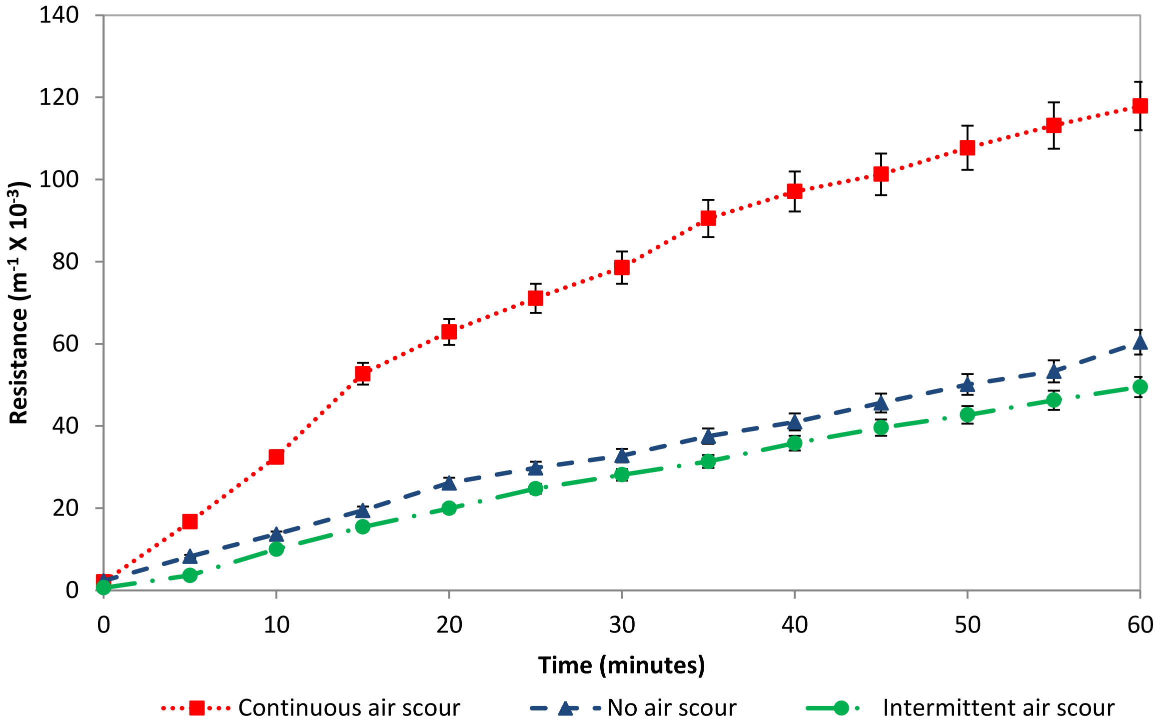


Figure 5-12: Fouling resistance for Zandvliet WWTW activated sludge (MLSS = 9.5-9.7 g/l) for different operating regimes using a pump setting of 5%.

The exact same results as obtained on the other two activated sludge feeds were obtained on the Zandvliet WWTW activated sludge as represented by Figure 5-12. Continuous air-scour yielded the highest fouling rate (32.18 $m^{-1}s^{-1}$), whereas operating without air-scour (16.14$m^{-1}s^{-1}$) and with intermittent air-scour (13.58 $m^{-1}s^{-1}$) yielded significantly lower fouling rates.

Figure 5-13: Lab-scale comparison of the WFMF after continuous air-scouring (Left), intermittent air-scour (middle) and after no air-scour (Right) on Zandvliet WWTW activated sludge at using 5% pump setting.

The photos taken after the Zandvliet trials at a high flux were in close resemblance to that seen from photos taken after trials on Macassar and Bellville WWTW activated sludge feeds. Figure 5-13 shows that the membranes were kept clean during continuous air-scour runs and that a sludge blanket had formed on the membrane surface during no air-scour runs. During intermittent air-scour runs only a small portion of the membrane was covered with sludge.

5.4.2. Investigating operating regimes at a low flux

The second set of experiments done on the Zandvliet Wastewater Treatment Works activated sludge were done using the 1% pump setting; which imposed an initial flux of 27 LMH. Continuous air-scour was maintained at 3 l/min/module and intermittent air-scour was achieved by scouring every 4 minutes for 1 minute at a rate of 3 l/min/module. The details of the experiments performed are summarised in Table 5-6 and Figure 5-14 illustrates the respective average resistance profiles.

Table 5-6: Order and details of experiments done on Zandvliet WWTW Activated sludge at 1% pump setting

Experiment	MLSS (g/l)	Operating mode	Air-scour rate (l/min/module)
1	9.8	No air-scour	0
2	9.8	Continuous air-scour	3
3	10.1	Intermittent air-scour	3
4	10.1	No air-scour	0
5	10.1	Continuous air-scour	3
6	10.1	Intermittent air-scour	3

Figure 5-14 reconfirms that all the lab-scale results are in complete agreement with the pilot plant results. Operating with continuous air-scour (7.86 $m^{-1}s^{-1}$) yielded the highest fouling rate; whilst operating with no air-scour (1.77 $m^{-1}s^{-1}$) and intermittent air-scour resulted in significantly lower fouling rates (1.61 $m^{-1}s^{-1}$).

Moreover, it can be seen from Figure 5-15 that that continuous air-scour trials the WFMF membrane surface was kept clean and that there was also no sludge build-up between the modules either. During the no-scour trials however, it can be seen that majority of the active area had been covered with a thick layer of activated sludge and for intermittent air-scour trials, there seems to be very little sludge consolidation and there was also minimal sludge build-up between the membranes. This is also in agreement with all the photographic evidence provided throughout this chapter.

Lastly, with respect to cleaning the membrane, it was also noticed that the most effective cleaning regime was by scrubbing the dried membranes after doing a chemical clean. This resulted in membranes that were identical to clean membranes before doing any experiments on them. It is therefore postulated that by allowing the WFMF membranes to fully dry, could result in a less energy intensive cleaning process in terms of chemical cleaning.

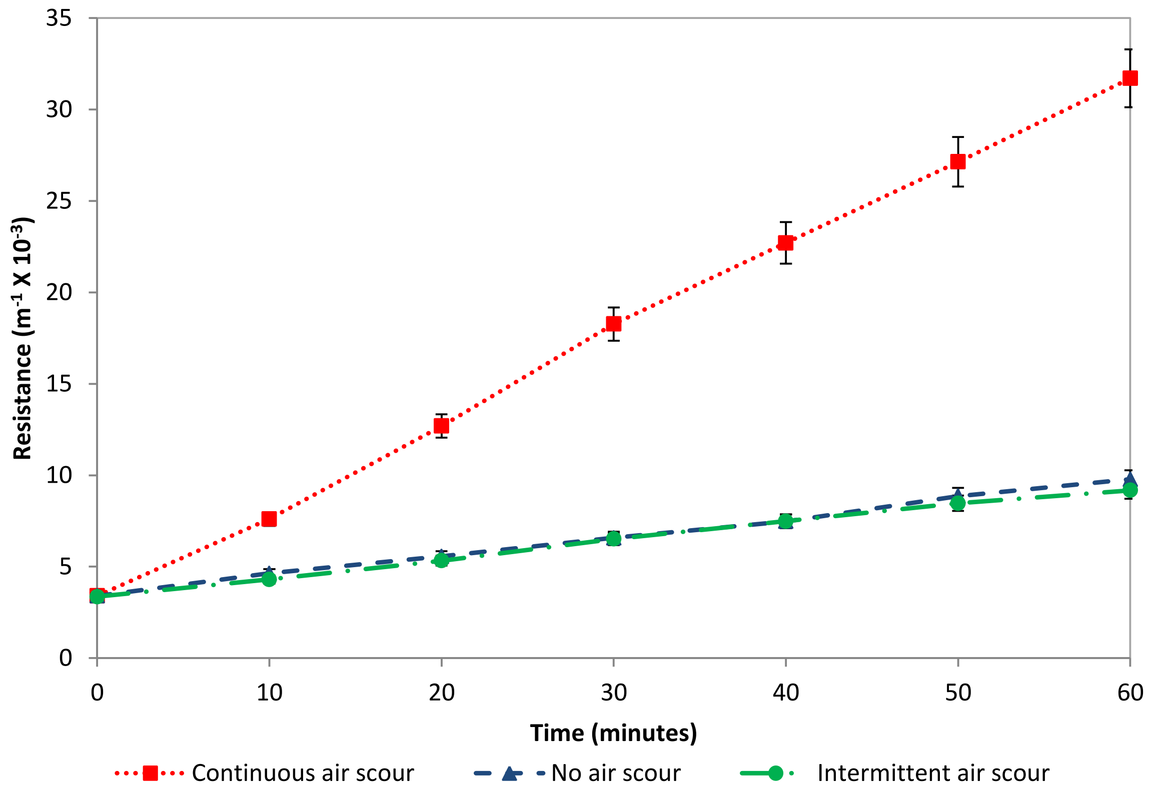


Figure 5-14: Fouling resistance for Zandvliet WWTW activated sludge (MLSS = 9.8-10.1 g/l) for different operating regimes using a pump setting of 1%.

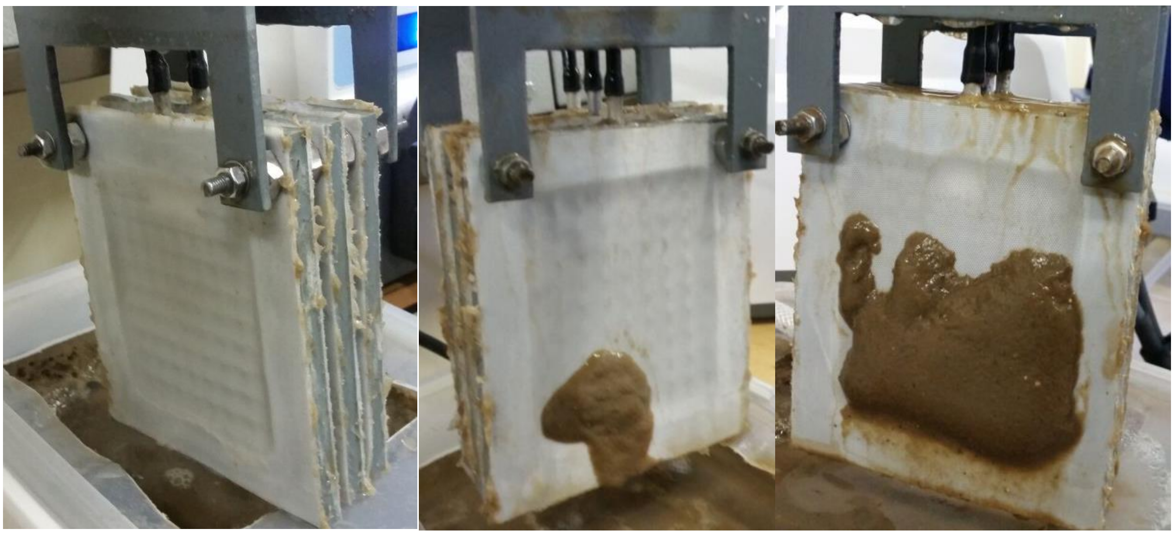


Figure 5-15: Lab-scale comparison of the WFMF after continuous air-scouring (Left), intermittent air-scour (middle) and after no air-scour (Right) on Zandvliet WWTW activated sludge at using 1% pump setting.

5.5. Overall comparison of lab-scale results

As mentioned throughout this chapter, the results obtained for each of the three sludge feeds investigated on a lab-scale WF-IMBR resembled what was being achieved on the pilot plant rig. Figure 5-16 and Figure 5-17 shows the three-dimensional bar graph comparisons of the various fouling rates obtained on the feeds for the different operating regimes investigated for both fluxes. It was an interesting coincidence that the feeds investigated had different ranges of MLSS concentrations and hence the graphs were plotted in terms of these concentrations instead of the sludge feed origins. The fouling rate used to plot these graphs was calculated by dividing the total increase in resistance by the duration of the experiment. Due to the fact that the resistance profiles were linear, the fouling rate calculated represents the average fouling rate throughout the experiment:

Equation 5-1 $$\textit{Fouling rate},\ F = \frac{R_{tot}}{\Delta t}$$

Where: R_{tot} = Total resistance = membrane resistance + resistance due to fouling (m^{-1});

Δt = Experiment duration (s);

F = Fouling rate ($m^{-1}.s^{-1}$).

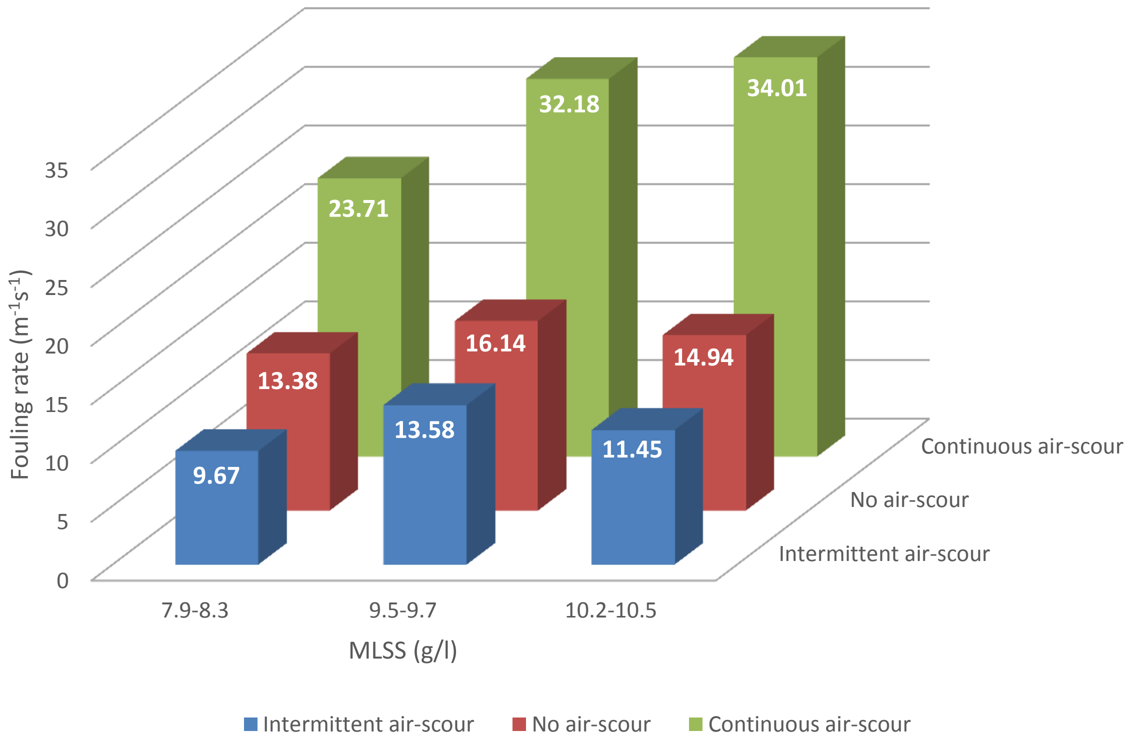


Figure 5-16: Overall comparison of operating regimes on different concentrations for a pump setting of 5%

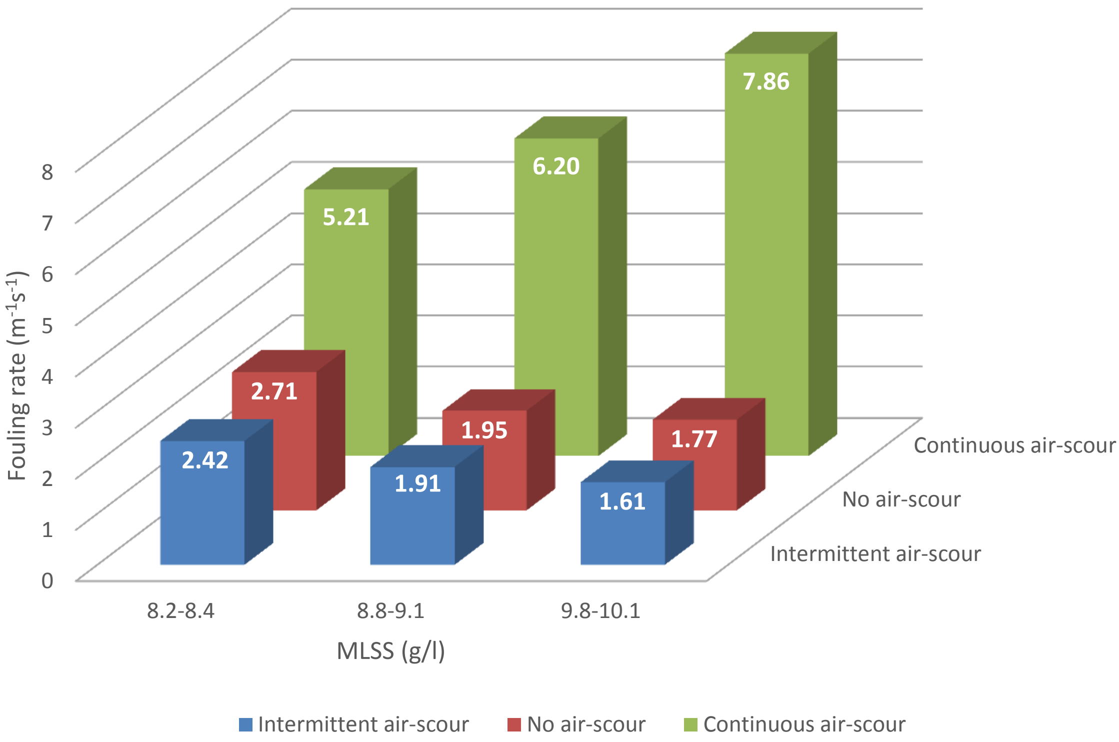


Figure 5-17: Overall comparison of operating regimes on different concentrations for a pump setting of 1%

The most obvious trend that can be observed in Figure 5-16 and Figure 5-17 is that for all the experiments, there seemed to be a significantly larger fouling rate when operating in with continuous air-scouring. Furthermore, operating without air-scouring gave a much lesser fouling rate with intermittent air-scouring providing a similar fouling rate when compared to operating without air-scouring.

This trend, which has been observed throughout this chapter, relates directly to the type of fouling experienced during the different operating regimes investigated. The effect of shear, caused by air-scouring, is to increase back transport, discouraging large particle deposition on the membrane surface and promoting mass transfer of liquid through the membrane. Since air-scouring ameliorates clogging, this operating regime could lead to more severe membrane fouling by fine materials (Judd, 2011; Maqbool, et al., 2014).

Conversely, operating with no or intermittent air-scouring resulted in lower fouling rates which may be explained through a difference in deposition kinetics under the different hydrodynamic conditions. It is hypothesised that the shear imposed by continuous air-scouring controlled the filter cake height rather than providing deposit reversibility (McAdam, et al., 2011). This means that when operating without scouring the membrane during filtration, the filter cake was allowed to grow, which consequently protected the membrane from pore-clogging. The reversibility of the cake can be attributed to the simultaneous deposition of soluble, colloidal and flocculent materials which created a more heterogeneous, porous and subsequently less tenacious deposit (McAdam, et al., 2011).

By operating with intermittent air-scouring, the filter cake could be periodically removed or minimized to decrease filter cake consolidation (McAdam & Judd, 2008). To ensure optimal intermittent air-scouring operation, the three main parameters involved would need to be further investigated, which is addressed in Section 6.1.2. The implications of operating with intermittent air-scouring will have a significant impact on the energy demand of the WF-IMBR system, which could make IMBR technology the most feasible option for wastewater treatment.

The second noticeable trend is that the MLSS concentration also played slight a role in the fouling rate. This analysis needs to be subjective however, since the MLSS concentrations plotted came from different feed sources; which could mean that the fouling propensities might be due to the sludge content and not necessarily due to the MLSS concentration. Nonetheless, there were different trends observed when operating at a large flux (ca. 140 LMH) than when operating at a lower flux (ca. 27 LMH).

On the one hand, when operating at higher fluxes, illustrated by Figure 5-16, there was an increase in fouling rate with an increase in MLSS concentration. This is consistent with majority of the available literature which states that studies have shown membrane permeability to decline with MLSS (Judd, 2011).

On the other hand, when operating at lower fluxes, illustrated by Figure 5-17, there was only an increase in fouling rate with MLSS when operating with continuous air-scouring. There is no real explanation in literature as to why the fouling rate increases inversely with MLSS concentration when operating with no or intermittent air-scouring regimes. However, it is hypothesised that this is based on the same principles which suggest that operating with no-air-scour results in lower fouling rates when compared to continuous air-scour regimes. This means that higher MLSS concentrations would provide an improved filter cake formation along the active area if the membrane, which consequently protected the membrane better from pore-clogging than lower concentrations. However this effect could become obsolete at higher fluxes simply due to faster process dynamics, as seen in Figure 5-16.

In conclusion, it was evident that operating with intermittent air-scour resulted in a marginally lower fouling rate compared to no air-scour. Both these air-scour regimes had a significantly lower fouling rate compared to continuous air-scouring.

CHAPTER 6. SUBSTANTIATION EXPERIMENTS

In order to validate the results obtained during the lab-scale trials, two additional experiments were set-up to investigate the effect of several air-scour rates on the fouling rate as well as doing a factorial design on the intermittent air-scour operation to assess which parameters have a significant effect on the fouling rate. Furthermore, due to the interesting results obtained with regards to intermittent operation on a lab-scale, similar experiments were performed on the pilot plant rig situated at Zandvliet WWTW. The results of the additional experiments done on the lab-scale WF-IMBR will be discussed (Section 6.1), followed by the results of the pilot plant substantiation experiments (Section 6.2). Lastly the results of the permeate quality analysis will be discussed in Section 6.3.

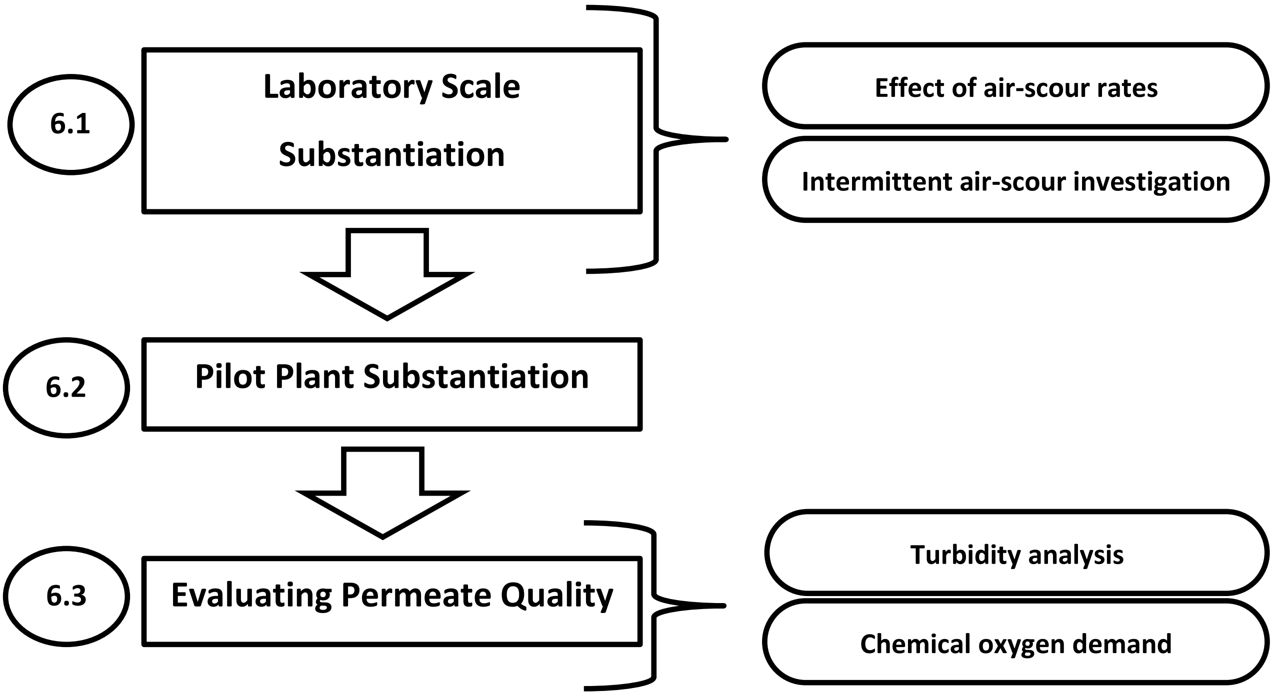


Figure 6-1: Flow chart of Chapter 6

6.1. Laboratory Scale Substantiation

6.1.1. Investigating effect of air-scour rates

According to various literature as summarized in the MBR Book (Judd, 2011), higher air-scour rates should permit higher fluxes before fouling can occur. To investigate this theory, various continuous air-scour rates, as well as no air-scour was investigated on the lab-scale WF-IMBR. The details of the experiments performed are summarised in Table 6-1 and the results are displayed in Figure 6-2.

Table 6-1: Order and details of experiments done on ZWWTW Activated sludge to investigate the effect of air-scour rate using 1% pump setting

Experiment	MLSS (g/l)	Operating mode	Air-scour rate (l/min)
1	11.5	Continuous air-scour	8
2	11.5	Continuous air-scour	30
3	11.5	Continuous air-scour	4
4	11.8	Continuous air-scour	6
5	11.8	No air-scour	0
6	11.8	Continuous air-scour	2
7	11.8	Continuous air-scour	10

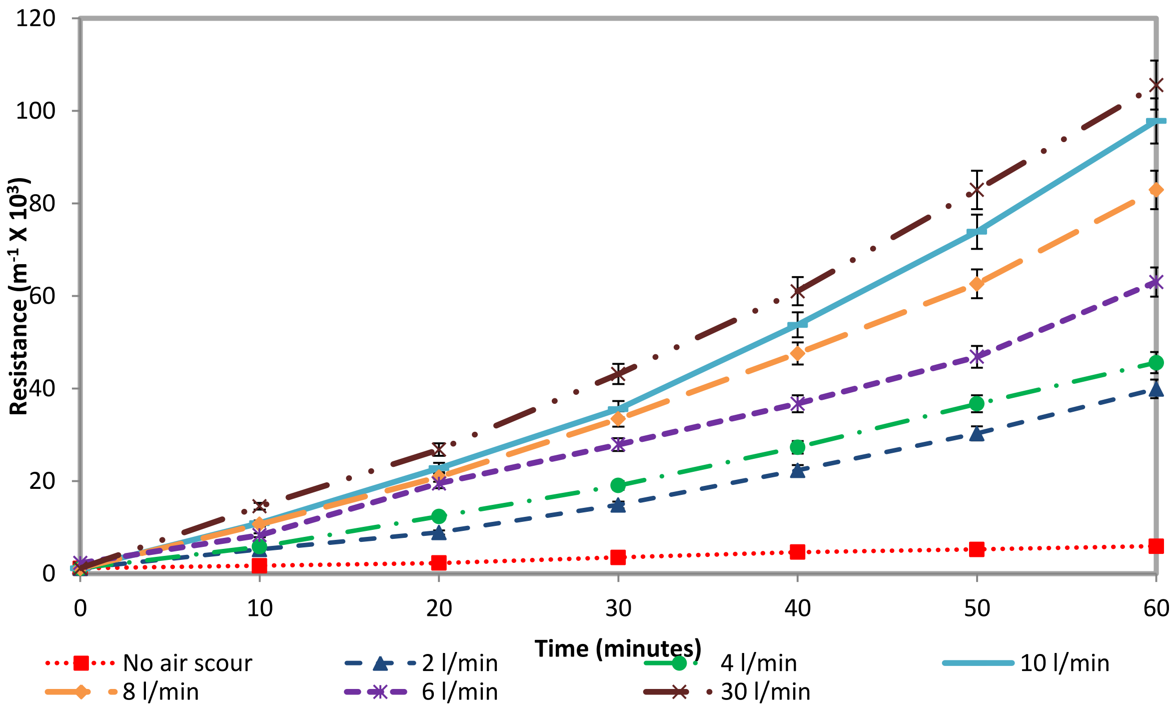


Figure 6-2: Fouling resistance as a function of air-scour rate for ZWWTW (MLSS = 11.5-11.8 g/l) using a pump setting of 1%.

There is a clear trend that can be immediately identified when examining the results displayed in Figure 6-2. This is that there seems to be an increase in the fouling rate with an increase in the air-scour rate. It is once again noticed that operating without air-scouring the membrane resulted in a significantly lower fouling rate. These results contradict literature which suggests that the opposite should occur i.e. higher air-scour rates should impose a lower fouling rate (Judd, 2011). It is speculated that this theory would probably apply well if the activated sludge consisted of a narrow size range of particles of relatively uniform properties.

Henceforth, a plausible explanation to why this strange phenomenon is occurring could be solely due to the nature of the activated sludge used during the various investigations throughout this study. In practice, activated sludge would consist of bacteria, dissolved inorganics and various micro-organics. These organics would comprise of organics in the feed that could not be digested, as well as organics produced by the activated sludge bacteria themselves, as a result of being 'stressed', e.g. extra-cellular polysaccharides (EPS). EPS is a gel-like substance with an extremely high fouling potential. The content of EPS in any activated sludge will be a function of how stressed the bacteria are i.e. if they have been highly stressed, the content of EPS would be high and if they have been relatively unstressed, the content of EPS would be lower. (McAdam, et al., 2011)

It is further postulated that in a conventional and well-run activated sludge plant, the settled bacteria are likely to be relatively un-stressed and hence the mixed liquor will contain low concentrations of EPS. In a wastewater treatment plant that includes anoxic and anaerobic zones (such as all the feeds examined), there is a higher likelihood that there will be a high population of stressed bacteria and therefore a higher EPS concentration. The significant component of EPS would arise from the fact that bacteria are being exposed to various zones (aerobic, anoxic and anaerobic) that stress them due to the various recycle streams in such systems.

Bacteria are relatively large (ca. 2 µm to 5 µm) and are therefore easy to filter. Hence, in terms of the propensity to foul membranes, bacteria are not regarded as problematic. EPS on the other hand, forms a gel type of structure that will block and penetrate membranes easily. Thus EPS has a high fouling potential and is difficult to clean off membranes.

Furthermore, if a membrane system is operated with high air-scour rates, all the bacteria will be swept away from the surface, which would allow smaller organic material to easily reach the membrane surface and penetrate the membrane (McAdam, et al., 2011). This type of fouling is not easily reversed hydrodynamically. Consequently, if the system is to operate without air-scouring, the bacteria will immediately form a fouling layer which will grow since there is no cross-flow across the membrane surface. Hypothetically this bacterial fouling layer would act as a pre-coat which prevents EPS from reaching the membrane surface. The net result is that fouling will be controlled by the bacteria (low fouling potential), rather than the EPS (high fouling potential).

It is hypothesised that the shear imposed by continuous air-scouring controlled the filter cake height rather than providing deposit irreversibility (McAdam, et al., 2011). This would explain why there was a clear trend signifying that the higher the air-scour rate, the higher the fouling rate; since the shear imposed by higher air-scour rates, minimized the filter cake, which in turn promotes pore clogging.

The above explanation is however only an attempt to explain the seemingly anomalous results obtained during the course of this study. Further investigations would be necessary to ascertain these claims since this would have significant implications for the operation of IMBRs in general.

Nonetheless, it can be concluded that an increase in the air-scour rate resulted in an increase in the fouling rate, which differs to what Is reported in literature (Judd, 2011), but as explained in this sub-section this phenomena could be attributed to the concentration of EPS in the sludge samples, or even simply due to the fact that the activated sludge samples did not consist of particles of relatively uniform properties.

6.1.2. Intermittent air-scour investigation

It has been well documented in the previous chapter that operating with intermittent air-scouring could potentially result in the development of an operating regime that could possibly benefit from the advantages of both operating with continuous air-scouring as well as with operating without air-scouring the WFMF membrane.

By operating the system without air-scouring during filtration, the WFMF could benefit from the sludge layer formed on the membrane surface as explained in the previous sub-section and by scouring the membrane periodically, whilst the system is off (relaxation mode), the sludge layer formed on the membrane surface can be minimized or even removed, to ensure that extreme sludge consolidation does not occur.

6.1.2.1. Experimental Approach

In order to investigate the effect of the main parameters associated with the intermittent air-scour regime, it was decided to use a three factor two level full factorial design. The three main factors that influence the intermittent air-scour regime is the air-scour rate, the air-scour duration and the filtration duration. The parameters that were fixed for this investigation were the MLSS concentration (which ranged between 8.5 and 8.8 g/l due to uncontrollable biological activity) and the 1% pump speed setting.

A total of eight experiments were done randomly to investigate the effect the effect of the three parameters mention. Each parameter consisted of a high and a low level and was only performed; the levels of the parameters were selected as follows:

- Air-scour rate (l/min): This parameter refers to the air-scour rate that was used to periodically scour the membrane whilst the system was in relaxation mode. The low level used was the lowest was 2 l/min, which was the lowest practical air-scour rate available. The high level used was 10 l/min, which was selected due to the fact that there was not much difference in the resistance profile to 30 l/min as per in Figure 6-2 although being 3 times less.
- Air-scour duration (s): This parameter refers to the duration of the intermittent air-scour used during the relaxation mode. The low level used was 30 seconds which was used in a similar study (McAdam, et al., 2011) and the high level was 60 seconds as per the experiments done in chapter 5.
- Filtration duration (min): This parameter refers to the duration that the system operates without air-scouring the membrane. Although scouring every 4 minutes was used during the lab-scale experiments, the low level was based on a suggestion by a similar study (McAdam, et al., 2011), which used a filtration duration of 10 minutes. The high level used was 20 minutes which was the maximum practical filtration duration for these experiments.

Table 6-2 summarises the random order and the details of the 8 experiments performed:

Table 6-2: Order and details of intermittent air-scour factorial design experiments done on Zandvliet WWTW activated sludge using 1% pump setting

Run	Air-scour rate (l/min)	Air-scour duration (s)	Filtration duration (min)	MLSS (g/l)
1	2	30	20	8.5
2	10	60	10	8.5
3	10	30	10	8.5
4	2	60	20	8.5
5	10	60	20	8.8
6	2	30	10	8.8
7	10	30	20	8.8
8	2	60	10	8.8

6.1.2.2. Factorial design results

The resistance profile plots for these set of experiments are shown in Figure 6-3. The plot shows a good distinction between the 8 runs. Although it was endeavoured to make use of a statistical approach to analyse the results of this subsection, clear trends could immediately be observed which will rather be discussed.

On the one hand, as represented by Figure 6-4, the run that had the highest fouling rate (3.58 $m^{-1}s^{1}$), was run 3 which was operated at an intermittent air-scour rate of 10 l/min every 10 minutes for 30 seconds. Close behind it in terms of fouling rate was run 2 (3.38 $m^{-1}s^{-1}$) and to conclude the top 3 was run 6 (2.95 $m^{-1}s^{-1}$). The main parameter that these 3 runs have in common was the fact that all of them were operated for a filtration duration of 10 minutes; this possibly suggests that the filtration duration plays a significant role in the fouling rate.

On the other hand, the three runs with the lowest fouling rates were run 4 (2.06 $m^{-1}s^{-1}$), run 1 (2.19 $m^{-1}s^{-1}$) and run 5 (2.12 $m^{-1}s^{-1}$). Once again, the main parameter that these three runs had in common was the filtration duration of 20 minutes, backing the claim mentioned above.

Moreover, three of the four runs with the lowest fouling rates used an air-scour rate of 2 l/min and air-scour duration of 60 seconds. These parameters seem to be less important than the filtration duration, but they definitely suggest that operating with lower air-scour rates for longer durations could results in a lower fouling rate.

Finally, by talking into account only the runs with the lowest (2.06 $m^{-1}s^{-1}$) and highest fouling rate (3.58 $m^{-1}s^{-1}$), a clear indication can be seen as to how the different levels of the three parameters investigated affect the fouling rate. The run with the lowest fouling rate (Run 4) was operated by scouring the membrane at a rate of 2 l/min for 60 second every 20 minutes and the run with the highest fouling rate (Run 3) was operated by scouring the membrane at a rate of 10 l/min for 30 second every 10 minutes. These two runs alone give a good indication as to how the 3 parameters investigated affect the fouling rate of the WF-IMBR system.

In conclusion, all three parameters investigated had some sort of effect on the fouling rate. The parameter with the most apparent effect was the filtration duration, which suggests that operating with longer filtration durations between periodic scouring, results in a lower fouling rate. Furthermore, the air-scour rate was seemingly the parameter that had the next noteworthy effect on the fouling rate, which suggests that operating with a lower air-scour rate would result in a lower fouling rate. Lastly, the air-scour duration also played a role, since operating with longer air-scour duration resulted in a lower fouling rate.

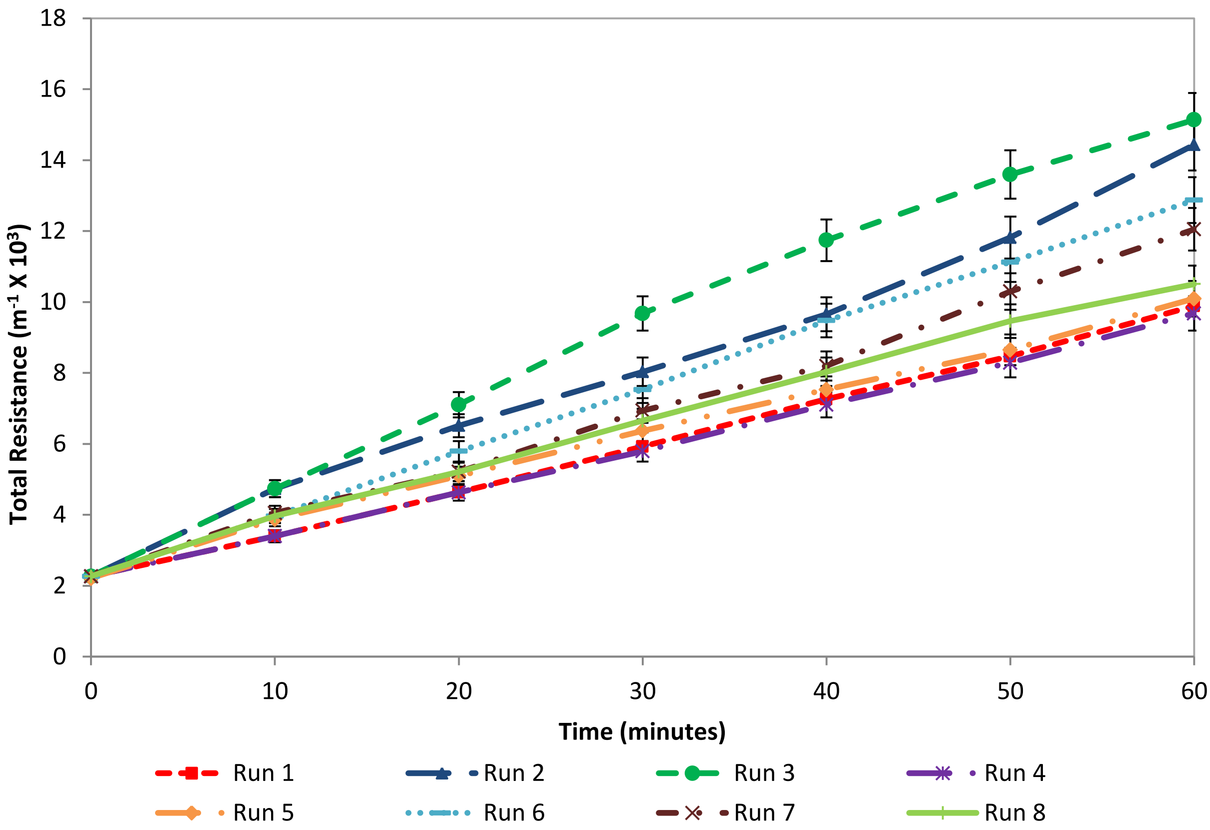


Figure 6-3: Fouling resistance for intermittent air-scour factorial design experiments done on Zandvliet WWTW activated sludge using 1% pump setting

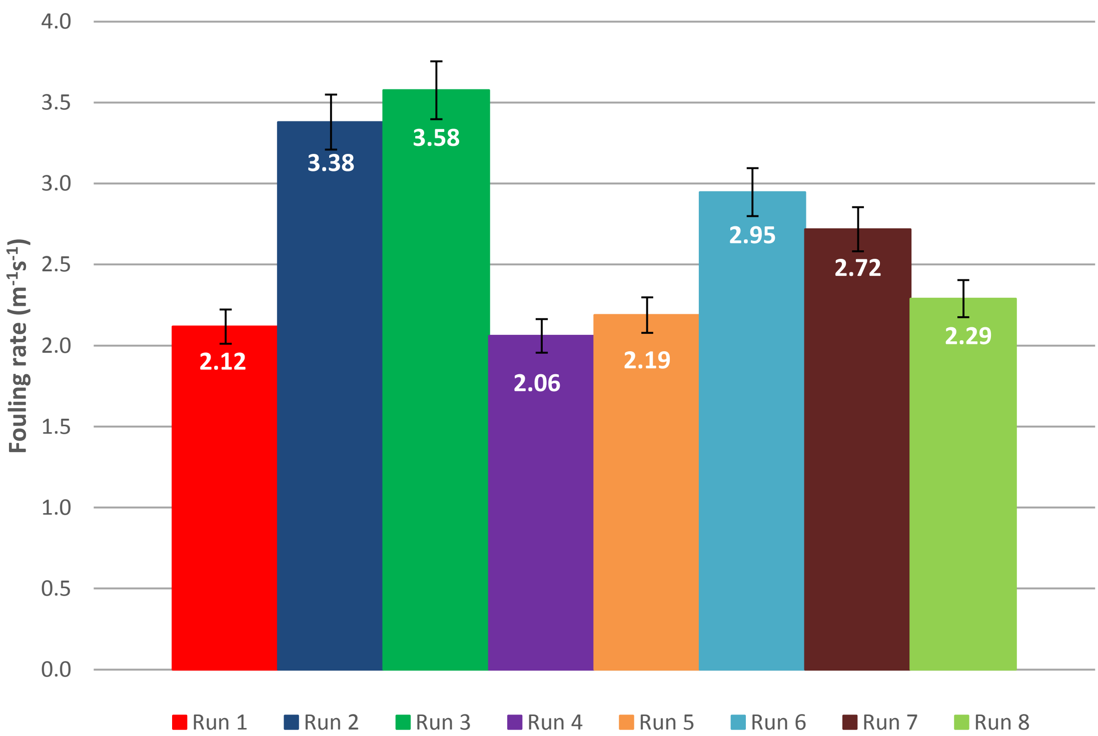


Figure 6-4: Bar column graph representing fouling rates for the intermittent air-scour factorial design experimental results done on Zandvliet WWTW Activated sludge using 1% pump setting as per Table 6-2

6.2. Pilot Plant Substantiation

Intermittent or no air-scour has a major advantage in terms of energy consumption when compared to continuous air-scour. They do however also have disadvantages since cake formation on the membrane surface is inevitable and would need to be removed physically. Eight experiments were performed on the pilot plant WF-IMBR situated at Zandvliet WWTW to investigate intermittent, continuous and no air-scour regimes. These experiments were performed using the 33% pump setting which had an approximate initial flux of 23 LMH. The details of the experiments are summarized in Table 6-3.

Table 6-3: Conditions of operating regime investigation

Experiment	Air-scour cycle	Air-scour rate (l/min/module)	MLSS (g/l)
1	Continuous	10	12.1
2	3min every 60 minutes	10	12.2
3	None	0	11.9
4	3min every 60 minutes	10	11.7
5	Continuous	10	11.8
6	None	0	11.8
7	3min every 20 minutes	10	12
8	3min every 20 minutes	10	12.1

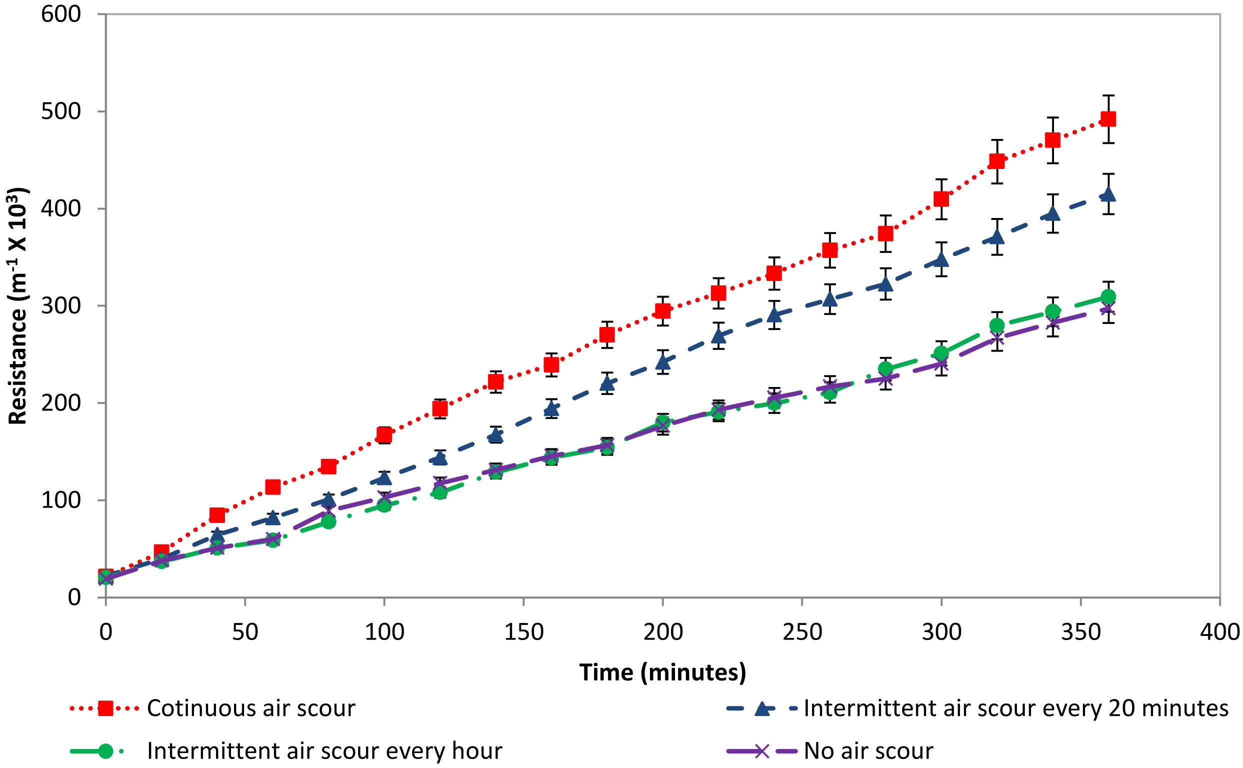


Figure 6-5: Fouling resistance for intermittent and no air-scour compared to continuous air-scour for a pump setting of 33% and an MLSS concentration of 11.2-12.1g/l

Figure 6-5 illustrates the resistance profiles for the three different operating modes. It can be seen that that operating with continuous and no air-scouring resulted in the highest (21.8 $m^{-1}s^{-1}$) and lowest fouling rates (12.9 $m^{-1}s^{-1}$) respectively. Furthermore operating with intermittent air-scour every 60 minutes and every 20 minutes resulted in fouling rates of 13.4 $m^{-1}s^{-1}$ and 18.2 $m^{-1}s^{-1}$ respectively.

Although air-scouring every 60 minutes had a lower fouling rate, it required a lot more water to hose and clean the membranes after the experiment; which was very similar to cleaning the WFMF after operating without air-scouring since sludge consolidation took place between the membranes. Air-scouring intermittently every 20 minutes resulted in sludge consolidation on the outer two membranes, but not between the membranes. Figure 6-6 and Figure 6-7 depict the WFMF after operating with intermittent air-scour every hour and every 20 minutes respectively. It can be seen from these two Figures that the sludge consolidation after-scouring every hour was more severe than after scouring every 20 minutes, due to the transparency of the sludge layer.

Although the lab-scale results suggested that operating with intermittent air-scouring would repeatedly result in a lower fouling rate than operating with no air-scouring, this cannot be said for the pilot plant experiments; since it is evident from Figure 6-5 that the filtration duration plays a major role in ensuring this. Frequent intermittent air-scouring would converge to the continuous air-scouring regime, whereas air-scouring less frequently would converge to no air-scouring regime. Therefore a balance would need to be found between the two limits to obtain an optimum intermittent air-scour regime.

Figure 6-6: Photograph of the WFMF membrane pack after air-scouring intermittently every hour

Figure 6-7: Photograph of the WFMF membrane pack after air-scouring intermittently every 20 minutes

Figure 6-8 and Figure 6-9 depict the WFMF after no air-scour and continuous air-scour respectively. On the one hand, it can be seen that severe cake formation and cake consolidation occurred during the no-scouring operating regime. Although the severe filter cake consolidation as seen in Figure 6-8, would definitely protect the membrane, cleaning it would require a large amount of permeate to rinse the cake off. On the other hand, it can be seen that there was absolutely no cake formation when operating with continuous air-scouring regime, which is exactly what was expected.

Figure 6-8: Photograph of the WFMF membrane pack after no-air-scouring

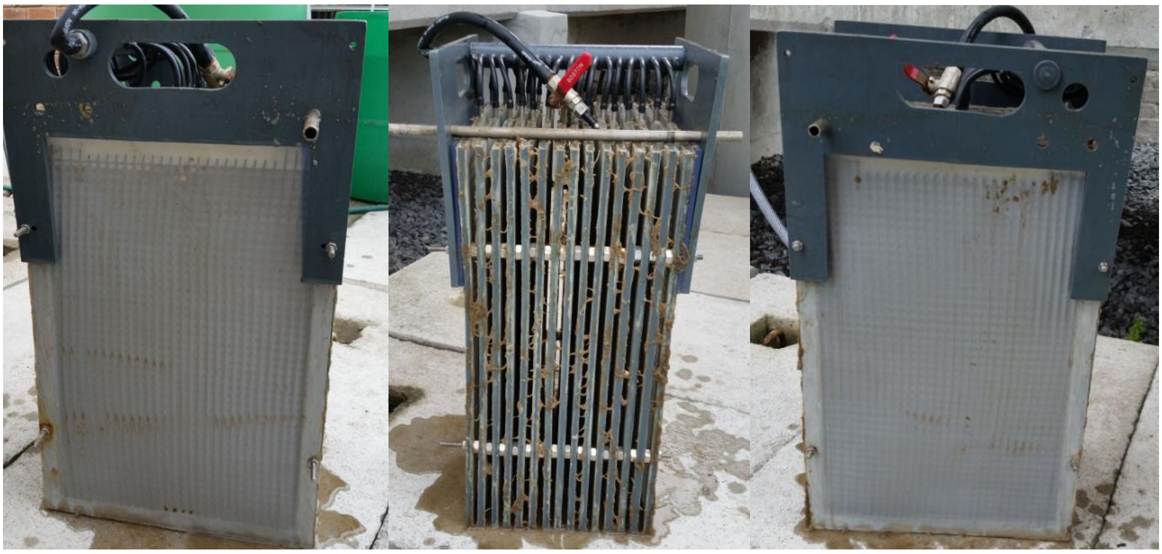


Figure 6-9: Photograph of the WFMF membrane pack after continuously air-scouring

With respect to the recovery cleaning of the membranes however, it was found that it took about 9 gravity-fed backwash cycles (1 cycle = 5 minutes back-flush and 30 seconds relax) to clean the membrane after operating under continuous air-scour conditions. Whereas, the no air-scour and intermittent air-scour runs only required 3-4 gravity-fed backwash cycles, after the membranes were rinsed off.

Ease of cleaning is an important aspect for the operational aspect of the WF-IMBR system. In light of the results obtained in this sub-section it can be once again reiterated that operating with intermittent air-scouring would not only result in better performance and majorly reduced energy consumption, but it is also more attractive in terms of cleaning the WFMF membrane pack after it has been removed from the MBR tank. Nonetheless, the reduced energy requirements is the greatest success of these trials since it would have significant operating cost implications which could be a game changer for IMBRs in general.

In conclusion, in terms of the second objective of this study, by improving the air-scouring regime of the WF-IMBR system, it was possible to not only significantly reduce the overall energy consumption but also to improve the performance in terms of operating with a reduced fouling rate. The intermittent air-scour regime only requires the membrane to be scoured for 3 minutes every hour, which results in a 95% percent reduction in terms of energy consumption for air-scouring related activities when compared to continuous air-scouring. A further advantage is that although an inevitable filter cake would grow on the membrane surfaces, it was in actual fact easier to clean the membrane after it had been fouled.

Lastly, possible implementation of the WFMF membrane pack for continuous usage would be to make use of two to three separate membrane packs per system. Whilst one membrane pack is being used the other two can part of the cleaning procedure which would consist of chemical cleaning (soaking and backwashing) as well as drying and scrubbing which was identified as a possible cleaning regime during lab-scale experiments. This would allow a continuous cycle of events to ensure that there is minimal down-time of the system. This would still be feasible since the manufacturing costs of the membrane pack are not overly expensive.

6.3. Evaluating Permeate Quality

Evaluating the permeate quality has two main outcomes. Firstly, to ensure that the permeate quality is of a high enough standard to be used or further processed depending on the final use of the permeate effluent and secondly, to ensure that there were no membrane leakages during the pilot plant substantiation experiments (Section 6.2). Turbidity was measured to give an indication of the clarity of the permeate effluent as well as being the main indicator of leaks during operation.

6.3.1. Turbidity

Table 6-4 summarizes the experimental conditions for the experiments for which turbidity was constantly measured, the plots for these experiments can be found in Figure 6-10 and the box and whiskers distribution plots can be found in Figure 6-11.

Table 6-4: Operating conditions for the experimental results represented in Figure 6-11

Experiment	Air-scour cycle	Air-scour rate (l/min/module)	MLSS (g/l)
1	Continuous	10	12.1
2	3min every 60 minutes	10	12.2
3	None	0	11.9
4	3min every 60 minutes	10	11.7
5	Continuous	10	11.8
6	None	0	11.8
7	3min every 20 minutes	10	12
8	3min every 20 minutes	10	12.1

It can be seen from Figure 6-11 that there was a uniform trend in the decrease of permeate turbidity over time. Although the starting turbidity's were above 1 NTU, this dropped below 1 NTU after around 150 minutes into the experiment as seen by the box and whiskers representation in Figure 6-11.

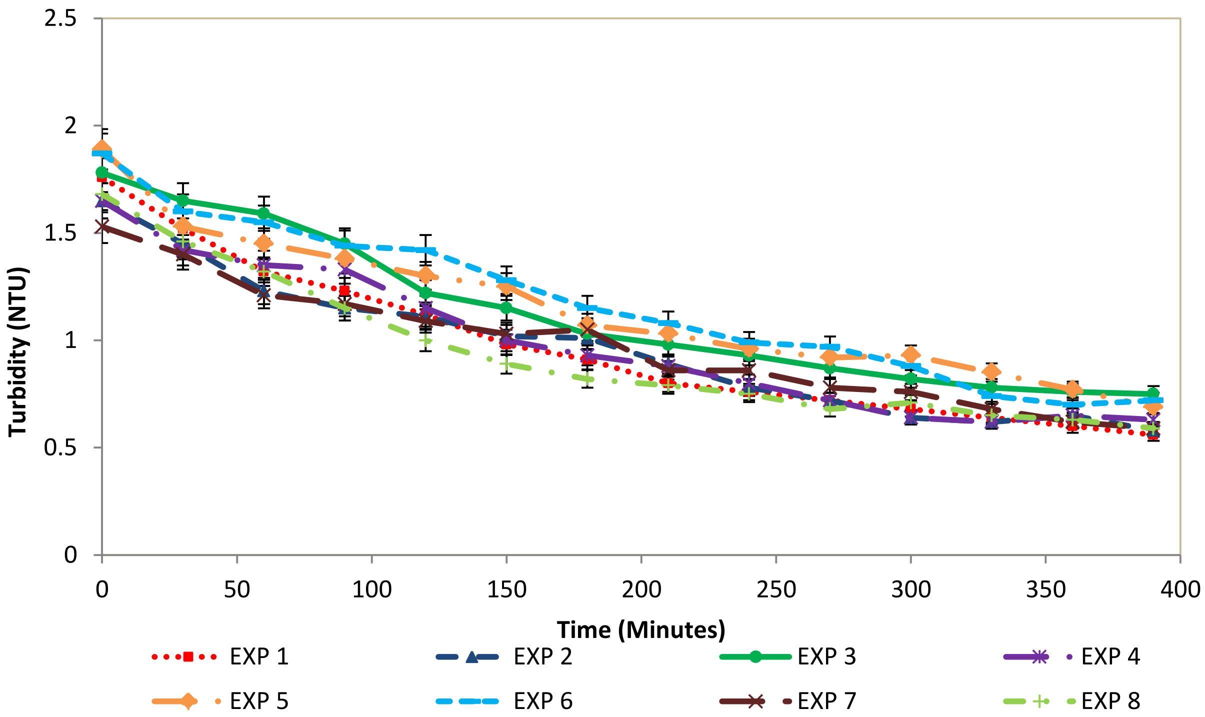


Figure 6-10: Turbidity profiles for various experiments on the WF-IMBR

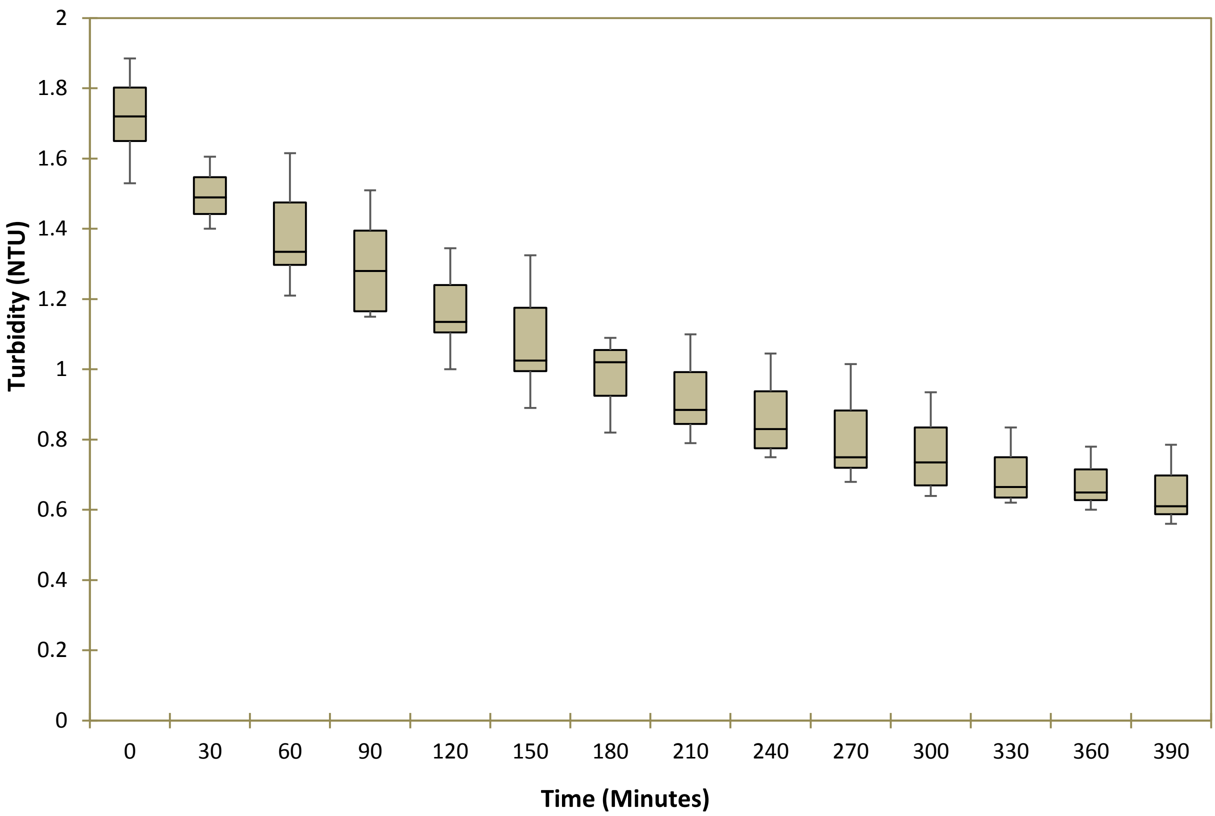


Figure 6-11: Turbidity box and whiskers plots for various experiments on the WF-IMBR

The fact that the permeate effluent continues to decrease uniformly suggest that not membrane leakages occurred during any the experiments performed. Furthermore, the main reason the turbidity decreases over time is due to the progressive fouling experiments by the membrane which actually conditions the membrane and acts as a secondary filter.

After close observation of Figure 6-11, it can be concluded that there is no real correlation between the operating conditions and the turbidity decrease.

6.3.2. Chemical Oxygen Demand (COD)

The next technique used to evaluate the permeate quality was to measure the chemical oxygen demand which will give a good indication on the organics in the permeate effluent as well of the MLSS in the bioreactor. Table 6-5 summaries the results of 4 sets of experimental analyses done on the permeate effluent of the pilot plant experiments. It should be noted that experiment 1 and 3 were done using a continuous air-scour regime, and experiments 2 and 4 were done using intermittent and no-air-scour respectively.

Table 6-5: COD Analysis Summary

Experiment	MLSS COD in IMBR (mg/l)	Initial permeate COD (mg/l)	Percentage COD removal (%)	Final permeate COD (mg/l)	Percentage COD removal (%)
1	977	41	95.80	27	97.24
1 Repeat	977	40	95.91	21	97.85
2	820	32	96.10	23	97.20
3	820	30	96.34	20	97.56
4	820	35	95.73	30	96.34

First of all, it can be seen from Table 6-5 that experiment 1 shows results for two different samples taken during the same experimental run. These two samples were evaluated independently and results showed al large deviation in final permeate quality results although taken from the same permeate stream. Secondly it can be seen that there was approximately a 95% reduction in COD measured in the initial permeate and approximately a 97% reduction in COD measured in the final permeate.

These results are extremely promising since the initial permeate results adhere to the general standards guidelines for wastewater discharge and the final permeate adheres to the special standards guidelines for wastewater discharge in South Africa, as shown in Table 2-1

CHAPTER 7. SUMMARY OF RESULTS, CONCLUSION AND RECOMMENDATIONS

The overall aim of this project was to investigate techniques to reduce the energy consumption in a WF-IMBR system. The two main objectives were as follows:

i. Improve the mechanical design of the WFMF membrane module;
ii. Improve the air-scour regime of the WF-IMBR;

The main objectives were then broken down into smaller sub-tasks which shaped the body of this investigation and the thesis layout. This chapter will first summaries all the findings within this thesis and conclude on all the results obtained. For ease of reading, the conclusions section will be broken down and discussed with respect to the two main objectives and the sub-tasks where applicable. Thereafter recommendations will be given as to how this technology and future investigations can be furthered. A simplified flow chart of the lay-out of this chapter is displayed in Figure 7-1.

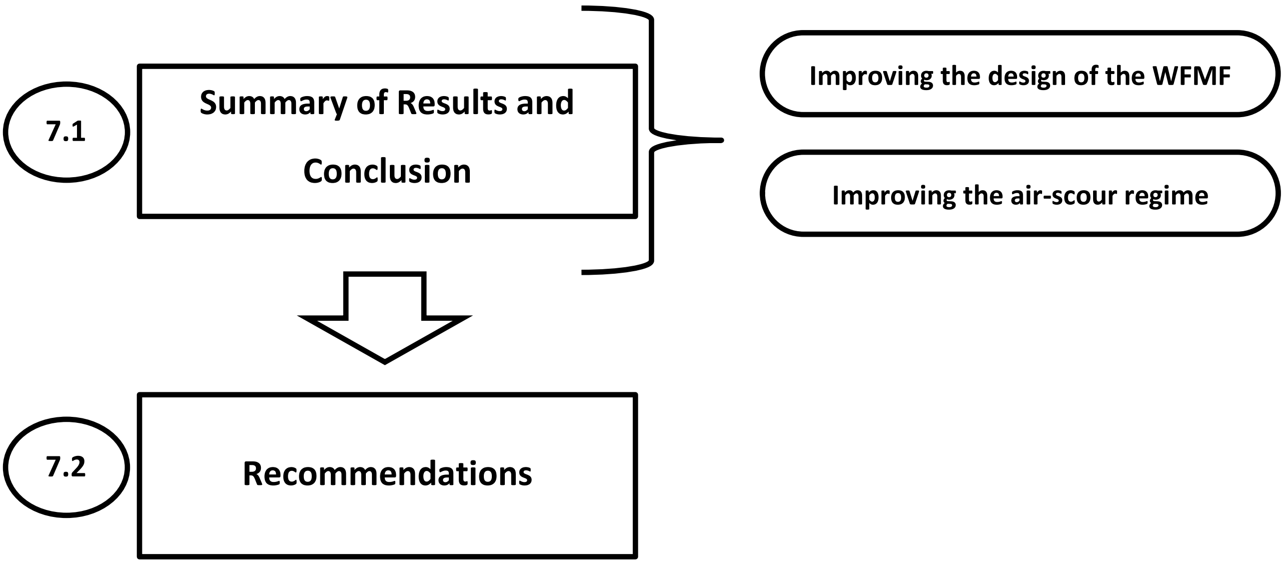


Figure 7-1: Flow chart of Chapter 7

7.1. Summary of Results and Conclusion

In this project the capabilities and concerns of the WF-IMBR was successfully demonstrated and investigated with a range of experiments on both a pilot plant scale as well as a laboratory scale. The following sub-sections will summaries and conclude all the findings obtained during the course study.

7.1.1. Improving the design of the WFMF module

By improving the mechanical design of the WFMF, it was possible to reduce the overall pressure drop across the membrane system and consequently increased the operating flux. The alterations made to the WFMF module would therefore significantly reduce the energy consumption of the WF-IMBR system.

Upon evaluating the initial design of the WFMF module, it was evident that the WFMF could not operate as well as anticipated. Initially there was a high pressure drop across the membrane pack and the permeate flux was also much lower than expected. Furthermore, it was apparent that the system could not operate beyond the 50% pump setting and increasing the pump setting beyond 50% either resulted in no increase or decrease in the Flux and TMP respectively, or it resulted in a decrease in flux in some circumstances. In order to alleviate this perceived limitation, an additional permeate outlet was installed on each of the WFMF modules.

The installation of an additional permeate outlet had a positive effect on both the TMP and the flux, however, there still seemed to be some sort of constriction leading to a decline in flux for a range of increasing pump settings when operating the system on activated sludge at the Zandvliet WWTW. In addition to this, the newly obtained TMP's and fluxes were still not in the ranges expected for such a system. Therefore, further modification was required in order to satisfy the first objective of this study.

The next step was then to include a more rigid spacer capable of keeping the flow channels within the WFMF modules open; to allow for sufficient permeate flow, which was the suspected cause of the apparent limitations experienced. In addition, the 2 mm (ID) permeate outlets were replaced with 5 mm steel outlets to further reduce the pressure drop across the membrane pack.

After applying the modification to the entire membrane pack, the results obtained were extremely promising. Smooth and linear pure water flux curves were obtainable for the first time during this study and decent fluxes as well as TMP's were achieved when operating the system on Zandvliet WWTW activated sludge. The changes to the module design resulted in approximately 90% decrease in the pressure drop across the membrane modules when operating on activated sludge, translating into significant saving in terms of energy reduction.

Further evaluation of the final WMF module and membrane pack design revealed that the critical flux of this system was in the range of 25 LMH. By operating at a permeate flux below the critical flux, the system should be able to function stably for a substantial duration of time. Accordingly, operating at a sub-critical flux with continuous air-scouring should minimize fouling which would subsequently lead to the WF-IMBR system being able to be operated for long durations of time without having to clean the membrane. However, this was not the case since operating at a flux of 11 LMH, resulted in an immediate decrease in flux as well as an increase of TMP. This experiment was done 3 times and for each run the total resistance increase remained consistent. Although this was a good sign that results are repeatable, it was clear that sub-critical operation was not possible for the WF-IMBR when operating on the Zandvliet WWTW activated sludge.

Lastly, experiments were done to determine what the best cleaning protocol is to ensure that the WFMF membrane pack could be cleaned after each experiment. This was vital since performing an experiment on a fouled membrane could affect the results, so the aim was to find an appropriate cleaning regime which would bring the fouled membrane back to its clean membrane state. Previous studies done on the WFMF used a coarse brush or a dilute sodium hypochlorite soak to clean the membrane, This was however not enough to ensure that the membrane was brought back to its clean membrane state. The only cleaning regime that seemed to do this was to soak the membrane in a dilute sodium hypochlorite solution overnight and then by applying a slow 30 minute gravity fed backwash to the membrane pack.

The summary of the conclusions are as follows:

i. By decreasing the inherent pressure drop of the initial WFMF module design, the system could achieve significantly larger fluxes;
ii. The extensive decrease in the inherent pressure drop across the WF-IMBR system will result in approximately 90% reduction in terms of energy related costs;
iii. Although a critical flux was determined, stable sub-critical operation was not possible, due to a significant increase in TMP and a decrease in flux over time;
iv. Cleaning the membrane was not as easy as expected, instead a newly determined procedure had to be followed, which consisted of chemically soaking the WFMF membrane pack overnight followed by a chemical gravity-fed back wash the following morning.

7.1.2. Improving the air-scour regime of the WF-IMBR

The second objective of the study was to determine optimal operating conditions to ensure a reduction in the energy requirement of the air-scouring regime. It was initially endeavoured to determine the critical flux of various process conditions and then to operate at the most feasible sub-critical flux to achieve this. It was soon noticed, upon evaluating the modified WFMF, that sub-critical operation was not possible. Moreover, it was noticed that fouling was not only indicated by an increase in TMP, but was coupled with an inevitable decrease in flux.

The project was therefore shifted in a different direction which involved quantifying the inevitable rate of fouling with resistance profile plots and by investigating the effects of different process conditions and different operating regimes on the fouling rate. A strange phenomenon was observed during the initial pilot plant experiments which gave rise to lab-scale experiments to determine the whether this phenomenon only applied to the Zandvliet activated sludge or whether it also applied to other activated sludge feeds. This subsection will summaries and then conclude the findings of the numerous experiments used to improve the air-scour regime in order to minimize the energy consumption of the WF-IMBR.

7.1.2.1. Preliminary pilot plant investigation

To examine the effect of various process conditions on the fouling rate within the WF-IMBR system, three main parameters were investigated. These parameters were the operating flux, the air-scour rate and the MLSS concentration.

The results of the effect of operating flux experiments, which was done using an air-scour rate of 7.5 l/min/module on an MLSS concentration ranging between 7.5 -8.0 g/l, showed that increasing pump speeds resulted in increasing fouling rates. This was also what was in line with what is reported in literature (Judd, 2011).

The next set of experiments investigated the effect of three different air-scour rates, as well as not scouring at all on the fouling rate. These experiments were performed for two pump speeds, viz. 20% and 30% pump settings, and the MLSS concentration ranged from 9.1 to 9.9 g/l. The results obtained for the 20% pump setting experiments showed that operating with higher air-scour rates resulted in higher fouling rates and operating without air-souring resulted in significantly less fouling when compared to continuous air-scouring. The results of the 33% pump setting experiments showed that there was not much of a difference between the fouling rates of the three continuous air-scour rates investigated. However it did show that once again there was a significantly lower fouling rate when operating the system without air-scouring the membranes.

The last set of experiments investigated the effect of the MLSS concentration on the fouling rate. These experiments were done using the 33% pump setting and a continuous air-scour rate of 10 l/min/module. For the three MLSS concentrations investigated, viz. 7.5 g/l, 10 g/l and 12g/l, there was a clear trend which corresponds with what was recorded in literature (Judd, 2011), which suggests that higher MLSS concentration would lead to higher fouling rates.

The summary of the conclusions are as follows:

i. Operating at higher pump speed setting or higher operating fluxes resulted in higher fouling rates;
ii. Operating with higher air-scour rates generally resulted in a higher fouling rate, except when operating at higher fluxes where no clear distinction between the different air-scour rates was observed;
iii. Operating with continuous air-scouring resulted in significantly higher fouling rates compared to operating with no air-scouring.
iv. Operating on increasing MLSS concentrations resulted in higher fouling rates.

7.1.2.2. Lab-scale investigation

Due to the results and conclusions obtained during the preliminary pilot plant experiments, attention was switched over to lab-scale experiments to investigate the effect of three different air-scouring regimes on various activated sludge feeds. For these experiments the average fouling rate was used to quantify and compare the effect of operating with continuous air-scouring, intermittent air-scouring and no air-scouring at a high flux (ca. 140 LMH) and a low flux (ca. 27LMH). Each if these experiments were performed on sludge feeds from Macassar WWTW, Bellville WWTW and Zandvliet WWTW.

For all the sludge feeds investigated, a both a high and low flux, there was a clear indication that continuous air-scouring resulted in significantly higher fouling rate in comparison to operating with intermittent air-scouring and no air-scouring. Moreover, operating with intermittent air-scouring resulted in a slightly lower fouling rate compared to no air-scouring with the added advantage of no sludge build-up or very little sludge consolidation after the experiment was completed.

Furthermore, it was also observed that, as noted during the pilot plant trials, an increase in MLSS resulted in an increase in the fouling rate when operating with continuous air-scouring for both pump settings investigated. However, when operating with intermittent or no air-scouring the opposite was observed, which was mainly prominent at the lower flux investigated.

There is no real explanation in literature as to why the fouling rate increases inversely with MLSS concentration when operating with no or intermittent air-scouring regimes. However, it is hypothesised that this is based on the same principles which suggest that operating with no-air-scour results in lower fouling rates when compared to continuous air-scour regimes. This means that higher MLSS concentrations would provide an improved filter cake formation along the active area if the membrane, which consequently protected the membrane better from pore-clogging than lower concentrations.

The summary of the conclusions are as follows:

i. Operating with continuous air-scouring resulted in significantly higher fouling rate in comparison to operating with intermittent air-scouring and no air-scouring;
ii. Operating with intermittent air-scouring resulted in a slightly lower fouling rate compared to no air-scouring with the added advantage of no sludge build-up or very little sludge consolidation after the experiment was completed;
iii. Operating on increasing MLSS concentrations resulted in increasing fouling rates but only for continuous air-scouring regimes;
iv. Operating on increasing MLSS concentrations resulted in a decrease in fouling rates when using intermittent or no air-scouring.

7.1.2.3. Substantiation experiments

In order to validate the results obtained during the lab-scale trials, two additional experiments were set-up to investigate the effect of several air-scour rates on the fouling rate as well as doing a factorial design on the intermittent air-scour operation to assess which parameters have a significant effect on the fouling rate. Furthermore, due to the interesting results obtained with regards to intermittent operation on a lab-scale, similar experiments were performed on the pilot plant rig situated at Zandvliet WWTW.

A. Laboratory scale substantiation experiments

The first set of substantiation experiments was done to investigate the effect of six different continuous air-scour rates as well as not air-scouring.

Once again there was a clear trend observed which suggested that the higher the air-scour rate, the higher the fouling rate. These results contradict literature which suggests that the opposite should occur i.e. higher air-scour rates should impose a lower fouling rate (Judd, 2011). It was speculated that this theory would probably apply well if the activated sludge consisted of a narrow size range of particles of relatively uniform properties.

Henceforth, a plausible explanation to why this strange phenomenon is occurring could be solely due to the nature of the activated sludge used during the various investigations throughout this study. It was further postulated that these results could be due to a high content of EPS in the feed samples. EPS is a gel-like substance with an extremely high fouling potential. The content of EPS in any activated sludge will be a function of how stressed the bacteria are i.e. if they have been highly stressed, the content of EPS would be high and if they have been relatively unstressed, the content of EPS would be lower. (McAdam, et al., 2011)

Furthermore, if a membrane system is operated with high air-scour rates, all the bacteria will be swept away from the surface, which would allow the EPS to easily penetrate the membrane surface, which is not easily reversible. Consequently, if the system is to operate without air-scouring, the bacteria will immediately form a fouling layer which will continue to grow. Hypothetically this bacterial fouling layer would prevent EPS from reaching the membrane surface. The net result is that fouling will be controlled by the bacteria (low fouling potential), rather than the EPS (high fouling potential).

The second set of experiments done on the lab-scale WF-IMBR was a full factorial design to investigate the effect of the intermittent air-scour rate, the duration of the intermittent air-scour and the filtration duration on the fouling rate. It was observed that all three parameters had an effect on the fouling rate. The parameter which had the most notable effect was the filtration duration, longer filtration durations lead to a lower fouling rate. This is due to the fact that when scouring the membrane too frequently, the protective sludge layer either has too little time to form or is washed away too easily, allowing the system to converge to the continuous air-scouring regime.

The air-scour rate and duration has seemingly less of an effect, however it was noted that lower air-scour rates for longer durations generally resulted in a lower fouling rate. This could be due to the fact that higher air-scour rates remove too much of the protective sludge layer and lower air-scour durations, do not allow enough time for the intermittent air-scouring to do its job.

The summary of the conclusions are as follows:

i. Operating at higher continuous air-scour rates, resulted in higher fouling rates;
ii. The most notable parameter of intermittent air-scouring was the filtration duration, longer filtration durations lead to a lower fouling rate; since this allowed more time for a protective layer to form;
iii. Lower air-scour rates for longer durations generally resulted in lower fouling rates, since this allowed for better intermittent air-scouring conditions.

B. Pilot plant substantiation experiments

Finally, in order to satisfy the second objective of this study, the operating regimes investigated and trends observed in the lab-scale trials were to be implemented on the pilot plant rig to determine whether intermittent air-scouring is a practical operating regime which would undoubtedly results in a major reduction of energy requirements.

It was noted that operating with continuous and no air-scouring resulted in the highest (21.8 $m^{-1}s^{-1}$) and lowest fouling rates (12.9 $m^{-1}s^{-1}$) respectively. Furthermore operating with intermittent air-scour every 60 minutes and every 20 minutes resulted in fouling rates of 13.4 $m^{-1}s^{-1}$ and 18.2 $m^{-1}s^{-1}$ respectively. Although air-scouring every 60 minutes had a lower fouling rate, it required a lot more water to hose and clean the membranes after the experiment. Furthermore, frequent intermittent air-scouring would converge to the continuous air-scouring regime, whereas air-scouring less frequently would converge to no air-scouring regime.

With respect to the recovery cleaning of the membranes however, it was found that it took about 9 gravity-fed backwash cycles (1 cycle = 5 minutes back-flush and 30 seconds relax) to clean the membrane after operating under continuous air-scour conditions. Whereas, the no air-scour and intermittent air-scour runs only required 3-4 gravity-fed backwash cycles, after the membranes were rinsed off.

In conclusion, in terms of the second objective of this study, by improving the air-scouring regime of the WF-IMBR system, it was possible to not only significantly reduce the overall energy consumption but also to improve the performance in terms of operating with a reduced fouling rate. The intermittent air-scour regime only requires the membrane to be scoured for 3 minutes every hour, which results in a 95% percent reduction in terms of energy consumption for air-scouring related activities when compared to continuous air-scouring. A further advantage is that although an inevitable filter cake would grow on the membrane surfaces, it was in actual fact easier to clean the membrane after it had been fouled.

To conclude this investigation, a brief analysis on permeate quality was done to ensure that he permeate produced by the WF-IMBR was to acceptable standards. It was evident that although the initial permeate turbidity was above 1 NTU; it would not take long for it to drop to below 1 and then stabilize at around 0.6 NTU. In terms of COD removal, the system was able to remove up to 97% of the COD present in the bioreactor. The average initial and final permeate quality, in terms of COD, was well below the general standards and the final permeate also adhered to the special standards guidelines for wastewater discharge in South Africa, as per Table 2-1.

The summary of the conclusions are as follows:

i. Operating with continuous and no air-scouring resulted in the highest and lowest fouling rates respectively;
ii. Operating with intermittent air-scouring every 60 minutes resulted in a slightly higher fouling rate than operating without air-scouring;
iii. Cleaning the membranes after continuous air-scouring was much harder that cleaning the membranes after intermittent or no air-scour operation;
iv. Intermittent air-scouring is the most feasible and practical operating regime which results in a 95% reduction in energy usage compared to operating with continuous air-scouring; and would therefore have positive cost implications if implemented;
v. Up to 97% of the COD present in the bioreactor was removed;
vi. Initial permeate quality, in terms of COD, adhered to general standards and final permeate quality adhered to special standards guidelines for wastewater discharge in South Africa.

7.2. Recommendations

It was endeavoured to do as many experiments as possible to examine, quantify and possibly optimize the system in terms of energy reduction strategies as well as the performance of the WF-IMBR in general. Nonetheless, there are numerous experiments and investigations that can still be done to take these investigations further. The following are recommendations of what could be done in further studies involving the WFMF and the WF-IMBR:

i. It had been postulated that by operating a well-run bioreactor the extreme fouling effects of EPS could be mitigated. It is therefore recommended that a pilot plant study be done on a well-run bioreactor, which consists if an anaerobic, anoxic and aerobic bioreactors to determine the effect of each of these zones on the performance of the WF-IMBR. Furthermore, the EPS content should be quantified in each of these runs to determine the effect of EPS when operating with and without continuous air-scouring;
ii. A pilot plant full factorial statistical analysis with more factors, levels and replicates should be done on the air-scouring regimes. The pump speed (operating flux) is also an important parameter which had not been investigated. This would give rise to an optimum operating regime which could in terms of performance as well as energy reduction;
iii. Lastly, it is recommended that an optimal cleaning regime for ‘in-situ’ cleaning of fouled membranes be developed, as well as investigating the viability of continuous operation over a long period of time by inter changing membrane packs to minimize down-time.

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APPENDIX A. RAW AND CALCULATED DATA

A.1. Preliminary pilot plant experiments

A.1.1. Evaluation of the initial WFMF module design

Table A-1: Raw and calculated data for the initial WFMF module design using potable water at various pump speed settings

Run	Speed (%)	volume measured (ml)	time taken (s)	flowrate (l/h)	flux (LMH)	TMP (kPa)	time step (min)	Total Resistance (10^3/m)
1	10	600	150	14,40	2,88	10	10	108,37
2	20	1000	126	28,57	5,71	15	20	81,93
3	30	1000	72	50,00	10,00	19	30	59,30
4	40	1000	59	61,02	12,20	23	40	58,82
5	50	1000	55	65,45	13,09	27	50	64,37
6	60	1000	55	65,45	13,09	30	60	71,53
7	70	1000	53	67,92	13,58	31	70	71,22
8	80	1000	53	67,92	13,58	31	80	71,22
9	90	1000	55	65,45	13,09	30	90	71,53
10	100	1000	55	65,45	13,09	30	100	71,53

Table A-2: Raw and calculated data for the flux stepping experiments on the initial WFMF module design using Zandvleit RAS (8.3 g/l) with continuous air-scouring (7.9 l/min/module)

Run	Speed (%)	volume measured (ml)	time taken (s)	flowrate (l/h)	flux (LMH)	TMP (kPa)	time step (min)	Total Resistance (10^3/m)	turbidity (NTU)
1	10	1000	258	13,95	2,79	15	10	167,76	2,59
2	10	1000	268	13,43	2,69	15	20	174,26	2,34
3	10	1000	278	12,95	2,59	15	30	180,76	1,71
4	10	1000	270	13,33	2,67	15	40	175,56	1,18
5	10	1000	275	13,09	2,62	15	50	178,81	1,04
6	10	1000	275	13,09	2,62	15	60	178,81	0,75
7	20	1200	200	21,60	4,32	29	70	209,52	0,8
8	20	1200	202	21,39	4,28	30	80	218,91	0,76
9	20	1200	204	21,18	4,24	30	90	221,08	0,58
10	20	1200	206	20,97	4,19	30	100	223,25	0,68
11	20	1400	247	20,40	4,08	30	110	229,44	0,62
12	20	1200	217	19,91	3,98	30	120	235,17	0,66
13	30	1200	190	22,74	4,55	38	130	260,81	0,7
14	30	1200	195	22,15	4,43	38	140	267,68	0,7
15	30	1200	195	22,15	4,43	38	150	267,68	0,72
16	30	1200	195	22,15	4,43	38	160	267,68	0,67
17	30	1200	196	22,04	4,41	38	170	269,05	0,63
18	40	1200	180	24,00	4,80	44	180	286,10	0,65
19	40	1200	182	23,74	4,75	44	190	289,28	0,55
20	40	1200	182	23,74	4,75	44	200	289,28	0,7
21	40	1200	182	23,74	4,75	44	210	289,28	0,61
22	50	1200	197	21,93	4,39	42	220	298,89	0,62
23	50	1200	197	21,93	4,39	42	230	298,89	0,65
24	50	1200	198	21,82	4,36	42	240	300,41	0,6
25	50	1200	198	21,82	4,36	43	250	307,56	0,62
26	60	1200	210	20,57	4,11	40	260	303,44	0,59
27	60	1200	210	20,57	4,11	41	270	311,03	0,6
28	60	1200	211	20,47	4,09	41	280	312,51	0,59
29	60	1200	211	20,47	4,09	41	290	312,51	0,58

A.1.2. Modification of the WFMF module design

Table A-3: Raw and calculated data for experiments done on one permeate outlet per module using potable water.

Run	Speed (%)	volume measured (ml)	time taken (s)	flowrate (l/h)	flux (LMH)	TMP (kPa)	time step (min)	Total Resistance (10^3/m)
1	10	600	150	14,40	2,88	10	10	108,37
2	20	1000	126	28,57	5,71	15	20	81,93
3	30	1000	72	50,00	10,00	19	30	59,30
4	40	1000	59	61,02	12,20	23	40	58,82
5	50	1000	55	65,45	13,09	27	50	64,37
6	60	1000	55	65,45	13,09	30	60	71,53
7	70	1000	53	67,92	13,58	31	70	71,22
8	80	1000	53	67,92	13,58	31	80	71,22
9	90	1000	55	65,45	13,09	30	90	71,53
10	100	1000	55	65,45	13,09	30	100	71,53

Table A-4: Raw and calculated data for experiments done on two permeate outlets per module using potable water.

Run	Speed (%)	volume measured (ml)	time taken (s)	flowrate (l/h)	flux (LMH)	TMP (kPa)	time step (min)	Total Resistance (10^3/m)
1	10	1000	260	13,85	2,77	7	10	78,89
2	20	1000	119	30,25	6,05	9	20	46,43
3	30	1400	106	47,55	9,51	10	30	32,82
4	40	1600	90	64,00	12,80	12	40	29,26
5	50	1600	72	80,00	16,00	14	50	27,31
6	60	1800	77	84,16	16,83	16	60	29,67
7	70	1800	75	86,40	17,28	17	70	30,71
8	80	1800	87	74,48	14,90	17	80	35,62
9	90	1800	90	72,00	14,40	16	90	34,68
10	100	1800	87	74,48	14,90	16	100	33,52

A.1.3. Evaluation of the Modified WFMF Design

Table A-5: Raw and calculated data for pure water flux curve for the modified WFMF design.

Run	Speed (%)	volume measured (ml)	time taken (s)	flowrate (l/h)	flux (LMH)	TMP (kPa)
1	30	1000	220	16.36	3.27	5
2	60	1000	110	32.73	6.55	6
3	90	1400	110	45.82	9.16	7
4	120	1400	83	60.72	12.14	8
5	150	1400	61	82.62	16.52	8.5
6	180	1600	58	99.31	19.86	9
7	210	1600	50	115.20	23.04	9.5
8	240	1600	45	128.00	25.60	10.5
9	270	1600	39	147.69	29.54	11.5
10	300	1800	39	166.15	33.23	12.5
11	330	1800	35	185.14	37.03	14
12	360	1800	33	196.36	39.27	15
13	390	1800	30	216.00	43.20	16.5
14	420	1800	27	240.00	48.00	18
15	450	1800	25	259.20	51.84	20
16	480	1800	24	270.00	54.00	22
17	510	1800	23	281.74	56.35	23
18	540	1800	22	294.55	58.91	25
19	570	1800	21	308.57	61.71	26
20	600	1800	20.5	316.10	63.22	27

Table A-6: Raw and calculated data for flux stepping experiment on Zandvleit returned activated sludge.

Run	Speed (%)	volume measured (ml)	time taken (s)	flowrate (l/h)	flux (LMH)	TMP (kPa)	time step (min)	Total Resistance (10^3/m)	turbidity (NTU)
1	5	1000	218	16.51	3.30	1	5	9.45	3.81
2	5	1000	218	16.51	3.30	1	10	9.45	3.19
3	10	1000	218	16.51	3.30	1	15	9.45	2.8
4	10	1200	139	31.08	6.22	3	20	15.06	1.54
5	10	1200	138	31.30	6.26	3	25	14.96	1.41
6	15	1200	139	31.08	6.22	3	30	15.06	1.3
7	15	1600	133	43.31	8.66	5	35	18.02	1.19
8	15	1600	133	43.31	8.66	5	40	18.02	1.09

9	20	1600	133	43.31	8.66	5	45	18.02	1.08
10	20	1600	104	55.38	11.08	6	50	16.91	0.93
11	20	1600	103	55.92	11.18	6	55	16.74	0.9
12	25	1600	103	55.92	11.18	6	60	16.74	0.85
13	25	1600	74	77.84	15.57	7	65	14.03	0.8
14	25	2000	93	77.42	15.48	7	70	14.11	0.95
15	30	1800	83	78.07	15.61	7	75	13.99	1.11
16	30	1800	70	92.57	18.51	8.5	80	14.33	1.17
17	30	1800	70	92.57	18.51	8.5	85	14.33	1.15
18	35	1800	70	92.57	18.51	8.5	90	14.33	1.3
19	35	1800	61	106.23	21.25	10	95	14.69	1.31
20	35	1800	61	106.23	21.25	10	100	14.69	1.35
21	40	1800	61	106.23	21.25	10	105	14.69	1.55
22	40	1800	55	117.82	23.56	12	110	15.89	1.55
23	40	1800	55	117.82	23.56	12	115	15.89	1.67
24	45	1800	55	117.82	23.56	12	120	15.89	1.83
25	45	1800	49	132.24	26.45	14	125	16.52	1.7
26	45	1800	49	132.24	26.45	14.5	130	17.11	1.67
27	45	1800	49	132.24	26.45	15	135	17.70	1.58
28	45	1800	49	132.24	26.45	16	140	18.88	1.56
29	45	1800	49	132.24	26.45	17	145	20.06	1.4
30	45	1800	49	132.24	26.45	17.5	150	20.65	1.39
31	45	1800	50	129.60	25.92	18	155	21.67	1.38
32	45	1800	50	129.60	25.92	19	160	22.88	1.33
33	45	1800	50	129.60	25.92	20	165	24.08	1.31
34	45	1800	51	127.06	25.41	20.5	170	25.18	1.11
35	45	1800	52	124.62	24.92	21	175	26.30	1.09
36	45	1800	53	122.26	24.45	21.5	180	27.44	1
37	45	1800	53	122.26	24.45	22	185	28.08	0.92
38	45	1800	53	122.26	24.45	23	190	29.36	0.91
39	45	1800	53	122.26	24.45	23.5	195	29.99	0.94
40	45	1800	54	120.00	24.00	24	200	31.21	0.98
41	45	1800	54	120.00	24.00	25	205	32.51	0.9
42	45	1800	54	120.00	24.00	26	210	33.81	0.85
43	45	1800	54	120.00	24.00	26.5	215	34.46	0.89
44	45	1800	55	117.82	23.56	27	220	35.76	0.84
45	45	1800	55	117.82	23.56	27	225	35.76	0.64
46	45	1800	55	117.82	23.56	27.5	230	36.42	0.67
47	270	1800	55	117.82	23.56	28	235	37.09	0.68

Table A-7: Raw and calculated data for Sub-critical runs on an MLSS concentration of 10 g/l using an air-scour rate of 10 l/min/module at a pump setting of 20%.

Run	Speed (%)	volume measured (ml)	time taken (s)	flowrate (l/h)	flux (LMH)	TMP (kPa)	time step (min)	Total Resistance (10^3/m)
1	20	1000	65	55.38	11.08	7.5	0	21.13
2	20	1000	68	52.94	10.59	10	30	29.48
3	20	1000	68	52.94	10.59	13	60	38.32
4	20	1000	69	52.17	10.43	16	90	47.86
5	20	1000	70	51.43	10.29	18	120	54.62
6	20	1000	72	50.00	10.00	20	150	62.42
7	20	1000	74	48.65	9.73	21	180	67.36
8	20	1000	75	48.00	9.60	22	210	71.53
9	20	1000	76	47.37	9.47	23	240	75.77
10	20	1000	79	45.57	9.11	25	270	85.61
11	20	1000	82	43.90	8.78	26	300	92.42
12	20	1000	86	41.86	8.37	27	330	100.66
13	20	1000	90	40.00	8.00	28	360	109.24

Table A-8: Raw and calculated data for Sub-critical runs on an MLSS concentration of 10 g/l using an air-scour rate of 10 l/min/module at a pump setting of 20%, repeated experiment.

Run	Speed (%)	volume measured (ml)	time taken (s)	flowrate (l/h)	flux (LMH)	TMP (kPa)	time step (min)	Total Resistance (10^3/m)
1	20	1000	68	52.94	10.59	7.5	0	22.11
2	20	1000	70	51.43	10.29	10	30	30.34
3	20	1000	71	50.70	10.14	13	60	40.01
4	20	1000	72	50.00	10.00	17	90	53.06
5	20	1000	74	48.65	9.73	18	120	57.74
6	20	1000	75	48.00	9.60	20	150	65.02
7	20	1000	76	47.37	9.47	22	180	72.48
8	20	1000	77	46.75	9.35	24.5	210	81.78
9	20	1000	79	45.57	9.11	25	240	85.61
10	20	1000	81	44.44	8.89	26	270	91.29
11	20	1000	84	42.86	8.57	27	300	98.31
12	20	1000	88	40.91	8.18	27.5	330	104.90
13	20	1000	92	39.13	7.83	28.5	360	113.66

Table A-9: Raw and calculated data for initial pure water flux curves before experiments.

Run	Speed (%)	volume measured (ml)	time taken (s)	flowrate (l/h)	flux (LMH)	TMP (kPa)
1	10	1000	110	32.73	6.55	6
2	20	1400	76	66.32	13.26	8
3	30	1600	58	99.31	19.86	9
4	40	1600	45	128.00	25.60	10.5
5	50	1800	39	166.15	33.23	12.5
6	60	1800	33	196.36	39.27	15

Table A-10: Raw and calculated data for pure water flux curves after scrubbing the membrane with a coarse brush.

Run	Speed (%)	volume measured (ml)	time taken (s)	flowrate (l/h)	flux (LMH)	TMP (kPa)
1	10	1000	147	24.49	4.90	11
2	20	1000	77	46.75	9.35	16
3	30	1400	72	70.00	14.00	19
4	40	1400	56	90.00	18.00	22
5	50	1600	50	115.20	23.04	24
6	60	1600	42	137.14	27.43	26

Table A-11: Raw and calculated data for pure water flux curves after soaking the membrane overnight.

Run	Speed (%)	volume measured (ml)	time taken (s)	flowrate (l/h)	flux (LMH)	TMP (kPa)
1	10	1000	136	26.47	5.29	8
2	20	1000	75	48.00	9.60	10
3	30	1000	44	81.82	16.36	13
4	40	1400	48	105.00	21.00	15
5	50	1400	37	136.22	27.24	18
6	60	1400	31	162.58	32.52	21

Table A-12: Raw and calculated data for pure water flux curves after applying a chemical backwash only.

Run	Speed (%)	volume measured (ml)	time taken (s)	flowrate (l/h)	flux (LMH)	TMP (kPa)
1	10	1000	131	27.48	5.50	6
2	20	1000	69	52.17	10.43	8
3	30	1400	60	84.00	16.80	10
4	40	1400	45	112.00	22.40	12
5	50	1600	40	144.00	28.80	14
6	60	1600	33	174.55	34.91	16

Table A-13: Raw and calculated data for pure water flux curves after applying a chemical soak followed by a gravity-fed chemical backwash

Run	Speed (%)	volume measured (ml)	time taken (s)	flowrate (l/h)	flux (LMH)	TMP (kPa)
1	60	1000	129	27.91	5.58	6
2	120	1000	67	53.73	10.75	7
3	180	1400	58	86.90	17.38	8
4	240	1400	44	114.55	22.91	9
5	300	1600	38	151.58	30.32	11
6	360	1600	32	180.00	36.00	13

A.1.4. Effect of operating flux

Table A-14: Raw and calculated data for the effect of operating flux at the 33% pump setting using an air-scour rate of 7.5 l/min/mod on a MLSS concentration of 7.5 g/l

Run	Speed (%)	volume measured (ml)	time taken (s)	flowrate (l/h)	flux (LMH)	TMP (kPa)	time step (min)	Total Resistance (10^3/m)
1	33	1400	53	95.09	19.02	14	0	22.97
2	33	1400	64	78.75	15.75	18	30	35.67
3	33	1400	72	70.00	14.00	22	60	49.05
4	33	1400	79	63.80	12.76	25	90	61.15
5	33	1400	84	60.00	12.00	27	120	70.22
6	33	1400	91	55.38	11.08	28	150	78.89
7	33	1400	99	50.91	10.18	29	180	88.90
8	33	1400	108	46.67	9.33	31	210	103.67
9	33	1400	119	42.35	8.47	32	240	117.91
10	33	1400	124	40.65	8.13	33	270	126.70
11	33	1400	132	38.18	7.64	34	300	138.96
12	33	1400	140	36.00	7.20	35	330	151.72
13	33	1400	151	33.38	6.68	36	360	168.32

Table A-15: Raw and calculated data for the effect of operating flux at the 33% pump setting using an air-scour rate of 7.5 l/min/mod on a MLSS concentration of 7.6 g/l, repeated run

Run	Speed (%)	volume measured (ml)	time taken (s)	flowrate (l/h)	flux (LMH)	TMP (kPa)	time step (min)	Total Resistance (10^3/m)
1	33	1400	56	90.00	18.00	13	0	22.54
2	33	1400	65	77.54	15.51	16	30	32.20
3	33	1400	66	76.36	15.27	20	60	40.87
4	33	1400	70	72.00	14.40	24	90	52.02
5	33	1400	79	63.80	12.76	27	120	66.04
6	33	1400	84	60.00	12.00	28	150	72.83
7	33	1400	96	52.50	10.50	29	180	86.20
8	33	1400	105	48.00	9.60	30	210	97.53
9	33	1400	111	45.41	9.08	31	240	106.54
10	33	1400	128	39.38	7.88	32	270	126.83
11	33	1400	135	37.33	7.47	33	300	137.94
12	33	1400	142	35.49	7.10	34	330	149.49
13	33	1400	150	33.60	6.72	35	360	162.56

Table A-16: Raw and calculated data for the effect of operating flux at the 25% pump setting using an air-scour rate of 7.5 l/min/mod on a MLSS concentration of 7.6 g/l

Run	Speed (%)	volume measured (ml)	time taken (s)	flowrate (l/h)	flux (LMH)	TMP (kPa)	time step (min)	Total Resistance (10^3/m)
1	25	1200	59	73.22	14.64	10	0	21.31
2	25	1200	60	72.00	14.40	12	30	26.01
3	25	1200	64	67.50	13.50	14	60	32.37
4	25	1200	68	63.53	12.71	16	90	39.30
5	25	1200	73	59.18	11.84	18.5	120	48.79
6	25	1200	78	55.38	11.08	20	150	56.35
7	25	1200	81	53.33	10.67	22	180	64.37
8	25	1200	85	50.82	10.16	25	210	76.76
9	25	1200	92	46.96	9.39	27	240	89.73
10	25	1200	105	41.14	8.23	28	270	106.20
11	25	1200	113	38.23	7.65	29	300	118.38
12	25	1200	120	36.00	7.20	30	330	130.05
13	25	1200	125	34.56	6.91	31	360	139.98

Table A-17: Raw and calculated data for the effect of operating flux at the 25% pump setting using an air-scour rate of 7.5 l/min/mod on a MLSS concentration of 7.9 g/l, repeat run

Run	Speed (%)	volume measured (ml)	time taken (s)	flowrate (l/h)	flux (LMH)	TMP (kPa)	time step (min)	Total Resistance (10^3/m)
1	25	1200	60	72.00	14.40	10	0	21.67
2	25	1200	63	68.57	13.71	12	30	27.31
3	25	1200	66	65.45	13.09	15	60	35.76
4	25	1200	69	62.61	12.52	19	90	47.36
5	25	1200	71	60.85	12.17	21	120	53.86
6	25	1200	76	56.84	11.37	24	150	65.89
7	25	1200	78	55.38	11.08	25	180	70.44
8	25	1200	89	48.54	9.71	26	210	83.59
9	25	1200	95	45.47	9.09	27.5	240	94.37
10	25	1200	99	43.64	8.73	28	270	100.14
11	25	1200	110	39.27	7.85	29	300	115.24
12	25	1200	115	37.57	7.51	30	330	124.63
13	25	1200	122	35.41	7.08	31.5	360	138.82

Table A-18: Raw and calculated data for the effect of operating flux at the 20% pump setting using an air-scour rate of 7.5 l/min/mod on a MLSS concentration of 7.6 g/l

Run	Speed (%)	volume measured (ml)	time taken (s)	flowrate (l/h)	flux (LMH)	TMP (kPa)	time step (min)	Total Resistance (10^3/m)
1	20	1000	65	55.38	11.08	7.5	0	21.13
2	20	1000	68	52.94	10.59	10	30	29.48
3	20	1000	68	52.94	10.59	13	60	38.32
4	20	1000	69	52.17	10.43	16	90	47.86
5	20	1000	70	51.43	10.29	18	120	54.62
6	20	1000	72	50.00	10.00	20	150	62.42
7	20	1000	74	48.65	9.73	21	180	67.36
8	20	1000	75	48.00	9.60	22	210	71.53
9	20	1000	76	47.37	9.47	23	240	75.77
10	20	1000	79	45.57	9.11	25	270	85.61
11	20	1000	82	43.90	8.78	26	300	92.42
12	20	1000	86	41.86	8.37	27	330	100.66
13	20	1000	90	40.00	8.00	28	360	109.24

Table A-19: Raw and calculated data for the effect of operating flux at the 20% pump setting using an air-scour rate of 7.5 l/min/mod on a MLSS concentration of 7.7 g/l, repeat run

Run	Speed (%)	volume measured (ml)	time taken (s)	flowrate (l/h)	flux (LMH)	TMP (kPa)	time step (min)	Total Resistance (10^3/m)
1	20	1000	68	52.94	10.59	7.5	0	22.11
2	20	1000	70	51.43	10.29	10	30	30.34
3	20	1000	71	50.70	10.14	13	60	40.01
4	20	1000	72	50.00	10.00	17	90	53.06
5	20	1000	74	48.65	9.73	18	120	57.74
6	20	1000	75	48.00	9.60	20	150	65.02
7	20	1000	76	47.37	9.47	22	180	72.48
8	20	1000	77	46.75	9.35	24.5	210	81.78
9	20	1000	79	45.57	9.11	25	240	85.61
10	20	1000	81	44.44	8.89	26	270	91.29
11	20	1000	84	42.86	8.57	27	300	98.31
12	20	1000	88	40.91	8.18	27.5	330	104.90
13	20	1000	92	39.13	7.83	28.5	360	113.66

Table A-20: Raw and calculated data for the effect of operating flux at the 10% pump setting using an air-scour rate of 7.5 l/min/mod on a MLSS concentration of 7.7 g/l

Run	Speed (%)	volume measured (ml)	time taken (s)	flowrate (l/h)	flux (LMH)	TMP (kPa)	time step (min)	Total Resistance (10^3/m)
1	10	1000	124	29.03	5.81	4	0	21.50
2	10	1000	129	27.91	5.58	4	30	22.37
3	10	1000	130	27.69	5.54	4.5	60	25.36
4	10	1000	131	27.48	5.50	5	90	28.39
5	10	1000	133	27.07	5.41	6	120	34.59
6	10	1000	134	26.87	5.37	7	150	40.66
7	10	1000	135	26.67	5.33	8	180	46.82
8	10	1000	137	26.28	5.26	8.5	210	50.48
9	10	1000	139	25.90	5.18	9	240	54.23
10	10	1000	141	25.53	5.11	9.5	270	58.07
11	10	1000	142	25.35	5.07	10	300	61.56
12	10	1000	143	25.17	5.03	10.5	330	65.09
13	10	1000	153	23.53	4.71	11	360	72.96

Table A-21: Raw and calculated data for the effect of operating flux at the 10% pump setting using an air-scour rate of 7.5 l/min/mod on a MLSS concentration of 8.0 g/l, repeat run

Run	Speed (%)	volume measured (ml)	time taken (s)	flowrate (l/h)	flux (LMH)	TMP (kPa)	time step (min)	Total Resistance (10^3/m)
1	10	1000	122	29.51	5.90	4	0	21.15
2	10	1000	126	28.57	5.71	4.5	30	24.58
3	10	1000	128	28.13	5.63	5	60	27.74
4	10	1000	129	27.91	5.58	6	90	33.55
5	10	1000	131	27.48	5.50	7	120	39.75
6	10	1000	132	27.27	5.45	8	150	45.78
7	10	1000	133	27.07	5.41	9	180	51.89
8	10	1000	135	26.67	5.33	9.5	210	55.59
9	10	1000	139	25.90	5.18	10	240	60.25
10	10	1000	143	25.17	5.03	10.5	270	65.09
11	10	1000	149	24.16	4.83	11	300	71.05
12	10	1000	155	23.23	4.65	11.5	330	77.27
13	10	1000	159	22.64	4.53	12	360	82.71

A.1.5. Effect of Air-Scour Rate

Table A-22: Raw and calculated data for the effect of air-scour rate at the 20% pump setting using an air-scour rate of 0 l/min/mod on a MLSS concentration of 9.5 g/l

Run	Speed (%)	volume measured (ml)	time taken (s)	flowrate (l/h)	flux (LMH)	TMP (kPa)	time step (min)	Total Resistance (10^3/m)	turbidity (NTU)
1	20	1000	74	48,65	11,31	7	0	19,31	1,76
2	20	1000	75	48,00	11,16	11	30	30,76	1,52
3	20	1000	76	47,37	11,02	14	60	39,67	1,32
4	20	1000	79	45,57	10,60	15	90	44,18	1,23
5	20	1000	84	42,86	9,97	16	120	50,10	1,12
6	20	1000	89	40,45	9,41	16,5	150	54,75	0,98
7	20	1000	93	38,71	9,00	17	180	58,94	0,91
8	20	1000	98	36,73	8,54	18	210	65,76	0,8
9	20	1000	102	35,29	8,21	19	240	72,25	0,76
10	20	1000	107	33,64	7,82	20	270	79,78	0,72
11	20	1000	110	32,73	7,61	20,5	300	84,07	0,68
12	20	1000	114	31,58	7,34	21	330	89,25	0,64
13	20	1000	119	30,25	7,04	22	360	97,60	0,6
14	20	1000	124	29,03	6,75	22,5	390	104,01	0,56

Table A-23: Raw and calculated data for the effect of air-scour rate at the 20% pump setting using an air-scour rate of 7.5 l/min/mod on a MLSS concentration of 9.7 g/l

Run	Speed (%)	volume measured (ml)	time taken (s)	flowrate (l/h)	flux (LMH)	TMP (kPa)	time step (min)	Total Resistance (10^3/m)	turbidity (NTU)
1	20	1000	75	48,00	11,16	8	0	22,37	1,65
2	20	1000	80	45,00	10,47	14	30	41,75	1,45
3	20	1000	90	40,00	9,30	17	60	57,04	1,23
4	20	1000	100	36,00	8,37	19	90	70,83	1,15
5	20	1000	110	32,73	7,61	22	120	90,22	1,11
6	20	1000	120	30,00	6,98	24	150	107,37	1,02
7	20	1000	124	29,03	6,75	26	180	120,19	1,01
8	20	1000	130	27,69	6,44	28	210	135,70	0,89
9	20	1000	134	26,87	6,25	30	240	149,86	0,78
10	20	1000	142	25,35	5,90	31	270	164,11	0,72
11	20	1000	150	24,00	5,58	31,5	300	176,15	0,64
12	20	1000	156	23,08	5,37	32	330	186,10	0,62
13	20	1000	162	22,22	5,17	32,5	360	196,28	0,65
14	20	1000	169	21,30	4,95	33	390	207,91	0,58

Table A-24: Raw and calculated data for the effect of air-scour rate at the 33% pump setting using an air-scour rate of 10 l/min/mod on a MLSS concentration of 9.8 g/l

Run	Speed (%)	volume measured (ml)	time taken (s)	flowrate (l/h)	flux (LMH)	TMP (kPa)	time step (min)	Total Resistance (10^3/m)	turbidity (NTU)
1	33	1000	42	85,71	19,93	13	0	20,35	1,78
2	33	1000	60	60,00	13,95	18	30	40,26	1,65
3	33	1000	71	50,70	11,79	26	60	68,82	1,59
4	33	1000	82	43,90	10,21	30	90	91,71	1,45
5	33	1000	98	36,73	8,54	32	120	116,91	1,22
6	33	1000	108	33,33	7,75	33	150	132,87	1,15
7	33	1000	120	30,00	6,98	35	180	156,58	1,03
8	33	1000	135	26,67	6,20	35,5	210	178,66	0,98
9	33	1000	140	25,71	5,98	36	240	187,89	0,93
10	33	1000	154	23,38	5,44	37	270	212,42	0,87
11	33	1000	166	21,69	5,04	38	300	235,16	0,82
12	33	1000	174	20,69	4,81	38	330	246,49	0,78
13	33	1000	193	18,65	4,34	38	360	273,41	0,76
14	33	1000	200	18,00	4,19	38,5	390	287,05	0,75

Table A-25: Raw and calculated data for the effect of air-scour rate at the 33% pump setting using an air-scour rate of 7.5 l/min/mod on a MLSS concentration of 9.9 g/l

Run	Speed (%)	volume measured (ml)	time taken (s)	flowrate (l/h)	flux (LMH)	TMP (kPa)	time step (min)	Total Resistance (10^3/m)	turbidity (NTU)
1	33	1000	43	83,72	19,47	12	0	19,24	1,65
2	33	1000	61	59,02	13,72	23	30	52,30	1,42
3	33	1000	77	46,75	10,87	29	60	83,25	1,35
4	33	1000	91	39,56	9,20	31	90	105,17	1,33
5	33	1000	102	35,29	8,21	33	120	125,48	1,15
6	33	1000	108	33,33	7,75	34	150	136,89	1
7	33	1000	117	30,77	7,16	35	180	152,66	0,93
8	33	1000	125	28,80	6,70	35,5	210	165,43	0,88
9	33	1000	136	26,47	6,16	36	240	182,52	0,8
10	33	1000	143	25,17	5,85	36	270	191,92	0,72
11	33	1000	159	22,64	5,27	36,5	300	216,35	0,64
12	33	1000	167	21,56	5,01	37	330	230,35	0,62
13	33	1000	182	19,78	4,60	38	360	257,83	0,65
14	33	1000	196	18,37	4,27	38	390	277,66	0,63

Table A-26: Raw and calculated data for the effect of air-scour rate at the 20% pump setting using an air-scour rate of 12.5 l/min/mod on a MLSS concentration of 9.7 g/l

Run	Speed (%)	volume measured (ml)	time taken (s)	flowrate (l/h)	flux (LMH)	TMP (kPa)	time step (min)	Total Resistance (10^3/m)	turbidity (NTU)
1	20	1000	75	48,00	11,16	8	0	22,37	1,53
2	20	1000	89	40,45	9,41	15	30	49,77	1,4
3	20	1000	99	36,36	8,46	20	60	73,81	1,21
4	20	1000	111	32,43	7,54	23	90	95,18	1,17
5	20	1000	118	30,51	7,09	26	120	114,37	1,09
6	20	1000	129	27,91	6,49	28	150	134,65	1,03
7	20	1000	136	26,47	6,16	30	180	152,10	1,05
8	20	1000	146	24,66	5,73	31	210	168,73	0,86
9	20	1000	150	24,00	5,58	31,5	240	176,15	0,86
10	20	1000	155	23,23	5,40	32	270	184,91	0,78
11	20	1000	167	21,56	5,01	32	300	199,22	0,76
12	20	1000	174	20,69	4,81	32	330	207,57	0,68
13	20	1000	179	20,11	4,68	32,5	360	216,88	0,62
14	20	1000	186	19,35	4,50	33	390	228,82	0,59

Table A-27: Raw and calculated data for the effect of air-scour rate at the 33% pump setting using an air-scour rate of 0 l/min/mod on a MLSS concentration of 9.9 g/l

Run	Speed (%)	volume measured (ml)	time taken (s)	flowrate (l/h)	flux (LMH)	TMP (kPa)	time step (min)	Total Resistance (10^3/m)	turbidity (NTU)
1	33	1000	43	83,72	19,47	12	0	19,24	1,89
2	33	1000	45	80,00	18,60	13	30	21,81	1,53
3	33	1000	47	76,60	17,81	14	60	24,53	1,45
4	33	1000	48	75,00	17,44	15	90	26,84	1,38
5	33	1000	51	70,59	16,42	16	120	30,42	1,3
6	33	1000	55	65,45	15,22	19	150	38,96	1,25
7	33	1000	57	63,16	14,69	20	180	42,50	1,07
8	33	1000	59	61,02	14,19	21	210	46,19	1,03
9	33	1000	62	58,06	13,50	23	240	53,16	0,96
10	33	1000	63	57,14	13,29	24	270	56,37	0,92
11	33	1000	66	54,55	12,68	25	300	61,51	0,93
12	33	1000	70	51,43	11,96	26	330	67,85	0,85
13	33	1000	72	50,00	11,63	27	360	72,47	0,77
14	33	1000	74	48,65	11,31	28	390	77,24	0,69

Table A-28: Raw and calculated data for the effect of air-scour rate at the 33% pump setting using an air-scour rate of 12.5 l/min/mod on a MLSS concentration of 9.1 g/l

Run	Speed (%)	volume measured (ml)	time taken (s)	flowrate (l/h)	flux (LMH)	TMP (kPa)	time step (min)	Total Resistance (10^3/m)	turbidity (NTU)
1	33	1000	45	80,00	18,60	12	0	20,13	1,87
2	33	1000	50	72,00	16,74	18	30	33,55	1,6
3	33	1000	63	57,14	13,29	24	60	56,37	1,55
4	33	1000	79	45,57	10,60	29	90	85,41	1,44
5	33	1000	94	38,30	8,91	31,5	120	110,39	1,42
6	33	1000	104	34,62	8,05	33	150	127,94	1,28
7	33	1000	118	30,51	7,09	35	180	153,97	1,15
8	33	1000	130	27,69	6,44	35,5	210	172,05	1,08
9	33	1000	138	26,09	6,07	36	240	185,21	0,99
10	33	1000	148	24,32	5,66	36,5	270	201,39	0,97
11	33	1000	160	22,50	5,23	36,5	300	217,71	0,88
12	33	1000	176	20,45	4,76	36,5	330	239,49	0,74
13	33	1000	192	18,75	4,36	37	360	264,84	0,7
14	33	1000	197	18,27	4,25	37,5	390	275,40	0,72

Table A-29: Raw and calculated data for the effect of air-scour rate at the 20% pump setting using an air-scour rate of 10 l/min/mod on a MLSS concentration of 9.5 g/l

Run	Speed (%)	volume measured (ml)	time taken (s)	flowrate (l/h)	flux (LMH)	TMP (kPa)	time step (min)	Total Resistance (10^3/m)	turbidity (NTU)
1	20	1000	70	51,43	11,96	8	0	20,88	1,53
2	20	1000	80	45,00	10,47	15	30	44,74	1,4
3	20	1000	89	40,45	9,41	20	60	66,36	1,21
4	20	1000	100	36,00	8,37	23	90	85,74	1,17
5	20	1000	112	32,14	7,48	25	120	104,38	1,09
6	20	1000	126	28,57	6,64	26,5	150	124,48	1,03
7	20	1000	130	27,69	6,44	28	180	135,70	1,05
8	20	1000	140	25,71	5,98	29	210	151,36	0,86
9	20	1000	146	24,66	5,73	30	240	163,29	0,86
10	20	1000	148	24,32	5,66	32	270	176,56	0,78
11	20	1000	155	23,23	5,40	32,5	300	187,80	0,76
12	20	1000	160	22,50	5,23	33	330	196,84	0,68
13	20	1000	164	21,95	5,10	33,5	360	204,82	0,62
14	20	1000	172	20,93	4,87	33,5	390	214,81	0,59

A.1.6. Effect of MLSS concentration

Table A-30: Raw and calculated data for the effect of MLSS concentration using the 33% pump setting and air-scour rate of 10 l/min/module at an MLSS concentration of 12g/l

Run	Speed (%)	volume measured (ml)	time taken (s)	flowrate (l/h)	flux (LMH)	TMP (kPa)	time step (min)	Total Resistance (10^3/m)
1	33	1000	40	90,00	20,93	13	0	19,39
2	33	1200	69	62,61	14,56	21	20	45,02
3	33	800	54	53,33	12,40	25	40	62,91
4	33	800	63	45,71	10,63	29	60	85,14
5	33	600	49	44,08	10,25	33	80	100,47
6	33	600	56	38,57	8,97	34	100	118,30
7	33	600	64	33,75	7,85	36	120	143,15
8	33	600	72	30,00	6,98	38	140	170,00
9	33	600	83	26,02	6,05	38	160	195,97
10	33	600	90	24,00	5,58	39	180	218,09
11	33	600	90	24,00	5,58	40	200	223,68
12	33	600	98	22,04	5,13	41	220	249,65
13	33	600	105	20,57	4,78	41,5	240	270,74
14	33	600	111	19,46	4,53	42	260	289,66
15	33	400	75	19,20	4,47	42,5	280	297,07
16	33	400	77	18,70	4,35	43	300	308,58
17	33	400	80	18,00	4,19	43,5	320	324,33
18	33	400	83	17,35	4,03	44	340	340,36
19	33	400	85	16,94	3,94	44	360	348,57

A.2. Lab-scale experiments

A.2.1. Macassar WWTP results

Table A-31: No air-scour on Macassar activated sludge for a pump setting of 5% and an MLSS concentration of 8.5 g/l

Run	Volume measured (ml)	Time taken (s)	flux (LMH)	TMP (kPa)	Time step (min)	Resistance (m^{-1} x 10^3)
1	70	30	141.41	10	0	2.21
2	50	23.5	128.95	31	5	7.5
3	50	39.2	77.30	40	10	16.15
4	50	59	51.36	45	15	27.35
5	50	62	48.88	47	20	30.01
6	50	74	40.95	49	25	37.35
7	30	49	37.11	50	30	42.06
8	30	53	34.31	51	35	46.4
9	30	57	31.9	51.5	40	50.39
10	30	64	28.41	52	45	57.13
11	30	65	27.97	53	50	59.14
12	30	70	25.97	53	55	63.69
13	30	74	24.57	53.5	60	67.96

Table A-32: Repeat of no air-scour on Macassar activated sludge for a pump setting of 5% and an MLSS concentration of 8.5 g/l

Run	Volume measured (ml)	Time taken (s)	flux (LMH)	TMP (kPa)	Time step (min)	Resistance (m-1 x 103)
1	70	34	124.78	10	0	2.50
2	50	33	91.83	29	5	9.86
3	50	43	70.47	36	10	15.94
4	50	55	55.10	41	15	23.23
5	50	68	44.56	43	20	30.12
6	50	76	39.87	45	25	35.22
7	30	45	40.40	46	30	35.53
8	30	53	34.31	46	35	41.85
9	30	56	32.47	47	40	45.18
10	30	64	28.41	48	45	52.73
11	30	67	27.14	49	50	56.36
12	30	72	25.25	49.5	55	61.18
13	30	75	24.24	50	60	64.37

Table A-33: Continuous air-scour on Macassar activated sludge for a pump setting of 5% and an MLSS concentration of 8.6 g/l

Run	Volume measured (ml)	Time taken (s)	flux (LMH)	TMP (kPa)	Time step (min)	Resistance (m-1 x 103)
1	40	18.44	131.47	10	0	2.37
2	30	25	72.73	40	5	17.17
3	30	42	43.29	46	10	33.16
4	30	54	33.67	50	15	46.35
5	30	66	27.55	52	20	58.91
6	30	73	24.91	55	25	68.92
7	30	80	22.73	57	30	78.28
8	30	88	20.66	59	35	89.13
9	30	95	19.14	61	40	99.48
10	30	97	18.74	63	45	104.90
11	30	104	17.48	64	50	114.26
12	30	105	17.32	66	55	118.96
13	30	107	16.99	67	60	123.06

Table A-34: Repeat of continuous air-scour on Macassar activated sludge for a pump setting of 5% and an MLSS concentration of 8.6 g/l

Run	Volume measured (ml)	Time taken (s)	flux (LMH)	TMP (kPa)	Time step (min)	Resistance (m-1 x 103)
1	40	15	161.62	10	0	1.93
2	30	24	75.76	41	5	16.89
3	30	44	41.32	46	10	34.74
4	30	52	34.97	50	15	44.63
5	30	68	26.74	51	20	59.53
6	30	73	24.91	53	25	66.42
7	30	83	21.91	55	30	78.36
8	30	95	19.14	56	35	91.32
9	30	98	18.55	58	40	97.57
10	30	102	17.83	60	45	105.06
11	30	110	16.53	61	50	115.18
12	30	111	16.38	63	55	120.04
13	30	113	16.09	65	60	126.08

Table A-35: Intermittent air-scour on Macassar activated sludge for a pump setting of 5% and an MLSS concentration of 8.6 g/l

Run	Volume measured (ml)	Time taken (s)	flux (LMH)	TMP (kPa)	Time step (min)	Resistance (m-1 x 103)
1	70	30	141.41	8	0	1.77
2	50	25	121.21	26	5	6.69
3	50	40	75.76	30	10	12.36
4	50	59	51.36	34	15	20.66
5	50	62	48.88	43	20	27.46
6	50	74	40.95	44	25	33.54
7	30	46	39.53	45	30	35.53
8	30	49	37.11	46	35	38.69
9	30	51	35.65	47	40	41.15
10	30	54	33.67	48	45	44.49
11	30	57	31.90	49	50	47.94
12	30	62	29.33	50	55	53.21
13	30	66	27.55	51	60	57.78

Table A-36: Repeat of intermittent air-scour on Macassar activated sludge for a pump setting of 5% and an MLSS concentration of 8.6 g/l

Run	Volume measured (ml)	Time taken (s)	flux (LMH)	TMP (kPa)	Time step (min)	Resistance (m-1 x 103)
1	70	28	151.52	8	0	1.65
2	50	22	137.74	25	5	5.66
3	50	38	79.74	29	10	11.35
4	50	54	56.12	33	15	18.35
5	50	58	52.25	42	20	25.09
6	50	64	47.35	43	25	28.34
7	30	42	43.29	44	30	31.72
8	30	45	40.40	45	35	34.76
9	30	47	38.68	46	40	37.11
10	30	53	34.31	47	45	42.76
11	30	55	33.06	48	50	45.32
12	30	59	30.82	49	55	49.63
13	30	62	29.33	50	60	53.21

Table A-37: Continuous air-scour on Macassar activated sludge for a pump setting of 1% and an MLSS concentration of 8.2 g/l

Run	Volume measured (ml)	Time taken (s)	flux (LMH)	TMP (kPa)	Time step (min)	Resistance (m-1 x 103)
1	20	44	27.55	2	0	2.27
2	20	45	26.94	3	10	3.48
3	20	46	26.35	4	20	4.74
4	20	46	26.35	4.5	30	5.33
5	20	46	26.35	5	40	5.92
6	20	46	26.35	5.5	50	6.51
7	20	47	25.79	6	60	7.26

Table A-38: No air-scour on Macassar activated sludge for a pump setting of 1% and an MLSS concentration of 8.2 g/l

Run	Volume measured (ml)	Time taken (s)	flux (LMH)	TMP (kPa)	Time step (min)	Resistance (m-1 x 103)
1	20	44	27.55	3	0	3.40
2	20	46	26.35	4.5	10	5.33
3	20	48	25.25	5.5	20	6.80
4	20	50	24.24	6.5	30	8.37
5	20	53	22.87	7.5	40	10.24
6	20	55	22.04	8.5	50	12.04
7	20	58	20.90	9.5	60	14.19

Table A-39: Intermittent air-scour on Macassar activated sludge for a pump setting of 1% and an MLSS concentration of 8.2 g/l

Run	Volume measured (ml)	Time taken (s)	flux (LMH)	TMP (kPa)	Time step (min)	Resistance (m-1 x 103)
1	20	44	27.55	3	0	3.40
2	20	46	26.35	4	10	4.74
3	20	48	25.25	5	20	6.18
4	20	49	24.74	6	30	7.57
5	20	53	22.87	7	40	9.55
6	20	55	22.04	8	50	11.33
7	20	56	21.65	8.5	60	12.26

Table A-40: Repeat of continuous air-scour on Macassar activated sludge for a pump setting of 1% and an MLSS concentration of 8.4 g/l

Run	Volume measured (ml)	Time taken (s)	flux (LMH)	TMP (kPa)	Time step (min)	Resistance (m-1 x 103)
1	20	45	26.94	3	0	3.48
2	20	48	25.25	5	10	6.18
3	20	51	23.77	7	20	9.19
4	20	52	23.31	9	30	12.05
5	20	53	22.87	11	40	15.01
6	20	53	22.87	14	50	19.11
7	20	56	21.65	15	60	21.63

Table A-41: Repeat of no air-scour on Macassar activated sludge for a pump setting of 1% and an MLSS concentration of 8.4 g/l

Run	Volume measured (ml)	Time taken (s)	flux (LMH)	TMP (kPa)	Time step (min)	Resistance (m-1 x 103)
1	20	44	27.55	3	0	3.40
2	20	45	26.94	4	10	4.63
3	20	45	26.94	5.5	20	6.37
4	20	46	26.35	7	30	8.29
5	20	46	26.35	8	40	9.48
6	20	47	25.79	9	50	10.89
7	20	47	25.79	10	60	12.10

Table A-42: Repeat of Intermittent air-scour on Macassar activated sludge for a pump setting of 1% and an MLSS concentration of 8.4 g/l

Run	Volume measured (ml)	Time taken (s)	flux (LMH)	TMP (kPa)	Time step (min)	Resistance (m-1 x 103)
1	20	42	28.86	3	0	3.24
2	20	45	26.94	4	10	4.63
3	20	46	26.35	5	20	5.92
4	20	47	25.79	6	30	7.26
5	20	48	25.25	7	40	8.65
6	20	50	24.24	8	50	10.30
7	20	51	23.77	9	60	11.82

A.2.2. Bellville WWTP results

Table A-43: No air-scour on Bellville activated sludge for a pump setting of 5% and an MLSS concentration of 8.5 g/l

Run	Volume measured (ml)	Time taken (s)	flux (LMH)	TMP (kPa)	Time step (min)	Resistance (m-1 x 103)
1	50	23	131.75	10	0	2.37
2	50	26	116.55	24	5	6.43
3	50	32	94.70	31	10	10.22
4	50	39	77.70	36	15	14.46
5	50	46	65.88	39	20	18.48
6	50	50	60.61	40	25	20.60
7	30	32	56.82	41	30	22.52
8	30	36	50.51	42	35	25.96
9	30	37	49.14	43	40	27.31
10	30	38	47.85	43.5	45	28.38
11	30	41	44.35	43.5	50	30.62
12	30	44	41.32	44	55	33.23
13	30	48	37.88	45	60	37.08

Table A-44: Continuous air-scour on Bellville activated sludge for a pump setting of 5% and an MLSS concentration of 8.5 g/l

Run	Volume measured (ml)	Time taken (s)	flux (LMH)	TMP (kPa)	Time step (min)	Resistance (m-1 x 103)
1	50	20	151.52	3	0	0.62
2	50	24	126.26	15	5	3.71
3	50	34	89.13	29	10	10.16
4	50	41	73.91	34	15	14.36
5	50	52	58.28	36	20	19.28
6	50	60	50.51	39	25	24.10
7	50	70	43.29	40	30	28.84
8	30	43	42.28	41	35	30.26
9	30	48	37.88	42	40	34.61
10	30	52	34.97	42.5	45	37.94
11	30	55	33.06	43	50	40.60
12	30	58	31.35	43.5	55	43.31
13	30	61	29.81	44	60	46.07

Table A-45: Intermittent air-scour on Bellville activated sludge for a pump setting of 5% and an MLSS concentration of 8.5 g/l

Run	Volume measured (ml)	Time taken (s)	flux (LMH)	TMP (kPa)	Time step (min)	Resistance (m-1 x 103)
1	50	21	144.30	3	0	0.65
2	50	22	137.74	9	5	2.04
3	50	24	126.26	15	10	3.71
4	50	28	108.23	22	15	6.34
5	50	32	94.70	26	20	8.57
6	50	37	81.90	30	25	11.43
7	50	42	72.15	33	30	14.28
8	50	46	65.88	34	35	16.11
9	30	28	64.94	35	40	16.82
10	30	31	58.65	36	45	19.16
11	30	32	56.82	37	50	20.32
12	30	35	51.95	38	55	22.83
13	30	36	50.51	38	60	23.48

Table A-46: No air-scour on Bellville activated sludge for a pump setting of 5% and an MLSS concentration of 8.5 g/l

Run	Volume measured (ml)	Time taken (s)	flux (LMH)	TMP (kPa)	Time step (min)	Resistance (m-1 x 103)
1	50	19	159.49	3	0	0.59
2	50	20	151.52	5	5	1.03
3	50	22	137.74	9	10	2.04
4	50	25	121.21	20	15	5.15
5	50	33	91.83	30	20	10.20
6	50	41	73.91	35	25	14.78
7	50	48	63.13	39	30	19.28
8	50	56	54.11	40	35	23.07
9	50	63	48.10	41	40	26.60
10	30	39	46.62	42	45	28.12
11	30	42	43.29	43	50	31.00
12	30	43	42.28	43.5	55	32.11
13	30	47	38.68	44	60	35.50

Table A-47: Repeat of continuous air-scour on Bellville activated sludge for a pump setting of 5% and an MLSS concentration of 8.5 g/l

Run	Volume measured (ml)	Time taken (s)	flux (LMH)	TMP (kPa)	Time step (min)	Resistance (m-1 x 103)
1	50	20	151.52	3	0	0.62
2	50	23	131.75	15	5	3.55
3	50	31	97.75	31	10	9.90
4	30	26	69.93	37	15	16.51
5	30	30	60.61	40	20	20.60
6	30	36	50.51	41	25	25.34
7	30	38	47.85	42	30	27.40
8	30	44	41.32	43	35	32.48
9	30	49	37.11	44	40	37.01
10	30	54	33.67	44.5	45	41.25
11	30	58	31.35	45	50	44.80
12	30	63	28.86	45.5	55	49.21
13	30	67	27.14	46	60	52.91

Table A-48: Repeat of intermittent air-scour on Bellville activated sludge for a pump setting of 5% and an MLSS concentration of 8.5 g/l

Run	Volume measured (ml)	Time taken (s)	flux (LMH)	TMP (kPa)	Time step (min)	Resistance (m-1 x 103)
1	50	21	144.30	3	0	0.65
2	50	23	131.75	9	5	2.13
3	50	24	126.26	16	10	3.96
4	50	34	89.13	22	15	7.70
5	50	39	77.70	26	20	10.44
6	50	43	70.47	28	25	12.40
7	50	48	63.13	30	30	14.83
8	50	49	61.84	31	35	15.65
9	30	31	58.65	32	40	17.03
10	30	32	56.82	33	45	18.13
11	30	34	53.48	34	50	19.84
12	30	36	50.51	36	55	22.25
13	30	37	49.14	37	60	23.50

Table A-49: No air-scour on Bellville activated sludge for a pump setting of 1% and an MLSS concentration of 8.8 g/l

Run	Volume measured (ml)	Time taken (s)	flux (LMH)	TMP (kPa)	Time step (min)	Resistance (m-1 x 103)
1	20	44	27.55	3	0	3.40
2	20	45	26.94	4	10	4.63
3	20	46	26.35	5	20	5.92
4	20	46	26.35	5.5	30	6.51
5	20	46	26.35	6	40	7.11
6	20	46	26.35	7.5	50	8.88
7	20	47	25.79	8	60	9.68

Table A-50: Continuous air-scour on Bellville activated sludge for a pump setting of 1% and an MLSS concentration of 8.8 g/l

Run	Volume measured (ml)	Time taken (s)	flux (LMH)	TMP (kPa)	Time step (min)	Resistance (m-1 x 103)
1	20	44	27.55	3	0	3.40
2	20	46	26.35	5.5	10	6.51
3	20	48	25.25	8	20	9.89
4	20	50	24.24	10	30	12.87
5	20	51	23.77	13	40	17.07
6	20	53	22.87	15	50	20.47
7	20	53	22.87	18	60	24.56

Table A-51: Intermittent air-scour on Bellville activated sludge for a pump setting of 1% and an MLSS concentration of 8.8 g/l

Run	Volume measured (ml)	Time taken (s)	flux (LMH)	TMP (kPa)	Time step (min)	Resistance (m-1 x 103)
1	20	44	27.55	3	0	3.40
2	20	45	26.94	3.5	10	4.06
3	20	46	26.35	4	20	4.74
4	20	46	26.35	5	30	5.92
5	20	47	25.79	6	40	7.26
6	20	47	25.79	7	50	8.47
7	20	47	25.79	8	60	9.68

Table A-52: Repeat of no air-scour on Bellville activated sludge for a pump setting of 1% and an MLSS concentration of 8.8 g/l

Run	Volume measured (ml)	Time taken (s)	flux (LMH)	TMP (kPa)	Time step (min)	Resistance (m-1 x 103)
1	20	44	27.55	3	0	3.40
2	20	44	27.55	4.5	10	5.10
3	20	46	26.35	5.5	20	6.51
4	20	46	26.35	7	30	8.29
5	20	46	26.35	8	40	9.48
6	20	47	25.79	8.5	50	10.29
7	20	48	25.25	9	60	11.12

Table A-53: Repeat of continuous air-scour on Bellville activated sludge for a pump setting of 1% and an MLSS concentration of 9.1 g/l

Run	Volume measured (ml)	Time taken (s)	flux (LMH)	TMP (kPa)	Time step (min)	Resistance (m-1 x 103)
1	20	44	27.55	3	0	3.40
2	20	47	25.79	6	10	7.26
3	20	49	24.74	8	20	10.09
4	20	52	23.31	11	30	14.73
5	20	53	22.87	14	40	19.11
6	20	54	22.45	16	50	22.25
7	20	55	22.04	19	60	26.91

Table A-54: Repeat of intermittent air-scour on Bellville activated sludge for a pump setting of 1% and an MLSS concentration of 9.1 g/l

Run	Volume measured (ml)	Time taken (s)	flux (LMH)	TMP (kPa)	Time step (min)	Resistance (m-1 x 103)
1	20	44	27.55	3	0	3.40
2	20	45	26.94	4	10	4.63
3	20	46	26.35	5	20	5.92
4	20	46	26.35	6	30	7.11
5	20	47	25.79	7	40	8.47
6	20	47	25.79	8	50	9.68
7	20	47	25.79	9	60	10.89

A.2.3. Zandvliet WWTP results

Table A-55: No air-scour on Zandvliet activated sludge for a pump setting of 1% and an MLSS concentration of 9.8 g/l

Run	Volume measured (ml)	Time taken (s)	flux (LMH)	TMP (kPa)	Time step (min)	Resistance (m-1 x 103)
1	20	44	27.55	3	0	3.40
2	20	45	26.94	4	10	4.63
3	20	46	26.35	4.5	20	5.33
4	20	47	25.79	5	30	6.05
5	20	47	25.79	6	40	7.26
6	20	48	25.25	7	50	8.65
7	20	48	25.25	7.5	60	9.27

Table A-56: Continuous air-scour on Zandvliet activated sludge for a pump setting of 1% and an MLSS concentration of 9.8 g/l

Run	Volume measured (ml)	Time taken (s)	flux (LMH)	TMP (kPa)	Time step (min)	Resistance (m-1 x 103)
1	20	44	27.55	3	0	3.40
2	20	46	26.35	6	10	7.11
3	20	48	25.25	10	20	12.36
4	20	51	23.77	14	30	18.38
5	20	54	22.45	17	40	23.64
6	20	55	22.04	20	50	28.32
7	20	57	21.27	23	60	33.76

Table A-57: Intermittent air-scour on Zandvliet activated sludge for a pump setting of 1% and an MLSS concentration of 10.1 g/l

Run	Volume measured (ml)	Time taken (s)	flux (LMH)	TMP (kPa)	Time step (min)	Resistance (m-1 x 103)
1	20	44	27.55	3	0	3.40
2	20	45	26.94	4	10	4.63
3	20	46	26.35	5	20	5.92
4	20	46	26.35	6	30	7.11
5	20	47	25.79	6.5	40	7.87
6	20	47	25.79	7	50	8.47
7	20	48	25.25	7.5	60	9.27

Table A-58: Repeat of no air-scour on Zandvliet activated sludge for a pump setting of 1% and an MLSS concentration of 10.1 g/l

Run	Volume measured (ml)	Time taken (s)	flux (LMH)	TMP (kPa)	Time step (min)	Resistance (m-1 x 103)
1	20	44	27.55	3	0	3.40
2	20	45	26.94	4	10	4.63
3	20	45	26.94	5	20	5.79
4	20	46	26.35	6	30	7.11
5	20	46	26.35	6.5	40	7.70
6	20	47	25.79	7.5	50	9.08
7	20	47	25.79	8.5	60	10.29

Table A-59: Repeat of continuous air-scour on Zandvliet activated sludge for a pump setting of 1% and an MLSS concentration of 10.1 g/l

Run	Volume measured (ml)	Time taken (s)	flux (LMH)	TMP (kPa)	Time step (min)	Resistance (m-1 x 103)
1	20	44	27.55	3	0	3.40
2	20	45	26.94	7	10	8.11
3	20	46	26.35	11	20	13.03
4	20	47	25.79	15	30	18.15
5	20	47	25.79	18	40	21.78
6	20	48	25.25	21	50	25.96
7	20	48	25.25	24	60	29.66

Table A-60: Repeat of intermittent air-scour on Zandvliet activated sludge for a pump setting of 1% and an MLSS concentration of 10.1 g/l

Run	Volume measured (ml)	Time taken (s)	flux (LMH)	TMP (kPa)	Time step (min)	Resistance (m-1 x 103)
1	20	43	28.19	3	0	3.32
2	20	44	27.55	3.5	10	3.97
3	20	46	26.35	4	20	4.74
4	20	46	26.35	5	30	5.92
5	20	46	26.35	6	40	7.11
6	20	47	25.79	7	50	8.47
7	20	47	25.79	7.5	60	9.08

A.3. Substantiation experiments

A.3.1. Lab-scale experiments

Table A-61: Effect of air-scour rate for 2l/min on Zandvliet WWTW activated sludge using a pump setting of 1% and an MLSS concentration of 11.8 g/l.

Run	Speed (%)	volume measured (ml)	time taken (s)	flowrate (l/h)	flux (LMH)	TMP (kPa)	time step (min)	Total Resistance (10^3/m)
1	1	20	44	1,64	27,55	1	0	1,13
2	1	20	45	1,60	26,94	4,5	10	5,21
3	1	20	46	1,57	26,35	7,5	20	8,88
4	1	20	48	1,50	25,25	12	30	14,83
5	1	20	51	1,41	23,77	17	40	22,32
6	1	20	56	1,29	21,65	21	50	30,28
7	1	20	62	1,16	19,55	25	60	39,91

Table A-62: Effect of air-scour rate for 4l/min on Zandvliet WWTW activated sludge using a pump setting of 1% and an MLSS concentration of 11.5 g/l.

Run	Speed (%)	volume measured (ml)	time taken (s)	flowrate (l/h)	flux (LMH)	TMP (kPa)	time step (min)	Total Resistance (10^3/m)
1	1	20	44	1,64	27,55	1	0	1,13
2	1	20	45	1,60	26,94	5	10	5,79
3	1	20	48	1,50	25,25	10	20	12,36
4	1	20	51	1,41	23,77	14,5	30	19,04
5	1	20	53	1,36	22,87	20	40	27,29
6	1	20	57	1,26	21,27	25	50	36,69
7	1	20	59	1,22	20,54	30	60	45,58

Table A-63: Effect of air-scour rate for 10l/min on Zandvliet WWTW activated sludge using a pump setting of 1% and an MLSS concentration of 11.8 g/l.

Run	Speed (%)	volume measured (ml)	time taken (s)	flowrate (l/h)	flux (LMH)	TMP (kPa)	time step (min)	Total Resistance (10^3/m)
1	1	20	44	1,64	27,55	1	0	1,13
2	1	20	47	1,53	25,79	9	10	10,89
3	1	20	52	1,38	23,31	17	20	22,76
4	1	20	60	1,20	20,20	23	30	35,53
5	1	20	72	1,00	16,84	29	40	53,76
6	1	20	82	0,88	14,78	35	50	73,90
7	1	20	100	0,72	12,12	38	60	97,85

Table A-64: Effect of air-scour rate for 8l/min on Zandvliet WWTW activated sludge using a pump setting of 1% and an MLSS concentration of 11.5 g/l.

Run	Speed (%)	volume measured (ml)	time taken (s)	flowrate (l/h)	flux (LMH)	TMP (kPa)	time step (min)	Total Resistance (10^3/m)
1	1	20	44	1,64	27,55	1	0	1,13
2	1	20	46	1,57	26,35	9	10	10,66
3	1	20	54	1,33	22,45	15	20	20,86
4	1	20	59	1,22	20,54	22	30	33,42
5	1	20	66	1,09	18,37	28	40	47,58
6	1	20	76	0,95	15,95	32	50	62,62
7	1	20	92	0,78	13,18	35	60	82,91

Table A-65: Effect of air-scour rate for 6l/min on Zandvliet WWTW activated sludge using a pump setting of 1% and an MLSS concentration of 11.8 g/l.

Run	Speed (%)	volume measured (ml)	time taken (s)	flowrate (l/h)	flux (LMH)	TMP (kPa)	time step (min)	Total Resistance (10^3/m)
1	1	20	44	1,64	27,55	2	0	2,27
2	1	20	46	1,57	26,35	7	10	8,29
3	1	20	54	1,33	22,45	14	20	19,47
4	1	20	57	1,26	21,27	19	30	27,89
5	1	20	62	1,16	19,55	23	40	36,72
6	1	20	65	1,11	18,65	28	50	46,86
7	1	20	72	1,00	16,84	34	60	63,03

Table A-66: Effect of air-scour rate for 30l/min on Zandvliet WWTW activated sludge using a pump setting of 1% and an MLSS concentration of 11.5 g/l.

Run	Speed (%)	volume measured (ml)	time taken (s)	flowrate (l/h)	flux (LMH)	TMP (kPa)	time step (min)	Total Resistance (10^3/m)
1	1	20	44	1,64	27,55	1	0	1,13
2	1	20	47	1,53	25,79	12	10	14,52
3	1	20	52	1,38	23,31	20	20	26,78
4	1	20	67	1,07	18,09	25	30	43,13
5	1	20	79	0,91	15,34	30	40	61,03
6	1	20	92	0,78	13,18	35	50	82,91
7	1	20	100	0,72	12,12	41	60	105,57

Table A-67: Effect of air-scour rate for 30l/min on Zandvliet WWTW activated sludge using a pump setting of 1% and an MLSS concentration of 11.8 g/l.

Run	Speed (%)	volume measured (ml)	time taken (s)	flowrate (l/h)	flux (LMH)	TMP (kPa)	time step (min)	Total Resistance (10^3/m)
1	1	20	44	1,64	27,55	1	0	1,13
2	1	20	44	1,64	27,55	1,5	10	1,70
3	1	20	44	1,64	27,55	2	20	2,27
4	1	20	45	1,60	26,94	3	30	3,48
5	1	20	45	1,60	26,94	4	40	4,63
6	1	20	45	1,60	26,94	4,5	50	5,21
7	1	20	46	1,57	26,35	5	60	5,92

Table A-68: Effect of intermittent air-scour for 30 seconds at 2l/min every 20 minutes using a pump setting of 1% and an MLSS concentration of 8.5 g/l.

Run	Speed (%)	volume measured (ml)	time taken (s)	flowrate (l/h)	flux (LMH)	TMP (kPa)	time step (min)	Total Resistance (10^3/m)
1	1	20	44	1,64	27,55	2	0	2,27
2	1	20	44	1,64	27,55	3	10	3,40
3	1	20	45	1,60	26,94	4	20	4,63
4	1	20	46	1,57	26,35	5	30	5,92
5	1	20	47	1,53	25,79	6	40	7,26
6	1	20	47	1,53	25,79	7	50	8,47
7	1	20	48	1,50	25,25	8	60	9,89

Table A-69: Effect of intermittent air-scour for 60 seconds at 10l/min every 10 minutes using a pump setting of 1% and an MLSS concentration of 8.5 g/l.

Run	Speed (%)	volume measured (ml)	time taken (s)	flowrate (l/h)	flux (LMH)	TMP (kPa)	time step (min)	Total Resistance (10^3/m)
1	1	20	44	1,64	27,55	2	0	2,27
2	1	20	46	1,57	26,35	4	10	4,74
3	1	20	46	1,57	26,35	5,5	20	6,51
4	1	20	48	1,50	25,25	6,5	30	8,03
5	1	20	50	1,44	24,24	7,5	40	9,66
6	1	20	54	1,33	22,45	8,5	50	11,82
7	1	20	59	1,22	20,54	9,5	60	14,43

Table A-70: Effect of intermittent air-scour for 30 seconds at 10l/min every 10 minutes using a pump setting of 1% and an MLSS concentration of 8.5 g/l.

Run	Speed (%)	volume measured (ml)	time taken (s)	flowrate (l/h)	flux (LMH)	TMP (kPa)	time step (min)	Total Resistance (10^3/m)
1	1	20	44	1,64	27,55	2	0	2,27
2	1	20	46	1,57	26,35	4	10	4,74
3	1	20	46	1,57	26,35	6	20	7,11
4	1	20	47	1,53	25,79	8	30	9,68
5	1	20	48	1,50	25,25	9,5	40	11,74
6	1	20	48	1,50	25,25	11	50	13,60
7	1	20	49	1,47	24,74	12	60	15,14

Table A-71: Effect of intermittent air-scour for 60 seconds at 2l/min every 20 minutes using a pump setting of 1% and an MLSS concentration of 8.5 g/l.

Run	Speed (%)	volume measured (ml)	time taken (s)	flowrate (l/h)	flux (LMH)	TMP (kPa)	time step (min)	Total Resistance (10^3/m)
1	1	20	44	1,64	27,55	2	0	2,27
2	1	20	44	1,64	27,55	3	10	3,40
3	1	20	45	1,60	26,94	4	20	4,63
4	1	20	45	1,60	26,94	5	30	5,79
5	1	20	46	1,57	26,35	6	40	7,11
6	1	20	46	1,57	26,35	7	50	8,29
7	1	20	47	1,53	25,79	8	60	9,68

Table A-72: Effect of intermittent air-scour for 60 seconds at 10l/min every 20 minutes using a pump setting of 1% and an MLSS concentration of 8.8 g/l.

Run	Speed (%)	volume measured (ml)	time taken (s)	flowrate (l/h)	flux (LMH)	TMP (kPa)	time step (min)	Total Resistance (10^3/m)
1	1	20	43	1,67	28,19	2	0	2,21
2	1	20	43	1,67	28,19	3,5	10	3,88
3	1	20	44	1,64	27,55	4,5	20	5,10
4	1	20	45	1,60	26,94	5,5	30	6,37
5	1	20	45	1,60	26,94	6,5	40	7,53
6	1	20	48	1,50	25,25	7	50	8,65
7	1	20	49	1,47	24,74	8	60	10,09

Table A-73: Effect of intermittent air-scour for 30 seconds at 2l/min every 10 minutes using a pump setting of 1% and an MLSS concentration of 8.8 g/l.

Run	Speed (%)	volume measured (ml)	time taken (s)	flowrate (l/h)	flux (LMH)	TMP (kPa)	time step (min)	Total Resistance (10^3/m)
1	1	20	44	1,64	27,55	2	0	2,27
2	1	20	44	1,64	27,55	3,5	10	3,97
3	1	20	45	1,60	26,94	5	20	5,79
4	1	20	45	1,60	26,94	6,5	30	7,53
5	1	20	46	1,57	26,35	8	40	9,48
6	1	20	48	1,50	25,25	9	50	11,12
7	1	20	50	1,44	24,24	10	60	12,87

Table A-74: Effect of intermittent air-scour for 30 seconds at 10l/min every 20 minutes using a pump setting of 1% and an MLSS concentration of 8.8 g/l.

Run	Speed (%)	volume measured (ml)	time taken (s)	flowrate (l/h)	flux (LMH)	TMP (kPa)	time step (min)	Total Resistance (10^3/m)
1	1	20	44	1,64	27,55	2	0	2,27
2	1	20	45	1,60	26,94	3,5	10	4,06
3	1	20	45	1,60	26,94	4,5	20	5,21
4	1	20	49	1,47	24,74	5,5	30	6,94
5	1	20	49	1,47	24,74	6,5	40	8,20
6	1	20	50	1,44	24,24	8	50	10,30
7	1	20	52	1,38	23,31	9	60	12,05

Table A-75: Effect of intermittent air-scour for 60 seconds at 2l/min every 10 minutes using a pump setting of 1% and an MLSS concentration of 8.8 g/l.

Run	Speed (%)	volume measured (ml)	time taken (s)	flowrate (l/h)	flux (LMH)	TMP (kPa)	time step (min)	Total Resistance (10^3/m)
1	1	20	44	1,64	27,55	2	0	2,27
2	1	20	44	1,64	27,55	3,5	10	3,97
3	1	20	45	1,60	26,94	4,5	20	5,21
4	1	20	47	1,53	25,79	5,5	30	6,66
5	1	20	48	1,50	25,25	6,5	40	8,03
6	1	20	49	1,47	24,74	7,5	50	9,46
7	1	20	51	1,41	23,77	8	60	10,51

A.3.2. Pilot plant experiments

Table A-76: Effect of operating procedure for continuous air-scour using a pump setting of 33% at an air-scour rate of 10 l/min/module and an MLSS concentration of 12.1 g/l.

Run	Speed (%)	volume measured (ml)	time taken (s)	flowrate (l/h)	flux (LMH)	TMP (kPa)	time step (min)	Total Resistance (10^3/m)
1	33	1000	40	90,00	20,93	14	0	20,88
2	33	1200	60	72,00	16,74	24	20	44,74
3	33	800	53	54,34	12,64	34	40	83,97
4	33	800	64	45,00	10,47	36	60	107,37
5	33	600	56	38,57	8,97	38	80	132,22
6	33	600	67	32,24	7,50	39	100	162,35
7	33	600	74	29,19	6,79	40	120	183,91
8	33	600	83	26,02	6,05	41	140	211,44
9	33	600	87	24,83	5,77	42	160	227,03
10	33	600	90	24,00	5,58	43	180	240,45
11	33	600	95	22,74	5,29	44	200	259,72
12	33	600	98	22,04	5,13	44,5	220	270,96
13	33	600	105	20,57	4,78	45	240	293,58
14	33	600	108	20,00	4,65	45,5	260	305,32
15	33	400	74	19,46	4,53	46	280	317,25
16	33	400	77	18,70	4,35	46,5	300	333,70
17	33	400	80	18,00	4,19	47	320	350,43
18	33	400	82	17,56	4,08	47,5	340	363,01
19	33	400	84	17,14	3,99	48	360	375,78

Table A-77: Effect of operating procedure for continuous air-scour using a pump setting of 33% at an air-scour rate of 10 l/min/module and an MLSS concentration of 11.8 g/l, repeated run

Run	Speed (%)	volume measured (ml)	time taken (s)	flowrate (l/h)	flux (LMH)	TMP (kPa)	time step (min)	Total Resistance (10^3/m)
1	33	1000	45	80,00	18,60	15	0	25,16
2	33	600	35	61,71	14,35	24	20	52,19
3	33	600	45	48,00	11,16	29	40	81,08
4	33	600	53	40,75	9,48	34	60	111,96
5	33	400	38	37,89	8,81	36	80	127,50
6	33	400	45	32,00	7,44	37	100	155,18
7	33	400	48	30,00	6,98	38	120	170,00
8	33	400	50	28,80	6,70	40	140	186,40
9	33	400	53	27,17	6,32	41	160	202,52
10	33	400	55	26,18	6,09	42	180	215,29
11	33	400	59	24,41	5,68	42	200	230,95
12	33	400	62	23,23	5,40	43	220	248,47
13	33	400	64	22,50	5,23	44	240	262,45
14	33	400	68	21,18	4,92	45	260	285,19
15	33	400	70	20,57	4,78	46	280	300,10
16	33	400	72	20,00	4,65	46,5	300	312,03
17	33	400	76	18,95	4,41	47	320	332,91
18	33	400	78	18,46	4,29	47,5	340	345,30
19	33	400	82	17,56	4,08	48	360	366,83

Table A-78: Effect of operating procedure for no air-scour using a pump setting of 33% and an MLSS concentration of 11.9g/l.

Run	Speed (%)	volume measured (ml)	time taken (s)	flowrate (l/h)	flux (LMH)	TMP (kPa)	time step (min)	Total Resistance (10^3/m)
1	33	1200	46	93,91	21,84	14	0	20,01
2	33	800	34	84,71	19,70	24	20	38,03
3	33	800	35	82,29	19,14	28	40	45,67
4	33	800	40	72,00	16,74	29	60	54,06
5	33	600	47	45,96	10,69	30	80	87,61
6	33	600	52	41,54	9,66	32	100	103,39
7	33	600	58	37,24	8,66	33	120	118,92
8	33	600	63	34,29	7,97	34	140	133,09
9	33	600	69	31,30	7,28	35	160	150,05
10	33	600	72	30,00	6,98	36	180	161,05

11	33	600	75	28,80	6,70	37	200	172,42
12	33	600	81	26,67	6,20	38	220	191,25
13	33	600	83	26,02	6,05	39	240	201,12
14	33	600	87	24,83	5,77	40	260	216,22
15	33	400	58	24,83	5,77	41	280	221,63
16	33	400	60	24,00	5,58	41	300	229,27
17	33	400	64	22,50	5,23	42	320	250,52
18	33	400	69	20,87	4,85	42	340	270,09
19	33	400	71	20,28	4,72	42	360	277,92

Table A-79: Effect of operating procedure for no air-scour using a pump setting of 33% and an MLSS concentration of 11.8 g/l, repeated run

Run	Speed (%)	volume measured (ml)	time taken (s)	flowrate (l/h)	flux (LMH)	TMP (kPa)	time step (min)	Total Resistance (10^3/m)
1	33	1000	39	92,31	21,47	14	0	20,35
2	33	800	38	75,79	17,63	20	20	35,42
3	33	600	31	69,68	16,20	26	40	50,08
4	33	600	34	63,53	14,77	28	60	59,15
5	33	600	41	52,68	12,25	30	80	76,42
6	33	600	45	48,00	11,16	31	100	86,68
7	33	600	51	42,35	9,85	32	120	101,40
8	33	600	55	39,27	9,13	33	140	112,77
9	33	600	60	36,00	8,37	34	160	126,75
10	33	600	63	34,29	7,97	35	180	137,00
11	33	600	72	30,00	6,98	36	200	161,05
12	33	600	76	28,42	6,61	37	220	174,72
13	33	600	80	27,00	6,28	38	240	188,88
14	33	400	54	26,67	6,20	39	260	196,28
15	33	400	56	25,71	5,98	40	280	208,77
16	33	400	60	24,00	5,58	41	300	229,27
17	33	400	68	21,18	4,92	41	320	259,84
18	33	400	70	20,57	4,78	42	340	274,01
19	33	400	74	19,46	4,53	42,5	360	293,11

Table A-80: Effect of operating procedure for intermittent air-scour for 3 minutes every 60 minutes using a pump setting of 33% at an air-scour rate of 10 l/min/module and an MLSS concentration of 11.7 g/l.

Run	Speed (%)	volume measured (ml)	time taken (s)	flowrate (l/h)	flux (LMH)	TMP (kPa)	time step (min)	Total Resistance (10^3/m)
1	33	1000	39	92,31	21,47	15	0	21,81
2	33	600	28	77,14	17,94	22	20	38,27
3	33	600	32	67,50	15,70	25	40	49,71
4	33	600	34	63,53	14,77	28	60	59,15
5	33	600	41	52,68	12,25	30	80	76,42
6	33	600	46	46,96	10,92	31	100	88,60
7	33	600	51	42,35	9,85	33	120	104,57
8	33	600	58	37,24	8,66	35	140	126,13
9	33	600	62	34,84	8,10	36	160	138,68
10	33	600	64	33,75	7,85	37	180	147,13
11	33	600	69	31,30	7,28	39	200	167,20
12	33	600	74	29,19	6,79	39	220	179,32
13	33	600	80	27,00	6,28	39	240	193,85
14	33	400	53	27,17	6,32	41	260	202,52
15	33	400	60	24,00	5,58	41	280	229,27
16	33	400	64	22,50	5,23	41	300	244,56
17	33	400	66	21,82	5,07	42	320	258,35
18	33	400	70	20,57	4,78	43	340	280,53
19	33	400	72	20,00	4,65	43	360	288,55

Table A-81: Effect of operating procedure for intermittent air-scour for 3 minutes every 60 minutes using a pump setting of 33% at an air-scour rate of 10 l/min/module and an MLSS concentration of 12.1 g/l, repeat run

Run	Speed (%)	volume measured (ml)	time taken (s)	flowrate (l/h)	flux (LMH)	TMP (kPa)	time step (min)	Total Resistance (10^3/m)
1	33	1000	40	90,00	20,93	14	0	20,88
2	33	600	27	80,00	18,60	22	20	36,91
3	33	600	32	67,50	15,70	26	40	51,69
4	33	600	34	63,53	14,77	28	60	59,15
5	33	600	40	54,00	12,56	29	80	72,07
6	33	600	48	45,00	10,47	30	100	89,47
7	33	600	52	41,54	9,66	31	120	100,16
8	33	600	56	38,57	8,97	33	140	114,82
9	33	600	61	35,41	8,23	34	160	128,86
10	33	600	64	33,75	7,85	35	180	139,18

11	33	600	68	31,76	7,39	36	200	152,10
12	33	600	71	30,42	7,08	37	220	163,22
13	33	600	74	29,19	6,79	38	240	174,72
14	33	400	51	28,24	6,57	39	260	185,37
15	33	400	55	26,18	6,09	39	280	199,91
16	33	400	57	25,26	5,88	40	300	212,49
17	33	400	60	24,00	5,58	41	320	229,27
18	33	400	64	22,50	5,23	41	340	244,56
19	33	400	68	21,18	4,92	41,5	360	263,01

Table A-82: Effect of operating procedure for intermittent air-scour for 3 minutes every 20 minutes using a pump setting of 33% at an air-scour rate of 10 l/min/module and an MLSS concentration of 12.0 g/l

Run	Speed (%)	volume measured (ml)	time taken (s)	flowrate (l/h)	flux (LMH)	TMP (kPa)	time step (min)	Total Resistance (10^3/m)
1	33	1000	40	90,00	20,93	15	0	22,37
2	33	600	29	74,48	17,32	22	20	39,64
3	33	600	34	63,53	14,77	28	40	59,15
4	33	600	35	61,71	14,35	32	60	69,59
5	33	400	28	51,43	11,96	33	80	86,12
6	33	400	33	43,64	10,15	34	100	104,57
7	33	400	37	38,92	9,05	35	120	120,69
8	33	400	40	36,00	8,37	36	140	134,21
9	33	400	42	34,29	7,97	37	160	144,83
10	33	400	45	32,00	7,44	38	180	159,37
11	33	400	47	30,64	7,13	40	200	175,22
12	33	400	54	26,67	6,20	41	220	206,34
13	33	400	56	25,71	5,98	42	240	219,21
14	33	400	59	24,41	5,68	42,5	260	233,70
15	33	400	65	22,15	5,15	43	280	260,49
16	33	400	67	21,49	5,00	43,5	300	271,63
17	33	400	71	20,28	4,72	44	320	291,16
18	33	400	76	18,95	4,41	44,5	340	315,20
19	33	400	80	18,00	4,19	44,5	360	331,79

Table A-83: Effect of operating procedure for intermittent air-scour for 3 minutes every 20 minutes using a pump setting of 33% at an air-scour rate of 10 l/min/module and an MLSS concentration of 12.1 g/l, repeat run

Run	Speed (%)	volume measured (ml)	time taken (s)	flowrate (l/h)	flux (LMH)	TMP (kPa)	time step (min)	Total Resistance (10^3/m)
1	33	1000	40	90,00	20,93	13	0	19,39
2	33	600	25	86,40	20,09	24	20	37,28
3	33	600	28	77,14	17,94	29	40	50,45
4	33	600	36	60,00	13,95	31	60	69,34
5	33	600	43	50,23	11,68	33	80	88,17
6	33	600	49	44,08	10,25	34	100	103,51
7	33	600	53	40,75	9,48	36	120	118,55
8	33	600	59	36,61	8,51	39	140	142,97
9	33	600	65	33,23	7,73	40	160	161,55
10	33	600	68	31,76	7,39	41	180	173,23
11	33	600	70	30,86	7,18	43	200	187,02
12	33	600	73	29,59	6,88	43,5	220	197,30
13	33	600	79	27,34	6,36	44	240	215,97
14	33	400	56	25,71	5,98	44	260	229,64
15	33	400	62	23,23	5,40	44,5	280	257,14
16	33	400	66	21,82	5,07	44,5	300	273,73
17	33	400	70	20,57	4,78	44,5	320	290,32
18	33	400	78	18,46	4,29	45	340	327,13
19	33	400	83	17,35	4,03	45	360	348,10

APPENDIX B. SAMPLE CALCULATIONS

The following sections will display sample calculations for the various calculations used throughout the different chapters in this study. Only one calculation per formula will be shown.

B.1. WF-IMBR Design

B.1.1. Total membrane area

The total number of modules used throughout experiments was 19 modules and the dimensions of a single module was summarised in Table 3-1. The effective surface are for a single module as well as for the entire membrane pack was calculated as follows:

$$\boldsymbol{A_{m,eff}} = 2\ sides \times\ L_{m,eff} \times W_{m,eff} = 2 \times 45.5\ cm\ \times 29.5\ cm\ \times \left(\frac{1\ m}{100\ cm}\right)^2 = \boldsymbol{0.27\ m^2}$$

$$\boldsymbol{A_{m,total}} = A_{m,eff}\ \times N_m = 0.27\ m^2 \times 19 = \boldsymbol{5.1\ m^2}$$

A.1.1. Production capacity

As per section 3.1.1.2, the minimum required production capacity of the WF-IMBR to satisfy the design requirement was calculated as follows, this was designed for 30 people (30 PE) at an estimated water usage of 100l/person/day:

$$\dot{V}_{Througput} = \ 30\ PE\ \times \frac{100\ l}{PE \cdot day} \times \frac{1\ day}{24\ h} = \ \boldsymbol{125\ l/h}$$

Therefore the minimum flux that should be attained to obtain this throughput was calculated as follows:

$$\boldsymbol{J_{Min}} = \frac{\dot{V}_{Througput}}{A_{m,total}} = \frac{125\ l/h}{5.1\ m^2} = \boldsymbol{24.5\frac{l}{m^2 \cdot h}}$$

A.1.2. Aerobic bioreactor volume

As per Section 3.1.2, the aerobic bioreactor was designed using a maximum HRT of 12 hours and a required throughput of 125 l/h when one train is in operation:

$$\boldsymbol{V_{reactor}} = \ \boldsymbol{\dot{V}_{Througput}} \times\ \boldsymbol{\theta = 125\frac{l}{h}} \times \boldsymbol{12\ h = 1\ 500\ l\ Bioreactor\ Vessel}$$

A.2. Experimental Calculations

With regards to the experimental sample calculation, a specific experiment and experimental run will be selected and the following will be calculated accordingly. To maintain ease of following, the very first run of the very first experiment will be used throughout these calculations i.e., the initial evaluation of the WFMF module design. The raw and calculated data is summarised in Table A-1 and the representative graph is plotted in Figure 3-17 under Section 3.5.1.1.

A.2.1. Flow rate

During experiments, the bucket and stopwatch method was used to determine the volumetric flow rate of the permeate product. As seen in Appendix A, a specific volume and the time taken to reach that volume was used to calculate the flow rate, as follows: :

$$\dot{\boldsymbol{V}} = \frac{V_{Permeate}}{\Delta t} = \frac{600\ ml}{150\ s} \times \frac{3600s}{1\ h} \times \frac{1\ l}{1000\ ml} = \mathbf{14.4}\ \boldsymbol{l/h}$$

A.2.2. Flux

$$\boldsymbol{J} = \frac{\dot{V}}{A_{m,total}} = \frac{14.4\ l/h}{5.1\ m^2} = \mathbf{2.88}\ \frac{\boldsymbol{l}}{\boldsymbol{m^2 \cdot h}}$$

A.2.3. Total Resistance

$$\boldsymbol{R_{Total}} = \frac{\boldsymbol{TMP}}{\boldsymbol{J \cdot \mu}} = \frac{\mathbf{10}\ \boldsymbol{kPa}}{\mathbf{2.88}\ \frac{\boldsymbol{l}}{\boldsymbol{m^2 \cdot h}} \times \mathbf{8.9} \times \mathbf{10^{-4}}\boldsymbol{Pa.s}}$$

$$= \frac{\mathbf{10} \times \mathbf{10^{-3}}\frac{\boldsymbol{N}}{\boldsymbol{m^2}}}{\mathbf{2.88} \times \mathbf{10^{-3}}\frac{\boldsymbol{m^3}}{\boldsymbol{m^2 \cdot h}} \times \mathbf{8.9} \times \mathbf{10^{-4}}\frac{\boldsymbol{N \cdot s}}{\boldsymbol{m^2}} \times \frac{\mathbf{1}\ \boldsymbol{h}}{\mathbf{3600}\ \boldsymbol{s}}} = \frac{\mathbf{10000}\frac{\boldsymbol{N}}{\boldsymbol{m^2}}}{\mathbf{9.23} \times \mathbf{10^{-3}}\ \frac{\boldsymbol{N}}{\boldsymbol{m^2}}}$$

$$= \mathbf{108.37} \times \mathbf{10^3}\boldsymbol{m^{-1}}$$

A.2.4. Membrane fouling rate

The membrane fouling rate was only calculated in Chapter 5, hence the very first experiential run on the lab-scale experiments will be used, which was the no-sir scour on Bellville WWTW sludge at a pump setting of 5%. This run is summarised in Table 5-1 as well as Figure 5-16 and calculated as follows:

$$\boldsymbol{F} = \frac{R_{Total,average}}{\Delta t} = \frac{(50.14 - 1.97) \times 10^3 m^{-1}}{60\ min \times \frac{60\ s}{1\ min}} = \mathbf{13.38}\boldsymbol{m^{-1}s^{-1}}$$

APPENDIX B. REPEATABILITY GRAPHS

The following graphs represent the degree of error for every data point for all experiments performed more than one. It should be noted that the actual curves have been omitted and that only the error bars have been shown for clarity.

B.1. Pilot plant experiments

B.1.1. Evaluation of the Modified WFMF Design

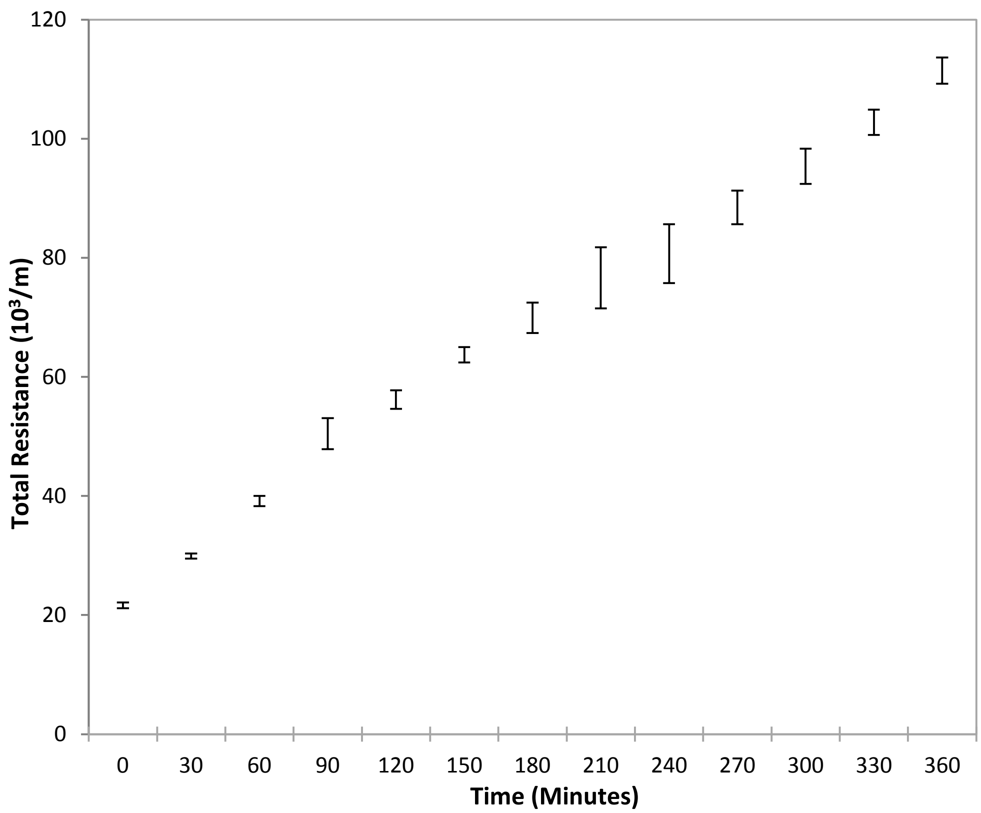

Figure B-1: Sub-critical runs on an MLSS concentration of 10 g/l using an air-scour rate of 10 l/min/module at a pump setting of 20%

B.1.2. Effect of operating flux

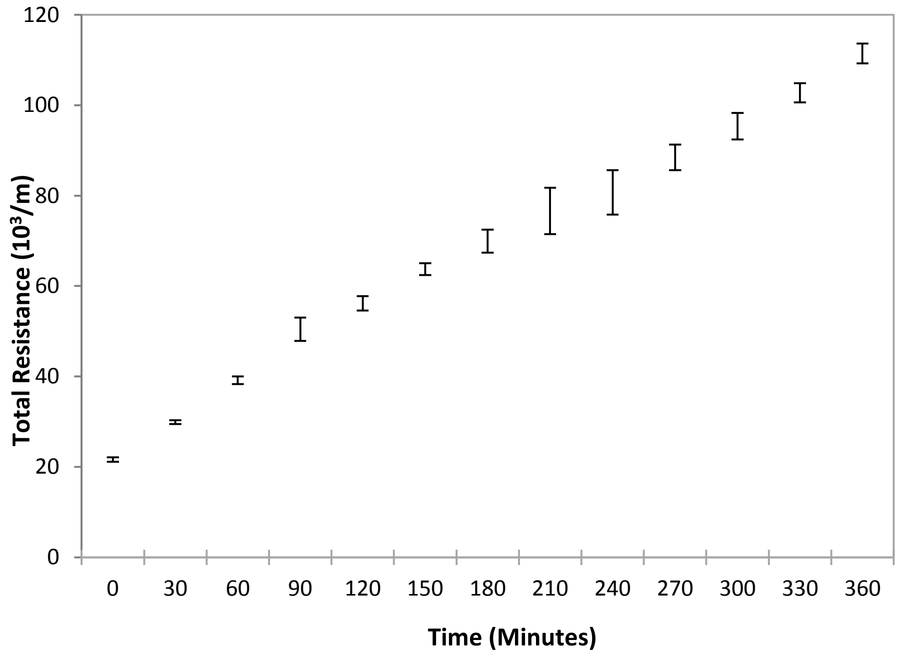

Figure B-2: Effect of operating flux for a pump setting of 20% and an MLSS concentration of 7.7 g/l

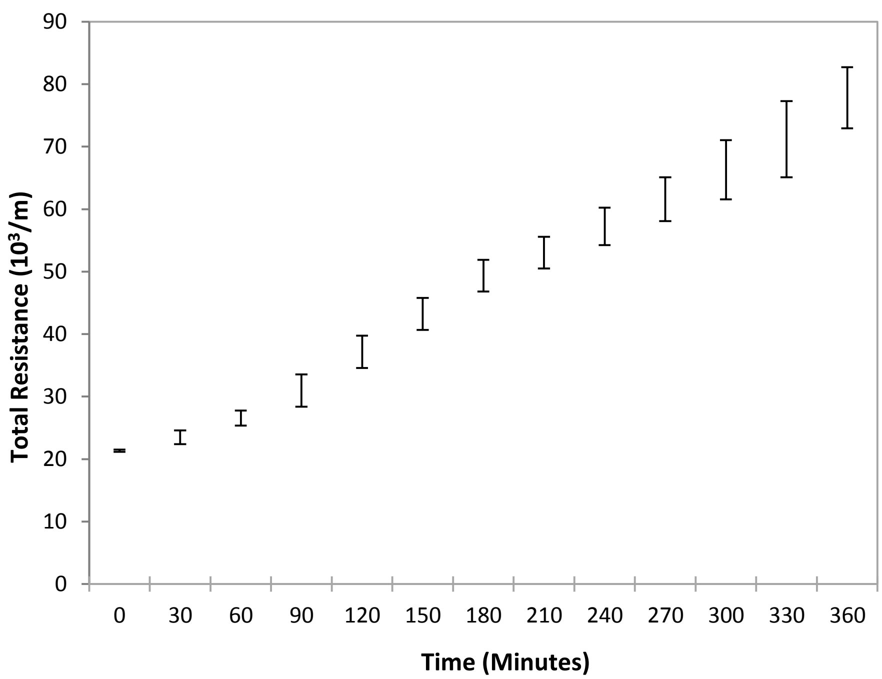

Figure B-3: Effect of operating flux for a pump setting of 10% and an MLSS concentration of 7.7-7.8 g/l

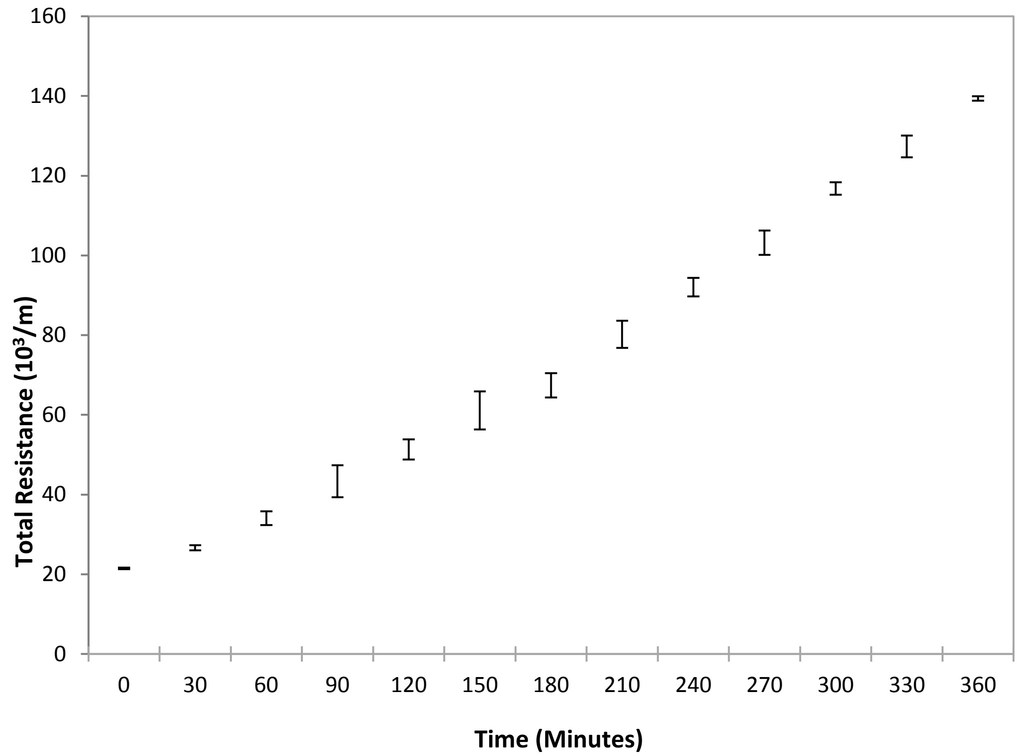

Figure B-4: Effect of operating flux for a pump setting of 25% and an MLSS concentration of 7.6-7.9 g/l

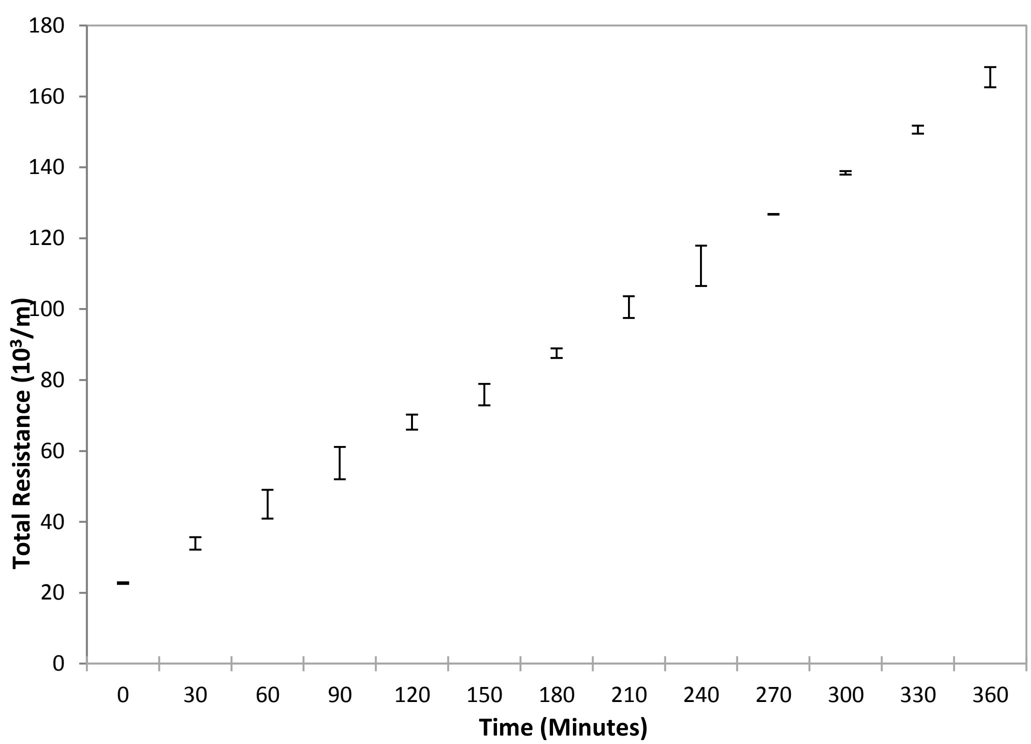

Figure B-5: Effect of operating flux for a pump setting of 30% and an MLSS concentration of 7.8 -8.0 g/l

B.2. Lab-scale experiments

B.2.1. Macassar WWTP results

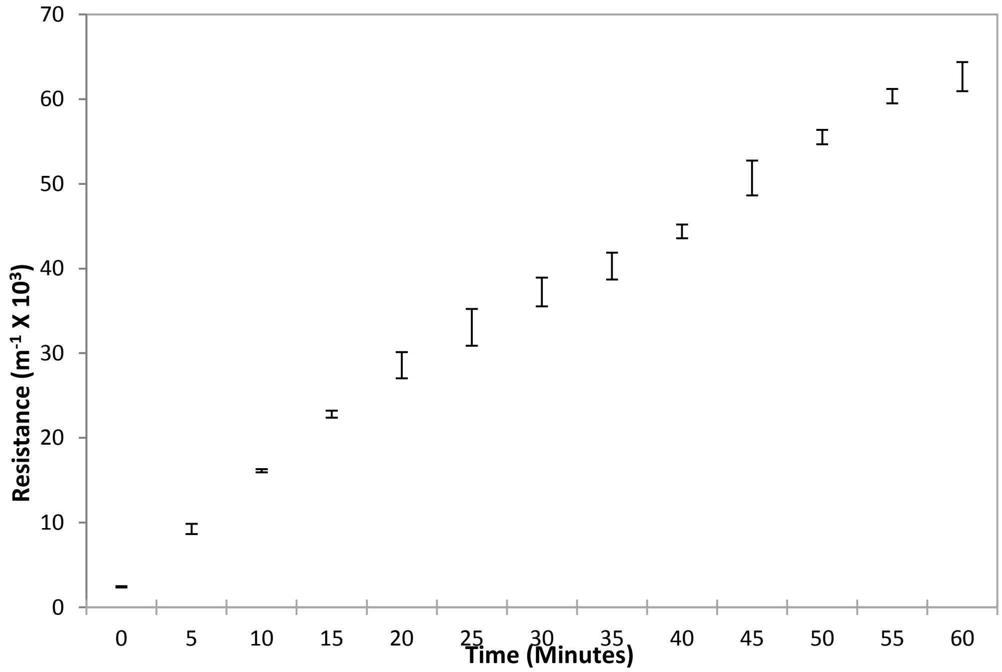

Figure B-6: No air-scour on Macassar activated sludge for a pump setting of 5% and an MLSS of 8.5 g/l

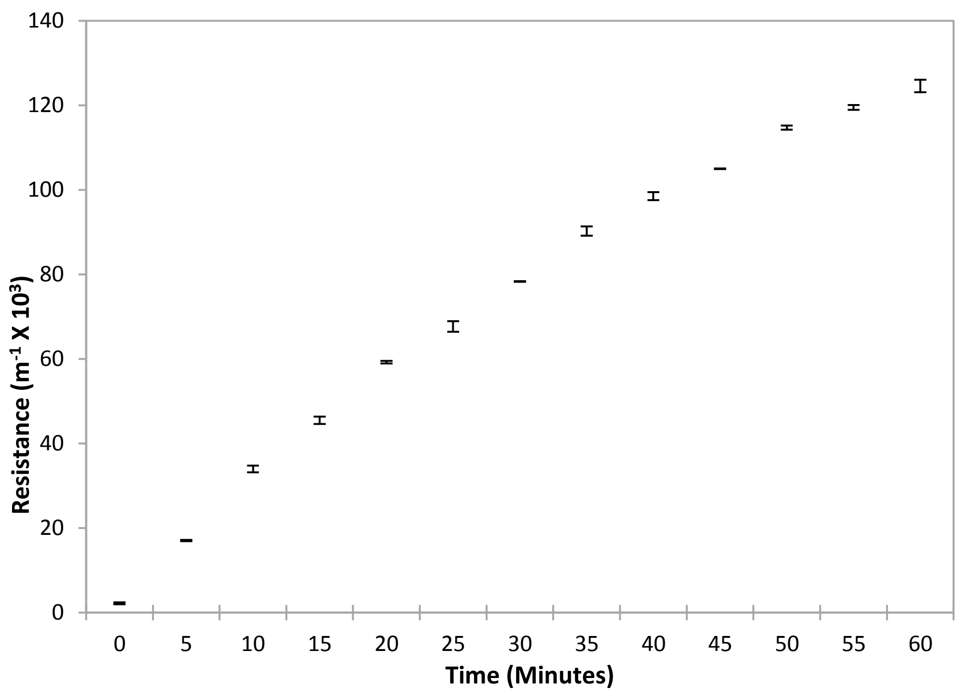

Figure B-7: Continuous air-scour on Macassar activated sludge for a pump setting of 5% and an MLSS concentration of 8.5-8.6 g/l

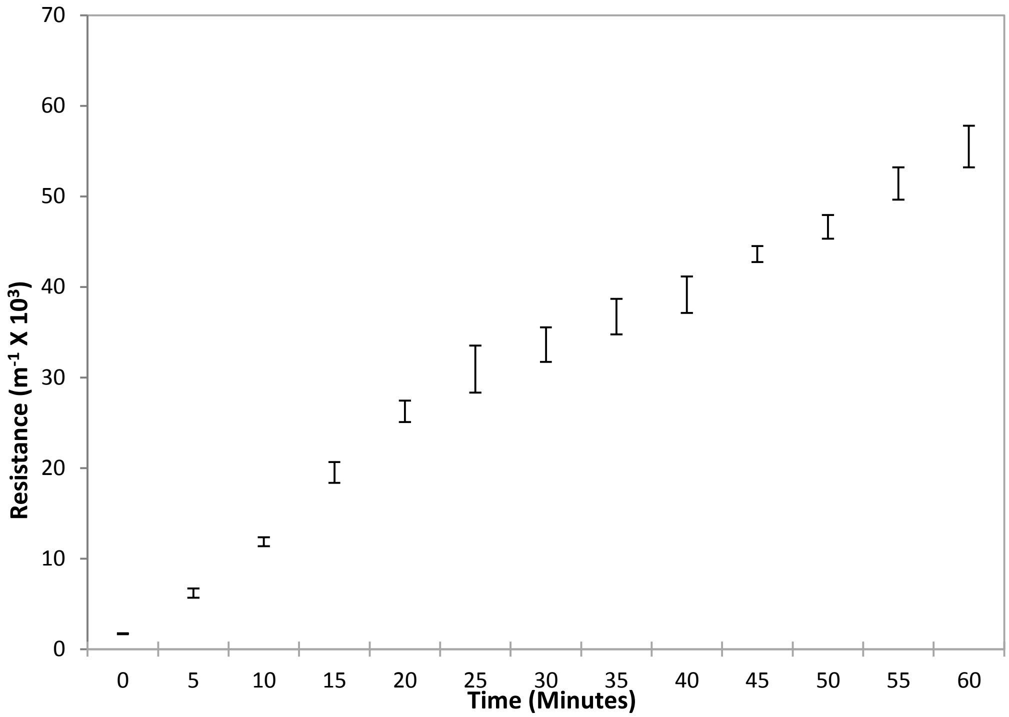

Figure B-8: Intermittent air-scour on Macassar activated sludge for a pump setting of 5% and an MLSS concentration of 8.5-8.6 g/l

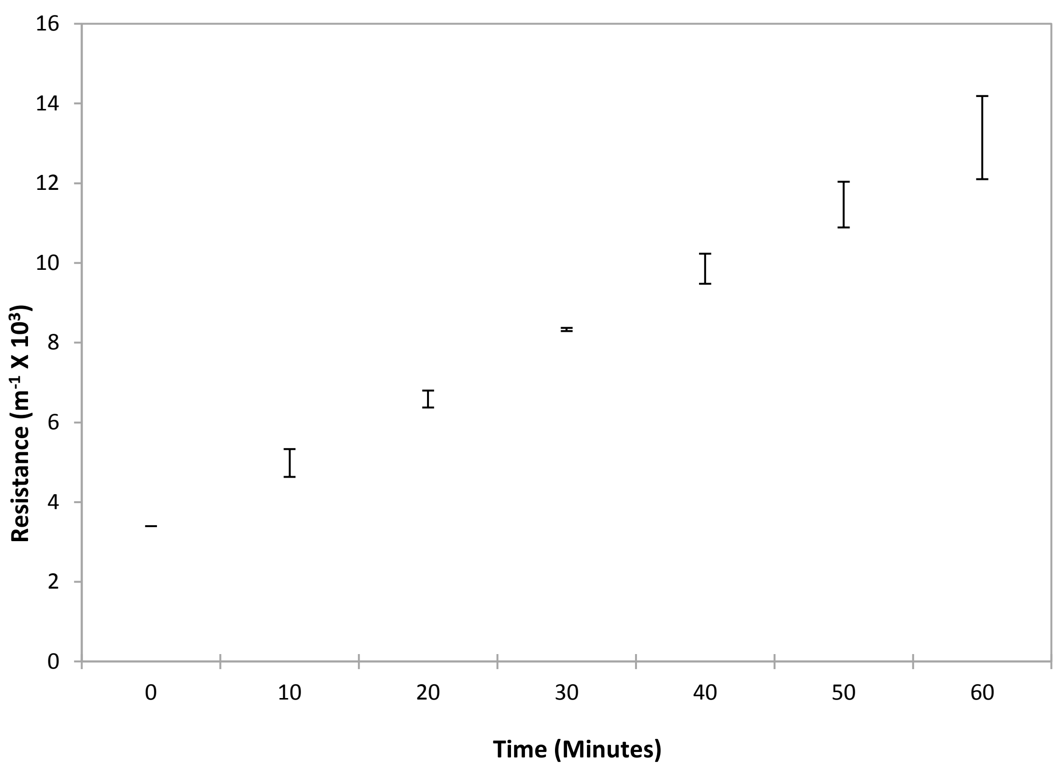

Figure B-9: No air-scour on Macassar activated sludge for a pump setting of 1% and an MLSS of 8.2-8.4 g/l

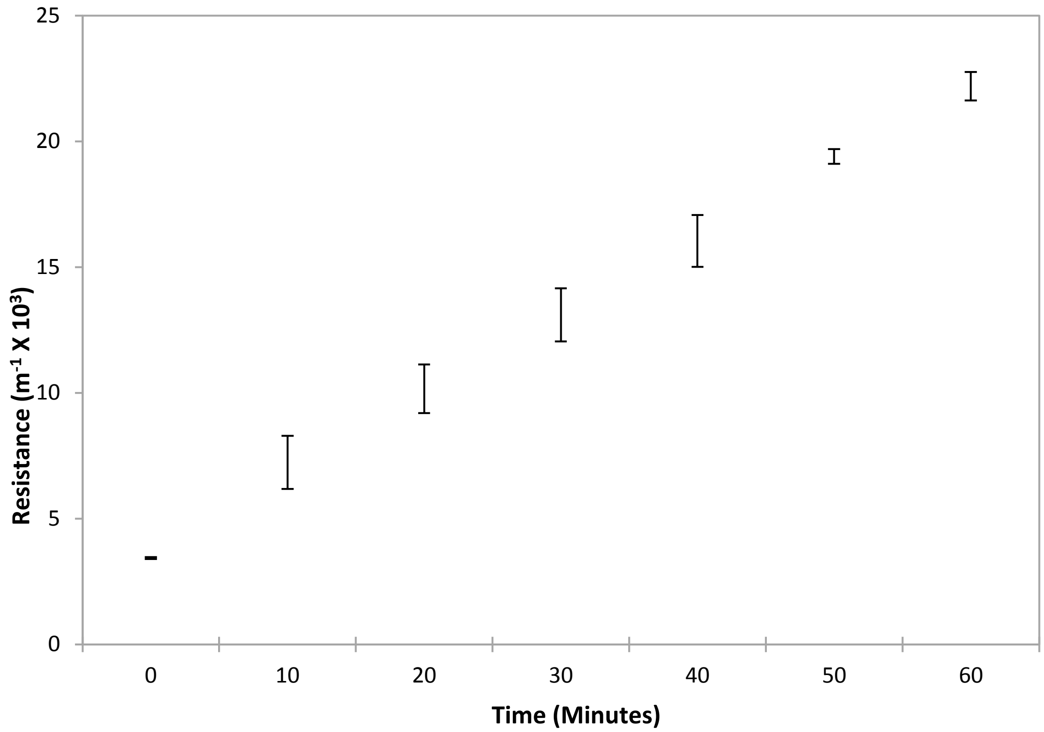

Figure B-10: Continuous air-scour on Macassar activated sludge for a pump setting of 1% and an MLSS concentration of 8.2-8.4 g/l

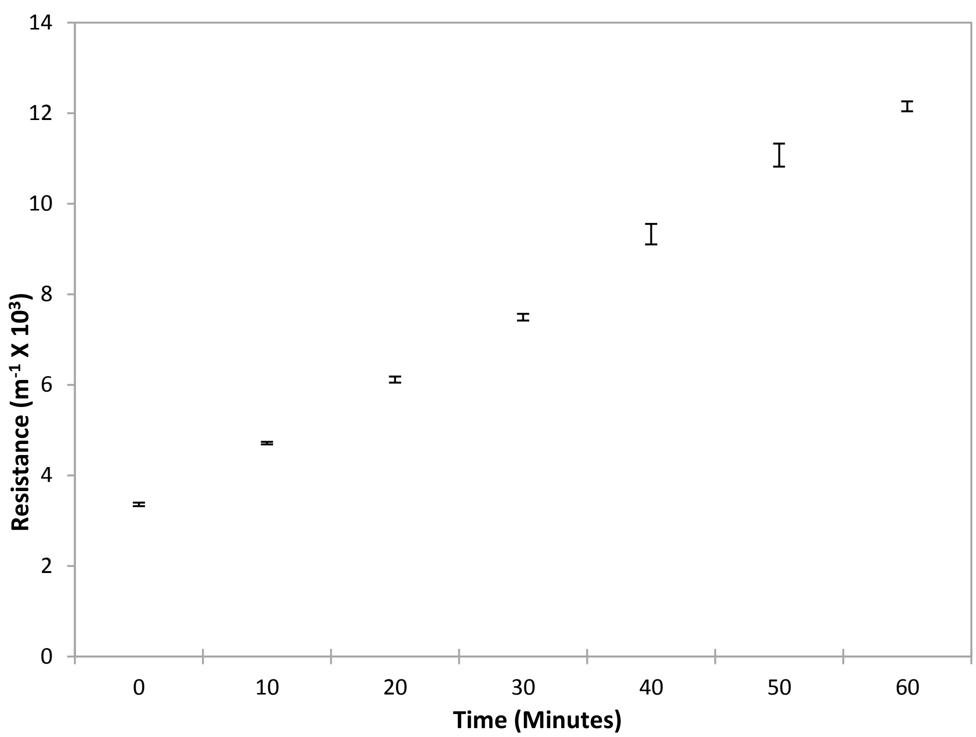

Figure B-11: Intermittent air-scour on Macassar activated sludge for a pump setting of 1% and an MLSS concentration of 8.2-8.4 g/l

B.2.2. Bellville WWTP results

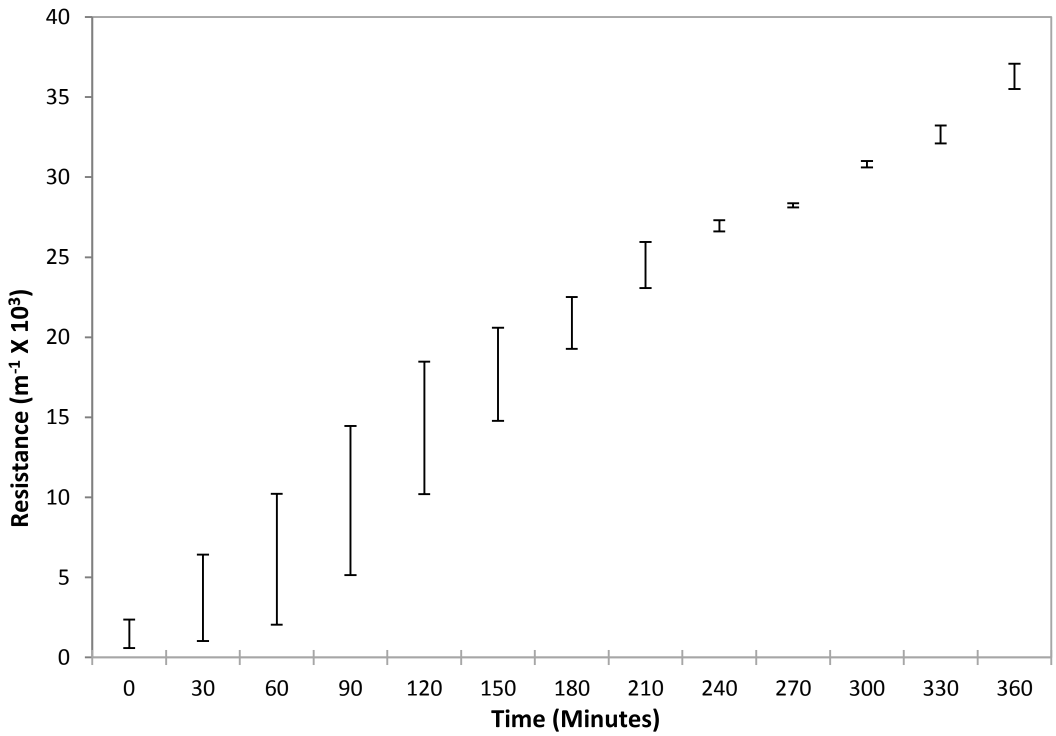

Figure B-12: No air-scour on Bellville activated sludge for a pump setting of 5% and an MLSS of 8.5 g/l

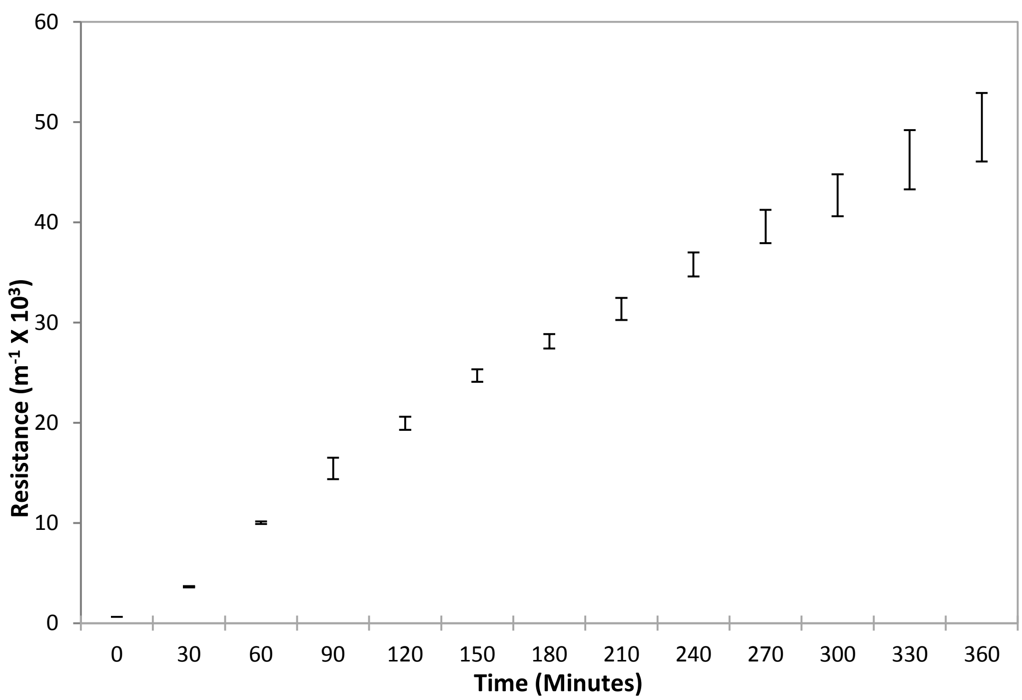

Figure B-13: Continuous air-scour on Bellville activated sludge for a pump setting of 5% and an MLSS concentration of 8.5 g/l

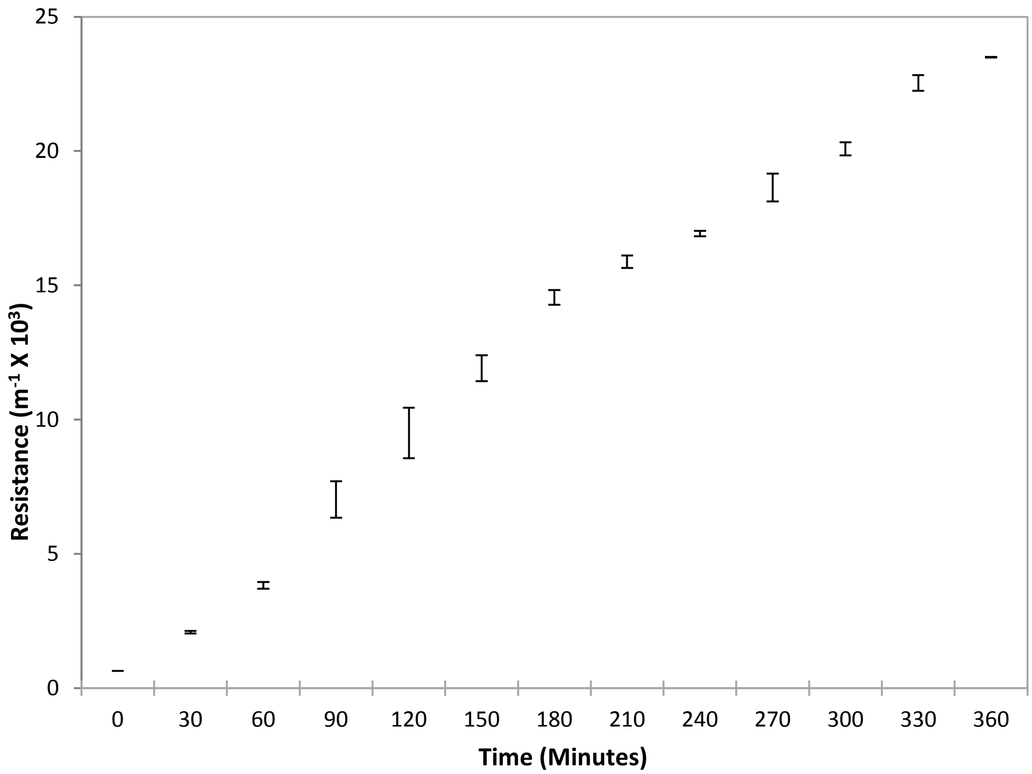

Figure B-14: Intermittent air-scour on Bellville activated sludge for a pump setting of 5% and an MLSS concentration of 8.5 g/l

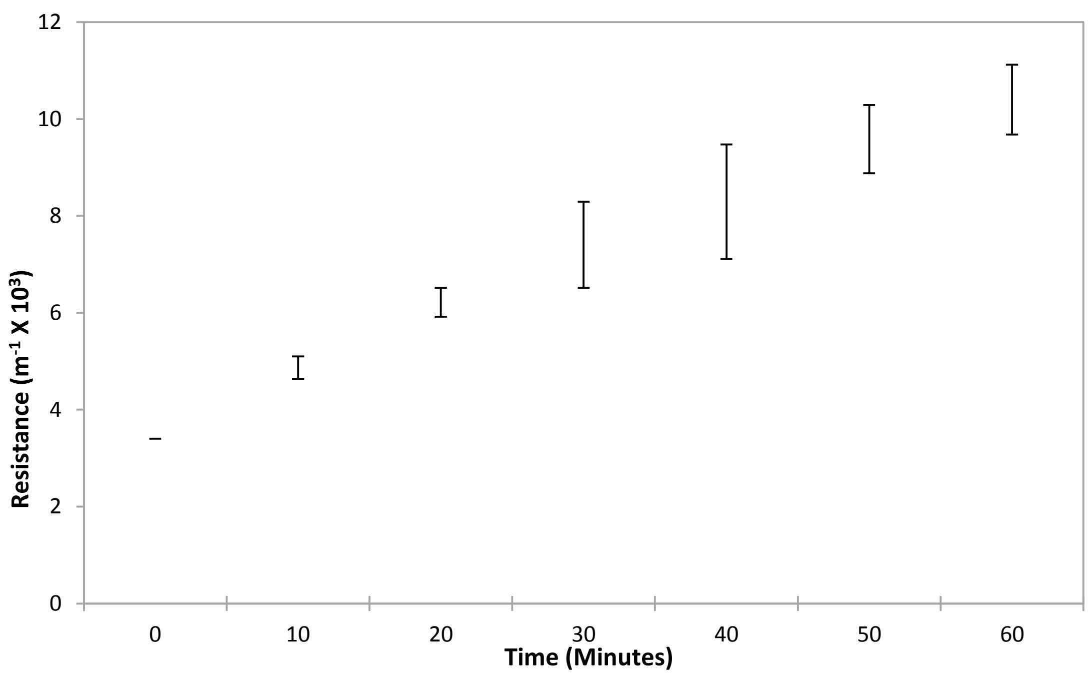

Figure B-15: No air-scour on Bellville activated sludge for a pump setting of 1% and an MLSS concentration of 8.9-9.1 g/l

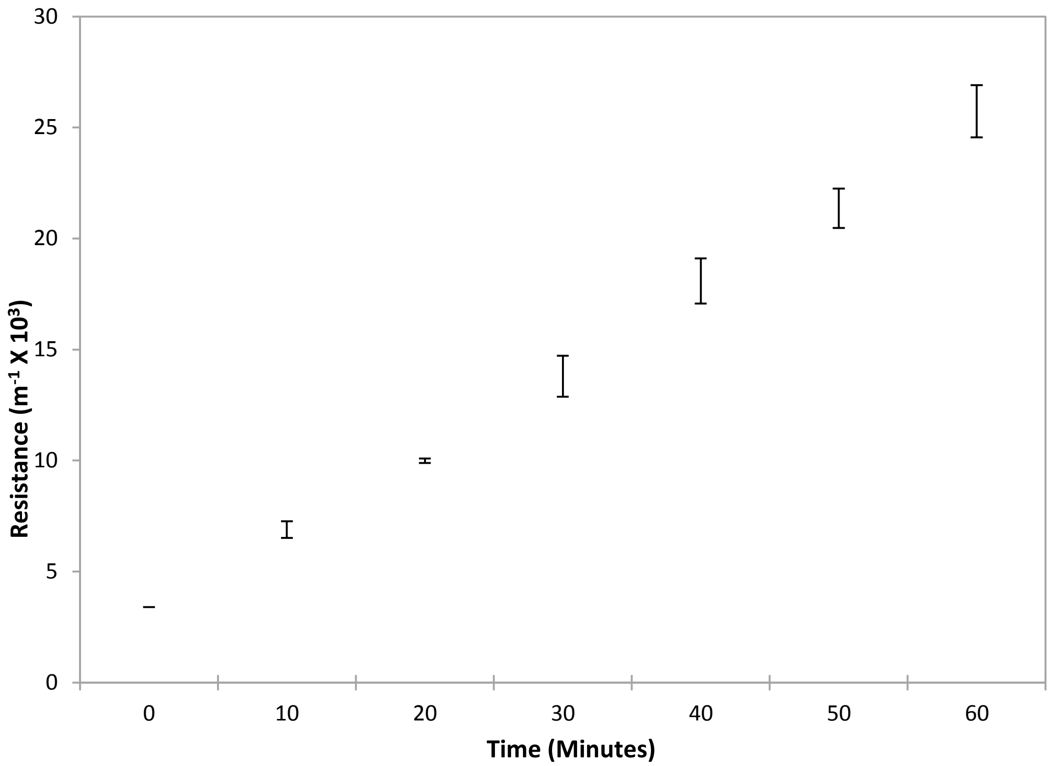

Figure B-16: Continuous air-scour on Bellville activated sludge for a pump setting of 1% and an MLSS concentration of 8.9-9.1 g/l

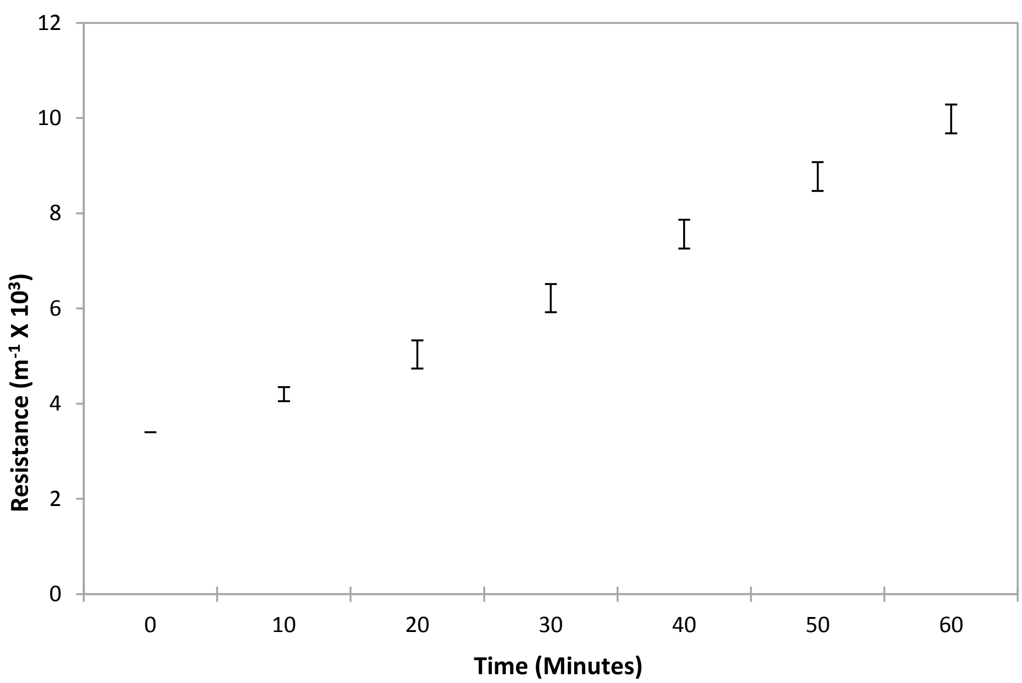

Figure B-17: Intermittent air-scour on Bellville activated sludge for a pump setting of 1% and an MLSS concentration of 8.9-9.1 g/l

B.2.3. Zandvliet WWTP results

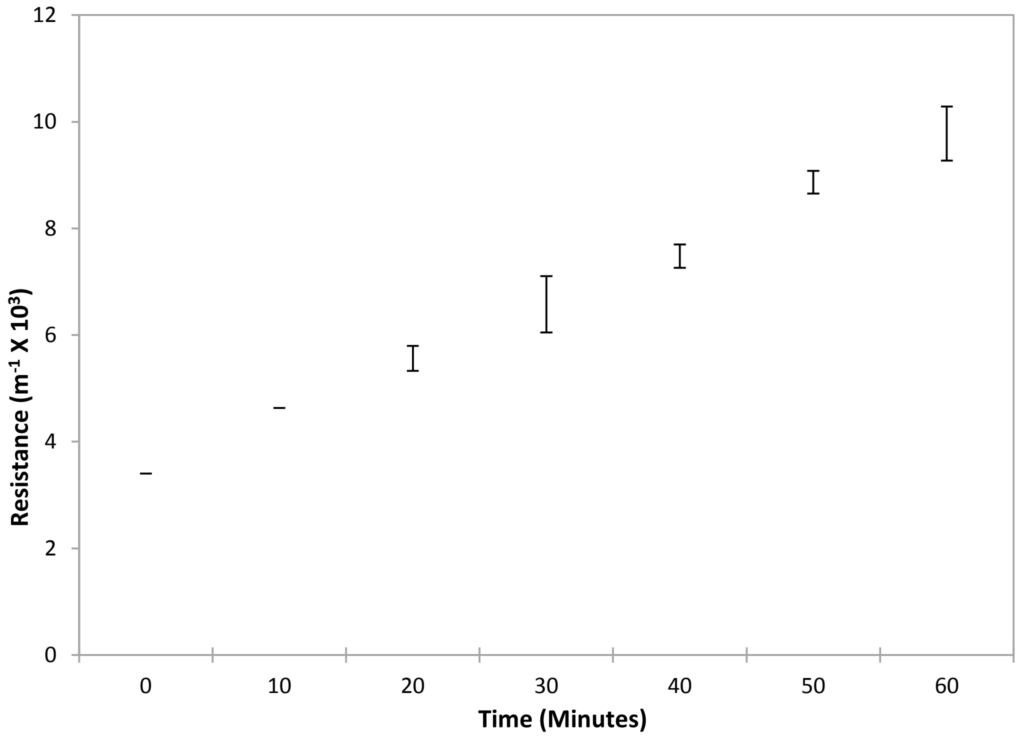

Figure B-18: No air-scour on Zandvliet activated sludge for a pump setting of 1% and an MLSS concentration of 9.8-10.1 g/l

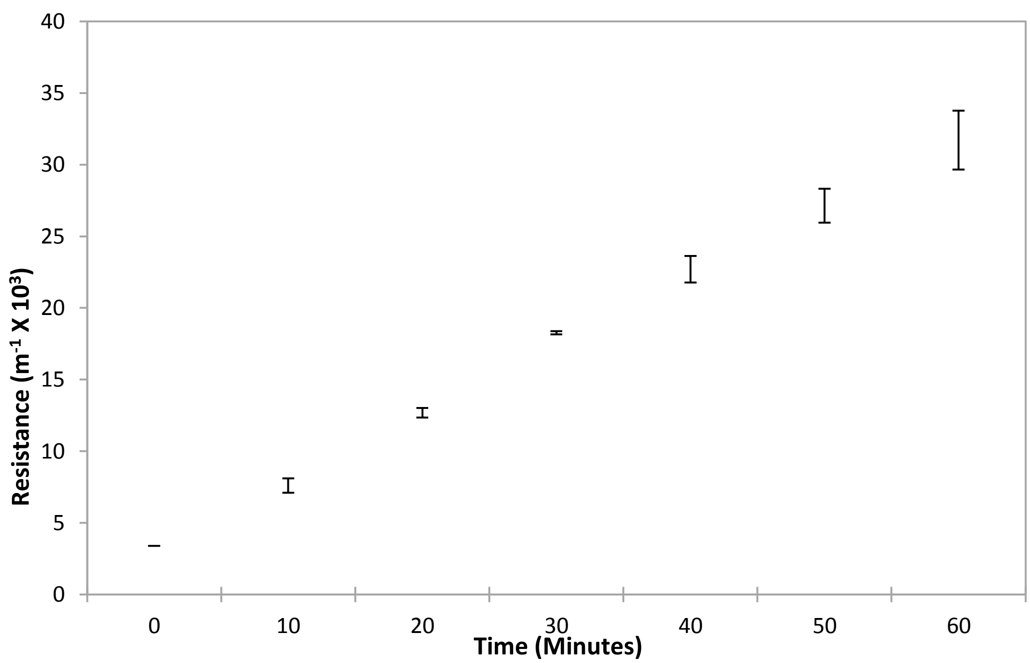

Figure B-19: Continuous air-scour on Zandvliet activated sludge for a pump setting of 1% and an MLSS concentration of 9.8-10.1 g/l

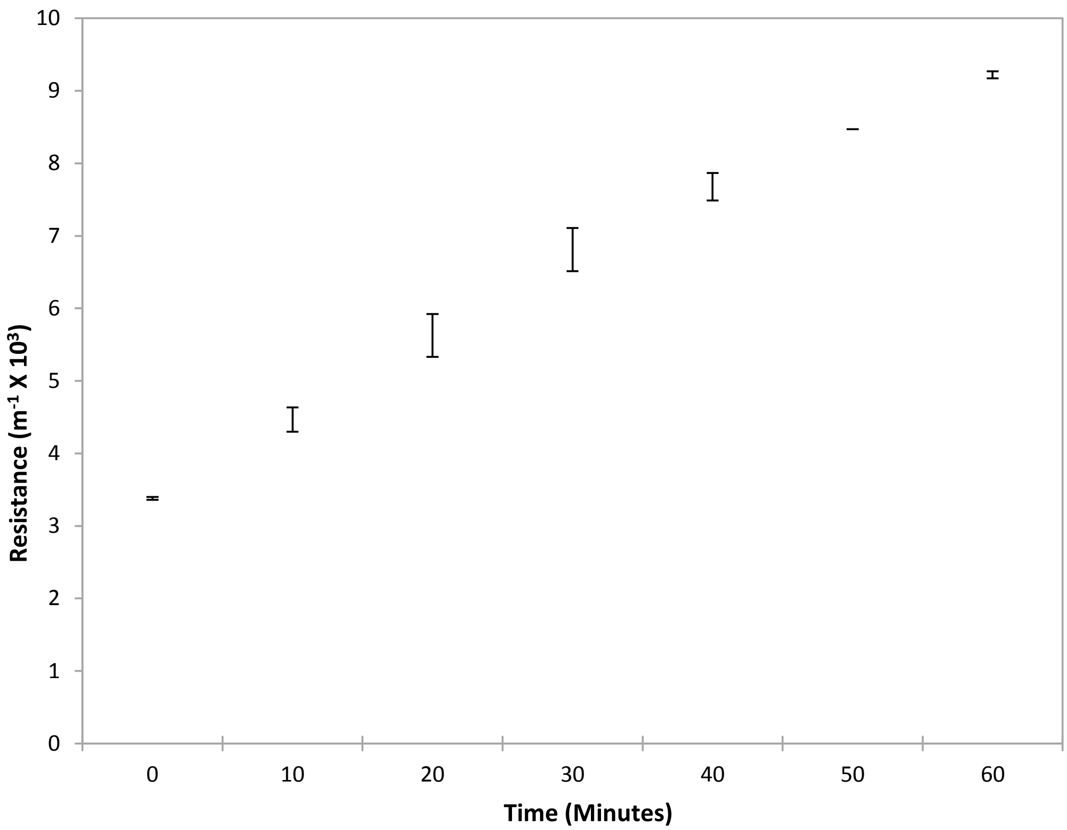

Figure B-20: Intermittent air-scour on Zandvliet activated sludge for a pump setting of 1% and an MLSS concentration of 9.8-10.1 g/l

B.3. Substantiation Experiments

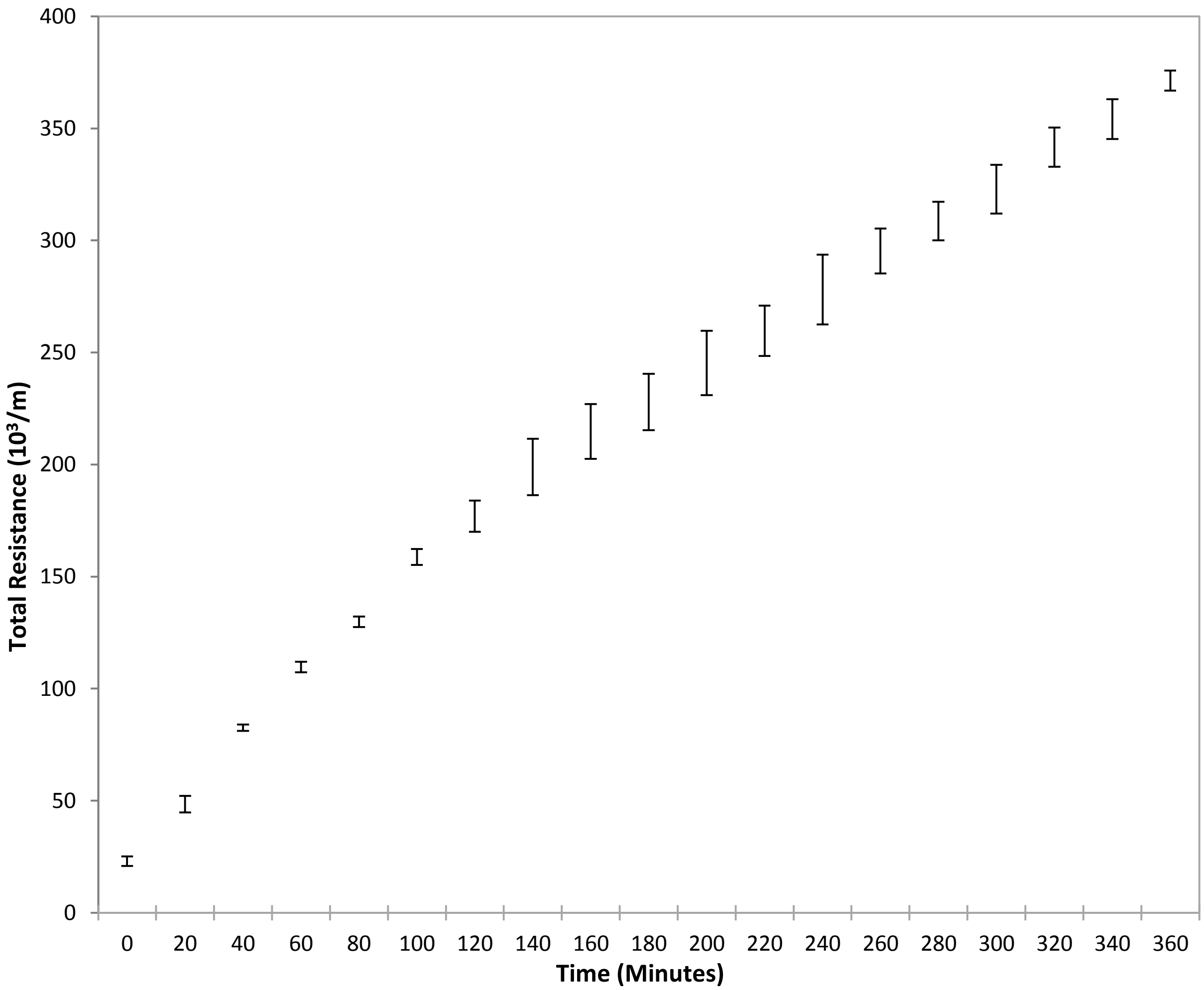

Figure B-21: Effect of operating procedure for continuous air-scour using a pump setting of 33% at an air-scour rate of 10 l/min/module and an MLSS concentration of 12.1 g/l.

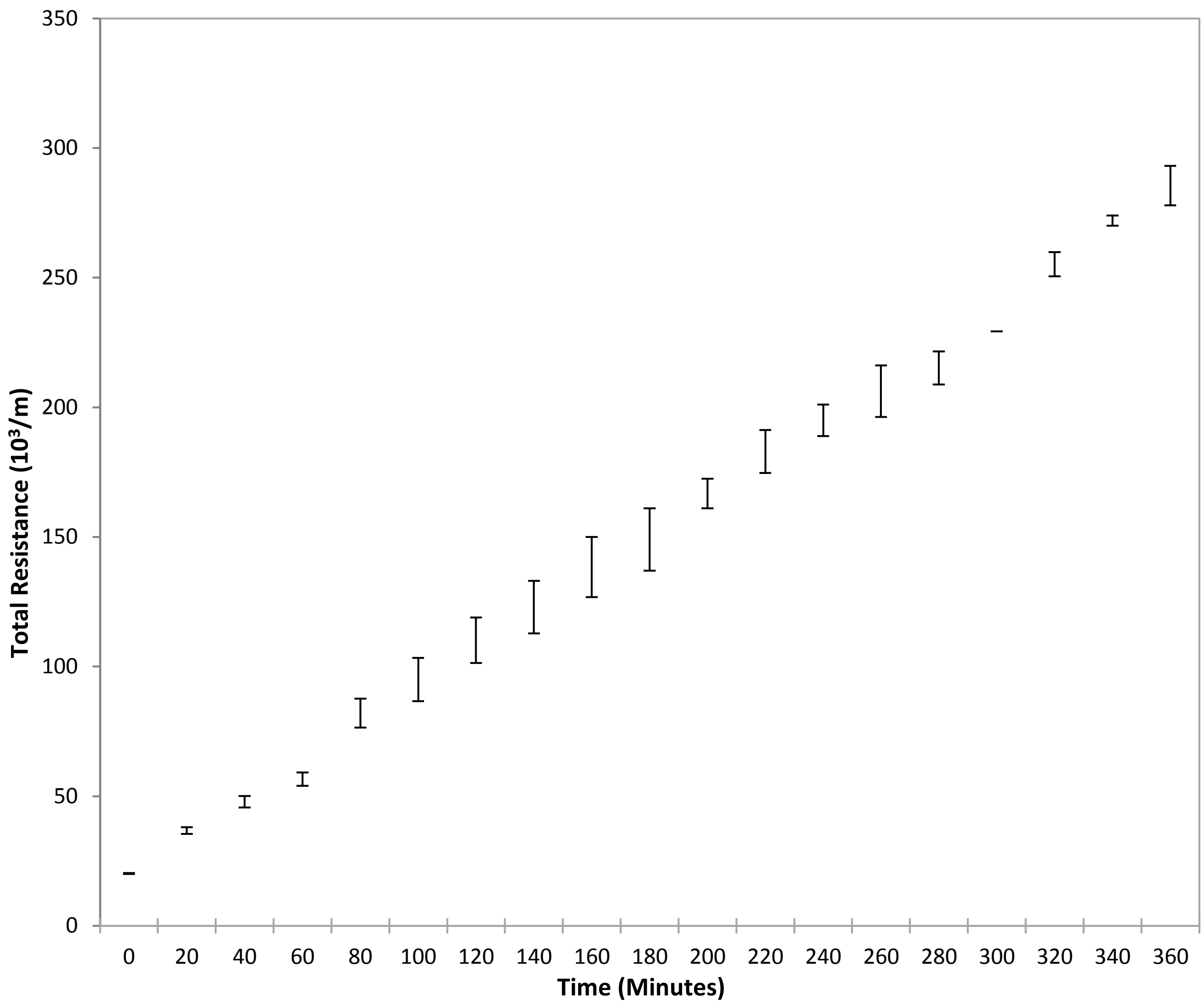

Figure B-22: Effect of operating procedure for no air-scour using a pump setting of 33% and an MLSS concentration of 11.9g/l.

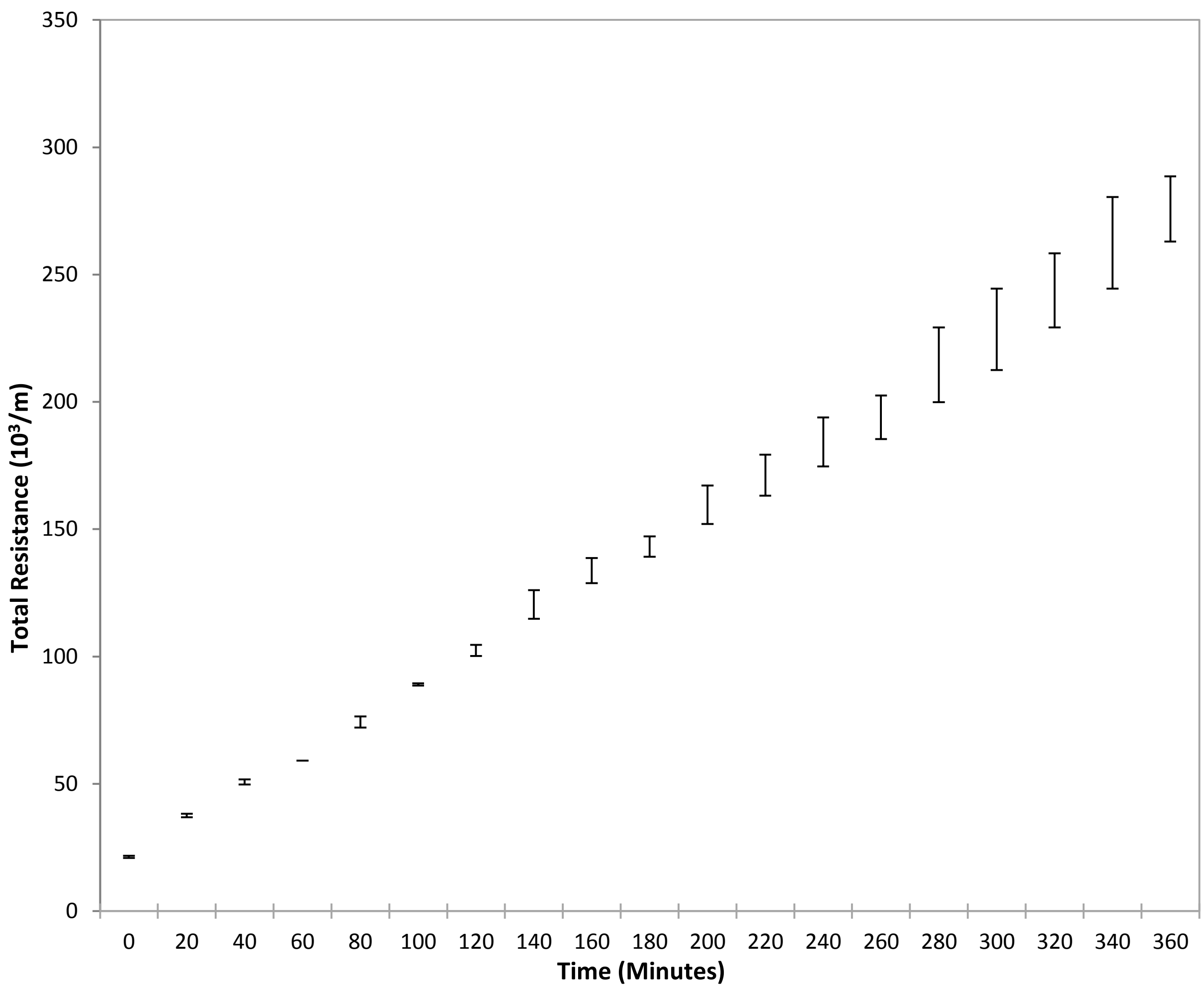

Figure B-23: Effect of operating procedure for intermittent air-scour for 3 minutes every 60 minutes using a pump setting of 33% at an air-scour rate of 10 l/min/module and an MLSS concentration of 11.7 g/l.

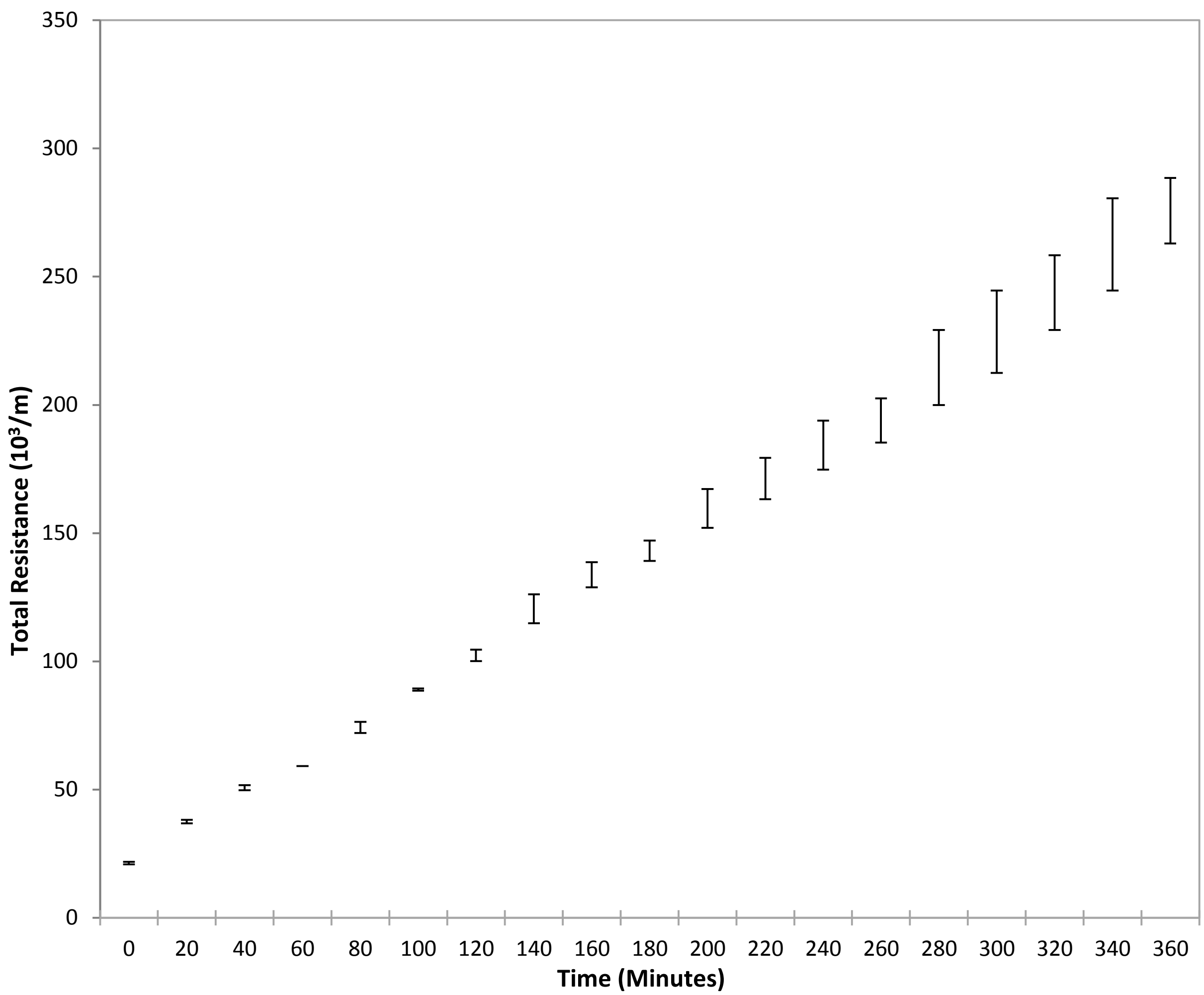

Figure B-24: Effect of operating procedure for no air-scour using a pump setting of 33% and an MLSS concentration of 11.8 g/l