DEVELOPMENT OF A WOVEN FABRIC IMMERSED MEMBRANE BIOREACTOR (WFIMBR) PACKAGE PLANT FOR DECENTRALIZED SANITATION

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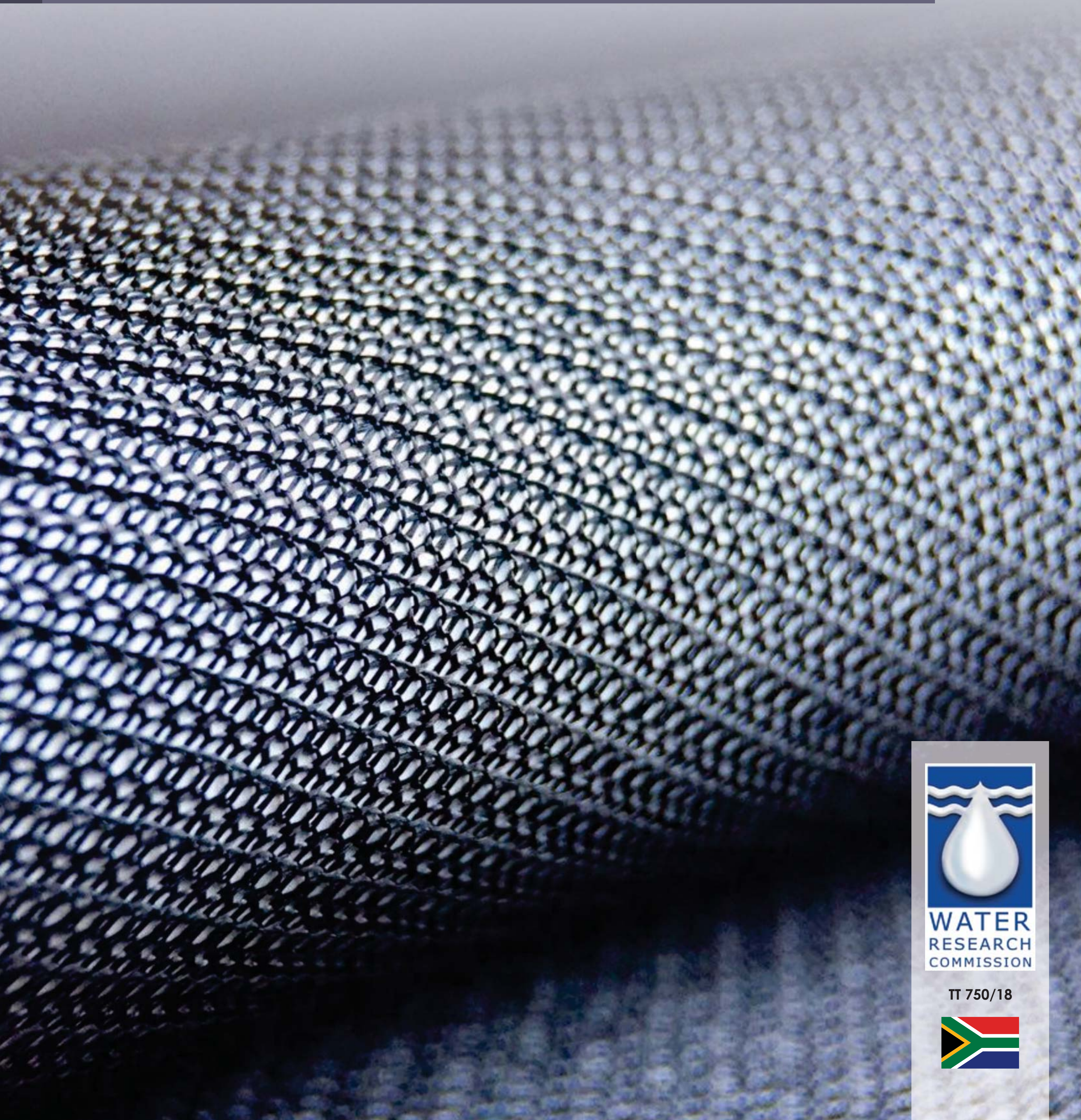

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DEVELOPMENT OF A WOVEN FABRIC IMMERSED MEMBRANE BIOREACTOR (WFIMBR) PACKAGE PLANT FOR DECENTRALIZED SANITATION

Report to the

Water Research Commission

by

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EXECUTIVE SUMMARY

Aims and Project History

The overall aim of this project was to develop and demonstrate the woven fabric immersed membrane bioreactor (WFIMBR) as a technology for small-scale and decentralised sanitation.

The specific objectives of this project were:

(i) To develop a 10-person equivalent (p.e.) package plant sanitation unit based on the novel woven fabric immersed membrane bioreactor technology (WFIMBR).

(ii) To investigate the optimisation of the unit in terms of energy usage, simplicity of construction, simplicity of operation, and robustness.

(iii) To develop a 30 p.e. unit based on the optimized geometry and operating conditions.

(iv) To demonstrate the 30 p.e. product to relevant stakeholders, including wastewater treatment practitioners, municipalities, vendors of systems, etc., so as to accelerate the implementation of IMBR wastewater treatment package plants in South Africa.

A 10 p.e. WFIMBR was constructed and installed at the Veolia Wastewater Reclamation Plant in Merebank, Durban. Initial experiments were performed on the returned-activated-sludge (RAS) stream and activated sludge obtained from the Veolia aerobic digestor. Subsequently the project team set up an aerobic digestor operating on the same raw feed as the Veolia plant. This was coupled to a tank containing the membrane modules and used in further investigations. The product quality and operational stability of the 10 p.e. unit was investigated.

The project was subsequently relocated to the Zandvliet Wastewater Treatment Works in Macassar, Cape Town. In addition to a conventional wastewater treatment process, the Zandvliet site also operates a commercial 'Zeeweed' IMBR. A 30 p.e. unit was constructed. Initial investigations indicated that the pressure drop across the membrane modules was excessive, and hence the design of the membrane modules was improved. The WFIMBR unit was then evaluated on the RAS stream from the Zeeweed IMBR as well as on the feed stream to the Zeeweed IMBR.

The product quality was consistent with that obtained in the Durban trials. However, the process stability differed substantially from that obtained in Durban. Furthermore, seemingly spurious results were obtained which contradicted most literature and accepted operational approaches to IMBRs.

The project was subsequently extended to investigate these seemingly spurious results. A laboratory-scale investigation was established to determine whether these results were in fact spurious, and whether these results were possibly due to some peculiar characteristic of the Zandvliet activated sludge. Activated sludges from three local wastewater treatment works were investigated in the laboratory trials, viz. Macassar, Zandvliet and Bellville.

Mechanical development of WFIMBR

The initial 10 p.e. WFIMBR was constructed according to the guidelines developed in WRC Project K8/885/3 "Evaluation of Woven Fabric Microfilters (WFMF) in Immersed Membrane Bioreactors (IMBRs)", and WRC Project K5/1369, "Development of a membrane pack for Immersed Membrane Bioreactors".

No mechanical restrictions were experienced in the Durban trials. However, initial trials at Zandvliet indicated that the pressure drop across the modules was excessive. It subsequently emerged that there was a great difference between the fouling potential of the feed used in Durban and the feeds used in Zandvliet. The project then focussed on redesigning the membrane modules to reduce the high pressure drop, by changing the design of the spacer in the module and the outlet ports.

The changes to the module design resulted in an approximately 90% decrease in the pressure drop across the membrane modules, translating into a significant saving in terms of energy.

Process Performance

Product Quality

The product quality from both the Veolia and Zandvliet trials are summarised in the table below.

Location	COD Removal			Permeate Turbidity (NTU)
	Feed COD (mg/L)	Average Permeate COD (mg/L)	% Reduction	
Veolia	250-300	15	97	0.8-0.2
Zandvliet	820-980	35	97	1.8-0.8

The COD removal is completely consistent with that of most commercial IMBRs. The product turbidities obtained from current commercial IMBRs are ~ 0.2 NTU, and hence lower than values indicated in the above table. However, in terms of decentralised sanitation applications, these turbidities are completely acceptable.

Process Hydrodynamics and Stability

A critical operational aspect of IMBRs is whether the hydrodynamics can be designed and manipulated to limit fouling of the membranes. In practice, where the flux of a unit is controlled, fouling is indicated by an increase in trans-membrane pressure, i.e. an increase in pressure drop across the membrane pack. Conventionally, air scouring is used to limit fouling, based on the assumption that increasing the air scouring rate will decrease fouling.

For WFIMBR trials based in Veolia in Durban, the project was able to achieve steady-state operation (no increase in fouling resistance) for over a month, by a suitable choice of permeate flux and air scouring rate. The operating conditions, i.e. the permeate flux and air scouring rate, were determined from 'critical flux' investigations on the activated sludge.

Using the same approach, critical flux experiments were performed at Zandvliet and an appropriate 'sub-critical' operating regime was identified. However, steady-state operation could not be obtained at these selected 'sub-critical' conditions, and the fouling resistance increased continuously with time. Further, the investigations at Zandvliet indicated that the fouling resistance was LOWER without air scouring, than with air scouring. This contradicted the performance obtained at Veolia, and current literature on IMBRs.

To investigate these seemingly spurious results further, a laboratory-scale IMBR rig was set up. Activated sludges from three wastewater treatment works were investigated, viz. Macassar, Bellville and Zandvliet. In the instances of Bellville and Zandvliet, the feed used in the laboratory-scale trials was the same as the feed to the commercial IMBR units.

The laboratory investigations confirmed the same behaviour for all three sources of activated sludge, i.e. that the fouling resistance increased faster as the air scouring rate was increased. The laboratory trials also indicated that intermittent scouring was marginally better than no scouring at all, and significantly better than continuous scouring.

Photos of membranes indicate that the 'air-scoured' membranes are 'clean' – yet give a higher resistance. The 'non-scoured' membranes are clearly covered in sludge yet gave a lower fouling resistance.

The above results contradict the 'critical flux' theory, and 'conventional wisdom' on how IMBRs should be operated. However, the results of this study are unequivocal, and are repeatable. There appears to be only one journal publication that supports the findings in this project.

Comparison of WFIMBR performance with commercial IMBRs

The commercial IMBRs at both Zandvliet and Bellville operate on the following sequence:

- filtration – 10 minutes, with continuous aeration
- backwash – 30 seconds or 1 minute

The extremely short filtration periods possibly confirm that the feed is highly fouling.

Accordingly, the operation of the commercial IMBRs are consistent with the performance of the WFIMBR technology obtained in this study, and the commercial IMBRs do not appear to offer any hydrodynamic advantage over the WFIMBR technology.

Implications for IMBR operation

A conclusion arising from this study is that the dominant fouling species in IMBRs may not be bacteria, but other small organic molecules. Bacteria could in fact be exploited as a 'dynamic membrane' or 'precoat' to protect the membrane from penetration by these fouling organics.

The conventional approach to IMBR operation is to operate at a high air-scouring rate. However, if the above conclusion is generally applicable, the appropriate operating strategy would be:

- Operate in the dead-end mode and allow a fouling layer of bacteria to develop to 'protect' the membranes from organics.

- Periodically, scour the membrane (possibly with a backwash) to remove the accumulated bacterial layer. Hence, the favoured operation would be dead-end filtration, with intermittent air scouring and possibly backwashing, to periodically remove the cake.

Conclusions regarding The WFIMBR Technology

In this project, the WFIMBR technology was up-scaled from a 'laboratory' technology to a stand-alone small-scale IMBR system for 10 p.e. and subsequently 30 p.e.

Evaluation of the performance of the WFIMBR indicated that:

(i) In terms of product quality, the trials at both Veolia and Zandvliet indicated that the WFIMBR produced a product quality consistent with that of commercial IMBRs.

(ii) In terms of process stability, the WFIMBR was operated stably at Veolia, but stable operation, where fouling could be controlled hydrodynamically, could not be achieved at Zandvliet.

(iii) Investigations indicate that this discrepancy is most likely due to the fouling potential of the different feeds used and is not a negative feature of the WFIMBR technology.

The project has demonstrated that the technology can be up-scaled and that the performance of the WFIMBR technology is completely comparable with that of conventional IMBRs, operated on the same feeds.

Accordingly, the WFIMBR technology remains potentially more attractive than conventional IMBRs for applications in developing economies:

(i) The membranes are significantly more robust than commercial polymeric IMBR membranes and are not destroyed when they dry out or are scratched.

(ii) The WFIMBR membranes do not require a chemical clean. They can be fully recovered by scrubbing them and soaking them in dilute hypochlorite ('Jik') overnight.

(iii) The WFIMBR technology is potentially less expensive than the current conventional IMBR technologies, especially in small-scale applications.

Recommendations

Prior to the trials at Zandvliet, it was expected that a WFIMBR plant would be able to operate stably (without fouling) for extended periods, based on the results obtained at Veolia. When cleaning was eventually necessary, this could be achieved by scrubbing the membranes or soaking them in dilute hypochlorite. The experiences with the feeds from Bellville, Macassar and Zandvliet indicate that stable IMBR operation is not feasible, even for the commercial IMBRs operating at Bellville and Zandvliet. Hence, an operating sequence needs to be developed to enable continuous operation of a WFIMBR operated on such feeds.

Hence, it is recommended that future research and development should focus on:

(i) <u>Developing and optimising an operating sequence for continuous operation of an IMBR unit</u>. The optimisation must consider: filtration flux and filtration period; intermittent air scouring frequency and flowrate; backflush frequency and duration; relaxation periods.

(ii) Developing an optimal cleaning strategy for 'in-situ' cleaning of fouled membranes. This should consider: air-scouring in combination with backflush; cleaning the membranes with dilute hypochlorite.

(iii) Investigations into fouling characteristics of mixed liquors from various zones in a wastewater treatment works. This study should be extended further, to characterise the fouling propensity of feeds from various sections within a wastewater treatment facility, as well as to attempt to confirm the hypotheses made in this study. Such a study may result in a different approach to the positioning of IMBRs in a wastewater treatment facility; the energy consumed in IMBRs, and hence could have a major future impact on 'new generation' approaches to wastewater treatment.

(iv) Development of a membrane with a more oleophobic surface characteristics. If this could be easily achieved, it would both decrease the rate of fouling by micro-organics and increase the ease of cleaning fouled membranes.

(v) Demonstration of small-scale WFIMBR for decentralized sanitation. The effort in this project deviated from 'demonstration' to 'investigation' of the seemingly spurious results obtained during the project. Hence a successful demonstration to potential users and other stakeholders was not achieved during the project timeframe. It is therefore recommended that once an optimised operating regime for 30 p.e. is obtained, following the recommendations above, a unit is set up at a suitable site for demonstration of the technology.

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(ii) Cape Metro, WSSA and Veolia Water, for allowing part of the project to be based at the Zandvliet Water Treatment Works in Maccasar, and for allowing the Project Team to obtain samples from the Macassar and Bellville Wastewater Treatment Works.

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• Dr W Edwards	Atl-Hydro
• Mr J Topkins	ERWAT
• Mr Mabuda Fortune	ERWAT

(iv) The WRC Project Managers, for their guidance and input to the project.

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CHAPTER 1: INTRODUCTION

1.1 BACKGROUND

South Africa, like other developing countries, faces a major challenge in providing adequate sanitation for all of its people. Decentralised, small-scale "package" sanitation plants have a great potential to overcome some of the logistical challenges, and could make a very significant contribution to the roll-out of sanitation in peri-urban areas, rural areas, farms, remote schools, remote clinics, small un-serviced communities, etc.

Internationally, there has been a major swing towards immersed membrane bioreactor (IMBR) technology for both domestic and industrial wastewater treatment due to the myriad of advantages that IMBRs offer over conventional biological wastewater treatment plants. These include: high product quality; smaller footprint; modularity; and a more stable biological system due to high biomass concentrations. IMBR package sanitation plants, therefore, could have a significant impact on addressing the sanitation backlog in developing countries.

However, a major barrier to the application of IMBRs in developing economies is the cost and lack of robustness of the current IMBR membranes. Generally, current commercial IMBR membranes are expensive and cannot withstand rough handling, e.g. drying out, being scoured, mechanical abrasion, etc. Further, there is a perception that IMBR technology is "first-world", complicated, requires highly skilled operators, and hence cannot be applied for decentralized sanitation in developing regions. The few industrial IMBRs and large-scale domestic wastewater IMBRs in the country are fairly sophisticated plants, which unfortunately support this latter perception. Hence, in order to enable South Africa to benefit from IMBR technology it is necessary to demonstrate to wastewater practitioners, vendors of package plants, etc. that IMBR technology can be simple, robust, easy to operate and cost effective.

In WRC Project No K5/1598 a novel flat-sheet immersed microfilter was developed for rural drinking water production, based on a locally produced woven fabric. Termed the woven fabric immersed microfilter (WFIMMF), the membrane has various advantages over current commercial flat-sheet membranes in terms of applications in developing countries. These include: very robust and not destroyed by drying, scouring, etc.; very easy to clean without chemicals; potentially very inexpensive. In WRC Project No K8/885, the potential of WFIMMF as an IMBR membrane was investigated. That project indicated, inter alia, that: the technical performance of the membrane was adequate for IMBR applications; the woven fabric immersed membrane bioreactor (WFIMBR) system would exhibit various advantages over current commercial systems for "developing economy" conditions; and that there would be a significant market if the technology could be translated into an inexpensive product.

The next stage in the development of a WFIMBR technology is to develop it into a stand-alone small-scale sanitation system that could be used as a sanitation package plant.

This proposed project has two main outcomes. Firstly, it will develop the promising WFIMBR technology into a final product – a package sanitation plant. The plant will be based strictly on locally available, inexpensive components. Secondly, the product will be used to demonstrate to relevant stakeholders that IMBR technology can be simple, inexpensive and robust, and could be a major potential contributor to decentralized sanitation schemes.

1.2 PROJECT AIMS AND WORKPLAN

The specific aims of this project were:

(i) To develop a 10-person equivalent (p.e.) package plant sanitation unit based on the novel woven fabric immersed membrane bioreactor technology (WFIMBR).

(ii) To investigate the optimisation of the unit in terms of energy usage, simplicity of construction, simplicity of operation, and robustness.

(iii) To develop a 30 p.e. unit based on the optimized geometry and operating conditions.

(iv) To demonstrate the 30 p.e. product to relevant stakeholders, including wastewater treatment practitioners, municipalities, vendors of systems, etc., so as to accelerate the implementation of IMBR wastewater treatment package plants in South Africa.

The project was divided into ten sub-tasks, representing the Project Deliverables, viz.

1) Ten p.e. base unit: Design, construct and commission a 10 p.e. WFIMBR unit.

2) Baseline performance: Obtain “baseline” performance data on the 10 p.e. in terms of product quality and membrane performance.

3) Optimisation (I): Investigate the improvement of the membrane filtration operation so as to reduce energy consumption whilst giving stable performance. Aspects to be investigated will include the geometry of the membrane pack (module spacing, module size), air scour regimes (continuous, intermittent, intermittent with slow backwash), and air scour rate.

4) Optimisation (II): Develop an improved operating regime for the 10 p.e. unit and demonstrate this improved operation for at least three months.

5) Thirty p.e. unit – Design: Develop a design for a 30 p.e. unit. The major criteria here will include simplicity, ease of construction and operation, and use of locally available and inexpensive components.

6) Thirty p.e. unit – Construct and Commission: Construct and commission the 30 p.e. unit.

7) Thirty p.e. unit – Operation: Operate the 30 p.e. unit for at least six months, adapting the operating conditions so as to achieve stable operation with a good product quality.

8) Economic Assessment: Perform an economic assessment of the 30 p.e. unit (capital and operating costs)

9) Demonstration: Demonstrate the unit to relevant stakeholders.

1.3 PROJECT HISTORY

The project was initially set up at the Veolia Wastewater Reclamation Plant in Merebank, Durban in 2012. The 10 p.e. unit was designed, constructed and commissioned, and baseline data for the operation of the WFIMBR was obtained. This work was done as part of an MTech degree, which has subsequently been accepted. The second task, i.e. investigations into stable operation and energy minimisation, was initiated, as part of another MTech study, also based at Veolia WRP. This study had not been written up at the time of writing of this report.

The project leader subsequently relocated from the Durban University of Technology to Stellenbosch University in January 2013. At the beginning of 2013, Veolia indicated that they were expanding their operations and would require the physical space on which the WFIMBR rig was located. It was then decided to relocate the investigation to Umgeni Water's Darville Wastewater Treatment Works in Pietermaritzburg.

For various reasons, the relocation to Darville never occurred. It was finally decided that the project should be relocated to the Western Cape, where it would be under closer supervision of the project leader. Discussions were held with WSSA and the Cape Metro, following which it was agreed that the main project would be based at the Zandvliet Wastewater Treatment Works. A student from Stellenbosch University registered for an MEng degree, and executed the project investigations as part of his study.

1.4 ORGANISATION OF THIS REPORT

This report is organised primarily along the lines of the deliverables stated in Section 1.2.

CHAPTER 2: DESIGN, CONSTRUCTION AND COMMISSIONING OF 10 P.E. UNIT

This section concerns the design, construction and commissioning of a 10 p.e. plant that will be used in the first stage of the investigations.

The elements of the 10 p.e. plant include:

(i) the membrane module, membrane pack and membrane housing;

(ii) the reactor vessels, controls and instrumentation; and

(iii) the physical environment where the plant is set up.

These are discussed in the following sub-sections.

2.1 MEMBRANE MODULE, MEMBRANE PACK AND MEMBRANE HOUSING

This project is a follow up to WRC Project K8-885. Some aspects concerning the modules and membrane pack were given in that report and are repeated here for completeness.

2.1.1 Membrane and membrane module

The membranes that will be used throughout the project are the woven fabric microfiltration membranes produced by Gelvenor. SEMs of the clean fabric, and the fabric after filtration, are given below (Figure 1):

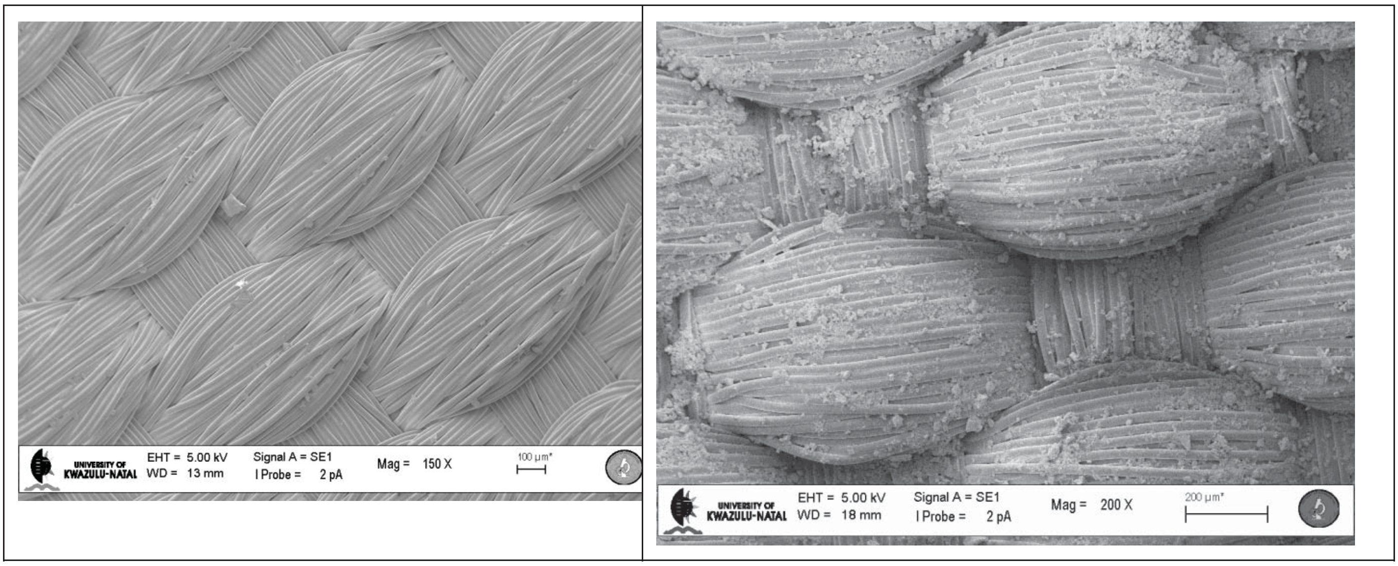


Figure 1: SEMs of woven fabric microfiltration membranes

Note that these membranes do not have “pores” as in conventional polymeric/ceramic membranes. The tight weave of the fibres forms a surface filter that allows fluid through but retains particles. Previous attempts to quantify an equivalent “pore size” for the WFMF indicated that the membrane had an effective pore size of about 1 to 2 µm.

The membrane module consists of a rectangular PVC frame onto which the fabric is glued on both sides. An internal mesh is included to act as a "spacer". This keeps the two membranes apart and allows fluid to flow internally in the module. The PVC frame has a 2 mm nipple which allows permeate to flow out of the module (Figure 2).

Figure 2: Module

The question arose as to what module dimensions should be used in the current project.

The international flat-sheet IMBR market is currently dominated by Kubota and Toray. However, both of these systems are focused on large scale operations, use relatively large modules, and hence are not of primary interest to this project.

A survey of European markets indicates that the main players in the small-scale IMBR market, defined as systems for approximately 50 p.e. are Weise, Huber and Copa. There is seemingly a rapidly developing small-scale IMBR market in South East Asia, but very little information on these systems is available in conventional literature. In terms of small-scale IMBR operations in South Africa, a company from the Western Cape has ventured into using Weise technology. There does not seem to be other small-scale IMBR systems currently being used in South Africa, although various companies/consultants are planning to move into this field.

Attempts were made to obtain data on the small-scale IMBR systems mentioned above by survey of the internet, survey of scientific journals and direct contact with the suppliers. Direct contact with the suppliers proved to be fruitless – they are very reticent to reveal details of their systems to researchers. This is not quite logical, since in principle anyone can obtain details of geometry and operating conditions from simply examining their installations. However, there are not many small-scale installations in South Africa that can be examined.

Weise produces two membrane packs, aimed at different scales of operation. The dimensions obtained for the Weise modules are shown below:

- Weisse small modules: 207 mm x 497 mm
- Weisse large modules: 415 mm x 490 mm

The WFMF modules are fabricated by hand, and hence can be fabricated in any size desired. In previous drinking water applications, A4 (approx. 250 mm x 340 mm) were used, and filtration seemed to occur across the whole module, with no "dead zones".

A further consideration was that the dimensions of the membrane pack. As noted in Section 3.2.2, it was decided to start off with dimensions developed during a hydrodynamic study performed as part of a previous WRC projects. As a starting point in this project it was decided to the largest modules that would fit into the membrane pack. If it is found that there are no significant flow maldistributions, the module size and membrane pack could be progressively increased during the course of the project.

Based on the above (Table 1):

Table 1: Dimensions of single module:

Total length	$L_{m,total}$	50,5	cm
Total Width	$W_{m,\ total}$	34,5	cm
Effective length	$L_{m,eff}$	45,5	cm
Effective Width	$W_{m,\ eff}$	29,5	cm
Effective surface area of a single module	SA_m	0,27	m^2

2.1.2 Membrane pack

The major issues here are the gap between the modules and the number of modules per pack.

Module gap:

The gap between the modules has a major influence on fluid flow patterns, and eventually the effectiveness of the air-scouring. The large-scale IMBRs (Kubota and Toray) use gaps of between 6 mm and 7 mm. Weisse uses gaps of 5.5 mm (small modules) and 6 mm (large modules).

It was decided that the gap size used in this project would be 5 mm to 5.5 mm.

Number of modules:

Weisse's module packs consist of either 24 modules (small modules) or 21 modules (large modules). In this project a further constraint is the need to have adequate free volume around the membrane pack for biomass circulation.

It is also required that the membrane pack should be able to filter 10 p.e. per day, i.e. 2 000 L/day. On the assumption that a flux of 20 LMH could be achieved, and that the unit would operate for at least 22 hours per day, a filtration area of ~ 4.6 m^2 would be required.

Based on the above criteria, it was found that a module pack of 18 to 20 modules was feasible, giving a filtration area per pack of 4.86 m^2 to 5.4 m^2. For comparison the small-module Weisse pack has a filtration area of 3.5 m^2, and the large modules 7 m^2.

The construction of the module is very straightforward and simple. Four holes are drilled into each module. Threaded rods are inserted through the holes, and each module is secured in place by nuts. Hence, the gap between modules can be maintained. Two "handles" are attached at the top of the pack. These allow the pack to be easily removed, as well as facilitate the positioning of the product manifold. The product manifold is simply a pipe with nipples attached to it. Once the pack is assembled, the permeate outlets from each module are connected to the permeate manifold with flexible tubing. The elements and the final membrane pack are shown in Figures 3 and 4.

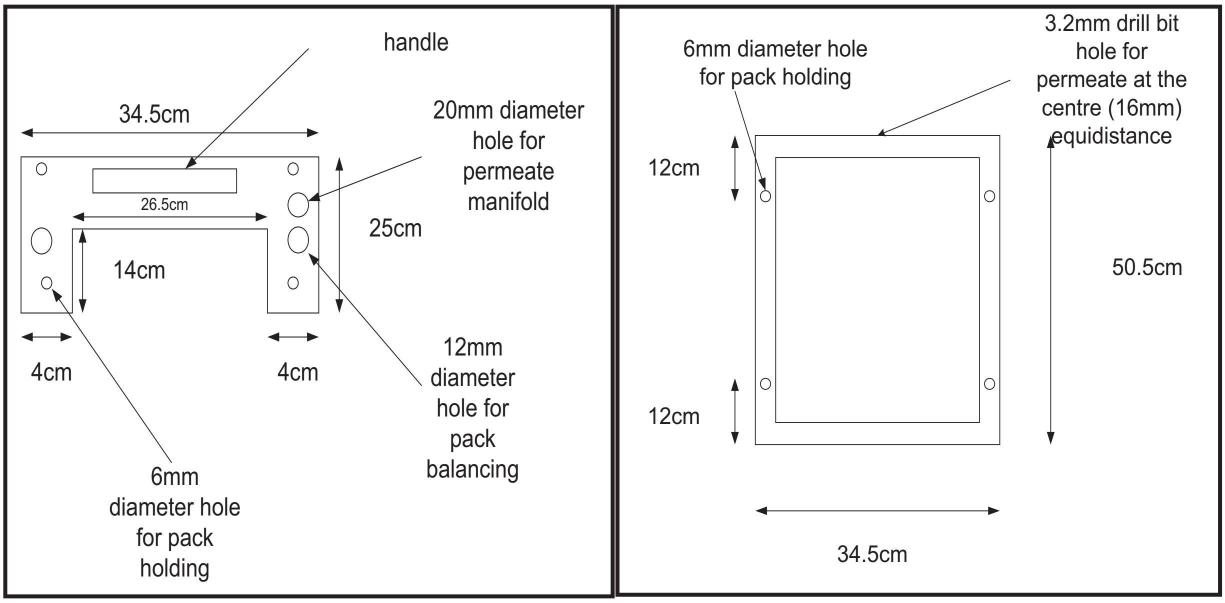


Figure 3: Schematic of construction elements

Figure 4: Final membrane pack showing side view (left) and top view (right)

2.1.3 Membrane housing

The membrane housing consists of a frame that holds the membrane pack and the air spargers for the air scouring. The design of the membrane housing is critical in determining whether unhindered free circulation of biomass will occur through and around the membrane pack, or whether there will be restrictions leading to poor circulation, frothing, etc.

The important geometry aspects of the membrane housing are shown below (Figure 5):

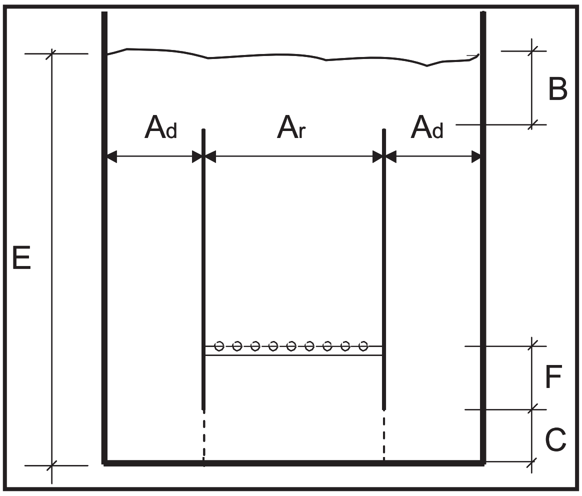


Figure 5: Important dimensions in membrane housing

A_d	area of the down-comer section
A_r	area of the riser section
B	clearance height between the top of the membrane stack and the liquor level
C	bottom entry clearance for fluid recirculation
F	position of the air diffuser relative to the top of the bottom entry clearance
E	total liquor head in reactor vessel

The effect that each dimension has on stable circulation has been studied in detail in WRC Project No K5/1369 "Development of a membrane pack for Immersed Membrane Bioreactors". That project also provided guidelines for dimensions and ratios that would ensure stable circulation.

This project followed those guidelines closely in determining the *initial configuration* for the membrane housing. Part of this project will involve re-examining the important geometric variables, and hence develop an "optimized" geometric design.

The starting design used in this project is summarized below (Figure 6).

PVC of 5mm thickness was selected as a material of construction. The following dimensions were selected:

- the overall height of the WF membrane pack casing is 0.8m
- the height between membrane pack and diffuser is 0.25m
- the height between casing base and diffuser is 0.1m
- the head above the membrane pack is 0.1m

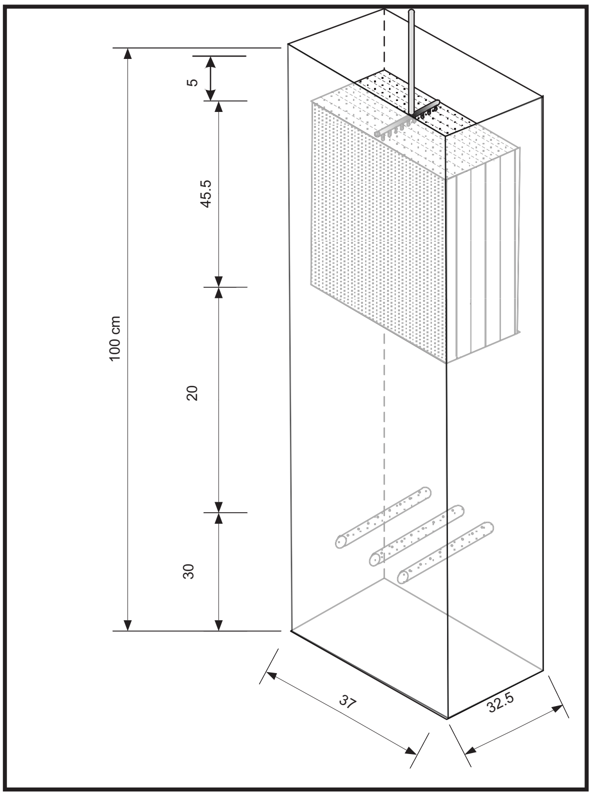


Figure 6: Schematic of WF membrane pack casing

A further important aspect of the membrane housing is the air sparger. The design of the sparger must ensure that:

(i) bubbles of an appropriate size are produced, to facilitate maximum scouring

(ii) there is an even distribution of scouring bubbles across the membrane pack, to prevent “dead zones”.

Generally, the sparger and the membranes are the most expensive capital elements of an IMBR system. Many IMBRs use exotic imported silicone membrane spargers to ensure that the above criteria are met.

A major aim of this project is to devise an IMBR system from inexpensive and locally available materials. Previous experience indicated that a simple sparger, fabricated from a pipe with holes of the appropriate size drilled into it, worked adequately.

Accordingly, the sparger was fabricated from a 20 mm rod which was drilled with 2 mm diameter holes. The number of holes was 15 and 15 mm equidistance. The geometry of the holes was cylindrical. The diffuser was inserted 5cm below the membrane pack, to equally distribute scouring air in all modules.

The final membrane housing, with the membrane pack, is shown in Figure 7.

Overview of membrane case

View from side, showing air inlet for gas spargers

Top view, showing gas spargers

Permeate off-takes on panels

Figure 7: Membrane pack with housing

2.2 REACTOR VESSELS, CONTROL AND INSTRUMENTATION

The overall aim of this project is to develop an IMBR based sanitation technology that could be used for decentralized sanitation, particularly in developing economies.

The major criteria for a sanitation system are:

(i) it must remove organic contaminants (COD) from the domestic wastewater feed; and

(ii) it must remove pathogens from the feed.

If the treated water is to be discharged into a water body (river, lake, dam) a further requirement is that nutrients in the form of nitrates and phosphates must be removed. However, if the final treated water is to be used for agricultural purposes, nitrates and phosphates would be an added advantage.

This project is expected to address both scenarios. Initially, it will focus on 'standard' IMBR technology, i.e. the removal of COD and pathogens only. However, it will then extend to the removal of nitrates and phosphates, to cater for waters that will be discharged to water bodies.

The "standard" IMBR configuration consists of an aerobic reactor tank and the membrane tank. This will remove COD and pathogens but will not remove nutrients.

In the plant that has been set up for this project, the membrane tank and membrane housing/pack was designed and set up as described in Section 2. The aerobic reactor consisted of a standard "Jojo" tank of capacity 550 L. The process and instrumentation diagram (P&ID) is shown in Figure 8.

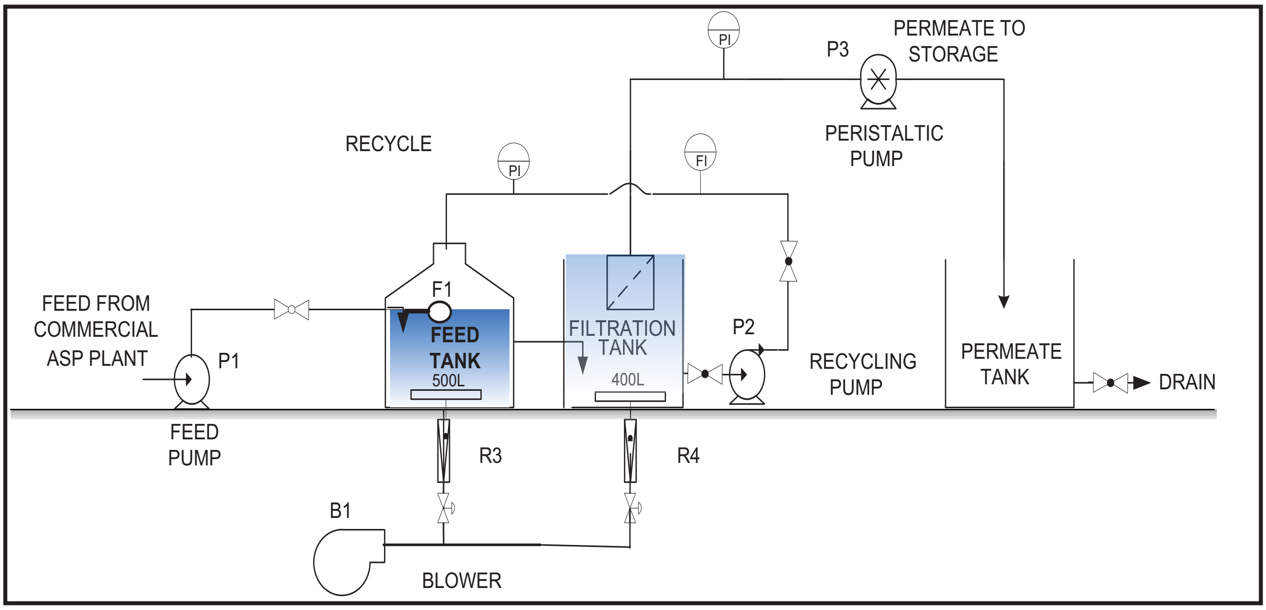


Figure 8: P&I of standard IMBR rig

The feed to the unit was settled sewage. This was obtained from the inlet channel to the Veolia activated sludge plant, i.e. it was free of biomass and had not undergone any COD degradation.

The feed was pumped to the bioreactor ("feed tank") by a submersible pump (P1) hung in the inlet channel. The pump was controlled by a level controller in the feed tank. Hence, feed was pumped intermittently as required to keep the level in the bioreactor constant.

From the bioreactor mixed liquor flowed under gravity into the bottom of the filtration tank, via a large diameter “L” shaped pipe. The filtration tank, in turn, had its own level control which activated the recycling pump (P2). This pump was set at a flowrate of 440 L/min, and simply recycled (concentrated) mixed liquor back to the bioreactor to maintain a constant level in the filtration tank. The level setpoint in the filtration tank was slightly below that in the bioreactor, so that there was a continuous flow between the two vessels.

Permeate was pumped out via a peristaltic pump which had a variable speed control to vary the permeate rate.

Hence in the above setup:

(i) the levels in the bioreactor and filtration tank are kept constant, irrespective of the permeate flowrate

(ii) the feed flowrate into the bioreactor equals the permeate withdrawal rate.

The flowrate of air to the aerobic tank (to maintain an acceptable DO), and the flowrate of air to the membrane tank (to achieve adequate air scour) are critical operating parameters. The physical setup for this project is shown in Figure 9.

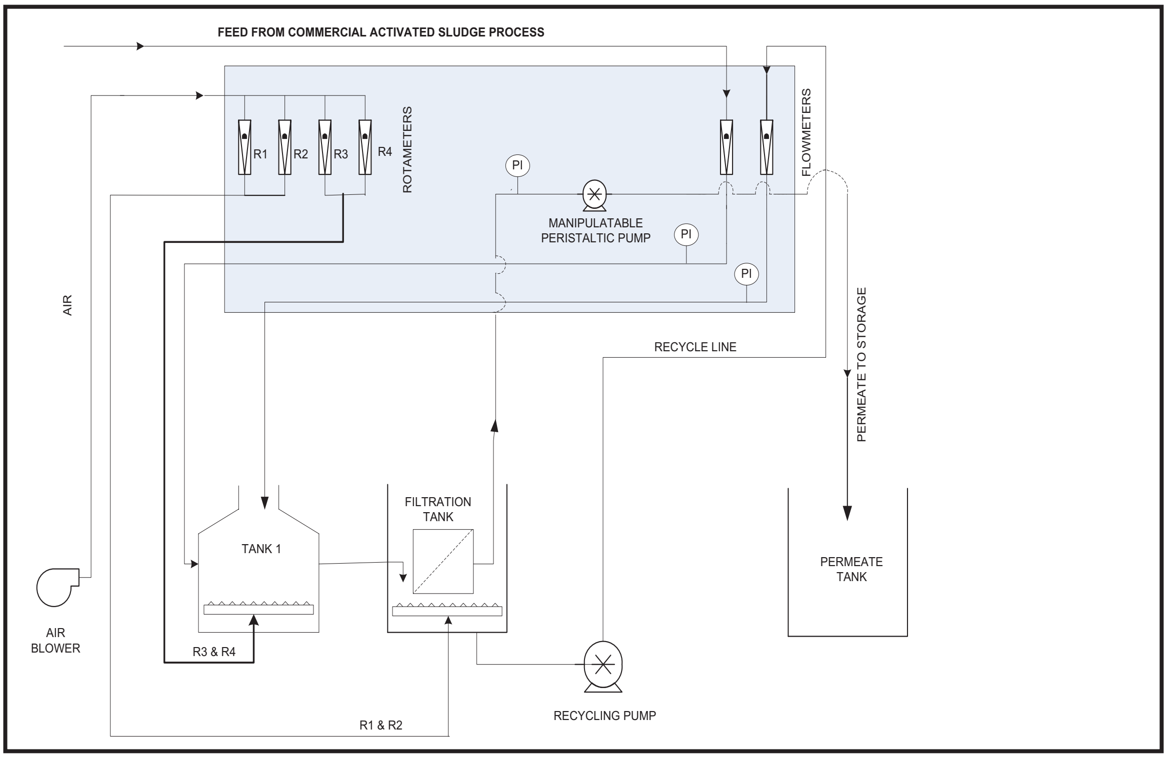


Figure 9: Control of air flowrates to aerobic reactor and membrane tank

2.3 INSTALLATION

The 10 p.e. plant was set up at the Veolia Water Reclamation Works in Merebank, Durban. All the required zones/tanks have been implemented in the plant, viz. an anaerobic tank, an anoxic tank, an aerobic tank and the filtration tank (Figure 10). The project will initially focus on ensuring that the "standard" IMBR configuration works well, viz. aerobic and filtration, where after the anoxic and anaerobic zones will be incorporated into the process.

The plant operates on the same settled sewage that feeds the Veolia aerobic digestor. A submersible pump is placed in the channel leading from Southern Works to the Veolia digestor.

Figure 10: Experimental rig for 10 p.e. unit

CHAPTER 3: BASELINE PERFORMANCE OF 10 P.E. UNIT

The baseline results reported here are:

(i) performance of the unit in terms of COD removal and product turbidity, as a function of MLSS;

(ii) stability of operation under sub-critical flux conditions.

3.1 BASELINE CONDITIONS

3.1.1 Apparatus and geometry

The membrane pack geometry is described in Section 3.3. The pack consisted of 20 modules, giving a nominal filtration area of 5.4 m^2.

3.1.2 Flux and air scour rate and hydraulic retention time

In WRC Project No K8/885, critical fluxes were determined for the waste activated sludge from the Veolia plant, using the flux-step method (repeated in Figure 11 below for convenience).

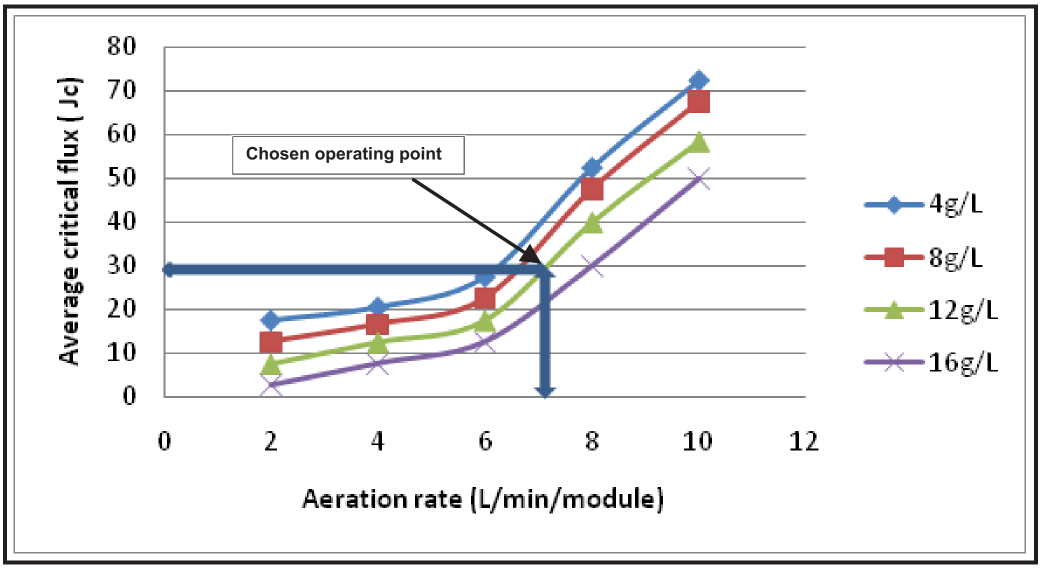


Figure 11: Critical fluxes for Veolia WAS as a function of air-scour rate and MLSS

At the onset of this project it was not known whether the above results would apply to continuous operation.

To meet the requirement of 10 p.e. per day, a flux of 17 LMH would be sufficient (22 hours filtration per day). However, based on the critical flux results it was ambitiously decided to start at an operating flux of 30 LMH and an air scour rate of 10 L/min/module. The air scour rate is in the same range as that used by commercial flat-sheet IMBRs. The flux selected is slightly higher than operating fluxes reported for commercial flat-sheet systems (15 LMH to 25 LMH). The flux would be lowered during the course of the project if stable operation was not achieved.

A further consideration is the hydraulic retention time (HRT) in the aerobic reactor. At steady state, the flowrate through the unit is determined by the permeate flux. With a flux of 30 LMH, filtration area of 5.4 m^2, and 22-hour operation, the throughput is 3 564 L/day. Aerobic degradation of COD is expected to occur in both the bioreactor and the filtration tank, since both are aerated. The approximate working volumes of the bioreactor and filtration tank were 500 L and 200 L respectively. Hence the HRT is approximately 4.7 hours when the combined volumes are considered. This is lower than the 6 to 7 hours HRT usually expected in activated sludge plants. However, it was decided to start off at the selected flowrate, and to decrease it (thereby increasing the HRT) if the product COD was too high.

3.1.3 Air flowrate to bioreactor

The dissolved oxygen (DO) in the aerobic reactor was monitored, and the air flowrate adjusted to ensure that the DO was always > 2 mg/L.

3.2 EXPERIMENTAL PROCEDURE

The investigation was carried out in three stages: sludge growth; sub-critical operation; supercritical operation.

(i) Sludge Growth: The bioreactor and filtration tank were seeded with activated sludge from the Veolia ASP (MLSS ~ 4 g/L). Aeration to both tanks was started, and the feed and recycle pump controls were activated. The permeate flux was started off at 10 LMH and increased to 30 LMH in 5 LMH increments. Each flux was held steady for four to eight days. No sludge was wasted. The MLSS increased to 12 g/L over a period of 21 days.

(ii) Sub-critical operation: Once an MLSS of 12 g/L and a flux of 30 LMH was achieved, the unit was operated under steady-state conditions, by wasting sludge to maintain an MLSS of 12 g/L. This sub-critical operation lasted 32 days.

(iii) Super-critical operation: After 32 days of absolutely steady operation, with no increase in transmembrane pressure (TMP), it was decided to investigate what would happen if the unit was operated super-critically. Hence, the flux was increased to 40 LMH, 50 LMH and 55 LMH. This stage lasted 11 days.

During the above investigation, the following parameters were monitored:

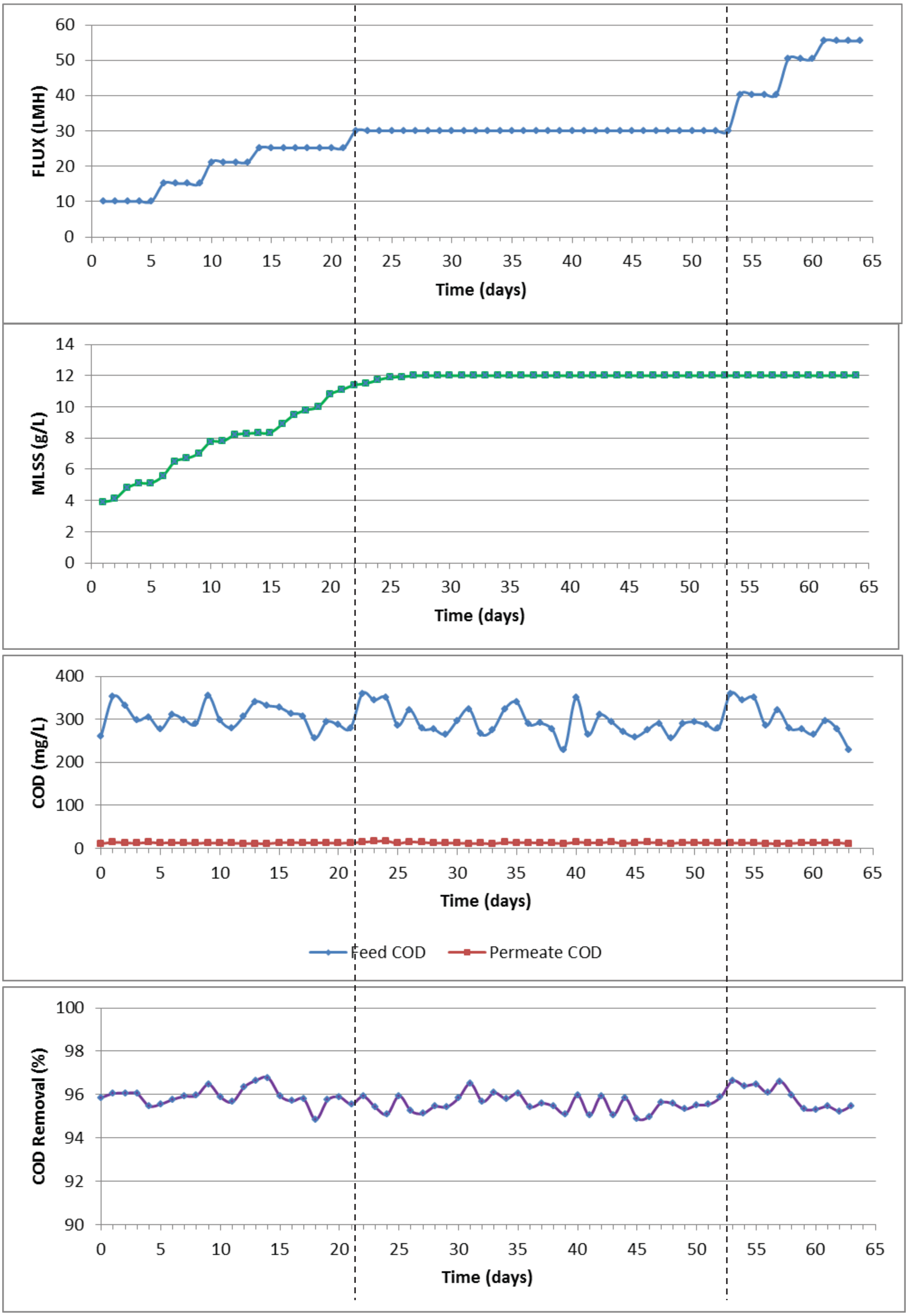
• permeate turbidity	(Hach 6789)
• feed and permeate COD	(Hach 6970)
• DO in the bioreactor	(Hach 5320AD)
• MLSS	(Hach 4560)
• trans-membrane pressure (TMP)	

3.3 RESULTS

3.3.1 Product Quality

The time profiles of flux, MLSS, COD in feed and permeate, COD removal and permeate turbidity are shown in Figure 12(a) and (b).

Figure 12 (a): Time profiles of J, MLSS, COD and COD removal (see next page)


FLUX (LMH)
0
10
20
30
40
50
60
Time (days)
0
5
10
15
20
25
30
35
40
45
50
55
60
65
MLSS (g/L)
0
2
4
6
8
10
12
14
Time (days)
COD (mg/L)
0
100
200
300
400
Time (days)
Feed COD
Permeate COD
COD Removal (%)
90
92
94
96
98
100
Time (days)

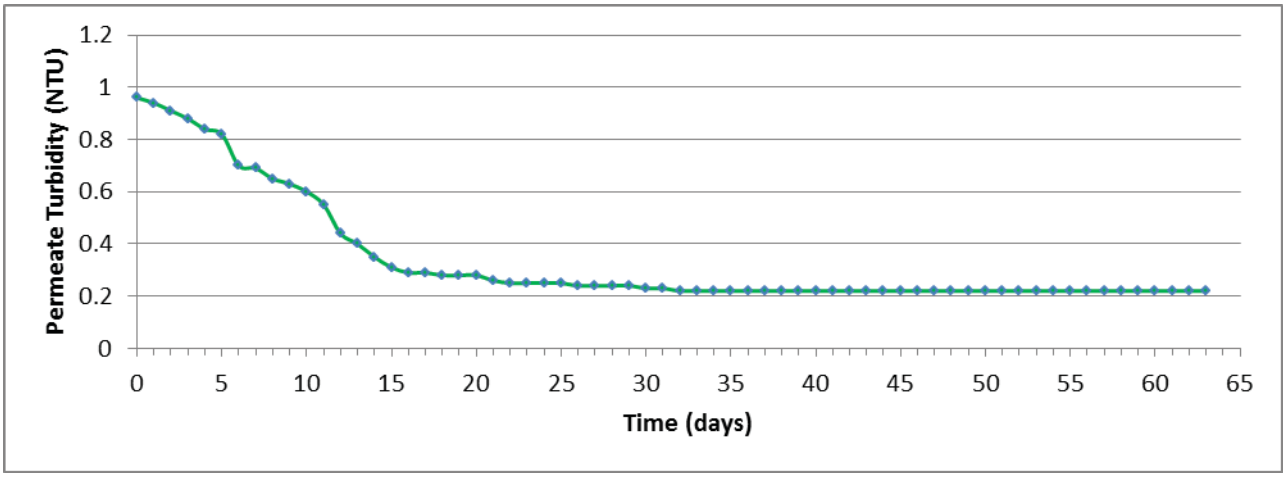


Figure 12(b): Time profiles of permeate turbidity

The feed COD ranges from 250 mg/L to 350 mg/L, while the permeate COD ranges from 10 mg/L to 14 mg/L. Hence the COD removal ranges from 95% to 97%. It is also clear that the permeate COD, and hence the % COD removal, is independent of the MLSS and is also independent of the flux.

In general, the WFIMBR performance in terms of COD removal is completely consistent with commercial IMBR systems. The permeate turbidity starts off at just below 1 NTU, and levels off at around 0.2 NTU. This is also completely consistent with the performance of commercial IMBR units.

3.3.2 Stability of sub-critical operation

The time profiles of flux, MLSS and TMP are shown in Figure 13.

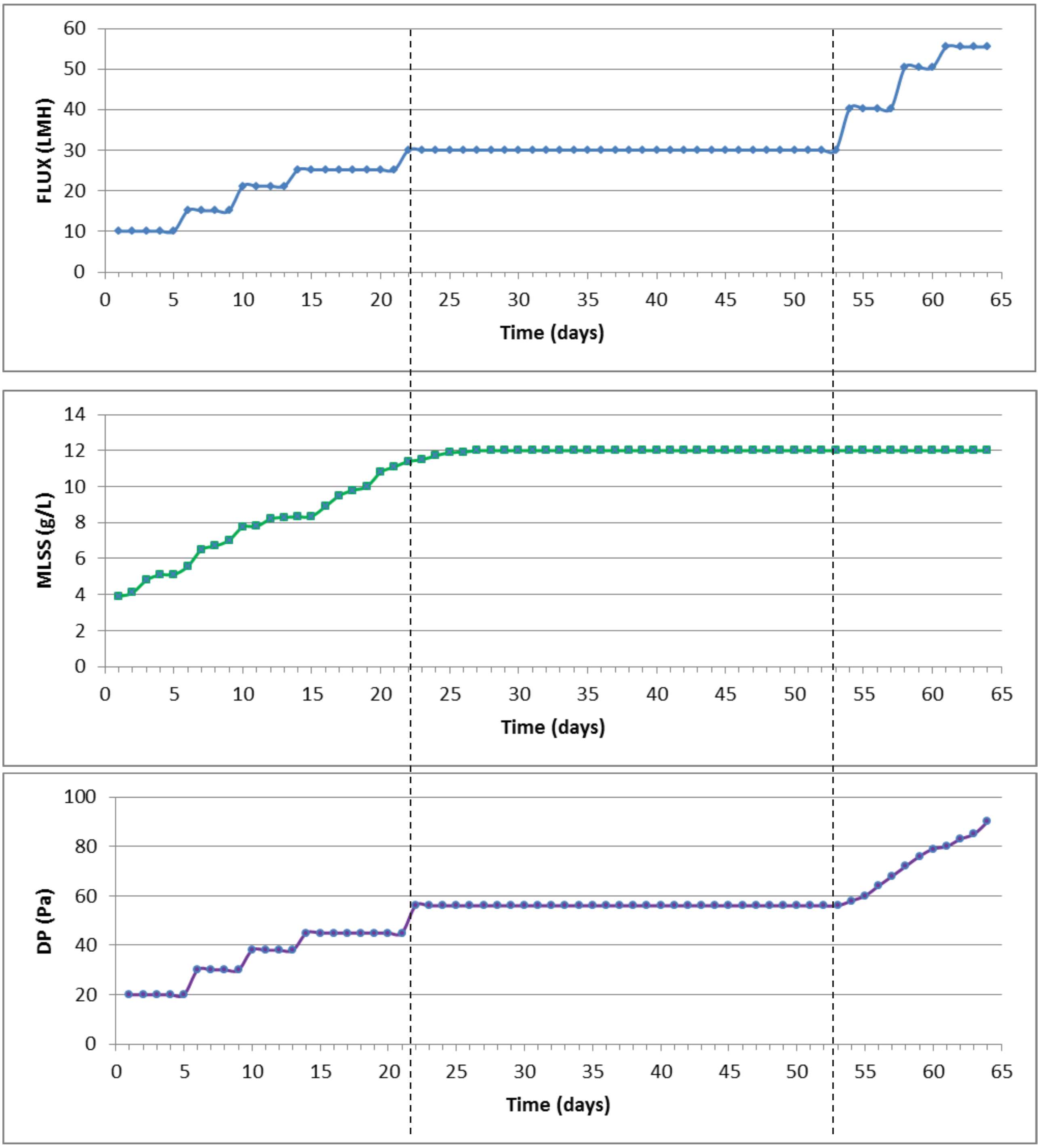


Figure 13: Time profiles of trans-membrane pressure drop (TMP or DP)

The TMP is comprised of the pressure drop across the membrane material, the pressure drop across the permeate outlet and manifold and the pressure drop across any fouling layer that may form. If the membrane is fouling with time, this will be indicated by a progressive increase in the TMP. Conversely, a constant TMP indicates that no fouling is occurring or that fouling is being restricted by the air scour.

In the first 21 days, there is a step increase in the TMP consistent with the step increase in flux. Importantly, the TMP remains constant until the flux is increased. In the second stage, where the flux was maintained at 30 LMH, the TMP remained absolutely constant for the period of 32 days, with no indication of instability or slow increase. This indicated unequivocally that the system was operating stably in the sub-critical region.

It should be noted that most commercial plants do not operate under continuous filtration. The operating sequence usually consists of a filtration period, a relaxation period (no permeate flow) and possibly a backflush period. In this investigation, the WFIMBR was operated continuously 24 hours a day for 32 days, at a completely stable TMP.

To confirm that the stable TMP was due to sub-critical operation, and not an instrument fault, the flux was increased after 32 days (day 53 of experiment). Then it was observed that the TMP increased steadily, indicative of fouling and super-critical operation.

3.4 SUMMARY

(i) In terms of product quality, the 10 p.e. unit operated on activated sludge at the Veolia Wastewater Reclamation Plant in Durban produced a COD removal of ~ 96%, for a feed of ~ 300 mg/L, and a product turbidity of ~ 0.9 NTU decreasing to 0.2 NTU.

(ii) In terms of hydrodynamic performance, the WFIMBR was operated at a stable sub-critical condition, i.e. no increase in TMP (fouling) for a period of 30 days without any cleaning.

CHAPTER 4: DESIGN OF 30 P.E. RIG

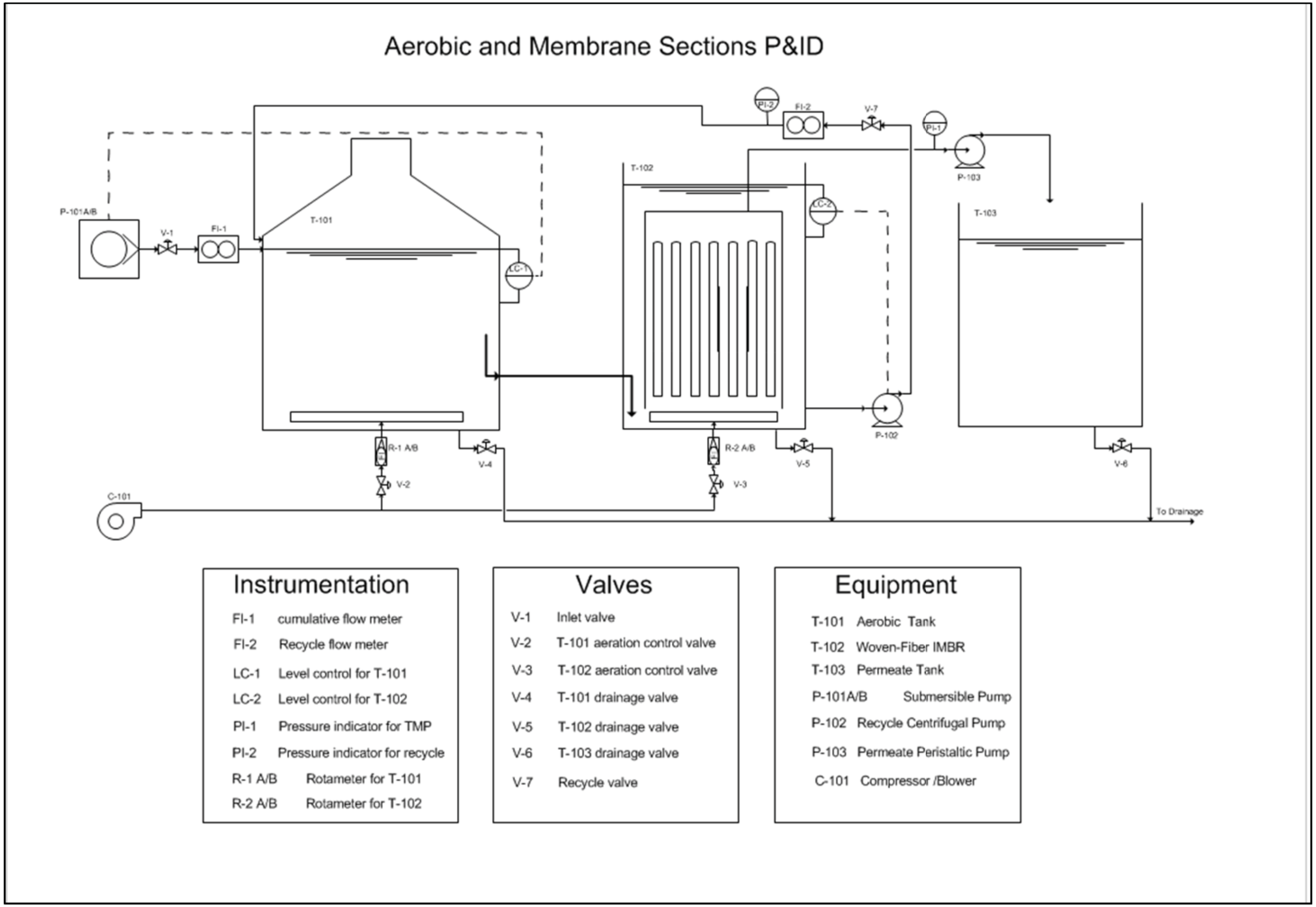
4.1 INTRODUCTION

Following on the results presented in the previous section, it was concluded that there appeared to be no major limitations in the WFIMBR geometry used in the 10 p.e. base study. Accordingly, the 10 p.e. unit could be geometrically up-scaled to the 30 p.e. unit.

The design of the up-scaled system is presented in this section.

4.2 PROCESS AND EQUIPMENT DESCRIPTION

The P&IDs of the 30 p.e. unit are shown in Figure 14(a) and 14(b), and various photos of the rig are shown in Figure 14(c).



Instrumentation	
FI-1	cumulative flow meter
FI-2	Recycle flow meter
LC-1	Level control for T-101
LC-2	Level control for T-102
PI-1	Pressure indicator for TMP
PI-2	Pressure indicator for recycle
R-1 A/B	Rotameter for T-101
R-2 A/B	Rotameter for T-102

Valves	
V-1	Inlet valve
V-2	T-101 aeration control valve
V-3	T-102 aeration control valve
V-4	T-101 drainage valve
V-5	T-102 drainage valve
V-6	T-103 drainage valve
V-7	Recycle valve

Equipment	
T-101	Aerobic Tank
T-102	Woven-Fiber IMBR
T-103	Permeate Tank
P-101A/B	Submersible Pump
P-102	Recycle Centrifugal Pump
P-103	Permeate Peristaltic Pump
C-101	Compressor /Blower

Figure 14(a): P&ID of aerobic reactor and membrane tank

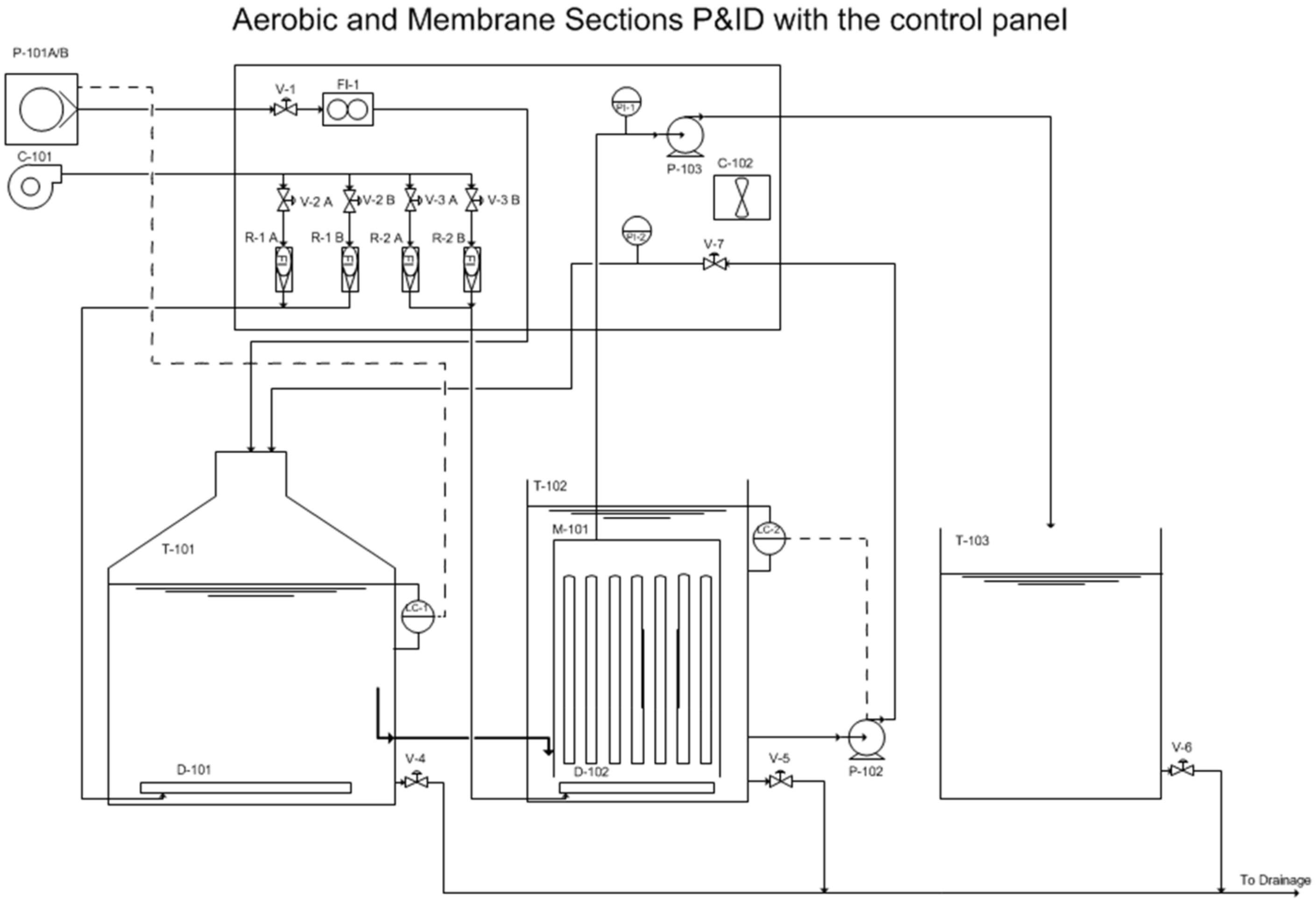


Figure 14 (b): P&ID showing connections to control panel

bioreactor (left) and membrane tank (right)

inside of bioreactor - sparger and level probe

inside of membrane tank showing level probe

original membrane pack

air blowers

control panel

Figure 14 (c): Various photos of 30 p.e. rig

4.2.1 Process Description

Wastewater from either the raw sewage feed or the returned activated sludge (RAS) from the Zandvliet reclamation plant was pumped into the aerobic tank (T-101) by means of a submersible pump (P-101 A/B). The level in the T-101 was kept constant by means of a level controller (LC-1); therefore, the desired residence time in the aerobic tank could be adhered to. An air diffuser (D-101), capable of blowing small bubbles, for optimal oxygen transfer, was placed in T-101. The biomass flowed freely by means of gravity to the membrane tank (T-102).

Two membrane packs (M-101) were submerged in T-102. Each of these packs were connected to a suction pump (P-102), which applied a partial vacuum to the immersed membrane to create a small pressure drop across the membrane (TMP); measured by (PI-2). P-103 pumped the clean permeate into the permeate tank (T-103). The air diffuser (D-102) in T-102 consisted of two tubular rods perforated with 2 mm diameter holes.

In order for the biomass to circulate through the system a centrifugal pump (P-102) was needed to recycle some of the biomass back to T-101 and also to ensure that T-102 does not overflow nor run dry. This will be controlled using a level controller (LC-2) for T-102.

4.2.2 Equipment description

Table 2: Equipment list

Code	Item	Function
T-101	Aerobic Tank	Operates as a feed tank as well as aerobic bioreactor
T-102	IMBR Tank	Tank in which the membrane pack is submerged: 250 L
T-103	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 to the aerobic tank.
P-103 and P-104	Peristaltic pump	Two variable speed permeate pumps, used for permeate suction to maintain an operating flux.
C-101	Blower	An air blower used to aerate the biological reactor as well as scour the membrane surface.
C-102	Fan	Needed to keep the pump and other instruments from overheating
D-101	Diffuser	Round disc diffuser needed to form smaller bubbles optimal for biological aeration.
D-102	Diffuser	Three rod diffusers perforated with 15 x 2 mm diameter holes. Used to allow the correct velocity profile for optimal membrane scouring
M-101 and M-102	Membrane pack	19 woven fibre flat sheet membranes, spaced 5 mm apart combining to an overall effective surface area of 5.1 m^2 installed in a membrane casing.

Table 3: Valves and instrumentation list

Code	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 probe 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	Level control	A probe controller attached to T-102 to ensure that it doesn't run dry or over flow, by sending an Off/On signal to P-102.
PI-1	Pressure gauge	A negative gauge needed to measure the suction pressure of P-103 and hence measure the Trans-membrane Pressure (TMP).
PI-2	Pressure gauge	A positive gauge placed on the recycle line to measure the output pressure of P-102
R-1 A/B	Rotameter	These will be used to measure the inlet air flow rate into D-101.
R-2 A/B	Rotameter	These will be used to measure the inlet air flow rate into D-102.
V-1	Control valve	A diaphragm valve needed to control the total inlet of raw wastewater into the system.
V-2 A/B	Control valve	Globe valves needed to control the air flow rate into D-101.
V-3 A/B	Control valve	Globe valves needed to control the air flow rate into D-102.
V-4	Drainage valve	Drainage valves situated at the bottom of T-101 used to drain all its contents.
V-5	Drainage valve	Drainage valves situated at the bottom of T-102 used to drain all its contents.
V-6	Drainage valve	Drainage valves situated at the bottom of T-103 used to drain all its contents.
V-7	Control valve	A diaphragm valve needed to control the total rate of the recycle stream from T-102 to T-101.

The air scour rate used in the 10 p.e. trials was 10L/min/module. Thus, for a system with two membrane packs of 19 modules each, the overall air flow rate would be 380 L/min. The coarse bubble membrane scour also contributes to the biological degradation; therefore, the biological process aeration could be reduced. The membrane tank should have adequate volume to accommodate two membrane packs and allow these to be removed and inserted with ease.

4.2.3 Aerobic Reactor

The permeate throughput is approximately 280 L/h for this set-up; therefore, the inlet flow rate should be the same to ensure there is no overall accumulation in the system. The HRT needs to be defined in order to determine the size of the aerobic bioreactor (T-101). 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 initially used – however 4 and 8 hours were also investigated in order to determine the optimal HRT for this specific set-up. This investigation required a 1200 L tank to be used as the aerobic tank (T-101), which could be used for various HRT's at a specified throughput of 280 L/h.

The main aim of the aerobic reactor was to provide an environment for optimal oxygen transfer to the biomass. This was achieved by the use of a fine bubble disc diffuser (D-101) situated at the bottom of T-101. The practical range for dissolved oxygen (DO) in the aerobic tank was generally between 100 and 150 mg O_2 /(L.h) (Judd, 2011).

4.2.4 Membrane Tank 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 p.e unit. The current woven fibre membrane has an effective membrane length of 45.5 cm and the effective membrane width of 29.5 cm, which results in an effective surface are of 0.268 m^2 per membrane. Therefore, the total surface area for the 19 modules that can fit into a membrane pack is 5.1 m^2. Using this information, the membrane tank could be fully defined.

A basis of 200 L/person/day of wastewater was used for further calculations.

Assuming 22 hours of operation, the wastewater flows that can be treated for a single or double membrane pack at various permeate fluxes is shown in Tables 4 and 5. The design aim was to design a 30 p.e unit, therefore two membrane packs would be required, as shown in Table 5.

Table 4: **Persons Equivalent for various permeate fluxes for a single membrane pack**

Permeate flux (LMH)	**24**	**25**	**26**	**27**	**28**	**29**	**30**
Permeate flow rate (l/h)	122,4	127,5	132,6	137,7	142,8	147,9	153,0
Persons equivalent (p.e.)	13,5	14,0	14,6	15,1	15,7	16,3	16,8

Table 5: **Persons Equivalent for various permeate fluxes for two membrane packs**

Permeate flux (LMH)	**24**	**25**	**26**	**27**	**28**	**29**	**30**
Permeate flow rate (l/h)	244,8	255,0	265,2	275,4	285,6	295,8	306,0
Persons equivalent (p.e.)	26,9	28,1	29,2	30,3	31,4	32,5	33,7

CHAPTER 5: PERFORMANCE OF 30 P.E. UNIT

5.1 INTRODUCTION

This section focuses on performance of the 30 p.e. unit, and comparison to other IMBR systems.

The initial project plan for the trials at Zandvliet was as follows:

(i) Determine the critical flux characteristics of the wastewater at Zandvliet Wastewater Treatment Works.

(ii) From (i) choose an operating point for sub-critical operation.

(iii) Operate the plant for an extended period at this sub-critical operating point

(iv) Compare the performance of the WFIMBR (final water quality, fouling characteristics, stability of operation) with commercial IMBR plants.

Due to stable operation not being achievable at Zandvliet, the project activities thus resolved to investigate the following:

(i) Determining the critical flux characteristics of Zandvliet return-activated-sludge (RAS). This exercise indicated that the pressure drop across the membrane modules was possibly too high. This led to Activity (ii) below.

(ii) Re-design the membrane modules to reduce the pressure drop across them.

(iii) Repeat determination of the critical flux characteristics. This indicated that the problem of high pressure drops had been solved. However, this led to the second operational problem, viz. that the membranes could not be cleaned by the "normal" methods employed in the past. This led to Activity (iv).

(iv) Determining a new cleaning regime for the membranes. This was successfully achieved, and the project moved to Activity (v).

(v) Determining membrane performance and stability under sub-critical operating conditions. Unfortunately, contradictory to all previous trials, stable operation under sub-critical operating conditions could not be achieved.

The above Project Activities are detailed in Sections 5.3 to 5.6 below. For completeness, the physical setup at Zandvliet is described in Section 5.2. Physical setup at Zandvliet Wastewater Treatment Works (ZWWTW)

ZWWTW has two process trains – a conventional wastewater treatment process and an IMBR process (Zeeweed) operating in parallel. A "birds-eye" view of the plant is shown in Figure 15, and a view of the Zeeweed IMBR plant is shown in Figure 16.

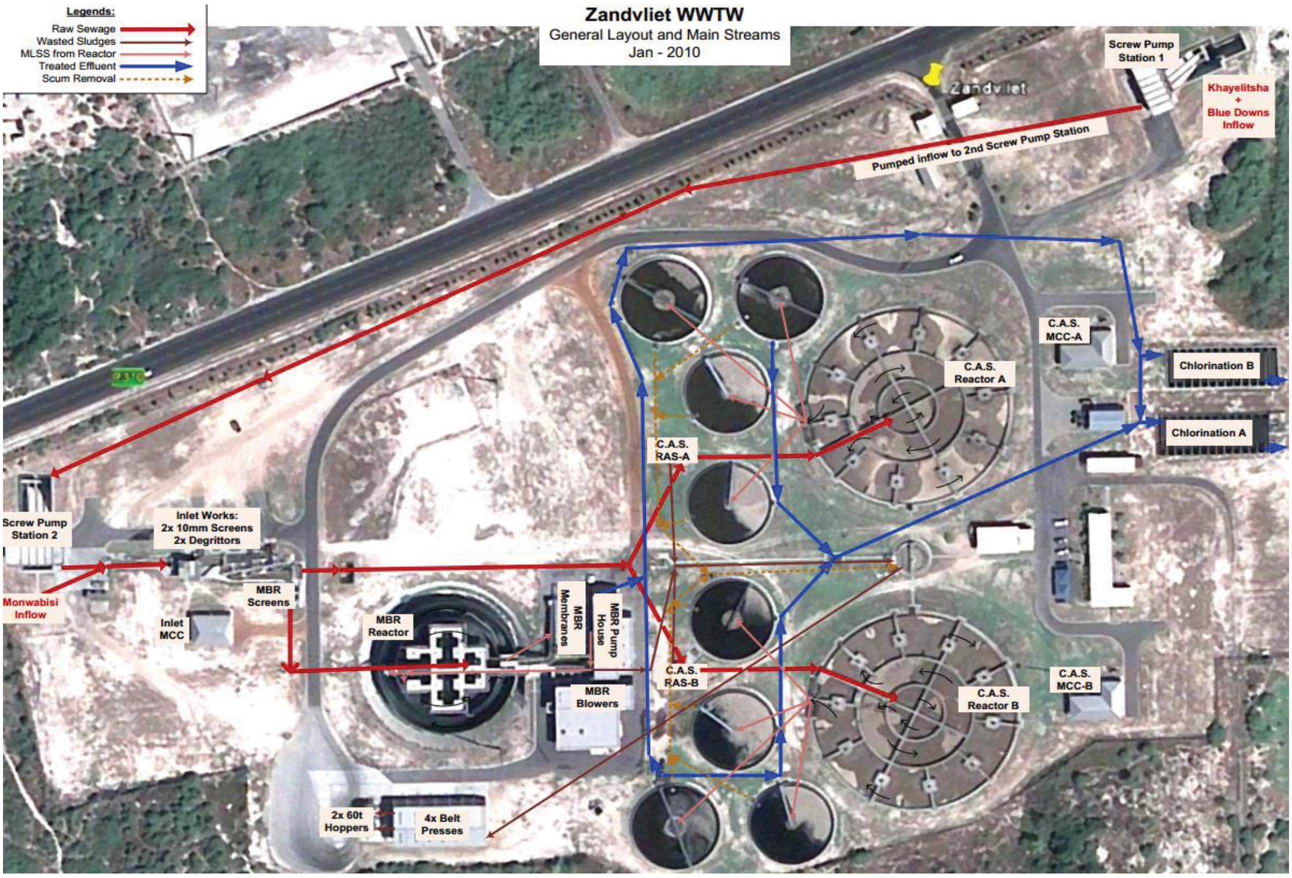


Figure 15: Aerial view of Zandvliet Wastewater Treatment Works

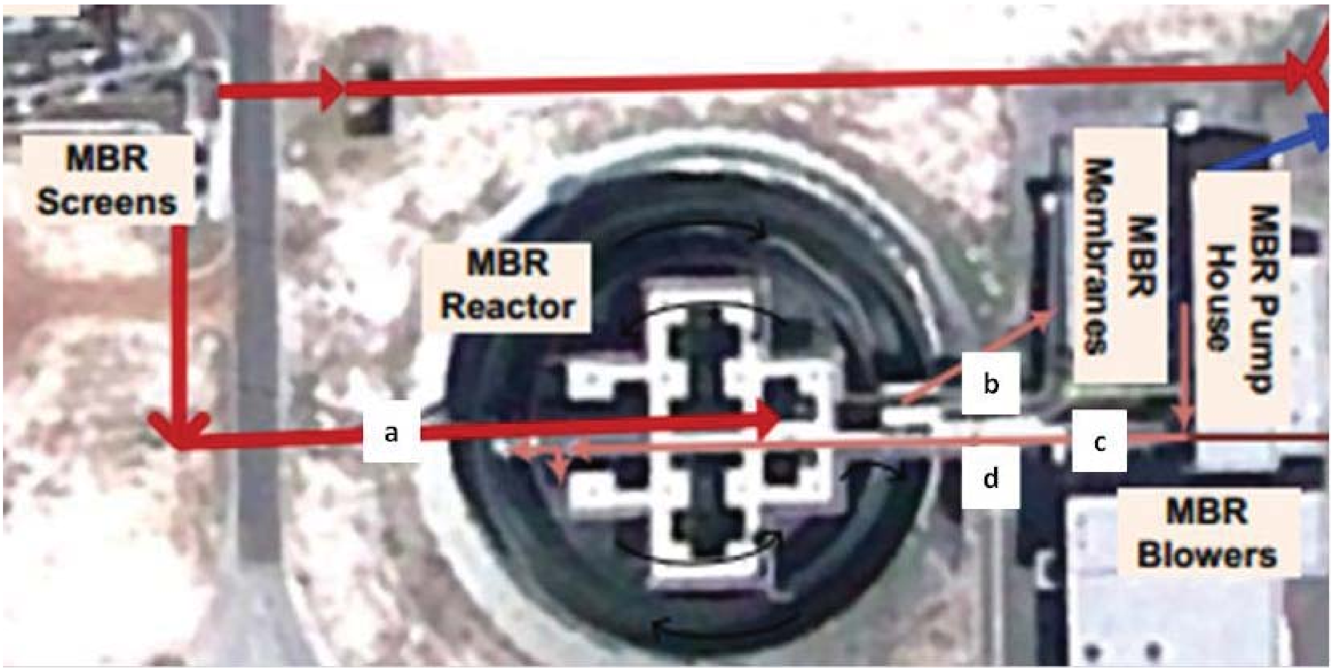


Figure 16: Zandvliet MBR plant (a) raw sewage manhole (b) Activated sludge from bioreactor (c) return activated sludge (RAS) (d) WFIMBR

The WFIMBR was set up next to the Zeeweed MBR (Z-IMBR) plant, to eventually enable performance comparison with the commercial unit. The WFIMBR can draw its feed from either the raw water manhole (“a” in Figure 16) or from the Zeeweed return activated sludge (RAS) line (“c” in Figure 16).

An important point in Figure 15 is that there is negligible pre-treatment of the raw water, except for some very rough screens. This has probably had a major influence on this project, as described later.

5.2 INITIAL INVESTIGATIONS INTO CRITICAL FLUX CHARACTERISTICS OF ZANDVLIET RAS

Critical flux experiments were performed on the returned activated sludge (RAS) from the Zeeweed Membrane Bioreactor, using the Flux Stepping method. This sludge had an MLSS of ~ 12 g/L and the air scouring rate used was 150 L/min for 19 modules. This scouring rate, ~ 8 L/module, was around the median of scouring rates used previously.

The original membranes which were used at Veolia (Durban) were used. However, these membrane modules and the manifolding were modified to have two permeate outlets instead of one, in order to reduce the pressure drops in the system (see Figure 17).

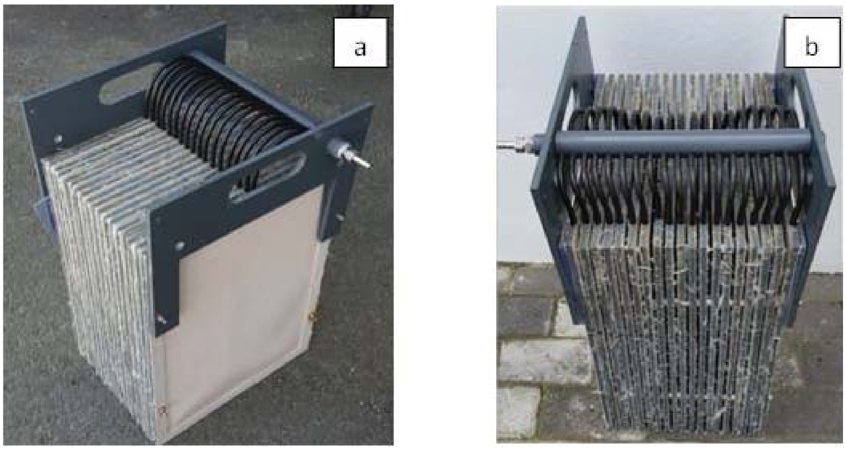


Figure 17: (a) Original membrane pack with one permeate outlet (b) Modified membrane pack with two permeate outlets

The flux-step experiment, using the original membranes with two permeate outlets, is shown in Figure 18.

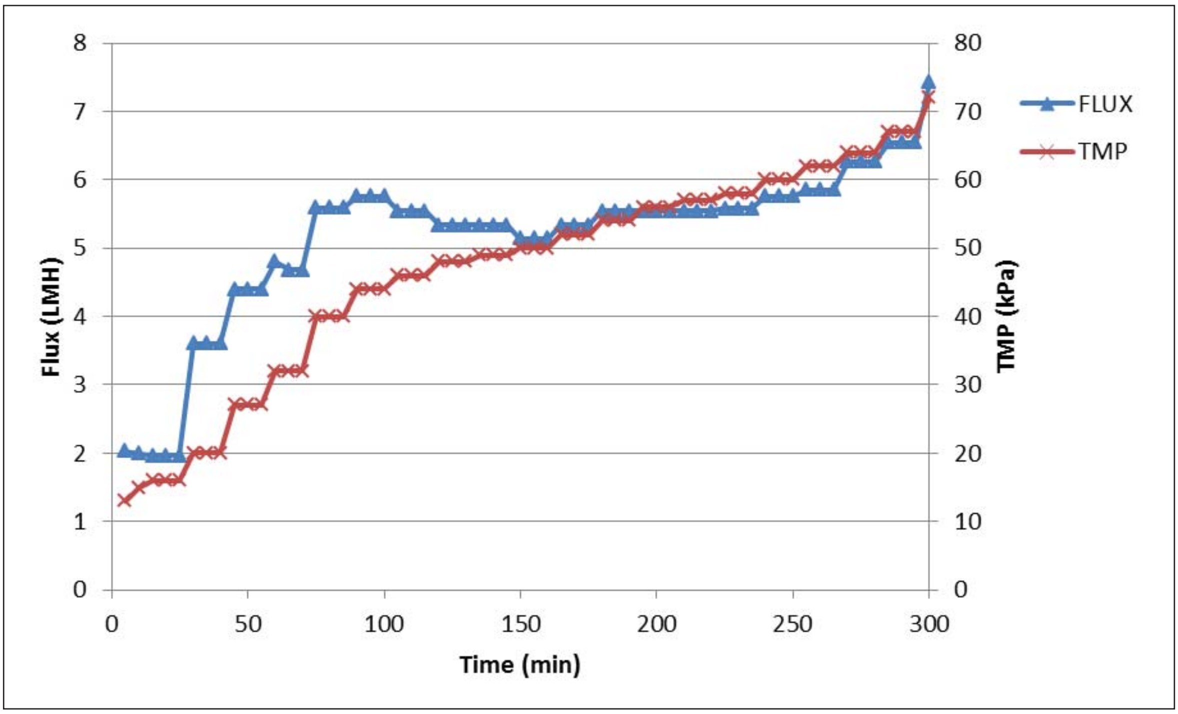


Figure 18: Initial critical flux experiments

Some important observations from Figure 18:

(i) The fluxes are extremely low, 2 LMH to 7 LMH at the maximum pump speed. Previously, fluxes of up to 40 LMH were obtained.

(ii) The transmembrane pressures (TMP) are extremely high, up to 70 kPa! This is phenomenally higher than the TMPs obtained previously, which were generally below 30 kPa.

(iii) The flux was very unstable, decreasing after 100 minutes, and then increasing again.

(iv) It is not easy to draw inferences on critical fluxes from the above graph.

The very high TMPs and very low fluxes are consistent with each other. Since a peristaltic pump was used, high pressure drops would result in low flowrates, due to constriction of the peristaltic tube.

It was hypothesized that the high TMPs were due to high flow resistances within the module, i.e. across the spacer and across the permeate outlets. Accordingly, it was decided that the project should focus on redesign of the modules before continuing.

5.3 RE-DESIGN OF THE MEMBRANE MODULE

The spacer serves to hold the membranes apart during filtration. However, the permeate then has to travel across the spacer to the permeate outlet. Hence, the spacer constitutes one of the major resistances to permeate flow. The other resistance is the permeate outlet itself. The modules used in Section 5.3 used the same spacer and permeate outlets as that in the "gravity water filter" (Figure 19). Previously, this seemingly was not a problem. However for whatever reason, it became a problem on the Zandvliet sludge.

Figure 19: Original spacer and original permeate outlet

Various options for improved spacers were investigated, focusing on meshes that were small enough to prevent the membranes from touching each other, whilst minimizing resistance to permeate flow. The material eventually selected was a mesh used for water drainage in the civil construction industry. In its original form, the mesh is orientated diagonally. This will result in permeate moving towards the sides of the module, and not towards the permeate outlet. This problem was overcome by cutting the spacers out diagonally from the roll and using two spacers 'back to back' (Figure 20 and 21). This resulted in all permeate flow being directed towards the permeate outlet.

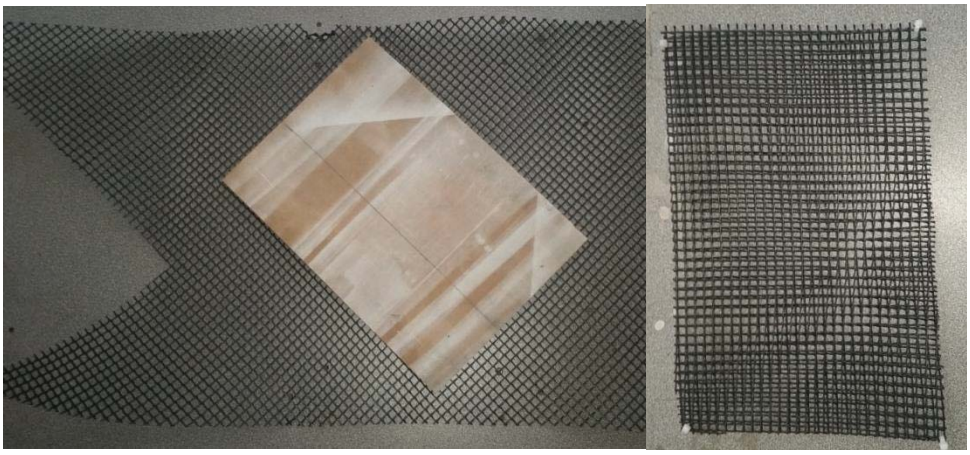


Figure 20: new spacer

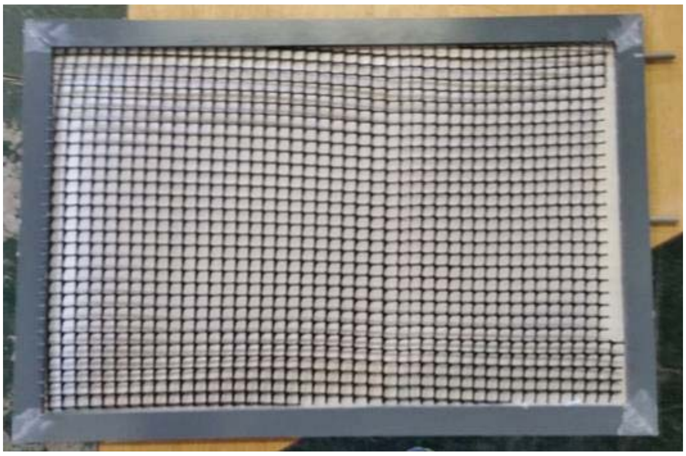


Figure 21: New spacer installed

The permeate outlet used previously was a 'hose-tail' used in agricultural irrigation systems (see Figure 19). This has an ID of about 2 mm. This was replaced by short lengths of stainless steel pipe that had an ID of about 3 mm. These permeate outlets were forced into holed drilled on the module frame using a press. Both the permeate outlets on the modules and the permeate inlets on the manifolds were replaced (Figure 22).

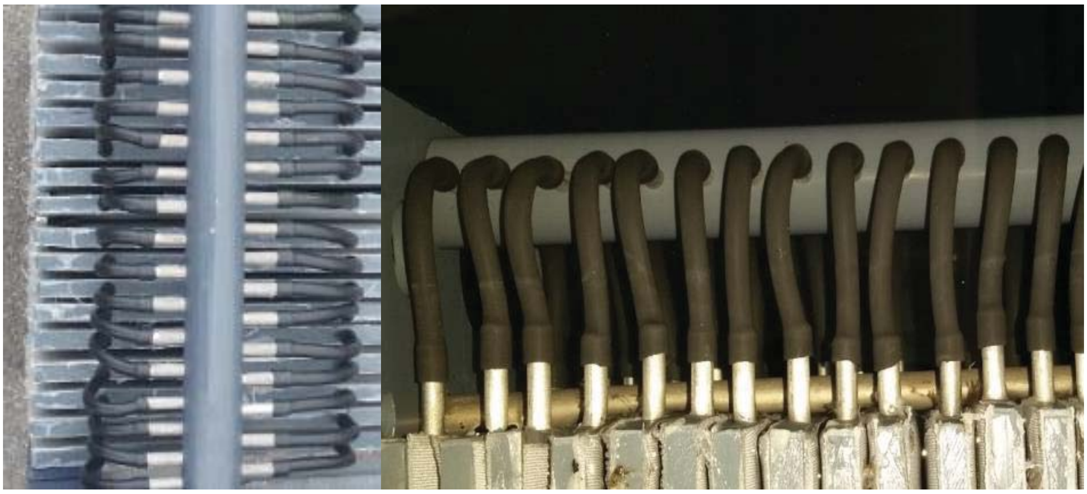


Figure 22: New permeate outlets and inlets on manifold (left) and module (right)

Pressure drop trials on the modified modules indicated that the pressure drops were less than 30% of the TMPs before the modifications.

5.4 REPEAT OF CRITICAL FLUX CHARACTERISTICS OF ZANDVLIET RAS

The MBR was filled using RAS with a concentration of 15 g/l and the air scouring rate was set to 150 L/min. Flux stepping was used to determine the critical flux, by operating at each flux for 15 minutes whilst noting the increases in TMP (Figure 23).

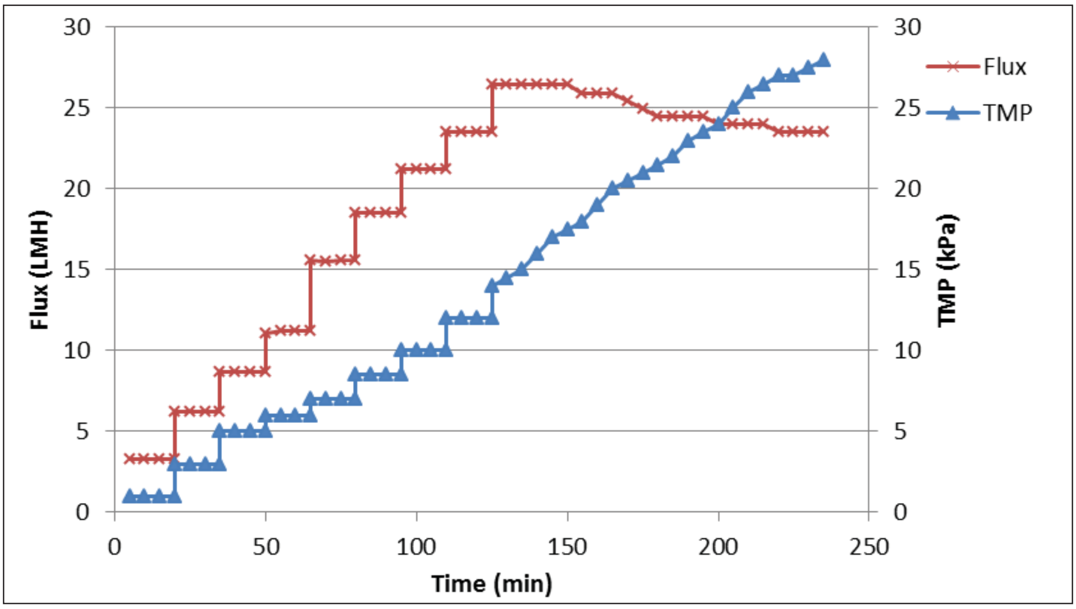


Figure 23: Critical flux characteristics with modified modules and manifold

Some observations from Figure 23 include the following:

(i) The fluxes with the modified modules are substantially higher, and the TMPS substantially lower, than that obtained previously (see Figure 18).

(ii) The critical flux for the conditions used appears to be around 25 LMH. This is completely consistent with previous results obtained at Veolia.

Figure 23 seemed to indicate that the problems previously experienced at Zandvliet were seemingly resolved by re-designing the modules.

Following the above experiment, an attempt was made to clean the membranes prior to repeating the critical flux experiment. However, this revealed the second operational problem, i.e. the membranes could not be cleaned using the regimes used previously. This is discussed in the following section.

5.5 NEW CLEANING REGIME FOR FOULED MEMBRANES

In all previous investigations into WFMF for potable water production, filtering of activated sludge and filtering of sludge from an anaerobic digestor, the membranes were easily cleaned simply by brushing them, or by soaking them in dilute sodium hypochlorite followed by brushing.

Following the critical flux experiment shown in Figure 23, the membranes were cleaned by brushing. This did not recover the pure water flux. The membranes were then cleaned by soaking in dilute sodium hypochlorite. This also failed to restore the pure water flux.

Further methods investigated to clean the membranes included slow gravity backwashing with dilute sodium hypochlorite, and a soak in hypochlorite followed by a slow hypochlorite backwash. The results of these investigations are shown in Figure 24.

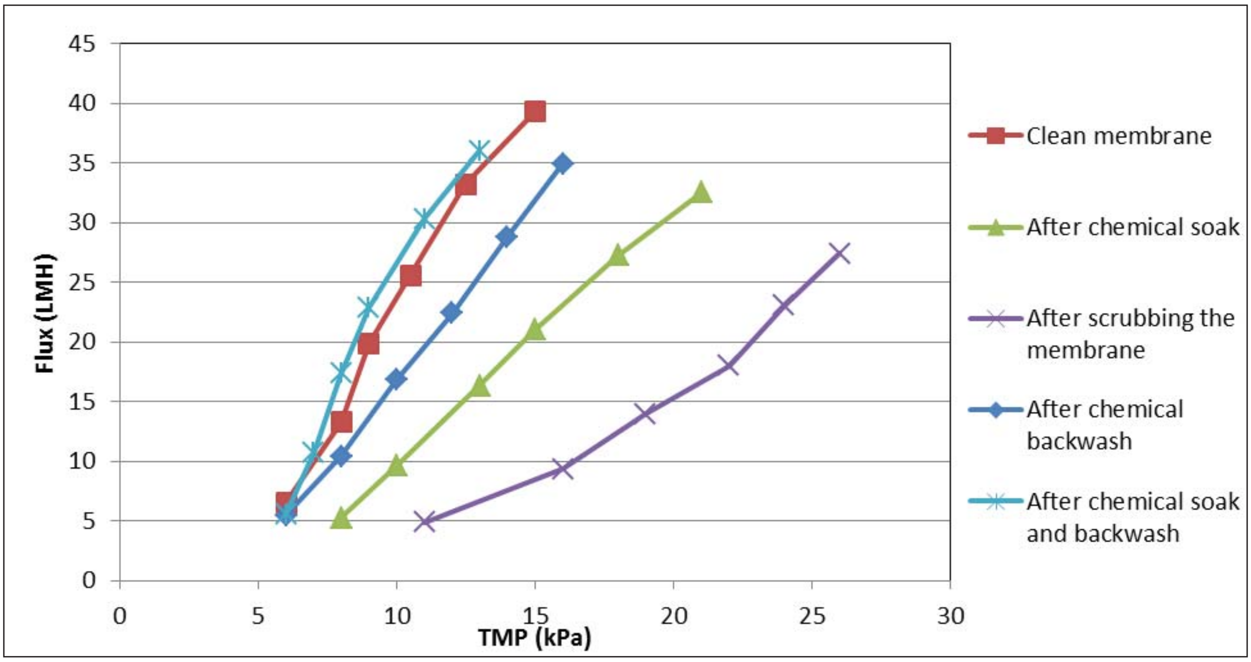


Figure 24: Investigations into improved cleaning strategies

It is clear that scrubbing the membrane did not removing the foulants. A hypochlorite soak gave a better performance, but the flux was still not restored. A hypochlorite backwash gave a very good flux recovery, whilst a hypochlorite soak followed by a slow hypochlorite backwash restored the flux fully.

Figure 24 is very indicative of organic fouling of the membranes. Further, it seems that the organics have penetrated deep into the membrane. This is discussed further in Section 7.7.

5.6 OPERATION AT SUB-CRITICAL CONDITIONS

The project then proceeded to demonstration of stable sub-critical operation. To set the context, in previous trials at Veolia the WFIMBR was run at a stable TMP for a period of over a month and a week respectively (see Chapter 3).

Figure 23 indicated that the critical flux for an MLSS of 15 g/L and a total scour rate of 150 L/min was approximately 25 LMH. Accordingly, the first sub-critical operation trials were conservatively started at 15 LMH. The flux and TMP profiles are shown in Figure 25. In the trials below, the MLSS was 14 g/L and the scouring rate was 150 L/min for 19 modules (~ 7.9 L/min per module).

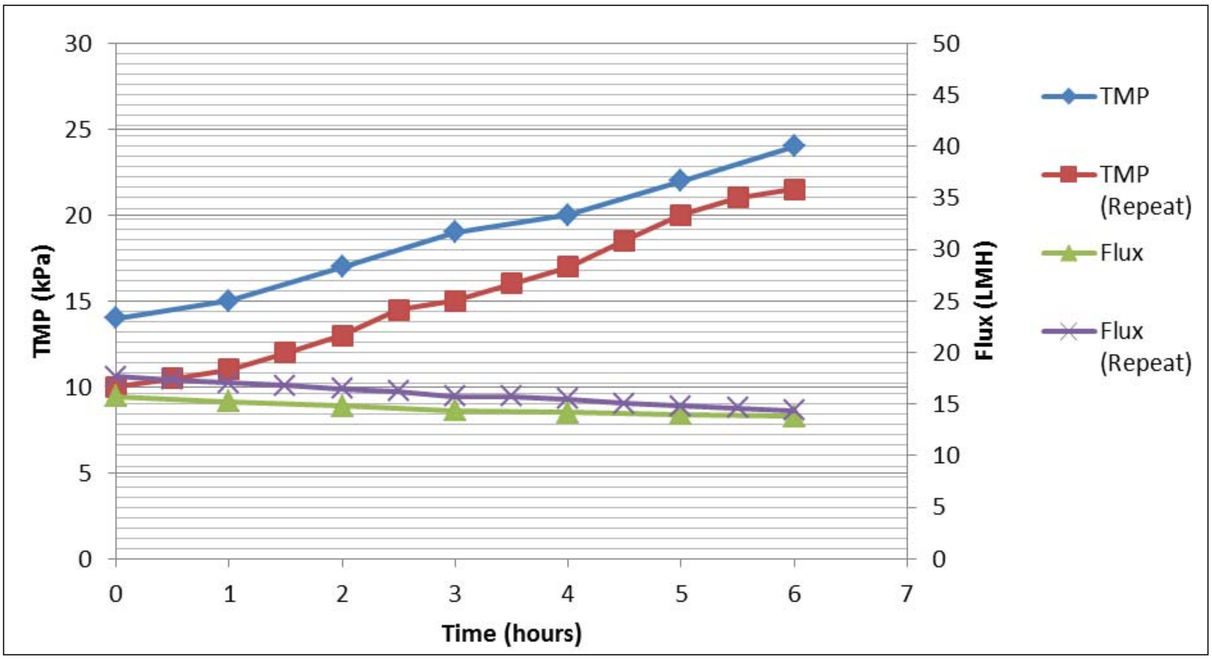


Figure 25: Flux and TMP profiles at a flux of 15 LMH

Within an hour of the commencement of filtration, the TMP began increasing, and doubled within six hours. The experiment was repeated, giving a similar result. Clearly the system was not operating at a stable sub-critical condition.

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 RAS since the critical flux trials. Hence, the sub-critical runs were repeated for two lower fluxes, viz. 10 LMH and 5 LMH (very low). The results are shown in Figures 26 and 27.

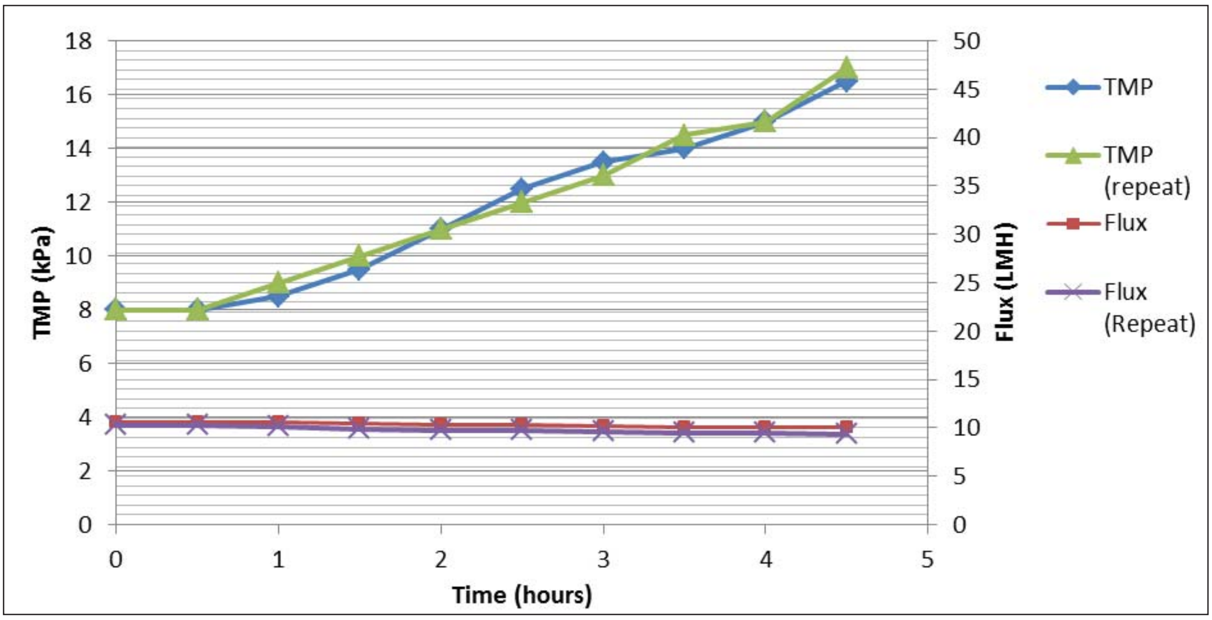


Figure 26: Flux and TMP profiles at a flux of 10 LMH

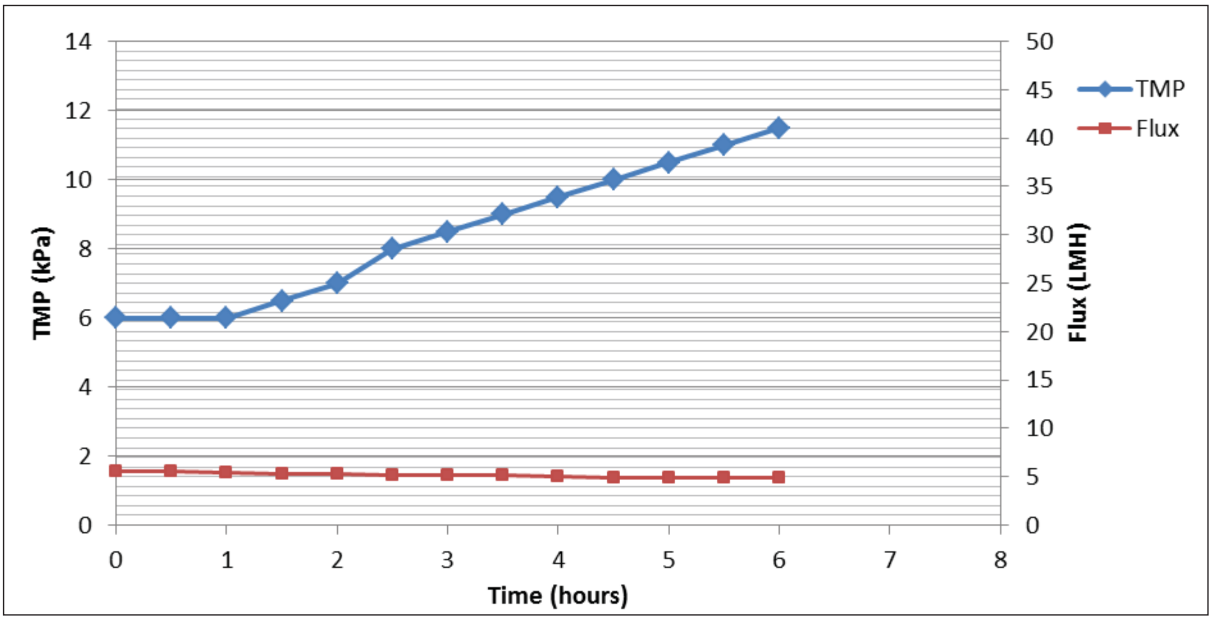


Figure 27: Flux and TMP profiles at a flux of 5 LMH

At a flux of 10 LMH, the TMP once again started increasing within an hour of filtration. Clearly, there was no stable sub-critical operation. Even at a very low flux of 5 LMH, the TMP increases after about an hour, and there is no stable operation. It is also interesting to note that the rate of increase of TMP is very similar for operation at the different fluxes.

It is clear that stable sub-critical operation was not obtained on Zandvliet RAS, even at extremely low fluxes.

It was feasible that, despite Figure 23, the air scour rate used in the above investigations (~ 7.9 L/min/module) was possibly insufficient to ensure effective scouring. Hence, the next stage was to increase the air-scour rate and observe whether this improved performance.

Air-scour rates of 7.5 L/min, 10 L/min and 12.5 L/min (per module) were investigated, for two starting fluxes, viz. 20 LMH and 11 LMH. ***Out of interest, an air-scour rate of 0 L/min (i.e. no air scouring) was also investigated.*** The TMP profiles and flux profiles obtained are shown in Figure 28 and Figure 29 below.

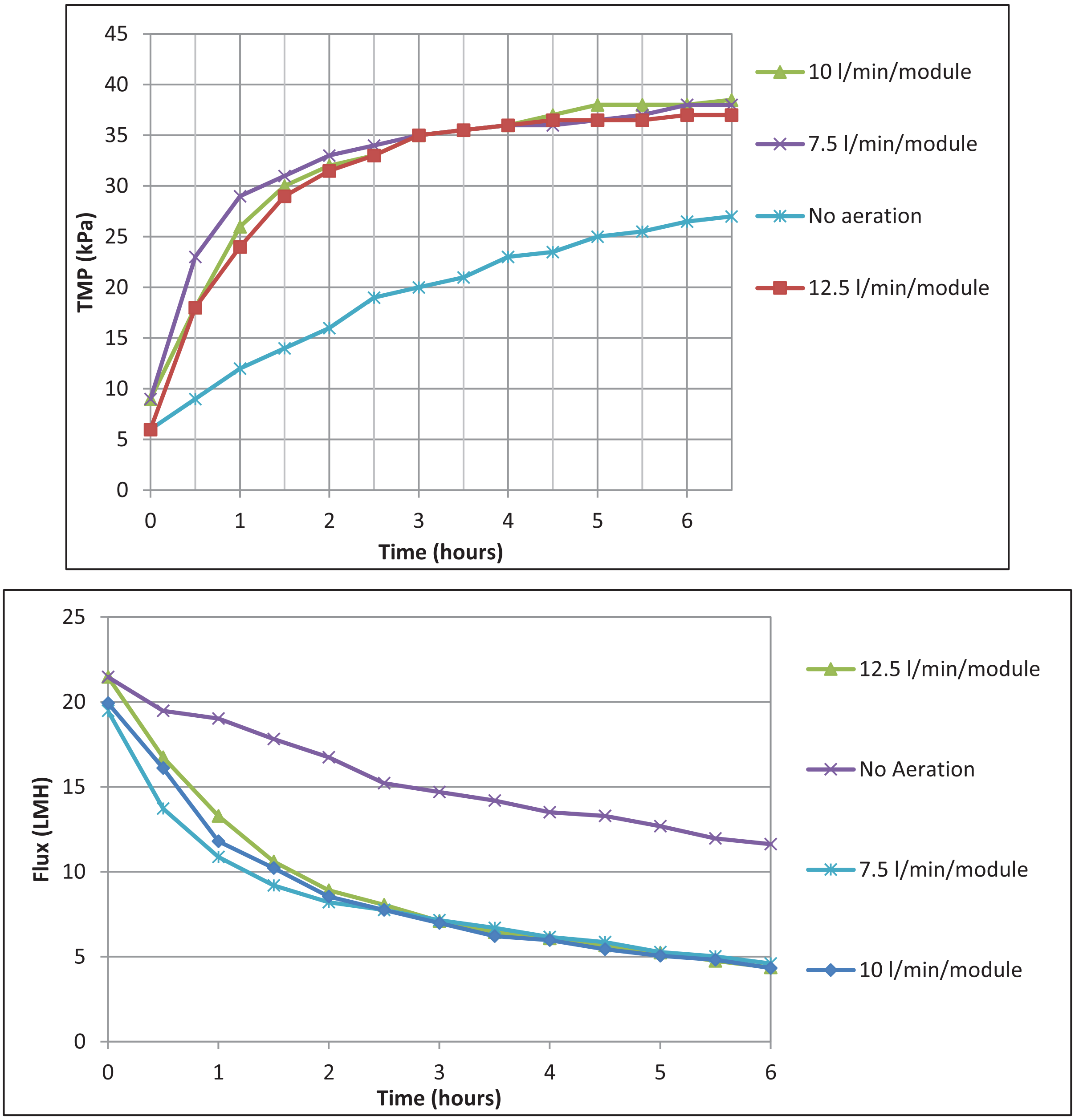


Figure 28: TMP and flux profiles for filtration runs with a starting flux of 20 LMH at different air scour rates

It would be expected that the rate of TMP increase would be inversely related to the air scour rate, i.e. at low air scour the TMP will increase rapidly, and *vice versa*. Figure 30 shows that regardless of the air scour rate, a similar TMP (37 kPa) was eventually reached. The initial slopes show that higher aeration rates have a slightly lower initial TMP increase, although it converges to the same TMP after 3 hours. The fluxes also seem to converge to similar values after 3 hours, although higher aeration rates seem to have a lesser decline that lower aeration rates until this point.

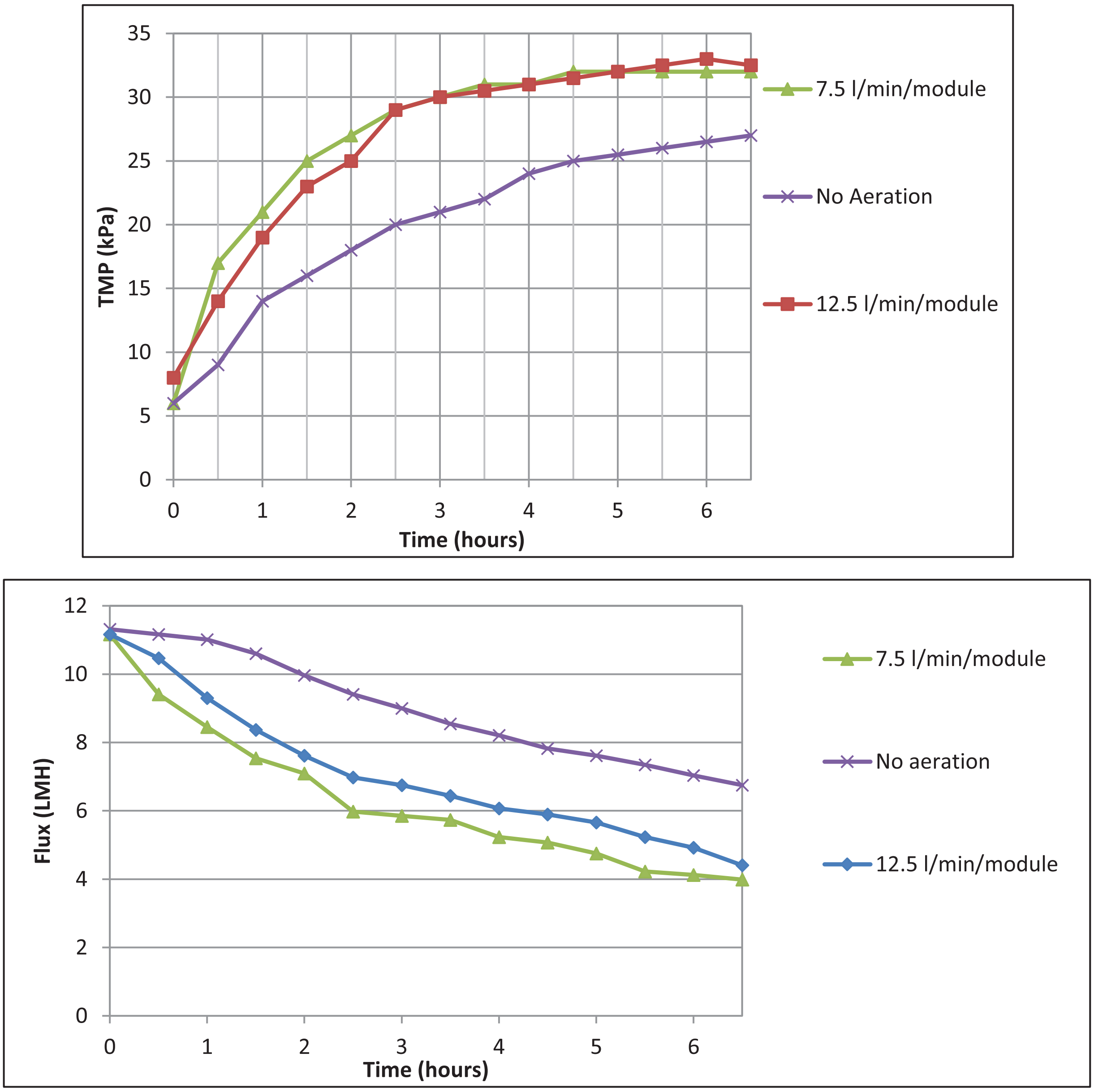


Figure 29: TMP and flux profiles for filtration runs with a starting flux of 11 LMH at different air scour rates.

Figure 29 shows similar results to that of Figure 28, i.e. that the TMP was relatively independent of the air scour rate. Once again higher aeration rates do decrease the rate of flux decline, although this is marginal.

It should be noted that simply comparing the TMP increases is not a valid method of assessing the effect of air scour rates, if the flux is also decreasing with time. A more rigorous approach is to compare the profile of the filtration *resistance* with time, defined by:

$$R_{total} = \Delta P/(\mu J)$$

where: ΔP = trans membrane pressure drop (i.e. TMP)
μ = fluid viscosity
J = permeate flux

The filtration resistance profiles for Figures 28 and 29 are shown in Figure 30 and Figure 31 respectively.

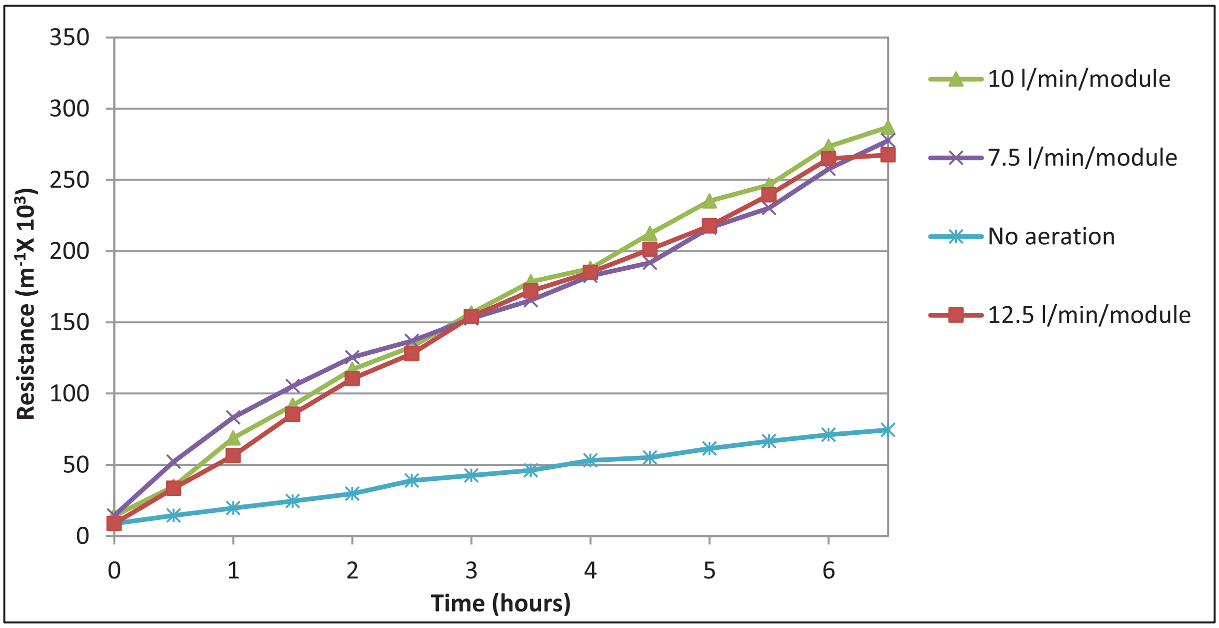


Figure 30: Resistance for filtration runs with a starting flux of 20 LMH at different air scour rates

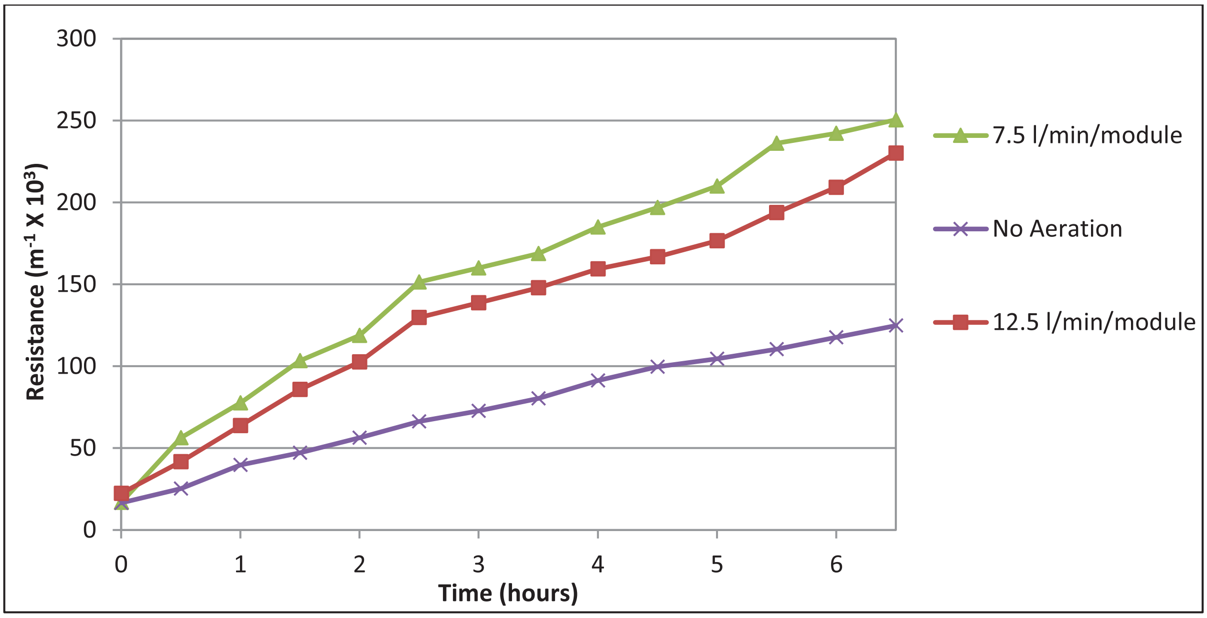


Figure 31: Resistance for filtration runs with a starting flux of 11 LMH at different air scour rates

Figures 30 and 31 confirm the tentative conclusions drawn from Figure 28 and 29, i.e. that the air scouring rate, over the range investigated here, had little effect on the growth of filtration resistance.

However, the most astounding result emerging from Figure 28 through to Figure 31 is that the lowest rate of growth of filtration resistance is obtained without any air scour! This implies that operating an IMBR without scouring the membranes would give a better permeate production than operating the IMBR with air scour. This completely contradicts the whole design concept of an IMBR, and all the major literature on IMBRs to date.

A further interesting point is that, on cleaning the modules after the above runs, it was observed that:

(i) for the runs with air scour, the modules were completely covered in dark crud, showing obvious signs of filtration resistance;

(ii) for all the runs with no air scour, the membranes were completely clear.

5.7 COMPARISON OF WFIMBR WITH ZEEWEED MBR

The Zandvliet WWTW has a commercial IMBR operating on site, using the Zeeweed technology. The operating data from the Zeeweed MBR was examined to establish whether it, also, experienced significant fouling. If it emerged that the Zeeweed MBR operated stably (i.e. long filtration periods without significant TMP increase) whilst the WFIMBR experienced significant fouling, then clearly something would be wrong with either the WFIMBR rig or the WFIMBR technology.

The Zeeweed MBR operating cycle is as follows:

(i) filtration at approximately 20 LMH for 10 minutes, with continuous air scour;

(ii) backwash for 30 seconds;

(iii) air purge for 45 seconds;

(iv) there are six chemical cleans per month.

Thus, the Zeeweed MBR has a very short filtration period, and hence no direct comparison could be made with the WFIMBR results above.

In comparison to other MBRs operating on domestic wastewater, the Zeeweed MBR has a very short filtration time, and the rate of chemical cleaning is high. Hence the Zeeweed MBR operating sequence is indicative of a highly fouling sludge.

5.8 INTERPRETING THE 30 P.E. UNIT PERFORMANCE AT ZANDVLIET

From all the above investigations it emerged that:

(i) The TMPs across the original modules were extremely high, resulting in low fluxes. This was not experienced at previous trials done at Veolia Durban or at Macassar, using a similar membrane module and membrane pack design.

(ii) The membranes were very difficult to clean and required both a soak in hypochlorite and a backwash (cleaning from the inside) to restore flux. This was also not experienced previously.

(iii) The TMP increases shortly after commencing filtration, even at extremely low fluxes.

(iv) A lower growth of filtration resistance was experienced without any air scour, than with air scouring at relatively high rates.

All the above point to significant organic fouling of the membranes, that cannot be easily removed by the brushing and/or soaking cleaning techniques used previously.

Possible sources of organic foulants include:

(i) Fats, oils and greases (FOG) in the Zandvliet raw wastewater. As noted in Section 2.3, there is only minimal pretreatment of the incoming raw wastewater to the Zeeweed MBR unit, and this is limited to a rough screen.

(ii) Extracellular polysaccharides (EPS) – these are generally emitted by bacteria when they are in a stressed condition and are very highly fouling substances.

A picture of the raw wastewater taken at the inlet manhole is shown in Figure 32. Clumps of fat are clearly visible in the manhole.

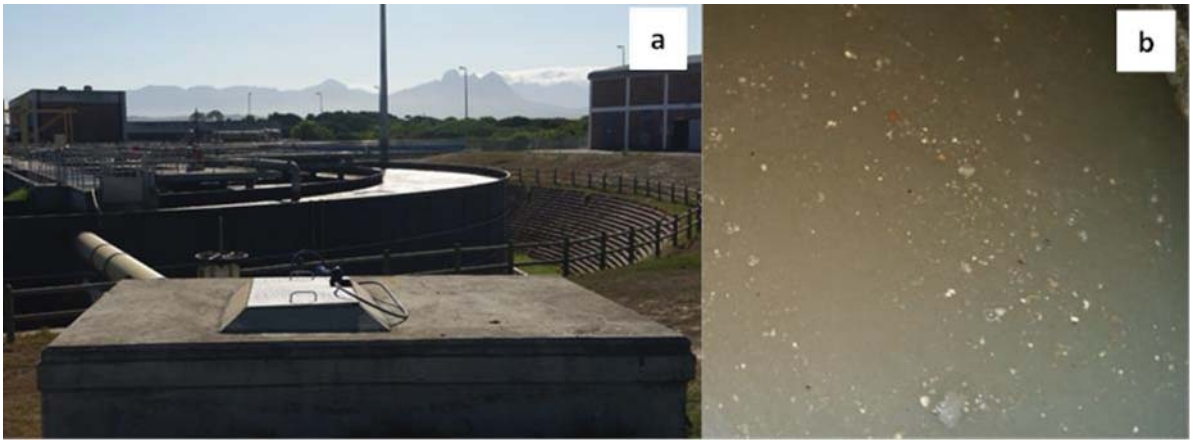


Figure 32: (a) Raw Sewage manhole (b) Clumps of Fat visible in the manhole

A grab sample of the raw wastewater feed to the Zeeweed MBR and the RAS were sent for a FOG analysis. This indicated that the raw wastewater had a FOG content of 14 mg/L, and the RAS had a FOG of < 2 mg/L. These concentrations are relatively low. However, the analyses would have to be repeated to discount FOG as a source of the problem, but at this stage it does not seem that FOG is the main cause of the poor flux results.

Bacterial EPS production is also a feasible cause. From visual observation of the aerobic and anoxic bioreactor zones before the membrane tank, it is clear that there are various dead-zones in the system. This could be a cause of bacteria being stressed and releasing EPS.

5.9 INVESTIGATING THE CAUSES OF THE PERFORMANCE OBTAINED AT ZANDVLIET

The results obtained during the first phase (Veolia, Durban) indicated that steady-state operation could be obtained for over a month using appropriate air scouring rates, i.e. the air-scouring was effective in preventing/limiting fouling of the membranes. However, the results obtained during the second phase, at Zandvliet, indicated that steady operation could not be obtained. There was significant fouling of the membranes, irrespective of the air-scouring rate. Further, in contradiction to current literature and theory, a *poorer* performance was obtained with high air-scouring rates.

The first stage in investigating this anomaly was to perform further detailed investigations on the effect of air scouring rate, flux and MLSS on Zandvliet mixed liquor. This is discussed in Chapter 6.

The next stage was to investigate mixed liquors from other wastewater works, to establish whether they gave similar performances to Zandvliet. This is discussed in Chapter 7.

CHAPTER 6: FURTHER INVESTIGATIONS AT ZANDVLIET

6.1 INVESTIGATIONS PERFORMED

The main aim of these investigations was to confirm the earlier anomalous behaviour observed at Zandvliet. Earlier investigations had indicated that steady-state operation, i.e. no increase in membrane fouling, could not be obtained at Zandvliet, even when operating at 'sub-critical' conditions.

To verify this, and establish whether this could be related to operating conditions, the following investigations were performed:

(i) Effect of air scour rate on rate of fouling

(ii) Effect of permeate flux on the rate of fouling

(iii) Effect of feed MLSS concentration on the rate of fouling

In all investigations, the feed used was activated sludge pumped from the feed chamber of the commercial IMBR unit at Zandvliet, i.e. the pilot WFIMBR rig operated on the same feed as the commercial IMBR rig at Zandvliet.

6.2 REPEATABILITY

Two investigations, performed under similar conditions, are shown in Figure 33. For each run, the MLSS concentration of the feed was kept constant. The permeate flux and air scour rates were set to specified values. The ΔP and J were then monitored over time. From this, the total resistance was calculated (see Section 5.6). The error bars associated with this are shown in Figure 34.

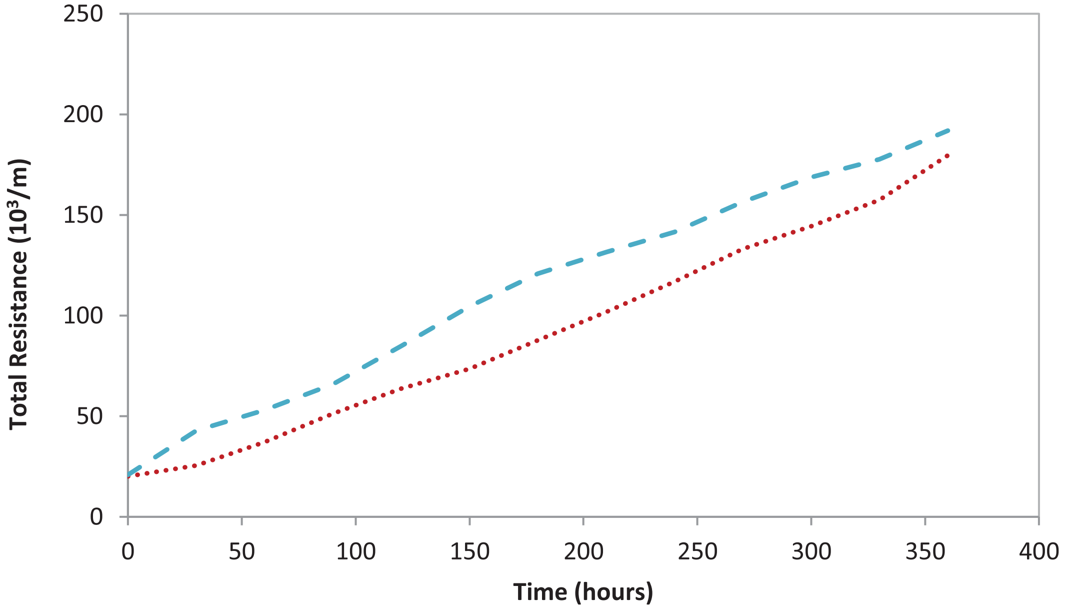


Figure 33: Resistance profiles obtained under similar conditions *(red and blue are repeat runs)*

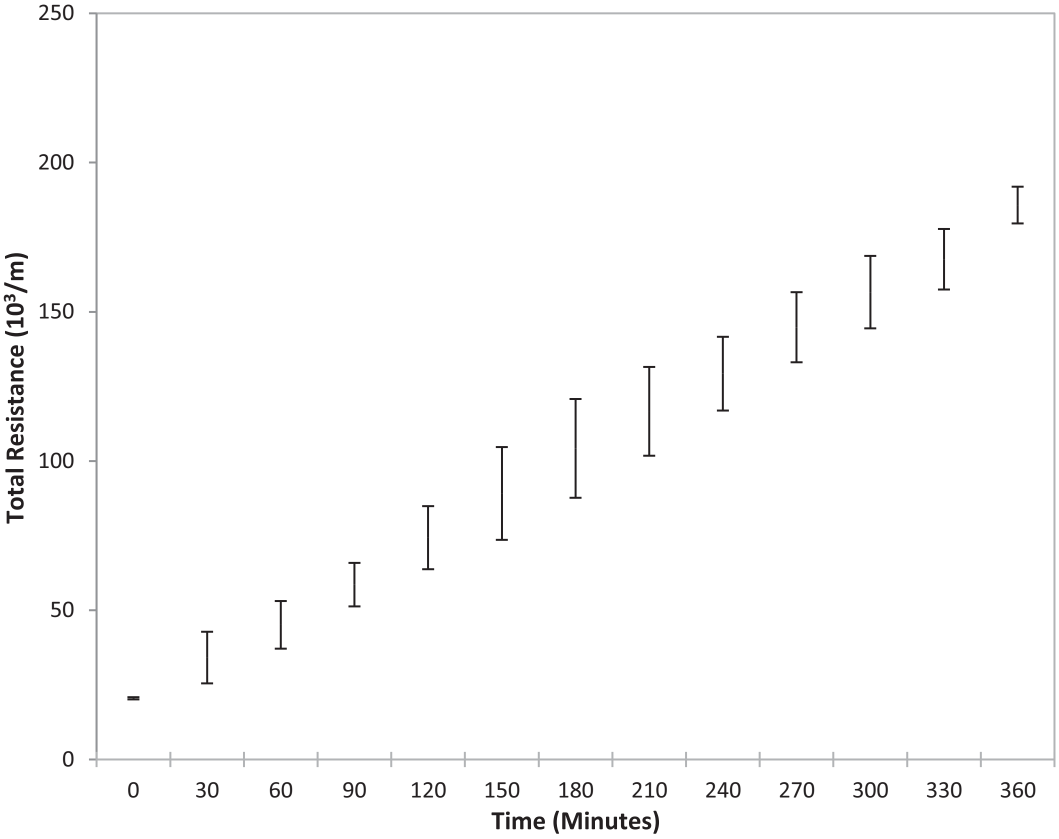


Figure 34: Error bars associated with Figure 33

The repeatability is reasonably good; bearing in mind that repeatability on biological sludges is notoriously difficult. The important issue are the error bars in Figure 34. In the presentation of subsequent results, curves which fall within these error bars would be regarded as statistically the same.

6.3 EFFECT OF AIR SCOUR RATE ON RATE OF FOULING

The MLSS concentration of the feed was kept constant at approximately 9.2 to 9.7 g/L. The permeate flux was set to ~ 20 LMH. Over four runs the air scour rate was set to 0 L/min, 120 L/min, 160 L/min and 200 L/min, respectively. Since 19 modules were employed, this corresponds to 0 L/min/module, 6.4 L/min/module, 8.4 L/min/module and 10.5 L/min/module. For each air scour rate, the ΔP and J were monitored with time. From this, the total resistance was calculated (Figure 35).

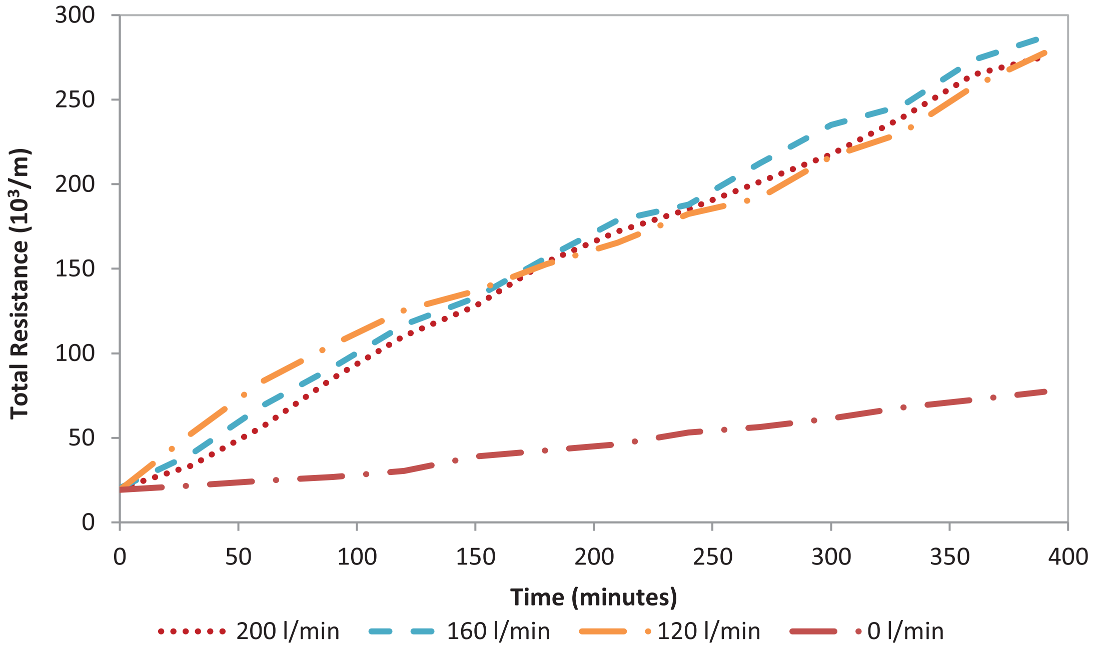


Figure 35: Effect of air scour rates at a starting flux of 20 LMH, and MLSS concentration range of 9.2-9.7 g/l

Observations from Figure 35:

(i) When the air scour rate is increased from 120 L/min to 200 L/min, the fouling resistance profiles are statistically the same, taking into account the error bars in Figure 34. Indeed, there is an indication that the higher air scour rate gives a *higher* rate of fouling!

(ii) Operating *without* air scour gives a significantly lower rate of fouling than operating with air scouring!

The above results verified that the seemingly anomalous results observed earlier were repeatable, and were not due to equipment or operator error.

These results obviously contradict current theory and literature reports on the operation of IMBRs. This is discussed further towards the end of this report.

6.4 EFFECT OF FLUX ON FOULING RESISTANCE

On the assumption that the investigations in Section 6.3 could have been above ‘critical flux’ conditions, the investigations were repeated at a significantly lower flux of 12.5 LMH. The results are shown in Figure 36.

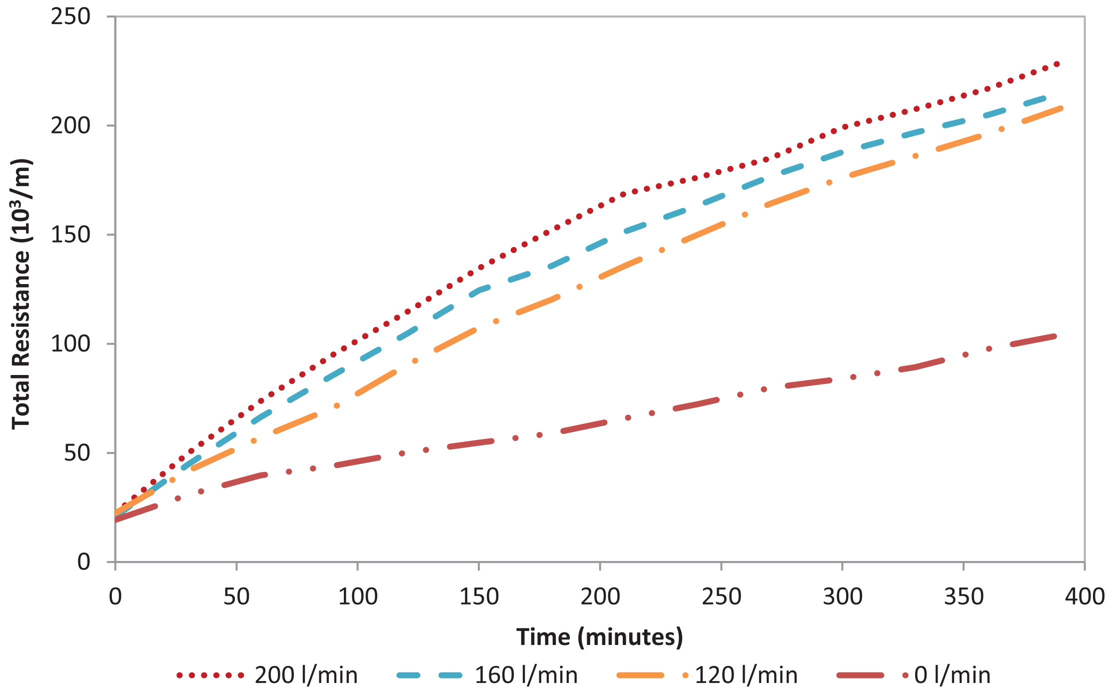


Figure 36: Effect of air scour rates at a starting flux of 12.5 LMH, and MLSS concentration range of 9.1-9.2 g/l

Observations from Figure 35 and Figure 36:

(i) The rate of fouling is lower than Figure 35. This can be expected from the lower flux.

(ii) Once again, the air scour rate appears to have very little effect on limiting fouling, and NO air scour appears to yield the best control of fouling!

6.5 EFFECT OF MLSS ON RATE OF FOULING

Investigations into the effect of MLSS concentration on the rate of fouling were performed by setting the starting flux to 12.5 LMH, the air scour rate to 10 L/min/module, and using activated sludge feeds ranging from 9.8 g/L to 12.1 g/L (the range available at Zandvliet). The results are shown in Figure 37.

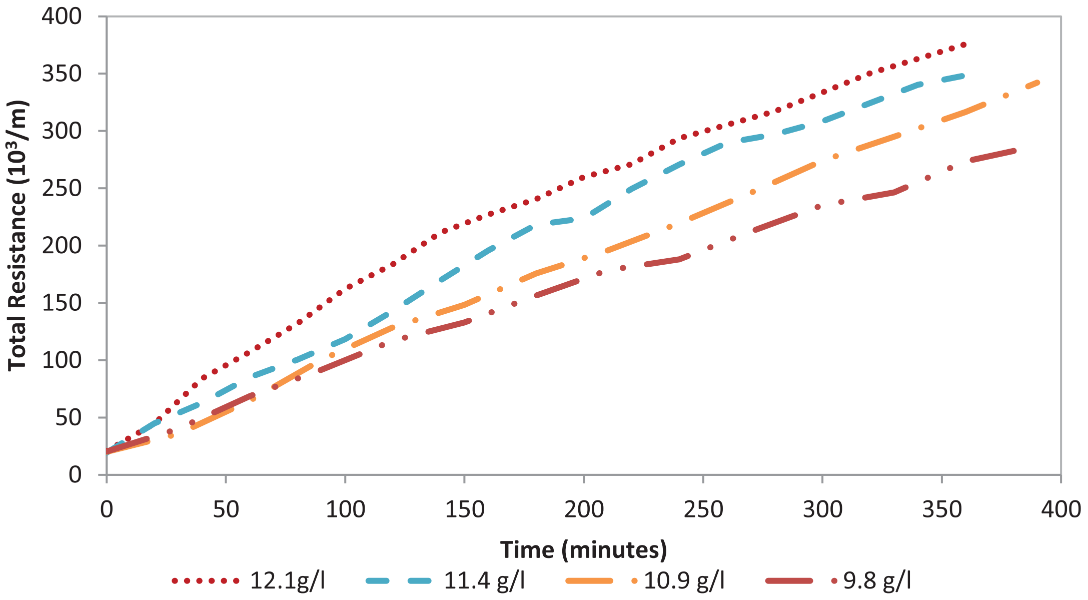


Figure 37: Effect of MLSS on fouling resistance, using a starting flux of 12.5 LMH, and air scour rate of 10 L/min/module

Taking into account the error bars in Figure 34, there nevertheless is an indication that the rate of fouling appears to increase with MLSS concentration, as would be expected. For all MLSS concentrations there is a clear increase in fouling resistance with time.

6.6 WFIMBR PERFORMANCE

To verify that the membranes were performing adequately, and that the above anomalous were not due to leaks in the membranes, etc., typical permeate turbidity profiles are shown in Figure 38, and typical COD removals are shown in Table 6. These are based on the various runs undertaken during the project.

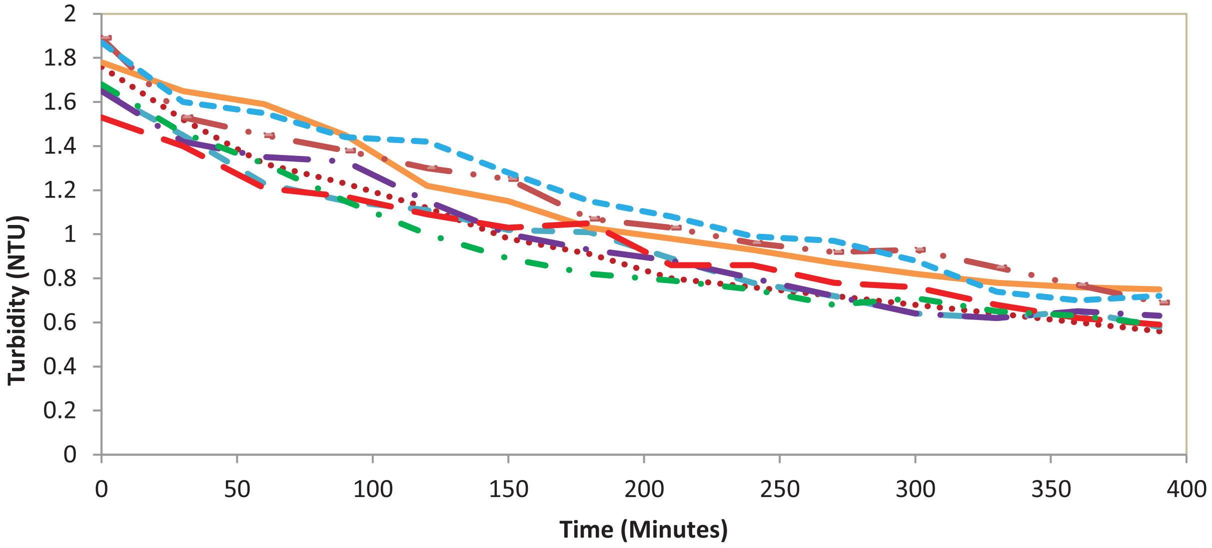


Figure 38: Typical permeate turbidity profiles

Table 6: Typical COD removal efficiency

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

It is clear that both the permeate turbidities and COD removals are typical of that obtained by conventional IMBRs, indicating that the membranes were not compromised in any way.

6.7 SUMMARY

The above investigations confirmed earlier preliminary findings that:

(i) air scouring did not limit fouling, even at sub-critical flux conditions, and

(ii) having no air scouring appeared to result in a significantly lower rate of fouling than employing air scouring.

CHAPTER 7: INVESTIGATIONS ON ACTIVATED SLUDGES FROM OTHER WASTEWATER TREATMENT WORKS

7.1 INTRODUCTION

The investigations at Zandvliet indicated the very interesting result that fouling was reduced when there was no air scouring of the membrane.

The next stage was to establish whether this was 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 investigation:

(i) Macassar Wastewater Treatment Works: Macassar has a conventional wastewater treatment process, and the feed used in the investigations was the return activated sludge (RAS) from the post-digestor settling tank.

(ii) Bellville Wastewater Treatment Works: Bellville has just installed an IMBR unit. Hence the feed used in investigations was the same activated sludge that feeds the Bellville IMBR unit.

Logistically, it would have been expensive and time consuming to relocate the pilot scale rig from Zandvliet to these other wastewater treatment works. Accordingly, it was decided that a laboratory-scale WFIMBR rig should be set up. Hence, activated sludge could be collected from any of the wastewater works and investigated the laboratory.

7.2 LABORATORY-SCALE RIG AND OPERATING PROCEDURES

The laboratory-scale 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 be independently varied.

The construction of the membrane modules was identical to that of the pilot plant, except for scale. The air scouring spargers were also similar. The P&I diagram of the rig is presented in Figure 39, and pictures of the rig are shown in Figure 40. The operational procedure is provided in Appendix 1.

The operating procedure was much the same as for the pilot rig. An air scour rate and initial flux was set. the ΔP and J profiles were then monitored with time. From this a plot of total resistance with time was developed.

The pilot scale rig was operated at fluxes between 8 LMH and 20 LMH, typical of many commercial IMBR units. However, these fluxes could not be stably maintained for the laboratory rig. Accordingly, the lab rig was operated at fluxes between 30 LMH and 140 LMH, significantly higher than practical IMBRs. However, since the intention was to compare the fouling characteristics of different feeds, these high fluxes are acceptable, as the fouling rates of different feeds would be equally affected.

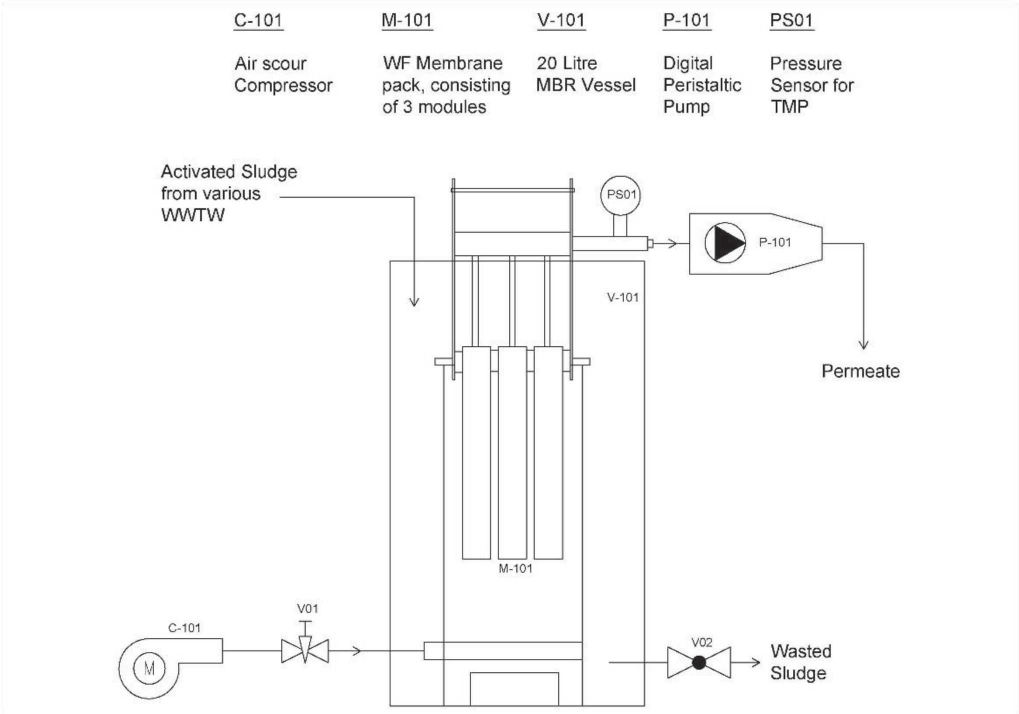


Figure 39: Laboratory WFIMBR rig

Figure 40: Laboratory-scale WFIMBR rig

7.3 INVESTIGATIONS ON MACASSAR ACTIVATED SLUDGE

The effect of air scour rate on fouling rate with Macassar activated sludge was investigated at two starting fluxes, viz. 140 LMH and 30 LMH, and an air scour rate of 10 L/min/module. Intermittent air scour was achieved by scouring every 4 minutes for 1 minute at a rate of 10 L/min/module. The results are summarised in Figures 41 and 42. Note that all investigations were repeated.

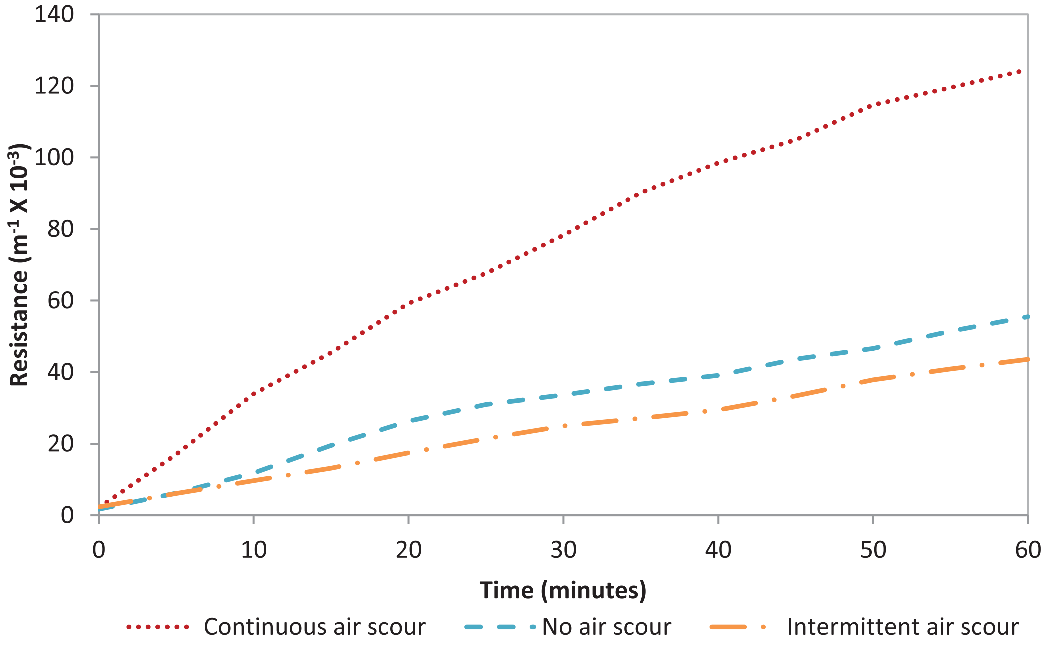


Figure 41: Trials on Macassar Activated Sludge using an initial flux of 140 LMH, MLSS of ~ 8.6 g/L and air scour rate of 10 L/min/module.

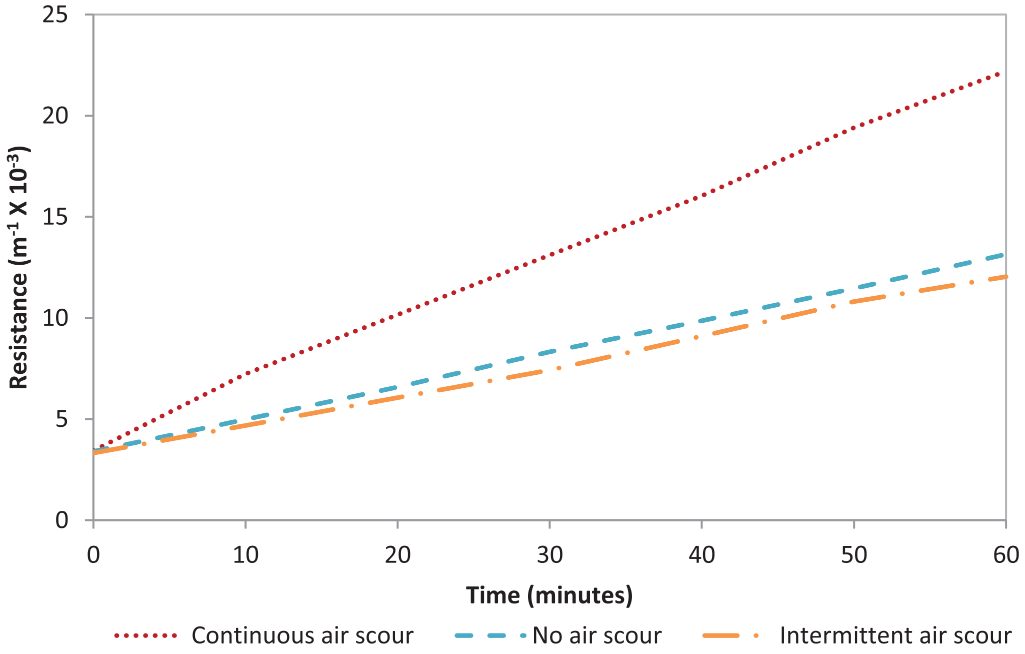


Figure 42: Trials on Macassar Activated Sludge using an initial flux of 30 LMH, MLSS of ~ 8.6 g/L and air scour rate of 10 L/min/module.

Observations from Figures 41 and 42:

(i) Similar to the pilot trials at Zandvliet, continuous air scouring gives a significantly greater rate of fouling than no air scouring.

(ii) Intermittent air scouring gives a marginally lower rate of fouling than no air scouring.

Photos of the membranes after the scouring and no-scouring runs are shown in Figure 43.

Figure 43: Membranes after air scouring trials (left) and no air scouring (right)

The membranes after runs with air scouring are generally ‘clean’ (left), and further there appears to be no sludge build-up between the modules. The modules after no-scouring runs are clearly covered in sludge.

Nevertheless, the fouling resistance for the former was substantially greater than the latter. This provides some possible clues on the nature of the fouling.

7.4 INVESTIGATIONS ON BELLVILLE ACTIVATED SLUDGE

These investigations were done under similar operating conditions to the Macassar investigations, with an MLSS of ~ 8.5 g/L to 8.9 g/L. The resistance profiles obtained at low and high fluxes are shown in Figures 44 and 45. Once again, these are the results of repeated runs.

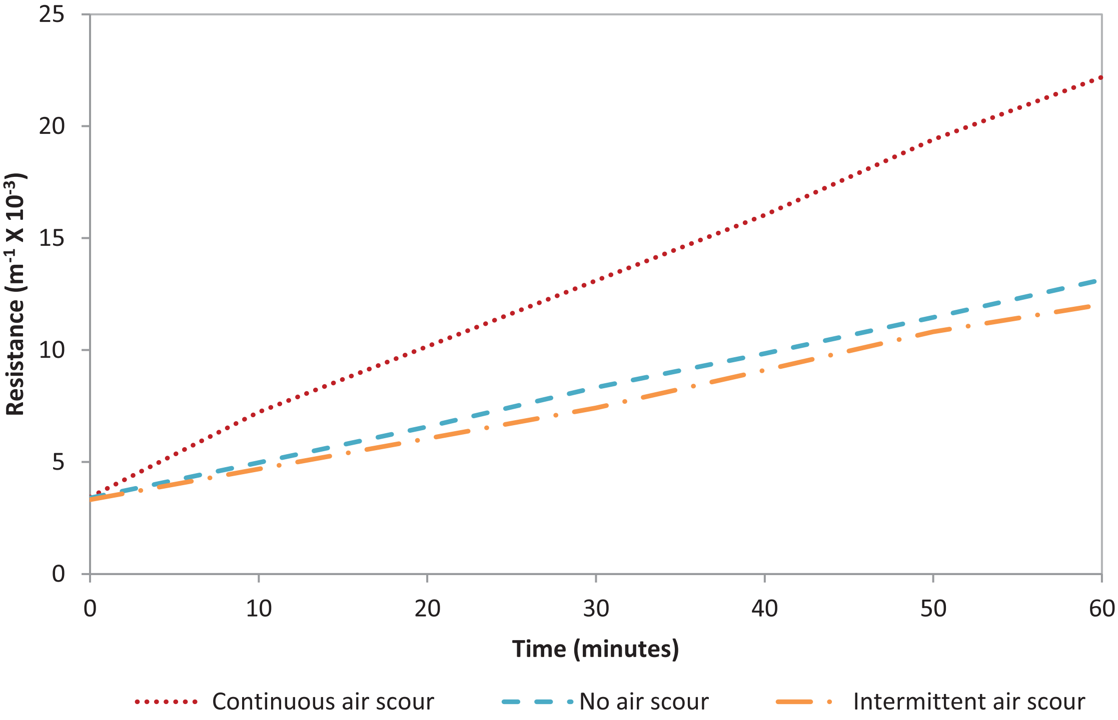


Figure 44: Resistance profiles for Bellville sludge using flux of ~ 30 LMH, air scour rate ~ 10 L/min/module

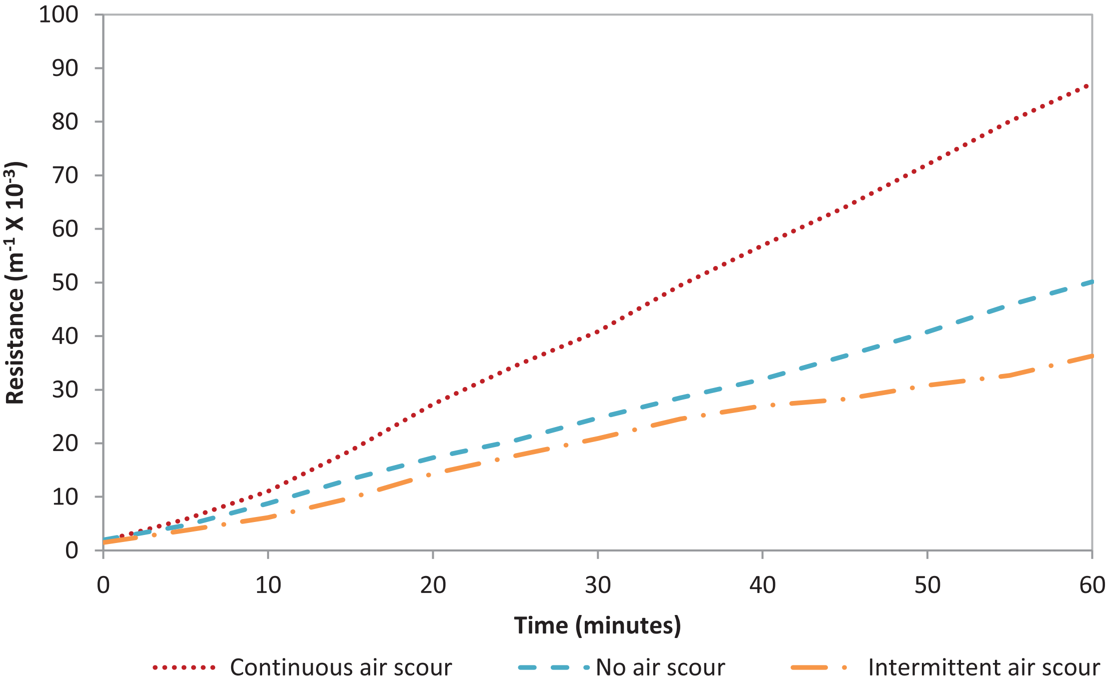


Figure 45: Resistance profiles for Bellville sludge using flux of ~ 140 LMH, air scour rate ~ 10 L/min/module

Observations from Figures 44 and 45:

(i) Similar to the pilot trials at Zandvliet, and the lab trials on Macassar activated sludge; continuous air scouring gives a significantly greater rate of fouling than no air scouring.

(ii) Intermittent air scouring gives a notably lower rate of fouling than no air scouring.

Photos of the membranes after the scouring and no-scouring runs are shown in Figure 46.

Figure 46: Membranes after no-scour runs (left) and continuous air scour (right)

Similar to the Macassar trials, the membranes after runs with air scouring are generally ‘clean’ (right), and further there appears to be no sludge build-up between the modules. The modules after no-scouring runs are clearly covered in sludge.

Nevertheless, once again, the fouling resistance for trial runs with air scouring are substantially greater than trial runs with no air scouring.

7.5 INVESTIGATIONS ON ZANDVLIET ACTIVATED SLUDGE

Whilst Zandvliet had been investigated on a pilot scale, investigations were repeated on the lab rig, to enable direct comparison with Macassar and Bellville activated sludges. The results are shown in Figures 47 and 48.

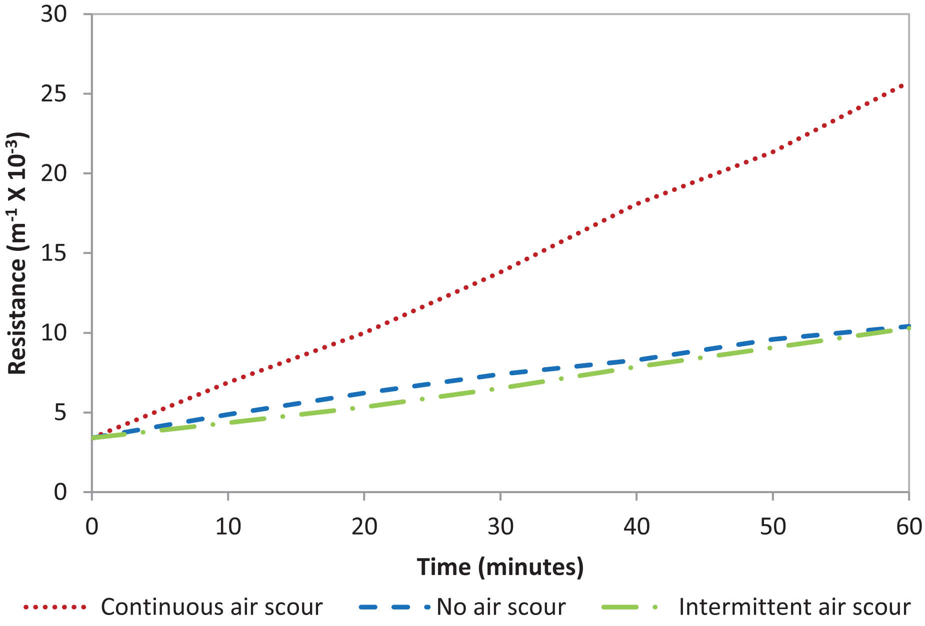


Figure 47: Resistance profiles for Zandvliet sludge using low flux of ~ 30 LMH, air scour rate ~ 10 L/min/module

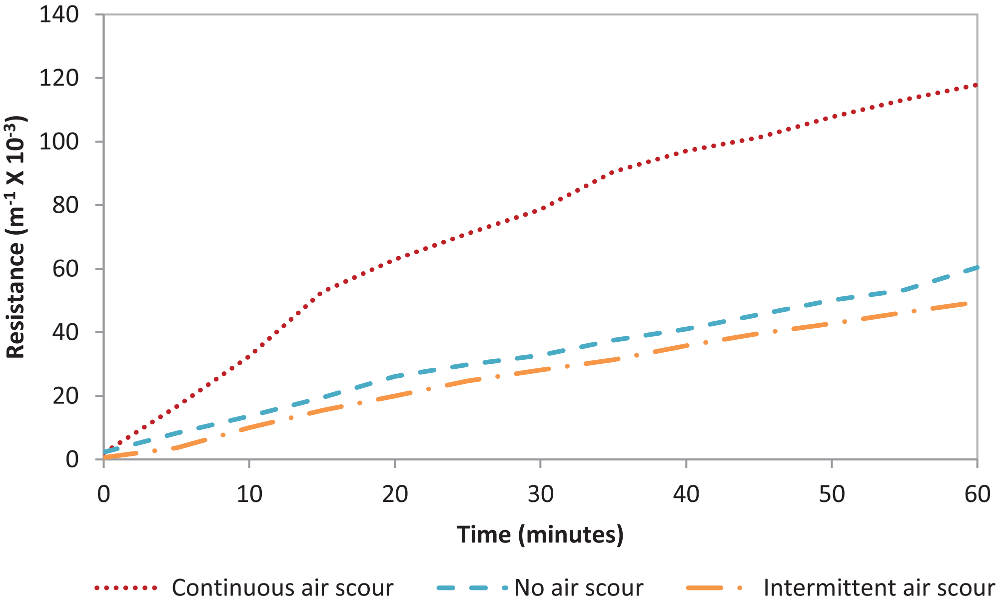


Figure 48: Resistance profiles for Zandvliet sludge, using high flux of ~ 140 LMH, air scour rate ~ 10 L/min/module

The observations from Figures 47 and 48 are the same as that obtained on Macassar and Bellville activated sludges.

7.6 OVERALL ASSESSMENT OF THE EFFECT OF SCOURING RATE ON THE RATE OF FOULING

The results of the trials on all three activated sludges are summarised in Figure 49 (low flux) and Figure 50 (high flux).

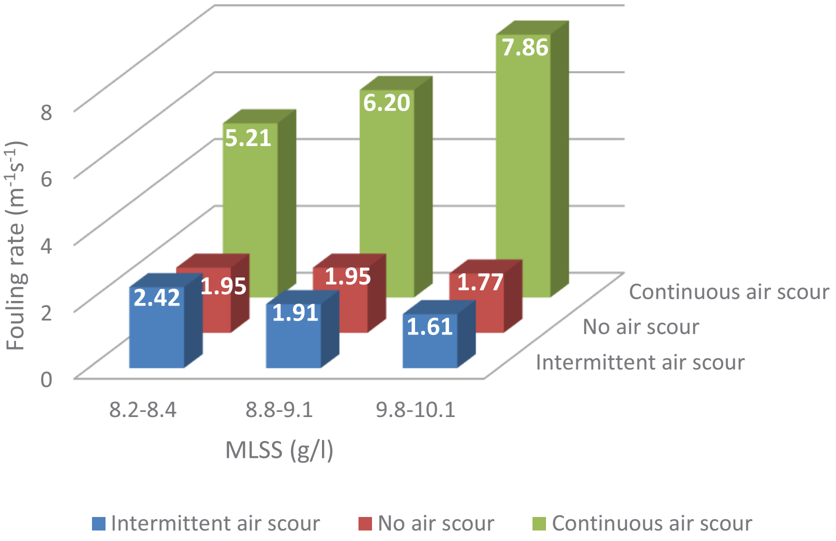


Figure 49: Fouling rates as a function of MLSS and air scouring regime (low flux of 30 LMH)

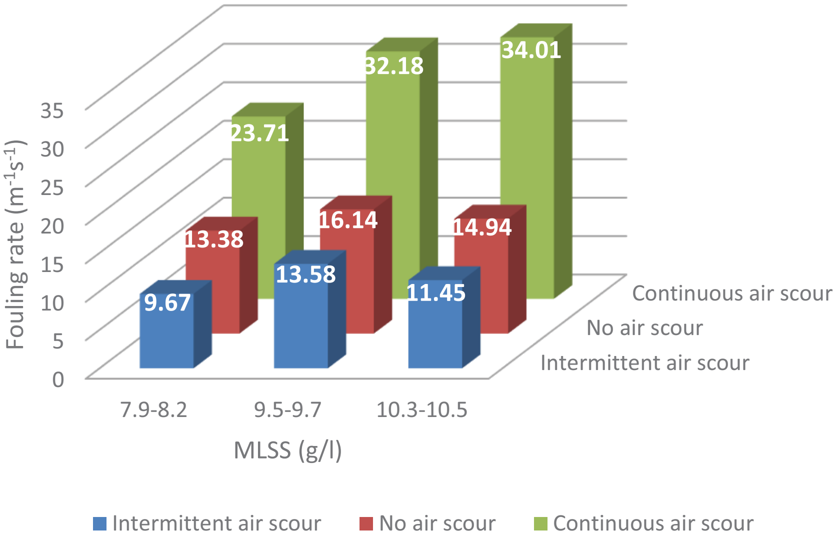


Figure 50: Fouling rates as a function of MLSS and air scouring regime, (high flux of 140 LMH)

General observations:

(i) Continuous air scouring gives the highest rate of increase in fouling. This is contrary to theory and most literature, but the results in this study are unequivocal on this.

(ii) Intermittent air scouring gives a marginally lower rate of fouling than no air scouring at all.

7.7 A POSSIBLE EXPLANATION OF THE 'SPURIOUS' RESULTS

Most of the 'science' concerning limiting fouling in IMBRs revolves around the 'critical flux theory'. This is based on the dynamics of particles being deposited onto 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 (the 'critical' flux). Hence higher air scouring rates should permit higher fluxes before significant fouling can occur, and *vice versa*. This theory will probably apply well if activated sludge consisted of a narrow size range of particles of relatively uniform properties.

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). It is well known that EPS is 'gel like' and fouls membranes significantly. The content of EPS in any activated sludge will be a function of how stressed the bacteria are. If they have been highly stressed, the content of EPS will be high. If they have been relatively unstressed, the content of EPS will be lower.

It is 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 process that includes anoxic and anaerobic zones, there is likely to be a high population of 'stressed' bacteria, and hence a higher EPS content. This significant component of EPS would arise from the fact that bacteria (aerobic, anoxic and anaerobic) are being exposed to zones that stress them due to the various recycle streams in such systems.

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

Accordingly, if activated sludge from a well-run straight activated sludge plant is filtered through a membrane, the fouling is dominated by the bacteria themselves. These are not very different from 'uniform spheres', and the 'critical flux' theory could apply. Here, the fouling rate could be controlled by air-scouring. This would explain why the project obtained very good results at the Veolia plant in Durban – the feed was from an activated sludge plant that was operated by project personnel.

However, if activated sludge from a typical wastewater treatment works is used, i.e. aerobic, anaerobic and anoxic zones exist, then the mixed liquor will consist of both discreet bacteria and probably a significant component of EPS. Here, the main fouling resistance of the membrane will be dominated by the EPS, and not the bacteria.

Now, if a membrane is operated with high air scouring, all the bacteria will be swept away from the surface. However the EPS can then easily reach the membrane surface, and penetrate the membrane, which would cause fouling which is not easily reversed hydro-dynamically. If the membrane is operated without air scouring, the bacteria will immediately form a fouling layer which will grow according to ‘dead-end’ filtration. However, this fouling layer will act as a ‘precoat’ and prevent EPS from reaching the membrane. The net result is that fouling will be controlled by the bacteria (low fouling potential), rather than EPS (high fouling potential).

The above attempt as an explanation seems to fit all the seemingly anomalous behaviours observed in this study. However this needs to be investigated further, since it has significant implications for the operation of IMBRs.

7.8 SUMMARY

The laboratory-scale investigations indicated that all the mixed liquors, viz. Macassar, Bellville and Zandvliet exhibited the same filtration performance, viz.:

(i) air scouring did not limit fouling, even at sub-critical flux conditions, and

(ii) having no air scouring appeared to result in a significantly lower rate of fouling than employing air scouring.

(iii) intermittent air scouring appears to give a marginally better performance than no air scouring, and a significantly better performance than continuous air scouring.

The observation that operating without continuous air scouring yields a lower rate of fouling than operation with continuous air scouring could have a huge implication for the operation of IMBRs, since it would decrease the operating costs of IMBR technology considerably.

CHAPTER 8: CONCLUSION AND RECOMMENDATIONS

8.1 PROJECT CONCLUSIONS

The overall aim of this project was to develop the woven fabric immersed membrane bioreactor (WFIMBR) as a technology for small-scale and decentralised sanitation.

The specific aims of this project were:

(a) To develop a 10 person equivalent (p.e.) package plant sanitation unit based on the novel woven fabric immersed membrane bioreactor technology (WFIMBR).

(b) To investigate the optimisation of the unit in terms of energy usage, simplicity of construction, simplicity of operation, and robustness.

(c) To develop a 30 p.e. unit based on the optimized geometry and operating conditions.

(d) To demonstrate the 30 p.e. product to relevant stakeholders, including wastewater treatment practitioners, municipalities, vendors of systems, etc., so as to accelerate the implementation of IMBR wastewater treatment package plants in South Africa.

In this project, the WFIMBR technology was successfully up-scaled from a 'laboratory' technology to a stand-alone small-scale IMBR system for 10 p.e., and subsequently 30 p.e., using non-specialist 'off-the-shelf' items, except for the WFMF fabric itself. This demonstrated that the WFIMBR technology was a 'simple-to-engineer' technology, with the obvious exception of the specialist membrane fabric.

Evaluation of the performance of the WFIMBR indicated that:

(i) In terms of product quality, the trials at both Veolia and Zandvliet indicated that the WFIMBR produced a product quality consistent with that of conventional IMBRs.

(ii) In terms of process stability, the WFIMBR was operated stably at Veolia, but stable operation, where fouling could be controlled hydrodynamically, could not be achieved at Zandvliet.

(iii) Investigations indicate that this discrepancy is most likely due to the fouling potential of the different feeds used, and is not a negative feature of the WFIMBR technology.

Overall, the project has demonstrated that the technology can be scaled up and that the performance of the WFIMBR technology is completely comparable with that of conventional IMBRs, operated on the same feeds.

The WFIMBR technology continues to be potentially more attractive than conventional IMBRs for applications in developing economies for the following reasons:

- The membranes are significantly more robust than commercial polymeric IMBR membranes, and are not destroyed when they dry out or are scratched.
- The WFIMBR membranes do not require a chemical cleaning step. They can be fully recovered by scrubbing them and soaking them in dilute hypochlorite ('Jik') overnight.
- The WFIMBR technology is potentially less expensive than the current conventional IMBR technologies, especially in small-scale applications.

8.2 RECOMMENDATIONS

8.2.1 Development of an optimised operating regime

Prior to the trials at Zandvliet, it was expected that a WFIMBR plant would be able to operate stably (without fouling) for extended periods, based on the results obtained at Veolia. When cleaning was eventually necessary, this could be achieved by scrubbing the membranes or soaking them in dilute hypochlorite.

The experiences with the feeds from Bellville, Macassar and Zandvliet indicated that stable IMBR operation is not feasible, even for the commercial IMBRs operating at Bellville and Zandvliet. Hence, an operating sequence needs to be developed to enable continuous operation of a WFIMBR operated on such feeds.

Hence, it is recommended that future research and development should focus on:

(i) Developing and optimising an operating sequence for continuous operation of an IMBR unit. The optimisation must consider: filtration flux and filtration period; intermittent air scouring frequency and flowrate; backflush frequency and duration; relaxation periods.

(ii) Developing an optimal cleaning strategy for 'in-situ' cleaning of fouled membranes. This should consider: air-scouring in combination with backflush; cleaning the membranes with dilute hypochlorite.

8.2.2 Investigations into fouling characteristics of mixed liquors from various zones in a wastewater treatment works

The study on fouling characteristics for various feeds should be extended further, to characterise the fouling propensity of feeds from various sections within a wastewater treatment facility, as well as to attempt to confirm the hypotheses made in this study.

Such a study may result in a different approach to the positioning of IMBRs in a wastewater treatment facility, the energy consumed in IMBRs, and hence could have a major future impact on 'new generation' approaches to wastewater treatment.

8.2.3 Development of a more oleophobic membrane

If the surface of the WFMF membranes could be modified to be more oleophobic, this would repel the microorganics that seem to be the major contributors to fouling of the membranes. This, in turn, would improve both the membrane fluxes and the ease of cleaning the membranes. This aspect should be investigated as part of future process development.

8.2.4 Demonstration of small-scale WFIMBR for decentralised sanitation

The effort in this project deviated from 'demonstration' to 'investigation' the seemingly spurious or unusual results obtained during the project. Hence a successful demonstration to potential users and relevant stakeholders was not achieved during the project timeframe.

It is recommended that once an optimised operating regime is established, a 30 p.e. unit is set up at a suitable site for demonstration of the technology under the Water Technologies Demonstration (WADER) platform.

CHAPTER 9: REFERENCES

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