Contents lists available at ScienceDirect

South African Journal of Chemical Engineering

journal homepage: http://www.journals.elsevier.com/south-african-journal-of-chemical-engineering

Fouling mitigation on a woven fibre microfiltration membrane for the treatment of raw water

Martha N. Chollom [a,*], **Kumnandi Pikwa** [a], **Sudesh Rathilal** [a], **V.L. Pillay** [b]

[a] *Faculty of Engineering and the Built Environment, Department of Chemical Engineering, Durban University of Technology, 4001, Berea, 70 Mansfield Road, Durban, South Africa*
[b] *Department of Process Engineering, Stellenbosch University, Private Bag X1 Matieland, 7602, South Africa*

ARTICLE INFO

Article history:
Received 9 February 2016
Received in revised form
31 August 2016
Accepted 23 December 2016

Keywords:
Fouling mitigation
Brushing
Adsorption
Woven fibre membrane
Cleaning

ABSTRACT

The main source of drinking water in rural areas of South Africa is surface water. Improving drinking water and sanitation facilities alone does not completely solve the problem of waterborne diseases. A novel simple gravity driven filtration unit incorporated with the woven fibre microfiltration (WFMF) membranes was developed for the treatment of raw water for drinking purposes. However, these membranes are susceptible to fouling which reduces flux permeation. This paper focused on evaluating the fouling mitigation strategies to improve on performance of the woven fibre membrane filtration unit with respect to fouling and flux recovery. The study found that the WFMF membrane fouled both internally by pore plugging and externally by adsorption and deposition on the membrane. As a result, a single flux enhancement strategy proved insufficient to maintain high flux successfully. A combination of strategies gave the best optimum conditions for flux production. Backwashing with a combination of brushing yielded the highest recovery of 187%. Soaking the membranes in 0.2% hypochlorite for an hour and thereafter by brushing them yielded 93% flux recovery. Mechanical cleaning however yielded the best result with 97% flux recovery. It was concluded that the selected strategies were the most successful strategies to prevent a sharp decline in flux due to fouling and giving high average flux for the filtration period.

© 2017 The Authors. Published by Elsevier B.V. on behalf of Institution of Chemical Engineers. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

1. Introduction

A new polyester woven fibre microfiltration membrane (WFMF) for raw water treatment has been incorporated as point of use system (POU) called the Remote rural water treatment system (RRWTS). Detailed reports on the effect of flux reduction on different feed samples and effects of aeration as a flux enhancement strategy has been evaluated in a previous study by Chollom et al. (manuscript under review). The focus of that study was to evaluate the effect of feed composition on the membrane performance and aeration was the main strategy to recover flux. Similarly, Alfa et al. (2016) evaluated the physical disinfection of the WFMF and chemical disinfection using two disinfectants namely waterguard (WG) and bromochlor tablet (BRCH). Mecha and Pillay (2014) incorporated silver nanoparticles (AgNPs) onto the WFMF membrane using modified chemical reduction method. Both studies found that the membrane unit removes suspended solids and colloids and gave permeates (product) with a turbidity of less than 1 NTU. Similarly, being a microfiltration membrane, it was able to remove most bacteria and protozoa and whatever virus that escaped the membrane was

---

* Corresponding author.

E-mail addresses: mnchollom@gmail.com (M.N. Chollom), kpikwa@gmail.com (K. Pikwa), rathilals@dut.ac.za (S. Rathilal), pillayvl@sun.ac.za (V.L. Pillay).

http://dx.doi.org/10.1016/j.sajce.2016.12.003

1026-9185/© 2017 The Authors. Published by Elsevier B.V. on behalf of Institution of Chemical Engineers. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

disinfected by disinfecting agents (Mecha and Pillay, 2014). Hence the system was found to be in the category of those that offer a multiple barrier approach to drinking water quality. These properties were however limited to the performance of the WFMF in terms of permeate quality. There is need to evaluate the WFMF with respect to fouling and flux recovery to ascertain its sustainability, and that is the scope of this study.

Potable water treatment can primarily be divided into; house-hold treatment and conventional water treatment. House-hold water treatment in nature has, or should have, minimal technical requirements and expertise. Regulation of the house-hold systems is almost non-existent due to the lack of monitoring, assessment and standardization (Brikké and Bredero, 2003). House-hold water treatment systems include the boiling of water, slow sand filtration and domestic chlorination. Boiling of water according to WHO (2005) kills or inactivates microorganisms but it negatively affects the taste of the water and does not improve the aesthetic state of the water. Slow sand filtration involves passing raw water through a bed of sand where it is treated by both biological and physical treatment. One critical problem with POU systems has been their lack of sustainability and the inability to scale up thereby making most POU system to fail to achieve long term adoption (Sobsey et al., 2008).

Small scale systems or POU systems have become the most suitable methods of treatment in the rural areas as it has many advantages. It does not require large volumes of water and is not affected by difficult topography or dispersed settlement. Most small scale systems may not require electricity (Sobsey, 2002). Although small scale systems have huge advantages, factors like lack of durability, short operational life span and lack of sustainability of the system have proven over the years to be major challenges in the implementation and survival of these systems in rural communities.

Membrane technology is a physical separation process, where a membrane serves as a filter to separate a mixture. There is no modification of the substances being separated. The separation is through a membrane using momentum such as a pressure difference, concentration difference, or potential difference (Pinnekamp, 2003). There is a wide application of this technology i.e. manufacturing, medical, water treatment and fuel cells. Despite the many advantages offered by membrane for water purification, they still suffer from fouling, which could add to the overall cost of running due to energy consumption.

Although membrane technology has been widely used in large scale water treatment, the application of current commercial membranes in rural areas is still questionable. This is because commercially available membranes are fragile and lack robustness. They can be easily damaged if left to dry. These membranes are relatively expensive and they require trained personnel both for their operation and cleaning. These challenges make the application and sustainability of commercial membranes in rural areas difficult. The WFMF is a new inexpensive polyester membrane that could be incorporated into POU systems for the treatment of raw water in rural areas.

This paper will discuss the optimisation of the new WFMF with respect to fouling mitigation and the best cleaning methods. The optimum conditions will be included in the final development of the filtration rig for water treatment in the rural areas. These are described in Section Two; Section Three will give an outline on the result and conclusion drawn from the study.

2. Materials and method

2.1. *Membranes*

The woven fibre microfiltration membrane (WFMF) is a polyester based fibre locally sourced and was supplied by the Gelvenor Consolidated Fabrics (PTY) Ltd in Durban, South Africa. The pore size of the membrane was unknown, hence was determined using the modified exclusion method (MSE). Synthetic feeds were prepared based on the characteristics of Duzi River. The Duzi River was made up of high turbidity and some microbial contents such as *Escherichia coli* and total coliforms in varying amounts. Synthetic feed were used because of the difficulty experienced in bringing large quantities of Duzi River samples to the laboratory due to logistical problems. The characteristic of the sewerage feed samples is shown in Table 1. The synthetic feed solution used in this study was made up of river clay, domestic sewerage, and tap water. The concentration of river clay in the synthetic feed was 3 g/ℓ and the domestic sewerage was maintained at 2% of the total volume of the synthetic feed solution prepared. The composition of the synthetic feed was adjusted until its composition was similar to that of the Duzi River. The activated sludge was kept in the refrigerator at 10 °C for a maximum of 5 days. Each experiment was repeated three times to give room for repeatability. Therefore results reported here are averages.

2.2. *MSE method*

The traditional methods to determine the pore size of a membrane, such as a bubble test and microscopic view were unsuccessful due to the configuration of the WFMF membrane, Fig. 1.

0.5 g/ℓ of $Ca(OH)_2$ was dissolved in 30 ℓ of de-ionized (0.1 ± 0.05 NTU). The particle size of the $Ca(OH)_2$ was 0.8 micron. The $Ca(OH)_2$ solution was passed through three different millipore filter papers (1, 0.45 and 0.22 μm). The filtration pressure was kept constant at 10 kPa. The experiment set up is shown in Fig. 2. The turbidity of the feed solution and that of the filtrate were measured and recorded

Table 1 – Characteristics of the synthetic feed.

Contaminants	Units	Synthetic feed
Turbidity	NTU	200
Colour	^{0}H	8.5
Total coliforms	Count per 100 mL	15,475
E. coli	Count per 100 mL	12,324

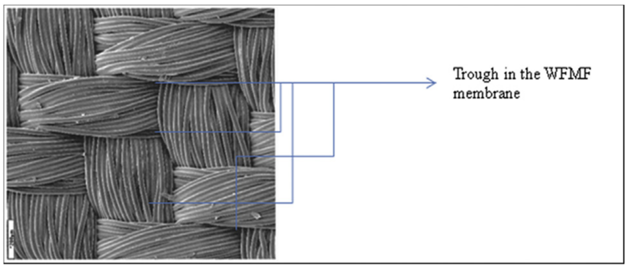

Fig. 1 – Magnified microscopic view of the WFMF membrane (×1000).

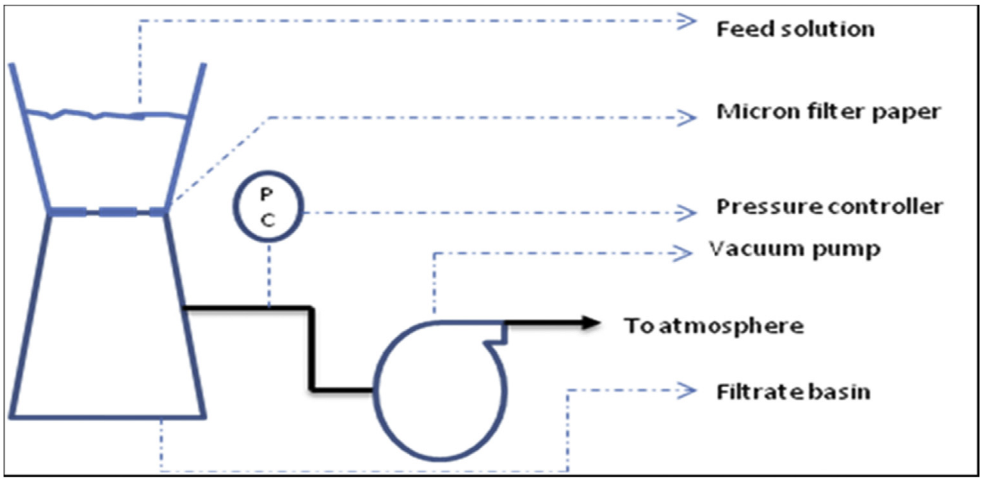

Fig. 2 – Filtration cell for 1 μm filter paper.

using HACH 2100Q Portable turbidi meter. The filter paper that retains all of the turbidity was regarded as having a smaller pore diameter than the clay particles. The same experiment was repeated but with the WFMF membrane in place of the filter paper. Feed and filtrate turbidity were measured and recorded. The filtrate turbidity of the WFMF membrane was compared to that of the individual filter papers and that of deionized water to check for percentage rejection. The pore size of the WFMF membrane was inferred to be equal to the filter paper with similar rejection capacity.

2.3. *Adsorption test of the WFMF membrane with the synthetic feed*

The method describing the making of the membrane modules have been described in a study by Chollom et al. (Manuscript under review). A total of 5 modules were incorporated in the RRWTS and were evaluated in this study. Adsorption fouling occurs on the membrane even in the absence of filtration. To evaluate adsorption fouling on the WFMF membrane, a pure water flux (PWF) test was carried out on the clean WFMF membranes and the obtained flux was recorded. Immediately after the PWF, the membranes were immersed into the synthetic feed solution. Care was taken that there was a minimum head above the WFMF membranes. This was to ensure that filtration does not occur. The WFMF membranes were immersed horizontally such that only 1 cm head was available to drive filtration. The membranes were immersed for 20 min after which the PWF was carried out again to see whether there was any loss of flux. Fig. 3 shows the filtration cell used for the determination of adsorption fouling on the WFMF. Fouling characterization experiments were conducted to determine the flux decline rate under constant flux operation. A base case fouling profile was developed and the performance of each flux enhancement strategy was measured against the base case. For each flux enhancement experiment the base case fouling profile was plotted. The base case profile indicates the lowest possible flux at the set operating conditions. Two external membranes in the membrane pack were used to plot the base case curve. These membranes were not exposed to the fouling mitigation strategies.

3. Fouling mitigation strategies

3.1. *Effect of reduced permeate flow*

High instantaneous flux (initial flux at the beginning of filtration) is common in constant pressure operated membrane systems. A high instantaneous flux drives the filtration process to be above critical flux, resulting in a high fouling rate and a decline in flux. This experiment was conducted to study the effect of reducing flux such that the filtration process was operated at a sub-critical flux (where little/no deposition on the membrane surface occurs). Permeate flux was controlled manually (by hand) by controlling valve. It was adjusted such that the permeate flux from the membrane pack was stable at 10 LMH. After some time of operation when the flux dropped below 10 LMH, the valve was opened to ensure that a stable flux of 10 LMH was obtained from the membrane pack, Fig. 3.

3.2. *Pre-coating the membrane*

The interaction between the foulants and membrane is a determining factor of the extent of membrane fouling. To study the effects of membrane interaction with foulants, (prior to filtration of the synthetic feed), big diameter $Ca(OH)_2$ solution was first filtered through WFMF membrane. 2 g/ℓ $Ca(OH)_2$ solution was prepared and filtered through the membrane pack. The particle size of the $Ca(OH)_2$ that was used is 2 μm. The filtration was allowed to run for 1 h allowing the calcium particles to accumulate on the membrane surface. Filtration of $Ca(OH)_2$ was conducted in the filtration system as shown in Fig. 3. After an hour, the filtration tank was drained-off and $Ca(OH)_2$ solution and synthetic feeds were introduced to the filtration tank. Care was taken that turbulence was not created as the synthetic feed was introduced such that the calcium layer on the membrane surface was not removed. The experiment was conducted to study the effect of pre-coating WFMF membranes with coarse $Ca(OH)_2$ prior to filtration of synthetic feed.

3.3. *Optimisation of flux enhancement strategies*

Flux enhancement optimization was done on the following strategies: backwashing, cycle brushing and membrane pre-

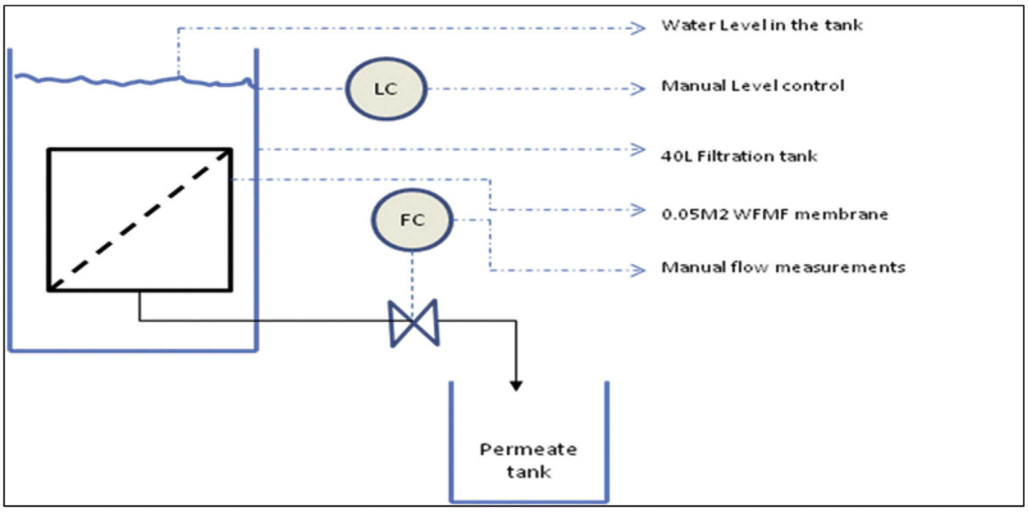

Fig. 3 – Schematic flow diagram for fouling test.

coating. The flux enhancement strategies were compared against each other.

Backwashing optimization was done by increasing and reducing backwashing duration time. Backwashing time was varied between 10, 20 and 30 min. Brushing was optimized in a similar way with backwashing where the brushing time was reduced and increased in order to evaluate its impact on flux. Brushing time was reduced from 60 s to 30 s.

Also, selected flux enhancement strategies were combined together in order to study the effect of combined flux enhancement strategies. Backwashing was combined with brushing as well as with aeration. The performances of each flux enhancement strategy were calculated on a daily basis as well as an overall flux after the experiments.

$$\%\ \text{flux improvement} = \frac{J_0 - J_1}{J_0} \times 100 \qquad (1)$$

where J_0 is the initial PWF of the membrane (no flux enhancement is employed) (LMH), J_1 is the average flux for the enhanced flux (LMH).

3.4. *Cleaning and assessment of cleaning*

The reason for membrane cleaning is to recover the flux of the fouled membrane to its original flux. Membrane cleaning is an integral part of any membrane system. It usually involves stopping of all filtration and doing a thorough cleaning of the membranes. The cleaning could be hydraulic, chemical or both. Cleaning methods are typically supplied by the membrane suppliers, with the aim of recovering flux to that of a new membrane or at worst to 90% of its original flux. To clean the WFMF membranes, different commercially available cleaning strategies were used. During WFMF membrane cleaning, filtration was stopped. Each individual membrane was removed from the pack and was cleaned solely. Cleaning strategies used for the WFMF membranes were: – (a) chemical cleaning using 0.1% NaOCl (b) rigorous brushing in a commercial soap solution followed by rinsing (c) soaking the membranes in a 0.1% NaOCl solution for 1 h followed by mild brushing of the membrane and rinsing in tap water (d) high pressure water cleaning using a Karcher high pressure cleaner. The model of the high pressure cleaner was; HD 6/16-4 M Plus at 30 bar, 230 l/h and 25 °C.

The test criteria for the effectiveness of cleaning were the physical observation of the mechanical and integrity of the membrane after cleaning. Flux recovery was evaluated using Equation (1). The difference between the PWF of the new WFMF membrane and cleaned WFMF indicated the success of the membrane cleaning method.

4. Results and discussion

4.1. *MSE method*

Table 2 shows the results obtained when 0.8 μm size $Ca(OH)_2$, solution of 0.5 g/ℓ was dissolved in de-ionized and was filtered with different pore sizes filter paper and then with WFMF membrane.

The WFMF membrane's turbidity rejection capacity was similar to a 0.45 μm filter paper. Even though the average particle size of the $Ca(OH)_2$ used was 0.8 μm, there could be larger particles and even smaller particles. It could be seen that the WFMF membrane had a similar rejection capacity with a 0.45 μm filter paper. Filtrate turbidity after 0 s was checked as the first filtrate sample. This sample represents the true rejection capacity of the filter or the membrane, because there was little or no additional secondary layer that had developed on the filter media at the initial stage of filtration.

As filtration time increased from 60 to 120 s, the rejection capacity for 1 μm filter paper, 0.45 μm filter paper and WFMF membrane improved. This indicated that a secondary layer on the filter media had developed that helped to improve the rejection capacities of these filters. On the 1 μm filter paper almost all the particles that are responsible for turbidity passed through the filter paper causing filtrate turbidity to be 7.3 NTU. This result meant that the majority of the particles in the solution were less than 1 μm in diameter, therefore they passed through the filter paper. But more than 90% of these particles were rejected by WFMF membrane but not all were rejected as it was the case with 0.2 μm filter paper. The conclusion from this analysis was that the rejection capacity of the WFMF membrane was better than 1 μm filter paper but less than the 0.2 μm filter paper. The close proximity in rejection capacity between the WFMF membrane and 0.45 μm filter paper lead to the conclusion that WFMF membrane pore size is 0.45 μm or very close.

Table 2 – Turbidity rejection of a 0.8 μm solution by different mediums.

Filter media	Lime feed turbidity (NTU)	De-ionized water turbidity (NTU)	Filtrate turbidity after 0 s (NTU)	Filtrate turbidity after 1 min (NTU)	Filtrate turbidity after 2 min (NTU)
1 μm Filter paper	10	0.12	7.3	4.1	1.01
0.45 μm Filter paper	10	0.12	0.51	0.32	0.28
0.2 μm Filter paper	10	0.11	0.12	0.11	0.13
WFMF Membrane	10	0.12	0.48	0.39	0.24

Particle size in relation to the membrane pore size affects the fouling rate on the membrane. Colloidal matter has a higher fouling rate than suspended particles [9, 8]. The lime particle size was known because it had already been determined and was used to determine the particle size of clay. Table 3 shows the results obtained when the clay particle size was determined using the MSE method.

Filtrate turbidity at zero filtration time represents the true filter separation capacity. This turbidity is before a cake layer developed on the surface of the filter paper which would help to improve the separation capacity of the filter paper. On the 1 μm filter paper, almost all the particles that cause turbidity passed through the filter paper. This was concluded that the clay particles in a solution are less than 1 μm in diameter. When same solution was passed through a 0.45 μm filter paper, almost 50% of the turbidity causing particles passed through the filter paper. This inferred that about 50% of the clay particles are less than 0.45 μm in diameter. The 0.2 μm rejected all the turbidity. It was interpreted as all the clay particles were bigger than 0.2 μm in diameter. From the results shown in Table 2 it was concluded that the clay particle size distribution is ±0.45 μm in diameter.

4.1.1. *Adsorption test*

The result shown in Table 4 reveals the effect of adsorption fouling on the WFMF membrane. The results show that soaking the WFMF membrane in a synthetic feed definitely resulted in a loss in PWF. The loss in PWF after soaking the WFMF membrane was attributed to adsorption fouling because no filtration was allowed to occur during this experiment to avoid deposition on the membrane. According to Bessiere et al. (2009), Nguyen et al. (2012) and Abdelrasoul et al. (2013), microbiological, bacterial and organic foulants mostly foul membranes by attaching on the membrane surface and adsorbing onto the membrane surface.

The conclusion from these results was that the synthetic feed sample had components that adsorbed on the WFMF membrane. These components were believed to be from the activated sludge that was added into the clay solution and these are represented as Total coliforms and *E. coli* on the feed characteristic. The soaking experiment was not conducted for the single component samples because in these samples there were no organic, bacterial or microbiological foulants present in these feed samples.

5. Fouling mitigation strategies

For the optimisation of the flux enhancement strategies and fouling mitigation, a base line fouling curve was determined and was used for comparison with respect to the performance of each strategy.

5.1. *Controlled flux operation below critical flux*

High filtration flux is believed to lead to high membrane fouling. The permeate flux was restricted to 10 LMH from the start of filtration. The purpose of the experiment was to stop the high instantaneous flux that occurs at the beginning of filtration because the WFMF membrane was clean and hopefully maintained the flux at 10 LMH for prolonged periods. Fig. 4 shows the obtained results when permeate flux was restricted to 10 LMH.

It can be seen from Fig. 4 that restricting/controlling filtration at 10 LMH delayed the sharp decline in permeate flux as seen on the base fouling curve. However, after 3 days a similar decline in flux as with the base fouling curve was observed. Controlling permeate flux at 10 LMH was intended to eliminate the effects of high instantaneous flux at the beginning of filtration by reducing the drag force that transports particles from the bulk solution to the membrane surface.

The typical starting flux at time zero for the base fouling curve was 35 LMH against 10 LMH for the controlled flux profile. The sudden decline in flux after 3 days implies that there was a sudden rise in fouling of the WFMF membrane after this period but this was not observed in the base fouling

Table 3 – Clay particle diameter determination results using the MSE method.

Filter media	Clay solution turbidity (NTU)	Filtrate turbidity after 0 s (NTU)	Filtrate turbidity after 1 min (NTU)	Filtrate turbidity after 2 min (NTU)
1 μm Filter paper	10	8.23	6.4	3.1
0.45 μm Filter paper	10	5.1	2.54	1.95
0.2 μm Filter paper	10	0.2	0.18	0.18
WFMF Membrane	10	4.85	3.51	1.4

Table 4 – Adsorption test of synthetic feed foulants on a WFMF membrane.

Test variable	Flux 1 (LMH)	Flux 2 (LMH)	Flux 3 (LMH)	Average flux
Pure water flux before soaking WFMF membrane in synthetic feed	61	58	59	59.3
Pure water flux after 20 min soaking of WFMF membrane in synthetic feed	43	45	39	44

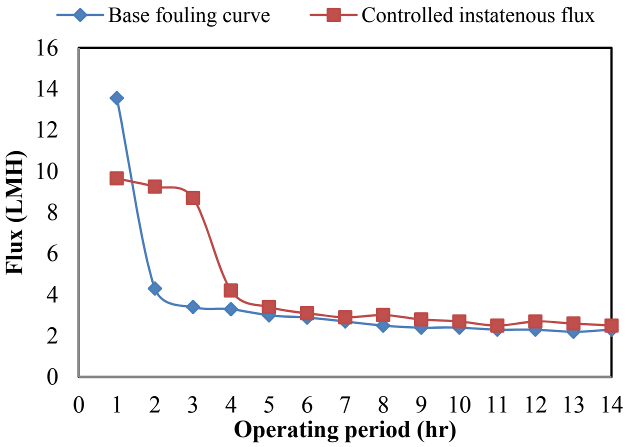

Fig. 4 – Effect of controlled flux on fouling.

curve. This was unexpected and could not be due to sudden changes in the feed or operating conditions because the sudden drop was not seen in the base fouling curve which was subjected to the same conditions. The reason for the sudden decline in flux of the WFMF membrane was believed to be due to the way the flux from the WFMF membrane pack was controlled.

The flux was controlled by manipulating the discharge/permeate flow. The limitation with this type of control was that the WFMF membrane module is hollow on the permeate side. Therefore, the permeate valve could be completely shut yet filtration would be proceeding on the membrane surface. Also the WFMF membrane bulges and expands when the permeate side of the membrane is filled with water, expanding its capacity to accumulate liquid on the permeate side. This means that the restrictions that were done on the permeate via the permeate had no effect on the filtration process taking place on the membrane surface. The implication of this is that normal filtration as with base fouling curve was occurring on the membrane surface and the membrane was getting fouled. The permeate was accumulating on the membrane permeate side because of the restrictions on the valve, hence during the first few days of filtration the constant flux of 10 LMH was the accumulated permeate on the membrane permeate side. The sudden decline in flux after 3 days could also be due to the fact that the accumulated volume in the permeate side had run out because the incoming permeate from the membrane had dropped due to fouling. So the decline in flux shown on the third day shows that the membrane was fouled and this fouling was believed to have occurred on day one but was hidden by the constant flux that was being drawn out of the membrane.

Controlling the filtration flux for WFMF membrane should be done on the feed side by reducing the driving pressure, because if flux control is done on the permeate side, the design of the WFMF membrane allows filtration to proceed even when the permeate valve is shut.

The profile of the base fouling curve and controlled flux after 5 days had similar fluxes. This implied that flux control in the filtrate side did not mitigate fouling of the WFMF membrane. The sharp decline after 3 days is a further indicator of pre-existing fouling even before that day. The results of this section were not compared to the rest of the flux enhancement strategy results, because proper flux control was not achieved. The decision not to further investigate the flux control on the feed side was because of the monitoring requirements that would have been required. For example, locating and moving the level float to a new position and moving it back up for the rest of the experiment. This exercise would have required more than one filtration tank, which was not the case. Also, 24 h monitoring of flux would have been necessary in-order to determine exactly when the time that flux started dropping to below 10 LMH for proper analysis and conclusion from the experiment. The latter also was not possible.

5.2. WFMF membrane pre-treatment

It was seen that filtration of 2 μm $Ca(OH)_2$ solution did not result in large decline in the flux that would be related to adsorption fouling or WFMF membrane internal fouling. It was therefore decided to filter first a 2 μm $Ca(OH)_2$ solution first for 30 min in order to coat the WFMF membrane surface with the 2 μm $Ca(OH)_2$ particles. The results of the experiment are plotted in Fig. 5.

Fig. 5 shows the results of the effect of pre-coating the WFMF membrane with 2 μm $Ca(OH)_2$ particles prior to filtration of synthetic feed. The results show a major improvement from the base fouling curve when pre-coating of the WFMF membrane was done. The average improvement in flux from the base fouling case was 66.2%. The large decline in the first day to the second day was reduced by a factor of 2.4. The flux decline gradient for the base fouling curve from day one to day two was calculated to be 8.6 LMH/day and the pre-coated membranes gradient dropped to 3.6 LMH/day. The reduction of flux decline and the improvement in the average value flux was attributed to the following reasons.

Firstly, the 2 μm $Ca(OH)_2$ particles were bigger than the WFMF membrane pores therefore these particles were porously packed on the membrane surface. The colloidal particles from the clay solution during filtration had no access to the membrane surface because of the $Ca(OH)_2$ particles that were already coated on the membrane surface. This prevented WFMF pore narrowing and plugging by the colloidal clay particles. WFMF membrane pore plugging and narrowing by the colloidal clay particles in the synthetic feed was believed to be the major cause for sharp decline in the filtration flux in the first day of filtration. This finding was in agreement with many other researchers such as Hong et al. (1997), Striemer et al. (2006) and Hwang et al. (2008).

The adsorption test showed that the WFMF membrane was prone to adsorption fouling by the synthetic feed. Adsorption

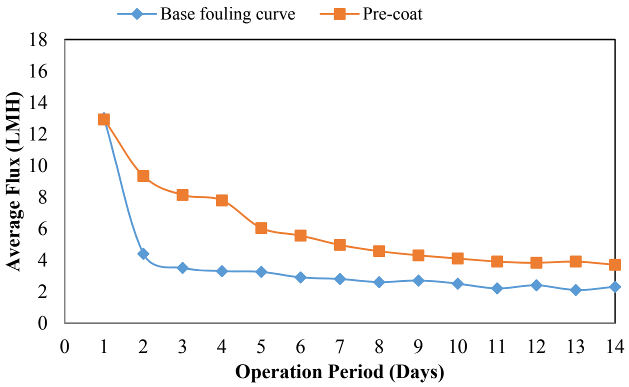

Fig. 5 – Effect of pre-coating the membrane with 2 μm $Ca(OH)_2$ solution.

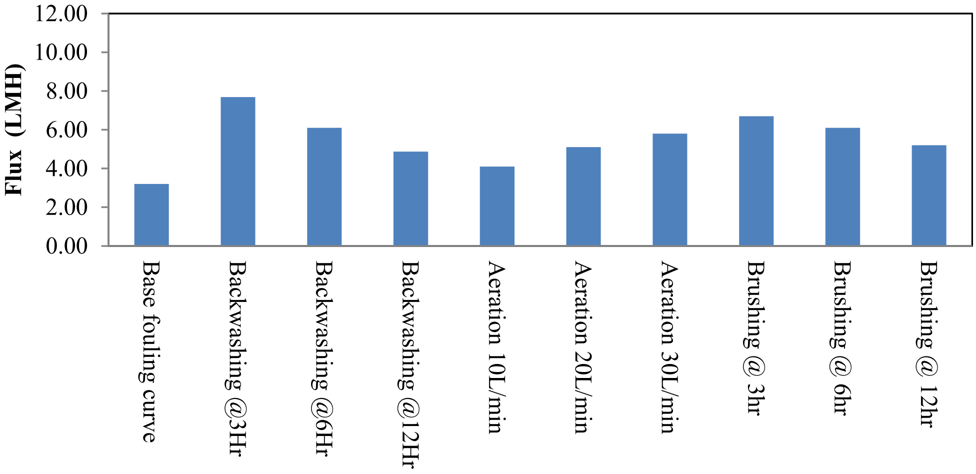

Fig. 6 – Comparison of flux enhancement strategies.

fouling occurs upon contact between the adsorptive materials in the feed solution with the membrane surface. Coating the WFMF membrane with 2 μm $Ca(OH)_2$ particles prevented contact between the membrane and the adsorptive foulants in the feed solution. Coating the WFMF membrane with 2 μm $Ca(OH)_2$ particles was effective in mitigating adsorption fouling, hence the decline in flux in the first day of filtration was minimal when compared to the base case.

5.3. *Optimisation of flux enhancement strategies*

Flux enhancement optimization was done on the following strategies: 3 h cycle backwashing, 3 h cycle brushing and membrane pre-coat. The flux enhancement strategies were compared against each other. The comparison was to identify the flux improvement strategy that resulted in the highest flux improvement and possibly optimize them.

From Fig. 6, it can be seen that the backwashing cycle of 3 h resulted in the highest average flux. This result implies that significant fouling of the WFMF membrane was from particles plugging the pores of the WFMF membrane and regular backwashing of the membrane was successful in removing these particles. The removal of the particles from the pore area cleared the path for the permeate to flow freely, resulting in high flux.

Second to the 3 h cycle backwashing was the 3 h cycle brushing, brushing forcibly removes the particles that were stuck on the WFMF membrane trenches. It was believed adsorption fouling was also loosened due to the force applied in brushing, even though this was for a short period of time. Removal of the particles in the membrane trenches, and agitating the adsorption fouling layer on the membrane was believed to be the main contributors to the good success of the 3 hourly brushing.

Flux improvement by controlling permeates flux and air scouring at 30 L/min was less than expected for both the flux enhancement strategies. The WFMF module design and the way flux was controlled made the flux control strategy ineffective because filtration rate on the membrane surface where fouling actually takes place was not impacted by the way the flux enhancement strategy was implemented. The lack of success by aeration was attributed to the fact that the shear offered by the rising air bubbles was not strong enough to remove particles trapped on difficult areas on the WFMF membrane.

The result from Fig. 6 shows that a single enhancement strategy was not sufficient enough, therefore a combination of flux enhancement strategies were used.

Fig. 7 clearly displays that combining two flux enhancement strategies had the most success in mitigating against WFMF membrane fouling and yielding higher average fluxes, with backwashing at the highest recovery of 187.2%. The advantage of combining two flux enhancement strategies lies in the fact that the limitation of the one strategy is covered by

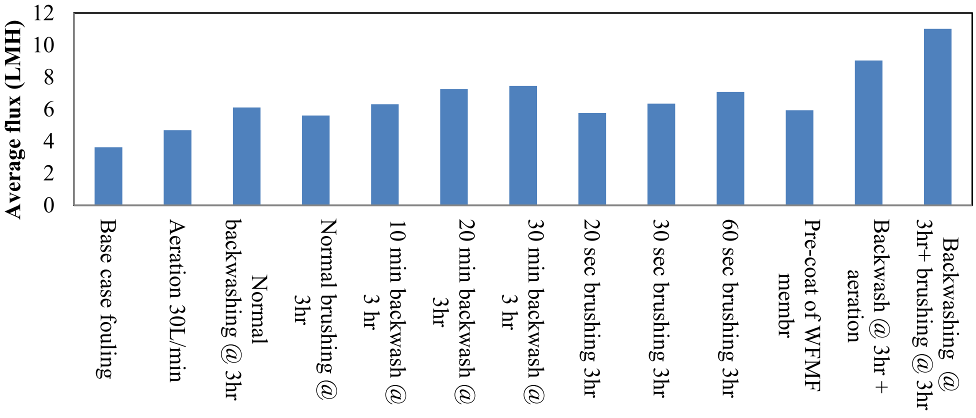

Fig. 7 – Comparison of various flux enhancement strategies on WFMF membrane.

Table 5 – Flux recovery table of comparison.

	New mem.	External brushing with feed	Brush. + soap	Soak in 0.3% NaOCl + brushing	Soak in 0.3% NaOCl only	High press. clean	Fouled mem.
Pure water flux (LMH)	60	43	49	56	47	58	3
Per. recovery		71.7	81.7	93.3	78	97	5

the strength of the other and the net result is high ability of the combined flux enhancement strategy to mitigate WFMF membrane fouling.

5.4. *Flux recovery*

Membrane cleaning aims to recover the membrane's original PWF after cleaning. Several membrane cleaning strategies were used to clean the WFMF membrane to recover its original flux. The cleaning strategies that were used to clean the WFMF membrane were brushing in tap water, brushing in a soap solution, brushing in a 0.3% NaOCl solution, soaking in a 0.3% NaOCl solution and high pressure cleaning. The results of PWF after cleaning are shown in Table 4.

Table 5 shows the results of flux recovery by different cleaning methods of a WFMF membrane. The membranes were cleaned using various cleaning methods as shown in Table 5. Once the membranes were cleaned the PWF experiments were repeated.

External brushing of the WFMF membranes with tap water recovered the PWF to 71.7%. The 71.7% recovery of flux by brushing was based on the removal of external fouling on the WFMF membrane because brushing had no access to the internal fouling of the WFMF membrane. External brushing of WFMF membranes removes both deposited particles on the membrane surface, trenches and also the adsorbed fouling on the membrane surface.

Brushing the membrane with a commercial soap solution recovered the PWF by 81.7%. The use of a detergent with brushing ensured that the strongly attached foulants on the membrane surface were loosened and removed by brushing. The emulsifying and dispersion effect of detergents were believed to be the factor that caused brushing of WFMF membrane in a commercial soap solution more effective than brushing the membrane with tap water alone. This is in agreement with a study by Abdelrasoul et al. (2013) which found that detergents are good emulsifying, dispersion and surface conditioners particularly for mud and clay stains.

Soaking of the WFMF membrane for an hour in a 0.3% hypochlorite solution followed with brushing recovered the PWF to 93.3%. Soaking the membranes only in the same solution recovered only the 78% of the PWF. The result shows that hypochlorite is effective in removing/loosening the strongly attached foulants both on the membrane surface and membrane internals. The loosened/removed particles included strong hydraulically attached particles on the membrane surface and chemically attached foulants (adsorbed fouling). The adsorbed materials in this study include bacteria, microbiologic contaminants, and organic particles. The combination of soaking the membranes in a 0.3% NaOCl and brushing ensured that fouling on the membrane was loosened by the oxidation and disinfection mechanism of NaOCl. Brushing ensured that the loosened attachments on the membrane are removed. The combined cleaning effect with this method resulted in the high PWF recovery of 93.3%. Chemical cleaning by oxidation and disinfection have also been studied by several researchers such as Holman and Ohlinger (2007), Arnal et al. (2012) and Abdelrasoul et al. (2013) who found similar findings when NaOCl was used as the cleaning chemical.

High pressure cleaning of the WFMF membranes recovered 97% of the PWF. This type of cleaning was only mechanical. 97% pure flux recovery by mechanical cleaning meant that the fouling on the membrane was more hydraulic than chemical. The low recovery by brushing alone was attributed to insufficient mechanical cleaning force by brushing alone. High pressure cleaning water was able to penetrate the WFMF membrane pores and mechanically clean the membrane surface. This method cleaned the membrane both externally and internally. According to Nguyen et al. (2012) microorganisms attach strongly on surfaces and this explains why it had to take high pressure cleaning to recover almost all of the PWF.

6. Conclusion

This study was aimed to evaluate the fouling mitigation and flux recovery of a new polyester woven fibre membrane for the treatment of raw water. WFMF were evaluated with respect to fouling and flux recovery. It was found that backwashing with a combination of flux enhancement strategy yielded the highest recovery of 187%. With respect to cleaning, 93% of the flux was recovered after the membranes were soaked for an hour in 0.3% hypochlorite followed by brushing. Most commercial membranes are susceptible to damage if not properly handled. Factors such as like lack of durability, short operational life span and lack of sustainability of the system have proven over the years to be major challenges in the implementation and survival of these systems in rural communities. The WFMF membranes were found to be sustainable with respect to durability, as such they can be used as POU system for the treatment of raw water in rural areas.

Acknowledgement

The authors wish to thank the Durban University of Technology for funding this research and the Young Water Professionals for organising a workshop with respect to article writing and publication.

References

Abdelrasoul, A., Doan, H., Lohi, A., 2013. Fouling in membrane filtration and remediation methods. In: Mass Transfer-Advances in Sustainable Energy and Environment Oriented Numerical Modeling. Intech Open Access Publisher, p. 195.

Alfa, D., Rathilal, S., Pillay, V.L., Chollom, M.N., 2016. Development and evaluation of small scale disinfection system. J. Water Sanit. Hyg. Dev. 389–400. http://dx.doi.org/10.2166/washdev.2016.093. Available online.

Arnal, J.M., Garcia-Fayos, B., Sancho, M., 2012. Membrane Cleaning. Universitat Politecnica, Valencia, Spain.

Bessiere, Y., Jefferson, B., Goslan, E., Bacchin, P., 2009. Effect of hydrophilic/hydrophobic fractions of natural organic matter on irreversible fouling of membranes. Desalination 249, 182–187.

Brikké, F., Bredero, M., 2003. Linking Technology Choice with Operation and Maintenance in the Context of Community Water Supply and Sanitation. World Health Organization and IRC Water and Sanitation Centre Geneva, Switzerland.

Chollom, M.N, Pikwa, K. Rathilal, S., Pillay, V.L. Evaluation of the effect of aeration on the woven fibre microfiltration membrane for treatment of raw water. Submitted on 4th June 2016 to J. Water Environ. Technol. Manuscript ID is JWET 16-042.

Hong, S., Faibish, R.S., Elimelech, M., 1997. Kinetics of permeate flux decline in crossflow membrane filtration of colloidal suspensions. J. Colloid Interface Sci. 196, 267–277.

Holman, S.R., Ohlinger, K.N., 2007. An Evaluation of Fouling Potential and Methods to Control Fouling in Microfiltration Membranes for Secondary Wastewater Effluent. WEFTEC.

Hwang, K.-J., Liao, C.-Y., Tung, K.-L., 2008. Effect of membrane pore size on the particle fouling in membrane filtration. Desalination 234 (1–3), 16–23.

Mecha, C.A., Pillay, V.L., 2014. Development and evaluation of woven fabric microfiltration membranes impregnated with silver nanoparticles for potable water treatment. J. Membr. Sci. 458 (0), 149–156.

Nguyen, T., Roddick, F.A., Fan, L., 2012. Biofouling of water treatment membranes: a review of the underlying causes. Monit. Tech. Control Meas. Membr. 2, 804–840.

Pinnekamp, I.J., 2003. Membrane Technology for Wastewatertreatment. Institute of Environmental Engineering for the RWTH Aachen University.

Sobsey, M.D., 2002. Managing Water in the Home: Accelerated Health Gains from Improved Water Supply. Department of Protection of the Human Environment World Health Organization, Geneva.

Sobsey, M.D., Stauber, C.E., Casanover, L.M., Brown, J.M., Elliott, M.A., 2008. Point of use household drinking water filtration, a practical, effective solution for providing sustained access to safe drinking water in the developing world. Environ. Sci. Technol. 42, 4261–4269.

Striemer, C.C., Gaborski, T.R., McGrath, J.L., Fauchet, P.M., 2006. Charge and size based separation of macromolecules using ultrathin silicon membranes. Nature 445, 749–753.

WHO, 2005. Health and the Millennium Development Goals. World Health Organization, Dept. of MDGs, Health and Development Policy. World Health Organization, Geneva.